COST Action FP0702

Net-Acoustics for Timber based lightweight buildings and elements

E-BOOK

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INTRODUCTION

Action FP0702 is a COST action in the field of Forestry and Forest Products. General information about the COST program can be found on the COST Website at http://www.cost.esf.org. COST Action FP0702 entered into force on February 2008; **15 European countries as well as Australia and New Zeeland** have participated in this Action. The Action lasted until 26 August 2012.

This COST Action has been focused on the **acoustics and low frequency vibration of timber based lightweight buildings**, for which methods for predicting and measuring performances, as well as methods for assessing comfort and acoustically designing buildings are not as well developed as for heavy building. Airborne and impact sound performances, and sound from service equipment have been considered over a frequency range including the low frequencies (50 to 100 Hz) where lightweight buildings are likely to have performances lower than in heavy buildings. Low frequency vibration (below 25 Hz) such as walking induced vibration of floors has also been considered, and particularly its subjective aspect.

Four working groups have been created, dealing with the above aspects: **WG1** on prediction methods for sound and vibration performances, **WG2** on measurement methods for sound and vibration performances, **WG3** on comfort assessment for sound and vibration and **WG4** on building acoustic design.

During this four year Action, knowledge has increased by gathering existing data, discussing proposals during WG meetings as well as by supporting, guiding and coordinating new research activities at national level in order to benefit from this research work. The main outcomes of these activities, focused on predicting and measuring building performances as well as assessing comfort and designing buildings with proper serviceability are presented in this **e-book**.

The e-book is divided into four chapters, corresponding to the activities of the four working groups:

- In **Chapter1** (**WG1** - Prediction methods for sound and vibration performances), the final proposals for prediction of the relevant building performances, resulting from discussions during WG1 meetings, are presented separately for acoustics and vibration; the documents produced are technical proposals which can be used as work documents in standardization committees

- In **Chapter2** (**WG2** - Measurement methods for sound and vibration performances), several papers propose general methods adapted to lightweight wood frame buildings for measuring sound or vibration quantities, identified in WG1 and relevant for evaluating and predicting building performances. These papers have been written by different WG2 members, from work performed or knowledge gathered in their institutes.

- In **Chapter3** (**WG3** – Comfort assessment for sound and vibration), a single document is presented, summarizing the WG3 activities, focused on the vibrational serviceability of timber floors and discussing and comparing the different criteria and variants used in the European countries and beyond. It should be noticed that not much has been done concerning comfort assessment for low frequency sound, mostly because of the lack of activities at the member institutes on this subject or because of activities performed for the private sector and not publicly available; however, this subject is part of the objectives of the on-going COST Action TU0901 (in activity up to the end of 2013), focused on harmonizing sound descriptors and classification schemes in Europe for all type of buildings and where several members are also members of FP0702; hopefully, useful results will be soon produced.

- In **Chapter4** (**WG4** – Building acoustic design), a single document is also presented, which goal is to give an idea of the different construction methods and the different building elements and junctions between building elements. An overview of “do’s and don’ts” are also given, as well as examples of innovative solutions.

As said above, one of the main objectives of the Action was to support, guide and coordinate new **research activities at national level** on timber based lightweight buildings in order to benefit from the results of these activities and make progress (since no research is financially supported by COST). However, **only the main outcomes are presented in this e-book** and not the results of all the studies performed at the different institutes during the action. In order for the reader of this e-book to have a better idea about these research activities and find information, an “overview of research” document has been created giving the current (and previous) research topics performed at the different institutes and the associated available papers and presentations. This document is given in **Chapter5**.

Finally it should be mentioned that **3 workshops** have been organized during this four year Action: in Växjo Sweden (2009), Delft The Netherlands (2010) and Zürich Switzerland (2011), where technical presentations on the different subjects considered were given; a list of these presentations can be viewed (and downloaded) on the Action Website [http://extranet.cstb.fr/sites/cost] and has also been put on the USB keys distributed at the FP0702 Final Conference organized in Grenoble France on October 18, 2012.

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CHAPTER 1
PREDICTION METHODS FOR SOUND AND VIBRATION PERFORMANCES, INCLUDING LOW FREQUENCIES

COST Action FP0702

Net-Acoustics for Timber based Lightweight Buildings and Elements

Working Group 1: Prediction methods for sound and vibration performances

CONTENTS

This chapter presents the final proposals for prediction of the relevant building performances, resulting from discussions during WG1 meetings; the proposals are presented separately for acoustics and vibration. The two documents produced can be seen as technical proposals which can be used as work documents in standardization committees

1 - FINAL PROPOSAL FOR PREDICTION OF ACOUSTIC PERFORMANCE IN LIGHTWEIGHT BUILDINGS

1.1 - Introduction

Lightweight building systems can have various appearances, combing heavy and light weight elements, lightweight homogeneous or lightweight composed elements and coupling between elements in various ways. Some important common aspects, different from the generally more heavy building elements normally considered are the clearer need to distinguish between forced and resonant transmission, the damping within the elements and the additional transmission paths between composed, layered elements. Based on the research work over the last years as regularly presented within this COST action and the discussion within this COST action, the global contours of an approach to predict sound transmission for lightweight buildings systems are emerging. This approach is based on refining and adjusting the model in EN 12354 in order to fit the specifics of lightweight building systems indicating also how to collect the necessary input data through measurements and calculations. While other methods can also be used for predicting acoustic performance of complete systems or elements, like FEM, SEA or reverse SEA measurements, it is felt that the EN 12354 approach can provide a practical method on an engineering level also for light weight building systems.

This memo will summarized the possible approach for the most important items in preparation for proposals to CEN/TC126/WG2 to amend EN 12354 accordingly

1.2 - EN 12354 bases

The bases for EN 12354-1 is the paper by Gerretsen (1979) applying power transmission and reciprocity:

$$\tau_{ij} = \tau_i d_{ij} \frac{\sigma_j}{\sigma_i} \frac{S_j}{S_s}$$

$$\tau_{ij} = \sqrt{\tau_i \tau_j} \sqrt{d_{ij} d_{ji}} \frac{\sqrt{S_i S_j}}{S_s} \qquad (1a)$$

where

τ_{ij} is the flanking transmission factor for path from element i to element j;

τ_i, τ_j is the transmission factor for resp. element i and element j;

d_{ij} is the average vibration ratio between excited element i and element j;

S_s, S_i, S_j are the areas of the separating element, element i and element j, in m^2;

σ_i, σ_j is the radiation factor for resp. element i and element j;

This is applicable to the whole frequency range provided that the transmission coefficients are for free transmission only with the main assumption that the radiation efficiency is not varying with wall dimensions; this was confirmed Bosmans & Nightingale in their comparison with SEA modeling. In all cases the additional presumption is that the forced waves in the sending side do not create a significant contribution to the free waves at the receiving side. To be more accurate equation (1) with these assumptions should have been written as, where the additional subscript *r* and *s* refer to resonant vibrations and structural excitation respectively:

$$\tau_{ij} = \tau_{r,i} d_{s,ij} \frac{\sigma_{r,j}}{\sigma_{r,i}} \frac{S_j}{S_s}$$
$$\tau_{ij} = \sqrt{\tau_{r,i}\tau_{r,j}} \sqrt{d_{s,ij} d_{s,ji}} \frac{\sqrt{S_i S_j}}{S_s} \quad (1b)$$

A comparable but different approach would have been to base the derivation on airborne excitation (though than a direct link to impact sound could be more questionable), indicated with an additional subscript *a*:

$$\tau_{ij} = \tau_{a,i} d_{a,ij} \frac{\sigma_{r,j}}{\sigma_{a,i}} \frac{S_j}{S_s}$$
$$\tau_{ij} = \sqrt{\tau_{a,i}\tau_{a,j}} \sqrt{d_{a,ij} d_{a,ji}} \frac{\sqrt{S_i S_j}}{S_s} \sqrt{\frac{\sigma_{r,i}\sigma_{r,j}}{\sigma_{a,i}\sigma_{a,j}}} \quad (1c)$$

As deduced in section 1.3., as a first approximation, the last term here is precisely the term to transfer the total transmission coefficient for airborne excitation into the one for free transmission (resonant transmission only), if we assume (reasonable with indirect excitation) that $\sigma_r = \sigma_s$.

Or if we use the second relation to transfer the transmission coefficient, we get a term which precisely transfers also the velocity ratio for airborne excitation in the one for structural excitation.

So the two approaches are identical, but for the difference and/or equality between vibration level difference with airborne and with structural excitation. The most practical to chose would basically be (1b): it is currently used in EN 12354, junction transmission is measured easier and is identical for airborne and impact sound transmission. So far only more or less homogeneous single elements have been considered, not only heavy, but also lightweight ones. This approach is now to be extended with the possibilities and additional aspects for double and triple constructions. In that case special attention is required for which element is to be considered in the predictions, the double element as a whole or just the inner leaf, single or multilayered. In principle both is possible in combination with the appropriate K_{ij}, which will be quite different. The choice will depend largely on the type of input data available. Considering the double element as a whole opens the possibility to apply measured data for the sound reduction index, but the K_{ij} measurements have to be adjusted to this choice (see ISO 10848). Considering primarily the inner leaf makes the K_{ij} measurements more straight forward, but the sound reduction index often is not directly available.

1.3 - Sound reduction index *R* for resonant transmission

One important item for lightweight elements, certainly homogeneous elements is the need to consider only resonant transmission in flanking path and hence the need to know *R* of the element for resonant transmission only. This means at the same time that for the corresponding transmission over the junction, K_{ij} shall also be for resonant transmission only and thus determined by mechanical excitation. Although somewhat different approaches seem also possible, this seems to be the most practical and appropriate approach.

The sound reduction index *R* as input can be based on pure calculation or, more common, laboratory measurements in accordance with ISO 10140.

Calculated input data

In case of calculated values for the sound reduction index these shall only refer to resonant transmission. For homogeneous elements this is already mentioned and presented in EN 12354-1, annex B, though the given equation needs some minor adjustment (i.e Davy [1]); see N20. For more complex elements other models from literature could be used, for layered elements possibly based on SEA. Care should be taken that with commercially available models it might not be possible to delete the forced transmission.

However, recent research has indicated that reliable predictions for the resonant transmission are hardly possible at the time [10], either due to insufficient estimates of the radiation efficiencies and/or the actual damping in the lightweight elements. Therefore this approach is not recommended for (very) lightweight elements.

Measured input data

Completely based on measured data, R_{lab}, we need not only the sound reduction index but also the measured radiation efficiencies with airborne and structural excitation. The correction is than given by [2]

$$R^*_{lab} = R_{lab} + 10\lg\left[1 + \frac{\sigma_f}{\sigma_r}\frac{\sigma_a - \sigma_r}{\sigma_f - \sigma_a}\right] \approx R_{lab} + 10\lg\frac{\sigma_a}{\sigma_s}\frac{1-\sigma_s}{1-\sigma_a} \approx R_{lab} + 10\lg\frac{\sigma_a}{\sigma_s} \qquad (2)$$

where σ_f and σ_r are radiation efficiencies for forced and resonant transmission (theory) and σ_a and σ_s are the radiation efficiencies with resp. airborne and structural excitation (measurement). The assumption in the estimations is that $\sigma_r = \sigma_s$ and $\sigma_f \approx 1$. It is recommended to apply only the most right estimation of the correction term in predictions.

As stated before, calculation of the correction term is as yet insufficiently reliable, so it should be based on measurements. Most recent measurements [2], [5], [9], [10], [11] have indicated that in case of double elements the correction is small or negligible, so as global estimate the measured data can be applied without correction in that case (correction of 0 dB). For single, homogeneous or layered, elements the correction seems to be reasonably independent of the type of element and around 8 to 10 dB below the critical frequency. This opens possibilities for global estimates of the correction in case measured data is not available (see later).

Measured sound reduction index only

The most common case currently is that only measured data on the sound reduction index are available, to which corrections according to eq. 2 should be applied. Since calculations of the radiation efficiency ratio has proven to be unreliable, in that case only a global correction can be applied, based on the measured data currently available. As summarized above, a global estimation of the correction could be as follows: no correction for double (or triple) elements and a correction of 8 dB for single, homogeneous or layered, elements below the critical frequency only. A simple implementation of this last correction is applying the method of subtracting the contribution of forced transmission with a limit of 8 dB. Although that method in itself is not very reliable due to the normally small contribution of the resonant transmission, it provides a smooth calculation method with continuous results over the frequency range without the need to know the critical frequency exactly [3]. The only values needed for this correction are the mass *m'* of the element and the radiation efficiency σ_f which is readily available for the fixed laboratory situation (10 m^2)

For $f \leq 2 f_c \approx 88000 / m'$ it follows:

$$\boldsymbol{R}^{*} = \boldsymbol{R}_{meas} + 10\,\mathbf{lg}\left[1 - 10^{\boldsymbol{R}_{meas}/10}\left(\frac{2\rho \boldsymbol{c}}{2\pi \boldsymbol{f}\boldsymbol{m}'}\right)^{2} 2\sigma_{f}\right]^{-1} \tag{3}$$

If the term between [ ] becomes smaller than 0,16 or even negative the correction shall be limited to 8 dB.

1.4 - Presenting overall performance per transmission path (D_{nf}, L_{nf})

1.4.1 - General

In lightweight building systems the elements normally have a larger damping and the vibration levels are thus less effected by the energy losses at the borders. Furthermore, with light elements the laboratory sound reduction index is also mainly determined by internal damping and thus independent form the situation in which it is built into. That means that measurement results in a mock-up or a field situation with reasonable dimension will give results that can easier by transferred to other situations and dimensions. In other words, the results for the overall flanking transmission, D_{nf} or L_{nf}, in one -laboratory – situation can be transferred to other situations as already indicated in EN 12354 [4].

$$R_{ij} = D_{nf} + 10\lg\frac{S_s l_{ij,lab}}{A_0 l_{ij}}; \quad L_{n,ij} = L_{nf} - 10\lg\frac{S_i l_{ij,lab}}{S_{i,lab} l_{ij}} \tag{4}$$

where l_{ij} and S_i refer to coupling length and excited area in the field situation and the same quantities with the additional subscript *lab* to the laboratory situation. This can be combined with estimations for other paths, either using the same equation or combining it with predictions following EN 12354 if appropriate.

1.4.2 - Direct measurement

In ISO 10848 it is prescribed how D_{nf} en L_{nf} can be measured in dedicated lab facilities. These measurements refer only to the path Ff. Though it seems that in many lightweight building that indeed is the dominating flanking path, we have seen element combinations and junctions were other paths, like Fd or Df, have a considerable contribution. Hence, those path can not be neglected from the start. Measuring D_{nf} and L_{nf} for other paths is not a principle problems but mainly a practical problem: the separating element should also be representative for the junction studied and transmission by the other paths than the one studied must be reduced by linings. Such an approach have been taken by the research at NRC, Canada, for instance. So direct measurements for each relevant flanking paths following eq. (4). will provide the data needed for predictions following 1.3.1

$$D_{nf} = L_s - L_r - 10\lg\frac{A}{A_0}; \quad L_{nf} = L_r + 10\lg\frac{A}{A_0} \tag{5}$$

1.4.3 - Hybrid approach

Besides direct measurements the overall flanking transmission could also be estimated from a combination of measured and calculated data. If the element damping is indeed not varying much between situation, as is the presumption for the application of D_{nf}, than it could be expressed as:

$$\begin{aligned} \boldsymbol{D_{nf}} &= \frac{\boldsymbol{R_i}}{2} + \frac{\boldsymbol{R_j}}{2} + \Delta\boldsymbol{R_i} + \Delta\boldsymbol{R_j} + \overline{\boldsymbol{D_{v,ij,n}}} + 10\,\mathbf{lg}\frac{\boldsymbol{A_o}}{\boldsymbol{l_{ij,lab}}} \\ \boldsymbol{L_{nf}} &= \boldsymbol{L_{n,ii}} + \frac{(\boldsymbol{R_i} - \boldsymbol{R_j})}{2} - \Delta\boldsymbol{L_i} - \Delta\boldsymbol{R_j} - \overline{\boldsymbol{D_{v,ij,n}}} - 10\,\mathbf{lg}\frac{\boldsymbol{S_{i,lab}}}{\boldsymbol{l_{ij,lab}}} \end{aligned} \tag{6}$$

where $l_{ij,lab}$ = 4,5 m (horizontal junction) or 2,6 m (vertical junction) and $S_{i,lab} \approx 19\ m^2$, R is the sound reduction index of the indicated element, L_n the normalized impact sound pressure level and ΔR the improvement of the sound reduction index by a lining for the indicated element.

The new quantity for the junction is actually the K_{ij} from ISO 10848 and EN 12354 with standardization to area. The make a more clear distinction this is further denoted as $\overline{D_{v,ij,n}}$; see also 1.4.4.

So D_{nf} can be estimated from the knowledge on elements, junctions and linings, either based on measurement or on calculations. The advantage of this approach is that it can be estimated more easily what would be the effect of changes in the elements. Furthermore, since R and K_{ij} or $\overline{D_{v,ij,n}}$ can vary hugely in number and it is only the combination that gives a correct ranking of systems, a correct ranking is directly provided by D_{nf} and not for instance by a high value for K_{ij} or $\overline{D_{v,ij,n}}$.

In eq. (5) distinction is made between the element and linings (ΔR, ΔL). Some research [4] has shown that indeed also for lightweight elements these can be treated independent, though the assumption $\Delta R_{direct} = \Delta R_f$ seems no longer valid.

1.4.4 - Renewed definition of $K_{,ij}$

With damped elements the standardization on damping is not only not necessary – no large differences between situations – but the structural reverberation time may also not be relevant in those cases. The structural reverberation time can be dominated by local effects, while the attenuation over distance is what should be taken into account (with homogeneous elements these are directly coupled but not necessarily with composed light weight elements). Hence, the practical and appropriate definition for the junction attenuation will be the normalized direction-average velocity level difference:

$$\overline{D_{v,ij,n}} = \frac{D_{v,ij}}{2} + \frac{D_{v,ji}}{2} + 10\lg\frac{l_{ij}}{\sqrt{S_{m,i}S_{m,j}}} \qquad (7)$$

were $S_{m,i}$ and $S_{m,j}$ are the measurement areas, equal or smaller than the element areas. In this way this quantity includes both the reduction effects at the actual junction as well as level reductions over the damped element. If the areas are not too small the result will be independent of the actual area. (in the current versions of EN 12354 and ISO 10848 this quantity is also denoted as K_{ij}). Furthermore it must be added, that due to the inclusions of the element damping it is necessary to specify additional positions for excitation and measurement (at least also not to far from the junction line). As a global estimate the effect of the junction and the element damping could be estimated by:

$$\overline{D_{v,ij,n}} \approx K_{ij,junction} + 10\lg\sqrt{\delta_i\delta_j} \qquad (8)$$

where $K_{ij,junction}$ could be estimated by taking into account the structural reverberation times for reasonable homogeneous elements and δ_i and δ_i are the average extra attenuation in dB per meter, over the geometric spreading of the elements. Eq. (7) could be used to estimate the effect of added damping to an element on $\overline{D_{v,ij,n}}$. Determining δ from measurements could be added to the measurement standard ISO 10848.

1.4.5 - Undamped elements in lightweight building systems

In lightweight building systems also less light and hardly damped elements can be present, or instance a concrete layer in the floor. Though in such cases the damping for such elements could be taken into account through the actual structural reverberation time, the variation in damping is likely to be rather small – mainly internal, small amount of border loss - , so it could be dealt with simpler. That means in $\overline{D_{v,ij,n}}$ and /or D_{nf} and L_{nf} with such elements can be treated as all the lightweight elements. The main effect will be that the sound reduction index and/or normalized impact sound pressure level can be quite different from the one determined under laboratory situations: the damping in the lab (losses at the border) will be generally larger than in the field here. The effect can not be neglected. Besides the possibility to estimate it by detailed calculations, a global estimate that could be used would be:

$$R^{*}_{situ} = R^{*}_{lab} + 10\lg \frac{0{,}01 + 0{,}05/\sqrt{f}}{0{,}01 + (m/485)/\sqrt{f}} \qquad (9)$$

1.5 - Impact sound transmission and sound due to service equipment

For impact sound transmission the approach can be fully identical, especially since structural excitation for K_{ij} or $\overline{D_{v,ij,n}}$ has been chosen. The use in this case of the total flanking transmission L_{nf}, directly measured or the hybrid approach, has already been presented. It is to be discussed if specific additional transmission path need to be considered in case of the application of floating floors [6].

For sound due to service equipment more or less the same holds, but for one aspect. Due to the fact that a piece of equipment will mostly excite the structure at one point or small area only, and not random over the element as with the tapping machine, that excitation point in relation to the junction can be important in case of well damped elements. Adjustment terms for that have been studied and proposed [3] but need further attention.

1.6 - References

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[10] Mahn, J. and J. Pearse, J.. *The calculation of the resonant sound reduction index for use in EN12354*, Euronoise 2012, Prague, Czech Republic, 10-13 June 2012, 168-173.

[11] Schoenwald, S.. *Comparison of proposed methods to include lightweight framed structures in EN12354 prediction model*, Euronoise 2012, Prague, Czech Republic, 10-13 June 2012, 174-179.

2 - FINAL PROPOSALS FOR PREDICTION OF RELEVANT VIBRATION QUANTITIES IN BUILDINGS

2.1 - Introduction

The low- frequency behaviour of floors with respect to walking induced vibrations, both on the same floor as the walker as on a neighbouring floor, is important for the comfort assessment. Yet the best descriptor for the subjective assessment of these vibrations is not yet completely clear or agreed.

For the 'own' floor the Canadian approach seems the best for the time being, so fundamental frequency f_r and unit force deflection w will have to be predicted. Furthermore, the damping is to be added as important factor and a response, for instance the unit impulse response v_{rms} [1] or the single step response OS-RMS$_{90}$ [3]. These last two quantities are the only one that can also be applied for neighbouring floors.

For the prediction of f_r and w it seems that the Eurocode 5 [1] approach is adequate, some improvements have been discussed in the report by de Klerk (STSM [2], see also Delft workshop). So a proposal is made, based on this report, to improve the Eurocode somewhat. (it should be checked if Eurocode 3 for steel constructions offers additional information that could be applicable).

For the response on the own floor or neighboring floor no simplified analytical method has been found adequate, hence a proper FEM-calculation is needed to calculate a transfer function as bases for the appropriate descriptor. However, due to the complexity of lightweight floors and building junctions the modelling is not self evident. A proposal is made for a step-by-step plan to create simplified but reproducible FEM-models that reliably represent the complex lightweight floors and junctions.

The proposals in this memo should be helpful to improve and extend existing standards like the Eurocodes and will be presented to the appropriate standardisation bodies.

2.2 - Own floor: fundamental frequency and unit load deflection

2.2.1 - fundamental frequency

2.2.1.1 - *isotropic plate*

To predict the fundamental frequency f_r the Euler-Bernoulli model as currently used in the Eurocode-5 seems adequate for solid and solid joist floors:

$$f_r = \frac{C}{2\pi l^2}\sqrt{\frac{D}{m}} \quad \text{with} \quad D = \frac{Eh^3}{12(1-\upsilon^2)} \tag{1a}$$

For joisted floors an improvement can be achieved by taking shear into account , leading to:

$$f_r = \frac{C}{2\pi l^2}\sqrt{\frac{D}{m}}\left[\frac{\pi^2}{L^2}\frac{D}{k'GA}+1\right]^{-1/2} \tag{1b}$$

where

D is the bending stiffness per unit width, in Nm;

E is Youngs modulus, in N/m^2;

h is the plate thickness, in m;

m is the area mass, in kg/m^2;

l is the span width, in m;

b is the floor width, in m;

C is a number depending on the dimensions and type of support of the floor and can be taken from table 1 according to Leissa or Blevin [4], [5];

k' is a shape factor for the joists which can be taken as $k' \approx 0,85$ for rectangular wooden beams;

G is shear stiffness, in N/m^2;

A is the effective beam cross section, in m^2.

Table 1: C-value for fundamental frequency ($f_r = f_{11}$) for orthotropic plates with SFSF support.

ratio	C from Leissa	C from Blevin
l/b = 0,5	9,87 (= π^2)	9,74
l/b = 1,0	9,87	9,63
l/b = 2,0	9,87	9,52

The results according to Leissa are thus somewhat higher than according to Blevin.

2.2.1.2 - ***orthotropic plate***

Orthotropic plate means orthogonal and anisotropic, with different stiffness ($D_x > D_y$) in the two directions of the plate. For floor constructions with wooden beams the Poisson's ratio can normally be neglected, i.e. $\nu = 0$. To predict the fundamental frequency f_r with that assumption Leissa proposes for simply supported floors all around (S-S-S-S):

$$\boldsymbol{f_r} = \frac{\pi^2}{2\pi \boldsymbol{l}^2}\sqrt{\frac{\boldsymbol{D_y}}{\boldsymbol{m}}\left[\left(\frac{\boldsymbol{l}}{\boldsymbol{b}}\right)^4 + \frac{\boldsymbol{D_x}}{\boldsymbol{D_y}} + 2\left(\frac{\boldsymbol{l}}{\boldsymbol{b}}\right)^2 \frac{\boldsymbol{D_{xy}}}{\boldsymbol{D_y}}\right]} \tag{2a}$$

D_{xy} can often be taken as D_y.

For free and simply supported plates (S-F-S-F) the results is:

$$\boldsymbol{f_r} = \frac{\pi^2}{2\pi \boldsymbol{l}^2}\sqrt{\frac{\boldsymbol{D_x}}{\boldsymbol{m}}} \tag{2b}$$

The same as with the isotropic plate, but in general the use of equation (2a) is recommended.

2.2.2 - *unit load deflection*

The unit load deflection *w* according to the Eurocode (load of 1000 N) can be estimated as:

$$\boldsymbol{w} = \frac{10^3 \boldsymbol{L}^3}{48\boldsymbol{EI}} \tag{3}$$

However, this formula is much too simple for plates structurally fastened to the beams. For such cases at present no simple, analytical equation is available, so the use of an adequate FEM model is necessary.

2.3 - FEM modeling for dynamic response, own floor and neighbor floor

2.3.1 - Modelling, transfer function and response descriptor

In the next paragraph 2.3.2 the floors and junction will be modelled step by step. In paragraph 2.3.3 recommendations are given to calculate the transfer mobility with the derived model and paragraph 2.3.4 gives the possibilities to use this transfer mobility to calculate appropriate responses for walking induced vibrations. Finally paragraph 2.3.5 compares calculated mobilities with measurement results.

2.3.2 - Step by step modelling

2.3.2.1 - *Step 1: Choosing the boundary conditions*

The choice of boundary conditions to be deployed in the model depends on the type of junction under investigation. The way in which the floors and the walls are connected to the junction is typical for specific junctions and thereby defines the boundary conditions in the model. Figure 1 displays schematically the boundary conditions of all relevant types of lightweight junctions.

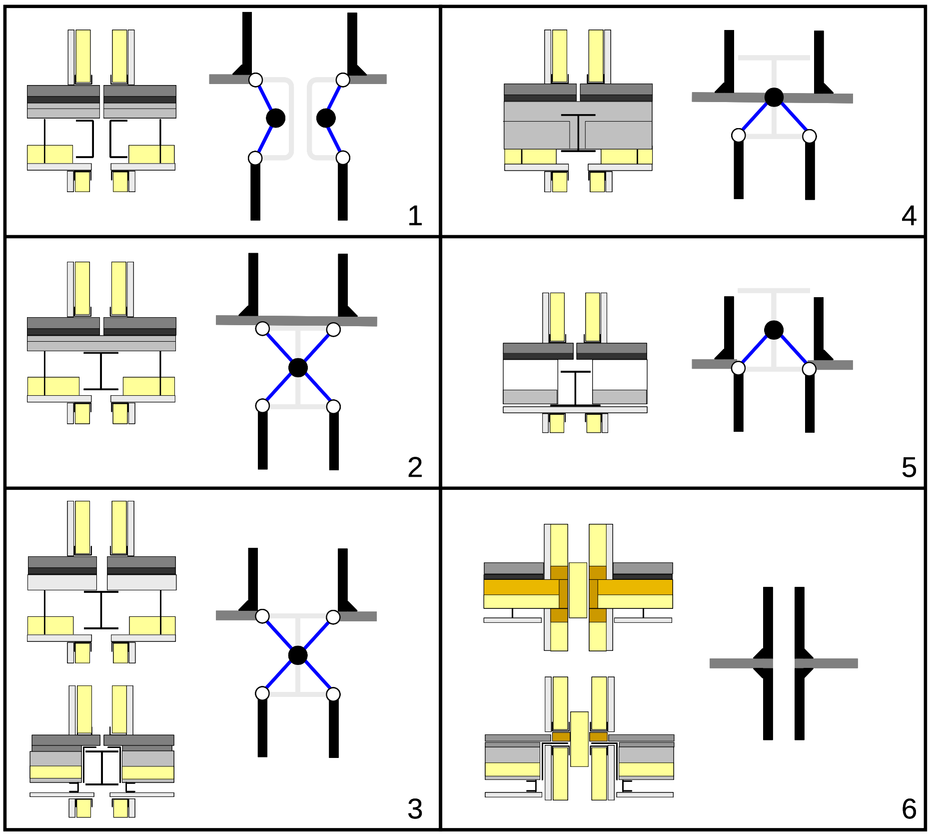

Figure 1: The required six types of boundary conditions to model all relevant types of lightweight junctions.

The modeller determines in which category the building system belongs and from the figure above he knows which boundary conditions are to be applied. The six types of boundary conditions are determined from a study in which all relevant lightweight building systems in the Netherlands are investigated. In the following a short description of the types is given.

***Type 1*:**

In group 1 the systems, consisting of a steel skeleton with floors supported by dilated joists, can be found. The floors are simply supported by the joist which is denoted by the white dots. Further, the floors are cinematically coupled to the joists. This is denoted by the blue lines. It basically means that the eccentricity has to be taken into account. Due to the weight of the walls it can be assumed that these are clamped at the bottom to the floors. On the top of the walls a hinged connection to the joists is assumed.

***Type 2*:**

In group 2 the systems, consisting of a steel skeleton with a single floor passing through the dwelling separating wall supported by a single joist, can be found. The base floor passes over the junction. It is therefore simply supported on the edges of the flanges of the joist. This is denoted by the white dots. Due to the weight of the walls it can be assumed that these are clamped at the bottom to the floors. On the top of the walls a hinged connection to the joists is assumed. The blue lines denote the node pairs that a kinematically coupled.

***Type 3*:**

In group 3 the systems, consisting of a steel skeleton with floors supported by single joists, can be found. In this group the floors are simply supported on the edges of the flanges of the joists. This is denoted by the white dots. Due to the weight of the walls it can be assumed that these are clamped at the bottom to the floors. On the top of the walls a hinged connection to the joists is assumed. The blue lines denote the node pairs that a kinematically coupled.

***Type 4*:**

In group 4 the systems, consisting of a steel skeleton with the joist moulded into the floors, can be found. As the joists are moulded into the floors, a clamped coupling between the joists and the floors has to be assumed. This is denoted by the black dots. Due to the weight of the walls it can be assumed that these are clamped at the bottom to the floors. On the top of the walls a hinged connection to the joists is assumed. The blue lines denote the node pairs that a cinematically coupled.

***Type 5*:**

In group 5 the systems, consisting of a steel skeleton with floors supported by the lower flange of single joists, can be found. Systems belonging to group 5 are modelled equally as the systems belonging to group 3. The only difference lies in the fact the the floors in group 5 are supported by the lower flange of the joists.

***Type 6*:**

The systems consisting of wooden skeletons or a steel frame can be found in group 6. These junctions are characterised by the horizontal decoupling between dwellings. The systems belonging to the platform method and those belonging to the balloon method are modelled equally. Due to the weight and the supporting role of the walls, it is assumed that these are clamped in between the floors.

Kinematical couplings can be realised without difficulty in the majority of commercially available FEM-packages. It is important that the modeller connects the building components properly (either hinged or clamped) and that the relative position between the components is taken into consideration. In the FEM-package DIANA, which is developed by TNO, the kinematical couplings can be realised by so-called *tyings*.

2.3.2.2 - ***Step 2: Modelling the floors***

As soon as the boundary conditions are determined, the floors are modelled subsequently. These, generally inhomogeneous, floors are represented by the modeller as equivalent homogeneous orthotropic plates with equal dimensions in the tangential plane. The process of homogenisation is performed according to the following steps:

- Choose a fictitious thickness h for the equivalent plate in the order of 1% of the span. Alternatively the thickness h can also be chosen such that the volume of the equivalent plate equals the volume of the real floor.
- Compute the bending stiffness per meter of the floor in the carrying direction, EI_y, and in the direction perpendicular to this, EI_x.
- If floor screed is applied, then its bending stiffness per meter has to be simply the bending stiffness of the base floor. It is assumed that no shear is transferred from the base floor to the floor screed.
- Compute the equivalent Young's moduli E_y and E_x such, that the homogeneous orthotropic plate contains a bending stiffness equal to that of the real floor (in both directions).
- The Poisson coefficients ν_{xy}, ν_{yz} and ν_{zx} of the equivalent plate are set equal to zero.
- The density of the homogeneous plate, ρ, is computed such that the total mass equals the total mass of the floor (base floor + floor screed + (suspended) ceiling). For the suspended ceiling it is thus assumed that only its mass will be taken into account.

The computed material properties are assigned to the orthotropic plate. Subsequently the element size D of the finite elements, discretising the floor, has to be chosen as

$$D = 0.2\lambda \quad \text{with} \quad \lambda = \sqrt{1.8c\frac{h}{f}} \quad \text{and} \quad c = \sqrt{\frac{E_{\min}}{\rho}}, \tag{4}$$

where f is the maximum frequency to be simulated with the model.

For resilient layers in the floor, as well as resilient supports of the floor, it is assumed that the resonance frequency is well above frequency domain of interest. Therefore no additional damping has to be taken into account.

2.3.2.3 - ***Step 3: Modelling the walls and the joists***

The, generally inhomogeneous, lightweight walls are also represented by equivalent homogeneous orthotropic plates. The procedure of homogenisation is equal to that described in step 2 for the floors. The supporting structure (of the categories 1 to 5) is modelled as a framework of finite beam elements. The properties of the beam elements are chosen such that the bending stiffness EI in both directions perpendicular to the longitudinal direction, the torsion stiffness GI_t and the mass per length μ are equal to those of the real beam.

2.3.2.4 - ***Step 4: Modelling the damping***

The damping ratio ζ is the last parameter defining the model. Determining the damping ratio by measurement is preferable. In case this is not possible, then the modeller is referred to the table published in the SBR guideline [3] (see Table 1).). In this table the damping for the whole system is determined as the sum of three parts. The three parts depend either on the used material of the floor, the type of furniture or the presence of floor screed and a suspended ceiling.

The damping ratio is simulated in the model using the Rayleigh damping model. The Rayleigh damping is computed using two quantities, namely the mass-factor α and the stiffness-factor β. The damping ratio ζ is then determined as

$$2\zeta\omega = \alpha + \beta\omega^2 \tag{5}$$

The Rayleigh damping is thus a frequency depending quantity. Generally, two frequencies are chosen with the corresponding damping ratios. From these two pairs, the two unknown α and β can be determined. Since the first eigenmode is the most dominant one when determining de OS-RMS$_{90}$ value it is important that the damping ratio at that frequency is fulfilled. Therefore the factor β can be set equal zero and α can be determined such that the damping at the first eigenfrequency is fulfilled identically. Therefore the modeller initially has to perform an eigenvalue analysis of the model in order to determine the eigenfrequency of the first bending mode of the floors.

Table 1: Table for determining the damping ratio [3].

Type	**Damping [%]**
Damping (material) ζ_1	
Wood	6%
Concrete	2%
Steel	1%
Steel-concrete	1%
Damping (furniture) ζ_2	
Traditional office for 1 to 3 people with separating walls	2%
Paperless office	0%
Office with open spaces	1%
Library	1%
Residences	1%
Schools	0%
Gymnasiums	0%
Damping (finishing) ζ_3	
Suspended ceiling	1%
Floating Floor screed	1%
Total Damping $\zeta = \zeta_1 + \zeta_2 + \zeta_3$	

2.3.3 - Computation of Y

The FEM-model is completed after performing the steps 1 to 4. The last step is to determine the transfer function, the transfer mobility's *Y,* with the created model. This can be done in three different ways. Which way has to be chosen, depends on the possibilities of the used FEM-software. Other quantities can be calculated from such mobility's or directly.

Explicit computation in the time domain

In an explicit computation in the time domain the modeller defines a force *F(t)* directed downward at the excitation position as

$$F(t) = \begin{cases} \sin\left(\pi \dfrac{t}{0.01}\right) & t < 0.01\text{s} \\ 0 & 0.01\text{s} \le t \le 4\text{s} \end{cases} \tag{6}$$

The time step size Δt is mostly chosen by the FEM-software such that the calculations remain stable. In case the time step size is not chosen automatically then is can be determined by the modeller as

$$\Delta t = 0.9 \frac{2}{\omega_{\max}} \tag{7}$$

where $\omega_{\max}$ denotes the maximum angular eigenfrequency of the system, which can be determined by an eigenvalue analysis. The described determination of the time step size is used with the common explicit *central difference* scheme. The maximum simulation time is set equal to 4s.

The transfer mobility, relating the velocity at the response point to the force at the excitation point, is determined by dividing the velocity spectrum by the force spectrum. For this procedure the modeller should use FFT-software (e.g. Matlab) to determine both spectra from the time traces generated by the FEM-software and determine the the relevant transfer mobilities *Y.*

Implicit computation in the time domain

In an implicit computation in the time domain the modeller defines a force *F(t)* directed downward at the excitation position as

$$F(t) = \begin{cases} \sin\left(\pi \dfrac{t}{0.01}\right) & t < 0.01\text{s} \\ 0 & 0.01\text{s} \le t \le 4\text{s} \end{cases} \tag{8}$$

The time step size Δt is chosen equal to 2 ms. This time step size satisfies the Nyquist criterium more than sufficiently in order to create spectra up to 80Hz. The maximum simulation time is set equal to 4s. Since the implicit computations are based on the inversion of large matrices, it is common that explicit computations use less computation time for these kind of analyses, even though the maximum time step size in implicit computations can be chosen much larger.

The transfer mobility, relating the velocity at the response point to the force at the excitation point, is determined by dividing the velocity spectrum by the force spectrum. For this procedure the modeller should use FFT-software (e.g. Matlab) to determine both spectra from the time traces generated by the FEM-software and determine the transfer mobilities *Y*.

Harmonic response analysis

In a harmonic response analysis the transfer mobility's can be determined in the FEM-software without the intervention of signal analysis procedures. Such an analysis is namely performed in the frequency domain. The transfer mobility's Y should be determined in the frequency range from 1Hz to 80 Hz. according to the SBR guideline [3]. However, in most cases it has appeared sufficient to determine the spectra in the frequency range from 1Hz to 30Hz. Further, the spectra should be determined with a resolution of at least 0,25Hz.

At the excitation point a unit force directed downwards is introduced and the velocities at the response points are exported as output from the FEM-software. With these settings the output equal the velocity spectrum at the response point due to an ideal pulse excitation with the amplitude equal one. This is equal to the transfer mobility *Y*.

2.3.4 - Computation of walking induced vibration levels

The determined transfer mobility *Y* can be used in the procedure described in the SBR guideline [3] or HIVOSS guideline to determine the OS-RMS_{90} values or any other response like the unit impulse response v_{rms}.

In this guideline the quantity OS-RMS_{90} is introduced which denotes the 90% upper limit of the RMS vibration levels due to one step of a walking person. In order to determine this quantity according to the guideline, the structural engineer is required to know the transfer mobility's *Y* from the excitation point to the receiving point of the structure as computed from the FEM-model. The receiving point being on the sending floor ('own' floor) or on the neighbouring floor.

Since the transfer mobilities are general quantities, also other response could be predicted by using appropriate source forces for other types of sources of structure-borne sound.

2.3.5 - Comparison with measurements

In the laboratory of TNO in Delft, the numerical models of several lightweight junctions have been experimentally validated. As an example the comparison of a junction consisting of two neighbouring lightweight floors of 5x5m, is described. The floors consists of 20mm chipboard and 185mm C-beams. The floors are supported by HE240A-beams. The Gyproc Metal Stud-walls are chosen as separating walls. The junction is illustrated in figure 2

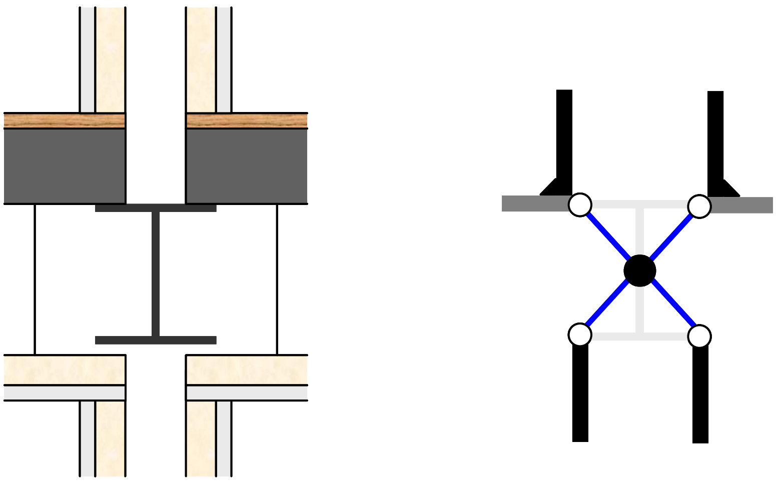

Figure 2: Schematic illustration of the junction and its boundary conditions.

Two variants are validated, namely one without floor screed and one with a lightweight floor screed consisting of 2x12.5mm gypsum board on mineral wool.

The measured (meting) and the predicted (DIANA harmonisch) transfer mobilities are presented in the following two figures.

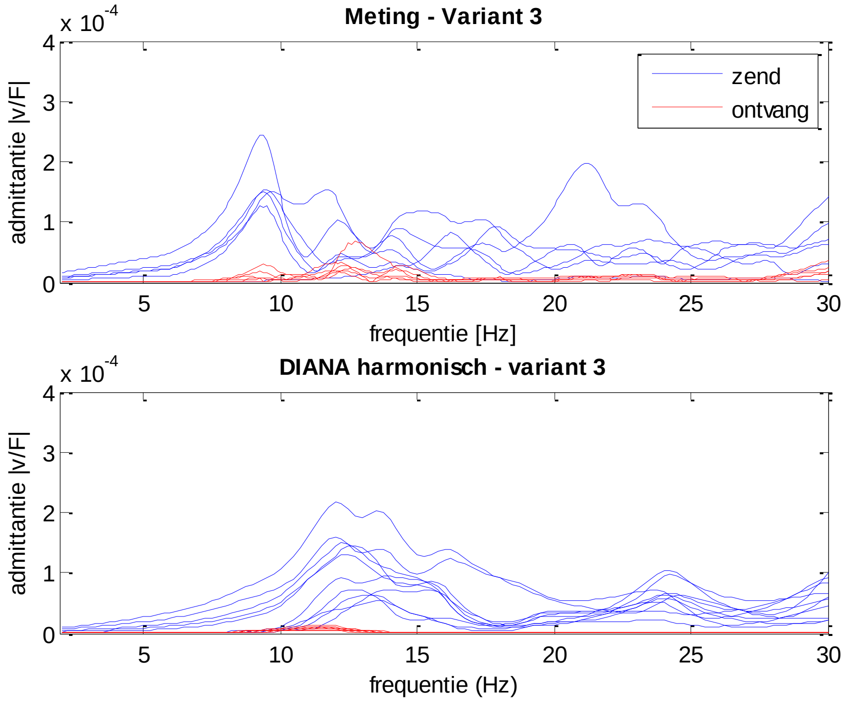

Figure .3: Comparison between the measured and the predicted transfer mobility of the junction without floor screed (meting=measurement, DIANA harmonisch=prediction, admittantie = mobility= transfer function, zend = send, ontvang= receive, frequentie=frequency)

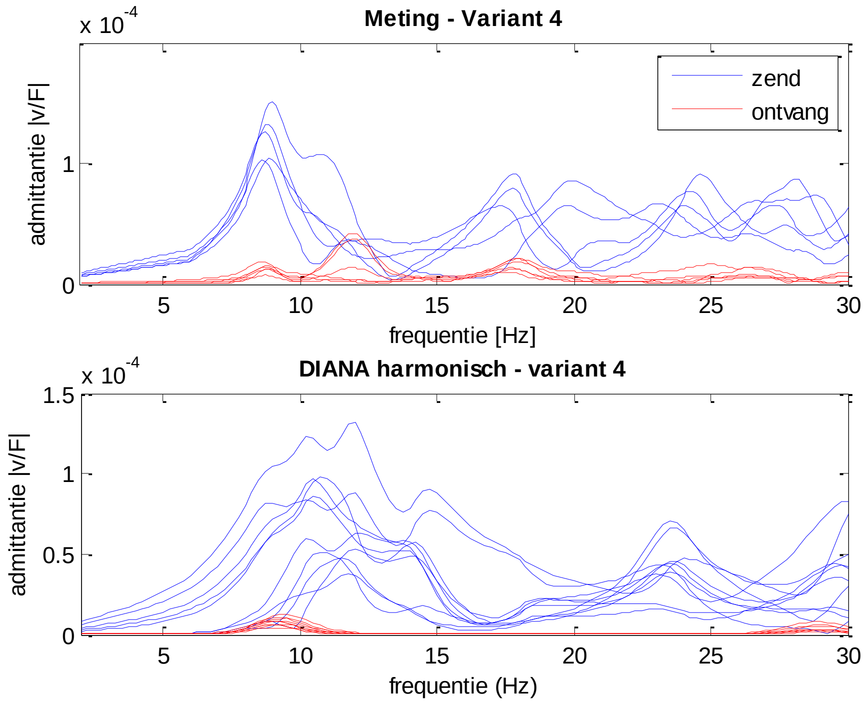

Figure 4: Comparison between the measured and the predicted transfer mobility of the junction with floor screed. (see figure 3 for the meaning of words)

The blue curves indicate transfer mobilities from on the excited floor and the red curves indicate transfer mobilities on the neighbouring floors.

From all the junctions that were investigated, the first eigenfrequency of the first variant deviated most. The difference between the measured and the predicted first eigenfrequency is about 2,5Hz. The predicted frequencies are always (somewhat) higher since the modeling will always assume stiffer connections between elements and at the boundaries than in reality. The overall response as in the one-step rms-value is not very sensitive to such a shift in predicted eigenfrequencies. In the predicted results the dominant harmonic of walking frequency is higher than in the measured results. In the resulting OS-RMS_{90} values this leads to a difference of 1,1 (measured: 4,1; predicted: 3,0).

In the second variant the damping is clearly under predicted. This leads to a difference of 1,2 (measured: 3,7; predicted 2,5). For both variants the OS-RMS_{90} on the neighbouring floor was measured to be 0,4 and predicted to be 0,2.

From all the junction that have been compared it was concluded that the simplified model can predict the OS-RMS_{90} for the excited as well as the neighbouring floor within a range of factor 2.

The predicted eigenfrequencies for a single junction, following the described procedure, compare well with those found in a larger simulation of a building with several junction. In that case the responses at neighbouring floors are somewhat lower though, which could be expected from the additional energy loss to added elements. The prescribed simulation is thus on the safe side.

2.4 - References

[1] EuroCode-5

[2] Klerk, M.E. de, *Improvement of the predictability of low frequency induced vibration response in timber based floor structures*, STSM report, Edinburgh Napier University, September 2010

[3] SBR richtlijn, *Trillingen van vloeren door lopen – Richtlijn voor het voorspellen, meten en beoordelen*, 2005. (Hivoss- Human Induced vibration of steel structures, Vibrition Design of floors- Background document, October 2008)

[4] Blevins, R.D., *Formulas for natural frequency and mode shape*, Van Nostrand Reinhold, New York, 1979

[5] Leissa, A., *Vibration of plates*, NASA SO-160, Washington DC, 1969

[6] Ohlsson, S., *Springiness and human induced Floor vibrations. A design guide,* report D12:1988, Swedish Council for Building Research, Stockholm, 1988.

[7] Klerk, Michiel, *presentation COST FP0702 workshop Delft*, 2010

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CHAPTER 2
MEASUREMENT METHODS FOR SOUND AND VIBRATION PERFORMANCES, INCLUDING LOW FREQUENCIES

COST Action FP0702

Net-Acoustics for Timber based Lightweight Buildings and Elements

Working Group 2: Measurement methods for sound and vibration performances

CONTENTS

This chapter presents six documents, written by different COST FP0702 member institutes and focused on general methods for measuring the main sound or vibration quantities, relevant for evaluating and predicting building performances.

Concerning *sound performances*, low-frequency airborne and impact sound insulation is especially important in lightweight buildings because of the low levels of sound insulation in the low-frequency range. Existing measurement methods show poor repeatability, reproducibility and relevance to room occupants in the low-frequency range. Improved procedures are proposed in the first two papers presented: the first paper proposes an improved procedure for measuring airborne sound insulation between rooms, from work performed at the University of Liverpool UK; a second paper proposes the use of sound intensity for measuring direct impact sound, from work performed at the University of Applied Sciences of Rosenheim, Germany.

Another difficulty appears in predicting acoustic performances of lightweight building, where, as explained in chapter 1 of this e-book, new (or modified) quantities are required. The third paper presented proposes methods for estimating two key quantities: the radiation efficiency of building elements and the velocity level difference of junctions between elements. Examples of results are given from work performed at CSTB France.

Concerning *vibration performances* of floors with respect to walking induced vibration, several key parameters are identified in the paper on vibration prediction presented in chapter 1: static floor deflection, floor fundamental frequency, unit floor response and single step floor response. Three papers related to these quantities and focusing on measurement methods are presented in chapter 2: the first paper presents a procedure for measuring floor deflection as used at SINTEF Buildings & Infrastructures, Norway; a second paper gives methods and examples on how to measure unit floor response (and goes even further through modal analysis, thus identifying resonant frequencies and mode shapes) and damping, from work performed at the University of Science and Technology of Trondheim, Norway; a third paper focuses on single step floor response, applied to both "own" floor and neighboring floor (through junctions), from work performed at TNO, The Netherlands.

1 - NEW PROPOSAL FOR FIELD SOUND INSULATION MEASUREMENTS IN THE LOW-FREQUENCY RANGE

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Low-frequency airborne and impact sound insulation is important in all buildings, but especially lightweight buildings. The reason for this is that walls or floors with a low mass per unit area typically have low levels of sound insulation in the low-frequency range. Standard procedures for field measurements of sound insulation between rooms are currently described in the ISO 140 series of International Standards. However, they are intended for use in rooms with sound fields that approximate diffuse fields. In practice, many dwellings contain rooms with volumes less than 25m^3, where the absence of a diffuse sound field at low-frequencies combined with the sampling of sound pressure in the central zone of a room makes measurements less reliable, and less relevant to building occupants. On the basis that sound insulation in the low-frequency range (particularly below 100Hz) is of importance in all buildings, but especially timber frame buildings, this COST FP0702 project provided the impetus to draw on recent research [1] to define new procedural changes that would improve the reliability and relevance of field sound insulation measurements. These procedural changes were subsequently used in a proposal to revise four International Standards on field sound insulation testing (ISO 140 Parts 4, 5, 7 and 14) at the ISO TC43 SC2 plenary session in Korea (November, 2009). This proposal was accepted and Carl Hopkins became the convenor of the work packages to write these new Standards. The first new International Standard, ISO/DIS 16283-1, has been written on the field measurement of airborne sound insulation and was circulated to all countries as a draft for comment in Spring 2012 [2].

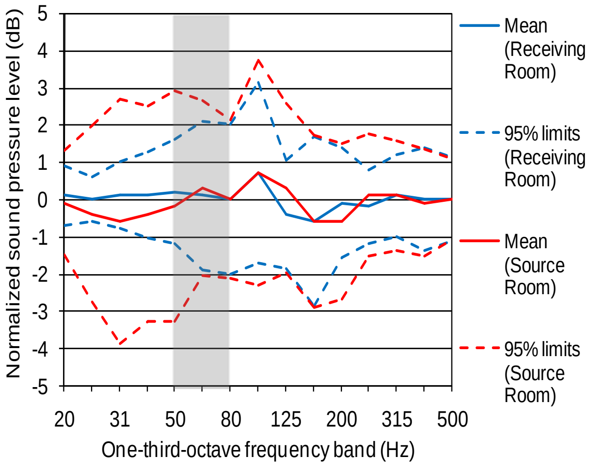
Two measurement procedures are described in ISO/DIS 16283-1 to measure the sound pressure level, the reverberation time and the background noise; a default procedure and an additional low-frequency procedure. The default procedure for all frequencies is to obtain the energy-average sound pressure level using a fixed microphone or a manually-held microphone moved from one position to another, an array of fixed microphones, a mechanized continuously-moving microphone or a manually-scanned microphone. These measurements are taken in the central zone of a room at positions away from the room boundaries. A new low-frequency procedure is introduced for the 50, 63, 80 Hz one-third octave bands in the source and/or receiving room when its volume is smaller than 25 m^3 (calculated to the nearest cubic metre). This procedure is carried out in addition to the default procedure and requires additional measurements of the sound pressure level in the corners of the source and/or receiving room using either a fixed microphone or a manually-held microphone. For the low-frequency procedure a fixed microphone is positioned in room corners at a distance of 0.3 m to 0.4 m from each room boundary that forms the corner – see Figure 1.

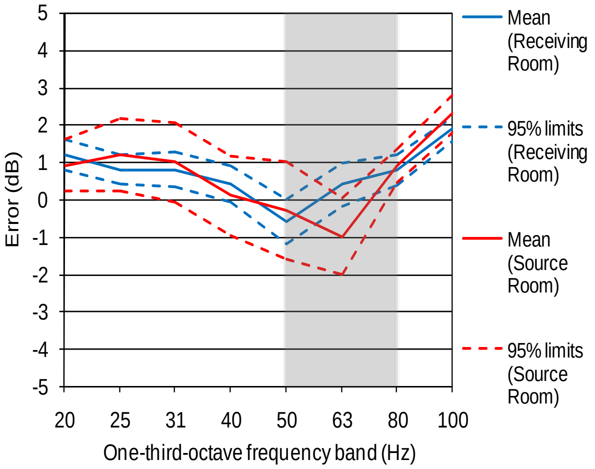
Figure 1. Fixed microphone in a room corner.

The low-frequency energy-average sound pressure level in the 50 Hz, 63 Hz and 80 Hz bands is calculated by combining the spatial-average sound pressure level, L, from the default procedure in the central zone of the room with L_{Corner} from the low-frequency procedure using

$$L_{\text{LF}} = 10\lg\left[\frac{10^{0,1L_{\text{Corner}}} + (2 \cdot 10^{0,1L})}{3}\right]$$

An example illustrating the improvement in the repeatability of measurements is shown in Figure 2 from sound pressure level measurements in a 29m^3 source room and an 18m^3 receiving room. For measurements in the central zone of the room it is common to use a set of five stationary microphone positions; hence each different set of five positions will contribute to the uncertainty in the spatial average value. For the default procedure, Figure 2(a) shows the results for many different sets of five positions in terms of the mean and 95% confidence intervals that have been normalized to the average of all possible positions in the central zone of the room. The uncertainty is large below 100Hz where the 95% confidence intervals span a range of 4 to 7 dB. This can be compared with Figure 2(b) which uses the low-frequency procedure and shows that the mean error is only 0dB to 1dB when using the low-frequency procedure to estimate the average sound pressure level over the entire room volume (i.e. including positions at the walls and corners). More importantly, the 95% confidence intervals for the low-frequency procedure are typically less than 2dB; hence they are similar to the uncertainty of the default procedure in the central zone for different sets of stationary microphone positions between 100 and 500 Hz. The low-frequency procedure can therefore be used in small rooms which have large spatial variations in the sound pressure level to improve the repeatability, reproducibility and relevance to room occupants.





(a) (b)

Figure 2. (a) default procedure in the central zone of a room (b) low-frequency procedure using corner measurements. NB Grey shaded areas highlight the 50, 63 and 80 Hz one-third octave bands.

In timber or steel frame buildings with gypsum or timber board linings the reverberation times in the 50 Hz, 63 Hz and 80 Hz bands can be sufficiently short that the decay curve is affected by the decay time of the one-third octave band filters in the analyser. Typically they are 0.3s < T < 0.8s for room volumes of 20 to 60m^3. Problems can be avoided by using a 63 Hz octave band filter due to its wider bandwidth which allows the measurement of shorter reverberation times. In addition, in small rooms there are relatively few room modes that determine the decay curve in the 50 Hz, 63 Hz and 80 Hz bands. Hence the use of 20 dB or 30 dB evaluation ranges on the decay curves from one-third octave bands are prone to error because single-slope decay curves usually only occur when there are many modes in each frequency band. This issue can partly be resolved through use of the 63 Hz octave band filter. The solution proposed in ISO/DIS 16283-1 is to define a default procedure that shall be used in the receiving room for all reverberation time measurements, and a low-frequency procedure that shall be used when the receiving room volume is smaller than 25m^3. The low-frequency procedure requires that the reverberation time is measured in the 63 Hz octave band instead of the 50 Hz, 63 Hz, 80 Hz one-third octave bands and that this single measured value is used to represent the 50 Hz, 63 Hz and 80 Hz bands in the calculation of D_{nT} and/or R'.

Approximately 250 individual reverberation time measurements using forward filter analysis with interrupted noise in unfurnished timber and steel frame buildings were used to assess the efficacy of this approach [1]. A summary is shown in Table 1.

One-third-octave band centre frequency (Hz)	% satisfying *BT* > 8 criterion	
	Using individual decay curves	Using ensemble average decay curves
50	37 %	33 %
63	48 %	57 %
80	87 %	86 %

Octave band centre frequency (Hz)	% satisfying *BT* > 8 criterion	
	Using individual decay curves	Using ensemble average decay curves
63	98.8 %	100 %

Table 1. Percentage of reverberation times satisfying the BT>8 criterion in timber and steel frame buildings when using one-third octave bands compared to octave bands.

In the near future, the same low-frequency procedures will also be introduced for impact sound insulation and facade sound insulation in the next two parts of the Standard that will be drafted in 2012/2013.

1.1 - References

[1] C. Hopkins and P. Turner. Field measurement of airborne sound insulation between rooms with non-diffuse sound fields at low frequencies. Applied Acoustics 66 (2005) 1339–1382.

[2] ISO/DIS 16283-1:2012. Acoustics - Field measurement of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation.

2 - LF IMPACT SOUND LEVEL USING INTENSITY,

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2.1 - Introduction

In a recently completed R&D project at the University of Applied Sciences Rosenheim a practical prediction tool based on EN 12354 for sound transmission of timber joist floors in heavy-weight buidings was developed and validated [1]. Usually the sound transmission of timber joist floors before remedial actions is dominated by direct sound transmission, whereas flanking transmission becomes more important after remedial actions. For measurements of airborne as well as impact sound insulation, timber joist floor constructions usually found in old buildings have been rebuilt in the laboratory and were measured according to ISO 140. Here, special consideration was given to the frequency range below 100 Hz. After that, the tested floor constructions were acoustically improved by various common remedial actions and measured again. Also, flanking sound transmission was determined in the laboratory by means of measurements using brick walls with different mass per unit area. In order to validate the prediction tool, field measurements were conducted as well. In these cases, the direct sound transmission was obtained using the intensity method according to the procedures described in ISO 15186. However, for impact sound transmission there is no measurement procedure found in the literature so far. Therefore a measurement survey has been performed on a concrete floor as well as on a timber joist floor similar to model 1 given in appendix B of ISO 140 – 11 and equipped with a floating screed. The results of this laboratory survey comparing impact sound insulation according to ISO 140 with intensity based impact sound insulation are presented. Another reason for detailed investigation of intensity based sound insulation measurements is due to the ongoing discussion about measuring sound insulation at low frequencies. Measurements of sound level as well as reverberation time at low frequencies are still problematic and are usually affected by various inaccuracies. The intensity method is expected to cope with these shortcomings.

2.2 - Basic equations

The following notation is based on the German version of the standard ISO 140 (ISO 10140 resp.) and the standard ISO 15186.

The normalized impact sound level L_n is given by the impact sound level L_i as

$$L_n = L_i + 10 \cdot \log\left(\frac{A}{10\,\mathrm{m}^2}\right).$$

Assuming that the impact sound level originates from a diffuse sound field, it can be written in terms of the sound power level of the source, which in our case is the floor, as

$$L_i = L_W + 10 \cdot \log\left(\frac{4 \cdot \mathrm{m}^2}{A}\right).$$

The sound power level L_W of the source can be written in terms of the normal sound intensity level $L_{I\mathrm{n}}$ as

$$L_W = L_{I\mathrm{n}} + 10 \cdot \log\left(\frac{S}{\mathrm{m}^2}\right).$$

Therefore the normalized impact sound (intensity) $L_{n,I}$ level is given by

$$L_{n,I} = L_{I\mathrm{n}} + 10 \cdot \log\left(\frac{S}{\mathrm{m}^2}\right) - 4\,\mathrm{dB}.$$

In order to compare this normalized impact sound (intensity) level with the normalized impact sound level from measurements according to ISO 140- 4, it is necessary to account for sound pressure enhancement near the surface similar to the standard ISO 15186. Therefore a modified normalized impact sound intensity level $L_{n,I,\mathrm{M}}$ is introduced. This modified normalized impact sound (intensity) level $L_{n,I,\mathrm{M}}$ can be written as

$$L_{n,I,\mathrm{M}} = L_{n,I} - K_C$$

with K_C as the Waterhouse correction [2] calculated according to Uosukainen [3] as

$$K_C = 10 \cdot \log\left(1 + \frac{S_b \cdot \lambda}{8 \cdot V} + \frac{L \cdot \lambda^2}{32 \cdot \pi \cdot V}\right).$$

The additional term in the argument of the logarithm given by Uosukainen increases the adaption term of ISO 15186 of less than 1 dB at 50 Hz for any common room size.

2.3 - Laboratory measurements

2.3.1 - Measurement conditions

2.3.1.1 - ***Intensity probe and measurement procedure***

For the measurements an intensity pp-probe of type Norsonic 240 together with a Norsonic Real Time Analyser 840 was used. Besides the mandatory calibration procedure additional verifications of the measurement system were carried out using identical intensity equipment and exchange intensity probes and analysers. For the measurements the probe was used with a 50 mm spacer. Therefore the frequency range possible for data evaluation was restricted from 40 Hz to 1600 Hz. Due to ageing effects the intensity probe used did not fulfill the criteria of class I measurement accuracy below 200 Hz. The residual PI-index obtained decreased from 18 dB at 200 Hz to 10 dB at 50 Hz (class I measurement accuracy requires 19 dB at 200 Hz and 12 dB at 50 Hz).

The measurements were performed using the scanning procedure according to ISO 15186. The distance of the intensity probe to the ceiling was 0,2 m, the scanning speed was 0,2 m/s, the distance of the scanning paths was 0,2 m.

2.3.1.2 - ***Conditioning of the receiving room***

The bottom of the receiving room was equipped with sound absorbing material. In figure 1 the arrangement is shown. The sound absorption coefficient of this arrangement for normal incidence was measured in a Kundt's tube. It is greater than 0,8 in the frequency range above 50 Hz. At a vertical height of approx. 0,8 m a metal grid was positioned in order to provide an operating platform.

Figure 1: sound absorption layer opposite the measurement surface

2.3.1.3 - ***Measurement area***

In order to minimize the measurement effort an investigation on smaller measurement subareas was made and compared to results of the whole ceiling. This survey was carried out on the above mentioned timber joist floor. The volume of the receiving room was approx. 50 m^3. The standard tapping machine was placed at six positions on the floor as indicated in figure 2. The ceiling area was divided into six subareas, also shown in figure 2.

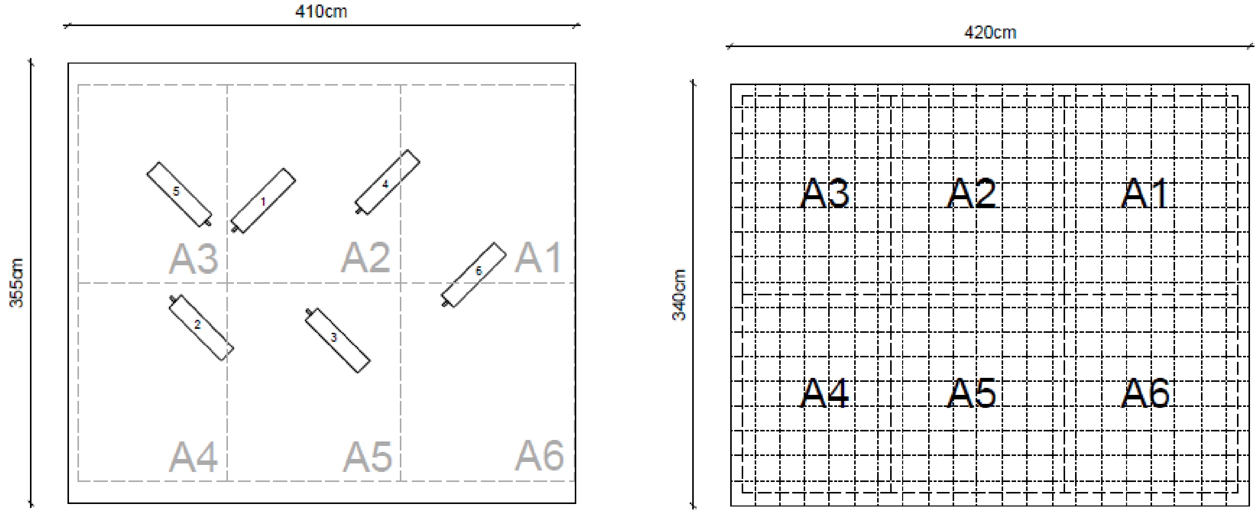

Figure 2: positions of the standard tapping machine and partition of the ceiling area into six subareas

In this laboratory survey an intensity measurement of subarea A7 only was carried out as well (see figure 3).

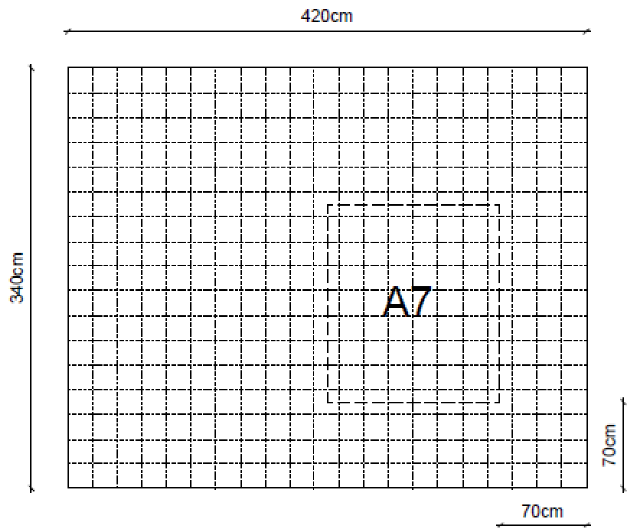

Figure 3: Single measurement subarea used for reduced measurement procedure

Figure 4 shows a comparison of the arithmetic mean intensity level of the six subareas A1 - A6 and the single value of subarea A7. At frequencies below 125 Hz differences of up to 2.5 dB occur. In fact a dependency of the distance of the tapping machine to the measurement subarea was observed, especially with respect to the PI-Index of the measurements. The bigger the distance of the tapping machine to the measurement subarea considered, the higher the PI-Index of the measurement. The difference may amount to 8 dB in the PI-Index.

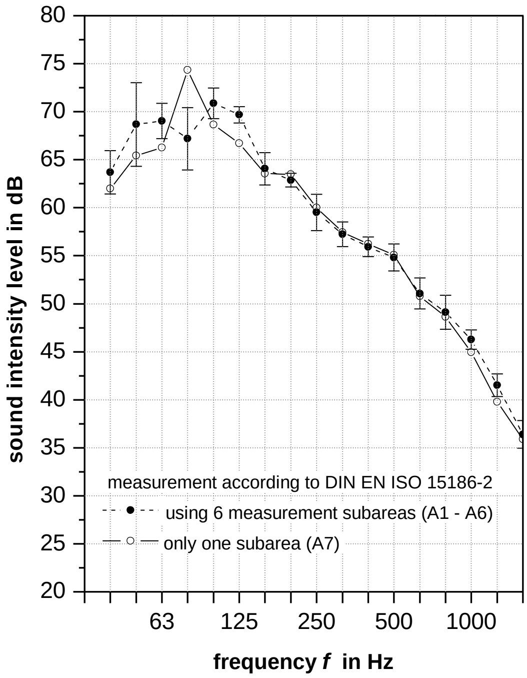

figure 4: Comparison of the sound intensity level, using the whole measurement surface (mean of subareas A1- A6, see figure 2) and the sound intensity level from subarea A7 (see figure 3). Uncertainty bars indicate the standard deviation of the measurements of the six subareas.

2.3.2 - Comparison of ISO 140 and ISO 15186 measurements

In order to compare measurement results in terms of impact sound level and sound insulation, measurements according to ISO 140 and ISO 15186 have been performed in a test facility without flanking transmission. The separating element for these test was a concrete floor of 14 cm thickness without any flooring. The volume of the receiving room was 69 m^3.

In figure 5 comparisons are shown. On the right hand side the figure shows the measurements of L_n and $L_{n,I,M}$ respectively, with the difference of these curves given at the top. Although the Waterhouse correction according to chapter 2 was applied, the discrepancy between the two measurement methods at low frequencies is evident. Similar result were obtained for the difference of R and $R_{I,M}$, shown on the left hand side of figure 5.

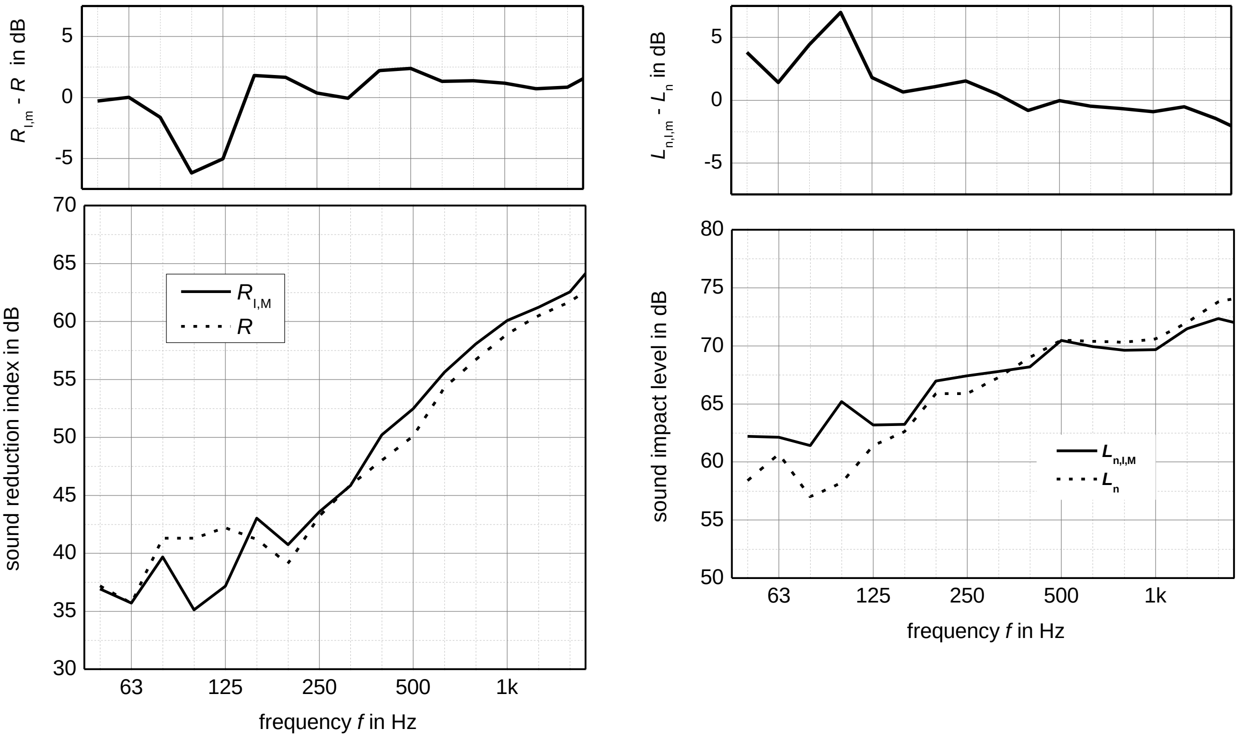

Figure 5: Comparison of the modified intensity impact sound level $L_{n,I,M}$ with the impact sound level L_n at the right hand side and the modified intensity sound reduction index $R_{I,M}$ according to ISO15186 with the sound reduction index R according to ISO 140 at the left hand side. At low frequencies a deviation is observable, which occured in both measurements.

The observed difference might be caused by uncertainties in the reverberation time, which is required for calculation of L_n. Especially at low frequencies, where room resonances may occur, exact determination of the reverberation time is difficult. However, in this measurement the reverberation time of the receiving room was quite short in low frequencies due to additional drywalls in front of the heavy-weight flanking walls and therefore had rather smooth characteristics (see figure 6). Also shown in figure 6 is the corner sound pressure level which indicates resonances at frequencies which correspond to half a wavelength in room dimension. Therefore more investigation is required in order do identify and understand the discrepancies between the different measurement methods in the low frequency region, shown in figure 5. Nevertheless the fact that the same discrepancy occur in both impact sound level measurements and sound reduction measurements indicate that measurement of impact sound level using sound intensity method is possible even at low frequencies.

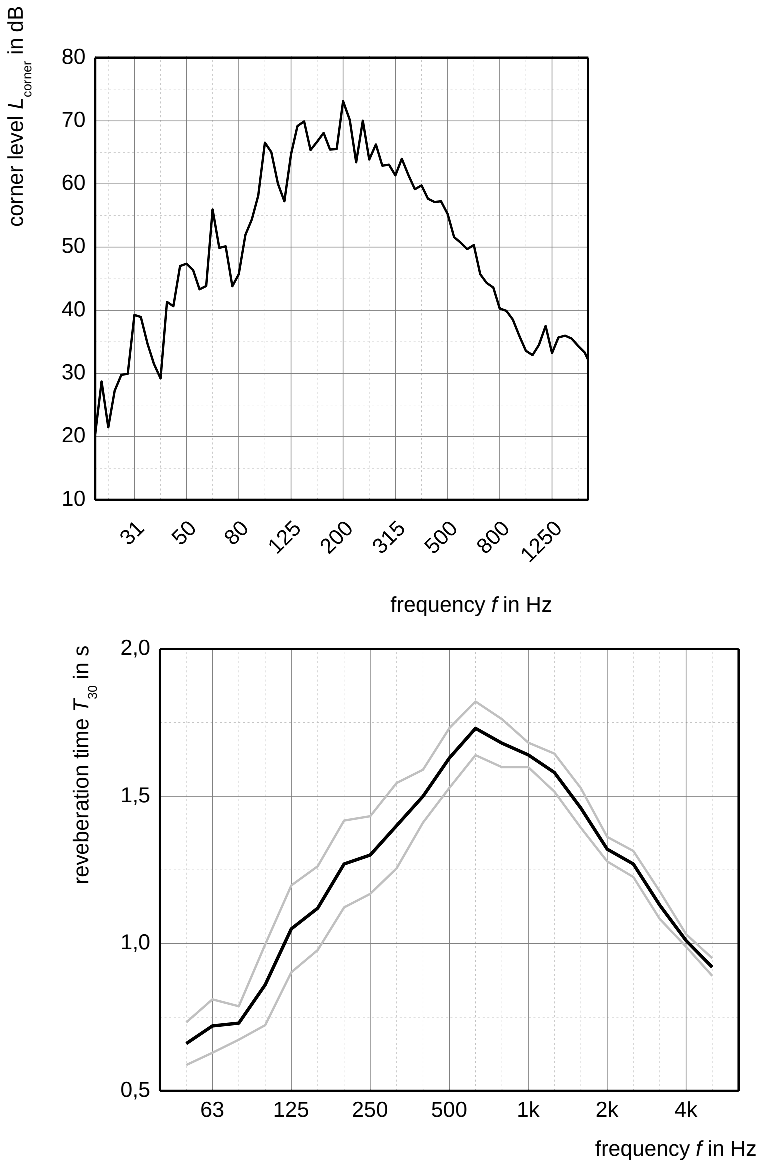

Figure 6: receiving room reverberation time and corner sound pressure level

2.4 - Field measurements

In the course of the mentioned R&D project field tests on various timber joist floors were carried out by measuring the sound insulation of the direct path using the intensity method. The contribution of the flanking paths (solid, heavy-weight walls) was obtained by measuring the surface velocity and assuming a unit radiation efficiency. The energetic sum of the individual transmission paths then yields the total sound reduction index R'_{sum}. Additionally the sound reduction index R‘ was directly measured according to ISO 140. The difference between both approaches is shown on the left hand side of figure 7. Results of the individual measurements are provided with the mean indicated by a bold line. The graph on the right hand side of figure 7 shows the difference of the impact sound level respectively. Again, the measurement of the direct path contributing to the impact sound level was carried out using the intensity approach described above.

Both graphs reveal a discrepancy in the low frequency range. This deviation is systematic in that the measured intensity sound levels are obviously higher compared to values obtained according to ISO 140.

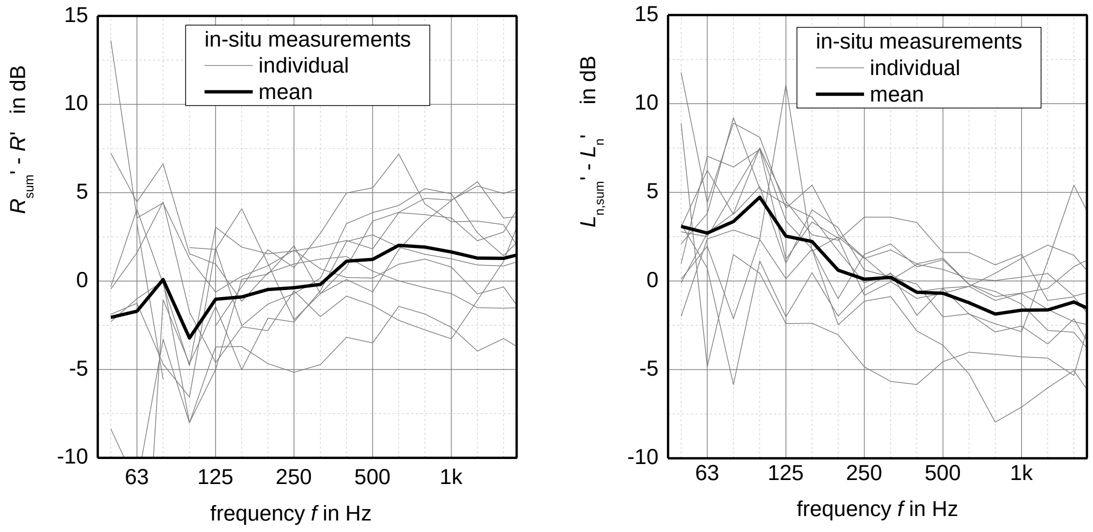

Figure 7: Comparison of in-situ measurements of airborne and impact sound insulation according to ISO 140 with results obtained by measuring the direct path of the sound transmission with intensity and the flanking paths with accelerometer and combining the contributions to a total sound reduction R'_{sum} and $L'_{n,sum}$, respectively.

2.5 - Conclusion

Results of laboratory and field surveys indicate that measurements of impact sound level using the intensity method combined with the equations given in chapter 2 is feasible and yield reasonable results even in the low frequency range. The advantage of this measurement approach is the independency on the rooms reverberation time and sound level which might vary, especially at low frequencies. The disadvantage is the large instrumental and operating expense. The reduction of measurement time in using only one subarea instead of scanning the whole ceiling seems to be possible if less accuracy is acceptable. However, this needs to be verified systematically, especially for inhomogeneous constructions like timber joist floors. A systematic deviation compared to conventional measurement results according to ISO 140 was found in the low frequency range, despite the application of the Waterhouse correction. These results confirm the findings of others published before [4], [5], [6], [7], [8] and need further investigation.

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3 - METHODS FOR MEASURING RADIATION EFFICIENCY AND JUNCTION VIBRATION LEVEL DIFFERENCE

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The proposal for prediction of acoustic performances of lightweight buildings presented in chapter 1 (WG1) of this e-book [1] shows (i) the need for estimating the sound reduction index R* (for resonant transmission only) of lightweight building elements and the importance of the radiation efficiencies in this estimation and (ii) the need for an appropriate definition (and associated measuring method) of the junction vibration attenuation between connected lightweight elements. This paper proposes methods for measuring the radiation efficiency of lightweight elements as well as for measuring and characterizing the velocity level difference of junctions between lightweight elements. Examples of measurement results are given. The principles of these methods have already been presented in a paper [2], which content has been up-dated taking into account more recent studies.

3.1 - Radiation efficiencies

3.1.1 - Measuring method

In building acoustics, the radiation efficiency σ of a building element is defined from the following expression of the power radiated:

$$\Pi_{rad} = \rho c \sigma . S < v^2 > \qquad (1)$$

where ρc is the air impedance, S the surface area of the element and $<v^2>$ the space average velocity of the element.

This radiated power can be measured in a room of absorption area A from the space average sound pressure $<p^2>$ in the room:

$$\Pi_{rad} = < p^2 > .A / 4\rho c \qquad (2)$$

Equations (1) and (2) are power based expressions assuming diffuse field in both structure and room. Expressed in dB in terms of sound level L_p (ref. 2 10^{-5} Pa) and velocity level L_v (ref. 5 10^{-8} m/s), (1) and (2) lead to:

$$10\log(\sigma) = L_p - 6 - L_v + 10\log(A/S) \qquad (3)$$

From equation (3), the following measurements method can then be proposed, knowing that low frequencies (below 100 Hz) are important, especially in lightweight buildings:

Sound pressure measurements: L_p and A can be measured according to ISO 140 Part 3, [3], which includes an annex for low-frequency measurements down to 50 Hz. Other methods adapted to low-frequency measurements such as the method developed for field measurements in smaller rooms [4] or the laboratory method based on acoustical intensity measurements [5] would probably give more accurate results.

Vibration measurements: L_v can be measured using the same method as when measuring the velocity level difference of junctions between elements (see section 2 of this paper)

The radiation efficiency depends on the type of excitation used (airborne or mechanical excitation) leading, in the case of lightweight elements to two different spectra for the radiation efficiency (σ_a and σ_r respectively). An airborne excitation (as in ISO 140 Part 3) will be uniformly distributed over the element, thus generating a rather diffuse vibrational field. In the case of mechanical excitation, only several positions of the tapping machine (as is ISO 140 Part 16, [6]) or "rain on the roof" hammer impacts can generate a uniformly distributed excitation.

The radiation efficiency eventually depends on which side of the element the power radiated is measured (see example below)

3.1.2 - Examples of results

The radiation efficiency of a two board single leaf wall (gypsum board BA13 + OSB) on (120 x 45) wooden studs is shown in Figure 1 in the two cases of airborne and mechanical excitation, the radiated power being measured either on the stud side or on the board side.

The results show that a difference of 10 dB can be found in the low frequency range between airborne and mechanical excitation, showing the importance of the correction term in equation (2) in the proposal for acoustic prediction given in the e-book first chapter [1]. This difference decreases near critical frequency (3150 Hz for the lightweight element presented here). Only small differences in radiation efficiency can be seen between the radiation sides (plate or studs). In the case of heavy building elements (low critical frequency), higher values of radiation efficiency would be found at low frequencies and results practically independent of the excitation (airborne or mechanical) would be obtained over the whole frequency range.

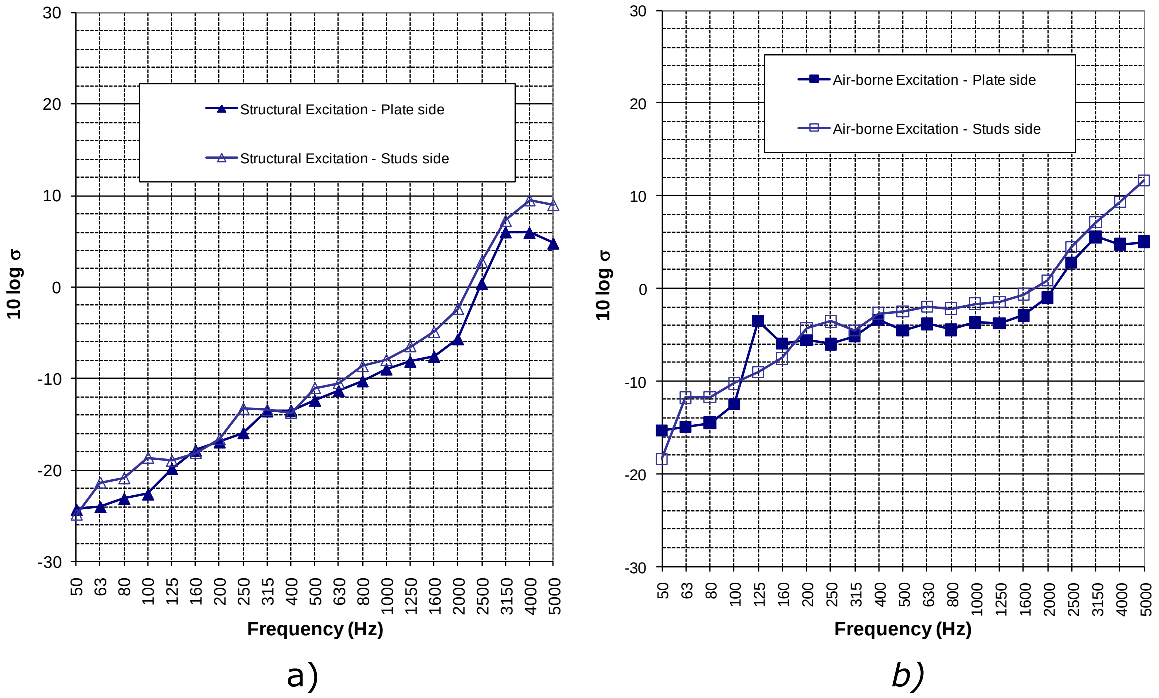

Figure 1: Measured radiation efficiency of a single leaf wall in the cases of (a) mechanical excitation and (b) airborne excitation.

3.2 - Junction velocity level difference

3.2.1 - Measuring method

The standard EN 10848 series [6] specifies laboratory measurement methods for characterizing flanking transmission of airborne and impact noise between adjoining rooms. According to this standard, two approaches can be used:

(i) the flanking path considered can be characterized by a flanking level difference $D_{n,f}$ and a flanking impact sound level $L_{n,f}$, each transmission path being separated by shielding (see Figure 2); according to the standard, this approach can be applied to any type of structures, including lightweight elements; but shielding is cumbersome (also true for heavy elements), might affect the behaviour of the lightweight elements involved in the junction considered and might not be efficient enough at low frequencies around and below 100 Hz (also true for heavy elements). Note that $D_{n,f}$ measurements require an airborne excitation in the emission room. This approach has been used by laboratories such as NRC in Canada [7] and EMPA in Switzerland [8].

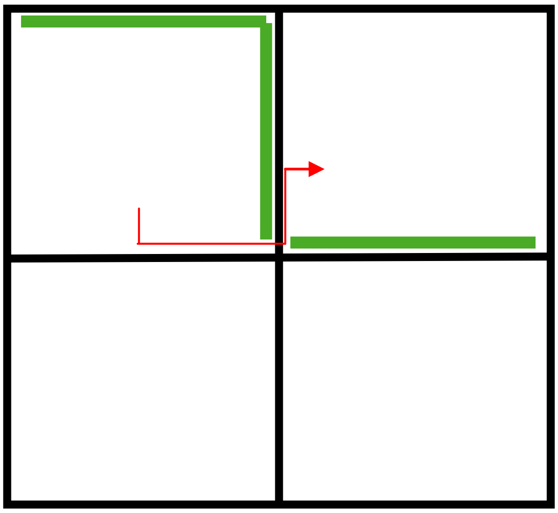

Figure 2: Example of shielding in the measurement of a particular flanking transmission path between two rooms

(ii) the flanking path considered can be characterized by a vibration level difference $D_{vs,ij}$ (the *s* subscript stands for structural excitation) from which an invariant (the vibration reduction index K_{ij}) of the junction is calculated. According to the standard, this K_{ij} approach and the related measurement methods are only valid with the assumption of a diffuse structural field which is not the case for lightweight and usually highly damped structures. In the standard, a condition of diffusivity is given in terms of vibration attenuation with distance, which should not exceed 6 dB across the element; the examples given in [2] show that this condition is rarely fulfilled in lightweight elements.

However, the notion of vibration level difference still makes sense with lightweight elements as explained in reference [9], which shows that first order SEA, on which the EN 10848 series is based, can still be applied to lightweight constructions, but only if the mechanical excitation is uniformly distributed over the emission plate (using several tapping machine positions for floors or "rain on the roof" hammer excitation for walls) and if the vibration fields are measured with a sufficient number of accelerometer positions (between 10 and 15, depending on the element size), and located over the whole element. Figure 3 shows a typical floor/wall X junction (top view), where the source positions are indicated as well as the vibration attenuation with distance in the receiving element (stronger with increasing frequencies). For a measured junction length l_{ij}, the structural power transmitted is proportional to the product $S_{m,j}$ $<v^2>$, which must stay the same in the field prediction when estimating the sound pressure radiated (the *m* subscript stands for measurement area). An invariant for lightweight element junctions can then be defined as the following normalized direction average velocity level difference:

$$\overline{D_{v,ij,n}} = (D_{v,ij} + D_{v,ji})/2 + 10\log(l_{ij} / \sqrt{S_{m,i}.S_{m,j}}) \qquad (4)$$

from which the in situ direction average velocity level difference of a similar junction can be calculated as

$$\overline{D_{v,ij,situ}} = \overline{D_{v,ij,n}} - 10\log(l_{ij,situ} / \sqrt{S_{situ,i}.S_{situ,j}}) \qquad (5)$$

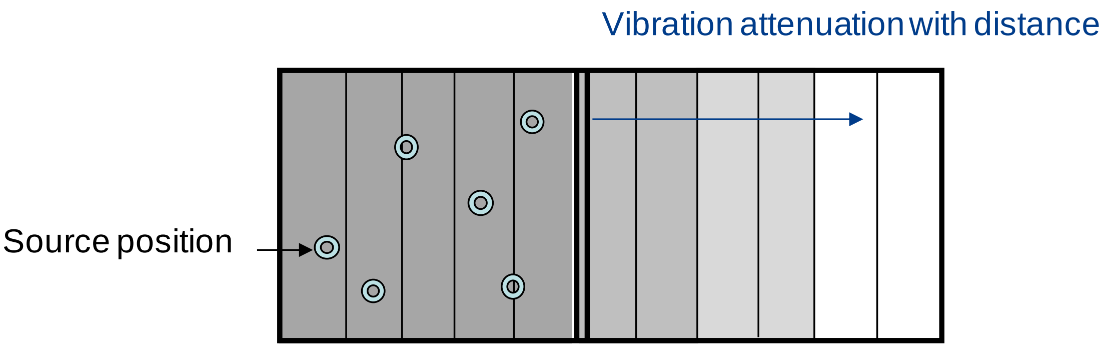

Figure 3: Top-view of a lightweight floor/wall junction with joists // junction

It should be noted that measuring the energy stored in a lightweight element ($S<v^2>$) generated by a known structural power injected might be a way of characterizing an apparent loss factor. Such method is proposed in a research study [10] on comparing structure borne noise from waste water installation in heavy and lightweight constructions.

3.2.2 - Examples of results

The normalized velocity level differences of a lightweight floor-wall X junction composed of a 25mm CTBH floor on wood joists (joist parallel to junction) and a single frame double wall (18 mm gypsum board on one side and 10 mm OSB on the other) are shown in Figure 4; the 3 paths (floor-floor, wall-wall and floor-wall) are given.

The results show that higher values of velocity level differences are obtained, compared to heavy junctions, and the slopes are stronger (stronger increase of velocity level difference with increasing frequencies).

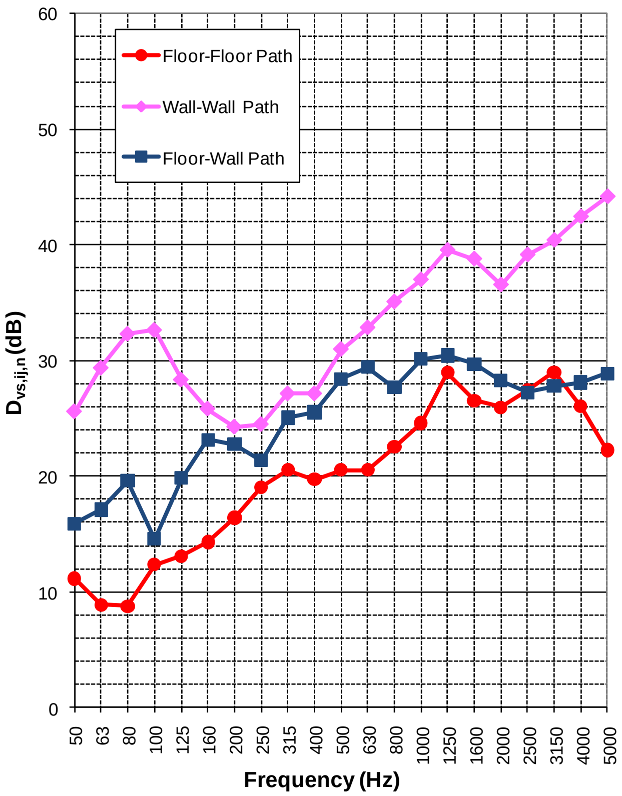

Figure 4: Measured normalized velocity level differences of a lightweight floor-wall X-junction.

3.3 - Conclusion

The above proposals for defining, measuring and characterizing the radiation efficiency of lightweight elements and the velocity level difference of junctions between lightweight elements can sure be further tested and improved, and will hopefully help the CEN/TC126 working groups prepare the corresponding (and missing) European standards.

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4 - MEASUREMENTS OF FLOOR DEFLECTIONS

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4.1 - Definition

In this document, the floor deflection is the measured deflection of the floor on the beams at the center (weakest point) of the span width with a point load of 1,0 kN.

4.2 - Measurement setup

4.2.1 - Principle

The beam floor construction has to be applied with a point load of 1,0 kN on the floor directly above a beam at the center of the span width. The deflection due to this load has to be measured in the same position, at the support and on one or more neighboring beams. The principle is shown in figure A-1. The positions of the beams have to be determined within an accuracy of approximately ± 5 mm. When the floor has a rather high transverse stiffness (perpendicular to the main beam direction), it is recommended to make measurements on at least 5 beams with a center distance of 0,6 m. It is necessary to establish a reference system for the deflection measurements to ensure that the values are independent of the load at the different measurement positions, see ch. 2.2.

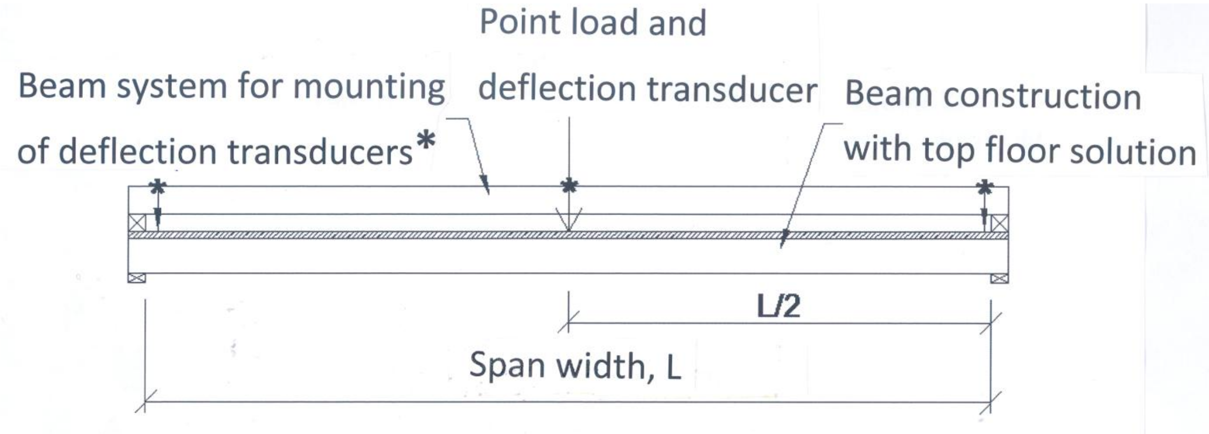

Figure A-1. Deflection measurements of beam floor construction

If possible, it is recommended to preload the floor construction in 2 to 6 minutes with a load comparable with load from normal use of the floor before the deflection measurements. An alternative is to put a number of dynamic loads into to floor, for instance heavy jumping on the floor.

4.3 - Reference system

The deflection transducers have to be mounted on a reference (beam) system. The stiffness of this system has to be adequate to avoid inaccuracy and movements of the transducers. It is necessary to establish the system in a way that avoids movements (from loading and unloading) at the support of the reference system. If the reference system is mounted above the floor, it will normally be safest to install the reference beam in the same direction as the floor beams with support as close as possible to the beam support. If the edges of the floor are sufficient stiff, the reference beam can be installed in the transverse direction of the floor beams.

4.4 - Point load

A person (additional mass included) can be used giving a total weight of 1 kN. An accuracy of 10 N of the load is acceptable. A support plate of 100 mm x 100 mm should be used between the floor (above the beam) and the point load. The load moves on and off the support plate minimum three times, with a recommended loading time of 20 sec.

If the measured deflection is below approximately 10 times the assumed measurement accuracy, we recommend to make measurements with increased point load, for instance + 500 N. Afterwards, the measurement results should be normalised to a point load of 1 kN.

4.5 - Measurement equipment

Electronic deflection transducers should be used with a resolution of 0,01 mm or better. The accuracy of the transducer (and registration system) should be calibrated regularly.

4.6 - Procedure

Values from the measurement system have to be registered before, at and after loading of the point, at least three times for each load position. If an unexpected change of the values occurs (at the same load point), the reason has to be clarified and the number of load cases has to be increased. It is necessary to chose minimum three load positions at the beam construction. If the deflection at the support increase 0,01 mm, it is recommended to improve the mounting of the reference system and redo the measurements.

4.7 - Results

The deflection of the beam construction is the average of the number of deflection results from each point load of 1,0 kN. Significant diverging values should be excluded from the averaging process.

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5 - HOW TO MEASURE FLOOR LOW FREQUENCY VIBRATION

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5.1 - Experimental modal analysis

Experimental Modal Analysis (EMA) is the field of measuring and analyzing the dynamic response of a structure when excited by a stimulus. The stimulus can consist of either a continuous periodic excitation provided by a shaker, or of an impact load, generally provided by a modal hammer. The vibration response of the structure is recorded by means of vibration sensors, usually accelerometers, which have to be located strategically on the structure in order to reveal its vibration modes. Specialized data acquisition hardware providing proper signal conditioning is needed to properly acquire these vibration signals. The frequency response function (FRF) compares the stimulus and response to calculate the transfer function of the structure. The result of the FRF is the structure's magnitude and phase response over a defined frequency range. It shows critical frequencies of the structure that are more sensitive to excitation. Those critical frequencies are the modes of the structure under test. Modal parameter extraction algorithms are used to identify the modal parameters from the FRF data.

Modal analysis issues have been extensively reviewed by Ewins [1] and Maia [2] , and excellent vulgarization has been provided by Schwarz and Richardson [3]. The relative advantages and drawbacks of shaker excitation versus modal hammer excitation have been reviewed by Reynolds and Pavic [4]. What follows is a general summary of information collected from the previously cited reviews.

5.1.1 - Modal hammer testing

Hammer testing is the most commonly used technique, since it is quick, easy and relatively cheap. The convenience of this technique is attractive because it requires very little hardware and provides shorter measurement times. Indeed, the only equipment needed is a modal hammer, shown in *Figure 5.1*, and an accelerometer, shown in *Figure 5.3*. In addition, the measurement method is fully portable, and therefore highly suitable for field work. When the modal hammer tip hits the structure, a wide frequency range is quickly excited. Hammer testing is decried mainly because of the lack of repeatability. The input force may indeed vary because of different operators, or difficult location. In addition, high crest factor due to impact may drive the structure into non-linear behavior. And since large structures require high peak force to be set into motion, there is always a risk of local damage. For instance, hammer testing is not recommended for composite testing.

Since the force is an impulse, the amplitude level of the energy applied to the structure is a function of the mass and the velocity of the hammer. Since it is difficult to control the velocity of the hammer, the force level is usually controlled by varying the mass. Impact hammer are available in weights varying from some grams to several kilograms, in order to allow the testing of different structures.

Figure 5.1: The modal hammer used for all experimental studies

The frequency bandwidth is inversely proportional to the pulse duration. In addition, the magnitude and pulse duration depends on:

- the weight of the hammer
- the hammer tip: steel, plastic or rubber
- the dynamic characteristics of the surface
- the velocity at impact

It is not feasible to change the stiffness of the tested structure; therefore the frequency content is controlled by varying the stiffness of the hammer tip. The harder the tip, the shorter the pulse duration and thus the higher the frequency content, as illustrated in *Figure 5.2*.

In general, small low-mass objects have higher response frequencies and thus require higher frequencies of excitation at lower force levels. Heavier structures with lower fundamental frequencies require lower frequency excitation at higher input force levels.

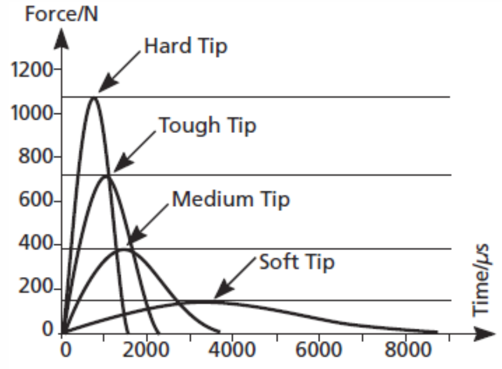

Figure 5.2: Impulse shapes of the modal hammer as a function of used impact tip [5]

5.1.2 - Shaker testing

Shaker testing is often used in more complex structures, and comprised many different excitation techniques. The structure is set into motion by "shaking" it, which is more repeatable than hammer testing, but requires a skilled operator. In addition, particular attention needs to be given to the attachment of force transducers and shaker [6]. In order to protect the shaker, which is expensive equipment, the force transducer is attached to the structure, and linked to the shaker via a connection rod, also called stinger. The stinger exhibits a high axial stiffness and a low bending stiffness, so that the excitation force acts only at the desired point and in the desired direction. In addition, the structure is free to vibrate with no moment excitation and no rotational inertia loading.

The chosen method for supporting the shaker may affect the force imparted to the structure. The main body of the shaker must be isolated from the structure to prevent any reaction forces from being transmitted through the base of the shaker back to the structure. This can be accomplished by mounting the shaker on a solid floor and suspending the structure from above. The shaker could also be supported on a mechanically isolated foundation. Another method is to suspend the shaker, in which case an inertial mass usually needs to be attached to the shaker body in order to generate a measurable force, particularly at lower frequencies. The location of the shaker is of great importance in order to minimize the amplitude of undesirable modes [7].

Different excitations may be implemented through a shaker. The sine excitation is best for studying non-linearities under the form of harmonic distortion. For broadband excitation, the sine wave is slowly swept through the frequency range of interest, under quasi-stationary condition. This process is therefore very slow. The random excitation consists of a random variation of amplitude and phase, and has the advantage of averaging. In other words, this gives optimum linear estimate in case of non-linearities. The random signal is characterized by a power spectral density and an amplitude probability density, which means it can be limited according to the frequency range of interest. Other types of excitation signals, such as burst random, pseudo-random, multisine, periodic random, or periodic pulse are studied in detail by Schwarz and Richardson [3].

5.1.3 - Operational modal analysis

Operational modal analysis uses the natural and ambient excitation of the structure. It is still a cutting edge technique, sometimes the only solution for very large structures e.g. long bridges, for which a huge amount of energy would have to be implemented by classical techniques of shaker or modal hammer. Since it is an in-situ measure, there is no need for special boundary conditions, and other tests may be performed in the same time. It is nevertheless a computation intensive measurement method, and it has to be ensured that the natural excitation covers the frequency range of interest. More importantly, there is no control of the excitation, and uncertainties must therefore be carefully taken into account.

5.1.4 - Vibration sensors

Vibration sensors may differ in number, depending on the experimental protocol. Very often the vibration sensor is an accelerometer, but sometimes a displacement transducer may be used. Accelerometers may be fixed to the structure via a threaded stud as shown in *Figure 5.3*, but may also use some cement, wax, or even magnetostatic forces.

5.1.5 - Experimental protocols

Various experimental protocols may be used, depending on the number of recorded inputs and outputs. The Single Input Single Output (SISO) measurement system is usually related to hammer testing, and consist of recording the vibration response at a single location, with the structure being excited at a single location. An extension of this method is used for the roving hammer method, which consists of several SISO measurements on a finite and predefined number of measurement points. A special case of SISO measurement system is the driving point method [8], which consists of recording the vibration response at the same single location where the structure is excited. The driving-point measurement on large structures can normally be performed, without introducing any significant errors, by applying the excitation very close to the transducer [9]. On small structures it is often possible to attach the force and driving-point transducers on opposite sides of the structure at the excitation point.

The Single Input Multiple Output (SIMO) measurement system consists in recording the vibration response at several locations, simultaneously, with the structure being excited at a single location. This is also compatible with the roving hammer method, which is that case would consist in several SIMO measurements on a finite and predefined number of measurement points. SIMO is also popular for shaker testing. It is common that in that case, all predefined measurement points are equipped with a vibration sensor, so as to optimize data consistency.

The Multiple Input Multiple Output (MIMO) measurement system consists in recording the vibration response at several locations, simultaneously, with the structure being excited at a several locations, simultaneously. Multiple inputs are required for large and complex structures in order to get the excitation energy sufficiently distributed, and in order to avoid non-linear behavior.

Figure 5.3: Accelerometer mounted using a double sided threaded stud

Lastly, the Multiple Input Single Output (MISO) measurement system consists in recording the vibration response at a single location, with the structure being simultaneously excited at several locations.

5.1.6 - Frequency Response Function

The full frequency response matrix **H** may be written as:

$$\begin{Bmatrix} X_1 \\ X_2 \\ \vdots \\ X_n \end{Bmatrix} = \begin{bmatrix} H_{11} & H_{12} & \dots & H_{1n} \\ H_{21} & H_{22} & \dots & H_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ H_{n1} & H_{n2} & \dots & H_{nn} \end{bmatrix} \begin{Bmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{Bmatrix} \quad (1)$$

H_{ij} terms may be defined as:

$$H_{ij}(\omega) = \frac{X_i(\omega)}{F_j(\omega)} = \frac{\text{Response "}i\text{"}}{\text{Excitation "j"}} \quad (2)$$

where $X_i(\omega)$ = Fourier transform of the response $x_i(t)$, and $F_j(\omega)$ = Fourier transform of the excitation $f_j(t)$. An example of experimental frequency response function is shown in *Figure 5.4*.

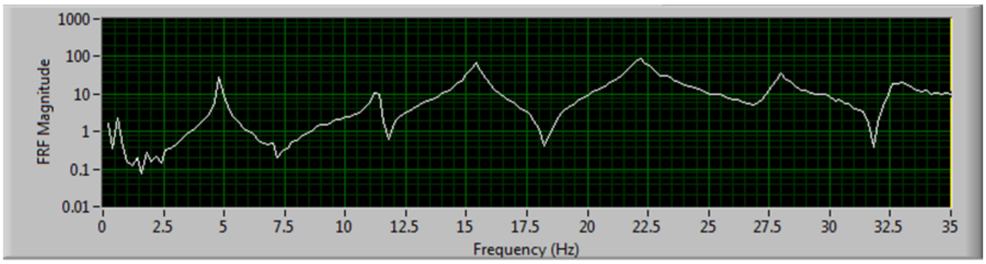

Figure 5.4: Experimental frequency response function

The knowledge of a unique row (from hammer testing), or of a unique column (from shaker testing), is usually enough to determine all the vibration modes of the system. For instance, the roving hammer method gives the knowledge of a unique row (SISO), or of several rows (SIMO), whereas the shaker testing method gives the knowledge of a unique column (SIMO). The driving point method determines one diagonal element of the frequency response matrix **H**.

The knowledge of a unique row or column from the frequency response matrix is not sufficient for determining all the vibration modes of the system when there are several modes for the same frequency, e.g. for symmetrical structures. In case of hammer testing, more locations for recording the vibration response are therefore required to increase the number of known rows. In case of shaker testing, the shaker has to be moved to different excitation locations in order to increase the number of know columns.

Experimental modal analysis is a linear theory. The frequency response function is therefore linear, i.e.:

$$\begin{cases}\{\mathbf{X}\}=\mathbf{H}\{\mathbf{F}\}\\ \{\mathbf{X}'\}=\mathbf{H}\{\mathbf{F}'\}\end{cases}\Rightarrow\begin{cases}\{\mathbf{X}+\mathbf{X}'\}=\mathbf{H}\{\mathbf{F}+\mathbf{F}'\}\\ a\{\mathbf{X}\}=\mathbf{H}\{a\mathbf{F}\}\end{cases} \tag{3}$$

The validity of the frequency response function is assessed by the coherence function γ^2, defined as:

$$\gamma^2(\omega)=\frac{\left|G_{XF}(\omega)\right|^2}{G_{FF}(f)G_{XX}(f)} \tag{4}$$

where G_{XF} = cross-spectral density, G_{FF} = load signal spectral density, G_{XX} = response signal spectral density. The coherence function is analogous to the squared correlation coefficient used in statistics, and measures the degree of linear relationship between the input and output signals at each fundamental frequency. A value close to one shows therefore good coherence. Coherence values lower than 0.75 are commonly considered poor, and may be due to noise in the measured output or input signal. Poor coherence may also be due to other input which would not be correlated with the measured input signal. By averaging several time records together, statistical reliability can be increased and random noise associated with nonlinearities can be reduced.

5.1.7 - Modal parameters extraction

Curve fitting is the process of estimating the modal parameters from the frequency response function evaluations. This is done by minimizing the squared difference between the assumed analytical function and the measured frequency response function. The modal parameters for all modes within the frequency range of interest constitute a complete dynamic description of the structure. Any free or forced dynamic response of a structure may be reduced to a discrete set of modes. The modal parameters are:

- Modal frequency
- Modal damping
- Mode shape

Suitable analytical expressions to curve fit the frequency response function with may be written as:

$$H_{i,k}=\sum_{r=1}^{n}\frac{(\psi_i\psi_k)_r}{\left[\omega_r^2-\omega^2+2j\xi_r\omega_r\omega\right]}$$
$$\text{with}\begin{cases}(\psi_i\psi_k)_r=\text{residues}\\ \omega_r=\text{undamped natural frequency}\\ \xi_r=\text{ equivalent viscous modal damping ratio}\end{cases} \tag{5}$$

where r = mode number, and n = total number of modes. The undamped natural frequency and the viscous modal damping ratio are directly extracted from Eq. (5). The mode shapes vectors $\mathbf{\Psi_r}$ are extracted as:

$$\mathbf{\Psi_r} = \left[\left\{ \psi_1{}^2 \right\}_r \quad \left\{ \psi_1 \psi_2 \right\}_r \quad \cdots \quad \left\{ \psi_1 \psi_{13} \right\}_r \right] \tag{6}$$

Single-degree-of-freedom (SDOF) methods estimate modal parameters one mode at a time, whereas multiple-degree-of-freedom (MDOF) methods can simultaneously estimate modal parameters for several modes, as shown in *Figure 5.5* a) and b), respectively. Local methods are applied to one frequency response function at a time, whereas global methods are applied to an entire set of frequency response functions. In general, local SDOF methods are the most convenient to use.

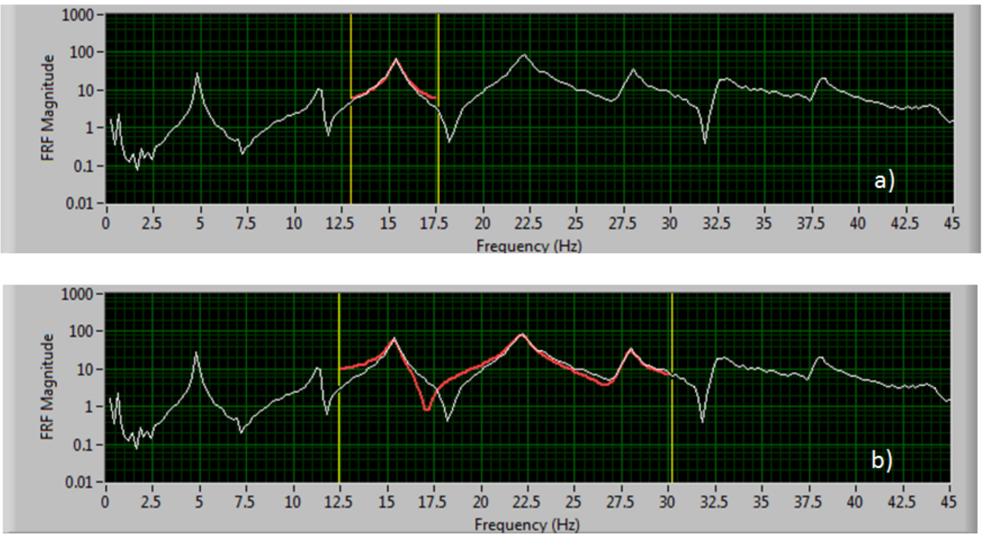

Figure 5.5: Curve fitting of frequency response function a) SDOF method b) MDOF method

SDOF methods are appropriate for lightly coupled modes, whereas multiple-degree-of-freedom MDOF methods are appropriate on heavily coupled modes. More detailed specific methods are described by Ewins [1].

Algorithms for fitting the analytical expressions are numerous, and are not further detailed here. An exhaustive review can be found from Srikantha Phani and Woodhouse's work [10], where they collected and compared different identification methods. Two years later, they applied the collected methods to experimental data [11]. They quantified and compared the performance of each method. For both studies, they considered three different groups:

- matrix methods, which are based directly on the FRF matrix, and give as outputs the mass, stiffness and damping matrices.
- modal methods, which use complex mode shapes and fundamental frequencies identified from modal testing, as defined in Section 5.1 - . In some cases, the

knowledge of the mass and stiffness matrices is brought by the finite element method

- enhanced methods, defined as possible improvements of matrix methods.

5.2 - Performed experimental studies

5.2.1 - Chosen experimental protocol

The modal hammer "heavy duty type 8208" from Brüel & Kjær, shown in Figure 5.1 was used to set the beam into motion. A soft tip was employed in order to excite lower frequencies. Transient vibrations due to modal hammer impact were recorded by one ceramic/quartz impedance head Kistler accelerometer type 8770A50 screwed into the timber structure, as shown in Figure 5.3. The load and acceleration time series were then digitalized and processed by a dynamic analyzer of signals. An experimental modal analysis software was provided by National Instruments [12] to record and process the data, using the graphical development environment LabVIEW. The sampling frequency was fixed to 1000 Hz (beams and floors) or 2048 Hz (panels), and 5 s data were recorded for each impact. A linear average of the estimated Frequency Response Function over 3 impacts (beams) or 2 impacts (panels and floors) was performed for each evaluation.

The present method is considered as non-destructive since the hammer impact is soft enough not to inflict any damage the structure or modify its properties. This also allows for an unlimited number of repeated measurements to be performed on each specimen.

Experimental Modal Analysis was used for determining the fundamental frequencies, the damping ratios and the mode shapes of the timber beams, via a software [12] provided by National Instruments as well. The parameter identification method is based on the Frequency-Domain Direct Parameter Identification (FDPI) fitting method, which is a frequency domain multiple degree of freedom modal analysis method suitable for narrow frequency band and well separated modes.

5.2.2 - Timber beams

A total of 22 beams were tested [13]: 11 solid wood beams and 11 glulam beams. Each beam was simply supported with a symmetric overhanging. Supports used were constructed of either rigid steel tripods or sections of thick steel cylinders. Teflon sheets were added in between the timber beam and the steel supports in order to minimize friction and other sources of structural damping. The impact and the data recording took place at the same location, 2.5 m from one end of beam, following the driving point method. The experimental setup is displayed in *Figure 5.6*.

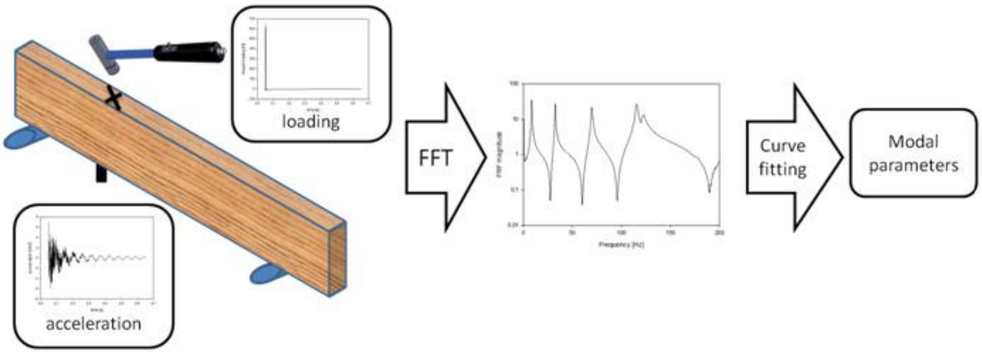

Figure 5.6: Driving point experimental setup for timber beams

Mode shapes of one glulam beam were evaluated following the roving hammer method. 13 measurement points were impacted along the beam, which corresponds to 50 cm spacing between consecutive points. The obtained three first mode shapes of a glulam beam, flatwise oriented, with a 5 m span are presented in *Figure 5.7*.

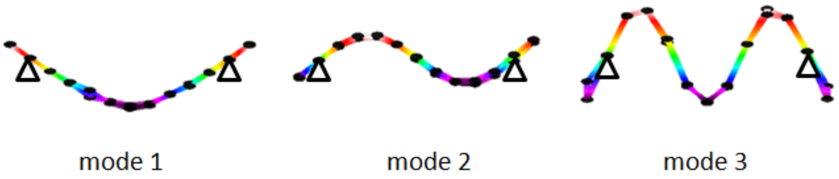

Figure 5.7: Experimental mode shapes of a glulam beam, flatwise oriented, with a 5 m span

5.2.3 - Timber panels

A total of 18 sheathing panels were tested [14]. Sheathing panels were either particleboard panels, Oriented Strand Board panels (OSB), or structural laminated veneer lumber panels (LVL). Steel cylinders whose outer diameter was 133 mm and whose thickness was 4 mm were used as supports, as shown in *Figure 5.8* a).

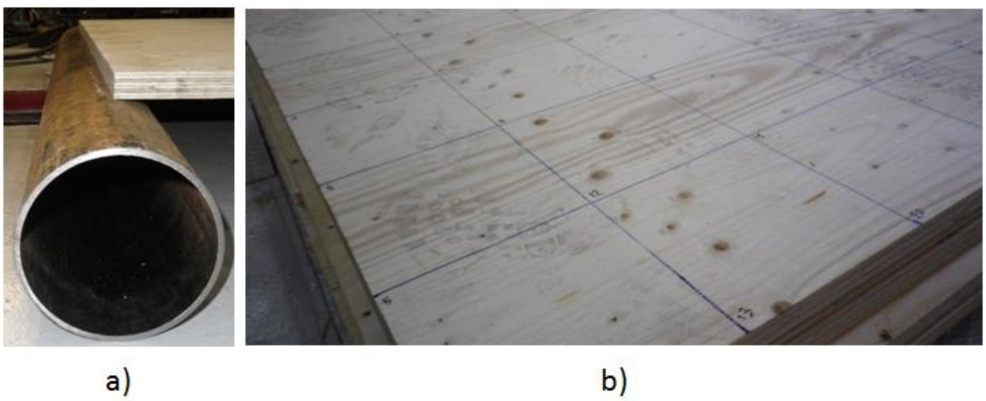

Figure 5.8: Experimental setup for timber panel testing a) supports b) discretization of the panel

Two different methods for evaluating dynamic properties of the sheathing panels were successively used. They are both illustrated in *Figure 5.9*. The unique location of both the accelerometer and the impact was designed so as to maximize the number of observed modes of vibration.

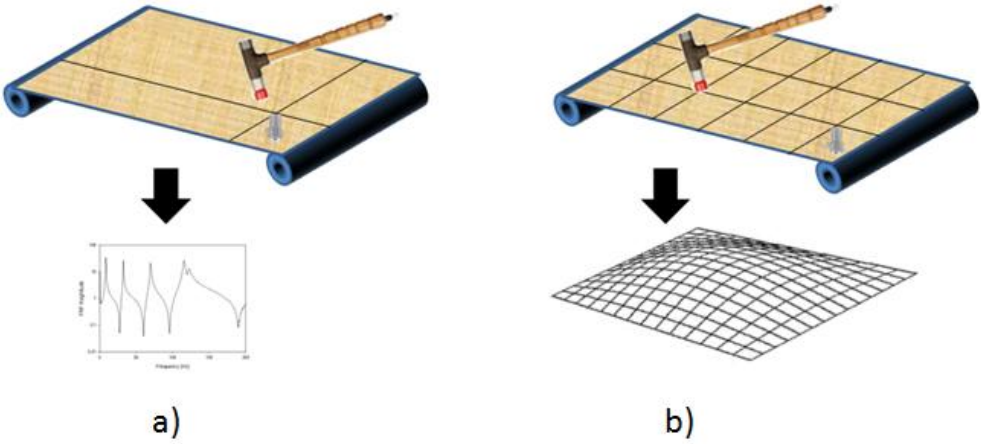

Figure 5.9: Timber panels experimentally evaluated by different methods: a) Driving point method and b) Roving hammer method

The mode shapes corresponding to each type of panel (given thickness and given material) were evaluated by means of the roving hammer method shown in *Figure 5.8* b), while the accelerometer remained at one unique location. The grid consisted of 84 to 91 measurement points, depending on the type of panel. This is equivalent to 20 cm to 25 cm spacing between each consecutive point. A total of 1484 measurements were performed. The obtained six first mode shapes for a 22 mm thick OSB panel, simply supported on short sides are presented in *Figure 5.10*.

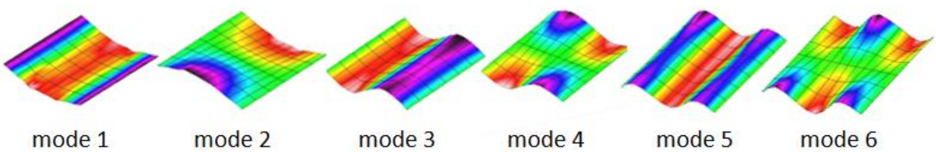

Figure 5.10: Experimental mode shapes for an OSB panels, simply supported on its two short sides

5.2.4 - Timber floors

Two timber floors were tested [15]: one whose connectors were all screws, one whose connectors were all nails. Both timber floors were simply supported on four corners, by means of 20 cm long steel cylinders located along the edge joists, as shown in *Figure 5.11*. A total of 784 measurements were performed.

The driving point method was first used to obtain modal damping and fundamental frequencies. The roving hammer method was then used to obtain the mode shapes. The grid consisted of 195 measurements points, which corresponds to a 20 cm spaced grid.

The first five modes for the timber floor assembled with screws, with the accelerometer located on a beam are shown in *Figure 5.12*.

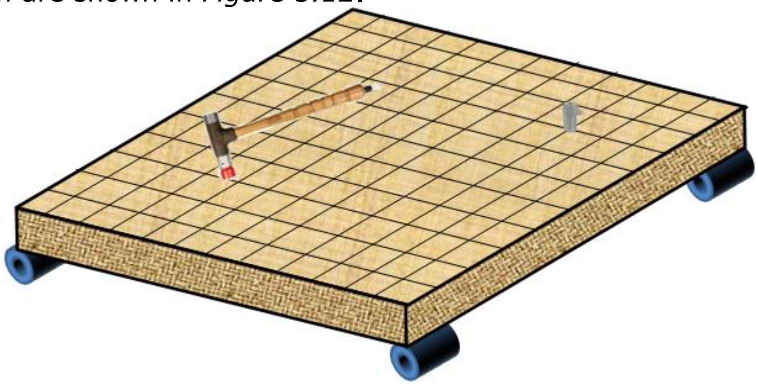

Figure 5.11: Experimental measurements on floors

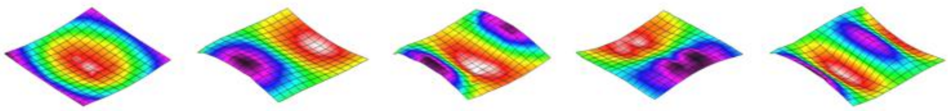

Figure 5.12: Experimental mode shapes of a floor simply supported at its corner

5.3 - Other methods for Experimental measurements of damping

There are different methods for estimating damping, using either time domain or frequency domain analysis. Accuracy of the estimation may vary depending on the prediction method, and is particularly influenced by the "noisiness" of the data.

5.3.1 - Logarithmic decrement

This is the simplest and most frequently used method for finding the equivalent viscous damping ratio through experimental measurements. When the system has been set into free vibration by any means, damping estimates can be made from the rate of decay of the transient response, as described in Figure 5.13. The logarithmic decrement δ is defined with respect to p consecutive cycles of vibration:

$$\delta = \frac{1}{p}\ln\frac{x_{n+p}}{x_n} \qquad (7)$$

The logarithmic decrement δ is dimensionless, e.g. a value of 0.1 means that the amplitude decreases of 10% in any consecutive cycle. A major advantage of the logarithmic decrement method is that equipment and instrumentation requirements are minimal; the vibrations can be initiated by any convenient method and only the relative displacement amplitudes need to be measured [16]. The damping ratio ξ is then evaluated from:

$$\xi = \frac{\delta}{2\pi} \tag{8}$$

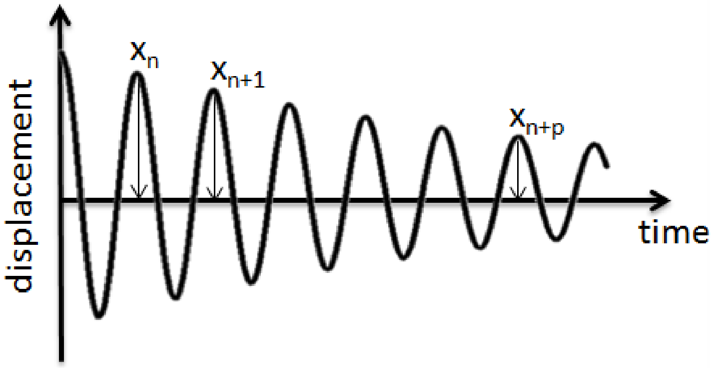

Figure 5.13: Transient response of an underdamped single-degree-of-freedom system and log decrement calculation

The simplicity of the method is its main advantage, and explains its broad use in damping investigations [17]. For instance, Obataya, Ono and Norimoto [18] used it for measuring damping in wood, Maslov and Kinra [19] for measuring the damping capacity of carbon foams, Gounaris et al. [20] for measuring the loss factor of a cantilever steel beam. If the damping is truly of viscous form, any set of consecutive cycles will yield the same damping ratio. However the damping ratio often is found to be amplitude dependent. This is of direct influence on the logarithmic decrement, since consecutive cycles in the earlier portion of high amplitude free vibration response will yield a different –often higher – logarithmic decrement than consecutive cycles in a later stage of much lower response. Caution must therefore be exercised [16]. Moreover, Cai et al. [21] reported that the consistency and repeatability of this method when applied to wood and wood-based materials were found lacking.

5.3.2 - Envelope fitting

Another widely used approach to determine damping from a free vibration curve is to fit an exponential curve passing though the peaks amplitudes, as presented in *Figure 5.14*. The decay profile is described by:

$$X(t) = Ae^{-\xi\omega_n t} \tag{9}$$

where A = constant and ω_n = fundamental frequency. The envelope fitting approach yields a higher degree of accuracy compared to the logarithmic decrement method, since it takes into account all selected consecutive cycles, instead of only the first and the last of a series. The more peaks are used in the calculation, the better the evaluation of damping.

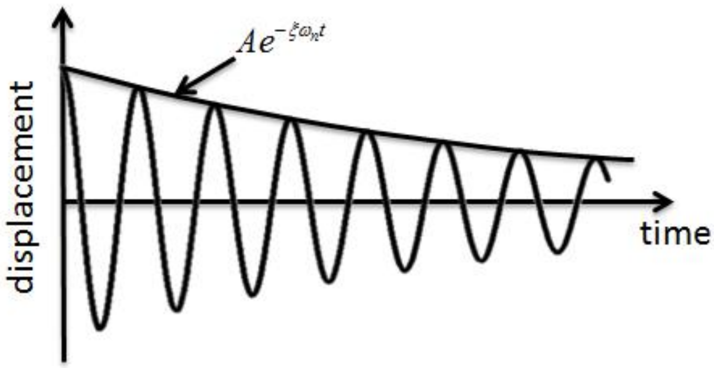

Figure 5.14: Envelope fitting of the transient response of an underdamped single-degree-of-freedom system

Though more accurate, the envelope fitting method yields a drawback similar to the logarithmic decrement method. If the damping is not of viscous form, the fitting of the envelope along the whole transient response is likely to be of limited quality. Besides, all points from the transient response contain damping information, but both methods use only a very small percentage of this available information, i.e. peak data only. Both methods are therefore limited in terms of efficiency. Another issue related to both methods is that they are both strongly dependant on the sampling rate used to collect data. The lower the sampling rate is, the worse the approximation of actual amplitudes is.

5.3.3 - Phase plot diagram

Cai et al [21] presented a different way to use the free vibration of a single-degree-of-freedom system. They used the $x-\dot{x}/\omega_n$ plane to plot the transient response, and obtained a spiral curve asymptotically approaching the origin. The radius *R* of the spiral curve in Figure 5.15 a), when plotted in the time domain, is the same as the decay profile curve of the free vibration. If the damping ratio ξ is less than 2%, the following relationship between the radius *R* and the damping ratio ξ can be written with an error not exceeding 1%:

$$R=\sqrt{x^2+\frac{\dot{x}^2}{{\omega_n}^2}}=Ae^{-\xi\omega_n t} \tag{10}$$

Taking the natural logarithm of Eq. (10) yields:

$$\ln R=\ln A-\xi\omega_n t \tag{11}$$

A simple linear regression can therefore be used to find the slope, which in turn determines the damping ratio ξ. Since all sample points in the time domain are used, this procedure makes the maximum use of the available information and provides more accurate damping evaluations. When using this method, the damping ratio does not depend on the initial amplitude and the phase, which are only contained in the intercept. Furthermore, the damping ratio does not depend on the time interval in which sample points are chosen for the linear regression because of the linearity.

Velocity is rarely directly measured during experiments, but can however be obtained either by numerical integration of acceleration (preferred) or numerical differentiation of displacement. Cai's method's accuracy is therefore dependent on the sampling rate, due to numerical manipulations on the signal.

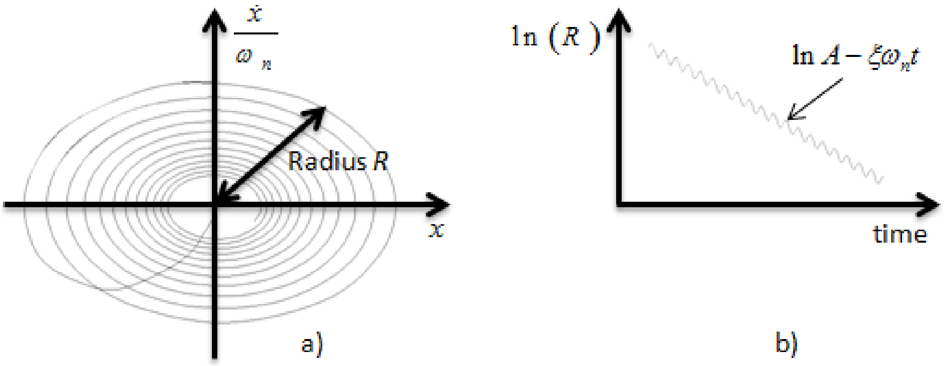

Figure 5.15: Cai's procedure: a) transient response of a single-degree-of-freedom in the phase plane b) linear regression

5.3.4 - Half-power bandwidth

The steady-state response of a vibrating system can also be used to evaluate damping. In such cases, the transfer function is preferred to any other representation of the signals. The level of damping can be subjectively determined by noting the sharpness of the peak: the more rounded the shape, the more damping [22]. The half-power bandwidth method achieves a quantitative evaluation of the hysteretic damping:

$$\eta = \frac{\Delta\omega}{\omega_0} \qquad (12)$$

where $\Delta\omega$ is determined from the half-power points ω_1 and ω_2 and from the resonant peak value ω_0, as illustrated in *Figure 5.16*. On a decibel scale, this corresponds to -3dB down from the peak value. The assumption of small damping [23] yields:

$$\eta = 2.\frac{\omega_1 - \omega_2}{\omega_1 + \omega_2} \qquad (13)$$

The half-power bandwidth method was used in many studies [18, 20, 24-27]. The hysteretic damping η provided by the half-power bandwidth method is extremely sensitive to the accuracy of peak location, which is itself highly dependent on the sampling rate. The half-power points ω_1 and ω_2 are dependent on both the accuracy of the peak location and the resolution of the transfer response, and therefore depend on the sampling rate as well.

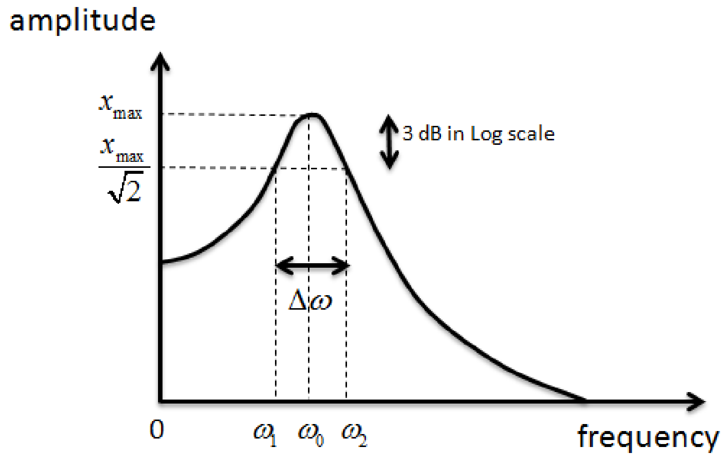

Figure 5.16: Half-power bandwidth method applied to the compliance transfer function of a single-degree-of-freedom system

5.3.5 - Resonant Amplification

The resonant amplification method is also based on the steady-state response of a vibrating system and its transfer function. The amplification factor *Q* is defined as the ratio of the response amplitude at resonance, ω_0, to the static response at $\omega = 0$, so that:

$$Q = \frac{x(\omega = 0)}{x(\omega = \omega_0)} = \frac{x_s}{x_{max}} \tag{14}$$

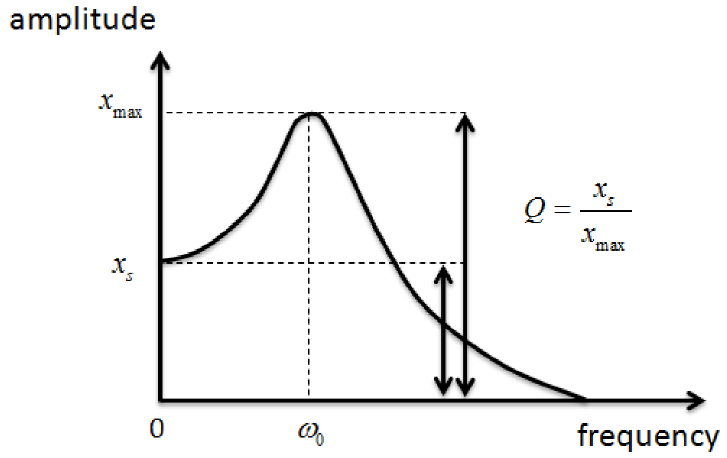

Figure 5.17: Resonant amplification method applied to the compliance transfer function of a single-degree-of-freedom system

This method of determining the damping ratio requires only simple instrumentation to measure the dynamic response amplitudes at discrete values of frequency and fairly simple dynamic loading equipment. Similarly to the half-power bandwidth method, it requires good resolution of the transfer function in the neighborhood of the peak. In addition, obtaining the static displacement may present a problem because the typical harmonic loading system cannot produce a loading at zero frequency [16].

5.3.6 - Resonant energy loss per cycle

Another evaluation of damping can be achieved by calculating the energy loss per cycle of oscillation under steady-state harmonic loading. This procedure involves establishing resonance by adjusting the forcing frequency until the displacement response is 90 ° out-of-phase with the applied loading. At resonance, the damping force f_D is exactly balanced by the excitation F [16]. The hysteresis loop is then defined by plotting the applied loading F versus the displacement x for one cycle of motion. If the system possesses linear viscous damping, as in *Figure 5.18* a), the hysteresis loop is an ellipse and the viscous damping ξ may be directly computed. Indeed:

$$F_{\max} = F_0 = f_{D,\max} = c\dot{x}_{\max} = 2\xi m\omega^2 X_0 \qquad (15)$$

Finally:

$$\xi = \frac{F_0}{2m\omega^2 X_0} \qquad (16)$$

If damping is of a non-linear viscous form, as in Figure 5.18 b), the hysteresis loop is not elliptical, because the response X is a distorted harmonic even though the applied loading F remains a pure harmonic. The area captured within the hysteresis loop, ΔE, is equal to the dissipated energy per cycle of harmonic motion by the system, and may be calculated as:

$$\Delta E = \pi F_0 X_0 \qquad (17)$$

The equivalent viscous damping ratio ξ_{eq} is then determined by:

$$\pi f_0 X_0 = \Delta E = \Delta E_{eq} = c_{eq}\pi\omega X_0{}^2 = 2\xi_{eq} m\omega^2 X_0{}^2 \qquad (18)$$

Finally:

$$\xi_{eq} = \frac{F_0}{2m\omega^2 X_0} \qquad (19)$$

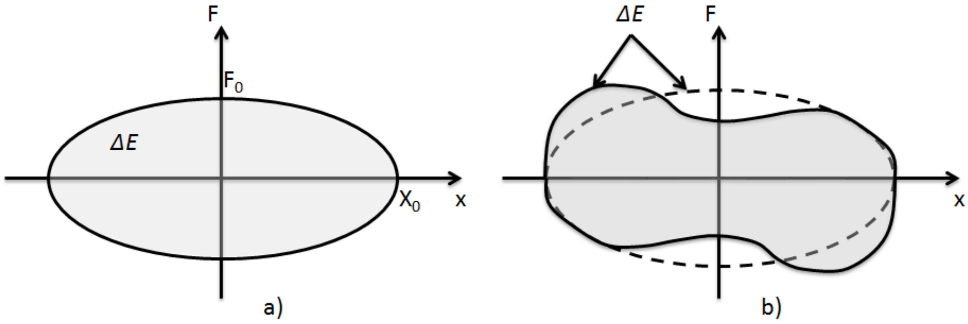

Figure 5.18: Hysteresis loops a) for a system of viscous damping form b) for an actual system

Implementing the resonant energy loss per cycle method requires to identify resonance, and to stay at this input frequency during the recording of signals. Identification of resonance is not easy for systems exhibiting non-viscous damping because the maximum amplitude of displacement does not correspond to resonance state. A possible solution lies in recording continuously the phase delay between the applied loading signal and the displacement signal. Another problem arises when the resonance frequency is identified. Due to structure-shaker interaction, the shaker is usually observed to be unable to apply the selected fundamental frequency [28]. In addition, even if the shaker is able to maintain the tested system in a true resonance state, one must ensure that the tested structure is not harmful in such a resonance state which usually induces high amplitudes.

5.3.7 - Acoustics

Ouis [29-31] used the room acoustical technique to detect decay in logs through measuring the dampening of bending vibrations. He presented a technique for evaluating the loss factor of a solid material element, and investigated the example of a Norway Spruce beam like specimen with artificial defects in the form of voids. The reverberation time *RT* is defined as the time in seconds needed for the sound level to drop by 60 dB from the time a sound source has been switched off. Ouis extended this concept to any vibrating system, and evaluated the loss factor η by the relation:

$$\eta = \frac{\ln 10^6}{\omega RT} \approx \frac{2,2}{fRT} \qquad (20)$$

This technique was also employed by Craik and Barry [32].

5.3.8 - Laboratory visco-elastic methods

Mechanical spectroscopy is a popular means for measuring the internal friction of materials. Typically, a torsion pendulum is used to stress harmonically a sample and the lag of the response (strain), relative to the stress, provides the loss tangent and thus the internal friction [33]. In 1984, Wert et al. [34] measured the internal friction and dielectric loss on whole wood, cellulose and lignin to elucidate new features of the loss components. The equipment used for internal friction measurements was a low frequency inverted torsional pendulum which had been designed for use with metals and alloys.

5.3.9 - Correspondence between measurement methods

With the exception of acoustical and visco-elastic methods, the different described methods for evaluating damping are summarized in Table 5.1. In addition, Gade and Herlufsen [35] compared several methods for measuring damping with respect to their advantages and disadvantages and provided a complete correspondence table relating the different quantities provided by different measurement methods.

Table 5.1: Characteristics of selected measurement methods of damping

Method	Time domain	Frequency domain	Impact excitation	Shaker excitation	Measured quantity
Logarithmic decrement	x		x		δ
Envelope fitting	x		x		ξ
Phase plot diagram	x		x		ξ
Half-power bandwidth		x	x	x	η
Resonant amplification		x		x	Q
Experimental modal analysis		x	x	x	ξ
Resonant energy loss per cycle	x			x	ξ,η
Phase angle	x			x	η

The amplification factor Q relates to the hysteretic damping ratio η through the equation:

$$Q = \frac{1}{\eta \cdot \sqrt{1-\eta^2/4}} \approx \frac{1}{\eta} \tag{21}$$

At resonance, the relationship between hysteretic damping ratio η and (equivalent) viscous damping ratio ξ is:

$$\eta = 2\xi \tag{22}$$

The viscous damping ratio ξ is obtained from the logarithmic decrement δ as:

$$\xi = \frac{\delta}{2\pi} \tag{23}$$

Sometimes the specific damping capacity φ is employed, and is defined as:

$$\varphi = 2\pi\eta = 4\pi\xi \tag{24}$$

5.4 - REFERENCES

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6 - ASSESSMENT OF WALKING-INDUCED FLOOR VIBRATIONS ACCORDING TO THE SBR GUIDELINE

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6.1 - Introduction

Lightweight floors are prone to high levels of vibration due to human activities. The Dutch building code imposes regulations on floors with respect to safety, health and serviceability. The walking-induced vibrations of floors are not incorporated in these regulations. The private law arrangement in the NEN 6702 (§10.5.2) [1] does not completely cover the physical background of the issues and is solely applicable to heavyweight floors with two- or four-sided simply supported or clamped conditions. It merely restricts the first eigenfrequency of a floor to be larger than 3Hz for walking and to be larger than 5Hz for jumping. These restrictions are not sufficient for lightweight floors as these are easily excited by the higher harmonics of (near) periodic loads.

Due to the growing interest in lightweight buildings the need for an appropriate assessment guideline for walking-induced floor vibrations increased. From the need of such a guideline two European research projects, funded by the Research Fund for Coal and Steel (RFCS), were initiated to find the appropriate assessment method [3,4]. This resulted into two guidelines, a European [4] and a Dutch one, namely the SBR guideline for walking-induced floor vibrations [5]. The Dutch guideline describes the complete assessment procedure, while the European guideline only covers the so-called hand calculation method.

In the following the general principles of the (Dutch) guideline are described with an emphasis on the experimental method. Finally, some recommendations are made to extend and to improve the guideline.

6.1.1 - Assessment quantity

The guideline introduces a new assessment quantity, namely the OS-RMS$_{90}$ (OneStep-RMS-90). This is the RMS-value of the vibration levels (in mm/s) on a position of the floor during the period of one step. The vibrations not only depend on the floor to be assessed, but they also on the characteristics of the source. The source is determined by the step frequency and the weight of the walking person. The source varies wildly in frequency and load. Therefore, based on a statistical approach, the OS-RMS$_{90}$ describes the vibration level that is not exceeded in 90% of all cases.

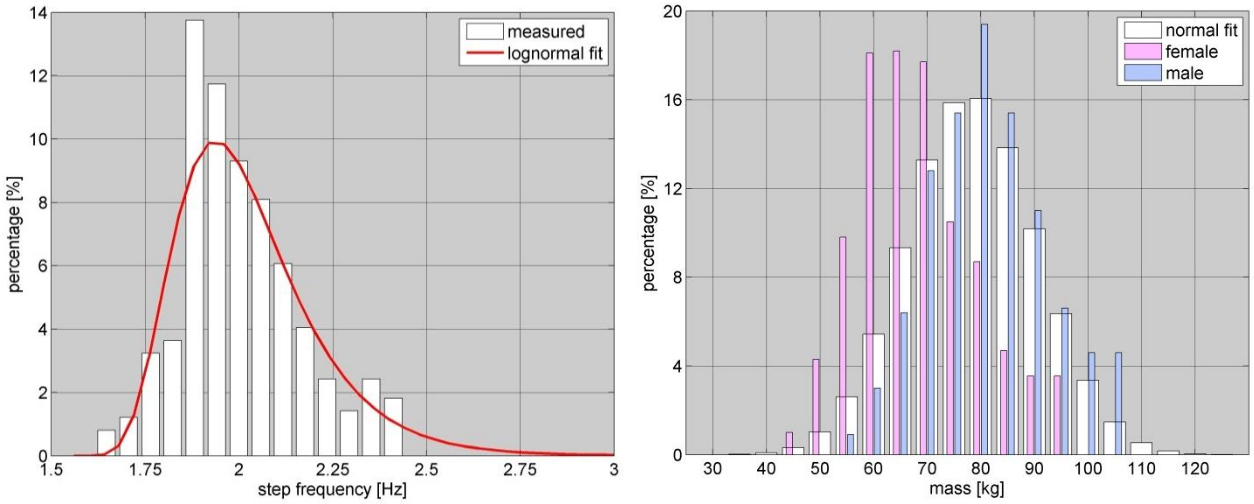

Figure 1: Demographic distribution of step frequencies and weight.

In Figure 1, the demographic distributions of step frequency and weight of the Dutch population is displayed. When the vibration response of the floor to be assessed is obtained for all combinations of step frequency and weight, then the 90%-upper limit of all these combinations (regarding the likelihood of appearance) poses the OS-RMS_{90}.

Due to the modal behavior, the OS-RMS_{90} is very dependent of the locations of excitation and of response. In the guideline it is therefore advised to choose the location of measurement where high nuisance is expected and to choose the location of excitation where walking excitation occurs frequently. In case these locations are unknown it is suggested to choose the floor center as point of excitation and of response.

6.1.2 - Classification

The floor assessment in the SBR-guideline is based on a number of classes. The class 0 – 0.1 is below the threshold of observation. Walking induced vibrations with a OS-RMS_{90} of 0.05 are just noticeable for 50% of the people, but they are not regarded as a annoying. A barely noticeable increase in vibration level occurs when the response increases with a factor 1.4. A clearly noticeable change in vibration level occurs when the response increases with a factor 2. One step in nuisance level is most likely to occur when the response increases with a factor 4. This factor is still under investigation.

These factors define the classes as depicted in Figure 2. For dwellings, the guideline recommends floors of class D (0.8 – 3.2). However, in practice floors in the upper half of this class are regarded as uncomfortable. Therefore, it is suggested by TNO to aim for floors (in dwellings) with an OS-RMS_{90} up to 1.6.

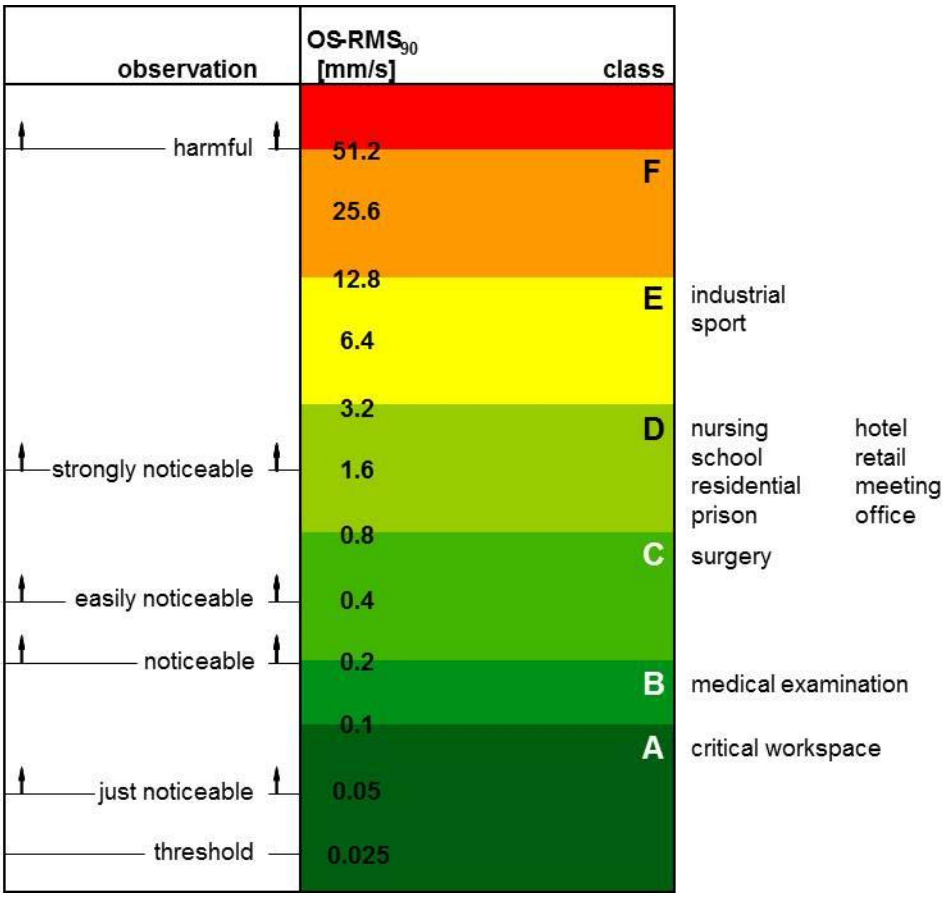

Figure 2: Table with the floor classes according to the SBR-guideline [5]

The guideline is only applicable to the treaded floors. It cannot be used to assess neighboring floors. Vibrations induced outside the sphere of influence are more annoying. Therefore, vibrations induced on neighboring floors have to be assessed more severely than vibrations induced on the floor itself. For this reason the assessment of the neighboring floor can play a more crucial part in the design stage than the treaded floor itself. In order to make the guideline applicable to neighboring floors, the assessment criteria should be altered according to the findings published in the international standard ISO 2631 [6].

According to ISO 2631 vibrations which are just above the threshold of observation can lead to "adverse reactions". Vibrations with the frequency range of 6 to 12Hz (which are common for lightweight floors) are characterized by a threshold of 0.2mm/s (see Figure 3). For the neighboring floor, TNO therefore advises a $OS\text{-}RMS_{90} < 0.2$ (for high comfort: $OS\text{-}RMS_{90} < 0.1$).

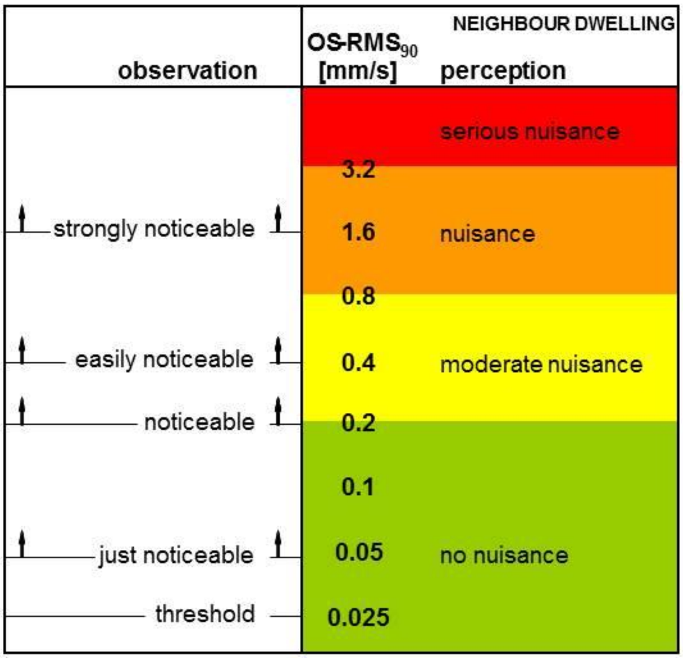

Figure 3: Table with the perception levels at neighboring floors based on ISO 2631 [6]

6.1.3 - Assessment methods

In the Dutch [5] guideline two different methods are presented to determine the OS-RMS$_{90}$, namely

- the hand calculation method
- the transfer function method

In both methods the walking load is described as a polynomial in time where the coefficients depend on the step frequency and the person's weight [3].

In the hand calculation method each dominant mode is described by a SDOF mass-spring-damper system. When the eigenfrequency, the modal mass and the damping ratio of a dominant mode is known, then the OS-RMS$_{90}$ can be obtained from graphs as shown in Figure 4. Those graphs are presented in the guideline for the damping ratios of 1% to 9%. In case more dominant modes exist then the final OS-RMS$_{90}$ is obtained as the RSS of the OS-RMS$_{90}$ of each individual mode.

The transfer function method is based on obtaining the transfer mobilities from point of excitation to the point of observation and to convolute them with the walking load spectra. The transfer functions can be obtained either numerically (FEM) or experimentally.

In the hand calculation method the eigenfrequency and the modal mass can be obtained using analytical (orthotropic) plate formulation with a predefined set of boundary conditions. The drawback of this method is that neighboring floors cannot be assessed. This drawback is overcome in the transfer function method.

The transfer functions are measured by exciting the floor with the so-called heeldrop-test. At the point of excitation a person between 60kg and 100kg stands on his toes and he subsequentially excites the floor with his heels and waits for six seconds (for highly damped floors) or sixteen seconds (for low damped floors). This process is repeated 10 times. The forces are measured using force cells, see Figure 5.

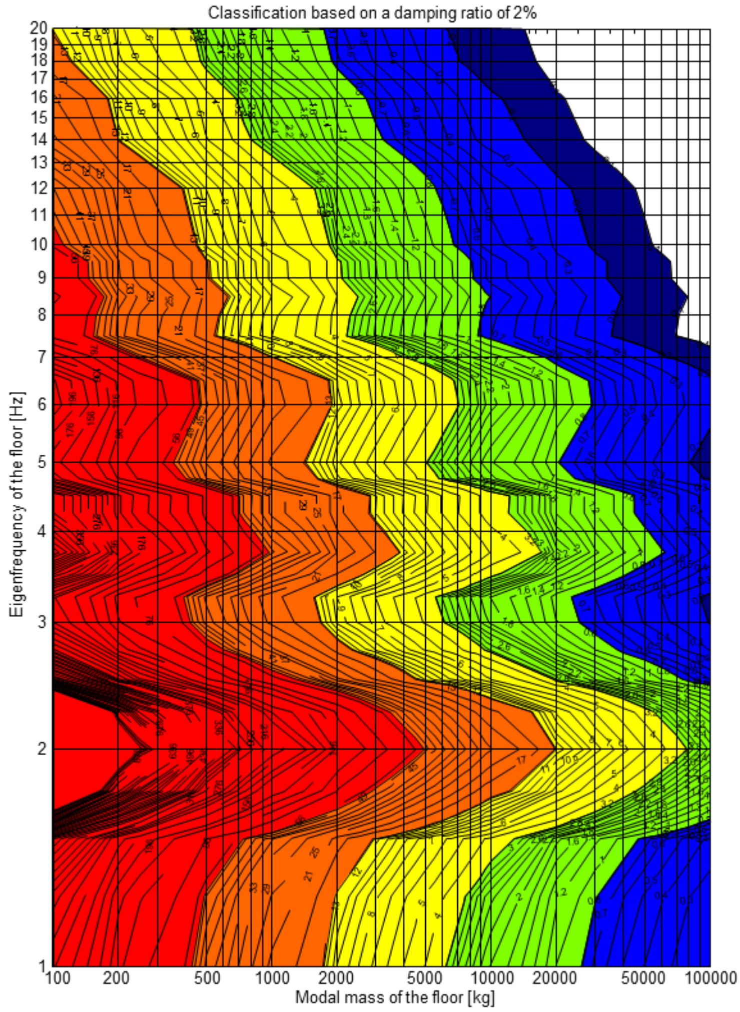

Figure 4: OS-RMS90 isograph for 2% damping

Figure 5: Plateau with force cells to measure the force during a heeldrop-test.

As the accelerations are measured at the points of reception with accelerometers, the transfer mobilities are obtained by integrating the transfer functions between the response and force signals.

6.1.4 - Walking loads

The walking loads are assumed to be described by eighth order polynomials in time

$$F(t) = m(K_1 t + K_2 t^2 + K_3 t^3 + K_4 t^4 + K_5 t^5 + K_6 t^6 + K_7 t^7 + K_8 t^8)$$

Where m is the mass of the walking person and the coefficients K_i depend on the step frequency as described in Table 1.

Table1: Polynom coefficients for the description of the walking load.

	$f_{step} \leq$ 1.75Hz	1.75Hz < f_{step} < 2Hz	$f_{step} \geq$ 2Hz
K_1	-8 f_{step} + 38	24 f_{step} -18	75 f_{step} -120.4
K_2	376 f_{step} -844	-404 f_{step} +521	-1 720 f_{step} +3 153
K_3	-2 804 f_{step} +6 025	4 224 f_{step} -6 274	17 055 f_{step} -31 936
K_4	6 308 f_{step} -16 573	-29 144 f_{step} +45 468	-94 265 f_{step} +175 710
K_5	1 732 f_{step} +13 619	109 976 f_{step} -175 808	298 940 f_{step} -553 736
K_6	-24 648 f_{step} +16 045	-217 424 f_{step} +353 403	-529 390 f_{step} +977 335
K_7	31 836 f_{step} -33 614	212 776 f_{step} -350 259	481 665 f_{step} -888 037
K_8	-12 948 f_{step} +15 532	-81 572 f_{step} +135 624	-174 265 f_{step} +321 008

In Figure 6 the simulated walking loads for one step and for multiple subsequent steps are displayed.

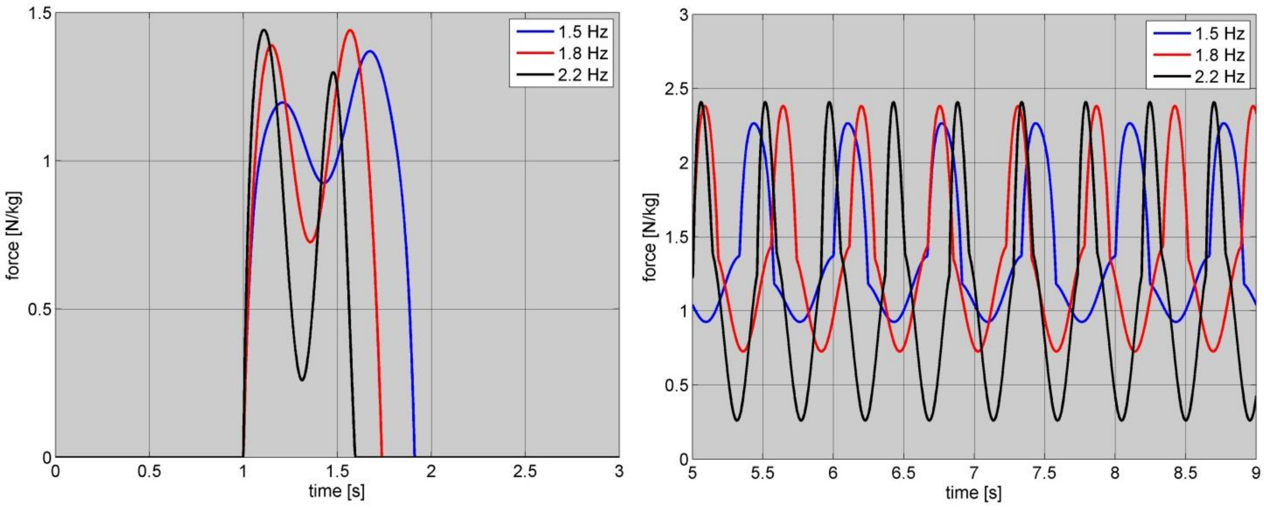

Figure 6: Load trace of a single step (left) and of multiple subsequent steps (right) for three different step frequencies.

The guideline suggests to obtain the walking load spectrum from load time traces which include 50 subsequent steps as depicted by the blue curves in Figure 7.

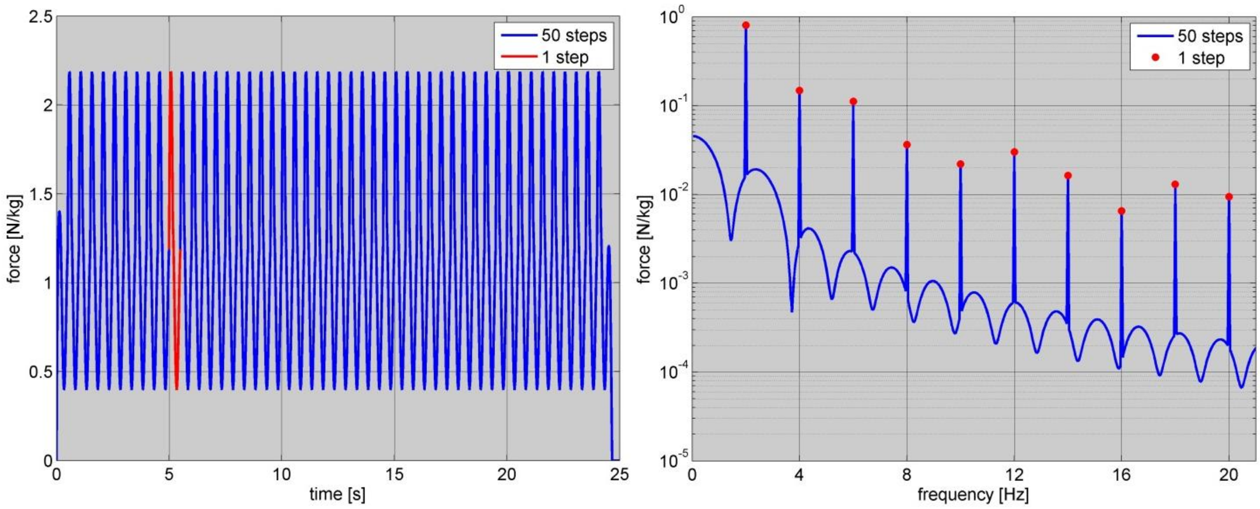

Figure 7: Load trace in the time domain (left) and load trace in the frequency domain (right).

As walking constitutes, according to the guideline, a periodic loading of the floor, it should be sufficient to only obtain the harmonic peaks of the load in the frequency domain. It is therefore also sufficient to only consider a load time trace of length $1/f_{step}$. The resulting load spectrum then only consists of the harmonic amplitudes. This is shown by the red curve and dots in Figure 7.

The response spectrum is obtained by convoluting the load spectrum with the transfer mobilities and the RMS-value during one step is computed as the surface integral of the response spectrum. However, the vibration perception of human beings is frequency dependent and therefore the response spectrum should be weighed before the RMS-value is determined. The weighing function is described according to

$$|H(f)|] = \frac{1}{v_0}\frac{1}{\sqrt{1+\left(\frac{f_0}{f}\right)^2}}$$

where f_0 = 5.6Hz and v_0 = 1mm/s.

6.1.5 - Future recommendations

It has been discussed that the criteria have to be extended to neighboring floors. One could also consider making the guideline suitable to assess the vibrations on balconies or staircases. It is additionally suggested that load spectra should be obtained for the harmonic frequencies.

When the eigenfrequencies and modal ratios are obtained, either analytically or experimentally, then the OS-RMS90 can be determined from several graphs like the one shown in Figure 4. This can be cumbersome especially when values have to be interpolated between different damping ratios. It is suggested to summarise all graphs into one, as displayed in Figure 8.

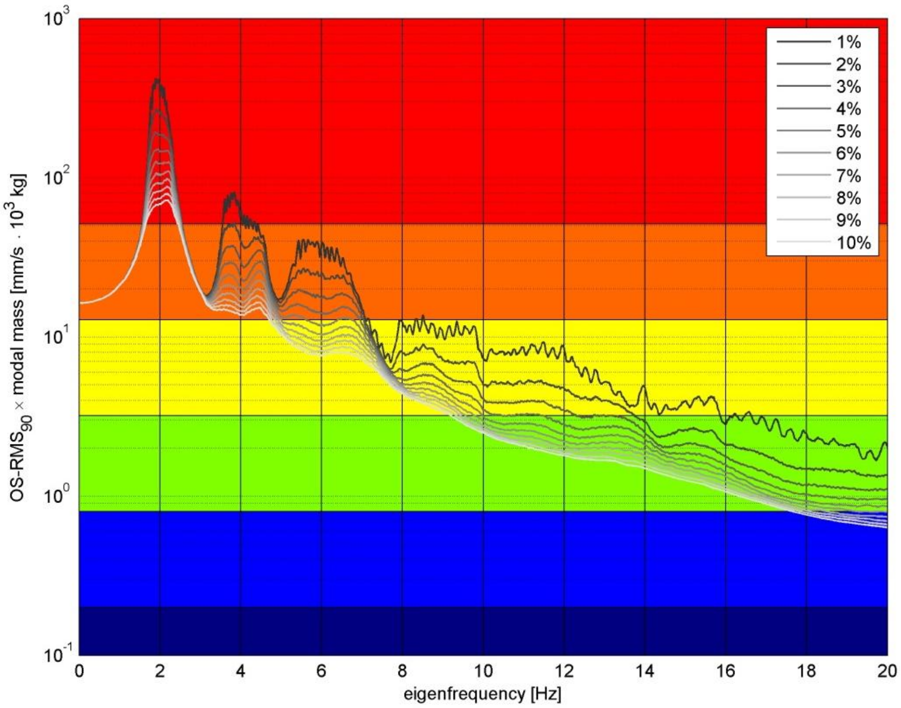

Figure 8: All OS-RMS$_{90}$ iso-graphs summarized into one

From this graph a normalized OS-RMS$_{90}$ value can be determined depending on the eigenfrequency and the damping ratio. Eventually, the normalized value has to be divided by the modal mass in tons.

For the sake of reproducibility of the measurements it is recommended to not perform the assessment based on the maximum vibration level, but rather the 50, or 90-percent upper level over the floor.

The assessment described in the guideline is based on the assumption that a stationary state of vibration can be reached. For small floor, such as balconies, this is rarely the case. Also, the guideline assumes perfect symmetrical striding. In practice this is rarely occurs, which results in an overestimation of the higher harmonics of the load spectrum. Therefore, in the literature a distinction is made between LFF (low-frequencies floors) and HFF (high-frequency floors). Stationary behavior is to be expected in LFF, which have a first eigenfrequency below around 10Hz and can thus resonate with the lower harmonics. Transient response is to be expected with HFF as the higher harmonics are in general to be neglected. It is therefore recommended to extend the guideline to assess the transient behavior of floors due to walking.

6.2 - References

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CHAPTER 3
COMFORT ASSESSMENT FOR SOUND AND VIBRATION

COST Action FP0702

Net-Acoustics for Timber based Lightweight Buildings and Elements

Working Group 3: Comfort assessment for sound and vibration

CONTENTS

A single document is presented in this chapter. The document summarizes the WG3 activities, focused on the vibrational serviceability of timber floors and discusses and compares the different criteria and variants used in the European countries and beyond. It should be noticed that not much has been done concerning comfort assessment for low frequency sound, mostly because of the lack of activities at the member institutes on this subject or because of activities performed for the private sector and not publicly available ; however, this subject is part of the objectives of the on-going COST Action TU0901 (in activity up to the end of 2013), focused on harmonizing sound descriptors and classification schemes in Europe for all type of buildings and where several members are also members of FP0702; hopefully, useful results will be soon produced.

1 - COMPARISON OF VIBRATIONAL SERVICEABILITY CRITERIA FOR DESIGN OF TIMBER FLOORS AMONG THE EUROPEAN UNION COUNTRIES

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ABSTRACT

As part of the research work done by the Working Group 3 of COST Action FP0702, the need for vibrational comfort for buildings, current regulations for comfort assessment of structural vibrations of timber floors in Europe and design practices of timber floors with respect to vibrational serviceability criteria, including fundamental frequency, unit point load deflection and unit impulse velocity, in the EU countries have been summarised and their differences been further assessed by analysing flooring systems constructed with three types of joists, i.e. solid timber joists, I-joists and metal web joists. The unit point load deflection criterion is the most crucial one for design of timber floors with various types of joists and usually dominates the whole design. Finland tends to be the strictest, followed by Italy, the Netherlands, Austria and Norway, while Denmark, the UK and Ireland are the most generous. Even though EN 1995-1-1 has given general criteria for vibrational serviceability design of timber floors, the variations in the design equations and design limits are still large in the EU countries, and hence further harmonisation is still needed.

KEYWORDS

Timber floors, Serviceability limit state, Vibrational comfort, Design regulations, Eurocodes.

1.1 - Introduction

With the rapid development of modern construction technology, there is an increasing requirement for timber based lightweight components and buildings (TBLB). This type of construction can largely reduce the negative effects caused by the global warning. In addition, it also allows an economic and very accurate industrial manufacturing.

In general the vibrational serviceability performance of buildings and components under structural and acoustic vibrations, in particular timber flooring systems, has become an important issue in Europe, and it is even more relevant for TBLBs due to their natural frequencies of resonance and the low mass of building materials used for constructing these components.

Building acoustics on timber flooring systems concerns airborne and impact sound performances as well as sound from service equipment for mid-frequencies ranging from 200 Hz to 5000 Hz and high-frequency ranging from 5000 Hz to 20000 Hz. Nowadays, much attention has been paid to low-frequencies ranging from 25 Hz to 100 Hz where timber-based lightweight buildings are likely to have less favourite performances than heavy buildings. Structural vibrations of timber flooring systems due to human activities and machinery produce low frequencies ranging from several Hz up to 50 Hz, which can cause significant annoyance and affect the occupant's comfort.

In the European Union countries, Eurocode 5 has been widely used for design of timber floors. A building or its component, e.g. a timber floor is generally designed to satisfy both ultimate limit state criteria and serviceability limit state criteria [1]. The former are to ensure that the building or its component should be safe when subjected to bending, shear, axial loading, bearing and lateral stability under combined self-weight, imposed load, snow, wind and other possible loading, and include equilibrium, structural, geotechnical and fatigue designs. The latter are to ensure that the building or its component is serviceable, i.e.

- provide acceptable human comfort,
- maintain functioning of the structure under normal use,
- uphold acceptable appearance of the construction works,

by controlling deformations, vibrations and damage adversely effecting durability. Acoustic and structural vibrations fall to the category of ensuring human comfort.

Vibrational serviceability limit state criteria often dominate the design of timber floors, e.g. long span floors constructed with engineered timber joists. The vibrational parameters which need to be checked include the fundamental frequency, unit point load deflection and unit impulse velocity response. The methods for determining these parameters and the corresponding design limits are proposed in EN 1995 Part 1-1 [2] and the National

Annexes of the EU countries, and they vary largely from country to country due to different design methods, fabrication procedures and construction techniques.

As part of the research work carried out by the Working Group 3 of COST Action FP0702, this paper will summarise the need for vibrational comfort for buildings, current regulations for comfort assessment of structural vibrations of timber floors in Europe and main design practices of timber floors on this aspect among the EU countries, assess their variations by using some design examples of timber flooring systems constructed from various types of floor joists, and finally propose the recommendations on vibrational serviceability design of timber floors.

1.2 - The need for vibrational comfort for housing

Social surveys in several European countries have shown that the occupants of multi-storey housing are considerably annoyed by the acoustic and structural vibrations caused by a number of sources [3-7]. Traffic noise alone is the top annoying source and harms the health of almost every third person in the WHO European Region. It is followed by acoustic and structural vibrations caused by neighbouring residents. It is estimated that more than 50 million Europeans are subjected to the latter, which largely causes adverse effects on quality of life. The World Health Organisation (WHO) defines the health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" and this definition has not been amended since 1948 [8]. Based on this definition, the effects of acoustic and structural vibrations on health should not be simply understood as the adverse physical effects but also as disturbance of well-being, i.e. mental and psychological effects, which in long term will lead to adverse physical effect. In particular, excessive environmental noise seriously harms human health and interferes with people's daily activities at school, at work, at home and during leisure time [9]. It can disturb sleep, cause cardiovascular and psycho-physiological effects, reduce performance and provoke annoyance responses and changes in social behaviour.

Normally, annoying vibrations for occupants in lightweight buildings is divided into structural vibrations with low frequencies and acoustic vibrations with higher frequencies. Table 1 summarises the common sources and types of annoyance for both structural and acoustic vibrations. There is an increasing interest in timber based lightweight components and buildings (TBLB) because of some important requirements. The raw material wood has to be used effectively because of its quantitative limitation and needs to be bounded in buildings for a long time in respect of CO_2-storage regarding the global warming. This type of construction supplementarily allows an economic and very accurate industrial manufacturing. In general the acoustic and vibrational performance of buildings and elements is an important topic in Europe but especially it is even more relevant for TBLBs. However, acoustic measurement procedures and characterisations of timber based components as well as the prediction of the acoustic performance in situ are research domains that still require further activities.

For all of these, the COST Action FP0702 was approved in November 2007 for carrying out the research on Net-acoustics for timber based lightweight buildings and elements, and its main aim is to improve the acoustic behaviour of timber based lightweight buildings and to develop effective prediction models and measurement schemes [10]. Airborne and impact sound performances as well as sound from service equipment are considered over a frequency range including low frequencies (50 to 100 Hz) where lightweight buildings are likely to have performances lower than in heavy buildings. Vibrations with further lower frequencies (below 25 Hz) such as floor vibrations due to people walking is also considered, and particularly its subjective aspect. The following important topics were identified accordingly

- prediction methods of building acoustic performances adapted to timber based lightweight constructions because the methods for heavy weight constructions do not work for lightweight buildings;
- low frequency vibrations of floors and of the whole building because of the body perception of this type of vibration and its consequence on comfort;
- need for assessing comfort and defining proper requirements for this type of building;
- need for acoustic design taking also into account the other technical domains, e.g. thermal aspect in particular.

As a result, four working groups were created, all dealing with timber based lightweight buildings and building elements

- Working Group 1 (WG1) on Prediction methods for sound and vibration performances of lightweight buildings;
- Working Group 2 (WG2) on Measurement methods for sound and vibration performances;
- Working Group 3 (WG3) on Comfort assessment for sound and vibration;
- Working Group 4 (WG4) on Acoustic design.

The Working Group 3 (WG3) in this Action was formed to identify problems with classification of acceptability of floors from inhabitants' point of view and subjective evaluation on floor vibration and to review international design requirements related to low frequency sound and vibration performance [11]. The aim of the Working Group is to look into all aspects of low frequency sound and vibration in order to assess acoustic and vibrational comfort of timber based buildings. The results will be especially relevant to design engineers, material and product manufacturers and acoustic scientists. They should be related regulatory requirements regarding sound transmission and impact as well as structural vibrations. The following two topics were identified accordingly:

- rating of the annoyance associated to vibration in lightweight buildings, typically below 25 Hz;
- rating of the annoyance associated with sound in lightweight buildings, especially at low frequencies, typically 50-100 Hz or even 25-100 Hz.

Two objectives in the WG3 were set to

- review national requirements related to low frequency sound and vibration performance;
- identify problems with classification of acceptability of floors from inhabitants' point of view and subjective evaluation of floor vibrations.

The expected outputs include the state of the art of the current assessment procedures related to low frequency acoustic and vibrational comfort and the recommendations for future standardisation work.

Within the WG3, Rasmussen [6,7,12] summarised the current descriptors and regulatory requirements for sound insulation housing in Europe and confirmed the importance of the harmonisation of sound insulation requirements in Europe. Zhang et al [13,14] extensively investigated the vibrational performance of lightweight timber floors constructed from various joists and also compared the test results with the current design codes for timber flooring systems. Labonnote [15] systematically investigated the damping in timber structures, including material damping and structural damping in timber members and structures. Several Short Term Scientific Missions (STSMs) were also carried out in the WG3 to enrich the Group’s research activities and strengthen the cooperation between the WG3 members. Su from Edinburgh Napier University of the UK visited the Technical University of Denmark (DTU) and Danish Building Research Institute (SBi) in April-May 2010 where she collected and compared current timber floor design codes and regulatory requirements for impact sound insulation and vibration control in the UK and the Nordic countries [16]. De Klerk from Eindhoven Technical University of the Netherlands visited Edinburgh Napier University in May-August 2010 where he tried to improve the predictability of low frequency induced vibration response in timber based floor structures [17]. This paper only presents the research work carried out in the WG3 of COST Action FP0702 on structural vibrations of timber floors and the work on acoustic vibrations will be presented somewhere else.

1.3 - Current regulations on comfort assessment for structural vibrations of timber floors in Europe

Table 2 summarises major design standards and codes which are currently used in Europe for comfort assessment of structural vibrations of timber floors, together with rating methods, frequency ranges, descriptors and available limiting values.

EN 1995-1-1 [2] has set three criteria

- the fundamental frequency f_1 of residential floors must be larger than 8 Hz otherwise a special investigation should be made but no indication is given about the investigation;
- the maximum instantaneous vertical deflection w caused by a vertical concentrated static force F applied at any point on the floor, taking account of load distribution, is smaller than its limit a but no value or equation is given for calculating a except that in Fig. 7.2 of the code where a range of 0.5 to 4.0 mm is defined;
- the maximum vibration velocity v in m/Ns^2 caused by an ideal unit impulse (1 Ns) applied at a point of the floor should be smaller than its limiting value $b^{(f_1 \zeta - 1)}$ where b is a parameter depending on a, and ζ is the damping ratio, with the components above 40 Hz disregarded.

Feldmann et al. [18] in a JRC scientific and technical report have suggested the use of a single response parameter to reflect both the comfort perception of users and the dynamic response of the floor structure. This first needs a weighting function $B(f)$ for the spectrum of vibration velocities, and the root mean square values (the RMS values) are used as effective response values by evaluating a time window T_s. The one step-root mean square value (the OS-RMS values) with certain fractile, e.g. 90%, can be defined for further establishing the perception curves for vertical vibrations (W_b curves) and for horizontal vibrations (W_d curves) so as to assess the vibrational comfort of floors. The working frequency f ranges from 1 to 80 Hz, and the OS-RMS$_{90}$ has a limit ranging from 0.1 to 3.2 mm/s for residential buildings depending on the building class ranging from Class A to Class D.

ISO 2631 Part 1 [19] and Part 2 [20] also suggest either the perception curves for vertical vibrations (W_b curves) and horizontal vibrations (W_d curves) or combined W_m weighting curves to assess the vibrational comfort of floors with the working frequency f ranging between 1 and 80 Hz. The proposed parameters include the weighted root-mean-square velocity v_{rms} and acceleration a_{rms} but no limits are given.

ISO 10137 [21] suggests the perception curves for vertical vibrations (W_b curves) and horizontal vibrations (W_d curves) to assess the vibrational comfort of floors with the working frequency f ranging between 0.5 and 80 Hz. The vibration dose values for vertical and horizontal vibrations, VDV$_b$ and VDV$_d$, are used here, and their limits for different levels of adverse comment within residential buildings are largely dependent on day time or night time, see Table 3. BS 6472-1 suggests the same perception curves for W_b and W_d curves by using the parameters VDV$_b$ and VDV$_d$, with similar limits for different levels of adverse comment within residential buildings, see Table 4.

DIN 4150 Parts 1 to 3 [23-25] use the maximal weighted vibration strength KB to assess the structural related low frequency vibrational perception for human beings. KB is dimensionless and is related to the peak particle velocity v_i in mm/s, the reference frequency f_0 = 5.6 Hz, and the vibrational frequency f in Hz. The limit for KB in residential buildings varies between 0.15 and 0.3.

NS 8176 E [26] suggests the W_m perception curves to assess the vibrational comfort of floors with the working frequency f ranging between 0.5 and 160 Hz compared with the original range between 1 and 80 Hz. The proposed parameters include the 95% fractile weighted velocity $v_{w,95}$ in mm/s and acceleration $a_{w,95}$ in mm/s^2, and the corresponding limits are largely dependent on various classes from Class A to Class D. Table 5 lists the upper limits for the maximum values of the 95% fractile weighted velocity $v_{w,95}$ and weighted acceleration $a_{w,95}$ for classifying residential buildings.

SRB Directive Part B [27] uses the 95-percentile maximum vibration strength V_{max} and the mean vibration strength V_{per} to evaluate the degree of nuisance to human beings caused by the structural vibrations. Both parameters are dimensionless but the former is actually the maximum value of the latter and is used as the main parameter. The target values of V_{max} are normally controlled over three assessment periods: (i) Day from 07.00 to 19.00, (ii) Evening from 19.00-23.00, and (iii) Night from 23.00-07.00, and five categories for V_{max} are proposed, see Table 6. Table 7 lists the limiting values of V_{max} and V_{per} for various building functions.

1.4 - Criteria for vibrational serviceability limit state design of timber floors to Eurocode 5

The vibrational serviceability design for timber floors in EN 1995-1-1 is largely based on Ohlsson's research work [28]. Human beings are regarded as the critical sensors of vibration and their discomfort due to structural vibrations of timber floors becomes great concern to various professionals. For building design, human activities and machinery are the two most important internal sources of vibration in timber based lightweight buildings (TBLBs). Human activities include footfall from normal walking and children's jumping, which may cause two major critical load response cases:

- human discomfort from footfall-induced vibrations,
- human discomfort from machine-induced vibrations.

From Ohlsson, the human sensitivity and perception to structural vibrations is regarded to be

- related to vibration acceleration for frequencies which are lower than 8 Hz,
- related to vibration velocity for frequencies which are larger than 8 Hz,
- increased by the duration of vibration,
- decreased by proximity to or awareness about the vibration source,
- decreased by physical activities.

Based on those facts, Ohlsson systematically carried out experimental testing and numerical analysis on structural vibrations of timber floors and proposed several parameters for controlling the vibrational serviceability design of timber floors, including the fundamental frequency *f*, the maximum deflection *w* of the floor under unit point load applied at the floor centre, and the maximum velocity response *v* under unit impulse. These three parameters have been adopted in EN 1995-1-1 for vibrational serviceability design of timber floors.

1.4.1 - Fundamental frequency

EN 1995-1-1 requires that the fundamental frequency of residential floors, i.e. the first first-order modal frequency f_1 in cycles per second or Hz, should satisfy the following equation

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_\mathrm{L}}{m}} > 8\ (\mathrm{Hz}) \qquad (1)$$

where m is the mass per unit area in kg/m^2, L is the floor span in m, and $(EI)_\mathrm{L}$ is the equivalent plate bending stiffness of the floor about an axis perpendicular to the beam direction in Nm^2/m.

1.4.2 - Unit point load deflection

For residential floors with f_1 > 8 Hz, the maximum instantaneous vertical deflection caused by a unit point load, w, in mm/kN, should satisfy the following equation

$$w \leq a\ (\mathrm{mm/kN}) \qquad (2)$$

where a is the design limit of the deflection of the timber floor under unit point load.

1.4.3 - Unit impulse velocity response

For residential floors with f_1 > 8 Hz, the unit impulse velocity response, or the maximum initial value of the vertical floor vibration velocity (in m/s) caused by an ideal unit impulse (1 Ns) applied at the point of the floor which gives maximum responds, v, should satisfy

$$v \leq b^{(f_1\zeta - 1)}\ (\mathrm{m/Ns^2}) \qquad (3)$$

For a rectangular floor with an overall dimension of $L \times B$, simply supported along all four edges, the value of v may be taken as

$$v = \frac{4(0.4 + 0.6 n_{40})}{m B L + 200}\ (\mathrm{m/Ns^2}) \qquad (4)$$

where B is the floor width in m, n_{40} is the number of first-order modes with natural frequencies up to 40 Hz, given as follows

$$n_{40} = \frac{B}{L}\left\{\left(\left(\frac{40}{f_1}\right)^2 - 1\right)\frac{(EI)_\mathrm{L}}{(EI)_\mathrm{B}}\right\}^{1/4} \tag{5}$$

and $(EI)_\mathrm{B}$ is the equivalent plate bending stiffness of the floor about an axis parallel to the beam direction in Nm^2/m. The parameter b for assessing v is dependent on the deflection limit a and can be directly obtained from Fig. 7.2 of EN 1995-1-1 (see Fig. 1). ζ is the modal damping ratio, recommended as $\zeta = 0.01$.

1.5 - Current National Annexes to EN 1995-1-1 in the EU countries

The National Annexes (NAs) to EN 1995-1-1 have been collected from thirteen European Union countries, including

- Austria (AT) [29]
- Belgium (BE) [30]
- Denmark (DK) [31,32]
- Finland (FI) [33]
- France (FR) [34]
- Germany (DE) [35]
- Ireland (IE) [36]
- Italy (IT) [37]
- Netherlands (NL) [38]
- Norway (NO) [39]
- Spain (ES) [40]
- Sweden (SE) [41]
- United Kingdom (UK) [42]

1.5.1 - Fundamental frequency

Eq. (1) for calculating the fundamental frequency f_1 is a simplified design equation which is actually applied for two-side supported floors and the effect of the transverse stiffness is omitted because the errors caused are not large. EN 1995-1-1 does not clearly indicate how the participating mass should be calculated and whether the composite effect of floor joists and deck in the floor direction should be considered. Table 8 summarises the design equations and the corresponding limits for the fundamental frequency f_1 proposed from EN 1995-1-1 and the National Annexes.

The majority of the EU countries have directly adopted Eq.(1) for determining the fundamental frequency and the limit of 8 Hz specified in EN 1995-1-1 except Austria and Finland. Austria adopts Eq. (1) for two-side supported floors and provides a fairly accurate equation for four-side supported floors by including a quadratic term about L/B to reflect the effect of transverse stiffness [29]. The equation, however, omits a term about $(L/B)^2$. Finland provides a more accurate equation for four-side supported floors by including both second-order and fourth-order terms about L/B for the transverse stiffness effect [30]. The frequency limit is also raised to 9 Hz. Spain specifies the limiting values for the fundamental frequency f_1 for all construction materials including timber: $f_1 > 8$ Hz for gymnasiums and sport buildings, $f_1 > 7$ Hz for public spaces without fixed seats, and $f_1 > 3.4$ Hz for public spaces with fixed seats [40].

Austria and Finland specify that the floor mass *m* should be determined using quasi-permanent combination of dead and imposed loads, as specified in Eq.(6.16b) of EN 1990 [1]

$$m = m_{\mathrm{Gk}} + \psi_2 m_{\mathrm{Qk}} \qquad (6)$$

where m_{Gk} is the mass due to the characteristic dead load G_{k}, and m_{Qk} is the mass due to the characteristic imposed load Q_{k}. ψ_2 is the factor for quasi-permanent value of a variable action, e.g. imposed load, and its values for different building categories can be taken from Table A1.1 of EN 1990 or the tables of the National Annexes to EN 1990. In general, ψ_2 can be taken as 0.3 for domestic residential buildings and office buildings, 0.6 for congregation areas and shopping malls, and 0.8 for storage areas.

1.5.2 - Unit point load deflection

Eq. (2) provides the criterion for checking the vertical deflection of the timber floor under the unit point load of 1 kN but does not provide the detailed equations for calculating the deflection of the floor and the limiting values. Table 9 summarises the design equations and the corresponding limits for the vertical deflection *w*, quoted from EN 1995-1-1 and the corresponding National Annexes.

The equations for calculating the vertical deflection *w* are established based on the beam bending theory by considering the contribution of the transverse stiffness to the longitudinal stiffness in the floor direction. In general, the deflection limiting values largely vary, with Finland and Norway being the strictest, Italy and the Netherlands the next, Ireland, the UK and Denmark the most generous and other countries in-between.
Austria introduces a modification factor of bF to consider the effect of the transverse stiffness on the vertical deflection w [29] and proposes the limiting value a as 1.5 mm/kN for normal floors and 1.0 mm/kN when the adjacent structures are disturbed. Belgium [30] and Sweden [41] define the limiting value a = 1.5 mm/kN, while Italy [37] and the Netherlands [38] defines a lower limiting value a = 1.0 mm/kN. Denmark earlier proposed the limiting value a = 4.0 mm/kN [31] but has later revised to a reasonable value a = 1.7 mm/kN [32] for the normal timber joists in residential buildings with spans up to 6.0 m.

Finland introduces a modification factor of k_δ to consider the effect of the transverse stiffness on the vertical deflection w and also includes the effect of the timber joist spacing s. A strict value a = 0.5 mm/kN is proposed for floors with L > 6 m. For small rooms with L ≤ 6 m, the limiting value can be increased to a = 0.5k mm/kN [33]. Here k is an increasing factor of the floor span L and can be determined from Fig. 2. An extra 0.5 mm is permitted for skin plate or floating floors. France defines a = 1.3 ± 0.3 mm/kN but does not indicate when the variation of ± 0.3 mm/kN is applied [34]. Germany [35] and Spain [40] do not provide any design equations or limiting values for deflection. Norway defines the limiting value a = 0.9 mm/kN for floors with normal stiffness but a = 0.6 mm/kN for floors with high stiffness [39].

Ireland [36] and the UK [42] define a complex but philosophical design equation for calculating the vertical floor deflection w. A factor k_{dist} is introduced first to justify the point load acting on a single joist as

$$k_{\mathrm{dist}} = \max \begin{cases} k_{\mathrm{strut}} \left\{ 0.38 - 0.08 \ln \left[14 \, (EI)_{\mathrm{B}} / s^4 \right] \right\} \\ 0.30 \end{cases} \qquad (7)$$

where k_{strut} = 0.97 for single or multiple lines of strutting otherwise k_{strut} = 1.0. An amplification factor k_{amp} is then introduced to account for shear deflection in solid timber and glued thin-webbed joists or joint slip due to use of mechanical connections and it can take

- 1.05 for simply-supported solid timber joists,
- 1.10 for continuous solid timber joists,
- 1.15 for simply-supported glued thin-webbed joists,
- 1.30 for continuous glued thin-webbed joists,
- 1.30 for simply-supported mechanically-jointed floor trusses,
- 1.45 for continuous mechanically-jointed floor trusses.

If the lateral floor stiffness is contributed from the timber floor deck, roof ceiling and strutting, the overall equivalent plate bending stiffness of the floor about an axis parallel to the beam direction, $(EI)_{\mathrm{B}}$, can be obtained by simply superpositioning the stiffnesses of individual components and ignoring the composite effect as follows

$$(EI)_{\mathrm{B}} = (EI)_{\mathrm{B,deck}} + (EI)_{\mathrm{B,ceiling}} + (EI)_{\mathrm{B,strut}} \qquad (8)$$

An equivalent floor span L_{eq} is used for calculations, which can take the following values

- L for simply supported single span joists,
- 0.9L for the end spans of continuous joists,
- 0.85L for the internal spans of continuous joists.

The limiting value *a* for the floor deflection *w* in Ireland and the UK is regarded as a decrease function of the floor span *L* in mm if *L* is larger than 4 m otherwise defaulted as 1.8 mm/kN. When *L* increases from 4 m to 10 m, *a* will decrease from 1.8 mm/kN to 0.66 mm/kN, down by 1.14 mm/kN or 63.5%, with the largest variation among the EU countries.

Figs. 3 to 5 further show the comparisons of the values of the deflection limit *a* among the EU countries for the floor span *L* = 3 m, 6 m and 10 m, respectively, together with the average values for *a*.

For *L* = 3 m, the average value of the deflection limit, a_{av}, is 1.34 mm/kN among the eleven EU countries that define the limit *a*. Six countries have the limits higher than a_{av}, with Denmark, Ireland and the UK having the highest values of 1.70 mm/kN, 1.80 mm/kN and 1.80 mm/kN, respectively. Five countries have the limits lower than a_{av}, with Finland having the lowest value of only 0.75 mm/kN.

For *L* = 6 m, the average value of the deflection limit, a_{av}, slightly decreases to 1.23 mm/kN among the ten EU countries that give the limit *a*. Five countries have the limits higher than a_{av}, with Denmark still having the highest values of 1.70 mm/kN. The remaining five countries have the limits lower than a_{av}, with Finland still having the lowest value of only 0.5 mm/kN and both Italy and the Netherlands having the second lowest value of 1.00 mm/kN.

For *L* = 10 m, the average value of the deflection limit, a_{av}, further decreases to 1.07 mm/kN among the nine EU countries with the available limit *a*. Four countries have the limits higher than a_{av}, with Austria, Belgium and Sweden having the highest values of 1.50 mm/kN. The remaining five countries have the limits lower than a_{av}, with Finland still having the lowest value of 0.5 mm/kN, and Ireland and the UK having the second lowest value of 0.66 mm/kN.

1.5.3 - Unit impulse velocity response

Before the variations of the unit impulse velocity as a vibrational serviceability design criterion are assessed, the meaning of the parameter *b* is discussed. Fig. 6 shows the relationship between the design limit of the unit impulse velocity, $b^{(f_1\zeta-1)}$, and the parameter *b* over the range from 50 to 150 suggested by EN 1995-1-1. The fundamental frequency f_1 is assumed to be 10 Hz with the damping ratio $\zeta = 0.01$.

The design limit $b^{(f_1\zeta-1)}$ for *v* monotonically decreases with the increased *b*. Also by comparing the relationship between *b* and the deflection limit *a*, it can be seen that the higher the value of *b*, the lower the values of *a* and $b^{(f_1\zeta-1)}$. This indicates that a higher *b* value corresponds to a more strict design limit for the unit impulse velocity.

Several countries have disregarded the unit impulse velocity as the vibrational parameter for serviceability limit state design due to its theoretical complexity and measuring difficulty. The limit values largely vary from country to country as well, with main changes in the parameters b and ζ. Table 10 summarises the design criteria for the unit impulse velocity v.

Most EU countries have fixed the values for b when determining the design limit of unit impulse velocity except Ireland and the UK which link b to the deflection limit a by following the trend given in Fig. 7.2 of EN 1995-1-1. It can also be seen that the parameter b varies from country to country. Fig. 7 shows the values of the parameter b proposed by nine EU countries for L = 6 m. The average value of the parameter, b_{av}, is 106.20. Five countries have the proposed values of b higher than b_{av}, with Italy and the Netherlands having the highest value of 120, and Ireland and the UK having the second highest value of 113.91, which indicates that these countries are stricter. The remaining four countries have the values of b lower than b_{av}, with Demark having the lowest value of 80 which is the most generous, and Austria, Belgium and Sweden having the second lowest value of 100 which tends to be generous.

Fig. 8 shows the values of the design limit of the unit impulse velocity, $b^{(f_1\zeta-1)}$, calculated based on the values of b proposed by the nine EU countries for L = 6 m. Here f_1 is assumed to be 10 Hz together with ζ = 0.01 except for the UK where ζ = 0.02 is adopted to make this criterion redundant.

The average value of the design limit for the unit impulse velocity, $b^{(f_1\zeta-1)}$, is 0.0161 m/Ns^2. Now only two countries have the design limit values higher than the average, with the UK having the highest value of 0.0226 m/Ns^2 and Denmark having the second highest value of 0.0194 m/Ns^2, which indicates that these two countries are more generous. The remaining countries all have the design limit values lower than the average, with Italy and the Netherlands having the lowest value of 0.0135 m/Ns^2 which is the strictest, Ireland having the second lowest value of 0,0141 m/Ns^2, France having 0.0148 m/Ns^2, and Austria, Belgium and Sweden having the design limit value of 0.0158 m/Ns^2.

It should be pointed out that damping is an important parameter which significantly influences the response of occupants to floor vibrations even though it hardly affects the fundamental frequency f_1. Previous research has shown that the timber floors constructed with I-joists had a damping ratio ζ = 2% to 4% [43] while the floors with metal-webbed joists only had a very low damping ratio ζ = 0.87% which is below 1% [44]. This indicates that the design damping ratio ζ = 1% proposed in EN 1995-1-1 [1] may not cover all timber floor design cases but a damping ratio ζ = 2% proposed in the corresponding UK National Annex [42] may cover most practical cases.

1.6 - Vibrational design of floors with solid timber joists, I-joists and metal web joists

The floors to be designed are constructed with solid timber joists, engineered I-joists and metal web joists and are presented to show the variations in the vibrational serviceability design of timber floors among the EU countries.

1.6.1 - Floors constructed with solid timber joists

Two floors are designed for a domestic timber frame building and are constructed with solid timber joists, see Fig. 9. Floor 1 has a dimension of $L \times B$ = 3.0 m × 3.0 m and is constructed with 47 mm × 147 mm C24 solid timber joists at a spacing s = 450 mm, and Floor 2 has a dimension of $L \times B$ = 5.0 m × 5.0 m and is constructed with 75 mm × 220 mm C24 solid timber joists at s = 400 mm. The P5 particleboard with a thickness of 22 mm is chosen for the decking, and the Gyproc plasterboard with a thickness of 12.5 mm is chosen for the ceiling. The total self-weight of the flooring system including the timber joists is assumed to be 50 kg/m^2, and Service Class 2 is assumed. The imposed load is taken as Q_k = 1.5 kN/m^2 from EN 1991-1-1 [45].

Table 11 presents the geometric dimensions and materials properties of the two floors. The materials properties are quoted from EN 338:2009 [46]. Table 12 lists the calculated values of the fundamental frequency f_1, the design limits $f_{1,\text{limit}}$ and the ratios of $f_{1,\text{limit}} / f_1$ for the floors using the National Annexes of the EU countries (see the detailed formulae in Table 8) and EN 1995-1-1. Table 13 lists the calculated values of the deflection w, the limit values of a and the ratios of w/a (see the formulae in Table 9). Table 14 lists the calculated values of the unit impulse velocity v, the limiting values of $b^{(f_1\zeta-1)}$, and the ratios of $v/b^{(f_1\zeta-1)}$ (see the formulae in Table 10). If the ratio for any of the three vibrational serviceability parameters is smaller than 1.0, the design can be regarded to be satisfactory with respect to the criterion for that parameter.

Fig. 10 shows the calculated the frequency ratios of $f_1/f_{1,\text{limit}}$ for the two floors studied in this section based on the National Annexes to EN 1995-1-1 in the thirteen EU countries. The light blue line for $f_1/f_{1,\text{limit}}$ = 1.0 represents the design threshold, below which the design criterion is regarded to be satisfied. The calculated results show that Floor 1 has passed all the EU National Annexes with respect to the fundamental frequency and Floor 2 has passed almost all the EU National Annexes except that it has marginally failed the design in Finland.

Fig. 11 shows the calculated deflection ratios of w/a under unit point load at mid-span for the two floors studied. The light blue line for w/a = 1.0 represents the design threshold, below which the design criterion is regarded to be satisfied. The calculated results also show that Floor 1 has only passed the design criterion in Denmark, Ireland and the UK with respect to the unit point load deflection and Floor 2 has passed the design criterion in six countries, i.e. Belgium, Denmark, France, Ireland, Sweden and the UK. The fact that both floors have failed the design criterion in majority of the EU countries indicates that the unit point load deflection criterion is more crucial than the fundamental frequency criterion.

Fig. 12 shows the calculated velocity ratios of $v/b^{(f_1\zeta-1)}$ under unit impulse for the two floors studied. Similarly, any value below the design threshold of $v/b^{(f_1\zeta-1)}$ = 1.0 (the light blue line) indicates that the design criterion is satisfied. The calculated results show that Floor 1 has only passed the design criterion in Austria, Denmark and the UK with respect to the unit impulse velocity but Floor 2 has passed the design criterion in seven out of nine EU countries except Italy and the Netherlands. This indicates that the unit impulse velocity criterion is less crucial than the unit point load deflection criterion but is still more crucial than the fundamental frequency criterion.

Fig. 13 shows the cohort ratios of all three vibrational parameters calculated based on the National Annexes of the EU countries for Floors 1 and 2, respectively. It can be seen that Floor 1 with a span of 3 m has passed all three vibrational serviceability criteria only in Denmark and the UK and has either partially or fully failed to pass the design criteria in the rest EU countries. Finland has the strictest design criteria and is then followed by Norway, Italy, the Netherlands, Austria and France. The failure of the floor design in Belgium, Ireland and Sweden is only marginal. For Floor 2 with a span of 5 m, more countries have now passed all three vibrational serviceability criteria, including Belgium, Denmark, France, Ireland, Sweden and UK.

1.6.2 - Floors constructed with engineered I-joists

Floors 3 and 4 are designed for a domestic timber frame building and are constructed with the engineered I-joists (JJI-Joists) produced by James Jones & Sons Ltd in the UK [47], see Fig. 14. The top and bottom flanges are manufactured from C24 solid timber with the width b ranging from 47 mm to 97 mm (A to D) and a constant height of h_f = 45 mm. The web is manufactured from 9 mm OSB3 which is embedded into the flanges by 12 mm. The 22 mm P5 particleboard is chosen for the decking, and the Gyproc plasterboard with a thickness of 12.5 mm is chosen for the ceiling. The total self-weight of the flooring system including the I-joists is assumed to be 75 kg/m^2, and also Service Class 2 is assumed. The imposed load is taken as Q_k = 1.5 kN/m^2 [45]. Floor 3 has a dimension of $L \times B$ = 5.4 m × 5.0 m and is constructed with the JJI 300B Joists at s = 400 mm, and Floor 4 has a dimension of $L \times B$ = 7.3 m × 6.0 m and is constructed with the JJI 400D Joists at s = 300 mm.

Table 15 presents the geometric dimensions and materials properties of the floors constructed with JJI-Joists. Table 16 presents the calculated values of the fundamental frequency f_1, the design limits $f_{1,\text{limit}}$ and the $f_{1,\text{limit}} / f_1$ ratios for the floors using the National Annexes of the EU countries and EN 1995-1-1. Table 17 lists the calculated values of the deflection w, the limit values of a and the w/a ratios. Table 18 lists the calculated values of the unit impulse velocity v, the limiting values of $b^{(f_1\zeta-1)}$, and the $v/b^{(f_1\zeta-1)}$ ratios.

Fig. 15 shows the calculated the frequency ratios of $f_{1,limit}/f_1$ for the two JJI-Joist floors based on the National Annexes to EN 1995-1-1 in the thirteen EU countries. The calculated results show that both Floors 3 and 4 have passed almost all the EU National Annexes with respect to the fundamental frequency except that Floor 3 has marginally failed the design in Austria and Finland, and Floor 4 has only marginally failed the design in Finland.

Fig. 16 shows calculated deflection ratios of w/a under unit point load at mid-span for the two floors. Floor 3 has only failed the design criterion in Finland, Italy, the Netherlands and Norway with respect to the unit point load deflection. Floor 4 has passed the design criterion in almost every country except Finland, but it has only just done so in Ireland, Norway and the UK. This indicates that Finland has given the strictest criterion on the deflection and is followed by Norway, Italy and the Netherlands. Belgium, Denmark and Sweden become more generous than other EU countries.

Fig. 17 shows the calculated velocity ratios of $v/b^{(f_1\zeta-1)}$ under unit impulse for the two floors studied. Both Floors 3 and 4 have passed the design criterion in all the EU countries included with respect to the unit impulse velocity. In general, the unit point load deflection criterion is more crucial than other two criteria.

Fig. 18 shows the cohort ratios of all the three vibrational parameters calculated based on the National Annexes of the EU countries for Floors 3 and 4, respectively. Fig. 18(a) shows that Floor 3 with a span of 5.4 m has passed all three vibrational serviceability design criteria in Belgium, Denmark, France, Ireland, Sweden and the UK and has either partially or fully failed to pass the design criteria in other EU countries. Finland has the strictest design criteria and is followed by Italy, the Netherlands and Norway. The failure of the floor design in Austria is only marginal. Fig. 18(b) shows that Floor 4 with a span of 7.3 m has followed a similar trend as Floor 3. All three vibrational serviceability design criteria have been satisfied in Austria, Belgium, Denmark, France, Ireland, Sweden and the UK while the design criteria have not partially or fully been satisfied in Finland, Italy, the Netherlands and Norway.

1.6.3 - Floors constructed with metal web joists

Two floors are designed for a domestic timber frame building and are constructed with the metal web joists (Posi-Joists) produced by Mitek Industries Ltd [48], see Fig. 19. The top and bottom flanges (chords) are manufactured from TR26 solid timber [49] with the width b ranging from 72 mm to 147 mm (PS8 to PS16) and a constant height of h_f = 47 mm. The engineered V shaped galvanized steel webs of 203 mm (8") to 406 mm (16") are fixed to the top and bottom chords via the nail-plated zones. The 22 mm P5 particleboard is chosen for the floor decking, and the Gyproc plasterboard with a thickness of 12.5 mm is chosen for the ceiling. Floor 5 is laterally stiffened using a TR26 solid timber strongback of 47 mm × 147 mm in the transverse direction at the mid-span, while Floor 6 is stiffened using two TR26 strongbacks of the same sizes at two-thirds spans. The previous experimental research confirms that both cases produced the same stiffening effect [44]. The total self-weight of the flooring system including the Posi-Joists and the strongbacks is assumed to be 75 kg/m^2, and also Service Class 2 is assumed. The imposed load is taken as Q_k = 1.5 kN/m^2. Floor 5 has a dimension of $L \times B$ = 5.0 m × 5.0 m and is constructed with PS10 Joists at s = 600 mm, and Floor 6 has a dimension of $L \times B$ = 7.5 m × 6.0 m and is constructed with PS16 Joists at s = 400 mm.

Table 19 presents the geometric dimensions and materials properties of the floors constructed with Posi-Joists. Table 20 presents the calculated values of the fundamental frequency f_1, the design limits $f_{1,\text{limit}}$ and the $f_{1,\text{limit}} / f_1$ ratios for the floors using the National Annexes of the EU countries and EN 1995-1-1. Table 21 lists the calculated values of the deflection w, the limit values of a and the w/a ratios. Table 22 lists the calculated values of the unit impulse velocity v, the limiting values of $b^{(f_1\zeta - 1)}$, and the $v/b^{(f_1\zeta - 1)}$ ratios.

Fig. 20 shows the calculated the frequency ratios of $f_{1,\text{limit}} / f_1$ for the two Posi-Joist floors based on the National Annexes to EN 1995-1-1 in the thirteen EU countries. The calculated results show that Floor 5 has passed almost all the National Annexes with respect to the fundamental frequency except those in Austria and Finland, and Floor 6 has only failed to satisfy the fundamental frequency criterion in Finland.

Fig. 21 shows calculated deflection ratios of w/a under unit point load at mid-span for the two floors. Floor 5 has only failed the design criterion in Finland and Norway with respect to the unit point load deflection. Floor 6 has passed the design criterion in almost every country except Finland. This again indicates that Finland has set the strictest criterion on the deflection and is followed by Norway, Italy and the Netherlands. Austria, Belgium, Denmark, France, Ireland, Sweden and the UK are more generous.

Fig. 22 shows the calculated velocity ratios of $v/b^{(f_1\zeta - 1)}$ under unit impulse for the two floors studied. Both Floors 5 and 6 have passed the design criterion in all the EU countries considered with respect to the unit impulse velocity. This confirms again that in general, the unit point load deflection criterion is more crucial that other two criteria.

Fig. 23 shows the cohort ratios of all the three vibrational parameters calculated based on the National Annexes of the EU countries for Floors 5 and 6, respectively. Fig. 23(a) shows that Floor 5 with a span of 5 m has passed all three vibrational serviceability design criteria in almost all countries and only marginally failed in Austria and Norway but largely failed in Finland. Finland has the strictest design criteria and is followed by Austria and Norway and then by Italy and the Netherlands. Similarly Fig. 23(b) shows that Floor 6 with a span of 7.5 m has passed all three vibrational criteria in most EU countries and only failed in Finland and Norway.

1.6.4 - Summary of the floor design results

Table 23 summarises the design results of all six timber floors constructed with various types of floor joists for the vibrational serviceability criteria with respect to the fundamental frequency *f*, the unit point load deflection *w* and the unit impulse velocity *v* in all thirteen EU countries included. Thus, there are a total of eighteen cases which need to be checked for each country. Here Pass (P), Fail (F) and Not Available (N) are classified to indicate whether each floor has passed or failed the vibrational design requirements. The average values of those vibrational parameter ratios listed in Tables 12 to 14, 16 to 18 and 20 to 22 are also included in the table. From all of these results, these EU countries can be ranked from the most generous to the strictest. First consideration is the number of Fails and a country with the fewest Fail number will be ranked in the top. If the Fail numbers are the same, the numbers of Passes will be considered. The country with more Passes will stay in front. If the Pass numbers are still the same, the average values of the vibrational parameter ratios will be compared and countries with lower average values will be ranked higher.

Four countries have no Fails, e.g. Denmark, Germany, Spain and the UK. Both Denmark and the UK have gained 18 out of 18 Passes but Denmark has only an average of 0.65 which is smaller than the value for the UK. Hence, Denmark is ranked as the most generous country for the design of timber floors and is then followed by the UK. Both Germany and Spain only have six Passes and the remaining are all Not Availables so they are ranked as an equal third. However, the ranking for these two countries is quite subjective and may not be very convincing. Ireland has 17 Passes and only one Fail so it is ranked as the fifth. Belgium, Sweden and France all have 16 Passes and 2 Fails but France has a higher average of 0.77 compared with 0.72 for Belgium and Sweden. Hence, Belgium and Sweden are ranked as an equal sixth and France ranked as the eighth. Norway has 8 Passes, 4 Fails and 6 Not Availables and is ranked as the ninth. Austria has 14 Passes and 4 Fails so it is ranked as the tenth place. Both Italy and the Netherlands have 13 Passes and 5 Fails with an equal average of 0.88 so they are ranked as the equal eleventh, the second strictest countries. Finally, Finland has only 1 Pass, 11 Fails and 6 Not Availables and is ranked as the last, the strictest country.

1.7 - Discussion and recommendations

For vibrational serviceability design of timber floors constructed with various types of joists, human activities including walking people and jumping children are still the primary annoyance sources, which cause structural vibrations with frequencies ranging from 0 to 80 Hz and acoustic vibrations with frequencies above 25 Hz (50 Hz). For structural vibrations, various standards and design codes have been proposed, together with different rating methods, descriptors and limits, as indicated in Table 1.

All design practices, except EN 1995-1-1, use the perception curves to assess people's comfort to structural vibrations on timber floors, with the frequency ranging from 0.5 to 80 Hz except Norway which has expanded the range up to 160 Hz. The descriptors used are related to either weighted velocity, e.g. OS-RMS$_{90}$, v_{rms}, KB, $v_{w,95}$, V_{max} and V_{per}, or weighted acceleration, e.g. a_{rms}, VDV and $a_{w,95}$. All the descriptors cannot be obtained analytically but need to be determined, directly or indirectly, through site experimental testing. This nevertheless requires expertise from acoustic scientists but causes difficulties for structural design engineers because the latter do not have enough knowledge on these complex comfort perception design curves. Hence, completely satisfactory vibrational serviceability design for structural vibrations indeed needs cooperation between acoustic scientists and structural design engineers.

The vibrational parameters proposed in EN 1995-1-1, i.e. the fundamental frequency, unit point load deflection and unit impulse velocity, have clear physical meanings to various professionals and can reflect people's comfort to structural vibrations on timber floors even though they cannot be used to directly assess perception levels of structural vibrations. All three parameters can be determined either analytically or experimentally and are easily accepted by structural design engineers so they still have their advantages over other comfort perception descriptors.

As mentioned above, Eq. (1) for calculating the fundamental frequency f_1 is largely applicable for two-side supported floors and may underestimate the frequency for four-side supported floors. The difference in f_1 may be no more than 1 Hz, so EN 1995-1-1 and majority of National Annexes to the code in the EU countries have adopted Eq. (1) for calculations. However, this small difference can be crucial when f_1 is close to 8 Hz and lead the design to fail. Therefore the contributions of the lateral stiffness $(EI)_B$ from floor decking, roof ceiling and struts should be included. The following question is how these individual lateral stiffnesses should be combined. The UK National Annex suggests to superposition these stiffnesses by simply adding them together, which is generally conservative. However full composition of floor decking, roof ceiling and struts with floor joists will overestimate the global stiffness because the connections of these components with floor joists are not perfectly rigid and there always exist slips which unavoidably reduce the overall stiffness of the floor. Some stiffness values in-between should be adopted for calculating f_1. In this way, the formulae used in Austria and Finland are more rational. Another issue is how to calculate the participating floor mass. Based on the design philosophy in EN 1990 [1], for serviceability limit design, quasi-permanent load should be used, i.e. certain proportion of imposed load, e.g. furniture, partitions, etc., should be added onto dead load for calculating the design load. Vibrational design of timber floors is indeed a serviceability issue and it is more reasonable to include certain proportion of imposed load for calculating the mass m. Again both Austria and Finland adopt the quasi-permanent combination for determining m. The final issue on the fundamental frequency f_1 is its limit. The threshold of 8 Hz seems to be well accepted by almost all EN countries except Finland which requires 9 Hz. If both the composition effect on the global stiffness $(EI)_B$ of the timber floor and the quasi-permanent combination for the mass m are considered, the limit of 8 Hz should still be reasonable.

EN 1995-1-1 only gives a general design criterion expression for the unit point load deflection w as illustrated in Eq. (2) but has failed to provide with the detailed formulae for calculating w because Eurocodes assume that these formulae are regarded as common knowledge and should be found from normal textbooks. There are a number of factors which influence the deflection. First shear will all extra deflection to the bending deflection, and connections between floor members also contribute the overall deflection due to slips between the connectors and the surrounding timber materials. However, the applied unit point load can be redistributed to neighbouring joists due to lateral stiffness contributed by floor decking, roof ceiling and struts so that the actual deflection can be largely reduced. Joist spacing also largely influences the vertical deflection. The smaller the joist spacing, the smaller the mid-span deflection. Austria, Finland, Ireland and the UK consider the stiffening effect from transverse floor members. Finland, Ireland and the UK include the effect of floor joist spacing, and Ireland and the UK also consider the shear effect in the formulae for calculating the deflection w. Hence the formulae proposed in Ireland and the UK are more comprehensive. EN 1995-1-1 only gives a permitted range for the deflection limit a which largely varies from country to country. As discussed above, for short floor span floors below 3 m, Denmark, Ireland and the UK are more generous than other EU countries. For long floor span up to 6 m, Austria, Belgium, Denmark and Sweden have set more relaxed limits. For extra long floor span up to 10 m, Austria, Belgium and Sweden remain the most generous. It can be seen that the current National Annexes among the EU countries use largely different formulae for calculating the deflection w and set different limits. Hence there is an urgent need to harmonise the formulae for calculating the deflection and the corresponding limits.

The unit impulse velocity response v is the most mysterious parameter for vibrational serviceability design of timber floors in EN 1995-1-1. The formula Eq. (4) for determining v cannot be easily deduced and its physical meanings are difficult to understand because it is more empirical rather than analytical or theoretical. Unlike the fundamental frequency and unit point load deflection, the unit impulse velocity response is difficult to be determined numerically and experimentally. Occasionally, this parameter influences design of timber floors in a funny way by failing to give any practical solutions or even producing singular solutions. Thus, several countries have disregarded this design criterion, e.g. Finland, Germany, Norway and Spain. The UK has deliberately increased the damping ratio to 2% to make this criterion redundant. Some parameters in the formulae are also defined in an arbitrary way, e.g. the upper limit of 40 Hz for the included modal frequencies, the extra participating mass of 50 kg, etc. Most EU countries have adopted the formulae for determining the unit impulse velocity response but largely different values have been proposed for the parameter *b* for calculating the design limit. The larger the value of *b*, the stricter the floor design. In general, Denmark and the UK are more generous than other EU countries while Italy and the Netherlands are stricter. The design value of damping ratio is also an issue because it covers for timber floors constructed with most types of joists but fails to cover for some other types of joists e.g. metal web joists. Therefore it is suggested that a varied damping ratio for various types of timber flooring systems should be used to reflect practical situations.

As for the influencing order of the three vibrational serviceability design criteria, the unit point load deflection criterion is the most crucial one for timber floor design but it is difficult to tell which one will be the next most crucial criterion, with respect to the fundamental frequency or to the unit impulse velocity response. From the given six design examples, it is interesting to observe that for the floors constructed with solid timber joists, the unit point load deflection criterion is the most crucial one and is followed by the unit impulse velocity response criterion, while the fundamental frequency criterion has become the least crucial one. For the floors constructed with engineered I-joists, the unit point load deflection dominantly controls the vibrational serviceability design, and is followed by the fundamental frequency criterion, while the unit impulse velocity response criterion has become the least crucial. Finally, for the floors constructed with metal web joists, the unit point load deflection criterion remains the predominant one in some countries but the fundamental frequency criterion seems no less important on average while the unit impulse velocity criterion is far less crucial. For other types of floor joists, different trends may be observed.

1.8 - CONCLUSIONS

As part of the research work carried out within the Working Group 3 of COST Action FP0702, sources of annoyance, types of annoyance for both structural and acoustic vibrations and the corresponding frequency ranges have been summarised and evaluated. Human activities including walking people and jumping children remain the predominant annoyance sources. For structural vibrations, various standards and design codes have been collected, and the comfort rating methods, descriptors and their limiting values have been discussed in detail. Most codes use the perception curves for assessing people’s comfort to structural vibrations on timber floors. The used descriptors which are related to either weighted velocity or acceleration cannot be obtained analytically but need to be determined experimentally. Completely satisfactory vibrational serviceability design of timber floors with respect to structural vibrations needs cooperation between acoustic scientists and structural design engineers.

Eurocode 5 Part 1-1 has provided structural engineers for design of timber floors with three vibrational serviceability design criteria, with respect to the fundamental frequency, unit point load deflection and unit impulse velocity response, respectively. The first two parameters are physically clear and easily determined with analytically or experimentally. The third parameter is slightly mysterious. The national design practices of timber floors among thirteen EU countries have been summarized, and their similarities and differences have been further discussed by realistically designing the flooring systems constructed with three different types of joists, i.e. solid timber joists, I-joists and metal web joists.

For calculating the fundamental frequency, the composite effect of floor decking, ceiling and struts on the global stiffness in the floor joist direction should be included so as to make the design formulae applicable for both two-side supported and four-side supported floors. It is more rational to use the quasi-permanent combination for calculating the participating mass because during the design life there are always certain proportions of imposed loads acting on the floors together with dead loads. Among the thirteen EU countries, only Austria and Finland consider the lateral composite effect and quasi-permanent combination for design of timber floors. Further harmonisation on these issues among the EU countries is needed.

EN 1995-1-1 only gives a general design criterion for the unit point load deflection but has failed to provide with detailed formulae for calculating the deflection and also failed to set the design limits. Ireland and the UK have considered more influencing factors than other countries when determining the mid-span deflection of the floor under unit point load, e.g. shear induced deflection, stiffening and composite effect of floor decking, ceiling and struts, joist spacing, etc. Austria and Finland have considered the contribution of these transverse components to the global stiffness. Finland has also included the effect of joist spacing. The remaining EU countries have failed to provide with detailed formulae in their National Annexes for calculating the mid-span deflection under unit point load. The design limit for the unit point load deflection also varies largely between the EU countries. In general, Denmark, Ireland, Sweden and the UK are more generous than others, while Finland is the strictest and is followed by Austria, Italy and the Netherlands. Hence there is also an urgent need to harmonize the formulae for calculating the deflection under unit point load and setting up the corresponding limits.

The design criterion for unit impulse velocity response remains as a trickiest one for many design engineers due to the difficulty to understand its physical meanings and to physically measure it. Some parameters used for determining the unit impulse velocity are also very arbitrary. This criterion occasionally stops engineers obtaining meaningful solutions so some countries have disregarded this design criterion like Finland, Germany, Norway and Spain, or made it redundant like the UK. On the other hand, the differences in the design limit also remain large between the EU countries. In general, Denmark and the UK are more generous than other EU countries while Italy and the Netherlands are stricter. It is also suggested that a varied damping ratio should be adopted for timber flooring systems with various types of joists.

In general, the unit point load deflection criterion is the most crucial one for timber floor design, but to be followed by which criterion will largely depend on practical situations. For the floors constructed with solid timber joists, the unit impulse velocity response criterion is more crucial than the fundamental frequency criterion. For the floors constructed with engineered I-joists, the fundamental frequency criterion is more crucial than the unit impulse velocity response criterion. For the floors constructed with metal web joists, the fundamental frequency criterion seems no less important than the unit point load deflection criterion while the unit impulse velocity criterion becomes far less crucial than the other two criteria.

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Table 1: Sources and types of annoyance for comfort assessment

Sources of annoyance	Structural vibrations		Acoustic vibrations	
	Type of annoyance	Frequency range	Type of annoyance	Frequency range
Walking people	Vibrations from neighbours, people in the same room or person himself	0 – 80 Hz	Noise from neighbours, people in the same room or person himself	> 25 Hz (> 50 Hz)
Jumping children	The same as walking people	0 – 80 Hz	The same as walking people	> 25 Hz (> 50 Hz)
Service equipment	Indoors vibrations	N/A	Indoors noise	> 25 Hz (> 50 Hz)
Domestic appliances	Indoors vibrations	N/A	Indoors noise	> 25 Hz (> 50 Hz)
Traffic	Outdoors vibrations	1 – 80 Hz	Outdoors noise	N/A
Wind	Outdoors vibrations	N/A	Outdoors noise	N/A

Table 2: Design standards for comfort assessment of structural vibrations of timber floors

Standards	Rating methods	Frequency range	Descriptors	Limiting values
EC5-1-1 [2]	f_1, w and v	8 – 40 Hz	f_1 (Hz)	> 8 Hz
			w (mm/kN)	a = 0.5 – 4.0 mm/kN, depending on NAs
			v (m/Ns^2)	$b^{(f_1\zeta-1)}$ m/Ns^2, depending on NAs
JRC Report [18]	W_b &W_d curves	1 – 80 Hz	OS-RMS$_{90}$ (mm/s)	0.1 – 3.2 mm/s
ISO 2631-1 & 2 [19,20]	W_b &W_d curves or W_m curves	1 – 80 Hz	v_{rms} (m/s)	N/A
			a_{rms} (m/s^2)	N/A
ISO 10137 [21]	W_b &W_d curves	0.5 – 80 Hz	VDV (m/s$^{1.75}$)	Varied with day or night
BS 6472-1 [22]	W_b &W_d curves	0.5 – 80 Hz	VDV (m/s$^{1.75}$)	Varied with day or night
DIN 4150-1 to 3 [23-25]	KB values	1 – 80 Hz	KB	0.15 to 0.3 for residential buildings
NS 8176 E [26]	W_m curves	0.5 – 160 Hz	$v_{w,95}$ (mm/s)	Varied with Class A to D
		(0 – 80 Hz)	$a_{w,95}$ (mm/s^2)	Varied with Class A to D
SBR Deel B [27]	Nuisance degree	1 – 80 Hz	V_{max} V_{per}	Varied with day, evening or night

Table 3: Vibration dose value (DVD) ranges which might result in various probabilities of adverse comment within residential buildings in ISO 10137 [21]

Place and time	Low probability of adverse comment	Adverse comment possible	Adverse comment probable
Daytime (16 h)	0.2 to 0.4 m/s$^{1.75}$	0.4 to 0.8 m/s$^{1.75}$	0.8 to 1.6 m/s$^{1.75}$
Night-time (8 h)	0.13 m/s$^{1.75}$	0.26 m/s$^{1.75}$	0.51 m/s$^{1.75}$

Table 4: Vibration dose value (DVD) ranges which might result in various probabilities of adverse comment within residential buildings in BS 6472-1 [22]

Place and time	Low probability of adverse comment	Adverse comment possible	Adverse comment probable
Daytime (16 h)	0.2 to 0.4 $m/s^{1.75}$	0.4 to 0.8 $m/s^{1.75}$	0.8 to 1.6 $m/s^{1.75}$
Night-time (8 h)	0.1 to 0.2 $m/s^{1.75}$	0.2 to 0.4 $m/s^{1.75}$	0.4 to 0.8 $m/s^{1.75}$

Note: For offices and workshops, multiplying factors of 2 and 4 respectively should be applied to the above vibration dose value ranges for a 16 h day.

Table 5: Guidance classification of residential buildings with the upper limits for the maximum values of the 95% fractile weighted velocity $v_{w,95}$ and acceleration $a_{w,95}$ in NS 8176 E [26]

Type of vibration value	Class A	Class B	Class C	Class D
Statistical maximum value for weighted velocity $v_{w,95}$ (mm/s)	0.1	0.15	0.3	0.6
Statistical maximum value for weighted acceleration $a_{w,95}$ (mm/s^2)	3.6	5.4	11	21

Table 6: Vibration nuisance assessment based on V_{max} in SBR Richtlijn – Deel B [27]

V_{max}	< 0.1	0.1 – 0.2	0.2 – 0.8	0.8 – 3.2	> 3.2
Annoyance	Does not interfere	Hardly affected	Moderate impairment	Nuisance	Severe nuisance

Table 7: Limiting values of V_{max} and V_{per} for building functions in SBR Richtlijn – Deel B [27]

Building function	Day and Evening			*Night*		
	A1	A2	A3	A1	A2	A3
Health and living	0.1	0.4	0.05	0.1	0.2	0.05
Education, office and meeting	0.15	0.6	0.05	0.15	0.6	0.05
Critical workplace	0.1	0.1	0.05	0.1	0.1	0.05

Note: A_1 is the target value for V_{max}, A_2 is the threshold value for V_{max}, A_3 is the limit value for V_{per}.

Table 8: Design criteria for fundamental frequency f_1

Country	Design equations for f_1 (Hz)		Limit
EC5-1-1	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}$	for 4-side supported	> 8 Hz
AT	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}$	for 2-side supported	EC5-1-1
	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}\sqrt{1+\left(\frac{L}{B}\right)^4\frac{(EI)_B}{(EI)_L}}$	for 4-side supported	
BE	EC5-1-1		EC5-1-1
DK	EC5-1-1		EC5-1-1
FI	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}$	for 2-side supported	> 9 Hz
	$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{(EI)_L}{m}}\sqrt{1+\left(2\left(\frac{L}{B}\right)^2+\left(\frac{L}{B}\right)^4\right)\frac{(EI)_B}{(EI)_L}}$	for 4-side supported	
FR	EC5-1-1		EC5-1-1
DE	EC5-1-1		EC5-1-1
IE	EC5-1-1		EC5-1-1
IT	EC5-1-1		EC5-1-1
NL	EC5-1-1		EC5-1-1
NO	EC5-1-1		EC5-1-1
ES	EC5-1-1		EC5-1-1
SE	EC5-1-1		EC5-1-1
UK	EC5-1-1		EC5-1-1

Table 9: Design criteria for unit point load deflection w

Country	Design equations for *w*	Limit *a* (mm/kN)
EC5-1-1	N/A	0.5 – 4.0
AT	$w = \frac{FL^3}{48(EI)_L b_F}$ where $b_F = \frac{L}{1.1}\sqrt[4]{\frac{(EI)_B}{(EL)_L}}$	1.5 normal floors 1.0 when adjacent structures are disturbed
BE	N/A	1.5
DK	N/A	1.7 for timber joists with $L \le$ 5000 - 6000 mm
FI	$w = \min\begin{Bmatrix} FL^2/[42 k_\delta (EL)_L] \\ FL^3/[48 s (EL)_L] \end{Bmatrix}$ where $k_\delta = \sqrt[4]{(EI)_B/(EI)_L}$ and $k_\delta \le B/L$ for 4-side supported	0.5*k* for $L \le$ 6000 mm *k* depends on span; 0.5 for $L >$ 6000 mm; Additional 0.5 mm allowed for floating and raised floors.
FR	N/A	1.3 ± 0.3
IE	$w = \frac{1000\, k_{dist}\, L_{eq}^{3}\, k_{amp}}{48\,(EI)_{joist}}$ where $k_{dist} \ge 0.30$ and k_{amp} = 1.05 - 1.45	1.8 for $L \le$ 4000 mm $16500/L^{1.1}$ for $L >$ 4000 mm
DE	N/A	N/A
IT	N/A	1.0
NL	N/A	1.0
NO	N/A	0.9 for normal stiff 0.6 for high stiff only for $L \le$ 4500 mm
ES	N/A	N/A
SE	N/A	1.5
UK	$w = \frac{1000\, k_{dist}\, L_{eq}^{3}\, k_{amp}}{48\,(EI)_{joist}}$ where $k_{dist} \ge 0.30$ and k_{amp} = 1.05 - 1.45	1.8 for $L \le$ 4000 mm $16500/L^{1.1}$ for $L >$ 4000 mm

Table 10: Design criteria for unit impulse velocity v

Country	Design equations	Limit (m/Ns^2)
EC5-1-1	$v = \dfrac{4(0.4 + 0.6 n_{40})}{m\,B\,L + 200}$	$b^{(f_1 \zeta - 1)}$, ζ = 1%
AT	EC5-1-1	*b* ≥ 100 normal floors
		b ≥ 120 when adjacent structures are disturbed
BE	EC5-1-1	EC5-1-1 and *b* = 100
DK	EC5-1-1	EC5-1-1 and *b* = 80
FI	N/A	N/A
FR	EC5-1-1	EC5-1-1 and *b* = 108, from Fig. 7.2 but *a* < 3 mm/kN
DE	EC5-1-1	N/A
IE	EC5-1-1	EC5-1-1 and *b* from Fig. 7.2
		but not applicable to Category A1 (areas of domestic activities)
IT	EC5-1-1	EC5-1-1 and *b* = 120
NL	EC5-1-1	EC5-1-1 and *b* = 120
NO	N/A	N/A
ES	N/A	N/A
SE	EC5-1-1	EC5-1-1, *b* = 100
UK	EC5-1-1	EC5-1-1, ζ = 2%, *b* ≥ 88 for *a* ≤ 1.8 mm/kN

Table 11: Basic properties of floors with solid joists

Parameters		Floor 1	Floor 2
L	(m)	3.0	5.0
B	(m)	3.0	5.0
s	(mm)	450	400
b	(mm)	47	75
h	(mm)	147	220
t_{deck}	(mm)	22	22
$t_{ceiling}$	(mm)	12.5	12.5
$E_{0,mean,\ C24}$	(N/mm^2)	11000	11000
$E_{mean,P5}$	(N/mm^2)	3000	3000
$E_{mean,plaster}$	(N/mm^2)	2000	2000
G_k	(kN/m^2)	0.491	0.491
Q_k	(kN/m^2)	1.5	1.5
m	(kg/m^2)	50	50
ψ_2		0.3	0.3
$(EI)_L$	(Nm^2/m)	304122.67	1830125.00
$(EI)_B$	(Nm^2/m)	2987.52	2987.52

Table 12: Calculated fundamental frequency f_1 and limit $f_{1,limit}$ for solid timber joist floors

Floor	Floor 1 (L = 3 m)			Floor 2 (L = 5 m)		
Country	f_1 (Hz)	$f_{1,\text{limit}}$ (Hz)	$f_{1,\text{limit}}/f_1$	f_1 (Hz)	$f_{1,\text{limit}}$ (Hz)	$f_{1,\text{limit}}/f_1$
AT	9.88	8.0	0.81	8.69	8.0	0.92
BE	13.61	8.0	0.59	12.02	8.0	0.67
DK	13.61	8.0	0.59	12.02	8.0	0.67
FI	9.97	9.0	0.90	8.70	9.0	1.03*
FR	13.61	8.0	0.59	12.02	8.0	0.67
DE	13.61	8.0	0.59	12.02	8.0	0.67
IE	13.61	8.0	0.59	12.02	8.0	0.67
IT	13.61	8.0	0.59	12.02	8.0	0.67
NL	13.61	8.0	0.59	12.02	8.0	0.67
NO	13.61	8.0	0.59	12.02	8.0	0.67
ES	13.61	8.0	0.59	12.02	8.0	0.67
SE	13.61	8.0	0.59	12.02	8.0	0.67
UK	13.61	8.0	0.59	12.02	8.0	0.67

Note: * indicates that the design fails.

Table 13: Calculated deflection w and limit a for solid timber joist floors

Floor	Floor 1 (L = 3 m)			Floor 2 (L = 5 m)		
Country	w (mm/kN)	a (mm/kN)		w (mm/kN)	a (mm/kN)	
AT	2.15	1.50	1.44*	1.56	1.50	1.04*
BE	1.63	1.50	1.09*	1.27	1.50	0.85
DK	1.63	1.70	0.96	1.27	1.70	0.75
FI	2.24	0.75	2.98*	1.62	0.57	2.84*
FR	1.63	1.30	1.26*	1.27	1.30	0.98
DE						
IE	1.63	1.80	0.91	1.27	1.41	0.90
IT	1.63	1.00	1.63*	1.27	1.00	1.27*
NL	1.63	1.00	1.63*	1.27	1.00	1.27*
NO	1.63	0.90	1.82*	1.27	0.90	1.41*
ES						
SE	1.63	1.50	1.09*	1.27	1.50	0.85
UK	1.63	1.80	0.91	1.27	1.41	0.90

Note: * indicates that the design fails.

Table 14: Calculated unit impulse velocity v and limit $b^{(f_1\zeta - 1)}$ *for solid timber joist floors*

Floor	Floor 1 (L = 3 m)			Floor 2 (L = 5 m)		
Country	v (10^{-2} m/Ns^2)	$b^{(f_1\zeta - 1)}$ (10^{-2} m/Ns^2)	$v/b^{(f_1\zeta - 1)}$	v (10^{-2} m/Ns^2)	$b^{(f_1\zeta - 1)}$ (10^{-2} m/Ns^2)	$v/b^{(f_1\zeta - 1)}$
AT	1.571	1.576	1.00	1.036	1.492	0.70
BE	2.196	1.872	1.17*	1.577	1.740	0.91
DK	2.196	2.270	0.97	1.577	2.117	0.75
FI						
FR	2.196	1.751	1.25*	1.577	1.626	0.97
DE						
IE	2.196	2.090	1.05*	1.577	1.685	0.94
IT	2.196	1.599	1.37*	1.577	1.482	1.07*
NL	2.196	1.599	1.37*	1.577	1.482	1.07*
NO						
ES						
SE	2.196	1.872	1.17*	1.577	1.740	0.91
UK	2.196	3.845	0.57	1.577	2.944	0.54

Note: * indicates that the design fails.

Table 15: Basic properties of floors with JJI-Joists

Parameters		Floor 3	Floor 4
L	(m)	5.4	7.3
B	(m)	5.0	6.0
s	(mm)	400	300
b	(mm)	63	97
h	(mm)	300	400
h_f	(mm)	45	45
t_w	(mm)	9	9
t_{deck}	(mm)	22	22
$t_{ceiling}$	(mm)	12.5	12.5
$E_{0,mean,C24}$	(N/mm^2)	11000	11000
$E_{mean,P5}$	(N/mm^2)	3000	3000
$E_{mean,OSB3}$	(N/mm^2)	4930	4930
$E_{mean,plaster}$	(N/mm^2)	2000	2000
G_k	(kN/m^2)	0.736	0.736
Q_k	(kN/m^2)	1.5	1.5
m	(kg/m^2)	75	75
ψ_2		0.3	0.3
$(EI)_L$	(Nm^2/m)	2606249.39	10393003.99
$(EI)_B$	(Nm^2/m)	2987.52	2987.52

Table 16: Calculated fundamental frequency f_1 and limit $f_{1,limit}$ for JJI-Joist floors

Floor	Floor 3 (L = 5.4 m)			Floor 4 (L = 7.3 m)		
Country	f_1 (Hz)	$f_{1,\mathrm{limit}}$ (Hz)	$f_{1,\mathrm{limit}} / f_1$	f_1 (Hz)	$f_{1,\mathrm{limit}}$ (Hz)	$f_{1,\mathrm{limit}} / f_1$
AT	7.92	8.0	1.01*	8.65	8.0	0.93
BE	10.04	8.0	0.80	10.97	8.0	0.73
DK	10.04	8.0	0.80	10.97	8.0	0.73
FI	7.93	9.0	1.14*	8.65	9.0	1.04*
FR	10.04	8.0	0.80	10.97	8.0	0.73
DE	10.04	8.0	0.80	10.97	8.0	0.73
IE	10.04	8.0	0.80	10.97	8.0	0.73
IT	10.04	8.0	0.80	10.97	8.0	0.73
NL	10.04	8.0	0.80	10.97	8.0	0.73
NO	10.04	8.0	0.80	10.97	8.0	0.73
ES	10.04	8.0	0.80	10.97	8.0	0.73
SE	10.04	8.0	0.80	10.97	8.0	0.73
UK	10.04	8.0	0.80	10.97	8.0	0.73

Note: * indicates that the design fails.

Table 17: Calculated deflection w and limit a for JJI-Joist floors

Floor	Floor 3 (L = 5.4 m)			Floor 4 (L = 7.3m)		
Country	w (mm/kN)	a (mm/kN)		w (mm/kN)	a (mm/kN)	
AT	1.39	1.50	0.93	0.90	1.50	0.60
BE	1.23	1.50	0.82	0.90	1.50	0.60
DK	1.23	1.70	0.73	0.90	1.70	0.53
FI	1.45	0.53	2.73*	0.94	0.50	1.88*
FR	1.23	1.30	0.95	0.90	1.30	0.69
DE	1.23			0.90		
IE	1.23	1.29	0.95	0.90	0.93	0.97
IT	1.23	1.00	1.23*	0.90	1.00	0.90
NL	1.23	1.00	1.23*	0.90	1.00	0.90
NO	1.23	0.90	1.37*	0.90	0.90	1.00
ES	1.23			0.90		
SE	1.23	1.50	0.82	0.90	1.50	0.60
UK	1.23	1.29	0.95	0.90	0.93	0.97

Note: * indicates that the design fails.

Table 18: Calculated unit impulse velocity v and limit $b^{(f_1\zeta-1)}$ *for JJI-Joist floors*

Floor	Floor 3 (L = 5.4 m)			Floor 4 (L = 7.3 m)		
Country	v (10^{-2} m/Ns^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/Ns^2)	$v/b^{(f_1\zeta-1)}$	V (10^{-2} m/Ns^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/Ns^2)	$v/b^{(f_1\zeta-1)}$
AT	0.822	1.440	0.57	0.615	1.489	0.41
BE	1.138	1.588	0.72	0.860	1.658	0.52
DK	1.138	1.941	0.59	0.860	2.022	0.43
FI						
FR	1.138	1.482	0.77	0.860	1.548	0.56
DE						
IE	1.138	1.479	0.77	0.860	1.380	0.62
IT	1.138	1.348	0.84	0.860	1.409	0.61
NL	1.138	1.348	0.84	0.860	1.409	0.61
NO						
ES						
SE	1.138	1.588	0.72	0.860	1.658	0.52
UK	1.138	2.367	0.48	0.860	2.340	0.37

Table 19: Basic properties of floors with Posi-Joists

Parameters		Floor 5	Floor 6
L	(m)	5.0	7.5
B	(m)	5.0	6.0
s	(mm)	600	400
b	(mm)	97	97
h	(mm)	254	421
h_f	(mm)	47	47
b_{strut}	(mm)	47	47
h_{strut}	(mm)	147	147
t_{deck}	(mm)	22	22
$t_{ceiling}$	(mm)	12.5	12.5
$E_{0,mean,TR26}$	(N/mm^2)	11000	11000
$E_{mean,P5}$	(N/mm^2)	3000	3000
$E_{mean,plaster}$	(N/mm^2)	2000	2000
G_k	(kN/m^2)	0.736	0.736
Q_k	(kN/m^2)	1.5	1.5
m	(kg/m^2)	75	75
ψ_2		0.3	0.3
$(EI)_L$	(Nm^2/m)	1821467.40	11086227.89
$(EI)_B$	(Nm^2/m)	30358.56	21234.88

Table 20: Calculated fundamental frequency f_1 and limit $f_{1,limit}$ for Posi-Joist floors

Floor	Floor 5 (L = 5 m)			Floor 6 (L = 7.5 m)		
Country	f_1 (Hz)	$f_{1,\text{limit}}$ (Hz)	$f_{1,\text{limit}} / f_1$	f_1 (Hz)	$f_{1,\text{limit}}$ (Hz)	$f_{1,\text{limit}} / f_1$
AT	7.78	8.0	1.03*	8.48	8.0	0.94
BE	9.79	8.0	0.82	10.74	8.0	0.75
DK	9.79	8.0	0.82	10.74	8.0	0.75
FI	7.90	9.0	1.14*	8.50	9.0	1.06*
FR	9.79	8.0	0.82	10.74	8.0	0.75
DE	9.79	8.0	0.82	10.74	8.0	0.75
IE	9.79	8.0	0.82	10.74	8.0	0.75
IT	9.79	8.0	0.82	10.74	8.0	0.75
NL	9.79	8.0	0.82	10.74	8.0	0.75
NO	9.79	8.0	0.82	10.74	8.0	0.75
ES	9.79	8.0	0.82	10.74	8.0	0.75
SE	9.79	8.0	0.82	10.74	8.0	0.75
UK	9.79	8.0	0.82	10.74	8.0	0.75

Note: * indicates that the design fails.

Table 21: Calculated deflection w and limit a for Posi-Joist floors

Floor	Floor 5 (L = 5 m)			Floor 6 (L = 7.5 m)		
Country	*w* (mm/kN)	*a* (mm/kN)	,	*w* (mm/kN)	*a* (mm/kN)	,
AT	0.88	1.50	0.58	0.56	1.50	0.37
BE	0.93	1.50	0.62	0.77	1.50	0.52
DK	0.93	1.70	0.55	0.77	1.70	0.46
FI	0.91	0.57	1.60*	0.58	0.50	1.16*
FR	0.93	1.30	0.71	0.77	1.30	0.60
DE						
IE	0.93	1.41	0.66	0.77	0.90	0.86
IT	0.93	1.00	0.93	0.77	1.00	0.77
NL	0.93	1.00	0.93	0.77	1.00	0.77
NO	0.93	0.90	1.03*	0.77	0.90	0.86
ES						
SE	0.93	1.50	0.62	0.77	1.50	0.52
UK	0.93	1.41	0.66	0.77	0.90	0.86

Note: * indicates that the design fails.

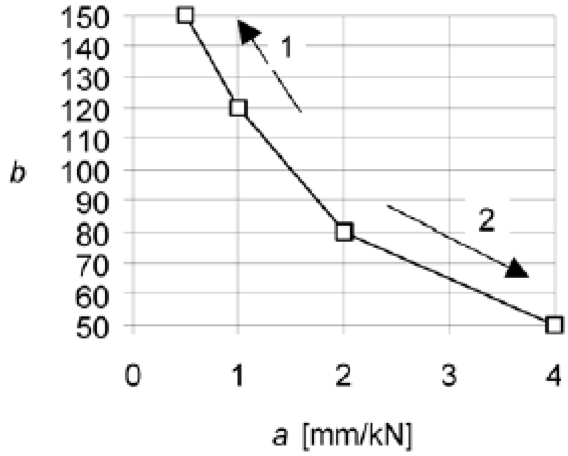
Table 22: Calculated unit impulse velocity v and limit $b^{(f_1\zeta-1)}$ *for Posi Joist floors*

Floor	Floor 5 (L = 5 m)			Floor 6 (L = 7.5 m)		
Country	V (10^{-2} m/Ns^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/Ns^2)	$v/b^{(f_1\zeta-1)}$	V (10^{-2} m/Ns^2)	$b^{(f_1\zeta-1)}$ (10^{-2} m/Ns^2)	$v/b^{(f_1\zeta-1)}$
AT	0.515	1.431	0.36	0.378	1.478	0.26
BE	0.718	1.570	0.46	0.531	1.640	0.32
DK	0.718	1.920	0.37	0.531	2.001	0.27
FI						
FR	0.718	1.465	0.49	0.531	1.531	0.35
DE						
IE	0.718	1.519	0.47	0.531	1.335	0.40
IT	0.718	1.332	0.54	0.531	1.393	0.38
NL	0.718	1.332	0.54	0.531	1.393	0.38
NO						
ES						
SE	0.718	1.570	0.46	0.531	1.640	0.32
UK	0.718	2.394	0.30	0.531	2.243	0.24

Table 23: Summary of floor design to EN 1995-1-1 among the European Union countries

EU Country	Floor 1			Floor 2			Floor 3			Floor 4			Floor 5			Floor 6			Ave ratio	Pass rank
	f_1	w	v	f_1	w	v	f_1	w	v	f_1	w	v	f_1	w	v	f_1	w	v		
AT	P	F	P	P	F	P	F	P	P	P	P	P	F	P	P	P	P	P	0.77	10
BE	P	F	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.72	6
DK	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.65	1
FI	P	F	N	F	F	N	F	F	N	F	F	N	F	F	N	F	F	N	1.62	13
FR	P	F	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.77	8
DE	P	N	N	P	N	N	P	N	N	P	N	N	P	N	N	P	N	N	0.72	3
IE	P	P	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.77	5
IT	P	F	F	P	F	F	P	F	P	P	P	P	P	P	P	P	P	P	0.88	11
NL	P	F	F	P	F	F	P	F	P	P	P	P	P	P	P	P	P	P	0.88	11
NO	P	F	N	P	F	N	P	F	N	P	P	N	P	F	N	P	P	N	0.99	9
ES	P	N	N	P	N	N	P	N	N	P	N	N	P	N	N	P	N	N	0.72	3
SE	P	F	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.72	6
UK	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	0.67	2

Note: P stands for Pass, F stands for Fail, and N stands for Not Available (N/A).



1. Better performance 2. Poorer performance

Fig. 1: Recommended range for b and a and the relationship between b and a

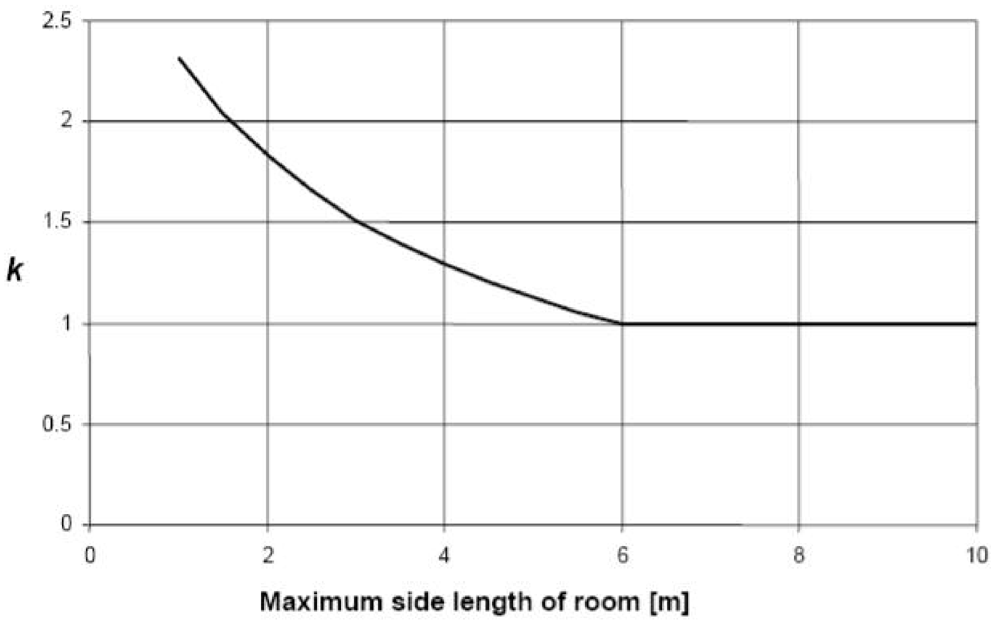


Fig. 2: The increasing factor k for the deflection limit

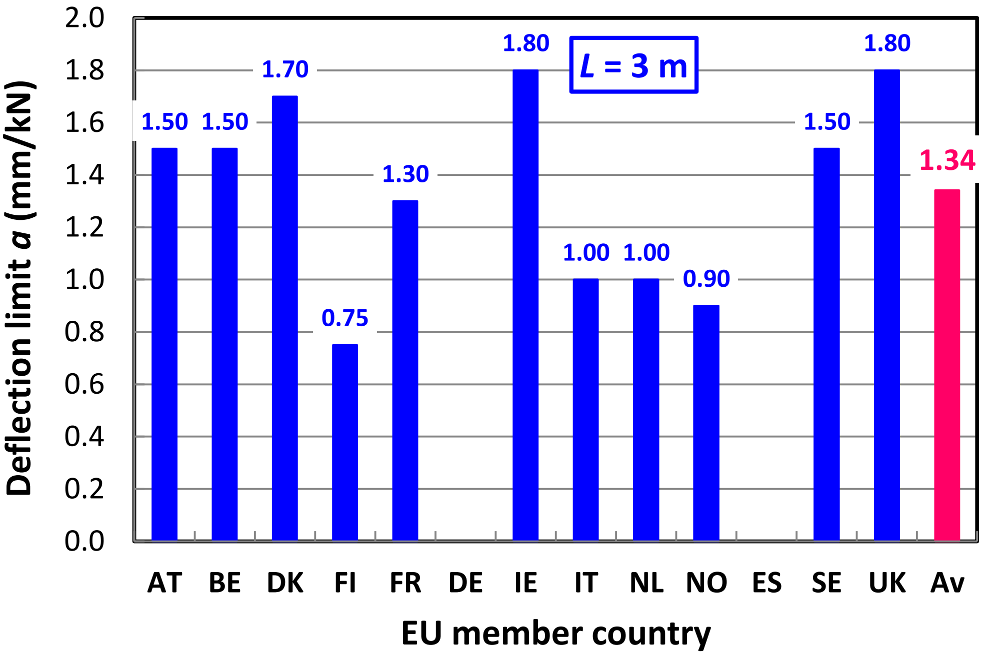


Fig. 3: Deflection limit a in EU countries for L = 3 m

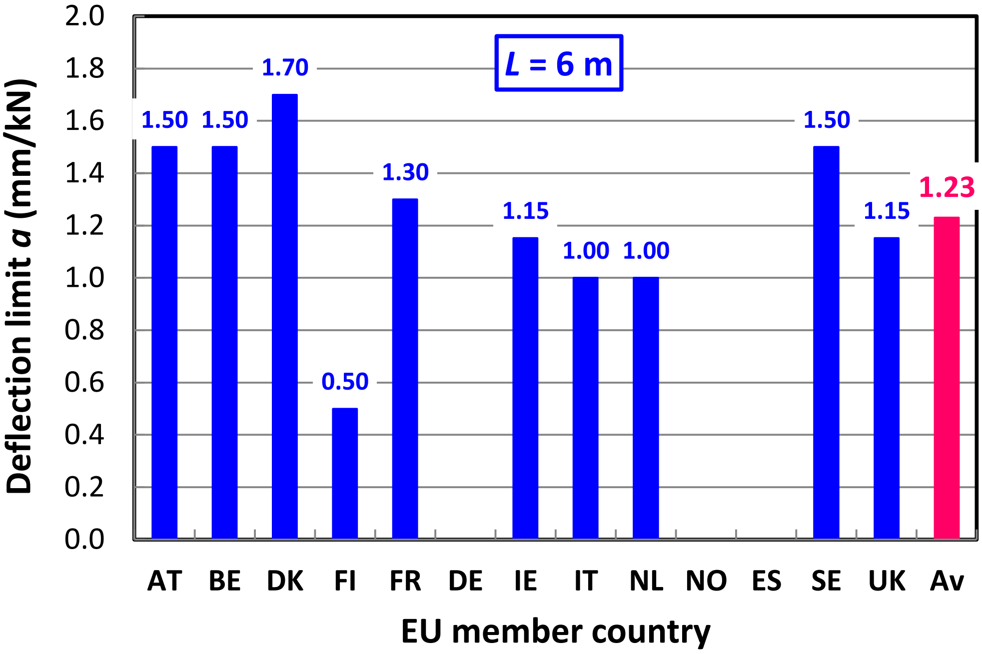


Fig. 4: Deflection limit a in EU countries for L = 6 m

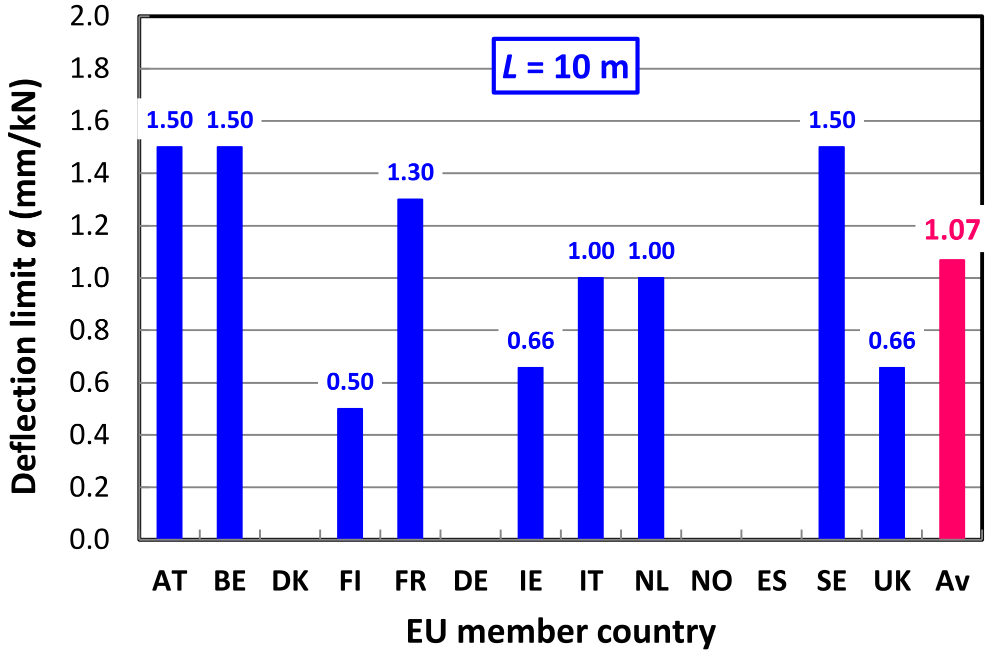


Fig. 5: Deflection limit a in EU countries for L = 10 m

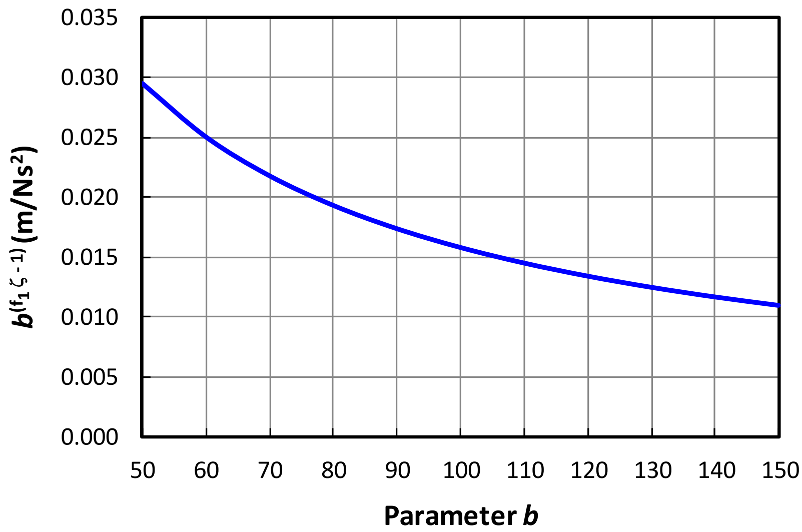


Fig. 6: Relationship between $b^{(f_1 \zeta - 1)}$ *and b*

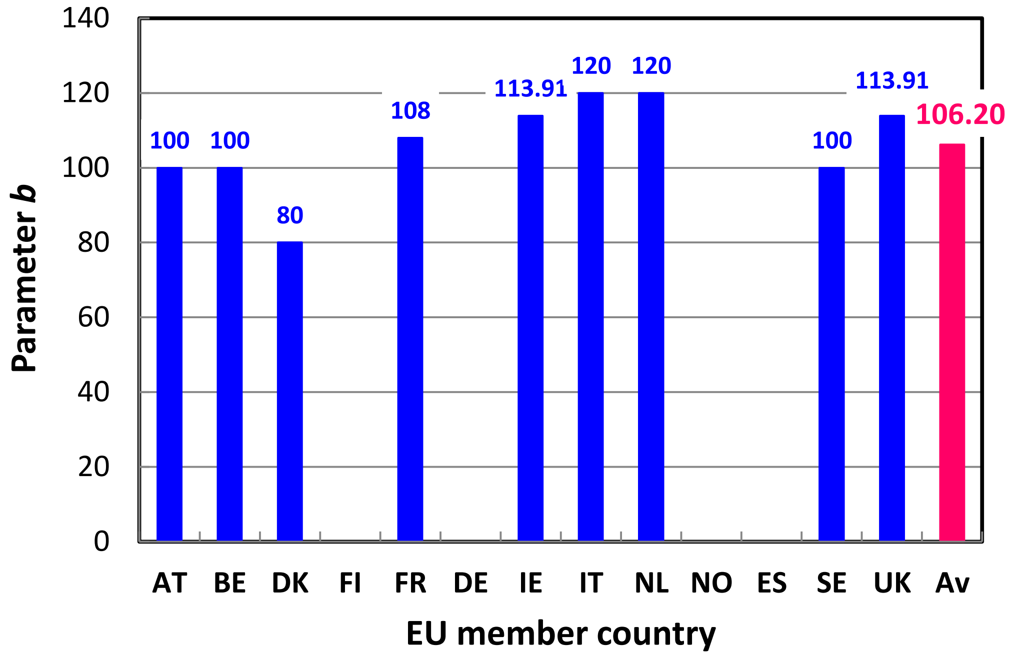


Fig. 7: Parameter b in the EU countries for L = 6 m

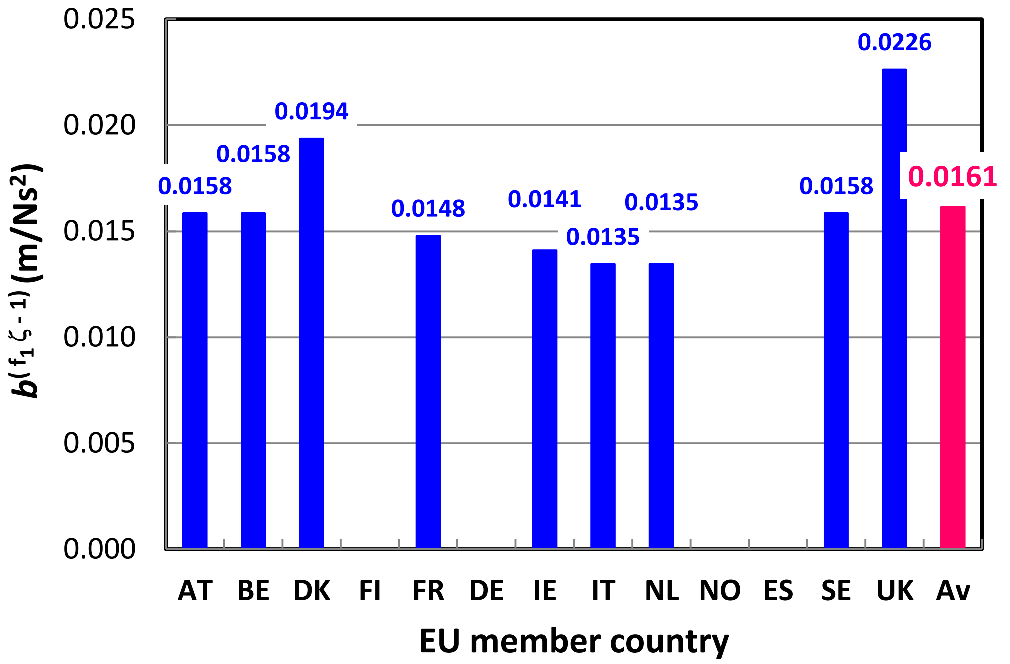


Fig. 8: Design limit $b^{(f_1\zeta-1)}$ *in the EU countries for L = 6 m*

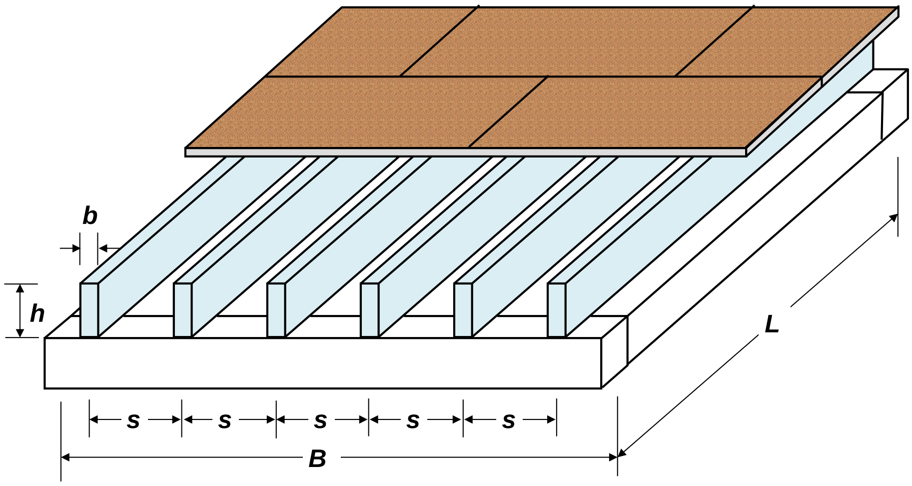


Fig. 9: A typical floor with solid timber joists

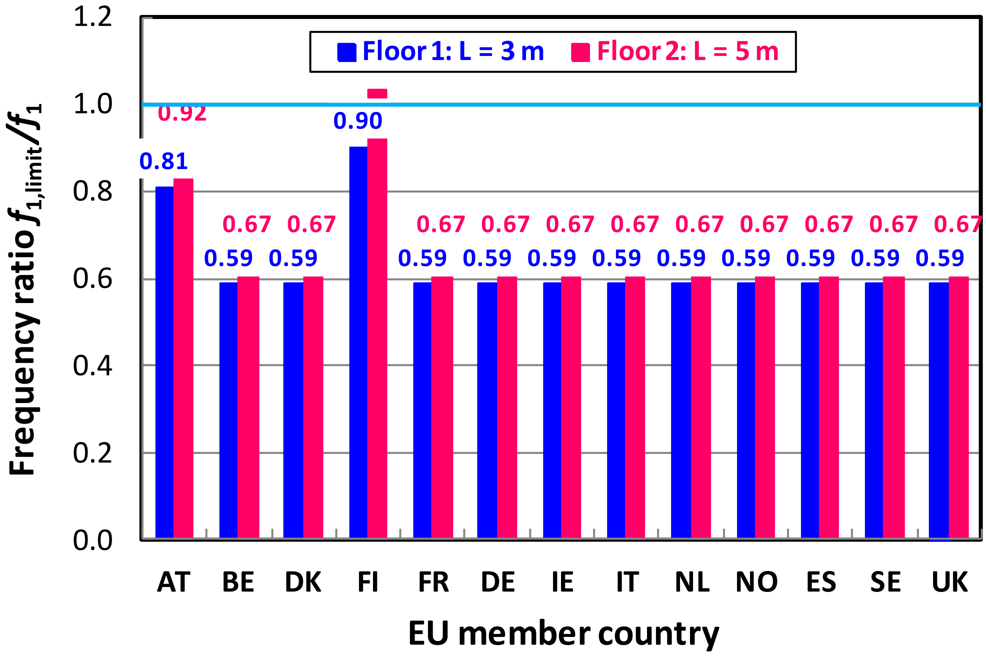


Fig. 10: Frequency ratios for solid timber joist floors

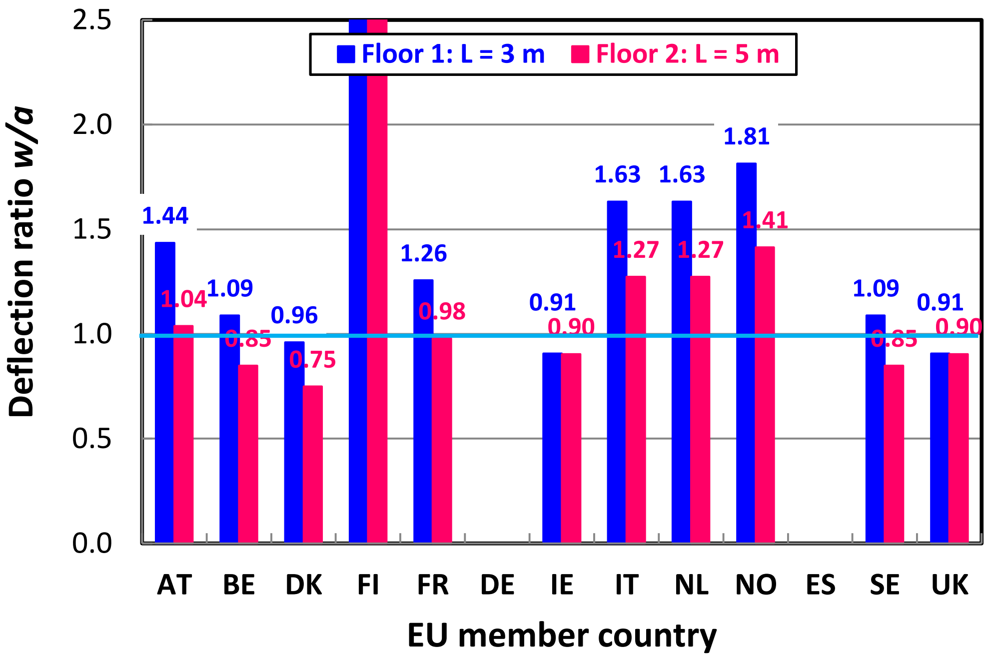


Fig. 11: Deflection ratios for solid timber joist floors

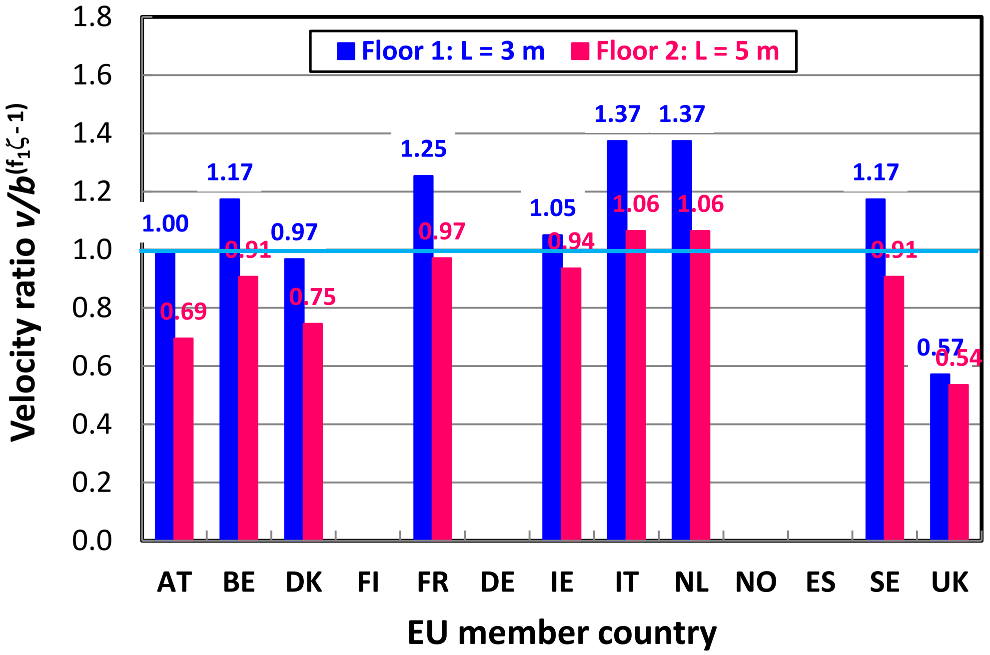
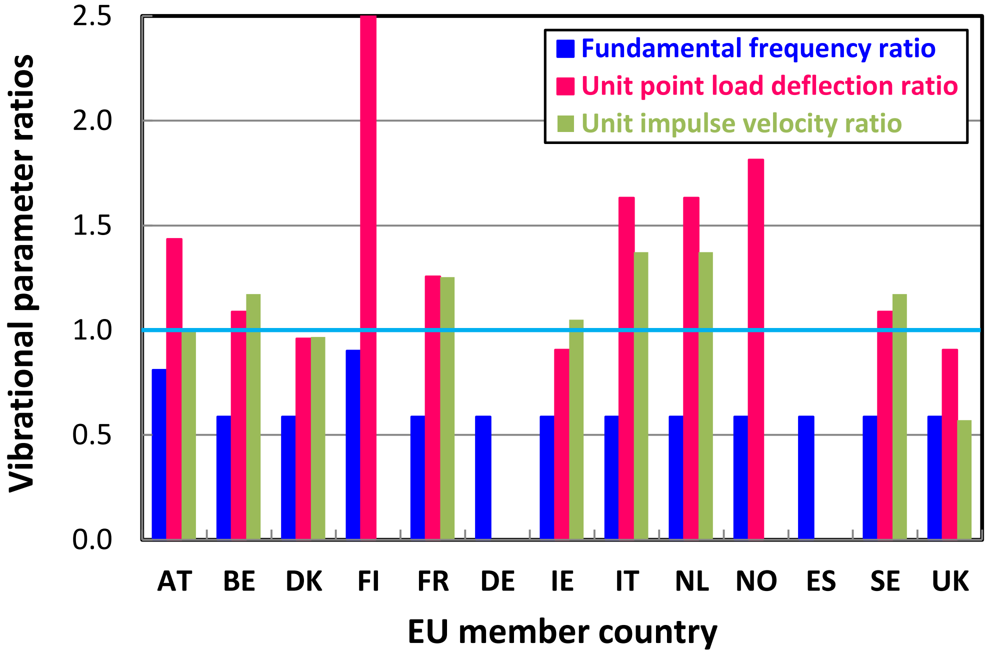
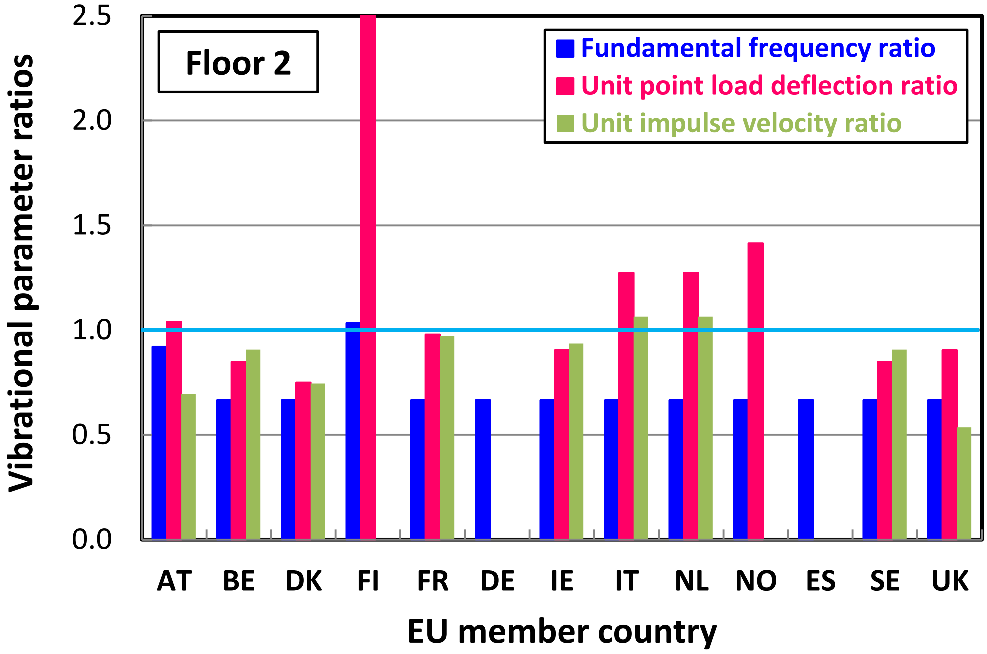


Fig. 12: Velocity ratios for solid timber joist floors



(a) Floor 1 with *L* = 3 m



(b) Floor 2 with *L* = 5 m

Fig. 13: Vibrational parameter ratios for Floors 1 and 2

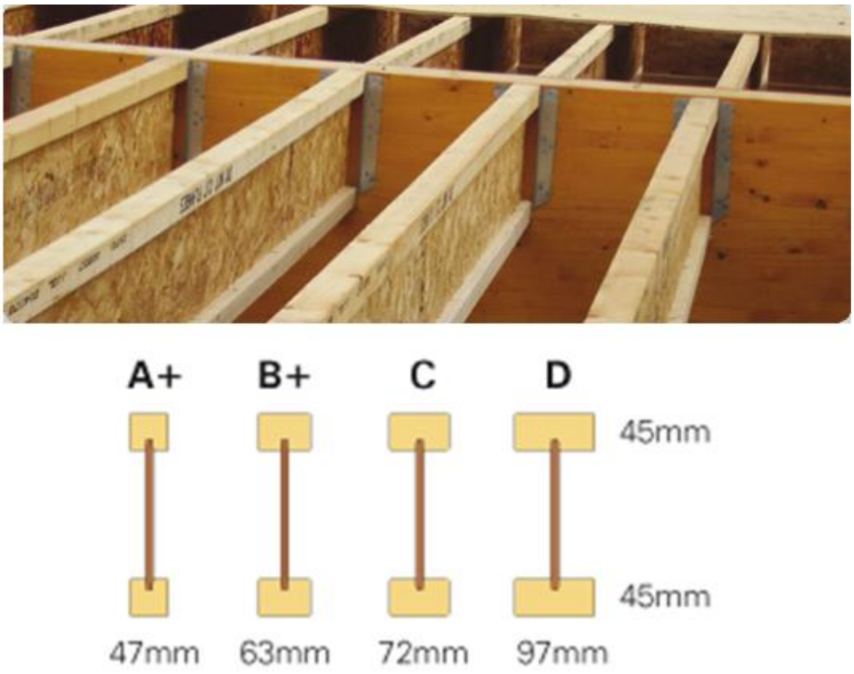


Fig. 14: Engineered I-joists (JJI-Joists)

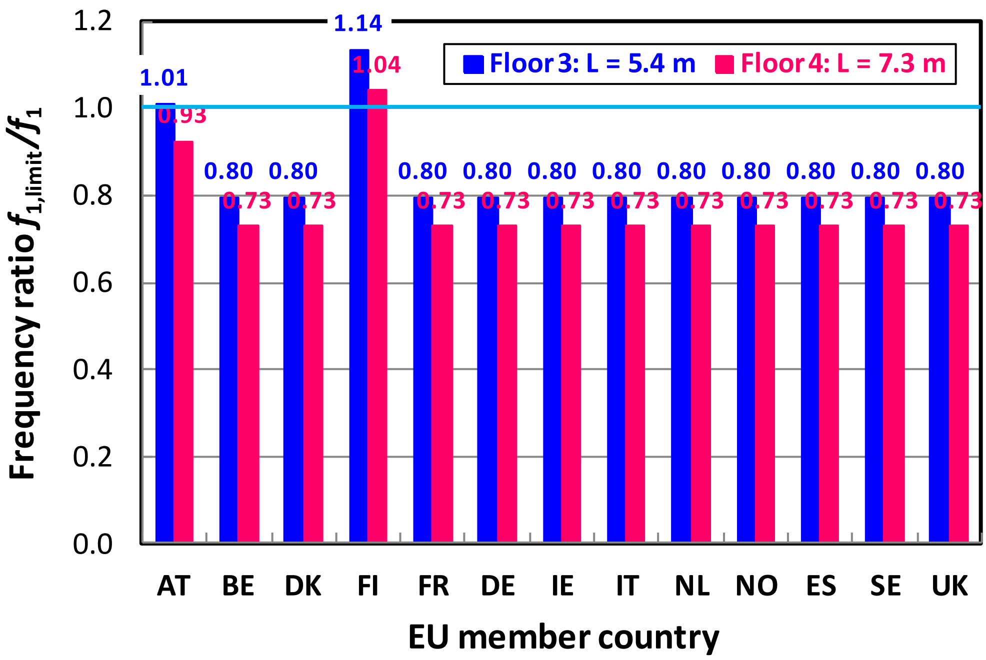


Fig. 15: Frequency ratios for JJI-Joist floors

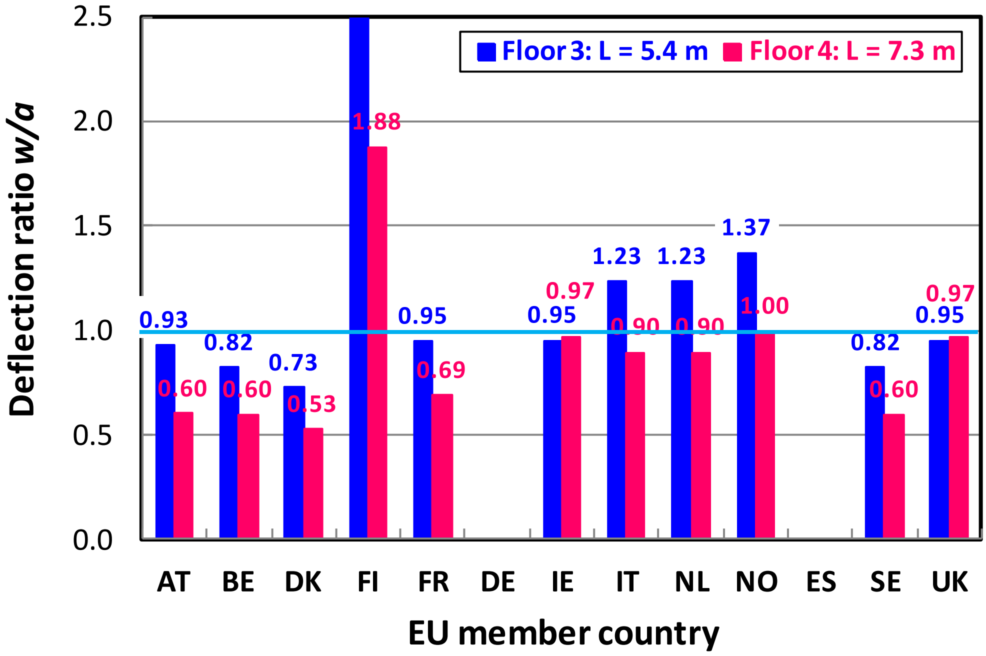


Fig. 16: Deflection ratios for JJI-Joist floors

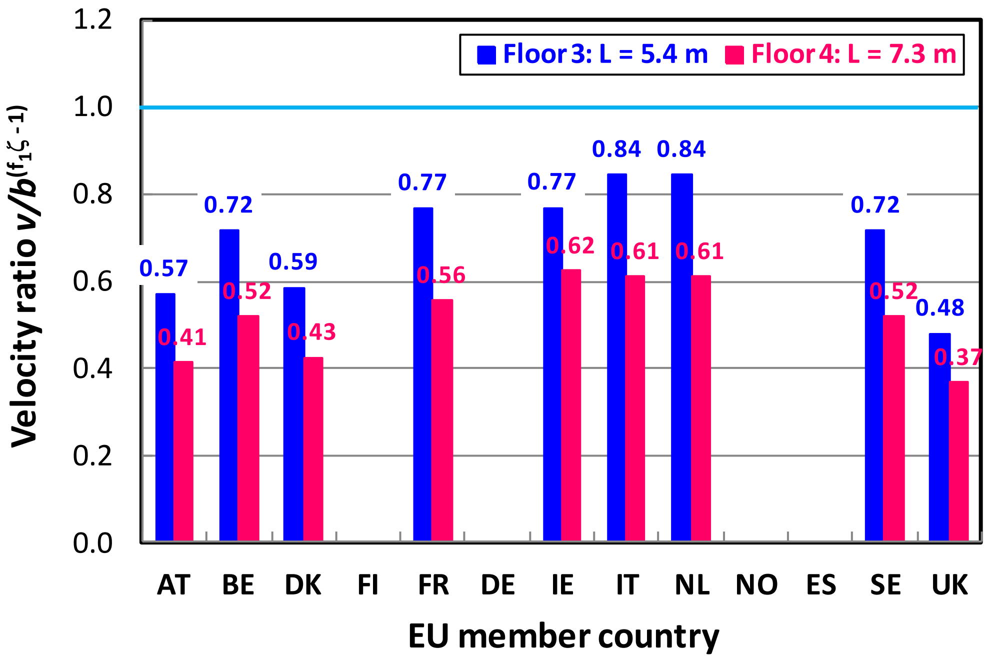
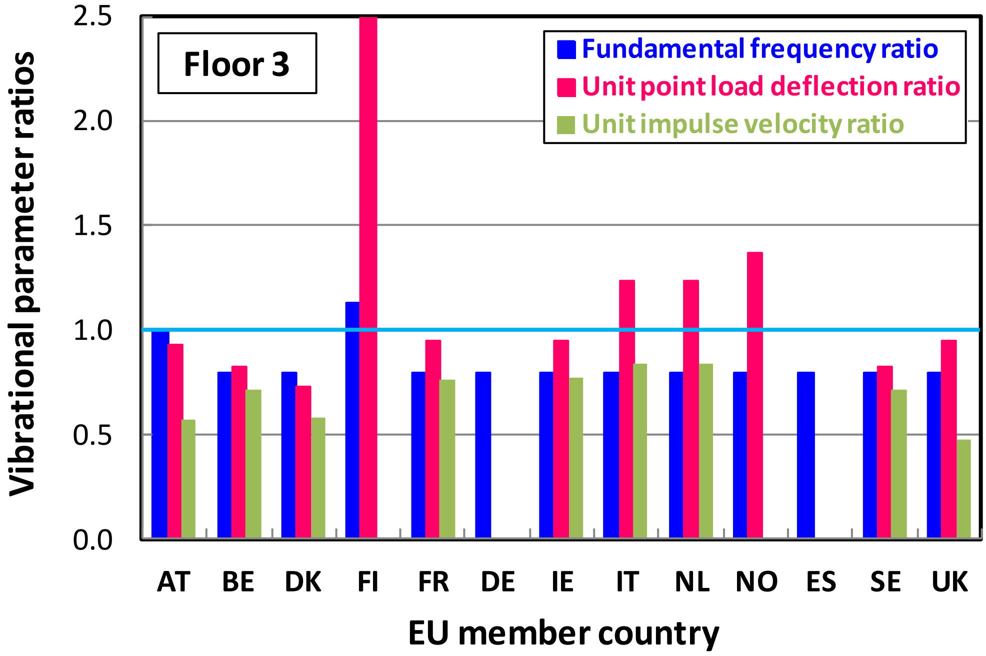
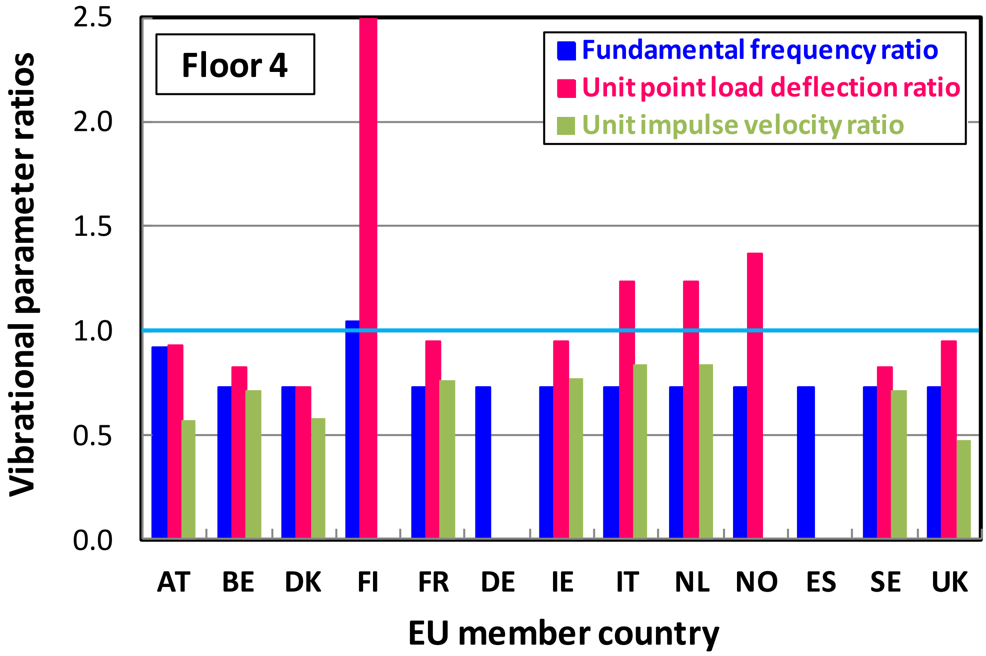


Fig. 17: Velocity ratios for JJI-Joist floors



(a) Floor 3 with *L* = 5.4 m



(b) Floor 4 with *L* = 7.3 m

Fig. 18: Vibrational parameter ratios for Floors 3 and 4

Fig. 19: Metal web joists (Mitek Posi-Joists)

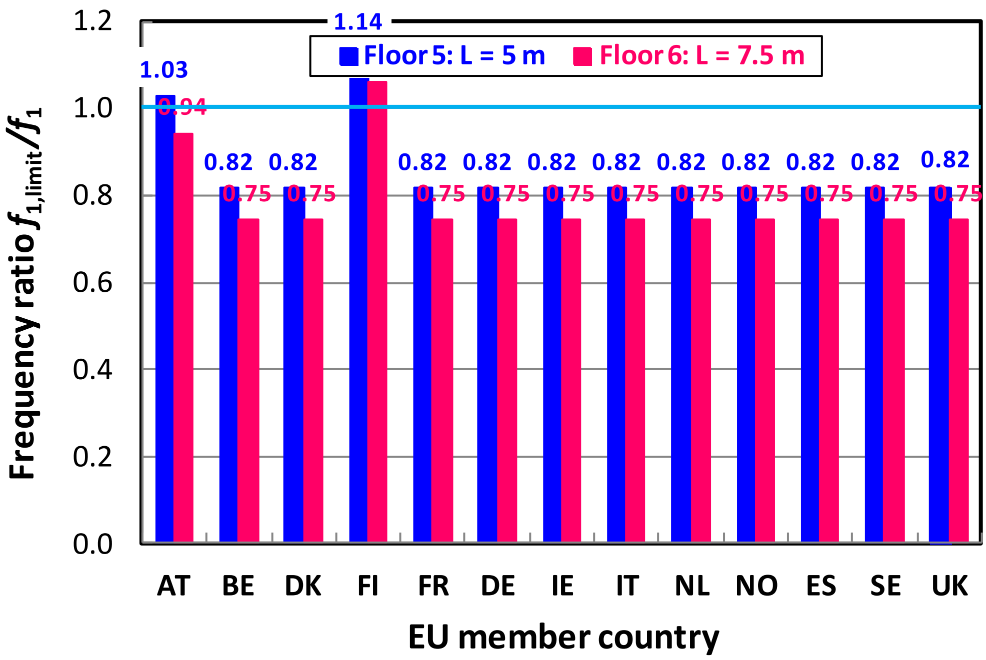


Fig. 20: Frequency ratios for Posi Joist floors

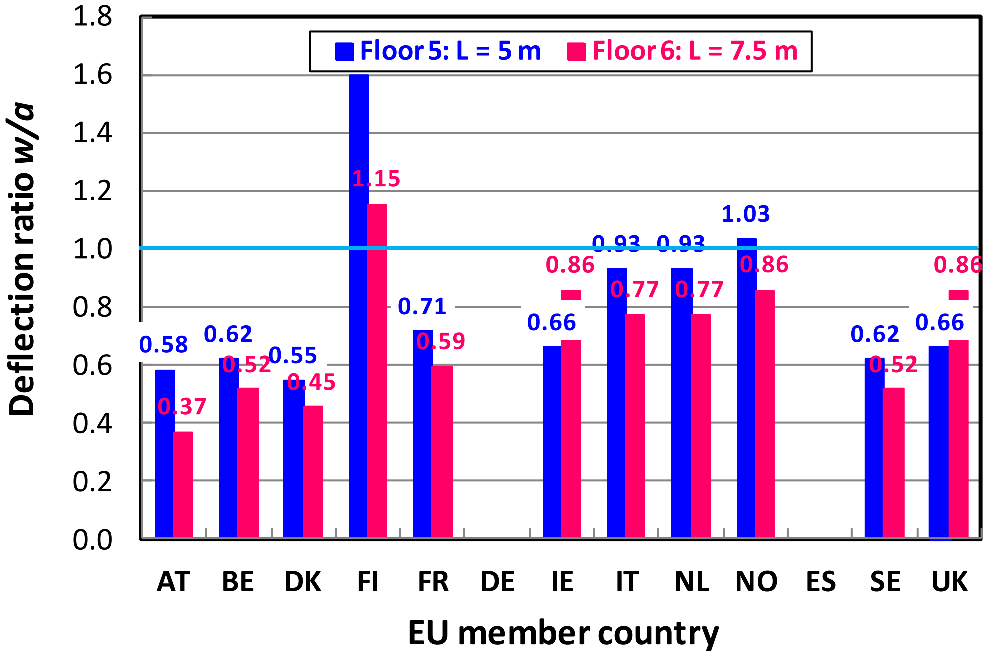


Fig. 21: Deflection ratios for Posi Joist floors

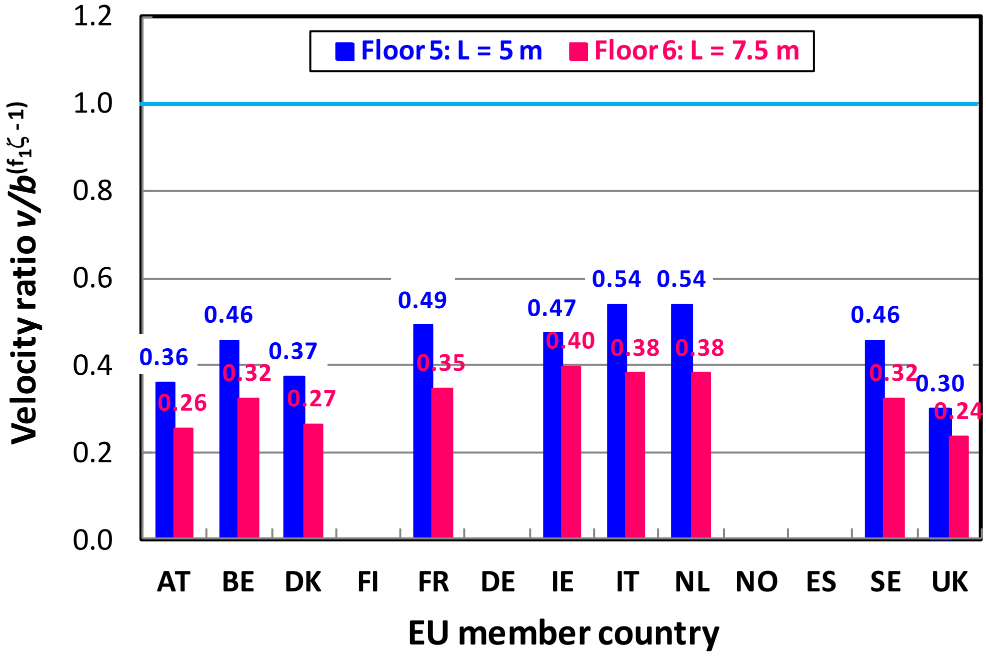
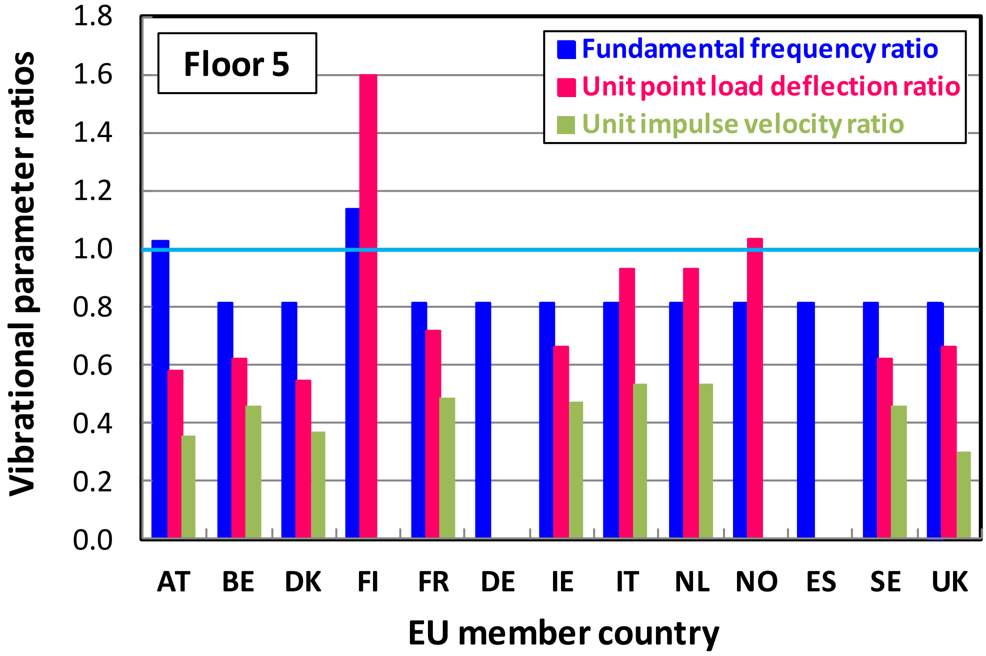
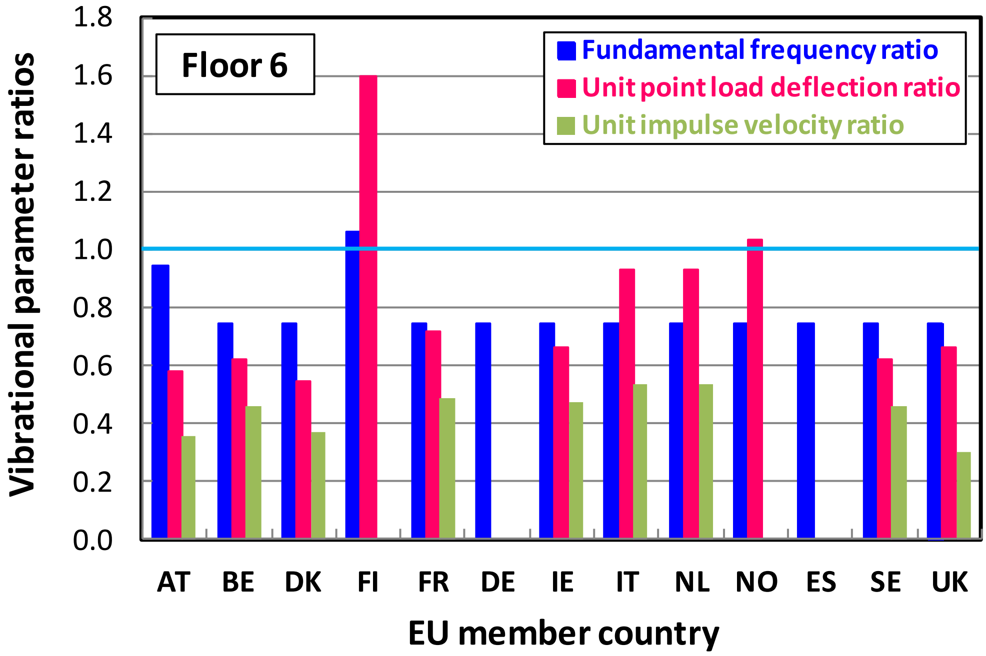


Fig. 22: Velocity ratios for Posi Joist floors



(a) Floor 5 with L = 5 m



(b) Floor 6 with L = 7.5 m

Fig. 23: Vibrational parameter ratios for Posi joist floors

CHAPTER 4
ACOUSTIC DESIGN OF LIGHTWEIGHT TIMBER FRAME CONSTRUCTIONS

COST Action FP0702

Net-Acoustics for Timber based Lightweight Buildings and Elements

Working Group 4: Building acoustics design

CONTENTS

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Last but not least, we would like to thank IWT for the research project 'optimisation of light weight timber frame constructions AH+' without which it would not have been possible to do this work.

This text is intended for acousticians with less experience in lightweight timber frame construction technology and for people with little background in acoustics working in the building sector with lightweight timber frame constructions. Relatively simplified acoustic concepts will be used to explain how things work acoustically and why the use of some concepts is advised and the use of others might not be such a good idea.

Disclaimer:

This document illustrates the state of the art solutions for buildings using timber and wood materials to achieve satisfactory sound insulations based on research and experience to-date. It is recommended that implementation of the solutions provided in this document, be checked and/or validated with the installation specifications of the various materials with respect to other requirements, such as allowable maximum deformation, moisture stability, etc. Furthermore, in critical situations or when you need assurance or written documentation that the design you have chosen to use meets the specific country regulations, we strongly recommend you engage the services of an acoustical consultant to assist you.

1 - INTRODUCTION

The use of wood for building is growing. This evolution is pushed by the Kyoto protocol. Wood construction presents numerous strong points for sustainability: it allows for CO2 storage, it is a renewable raw material, it provokes only small construction waste on site and it requires little energy to produce. There are other several more pragmatic reasons why lightweight timber frame constructions (abbreviated as LWTF further in the text) are increasing their market share to the detriment of heavy constructions: prefabrication, speed of assembly, new architectural tendencies (fashion trends), and not in the least the possibility of increasing the thermal insulation layers in the façade walls without increasing the traditional thickness of the façades.

In this way lightweight timber frame constructions are becoming ever more popular for free standing or terraced single family houses in Europe. But the share of single family housing in the number of dwellings is diminishing in many European countries: the cost of building plots and construction is rising, transport problems are stimulating people to settle near city centres, public authorities favour the urbananistic approach of more densely built environments to safeguard open spaces and to limit infrastructure costs etc. The dwindling share of single family houses in the construction market, the increase in number of competitors and the growth in size of many of these companies, are pushing LWTF companies to start building other projects than just single family houses. The use of LWTF in multifamily constructions is a fairly recent phenomena in almost all European countries (starting around 1990), even in those with a strong LWTF- tradition for the construction of single family houses.

Thermal insulation is a hot topic and most manufacturers focus on these issues. For single family houses in a quiet environment, this is indeed not a problem. But when it comes to terraced houses or apartments, acoustic quality becomes a major challenge. Unfortunately there are not that many examples of acoustically successful apartment constructions using the LWTF-technology. At least when the goal is to offer a level of acoustic comfort similar to that found in acoustically well- designed heavy constructions.

In most European countries, acoustic requirements have been developed based on the performance of traditional, heavy constructions. Requirements in most countries are based on evaluations of the acoustic performance from the 100 Hz third octave band upwards. Though there is an increasing need to look at the performance of the building below 100 Hz, even for traditional heavy buildings, this is an absolute necessity for lightweight constructions. For the latter it is much more difficult to obtain a performance comparable to that of heavy construction in the third octave bands below 100 Hz. The performance of LWTF constructions in the low frequencies is determined by the acoustic laws for 'double wall constructions'. These are characterized by mass-spring-mass resonances (see further in the text) and modal behaviour below 100 Hz, causing serious dips in the sound insulation in this frequency area.

Although these resonances can also occur in heavy constructions (due to linings, floating floors…), this is far less a problem. Taking in account the measurement reproducibility difficulties in the frequency bands below 125 Hz, most European countries with a tradition of heavy constructions (with the exception of Sweden) opted in the past for requirements that do not take in account the performance below 100 Hz, although this is still very audible for inhabitants (see the reports of WG2 and WG3). This is pretty dangerous for inhabitants of lightweight timber frame constructions: although the LWTF building complies with the acoustic requirements, this is still no guarantee for an acoustic comfort as good as in heavy buildings that also comply with the requirements!

So an 'acoustically good' lightweight timber frame construction is not just a construction that complies with the acoustic requirements. It should be a construction that offers at least the same "experienced" acoustic quality as that of acoustically well designed heavy constructions.

Airborne sound insulation between dwellings – Main requirements in 24 European countries.[a,b]

Country	Descriptor[c]	Multi-storey housing Req. (dB)	Row housing Req. (dB)
Austria	$D_{nT,w}$	≥55	≥60
Belgium	$D_{nT,w}$	≥54	≥58
Czech Rep.	R'_w	≥52	≥57
Denmark	R'_w	≥55	≥55
Estonia	R'_w	≥55	≥55
Finland	R'_w	≥55	≥55
France	$D_{nT,w} + C$	≥53	≥53
Germany[i]	R'_w	≥53[g]	≥57
Hungary	$R'_w + C$	≥51	≥56
Iceland	R'_w[e]	≥52[h]	≥55
Ireland	$D_{nT,w}$	≥53[g]	≥53
Italy	R'_w	≥50	≥50
Latvia	R'_w	≥54	≥54
Lithuania	$D_{nT,w}$ or R'_w	≥55	≥55
Netherlands	$I_{lu;k}$[d]	≥0	≥0
Norway	R'_w[f]	≥55[f]	≥55[f]
Poland	$R'_w + C$	≥50[g]	≥52[h]
Portugal[i]	$D_{n,w}$	≥50	≥50
Slovakia	R'_w	≥52	≥52
Slovenia	R'_w	≥52	≥52
Spain	$D_{nT,w} + C_{100-5000}$	≥50	≥50
Sweden	$R'_w + C_{50-3150}$	≥53	≥53
Switzerland	$D_{nT,w} + C$	≥52[j]	≥55
UK[k]	$D_{nT,w} + C_{tr}$	≥45	≥45

Notes:

[a] Study carried out in 2008. Data verified April 2008.
[b] Overview information only. Detailed requirements and conditions are found in the building codes.
[c] No generally applicable conversion between the different descriptors exists, as the relations depend on characteristics of rooms and constructions. Exact conversion can only be made in every specific case.
[d] $I_{lu;k} = R'_w + C - 52$ dB. Ref. [29].
[e] In addition to the rating procedure described in ISO 717, the Icelandic building regulations prescribe maximum 8 dB unfavourable deviation.
[f] It is recommended that the same criteria are fulfilled by $R'_w + C_{50-5000}$.
[g] Horizontal, requirement for vertical is 1 dB higher (Germany and Poland)/lower (Ireland).
[h] 55 dB recommended.
[i] Under revision, use of $D_{nT,w}$ has been proposed.
[j] Flats for rent. If owned by occupants, the criterion is the same as for row housing.
[k] England and Wales only. Scotland and Northern Ireland use different descriptors and performance levels.

Impact sound insulation between dwellings – Main requirements in 24 European countries.[a,b]

Country	Descriptor[c]	Multi-storey housing Req. (dB)	Row housing Req. (dB)
Austria	$L'_{nT,w}$	≤48	≤43
Belgium	$L'_{nT,w}$	≤58[g]	≤50
Czech Rep.	$L'_{n,w}$	≤58	≤53
Denmark	$L'_{n,w}$	≤53	≤53
Estonia	$L'_{n,w}$	≤53	≤53
Finland	$L'_{n,w}$[f]	≤53[f]	≤53[f]
France	$L'_{nT,w}$	≤58	≤58
Germany[j]	$L'_{n,w}$	≤53	≤48
Hungary	$L'_{n,w}$	≤55	≤45
Iceland	$L'_{n,w}$[e]	≤58[h]	≤53
Ireland	$L'_{nT,w}$	≤62	None
Italy	$L'_{n,w}$	≤63	≤63
Latvia	$L'_{n,w}$	≤54	≤54
Lithuania	$L'_{n,w}$	≤53	≤53
Netherlands	I_{co}[d]	≥ +5	≥ +5
Norway	$L'_{n,w}$[f]	≤53[f]	≤53[f]
Poland	$L'_{n,w}$	≤58	≤53
Portugal[j]	$L'_{n,w}$	≤60	≤60
Slovakia	$L'_{n,w}$	≤58	≤58
Slovenia	$L'_{n,w}$	≤58	≤58
Spain	$L'_{nT,w}$	≤65	≤65
Sweden	$L'_{n,w} + C_{I,50-2500}$	≤56[i]	≤56[i]
Switzerland	$L'_{nT,w} + C_I$	≤53[k]	≤50
UK[l]	$L'_{nT,w}$	≤62	None

Notes:

[a] Study carried out in 2008. Data verified April 2008.
[b] Overview information only. Detailed requirements and conditions are found in the building codes.
[c] No generally applicable conversion between the different descriptors exists, as the relations depend on characteristics of rooms and constructions. Exact conversion can only be made in every specific case.
[d] $I_{co} = 59 - (L'_{nT,w} + C_I)$ dB $\approx 70 - L'_{nT,w}$ dB for bare concrete floors or $I_{co} \approx 59 - L'_{nT,w}$ dB for other floors like wooden floors, floating floors and floors with soft coverings. Ref. [29].
[e] In addition to the rating procedure described in ISO 717, the Icelandic building regulations prescribe maximum 8 dB unfavourable deviation.
[f] It is recommended that the same criteria are fulfilled by $L'_{n,w} + C_{I,50-2500}$.
[g] From "non-bedrooms" outside the dwelling to a bedroom ≤ 54 dB is required.
[h] 53 dB recommended.
[i] The same criteria shall also be fulfilled by $L'_{n,w}$.
[j] Under revision, use of $L'_{nT,w}$ has been proposed.
[k] Flats for rent. If owned by occupants, the criterion is the same as for row housing.
[l] England and Wales only. Scotland and Northern Ireland use different performance levels.

Figure1: acoustic requirements in Europe for impact and airborne sound insulation. (Data from Birgit Rasmussen, SBi Danish Building Institute, Aalborg University. Published in Applied Acoustics, no° 71-2010 with the title 'Sound insulation between dwellings – Requirements in building regulations in Europe', pages 373-385.)

Sufficient impact sound insulation and the realisation of satisfying comfort against vibrations in particular appear to be the major challenges. People often complain about buzz or, the almost thunderous sound of someone walking on the floor above. They also complain about the possibility of hearing from where to where someone is walking. Some research shows that the evaluation should go below 50 Hz to explain all of this and to obtain a real description of the acoustic comfort.

But there is also positive news: if the construction allows for similar comfort in the low frequency bands as with heavy constructions, then it will generally offer a much better comfort in the middle and high frequency bands than do heavy constructions, due to the more steep increase in sound insulation with this technology.

All of this has serious consequences on the choice and adaptation of single ratings and measurement techniques. One can even wonder whether it will really be possible to evaluate the acoustic comfort using the same quantity for LWTF and heavy constructions. More information about these problems can be found in the reports of WG 2 and WG 3.

That leaves us, the regulators and the building industry, with some major problems and open questions: *with what measurements should I express the performance of my building to get a good comparison with the comfort of heavy constructions? How high should this performance be to get satisfied customers? How should I build this (robust details?)?* As long as these 'quality' questions remain unanswered, *building multifamily homes in lightweight timber frame remains difficult.*

Market competition can be disturbed by the distance between, on the one hand, an industry trying to build acoustically comfortable houses, and on the other hand people who just want to comply with the acoustic requirements, even knowing that they are inappropriate for LWTF constructions. The latter will create a bad image of the LWTF multifamily home and that is just something we want to avoid.

Many construction models available now in Europe focus only on the existing requirements. Some of these models are discussed below, but their acoustic quality very often dissatisfies inhabitants. The goal of the following chapters is to give an idea of the different construction methods, junctions between building elements and the construction of the building elements. This should allow for the experts in the development of acoustic prediction methods to see what kind of constructions and junctions need to be simulated. For building industry it should offer some explanation why some things work and others just don't. The document also aims to give an overview of 'do's and don'ts' as well as some examples of innovative ideas and solutions. As long as it is unclear what kind of performance should be obtained to get x% satisfied customers, this document does not seek to give THE instructions of how to build an acoustic optimized lightweight timber frame construction. *What we can try to do is to improve existing concepts to get as high as possible acoustic performances while still being in accordance with the other boundary conditions for a well-conceived building (see next chapter).* And of course a document like this is just a snapshot of the actual state of the art; it can never be complete and necessarily refers to on-going work and to databases of performances available on the internet.

2 - GENERAL BUILDING METHODS AND BOUNDARY CONDITIONS

2.1 - General building methods

Lightweight timber frame constructions can be completely built on site, but most lightweight timber frame constructions are made of prefabricated building elements such as walls, floors, etc. that are assembled on site. In some cases, complete rooms or even several rooms are manufactured in an industrial plant and assembled together on the building site. Prefabrication allows for significant cost reductions and for a better quality control in an industrial manufacturing environment. Building time on site can be greatly reduced and is less influenced by weather conditions.

A limited crimp (max 1 cm) is one of the advantages of the lightweight timber frame constructions compared to solid wooden constructions. Crimp in wooden beams occurs due to a reduction in moisture content and takes place perpendicular to the orientation of the wood fibres, i.e. in the width or thickness of the beams and columns. So the crimp in height happens only in horizontal beams and not in the height of the columns and thus remains limited.

Three main prefabricated building methods can be distinguished in Europe:

In the **platform-frame** method, floor elements are fixed on top of the walls of the lower floor and are most often continuous over different rooms. As such, these floors become a working platform for the construction of the next building layer. This is the standard approach in lightweight building frame construction in Europe.

In the **balloon-frame** method (or 'Chicago method'), walls are continuous over many storeys and the floors are hung between these walls. Though this method offers advantages for a better air tightness of the building, it is less used nowadays because of construction limitations in height, prefabrication problems and difficulties in the mounting of the construction on site.

Some mixed balloon/platform-frame methods exist in which the floors are fixed into notches in the walls.

The **box-assembly** method prefabricates box-like elements that are fitted together to realise a complete building. Each box can contain one or several rooms and is very often finished to a large degree in a manufacturing plant so that the work on site is limited to a strict minimum. Transportation costs and difficulties can be the main handicap for this building approach.

Lightweight timber frame constructions can be combined with other traditional constructions and are often used in the retrofitting of buildings or to add additional storeys on existing traditional heavy constructions. There are also all kind of hybrid constructions with e.g. a load carrying steel frame and lightweight timber frame fill-up elements.

Building with wood can also incorporate 'solid wooden' constructions. There are also a large variety of these kinds of building solutions. Some use massive wooden load carrying panels made of cross laminated timber; other 'solid wooden' constructions use superposed beams (e.g. pin and groove fixations) to build walls. The latter need specific solutions to cope with major crimp problems (the accumulation of the crimp in height of each wooden beam). 'Solid wooden' building constructions are not part of the major scope of this COST program and will only sporadically be treated in the following chapters.

The type of building method determines the junctions and will have important consequences for the flanking transmission between adjacent rooms.

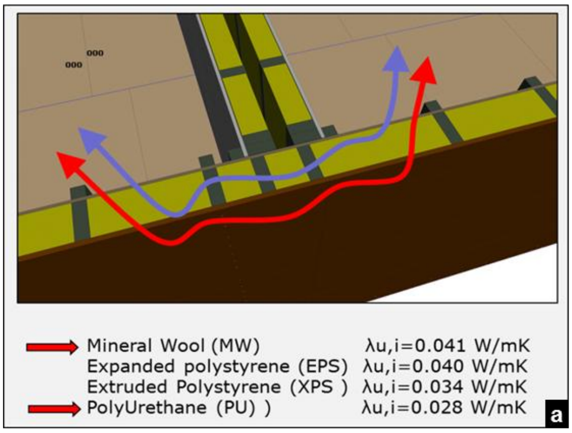
Figure 2: typical examples of light-weight timber frame constructions and junctions used in free-standing houses. Extending this technology towards terraced houses requires some adaptations but the challenges are huge for building apartment constructions.

2.2 - Boundary conditions and possible conflicts with acoustic optimisation

Building is necessarily a technically multidisciplinary activity. The acoustician is therefore used to being confronted with constraints. But in LWTF construction the acoustic challenges are much greater than with heavy constructions and the interactions with other disciplines such as stability requirements, thermal regulations, fire requirements and other can make it particularly difficult to attain goals. In the upcoming pages, ideal acoustic solutions are sometimes impossible because of these constraints and compromises are often necessary. Just let us have a look at some of these constraints that we will encounter.

2.2.1 - Thermal insulation

Most European countries have energy performance requirements and many architects want to go beyond these criteria (e.g. passive houses, o-energy dwellings…). Architects are therefore most inclined to choose the most favourable thermal insulation materials. Unfortunately, PU and EPS have better thermal performances than good acoustic absorption products such as cellulose, mineral wool etc. The use of these rigid, non-porous materials can be extremely problematic for the acoustician leading to a lack of façade sound insulation for vertical walls and roofs. The weak sound insulation of vertical façades and roofs can lead to additional flanking transmission or indirect airborne transmission paths (see red arrows in figure 3 'a').



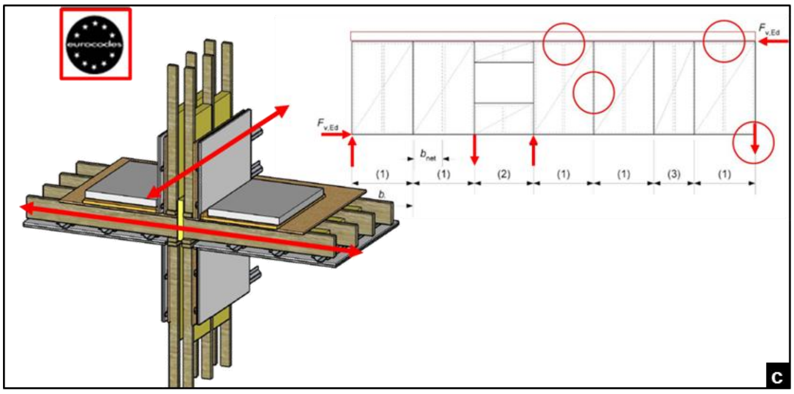


Figure3: some boundary constructions creating problems to optimise the acoustical performance of lightweight timber frame constructions

2.2.2 - The problematic 'idea' of the independence of each terraced house.

An apartment construction is everywhere considered as an entity. But in some countries, blocks of terraced houses are not considered as single building entities, but are required to stand alone after the demolition of the adjacent dwelling. This way of thinking can be criticised, as probably many non-acoustical problems will arise once only one house remains: what about water-tightness, sufficient thermal insulation, hygrothermal effects, aesthetic look….? So if and when the other house were to disappear, inevitably actions would have to be undertaken to create this independence of the remaining dwelling. This 'idea' or even requirement creates some serious low frequency issues (see 'party walls', section 3): wide cavities, good for low frequency sound insulation, are for these reasons difficult to achieve.

2.2.3 - Fire requirements

Fire requirements will largely influence the concept of walls and floors as well as the materials being used. Obvious acoustic solutions are therefore not always applicable. Requirements differ all over Europe, but use in general European classification expressed in minutes ('REI': see figure 'a'). Requirements differ for terraced houses (in general only applicable for the party wall), low rise and high rise blocks.

The requirements for the party wall in terraced houses are in fact expressed for each portion of the party wall, belonging to one of the adjacent houses. The idea is that when one of the houses is on fire, the collapse of one of its floors can work as a lever and provoke the collapse of the burning house or at least destroy its part of the party wall (see figure 4 'c'). The collapse of one house will result in a large fire attacking the adjacent house and its remaining part of the party wall. Most countries require a fire resistance of at least one hour for each part of the party wall (i.e. that part that belongs to each house separately). This explains (together with the reasons expressed in (1)) why LWTF constructions in many countries use extra boards in the cavity, although this is not favourable for the low frequency sound insulation.

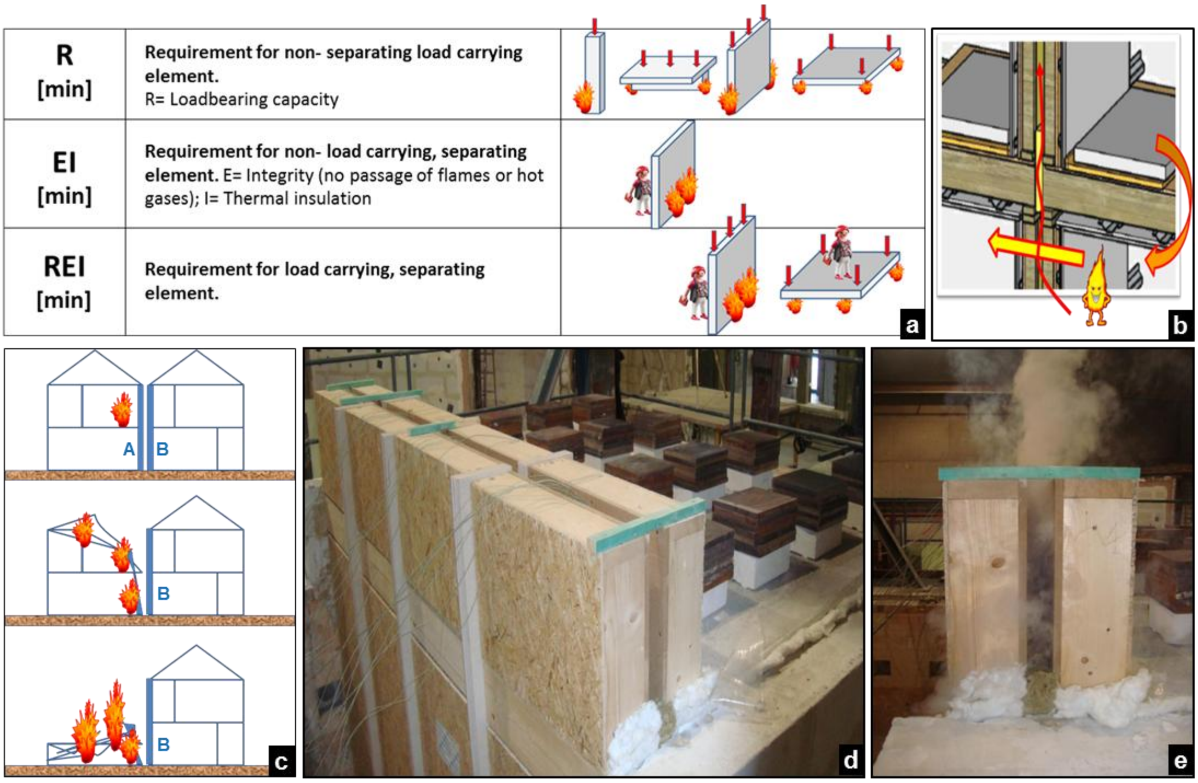


Figure 4: fire and the corresponding requirements have a major impact on how LWTF are conceived. This often leads to choices not very favourable for a good acoustic performance.

Fire requirements in apartments are far more severe and concern all load carrying walls, floors and party walls. In general at least an R or REI 60 is required. The situation is even more complex when a single family house (eventually part of a series of terraced houses) is adjacent to an apartment building. As party walls always exist as a double wall (called wall portions A and B below) with a central cavity, we can give a summary of requirements for party walls in the table below:

Situation	Wall portion (for fire attacking from the inside of the central cavity)	Wall portion (for fire attacking from the inside of the dwelling)
Between two terraced houses	REI 60 to 90 for walls A and B(# of minutes depending on the country)	'/
Between two apartments	'/	REI > 60 to 120 (# of minutes depending on the country)
Between a terraced house (e.g. left) and an apartment building (e.g. right).	REI 60 to 120 on the **side of the apartment, so only on wall portion B** (# of minutes depending on the country)	REI > 60 to 120 on the **side of the apartment** (# of minutes depending on the country)

To avoid chimney effects and fast spreading fire, cavities should be interrupted at least at each floor and all along the junction with the façades and adjacent apartments (see figure 4 'b' and the exploratory fire tests shown in figure 4 'd' and 'e').

Figure 5: automation and large industrial scale production has consequences for assembling techniques and acoustic concepts.

2.2.4 - Structural engineering

Structural engineering determines largely the LWTF concept. The building is not only subject to vertical, gravitational forces: horizontal forces due to wind load and earthquake resistance are major factors in the structural concept. This can cause problems with acoustical optimisation using continuous cavities from foundations to roofs between apartments and terraced houses. Perfect decoupling between apartments or the use of elastic interlayers will also be difficult for these reasons. Because of these shear and vertical forces, boards cannot be fixed in the acoustically optimized way of resilient fixing (using for example, additional resilient channels perpendicular to the studs): to increase the load-bearing capacity of LWTF walls, wood panels are today very often not only screwed to the studs but equally glued increasing the linear contacts and rigidity of the walls (radiation efficiency)

2.2.5 - Industrial production

Last but not least: fabrication can have positive (quality control) and negative effects on acoustic optimisation. The wish to maximize production in factory halls (with robots and automation) and minimize work in situ, has consequences on concepts. The acoustic technology that uses resilient metal channels and studs is a technique typically for in situ finishing. Manufacturers will go for lesser alternatives allowing easier transport and production in factory halls preferring staples in wooden studs to screwing in metal studs (see figure above).

2.3 - Comparison with heavy constructions

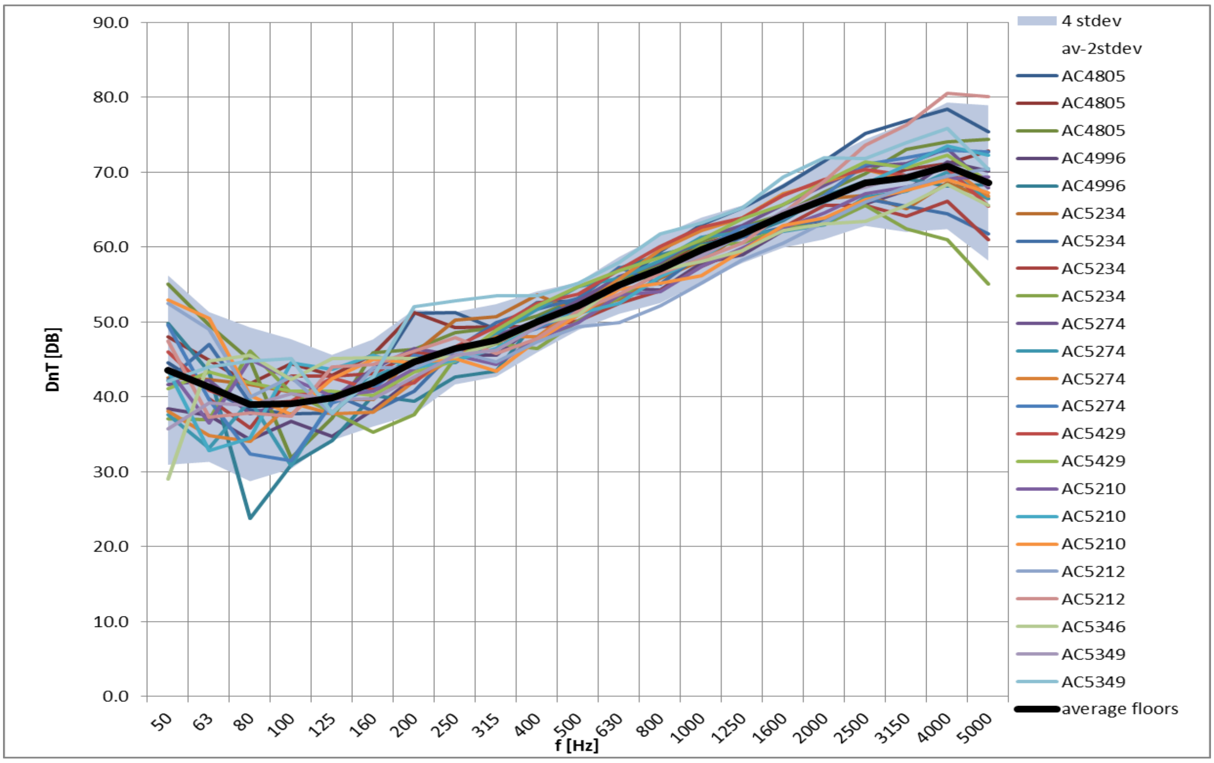
Although an acoustic study is being carried out now in the Scandinavian countries of LWTF constructions and the feeling of satisfaction with regard to acoustic comfort, no results are yet available (project ACULITE).

But people and acousticians know what to expect as acoustic comfort in heavy constructions. One could say that an acoustically good heavy construction will be the reference for inhabitants once they move to a lightweight timber frame construction. . As there is no real agreement on a single rating that could express, at a same absolute value, identical acoustic comfort in both lightweight and heavy constructions, it is vital to compare performances via / across insulation spectra. We propose for this report to confront insulation spectra between light and heavy weight constructions for some in situ and mock-up measurements. This allows also for a better understanding of the typical problems and challenges LWTF are confronted with.

2.3.1 - Vertical sound insulation

For vertical sound insulation, the most critical one in LWTF constructions, an analysis is made based upon field surveys of traditional floating floors in typical heavy built apartments in Belgium. All constructions have complied with a minimal requirement of $D_{nT,w}$>54 dB and

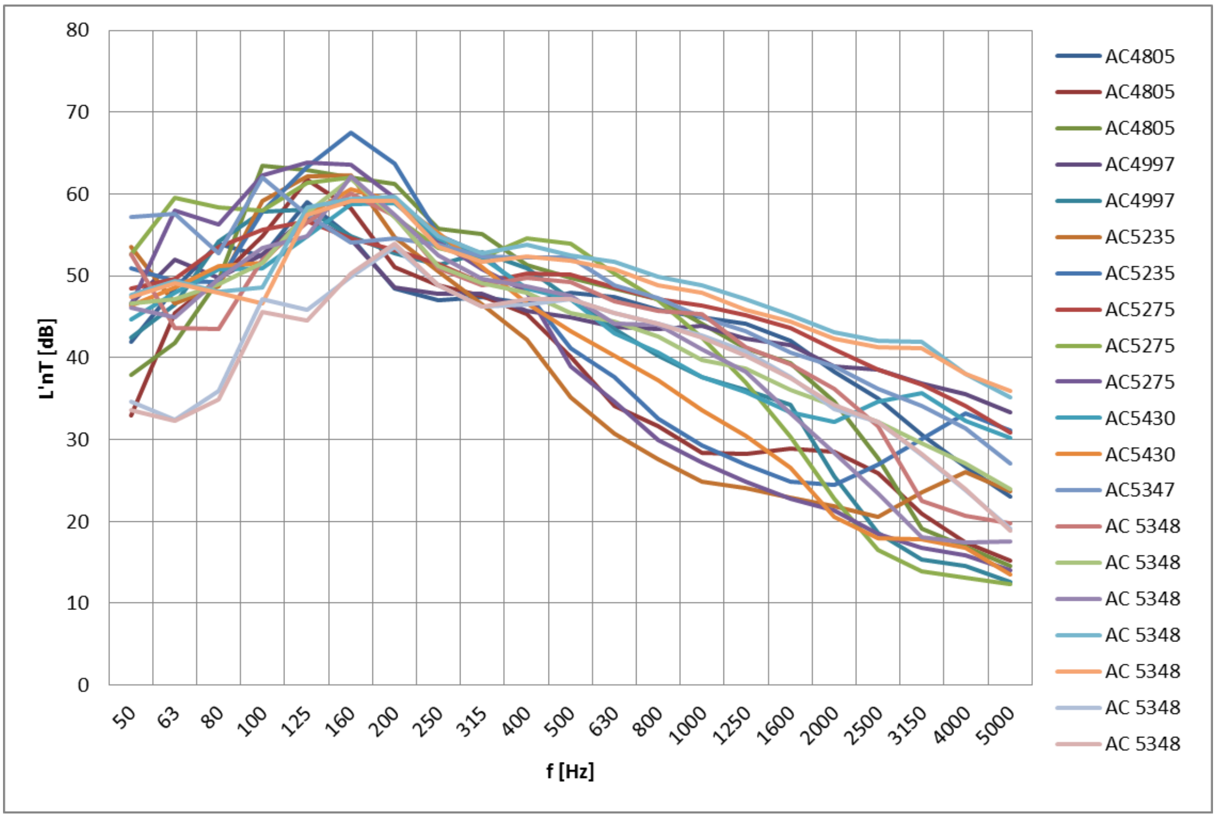
$L'_{nT,w}$ < 54 dB. No real inhabitants' satisfaction enquiry has been made, but there have been no complaints about the sound insulation for these constructions.



Graph 1: Different standardised level difference D_{nT} measured in situ on 23 well-executed traditional floating floors in Belgium. In the shaded zone, 95% of the measured values are situated.

In graph 1 and 3, the results are shown for airborne sound insulation performance while graph 2 and 4 analyse the impact sound level data. The average value for the weighted standardised level difference $D_{nT,w}$ is 57 dB ($D_{nT,w}$+$C_{50-5000}$ = 51 dB). The average spectrum will be used as some kind of reference graph for vertical airborne sound insulation DnT measured in some mock-up measurements with LWTF constructions. The average value for the weighted standardised impact sound pressure level $L'_{nT,w}$ is 48 dB ($L'_{nT,w}$+$C_{I,50-2500}$ = 49 dB). The average graph will likewise be used as reference graph for the impact sound insulation for in situ measurements.

The fact that the insulation graph for some LWTF construction is lower than the reference graph for the massive construction *does not necessarily mean that there is a lack of acoustic comfort.* More detailed psycho- acoustic studies and surveys should find out about this. *It only means that there can be reason to worry*. On the other hand, if the graph is everywhere above the reference graph, it probably shows good acoustic comfort. Comparing both graphs is also interesting to show the different acoustic behaviour of LWTF constructions compared to heavy weight constructions.



Graph 2: Average spectrum of the standardised impact sound pressure level L'_{nT} measured in situ on 20 well-executed traditional floating floors in Belgium.

The typical floor constructions are as follows (from bottom to top):

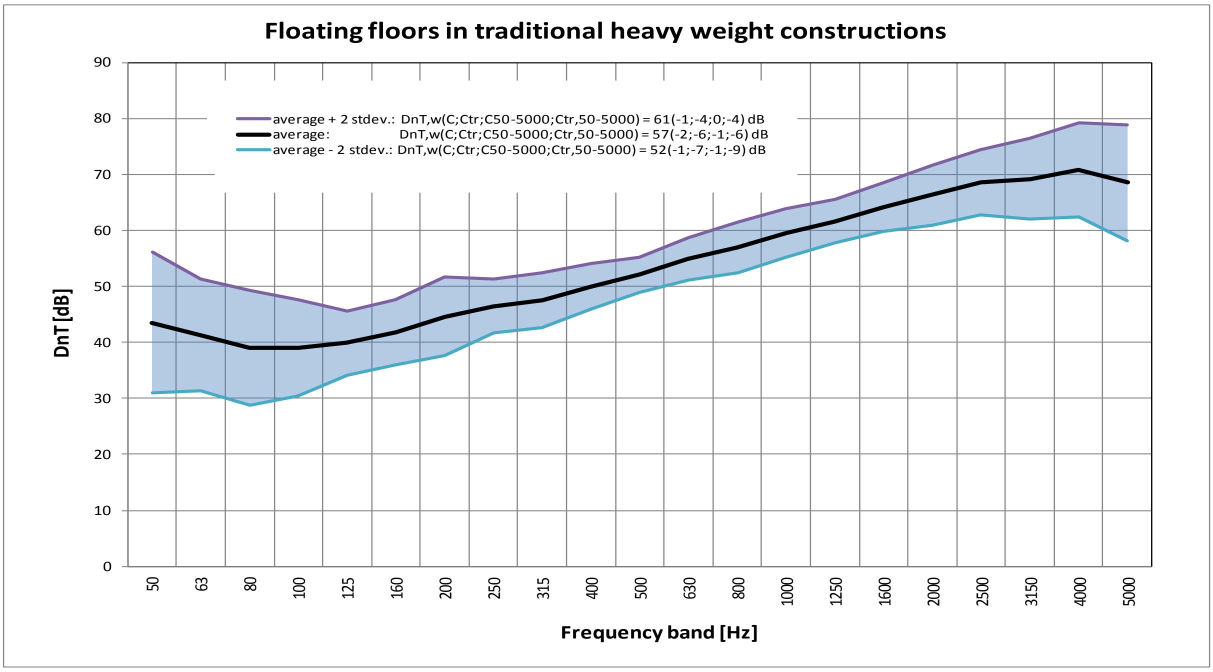
Base floor

- Type 1: 20 to 26 cm concrete, 4-5 cm cement-bounded levelling layer
- Type 2: 13 cm hollow-core concrete elements, 3 cm compression layer, 6 cm porous concrete levelling layer
- Type 3: 20 cm concrete, 3 cm PU foam, 2 cm Polyether foam

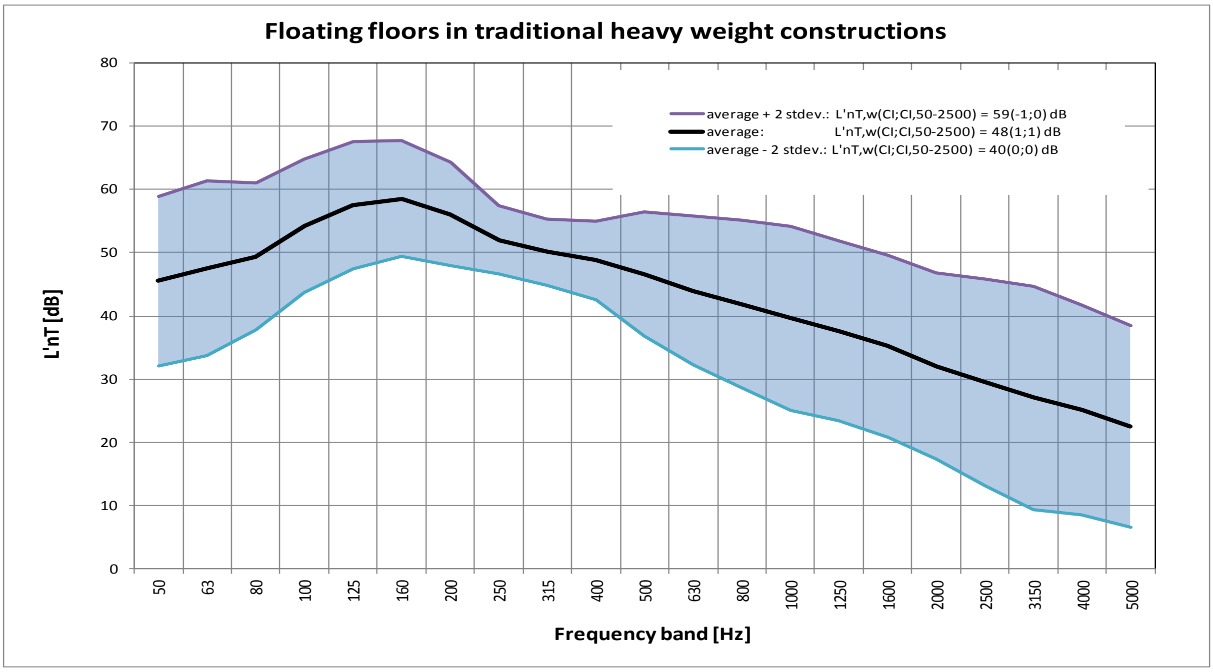
Resilient layer (only on type 1 and type 2 base floors): 3+3 mm, 5+3mm or 5+5 mm extruded PE membranes

Floating screed: 7 to 8 cm cement-bounded

Floor finishing: tiling or parquet



Graph 3: Average spectrum of the standardised level difference D_{nT} measured in situ on 23 well-executed traditional floating floors in Belgium. 95% of the measured values are situated inside the shaded zone.



Graph 4: Average spectrum of the standardised impact sound pressure level L'_{nT} measured in situ on 20 well-executed traditional floating floors in Belgium. 95% of the measured values are situated inside the shaded zone.

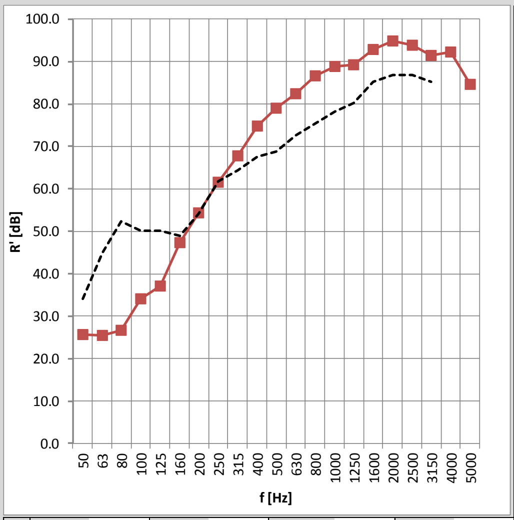
Since the data in both figures is largely based on the same set of floors, it is remarkable that the spread in impact sound level measurements largely exceeds the spread in airborne sound insulation measurements, especially at mid- and high frequencies. This points to the fact that impact sound insulation is particularly sensitive to small variations/errors during execution.

2.3.2 - Horizontal sound insulation

The sound insulation requirements between terraced houses are in several European countries higher than for apartments. The expectations of inhabitants are in general higher as well. In many countries, the sound insulation is solved by the use of tie-less double wall constructions with a complete decoupling from the foundations until the roof. This results in very high sound insulations. Impact noise is then no problem, except at the lowest floor if building guidelines are not well followed (floating floor necessary, special measures to be taken for foundations and concrete slabs). Low–rise apartment buildings most often use the same technique for common walls between apartments.

LWTF-constructions discussed in the next chapters also use techniques of complete horizontal decoupling between apartments and terraced houses.

Unfortunately, we do not dispose of a similar study as the one for the performance in the vertical direction. We will just use a typical result for the sound insulation in the horizontal direction of a construction with two typical brick walls of 14 cm (1200 kg/m³) and a cavity of 4 cm, partly filled up with 2 cm of glass wool. Similar constructions are most often used between apartments. If well executed, these constructions offer sound insulations that are far above what is required. LWTF constructions should not attain such high sound insulations to be good. So if the reference graph is shown, the only purpose is to show the different shape of the insulation graph of the LWTF –construction compared to the heavy weight tie-less wall. A lower LWTF-insulation graph than the reference graph for these horizontal insulations does not say anything about eventual acoustic discomfort.



f [Hz]	1	2
50	25.7	34.1
63	**25.5**	**44.9**
80	26.7	52.3
100	34.0	50.1
125	**37.0**	**50.1**
160	47.3	48.8
200	54.3	54.2
250	**61.6**	**61.7**
315	67.8	64.3
400	74.9	67.5
500	**79.1**	**68.7**
630	82.5	72.7
800	86.7	75.4
1000	**88.8**	**78.3**
1250	89.3	80.3
1600	92.8	85.2
2000	**94.9**	**86.7**
2500	93.9	86.9
3150	91.5	85.2
4000	**92.3**	
5000	84.6	

1	R'_{living}= 56 dB	$C_{50-5000}$= -9 dB	$C_{100-3150}$= -6 dB	R'_w= 65 dB
2	R'_{living}= 68 dB	$C_{50-5000}$= -2 dB	$C_{100-3150}$= -2 dB	R'_w= 70 dB

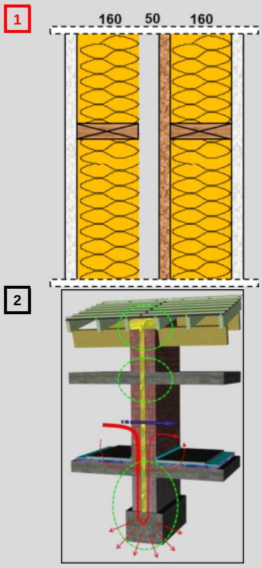
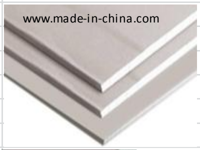
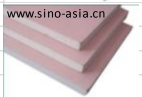
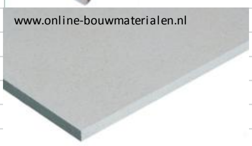
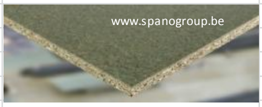
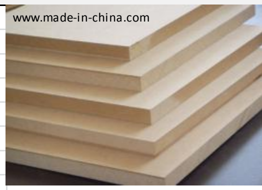
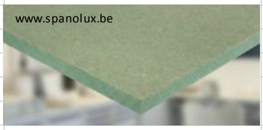


Figure 6: comparison between the sound insulation R' of two compartment walls: (1) of a lightweight timber frame wall; (2) of a traditional tie-less brick construction as a typical compartment wall between two terraced houses or apartments (reference graph)

2.4 - Characteristics of materials used in LWTF constructions

There are a large variety of boards available to be used in LWTF constructions. It is most useful to know there material properties, for instance for the calculations of mass-spring-mas resonance frequencies etc. In the last table, average densities were calculated for common used boards in LWTF constructions.

Gypsum board	dikte mm	ρ kg/m³	m" kg/m²	$E_\perp$ N/mm² (=MPa)	$E_{//}$ N/mm² (=MPa)	ν	c_L m/s	B' Nm	f_{gr} Hz			
Gypsum board												
standard	9.5	790	7.5		3530	0.5	2114	336	2797		Gyproc	Rigips Bauplatten 9.5
	9.5	740	7.0	> 2200	> 2800						Knauf	GKB A10
	12.5	760	9.5		3530	0.5	2155	766	2085		Gyproc	Rigips Bauplatten 12.5
	12.5	720	9.0	> 2200	> 2800						Knauf	GKB A13
	15	900	13.5								Knauf	GKB A15
	18	915	16.5								Knauf	GKB A18
fire resistant (RF)	12.5	808	10.1								Gyproc	RF 12.5
	12.5	840	10.5								Knauf	GKF 13
	15	866	13.0								Gyproc	RF 15
	15	900	13.5								Knauf	GKF 15
fibre reinforced	10	1150	11.5		3900						Knauf	Vidiwall
	12.5	1150	14.4		3900						Knauf	Vidiwall
	15	1150	17.3		3900						Knauf	Vidiwall
	10	1200	12.0	3500	4500						Gyproc	Rigidur
	12.5	1200	15.0	3500	4500						Gyproc	Rigidur
	15	1200	18.0	3500	4500						Gyproc	Rigidur
	10	1150	11.5								Fermacell	Gipsvezelplaat
	12.5	1150	14.4								Fermacell	Gipsvezelplaat
	15	1150	17.3								Fermacell	Gipsvezelplaat
	18	1150	20.7								Fermacell	Gipsvezelplaat
Particle board	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_\perp$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
standard	8	730	5.84		1800						Spano	Standard E1
	10	710	7.1		1800						Spano	Standard E1
	12	690	8.28		1800						Spano	Standard E1
	15	660	9.9		1600						Spano	Standard E1
	18	660	11.88		1600						Spano	Standard E1
	19	650	12.35		1600						Spano	Standard E1
	22	650	14.3		1500						Spano	Standard E1
	25	650	16.25		1500						Spano	Standard E1
	28	640	17.92		1350						Spano	Standard E1
	38	640	24.32		1200						Spano	Standard E1
moisture resistant	10	740	7.4		2550						Spano	Durélis/Populair
	12	720	8.6		2550						Spano	Durélis/Populair
	15	720	10.8		2400						Spano	Durélis/Populair
	18	720	13.0		2400						Spano	Durélis/Populair
	19	700	13.3		2400						Spano	Durélis/Populair
	22	700	15.4		2150						Spano	Durélis/Populair
OSB	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_\perp$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
OSB/2	9	600	5.4	1400	3500						Norbord	Sterling OSB/2 Zero
	11	600	6.6	1400	3500						Norbord	Sterling OSB/2 Zero
	12	600	7.2	1400	3500						Norbord	Sterling OSB/2 Zero
	15	600	9	1400	3500						Norbord	Sterling OSB/2 Zero
	18	600	10.8	1400	3500						Norbord	Sterling OSB/2 Zero
OSB/3	9	600	5.4	1400	3500						Norbord	Sterling OSB/3 Zero
	12	600	7.2	1400	3500						Norbord	Sterling OSB/3 Zero
	15	600	9.0	1400	3500						Norbord	Sterling OSB/3 Zero
	16	600	9.6	1400	3500						Norbord	Sterling OSB/3 Zero
	18	600	10.8	1400	3500						Norbord	Sterling OSB/3 Zero
	22	600	13.2	1400	3500						Norbord	Sterling OSB/3 Zero
	25	600	15.0	1400	3500						Norbord	Sterling OSB/3 Zero
OSB/4	12	620	7.4	1900	4800						Norbord	Sterling OSB/4 Zero
	15	620	9.3	1900	4800						Norbord	Sterling OSB/4 Zero
	18	620	11.2	1900	4800						Norbord	Sterling OSB/4 Zero
	22	620	13.6	1900	4800						Norbord	Sterling OSB/4 Zero
	25	620	15.5	1900	4800						Norbord	Sterling OSB/4 Zero

MDF	dikte mm	ρ kg/m³	m" kg/m²	$E_\perp$ N/mm² (=MPa)	$E_{//}$ N/mm² (=MPa)	ν	c_L m/s	B' Nm	f_{gr} Hz			
standard	6	800	4.8		3650	0.25	2136	70	4900		Spanolux	Standaard MDF LA
	7.5	780	5.9		3650	0.25	2163	137	3871		Spanolux	Standaard MDF LA
	9	750	6.8		3650	0.25	2206	237	3163		Spanolux	Standaard MDF LA
	10.5	740	7.8		3650	0.25	2221	376	2693		Spanolux	Standaard MDF LA
	12	730	8.8		3650	0.25	2236	561	2341		Spanolux	Standaard MDF LA
	15	720	10.8		3650	0.25	2252	1095	1860		Spanolux	Standaard MDF LA
	16	720	11.5		3650	0.25	2252	1329	1743		Spanolux	Standaard MDF LA
	17	720	12.2		3650	0.25	2252	1594	1641		Spanolux	Standaard MDF LA
	18	720	13.0		3650	0.25	2252	1892	1550		Spanolux	Standaard MDF LA
	19	720	13.7		3650	0.25	2252	2225	1468		Spanolux	Standaard MDF LA
	22	690	15.2		3650	0.25	2300	3455	1241		Spanolux	Standaard MDF LA
	25	690	17.3		3650	0.25	2300	5069	1092		Spanolux	Standaard MDF LA
	28	690	19.3		3650	0.25	2300	7122	975		Spanolux	Standaard MDF LA
	30	690	20.7		3650	0.25	2300	8760	910		Spanolux	Standaard MDF LA
moisture resistant	6	810	4.9		3000						Spanolux	MDF Umidax
	8	790	6.3		3000						Spanolux	MDF Umidax
	9	760	6.8		3000						Spanolux	MDF Umidax
	10	750	7.5		2800						Spanolux	MDF Umidax
	12	740	8.9		2800						Spanolux	MDF Umidax
	15	730	11.0		2700						Spanolux	MDF Umidax
	16	730	11.7		2700						Spanolux	MDF Umidax
	18	730	13.1		2700						Spanolux	MDF Umidax
	19	730	13.9		2700						Spanolux	MDF Umidax
	22	700	15.4		2600						Spanolux	MDF Umidax
	25	700	17.5		2600						Spanolux	MDF Umidax
	30	700	21.0		2600						Spanolux	MDF Umidax
fire retardant	6	820	4.9		3000						Spanolux	MDF Firax
	9	770	6.9		3000						Spanolux	MDF Firax
	10	760	7.6		2800						Spanolux	MDF Firax
	12	750	9.0		2800						Spanolux	MDF Firax
	15	740	11.1		2500						Spanolux	MDF Firax
	16	740	11.8		2500						Spanolux	MDF Firax
	18	740	13.3		2500						Spanolux	MDF Firax
	19	740	14.1		2500						Spanolux	MDF Firax
	22	710	15.6		2300						Spanolux	MDF Firax
	25	710	17.8		2300						Spanolux	MDF Firax
	30	710	21.3		2300						Spanolux	MDF Firax

Wood fibre cement board	dikte mm	ρ kg/m³	m" kg/m²	$E_\perp$ N/mm² (=MPa)	$E_{//}$ N/mm² (=MPa)	ν	c_L m/s	B' Nm	f_{gr} Hz			
	8	1250	10.0		4500						Eternit	Duripanel
	10	1250	12.5		4500						Eternit	Duripanel
	12	1250	15.0		4500						Eternit	Duripanel
	14	1250	17.5		4500						Eternit	Duripanel
	16	1250	20.0		4500						Eternit	Duripanel
	18	1250	22.5		4500						Eternit	Duripanel
	20	1250	25.0		4500						Eternit	Duripanel
	22	1250	27.5		4500						Eternit	Duripanel
	24	1250	30.0		4500						Eternit	Duripanel
	25	1250	31.3		4500						Eternit	Duripanel
	28	1250	35.0		4500						Eternit	Duripanel
	32	1250	40.0		4500						Eternit	Duripanel
	36	1250	45.0		4500						Eternit	Duripanel
	40	1250	50.0		4500						Eternit	Duripanel

Organic fibre cement board	dikte mm	ρ kg/m³	m" kg/m²	$E_\perp$ N/mm² (=MPa)	$E_{//}$ N/mm² (=MPa)	ν	c_L m/s	B' Nm	f_{gr} Hz			
	6	1417	8.5	10000	10000						Eternit	Hydropanel
	9	1411	12.7	10000	10000						Eternit	Hydropanel
	12	1417	17.0	10000	10000						Eternit	Hydropanel

Plywood board	dikte mm	ρ kg/m³	m" kg/m²	$E_\perp$ N/mm² (=MPa)	$E_{//}$ N/mm² (=MPa)	ν	c_L m/s	B' Nm	f_{gr} Hz			
	12	460	5.5	1200	8400						Finnforest	Spruce plywood
	15	460	6.9	2496	9504						Finnforest	Spruce plywood
	18	460	8.3	3111	8889						Finnforest	Spruce plywood
	21	460	9.7	3464	8536						Finnforest	Spruce plywood
	24	460	11.0	3563	8438						Finnforest	Spruce plywood
	27	460	12.4	4016	7984						Finnforest	Spruce plywood
	30	460	13.8	4224	7776						Finnforest	Spruce plywood

Cross laminated timber panels	dikte mm	ρ kg/m³	m" kg/m²	$E_\perp$ N/mm² (=MPa)	$E_{//}$ N/mm² (=MPa)	ν	c_L m/s	B' Nm	f_{gr} Hz			
	85	420									Finnforest	Leno
	100	400-550									Egoin	Ego_CLT
	100	470-500									KLH	
	75 - 217	470									HMS	
Wood fibre insulation board	**dikte mm**	**ρ kg/m³**	**m" kg/m²**	**$E_\perp$ N/mm² (=MPa)**	**$E_{//}$ N/mm² (=MPa)**	**ν**	**c_L m/s**	**B' Nm**	**f_{gr} Hz**			
	18	270	4.9								Celit	3D (wanden, vloeren)
	22	270	5.9								Celit	4D (onderdak)
	36	250	9.0								Hunton	Silencio 36

Average density of materials:

Material	class	ρ (average) kg/m³
Gypsum board	standard	750
	fire resistant (RF)	850
	fibre reinforced	1150
Particle board	standard	675
	moisture resistant	720
OSB	OSB/2 & OSB/3	600
	OSB/4	620
MDF	standard	725
	moisture resistant	735
	fire retardant	745
Wood fibre cement board		1250
Organic fibre cement board		1400
Plywood board		460
Cross laminated timber panels		450
Wood fibre insulation board		260

3 - TERRACED HOUSES SOLUTIONS

3.1 - General

3.1.1 - Introduction

All over Europe, minimal requirements exist for the sound insulation between terraced houses. In some European countries, these basic criteria are even higher than for the sound insulation between apartments (see section 1). But only a few countries have criteria for the sound insulation between rooms of the same dwelling and even then these values are easy to attain with LWTF constructions.

So the main focus should be on the acoustic optimisation of the party wall (and of course on other acoustic aspects such as equipment noise…).

Some LWTF manufacturers/contractors use a construction consisting of a heavy wall 'sandwiched' between the LWTF walls of the terraced houses. This gives a very good sound insulation, even in the low frequencies. But this kind of construction is not frequently met, it is moreover expensive and makes for very thick party walls that are time-consuming to construct.

So most constructions have party walls made of studs and boards. Building light and having good acoustic sound insulation is possible. But a general rule in acoustics is that the lighter you build, the more acoustic knowledge and craftsmanship you need to make things work. So if you are not familiar with acoustics, we advise you to read the next chapter to be able to fully understand the rest of this report.

3.1.2 - Some basic notions about the direct airborne sound insulation of walls

There are two main strategies to minimize the airborne sound transmission through a wall. One can use either an 'acoustic single wall', or an 'acoustic double wall' technology.

a) SINGLE WALLS: The acoustic performance of single walls is illustrated by the figures 7 'a' (the sound reduction index R of a single gypsum board of 12.5 mm and of two gypsum boards of 12.5 mm screwed together) and 'b' (examples with 1x18 mm hardboard, 2x18 mm hardboard screwed together and 1x36 mm hardboard). The maximum attainable sound insulation of single walls is mainly determined by the surface mass of the wall and its bending stiffness.

The first part of the sound reduction index spectrum R is governed by the *mass law*: it shows a steady increase of theoretically a maximum of 6 dB for every doubling of frequencies (in practice always a bit less).

In the second part of the spectrum, a deterioration in the sound insulation -called the *coincidence dip*- occurs around the *critical frequency*[1]. The coincidence dip is in both figures indicated by a '**c**'. The critical frequency depends on the surface mass and the bending stiffness of the wall. If boards of the same material are used, then the critical frequency and its coincidence dip will shift towards the lower frequencies for thicker panels (this is less advantageous for the sound insulation). If two hardboards are screwed together (figure 7 'b'), the coincidence dip will remain at the same place as for the individual hardboard as the boards still react independently. If rigidly glued, they will behave as a single hardboard of 36 mm thickness and the critical frequency will shift towards the lower frequencies.

The mass law also states that when the surface mass of the panel is doubled (e.g. figure 7'a'), then the sound reduction index for each frequency will increase theoretically with a maximum of 6 dB (in practice always less and this of course only in the area below the coincidence dip).

In order to obtain sufficient sound insulation for a compartment wall, surface masses of 500 kg/m² are necessary, far above the surface masses typically for LWTF constructions. So the second type of technology, i.e. 'acoustic double walls' is to be used.

b) Just an ordinary double wall will not do. There are some requirements to be fulfilled in order to obtain better performances than that of the single wall with the same surface mass. Perfect double walls behave as *mass-spring-mass systems* and have a sound reduction index spectrum that is characterized by the *mass-spring-mass resonance* provoking a deep dip in the sound insulation at the resonance frequency f_r (in the low frequencies in all the graphs below and indicated by 'r' in figure 7'c'). The sound reduction then increases very rapidly (theoretically with a maximum of 18 dB per doubling of frequency, in practice less). The coincidence dips of both panels of the double wall are visible in the spectrum (dips in the mid or high frequency range of the spectrum). Real walls behave slightly differently and in order to optimize the double wall acoustically, it is necessary to keep in mind the following parameter influences, illustrated by the different figures 'a' to 'g' below.

1) First of all, the *degree of structural decoupling* is important. This is illustrated by figure 7'c': in graph 3 both sides of the wall are rigidly connected by the studs. This results in a 12 dB lower R_w than in graph 1 where both sides of the wall are on separate studs and totally disconnected. The wall of which graph 2 represents the sound reduction index is somewhere in between both previous examples, but with still a 7 dB lower performance than the perfectly disconnected situation represented

[1] The 'why' of this all cannot be explained here. We refer to acoustic literature such as 'Sound Insulation' – Carl Hopkins - Elsevier ISBN 978-0-7506-6526-1 and/or 'Noise and Vibration Control Engineering' – I.M. Vér & L.L. Beranek – Wiley ISBN 13 978-0-471-44942-3

by graph 1: the staggered studs only have a rigid connection above and below the wall.

The more rigid the composing walls/panels, the more each rigid contact will diminish the maximal attainable sound insulation. This has to do with the structural transmission of vibrational power through the rigid connection and the radiation efficiency back to airborne sound of the wall at the reception side. A number of parameters come into play here, but it is good to know that increasing bending stiffness means that good radiation efficiency (the transformation of vibrations back into airborne sound) starts at ever lower frequencies. So a rigid connection between two very bending stiff walls such as masonry will almost annihilate all possible acoustic gain with the double wall construction. Less bending stiff materials such as boards will allow for some structural coupling between the two composing walls and still maintain some acoustic ‘double wall’ effect.

2) *Increasing the surface mass of the constituting walls* is another important aspect in obtaining not only a higher sound insulation in general, but *in combination with sufficient cavity width*, it also allows for better low frequency sound insulation. This is illustrated in figure 7 ‘g’. the additional gypsum on both sides of the wall results in an increase of 9 dB in R_{living}!

   Both constituting masses will resonate on the spring constituted by the air in the cavity (or eventual elastic fixing) and provoke a sharp diminishment at this resonance frequency.

   The sound insulation will increase dramatically beyond this resonance frequency f_r, (theoretically up to 18 dB per doubling of frequency, limited by coincidence effects, high frequency three room transmission…). As low frequency insulation is the problem, the choices of cavity width d [m] and surface masses m_1' and m_2' [kg/m²] of both panels should be made in such a way that the resonance frequency f_r occurs as low as possible and preferably way below 50 Hz. A simple formula (for pragmatic semi-diffuse sound incidence) allows for the calculation of this resonance frequency:

$$f_r \approx \frac{75}{\sqrt{d}} \cdot \sqrt{\frac{1}{m_1''} + \frac{1}{m_2''}} \text{ [Hz]}$$

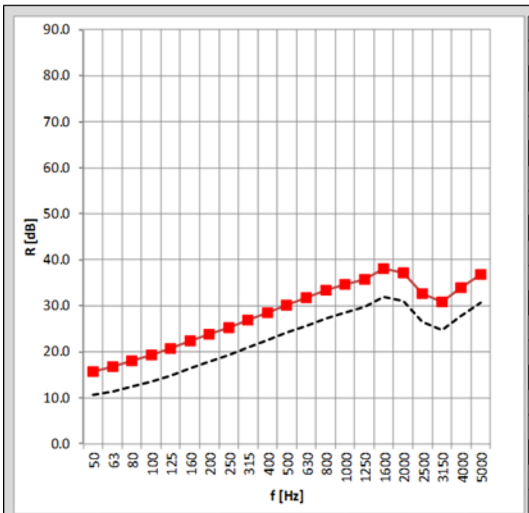
   One can easily see that large cavities will be necessary and that an economically optimized choice means symmetrical surface masses at both sides of the cavity. This is illustrated by the figures 7‘f’ where the wider cavity results in the resonance dip getting situated below 50 Hz with the resulting gain in sound insulation. Adding extra mass has similar effects as illustrated in figure 7’g’ with one extra gypsum board on both portions of the wall.

3) The *use of an acoustic absorbing, flexible material* such as mineral wool, cellulose fibres etc. in the cavity also increases greatly the sound insulation when there are no rigid connections between both sides of the wall (figure 7‘d’). The acoustically

absorbing material avoids cavity resonances. The greatest gain is obtained with the first centimetres of an acoustic absorbing material, but further filling will still increase the sound insulation in the situation of completely disconnected wall portions.

Unfortunately, this gain can be rather limited or non-existent when major rigid connections exist between both parts of the wall. Inserting 5 cm mineral wool in the cavity in figure 'e' only results in a gain of 5 dB in R_w, far less than the 15 dB in figure 7'd'. This is due to the structural transmission through the studs.

Of course when the whole cavity is filled with this material, it needs to be flexible enough not to increase the coupling between both walls. As thermal and often fire requirements require the placing of some thermal insulation in the cavity, one should take care that this fulfils the necessary conditions mentioned here above. The use of rigid and/or non-acoustically absorbing thermal insulation materials such as certain PU or EPS can dramatically diminish the direct and flanking sound insulation of walls (party walls, façades).



1	R_{living}= 32 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 33 dB
2	R_{living}= 26 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 27 dB

f [Hz]	1	2
50	15.7	10.6
63	**16.7**	**11.4**
80	18.0	12.4
100	19.3	13.5
125	**20.7**	**14.8**
160	22.3	16.4
200	23.8	17.8
250	**25.3**	**19.3**
315	26.9	20.9
400	28.6	22.6
500	**30.2**	**24.2**
630	31.7	25.7
800	33.3	27.3
1000	**34.6**	**28.6**
1250	35.7	29.7
1600	38.0	32.0
2000	**37.1**	**31.0**
2500	32.7	26.6
3150	30.8	24.7
4000	**33.9**	**27.8**
5000	36.8	30.7

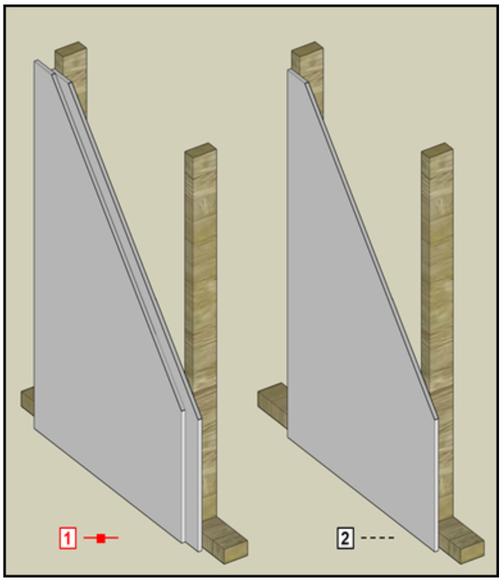
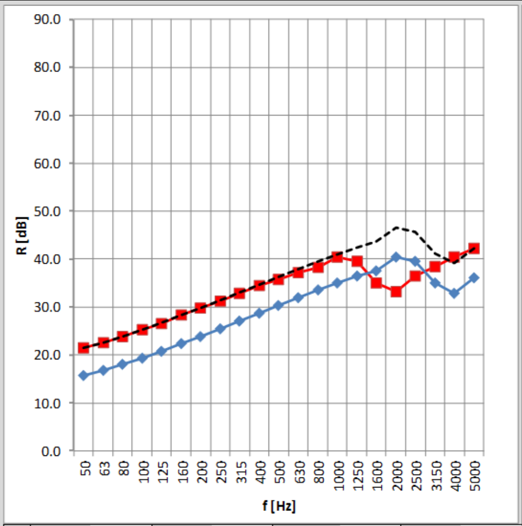


Figure 7a - SINGLE WALLS: illustration of mass law and of the coincidence dip (indicated by 'c'). The critical frequency of two panels screwed together (not glued) remains the same as that of the single panel: R of 1 gypsum board of 12.5 mm (graph 2) en 2 gypsum boards (2 x12.5 mm) screwed together (graph 1). [Simulation by INSUL 6.3 program (Marshall Day Acoustics)]



f [Hz]	1	2	3
50	21.4	21.4	15.7
63	**22.6**	**22.6**	**16.7**
80	23.9	23.9	18.0
100	25.2	25.2	19.3
125	**26.6**	**26.7**	**20.7**
160	28.3	28.3	22.3
200	29.7	29.8	23.8
250	**31.3**	**31.4**	**25.4**
315	32.8	33.0	27.0
400	34.4	34.7	28.7
500	**35.8**	**36.3**	**30.3**
630	37.2	37.9	31.9
800	38.3	39.6	33.6
1000	**40.5**	**41.0**	**35.0**
1250	39.6	42.4	36.4
1600	35.1	43.6	37.6
2000	**33.2**	**46.5**	**40.5**
2500	36.5	45.6	39.5
3150	38.4	41.2	35.0
4000	**40.5**	**39.1**	**32.9**
5000	42.3	42.3	36.1

1	R_{living}= 36 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 37 dB
2	R_{living}= 39 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 40 dB
3	R_{living}= 33 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 34 dB

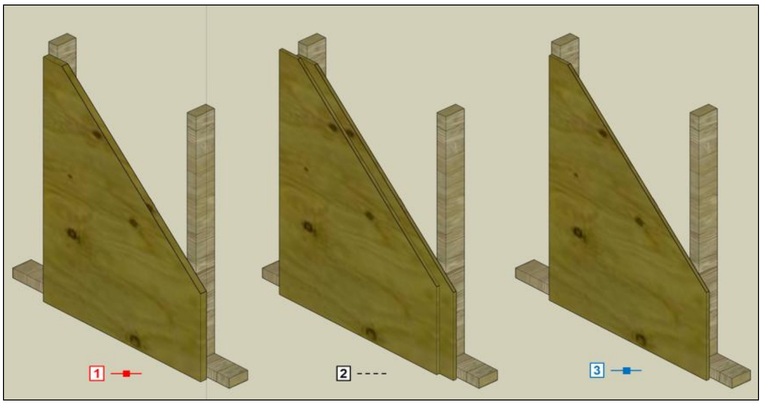
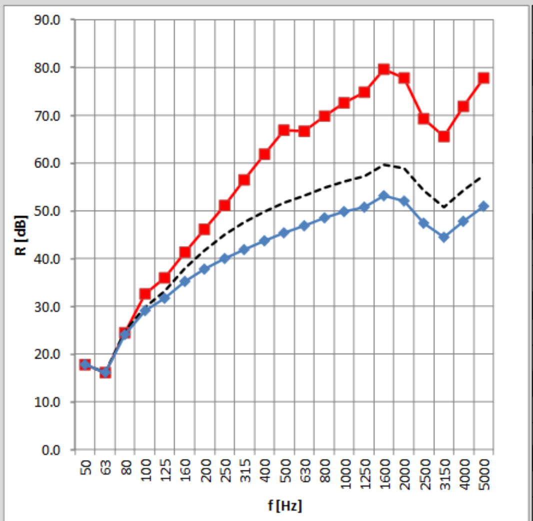


Figure 7b - SINGLE WALLS: the critical frequency decreases with the thickness for the same material. R of a single hardboard of 36 mm (graph 1); R of 2 hardboards of 18 mm screwed (not glued!) together (graph 2); R of a single hardboard of 18 mm (graph 3). [Simulation by INSUL 6.3 program (Marshall Day Acoustics)]



f [Hz]	1	2	3
50	17.8	17.8	17.8
63	**16.2**	**16.2**	**16.2**
80	24.4	24.9	24.1
100	32.6	29.9	29.1
125	**36.0**	**33.1**	**31.6**
160	41.3	37.9	35.2
200	46.2	41.7	37.8
250	**51.2**	**45.0**	**40.0**
315	56.4	47.6	41.9
400	61.8	49.9	43.7
500	**66.8**	**51.7**	**45.3**
630	66.6	53.2	46.9
800	69.8	54.9	48.5
1000	**72.6**	**56.2**	**49.8**
1250	74.9	57.3	50.8
1600	79.7	59.7	53.1
2000	**77.8**	**58.8**	**52.1**
2500	69.2	54.3	47.4
3150	65.6	50.8	44.5
4000	**71.8**	**54.2**	**47.7**
5000	77.7	57.5	51.0

1	Rliving= 50 dB	50-5000= -10 dB	100-3150= -3 dB	Rw= 60 dB
2	Rliving= 48 dB	50-5000= -5 dB	100-3150= -2 dB	Rw= 53 dB
3	R_{living}= 45 dB	$C_{50-5000}$= -3 dB	$C_{100-3150}$= -2 dB	R_w = 48 dB

Figure 7c1 – Graph 1: completely decoupled double wall / Graph 2: staggered constructions only connected on top and below the wall. / Graph 3: studs connect both wall portions. Coincidence dips are marked by 'c', the mass-spring-mass resonance dip is marked by 'r'.

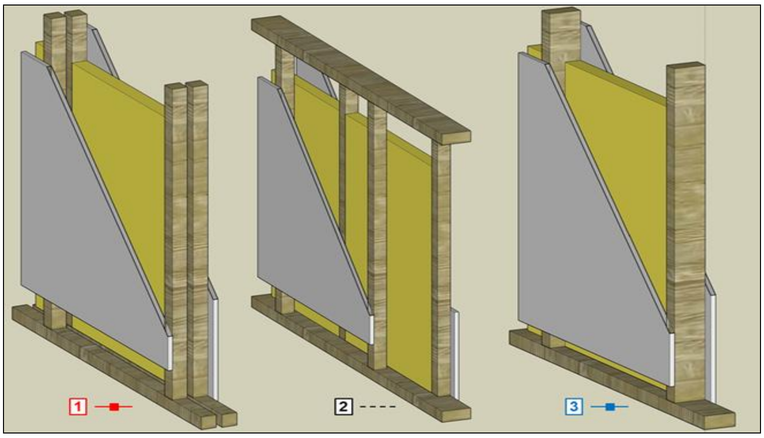
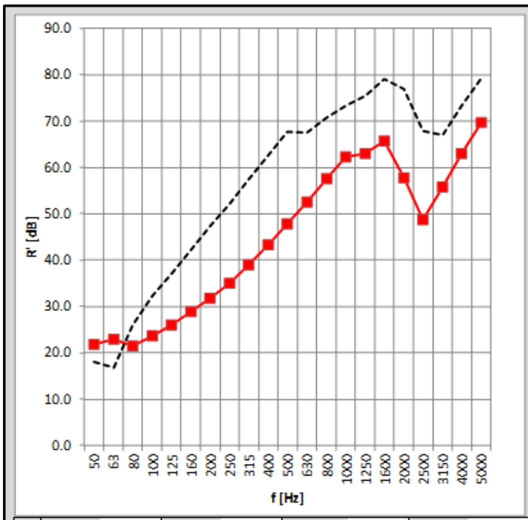


Figure 7c2 – DOUBLE WALLS: the more rigid connections are present, the bigger the losses in sound reduction index.

[Simulation with gypsum boards of 12.5 mm, mineral wool 5 cm, cavity width 10 cm, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2
50	21.9	18.0
63	23.0	16.7
80	21.5	25.9
100	23.7	32.3
125	26.0	37.0
160	28.8	42.3
200	31.7	47.2
250	35.1	52.2
315	38.9	57.4
400	43.4	62.7
500	47.8	67.7
630	52.5	67.5
800	57.5	70.7
1000	62.3	73.3
1250	63.0	75.4
1600	65.7	79.1
2000	57.8	76.9
2500	48.8	67.9
3150	55.8	67.0
4000	63.0	73.3
5000	69.7	79.2

1	R'_{living}= 45 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R'_w= 46 dB
2	R'_{living}= 51 dB	$C_{50-5000}$= -10 dB	$C_{100-3150}$= -4 dB	R'_w= 61 dB

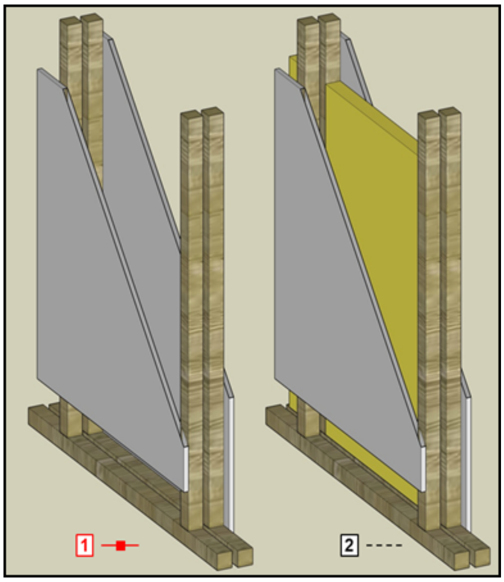
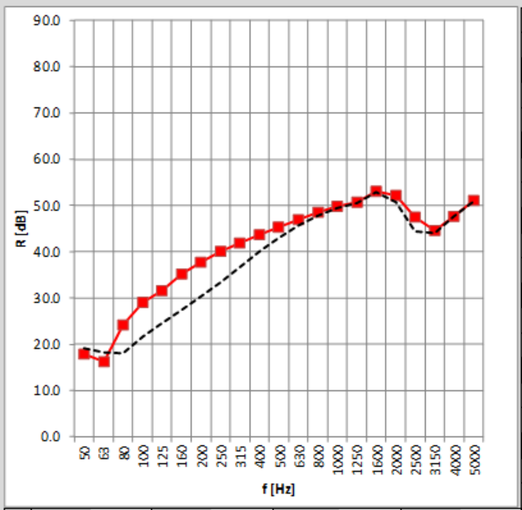


Figure 7d – DOUBLE WALLS: adding an acoustic absorbent increases dramatically the sound reduction index R when both wall portions are disconnected. [Simulation with gypsum boards of 12.5 mm, mineral wool 5 cm, cavity width 10 cm, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2
50	17.8	19.1
63	16.2	18.2
80	24.1	18.1
100	29.1	21.7
125	31.6	24.6
160	35.2	27.5
200	37.8	30.3
250	40.0	33.3
315	41.9	36.6
400	43.7	40.1
500	45.3	43.0
630	46.9	45.7
800	48.5	47.9
1000	49.8	49.5
1250	50.8	50.5
1600	53.1	52.8
2000	52.1	50.8
2500	47.4	44.4
3150	44.5	44.1
4000	47.7	47.6
5000	51.0	50.9

1	R_{living}= 45 dB	$C_{50-5000}$= -3 dB	$C_{100-3150}$= -2 dB	R_w = 48 dB
2	R_{living}= 42 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -1 dB	R_w = 43 dB

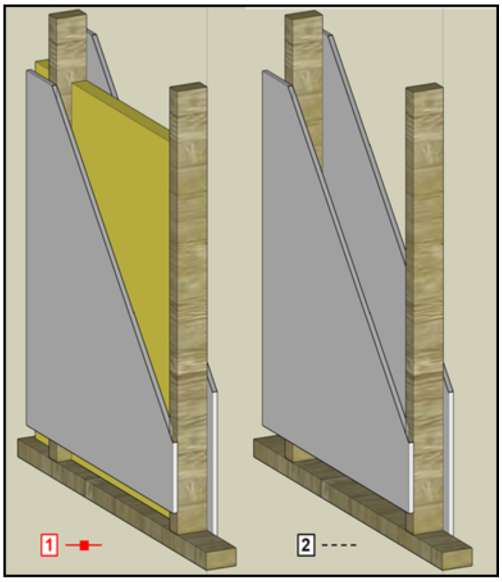
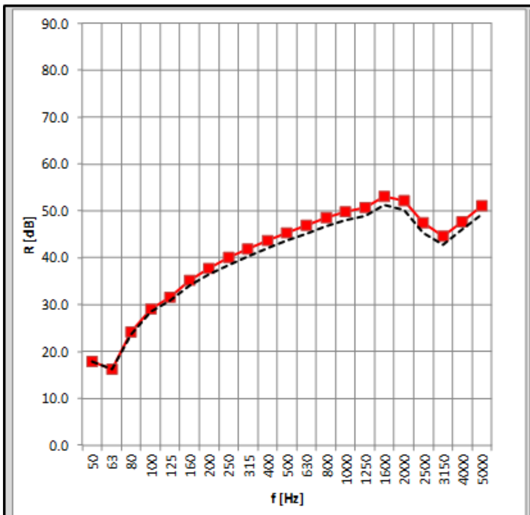


Figure 7e- DOUBLE WALLS: filling up the cavity with some acoustic absorbent can increase the sound reduction index even when there are rigid connections, though the effect is far less important than with disconnected walls (figure d). [Simulation with gypsum boards of 12.5 mm, mineral wool 5 cm, cavity width 10 cm, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2
50	17.8	17.8
63	16.2	16.2
80	24.1	23.7
100	29.1	28.6
125	31.6	30.9
160	35.2	34.1
200	37.8	36.4
250	40.0	38.4
315	41.9	40.2
400	43.7	42.0
500	45.3	43.6
630	46.9	45.2
800	48.5	46.7
1000	49.8	48.1
1250	50.8	48.9
1600	53.1	51.2
2000	52.1	50.2
2500	47.4	45.3
3150	44.5	42.7
4000	47.7	46.0
5000	51.0	49.3

1	R_{living}= 45 dB	$C_{50-5000}$= -3 dB	$C_{100-3150}$= -2 dB	R_w = 48 dB
2	R_{living}= 44 dB	$C_{50-5000}$= -2 dB	$C_{100-3150}$= -1 dB	R_w = 46 dB

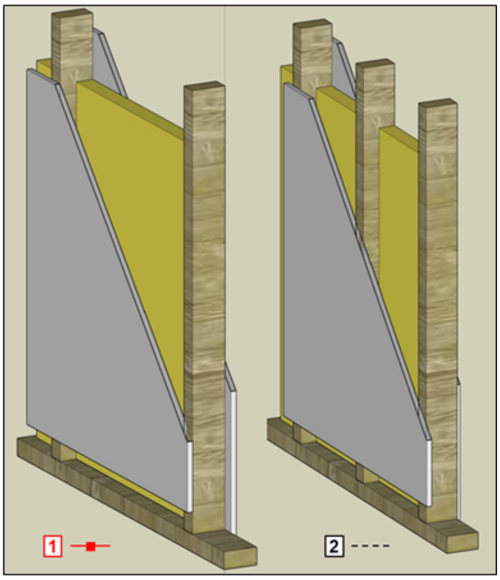
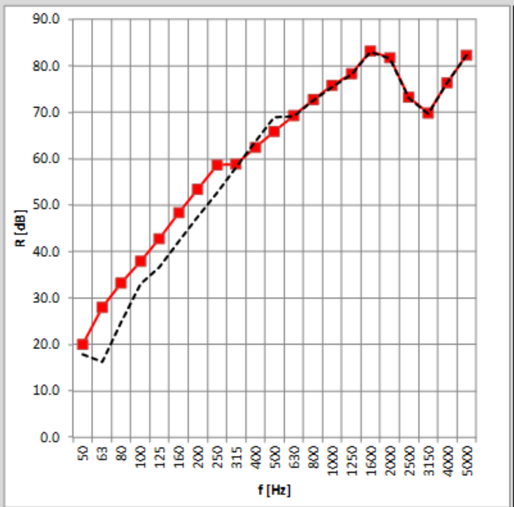


Figure 7f- DOUBLE WALLS: less rigid connections - for instance When the stud spacing increases, the number of rigid connections decreases which leads to a higher sound reduction index R. Graph 1 illustrates this effect for a stud spacing of 60 cm (o.c.), graph 2 shows the result for a stud spacing of 40 cm (o.c.). [Simulation with gypsum boards of 12.5 mm, mineral wool 5 cm, cavity width 10 cm, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2
50	20.1	17.8
63	28.0	16.2
80	33.2	24.7
100	37.9	33.1
125	42.8	36.7
160	48.4	42.3
200	53.5	47.4
250	58.7	52.7
315	58.8	58.1
400	62.5	63.7
500	65.9	69.0
630	69.4	69.1
800	72.8	72.5
1000	75.8	75.5
1250	78.3	78.1
1600	83.3	83.1
2000	81.7	81.5
2500	73.2	73.1
3150	69.8	69.7
4000	76.3	76.3
5000	82.4	82.4

1	R_{living}= 58 dB	$C_{50-5000}$= -8 dB	$C_{100-3150}$= -3 dB	R_w = 66 dB
2	R_{living}= 51 dB	$C_{50-5000}$= -10 dB	$C_{100-3150}$= -3 dB	R_w = 61 dB

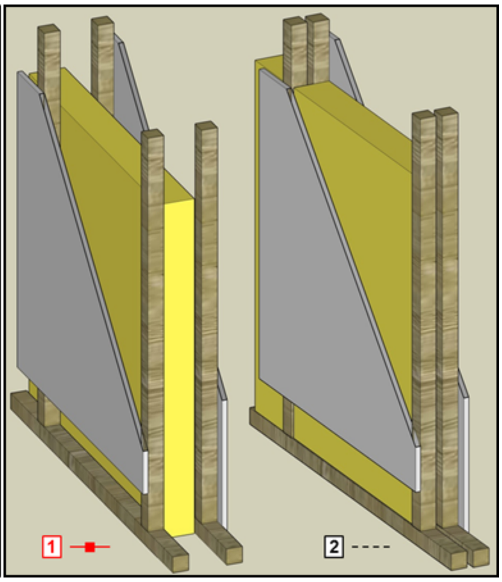
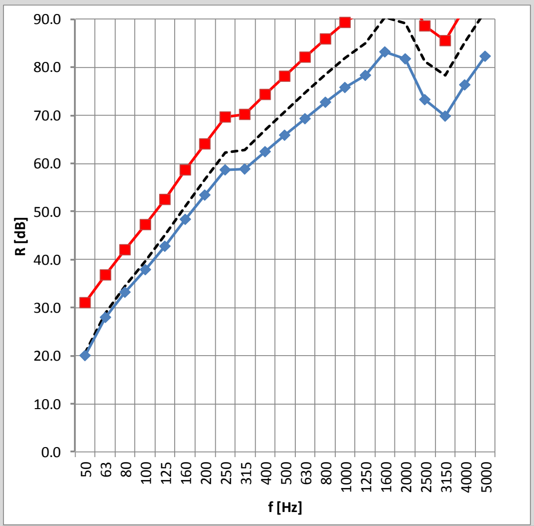


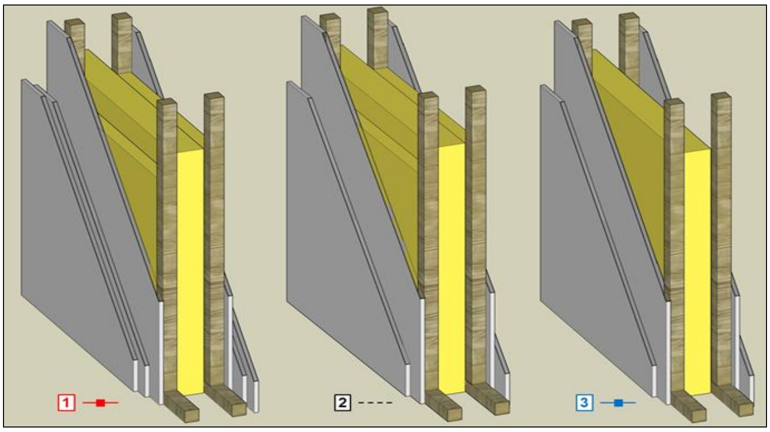
Figure 7f- DOUBLE WALLS: increasing the cavity width increases the sound insulation even in the very low frequencies. [Simulation with gypsum boards of 12.5 mm, mineral wool 10 cm, cavity width 10 cm for case 1 and 20 cm for case 2, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



f [Hz]	1	2	3
50	31.1	20.5	20.1
63	36.8	28.9	28.0
80	42.1	34.5	33.2
100	47.2	39.7	37.9
125	52.6	45.1	42.8
160	58.6	51.0	48.4
200	64.1	56.6	53.5
250	69.7	62.2	58.7
315	70.2	62.8	58.8
400	74.3	66.9	62.5
500	78.2	70.8	65.9
630	82.1	74.7	69.4
800	85.9	78.6	72.8
1000	89.3	82.0	75.8
1250	92.2	85.0	78.3
1600	97.7	90.4	83.3
2000	96.5	89.2	81.7
2500	88.6	81.2	73.2
3150	85.6	78.3	69.8
4000	92.5	85.2	76.3
5000	99.0	91.7	82.4

1	R_{living}= 68 dB	$C_{50-5000}$= -8 dB	$C_{100-3150}$= -3 dB	R_w = 76 dB
2	R_{living}= 59 dB	$C_{50-5000}$= -10 dB	$C_{100-3150}$= -4 dB	R_w = 69 dB
3	R_{living}= 58 dB	$C_{50-5000}$= -8 dB	$C_{100-3150}$= -3 dB	R_w = 66 dB

Figure 7g- DOUBLE WALLS: adding a supplementary thickness of acoustic absorbent (from graph 3 to graph 2) and more boards (from graph 2 to graph 1) allows for further increasing of the sound reduction index R. [Simulation with gypsum boards of 12.5 mm, mineral wool of 10 cm (case 3) and 20 cm (case 1 and 2), cavity width 20 cm,, stud spacing o.c. 60 cm by INSUL 6.3 program of Marshall Day Acoustics].



3.2 - Internal partitions

As the boards typically used in LWTF constructions have a reasonably low bending stiffness, this means that internal partitions made of boards rigidly connected with wooden studs can be used and still maintain a better sound insulation than what could be deduced from mass law. The calculated performances of some constructions are given in the figures 7‘c’ (staggered solution), ‘e’ and ‘f’. For internal partitions, this sound insulation is sufficient for basic acoustic comfort and complies with the standard requirements in most European countries (not many countries have requirements for internal partitions).

When the wall is not load carrying, the sound insulation can be increased using metal stud technology (or its improved versions).Some results are given in the table below. This could be a good idea for internal partitions that require a better than usual sound insulation, such as walls between waiting rooms and doctor and lawyers consulting rooms, but also between rooms with technical equipment (technical room with heating, pumps or ventilation devices, restrooms…) and other sensitive rooms.

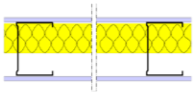
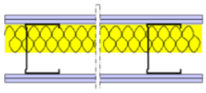
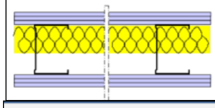
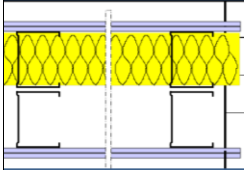
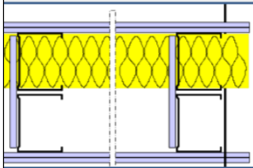
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	1 x 15 mm	40 mm	70 mm	-	34 (-1,-5)
	1 x 15 mm	40 mm	70 mm	30 mm	42 (-2,-7)
	1 x 12,5 mm	45 mm	70 mm	-	34 (-2,-6)
	1 x 12,5 mm	45 mm	70 mm	40 mm	41 (-3,-9)
	1 x 12,5 mm	50 mm	75 mm	-	34 (-2,-6)
	1 x 12,5 mm	50 mm	75 mm	40 mm	42 (-3,-10)
	1 x 12,5 mm	75 mm	100 mm	-	36 (-1,-6)
	1 x 12,5 mm	75 mm	100 mm	60 mm	43 (-4,-10)
	1 x 12,5 mm	100 mm	125 mm	-	38 (-1,-6)
	1 x 12,5 mm	100 mm	125 mm	75 mm	46 (-3,-9)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	2 x 12,5 mm	50 mm	100 mm	-	42 (-2,-7)
	2 x 12,5 mm	50 mm	100 mm	40 mm	50 (-2,-8)
	2 x 12,5 mm	75 mm	125 mm	-	45 (-2,-7)
	2 x 12,5 mm	75 mm	125 mm	60 mm	51 (-2,-8)
	2 x 12,5 mm	100 mm	150 mm	-	47 (-2,-6)
	2 x 12,5 mm	100 mm	150 mm	75 mm	52 (-3,-8)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	3 x 12,5 mm	50 mm	125 mm	-	45 (-2,-7)
	3 x 12,5 mm	50 mm	125 mm	40 mm	56 (-2,-7)
	3 x 12,5 mm	75 mm	150 mm	-	47 (-2,-7)
	3 x 12,5 mm	75 mm	150 mm	60 mm	57 (-2,-7)
	3 x 12,5 mm	100 mm	175 mm	-	49 (-2,-7)
	3 x 12,5 mm	100 mm	175 mm	75 mm	58 (-3,-8)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	2 x 12,5 mm	2 x 45 mm	145 mm	40 mm	57(-6,-13)
	2 x 12,5 mm	2 x 45 mm	145 mm	40 mm + 40 mm	61 (-4,-11)
	2 x 12,5 mm	2 x 50 mm	155 mm	40 mm	57 (-5,-13)
	2 x 12,5 mm	2 x 50 mm	155 mm	40 mm + 40 mm	61 (-4,-10)
	2 x 12,5 mm	2 x 75 mm	205 mm	60 mm	61 (-4,-10)
	2 x 12,5 mm	2 x 75 mm	205 mm	60 mm + 60 mm	63 (-4,-11)
	2 x 12,5 mm	2 x 100 mm	255 mm	-	52 (-2,-7)
	2 x 12,5 mm	2 x 100 mm	255 mm	75 mm	62 (-4,-10)
	2 x 12,5 mm	2 x 100 mm	255 mm	75 mm + 75 mm	63 (-3,-10)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	2 x 12,5 mm	2 x 45 mm	145 mm	40 mm	52 (-5,-13)
	2 x 12,5 mm	2 x 45 mm	145 mm	40 mm + 40 mm	55 (-5,-12)
	2 x 12,5 mm	2 x 50 mm	155 mm	40 mm	53 (-6,-13)
	2 x 12,5 mm	2 x 50 mm	155 mm	40 mm + 40 mm	55 (-4,-11)
	2 x 12,5 mm	2 x 75 mm	205 mm	60 mm	54 (-3,-10)
	2 x 12,5 mm	2 x 75 mm	205 mm	60 mm + 60 mm	57 (-4,-11)
	2 x 12,5 mm	2 x 100 mm	255 mm	-	52 (-3,-8)
	2 x 12,5 mm	2 x 100 mm	255 mm	75 mm	55 (-3,-9)
	2 x 12,5 mm	2 x 100 mm	255 mm	75 mm + 75 mm	57 (-3,-9)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	3 x 12,5 mm	2 x 100 mm	280 mm	-	58 (-2,-7)
	3 x 12,5 mm	2 x 100 mm	280 mm	75 mm	65 (-3,-9)
	3 x 12,5 mm	2 x 100 mm	280 mm	75 mm + 75 mm	66 (-4,-10)
	# boards each side	stud width	total width	mineral wool	$R_w(C;C_{tr})$
	3 x 12,5 mm	2 x 100 mm	280 mm	-	57 (-2,-7)
	3 x 12,5 mm	2 x 100 mm	280 mm	75 mm	59 (-3,-8)
	3 x 12,5 mm	2 x 100 mm	280 mm	75 mm + 75 mm	60 (-3,-8)

Figure 8: performances of gypsum board constructions (source: Belgisch Luxemburgse Gips Vereniging - Eenduidige geluidisolatie van gipskartonwanden. NBVG-BLGV-ABLG,Rijswijk/Kallo, s.d.)

3.3 - Party walls

The stud connection between the boards will anyhow reduce significantly the maximum attainable direct airborne sound insulation with the materials used. For party walls, this just will not do. Party walls need a complete structural decoupling. In the cases where some structural connection is absolutely necessary, this could be done in a more resilient way using elastic fixations etc.

3.3.1 - The intermediate heavy wall solution

This solution is not frequently met and its disadvantages (width, building cost, time) have already have been mentioned in the introduction. Its low frequency performance though is very good if a heavy concrete block is used. In the example below, only a 5 cm gas concrete element was used, giving moderate results in the low frequency band.

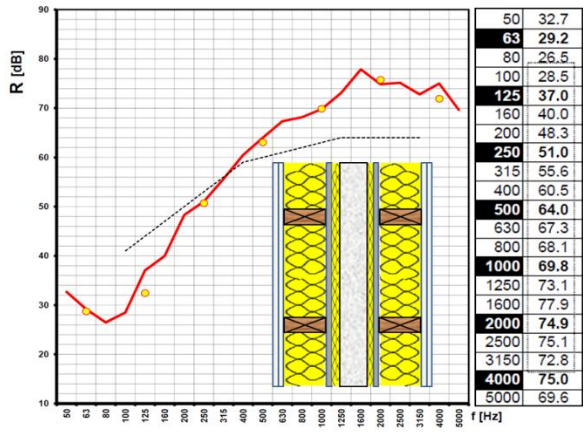


Figure 9: construction of the party wall composed of 5 cm gas concrete completed symmetrically on both sides with 20 mm glass wool, a cement board of 9 mm, studs of 90 mm x 40 mm and a cavity filled with mineral wool and finally 2 x 12.5 mm gypsum boards. Results: R_w= 60 dB $C_{50-5000}$=-6 dB (R_{living}=54 dB)

3.3.2 - Traditional party walls

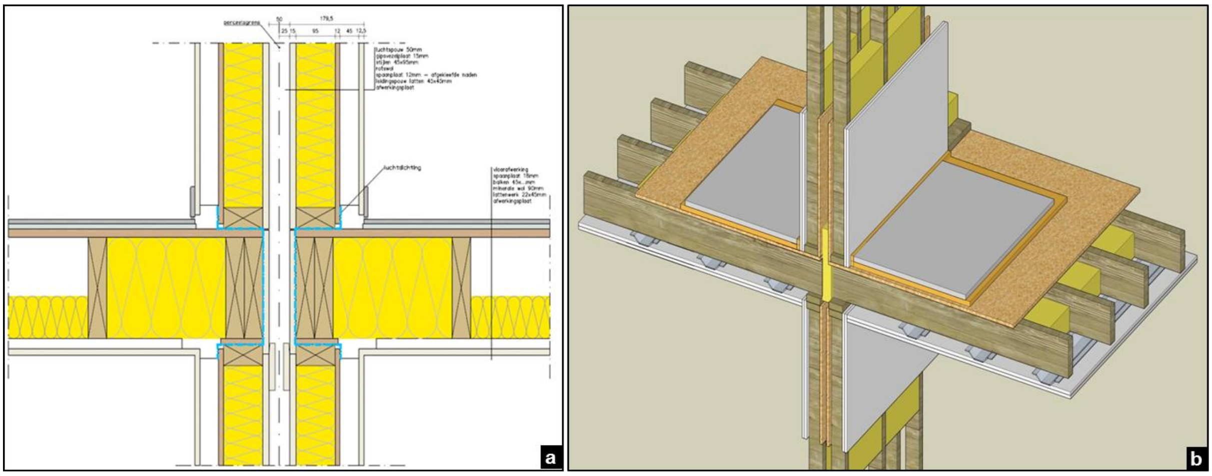
Many manufacturers all over Europe use a similar construction: the party wall is composed of a double stud wall, each stud wall (boards-studs-boards) belonging to one house and separated by a small cavity (e.g. figures 10 ‘a’ and ‘c’) and allowing for a structural decoupling of both dwellings from the foundations to the roof.

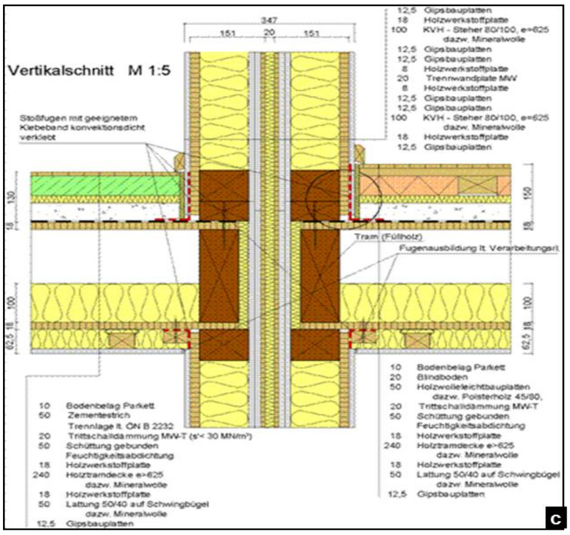
This simple concept has the advantage of solving the ‘house independency” problem mentioned in section 2.2 and it offers a good fire protection.

Unfortunately, traditional party walls can have a problem with the low frequency sound insulation.

In several European countries, there are more severe requirements for the sound insulation between terraced houses than between apartments. Though in many countries, the requirements are limited to the frequency range above 100 Hz, this could probably change in the near future as a result of, for instance the on-going work of the prEN ISO 16717 series and the generally accepted view that sound insulation in the low frequency bands is crucial for the comfort of inhabitants (see introduction).

The low frequency sound insulation of the party walls is very much determined by the mass-spring-mass resonances of the different composing layers. These resonances should be well below 50 Hz to maximize comfort. If one wants to limit the number of boards (costs!), this means the necessity of large cavities. The traditional solution discussed here above (figure 10 'a') has normally a poor performance in these low frequencies due to the succession of cavities with a rather limited width.

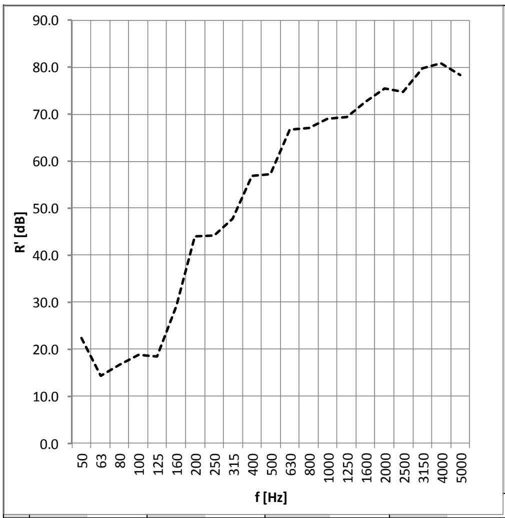




Figures 10: (a) and (b) this type of party wall has a rather poor sound insulation in the lower frequencies. (c) Typical Austrian 'heavy' construction with a small 2 cm central cavity filled with rock wool, surrounded on each side by a complex of an 8 mm rainproof wood panel, a fibre reinforced gypsum board and an RF gypsum board. On the sides of the rooms, the wall is composed of an 18 mm wooden board and a 12.5 mm gypsum board.

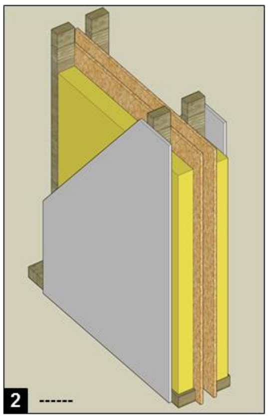
Using more boards ('the heavy' solution as in figure 10'b') allows for a good R_w and moderate performances at the low frequencies. In general, it is also a more expensive solution than the acoustic optimized solution with a large cavity (see below).

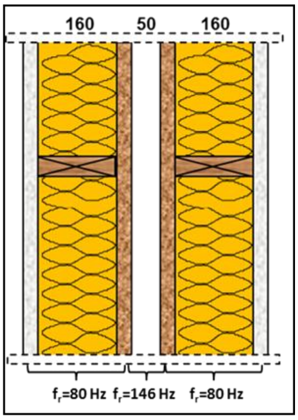
Note: in Canada, both leaves of the construction are sometimes connected by the continuous board from the floor of one house to the other. This of course diminishes dramatically the direct sound insulation and induces flanking transmission as well as impact sound to the adjacent dwelling. This continuous board is due to fire requirements to avoid *chimney effects and fire propagation in the cavity. But apparently, the use of rock wool is nowadays also tolerated and is beginning to be applied.*



f [Hz]	2
50	22.4
63	**14.4**
80	16.7
100	18.9
125	**18.5**
160	29.1
200	44.0
250	**44.2**
315	47.8
400	56.9
500	**57.2**
630	66.7
800	67.0
1000	**69.0**
1250	69.4
1600	72.6
2000	**75.5**
2500	74.8
3150	79.8
4000	**80.9**
5000	78.3

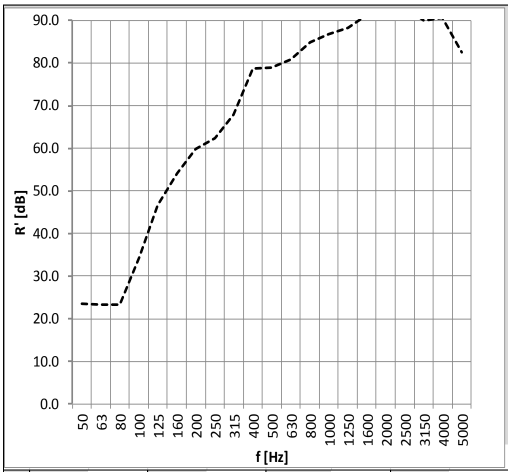
2	R'living= 42 dB	0-5000= -6 dB	00-3150= -6 dB	R'w= 48 dB





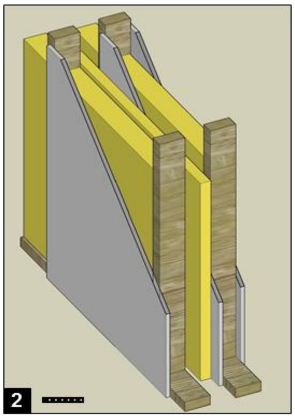
*1 x 12.5 mm fibre reinforced gypsum board *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm *** 1 x 15 mm OSB *** empty central 50 mm *** 1 x 15 mm OSB *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm ***1 x 12.5 mm fibre reinforced gypsum board*

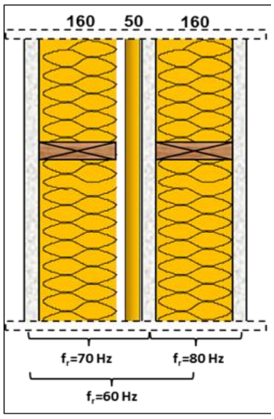
Figure 11- Some traditional party wall constructions have a poor sound insulation, especially in the low frequencies. This is due to the succession of resonance frequencies until the third octave band of 160 Hz (= resonance frequency of the OSB boards resonating on the empty cavity of 50 mm). Once the sound insulation index reaches 75 dB, the reception level becomes so low that the result is being influenced by the background noise (measurements on a mock-up installation project Mobic - BBRI).



f [Hz]	2
50	23.6
63	**23.3**
80	23.3
100	34.4
125	**46.7**
160	54.1
200	59.9
250	**62.4**
315	67.8
400	78.7
500	**79.0**
630	80.9
800	84.8
1000	**86.8**
1250	88.2
1600	91.3
2000	**93.6**
2500	93.3
3150	90.0
4000	**90.7**
5000	82.5

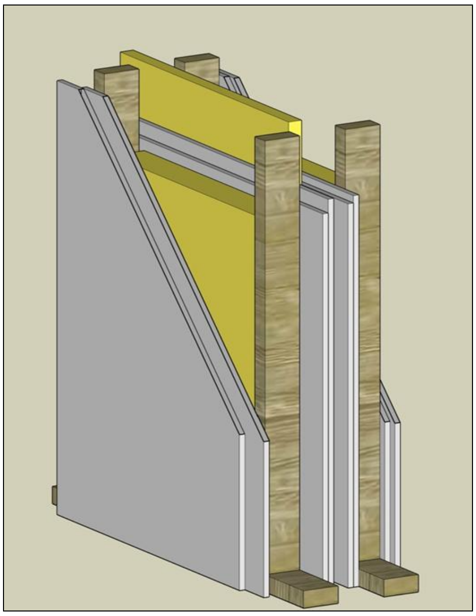
2	R'living= 54 dB	50-5000= -16 dB	00-3150= -7 dB	R'w= 70 dB





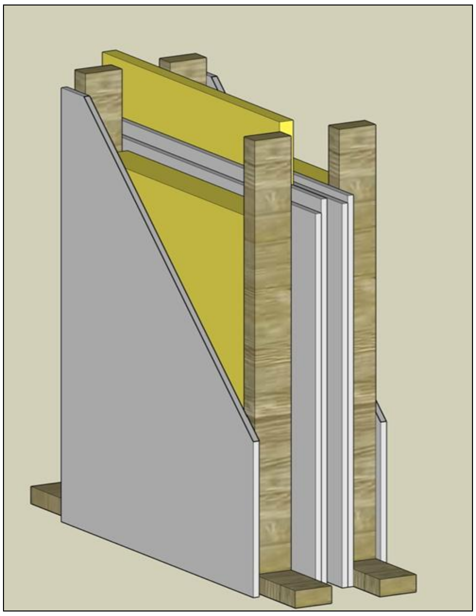
*1 x 12.5 mm fibre reinforced gypsum board *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm *** central cavity of 50 mm cavity filled with mineral wool 3 cm ca. 40 kg/m³ *** 1 x 12.5 mm fibre reinforced gypsum board *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm ***1 x 12.5 mm fibre reinforced gypsum board*

Figure 12-The disappearance of the small cavity of the previous figure greatly increase the sound insulation to $R'_{living}=R_w+C_{50\text{-}5000}$ = 54 dB although less boards have been used. These measurements have been done on a mock-up and might be influenced by indirect sound transmission. As such, the result might represent only the lower limit of the sound insulation. Once the sound insulation index reaches 75 dB, the reception level becomes so low that the result is being influenced by the background noise. (Measurements on a mock-up installation project Mobic - BBRI).



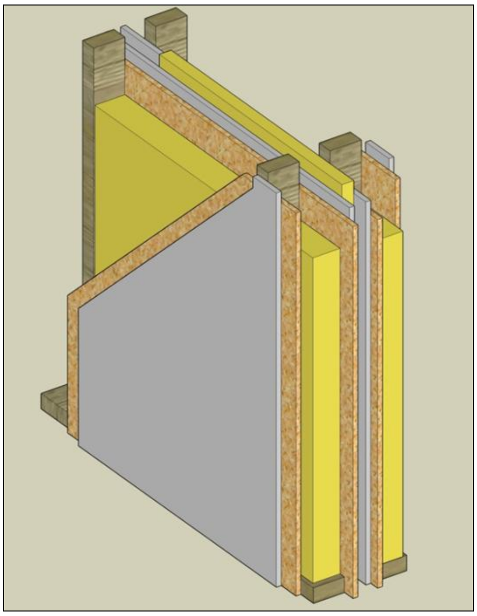
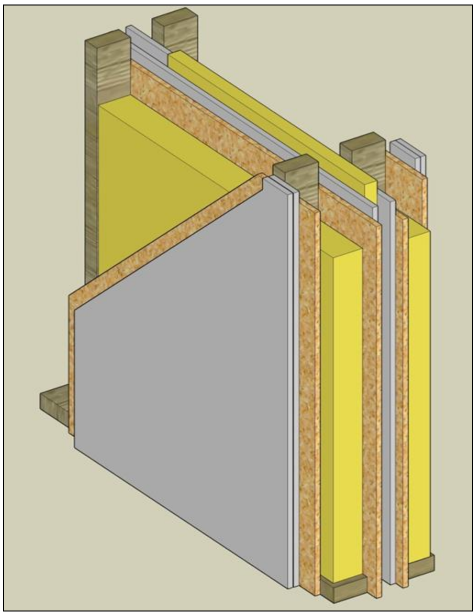
Composition: central cavity of 20 mm cavity filled with mineral wool 20 mm ca. 16 kg/m³ with symmetrically on both sides of the cavity (going from the inside towards the outside):: 2x12.5 mm fibre reinforced gypsum board *** 100x60 mm² studs, mineral wool 33 kg/m³ 100 mm *** 2x12.5 mm fibre reinforced gypsum board.

Figure 13: typical Austrian party wall Rw (C;Ctr)=59(-2;-10) dB. There is no sound reduction index spectrum nor is Rliving available (source www.dataholz.com).



Composition: central cavity of 20 mm cavity filled with mineral wool 20 mm ca. 16 kg/m³ with symmetrically on both sides of the cavity (going from the inside towards the outside):: 1x12.5 mm fibre reinforced gypsum board *** 100x60 mm² studs, mineral wool 33 kg/m³ 100 mm *** 2x12.5 mm fibre reinforced gypsum board.

Figure 14: typical Austrian party wall Rw (C;Ctr)=58(-3;-11) dB. There is no sound reduction index spectrum nor is Rliving available (source www.dataholz.com).

 Composition: central cavity of 20 mm cavity filled with mineral wool 20 mm ca. 16 kg/m³ with symmetrically on both sides of the cavity (going from the inside towards the outside): 1x12.5 mm fibre reinforced gypsum board + 1x15 mm OSB *** 100x60 mm² studs, mineral wool 33 kg/m³ 100 mm *** 1x15 mm OSB + 1x12.5 mm fibre reinforced gypsum board. *Figure 15: typical Austrian party wall Rw (C;Ctr)=59(-3;-10) dB. There is no sound reduction index spectrum nor is Rliving available (source www.dataholz.com).*	 Composition: central cavity of 20 mm cavity filled with mineral wool 20 mm ca. 16 kg/m³ with symmetrically on both sides of the cavity (going from the inside towards the outside): 1x12.5 mm fibre reinforced gypsum board + 1x15 mm OSB *** 100x60 mm² studs, mineral wool 33 kg/m³ 100 mm *** 1x15 mm OSB + 2x12.5 mm fibre reinforced gypsum board. *Figure 16: typical Austrian party wall Rw (C;Ctr)=60(-3;-10) dB. There is no sound reduction index spectrum nor is Rliving available (source www.dataholz.com).*

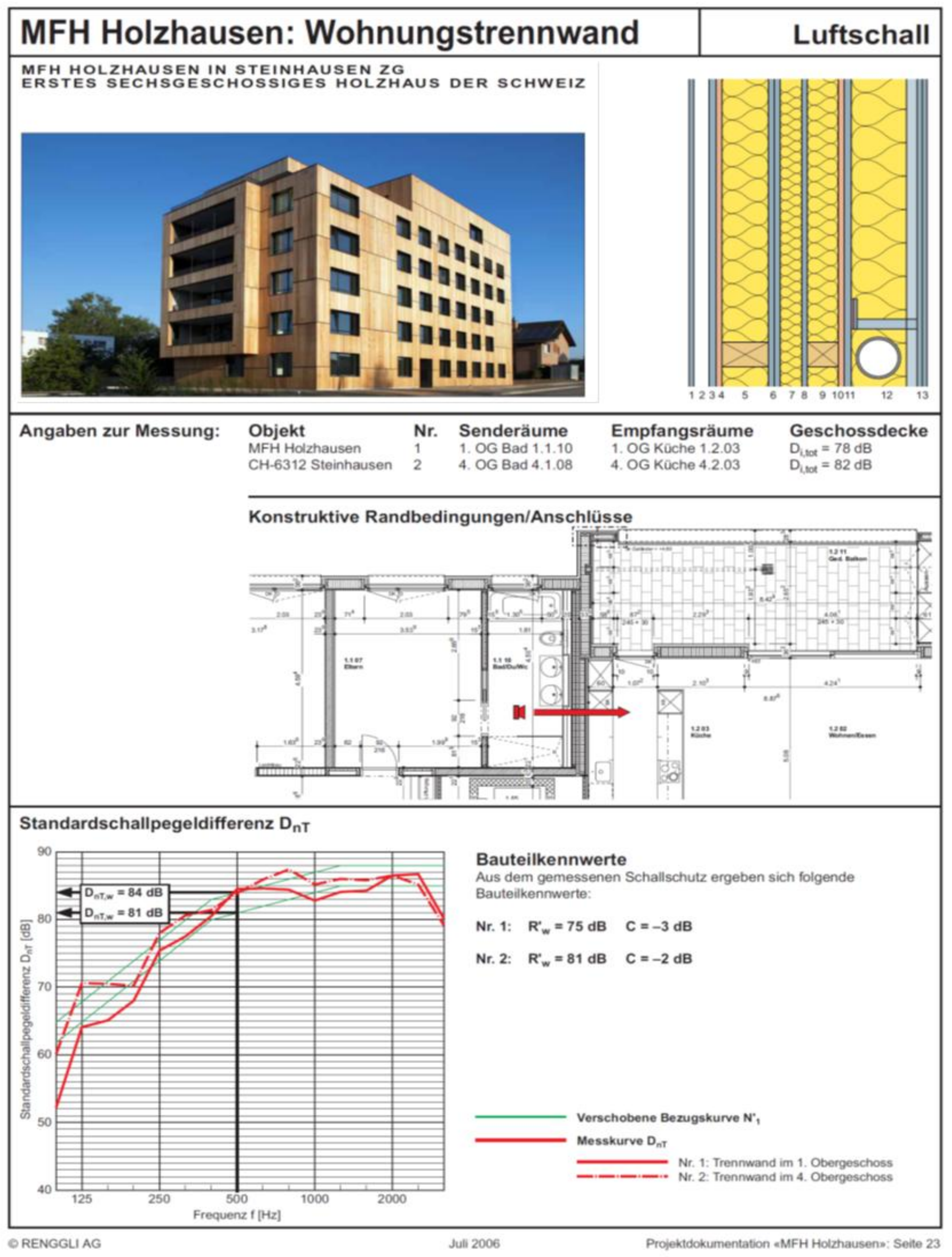


Figure 17: party wall construction in the first 6 floors high LWTF project in Steinhausen, Switzerland (MFZ Holzhausen, © Renggli AG, Sursee). Some words of explanation with the drawing: (1) Gypsum board 12.5 mm; (2) Cavity of 40 mm for technical reasons; (3) Gypsum board 18 mm; (4) OSB 15 mm; (5) Wooden stud and mineral wool 120 mm; (6) Gypsum fibre board 2 x 15 mm; (7) Mineral Wool 55 mm; (8) Gypsum fibre board 15 mm; (9) Wooden stud and mineral wool 80 mm; (10) OSB 15 mm; (11) Gypsum board 18 mm; (12) GYS system 170 mm with cavities filled with mineral wool; (13) Gypsum boards 2 x 12.5 mm.

3.3.3 - Party walls with a single large central cavity (and eventual technical linings)

One way of dramatically improving the low frequency performance is to shift all the boards on both sides of the central cavity of the common solution here above to the extreme sides of the party wall (see pictures in the middle and to the right in the figure below) with the cavity being filled up with rock wool. The possible advantages of this approach are shown in the figure below where the sound insulation increases by more than 20 dB and a with much better low frequency insulation.

This acoustically optimized solution (airborne sound insulation) does not offer a solution to the problematic idea of the 'independent terraced house'. As this approach only occurs in some countries (e.g. Austria) and can be criticized (see above), we can still maintain the idea of regrouping the boards to the extreme sides of the party wall.

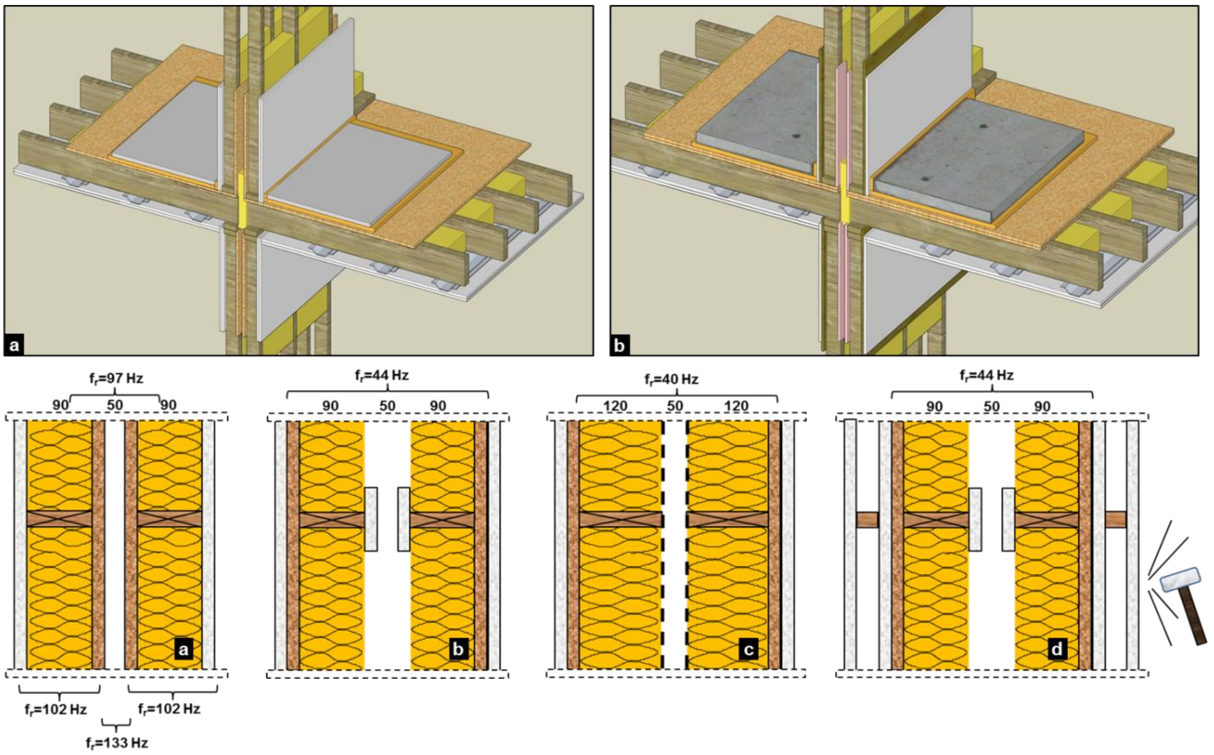


Figure 18: (a) traditional solution; (b) and (c) creating large cavities allows shifting the mass-spring-mass resonance frequency to the very low frequencies increasing considerably the low frequency sound insulation. Fire requirements impose special measures to be undertaken; (d) technical linings help to diminish sound coming from cupboards, tapping against the wall…

But of course the requirements of a fire resistance of one hour, even after the collapse of one of the houses and its part of the party wall, have to be fulfilled. That is why rock wool (or other products with similar acoustic and fire resistance characteristics) is fixed between the studs with at least the same thickness as the height (in section) of the stud. The thermal insulation and fire resistance of the rock wool protects the lateral sides of the studs. Of course this rock wool needs to remain in place (special glue, chicken wire, metal stud profiles….) when the other part of the party wall collapses. The fire will also attack the visible part of the stud (the 'head'). It burns in average depth-wise at a speed of ±1 cm every 10 minutes for traditional wooden studs. To maintain its constructional fire resistance during one hour, fire tests showed that studs of 120 x 45 mm² under a standard load complied. The alternative is the solution which is often used in the construction of technical shafts: small cement fibre or gypsum fibre boards can be fixed on the studs (figure) protecting the studs and maintaining the rock wool in place. These solutions allow for the use of normal, not over-dimensioned studs.

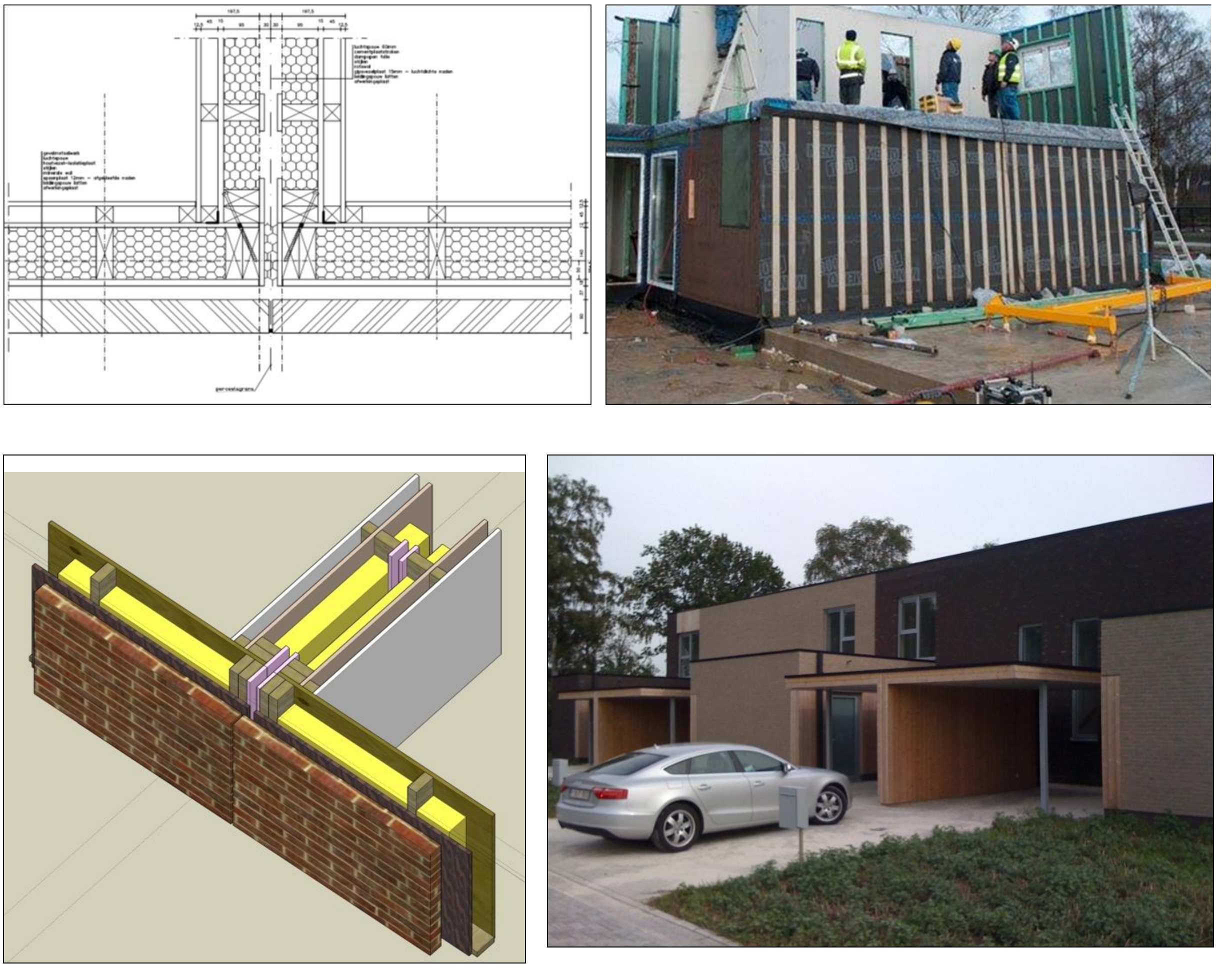
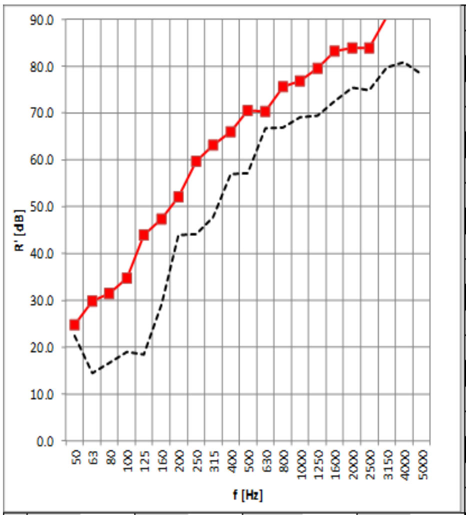
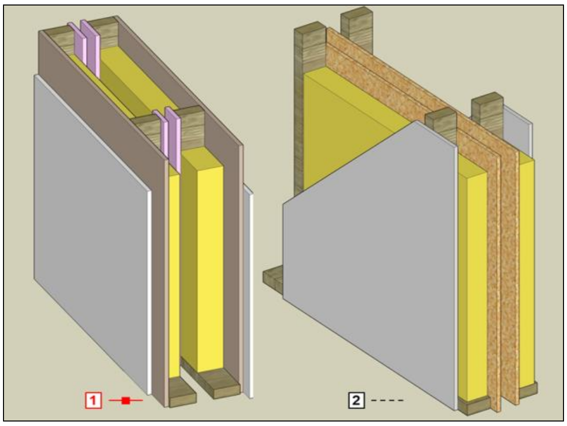


Figure19: fire tests show a resistance of 1 hour with the typical small boards cement boards nailed in the head of the studs. They also maintain the rock wool in place. On top to the right, a picture of half of the party wall belonging to one house and seen from the cavity. The rock wool is protected by a black thin plastic foil to protect the insulation during the construction phase. Down to the right: picture from the social building project in Hechtel-Eksel using this technology (Drawing and pictures from BBRI and Machiels Building Solutions)



f [Hz]	1	2
50	24.8	22.4
63	29.8	14.4
80	31.4	16.7
100	34.7	18.9
125	43.9	18.5
160	47.4	29.1
200	52.2	44.0
250	59.6	44.2
315	63.1	47.8
400	66.0	56.9
500	70.5	57.2
630	70.3	66.7
800	75.6	67.0
1000	76.9	69.0
1250	79.6	69.4
1600	83.2	72.6
2000	83.9	75.5
2500	83.9	74.8
3150	90.6	79.8
4000	92.6	80.9
5000	91.7	78.3

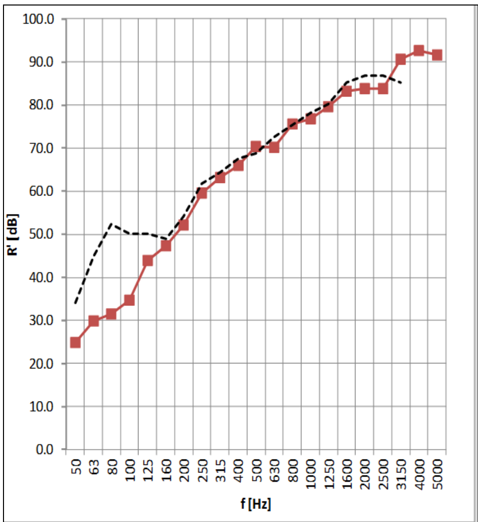
1	R'_{living}= 59 dB	$C_{50-5000}$= -7 dB	$C_{100-3150}$= -5 dB	R'_w= 66 dB
2	R'_{living}= 42 dB	$C_{50-5000}$= -6 dB	$C_{100-3150}$= -6 dB	R'_w= 48 dB



(1) *Central cavity of 60 mm (35 mm between fibre reinforced fire protection boards) and on both sides: 95x45 mm² studs, rock wool 35 kg/m³ 100 mm ***1 x 15 mm fibre reinforced gypsum board + 1 x 12.5 mm standard gypsum board.*

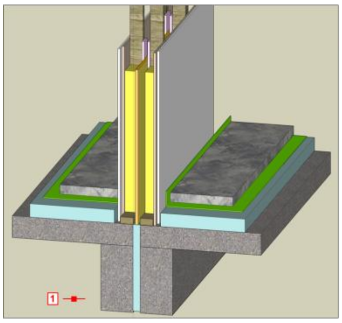
(2) *Central empty cavity of 50 mm and on both sides: 1 x OSB 15 mm *** 160x40 mm² studs, mineral wool 35 kg/m³ 160 mm ***1 x 12.5 mm fibre reinforced gypsum board*

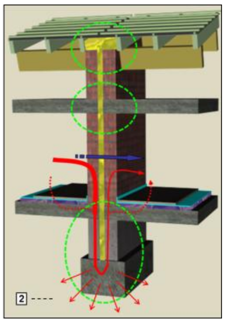
Figure 20- comparison party walls: (1) optimised system with large central cavity (2) traditional party wall with OSB boards in central cavity. For almost the same surface mass of the total wall, a difference of 17 dB in R'_{living}=R_w+$C_{50-5000}$ is measured in favour of the large cavity! (Measurements BBRI (1) project Hechtel-Eksel MBS liv23liv21; (2) project mock-up BBRI-Mobic)



f [Hz]	1	2
50	24.8	34.1
63	29.8	44.9
80	31.4	52.3
100	34.7	50.1
125	43.9	50.1
160	47.4	48.8
200	52.2	54.2
250	59.6	61.7
315	63.1	64.3
400	66.0	67.5
500	70.5	68.7
630	70.3	72.7
800	75.6	75.4
1000	76.9	78.3
1250	79.6	80.3
1600	83.2	85.2
2000	83.9	86.7
2500	83.9	86.9
3150	90.6	85.2
4000	92.6	
5000	91.7	

1	R_{living}= 59 dB	$C_{50-5000}$= -7 dB	$C_{100-3150}$= -5 dB	R_w= 66 dB
2	R_{living}= 68 dB	$C_{50-5000}$= -2 dB	$C_{100-3150}$= -2 dB	R_w= 70 dB





(1) *Central cavity of 60 mm (35 mm between fibre reinforced fire protection boards) and on both sides: 95x45 mm² studs, rock wool 35 kg/m³ 100 mm ***1 x 15 mm fibre reinforced gypsum board + 1 x 12.5 mm standard gypsum board.*

(2) *Central cavity of 40 mm filled with 2 cm glass wool and on both sides a 14 cm brick wall (silent brick Wienerberger). There are no ties between both walls and special measures have been taken for the junctions with foundations and façades.*

Figure 21- comparison with the reference heavy party wall construction, see chapter II.3. (Measurements BBRI (1) project Hechtel-Eksel MBS liv23liv21; (2) project Jabbeke – Wienerberger)

The party wall as an optimized acoustic double wall has very good airborne sound insulation - even in the very low frequencies - and can compete with anchorless heavy constructions. Yet the proposed construction can present problems when vibrational power is directly or indirectly injected in one of the walls. To make this more easily understandable for the non-acoustician, imagine the scenario in which one taps with his hand on the party wall. The boards on this side of the party wall will vibrate and radiate sound. So this side of the party wall is not part anymore of the 'acoustic protection' but becomes the sound source itself. Though this is a somewhat simplified explanation (incorrect for the low frequencies), one could say that the remaining part of the party wall acts as an 'acoustic single wall' and could –depending on the injected vibrational power- possibly offer too little protection especially in the lower frequencies.

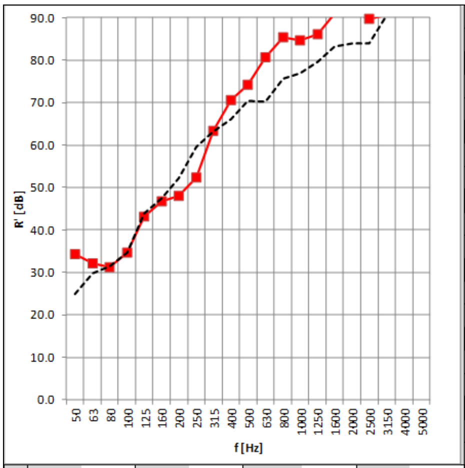
There are many possible sources which fall in this category and will create problems: the injected vibrational power of technical equipment (ventilation units, pumps,…), direct or indirect impacts on the party wall (closing of the door of a cupboard fixed to the party wall, ducts and pipes, sinks…) or structural vibration transmission transmitted from connected walls (closing of doors,…), floors (walking on floors without resilient floor coverings or floating floors), stairs that are fixed to the wall... In Switzerland a specific test method has been developed to measure this kind of noise.

Figure 22: Horizontal and vertical measurement with the pendulous hammer. This device was developed by the research institute EMPA in Switzerland. The aim was to evaluate impact noise of building service equipment in a simple and reproducible manner. The usage of the "pendulous hammer" is described in detail in the appendix B.3.5 of the SIA181:2006 standard.

Solutions are therefore needed. These will be provided by the use of technical linings.

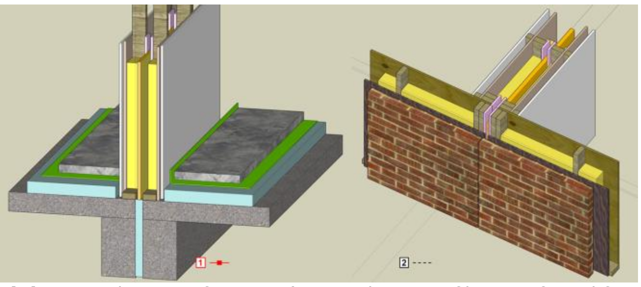
Technical linings will almost always be present in front of the party wall. These are necessary for electric wiring, electricity plugs, piping etc. … Indeed, any perforation of the basic party wall in the acoustically optimized solution is prohibited for fire reasons and concerns about air tightness (Energy Performance Requirements). The use of technical linings (gypsum board, small cavity of 4.5 cm normally containing no porous acoustic absorption material) on both sides of the party wall *will* improve the resistance against the passage of the above-mentioned sounds.

Direct impacts (cupboards, tapping against the wall etc.) will first strike against the technical lining, protecting the party wall behind as injected vibrational energy will only be passed on in a diminished way owing to the extra mass and more complicated structural transmission paths. The technical lining on the receiving side will act as an additional barrier (acoustic lining) except in the proximity of the mass-spring-mass resonance frequency around 125 Hz where its effect might even be slightly negative.



f [Hz]	1	2
50	34.2	24.8
63	**32.1**	**29.8**
80	31.2	31.4
100	34.6	34.7
125	**43.1**	**43.9**
160	46.8	47.4
200	48.1	52.2
250	**52.4**	**59.6**
315	63.4	63.1
400	70.6	66.0
500	**74.1**	**70.5**
630	80.6	70.3
800	85.4	75.6
1000	**84.6**	**76.9**
1250	86.1	79.6
1600	91.0	83.2
2000	**91.7**	**83.9**
2500	89.7	83.9
3150	90.5	90.6
4000	**94.8**	**92.6**
5000	96.5	91.7

1	R'_{living}= 59 dB	$C_{50-5000}$= -5 dB	$C_{100-3150}$= -3 dB	R'_w = 64 dB
2	R'_{living}= 59 dB	$C_{50-5000}$= -7 dB	$C_{100-3150}$= -5 dB	R'_w = 66 dB



(1) *Central cavity of 60 mm (35 mm between fibre reinforced fire protection boards) and on both sides: 95x45 mm² studs, rock wool 35 kg/m³ 100 mm ***1 x 15 mm fibre reinforced gypsum board + 1 x 12.5 mm standard gypsum board.*

(2) *Central cavity of 60 mm (30 mm between fibre reinforced fire protection boards) and on both sides: 95x40 mm² studs, rock wool 35 kg/m³ 100 mm ***1 x 15 mm fibre reinforced gypsum board *** studs 40x40 mm² with empty cavity *** 1 x 12.5 mm standard gypsum board.*

Figure 23: comparison between two constructions with equal surface mass. Case 2 has a technical lining while case 1 hasn't. (Measurements BBRI (1) project Hechtel-Eksel MBS liv23liv21; (2) project Hechtel-Eksel MBS slk23slk21)

These linings also have an impact on the *direct airborne sound insulation (figure above)*. The added mass will lower even more the mass-spring-mass resonance frequency of the party wall on the spring presented by the air in the widest cavity, resulting in even better performances in the very low frequencies. An economic choice is drawn in the above figure with a single fibre reinforced gypsum board for the basic party wall and a 12.5 mm standard gypsum board for the technical lining.

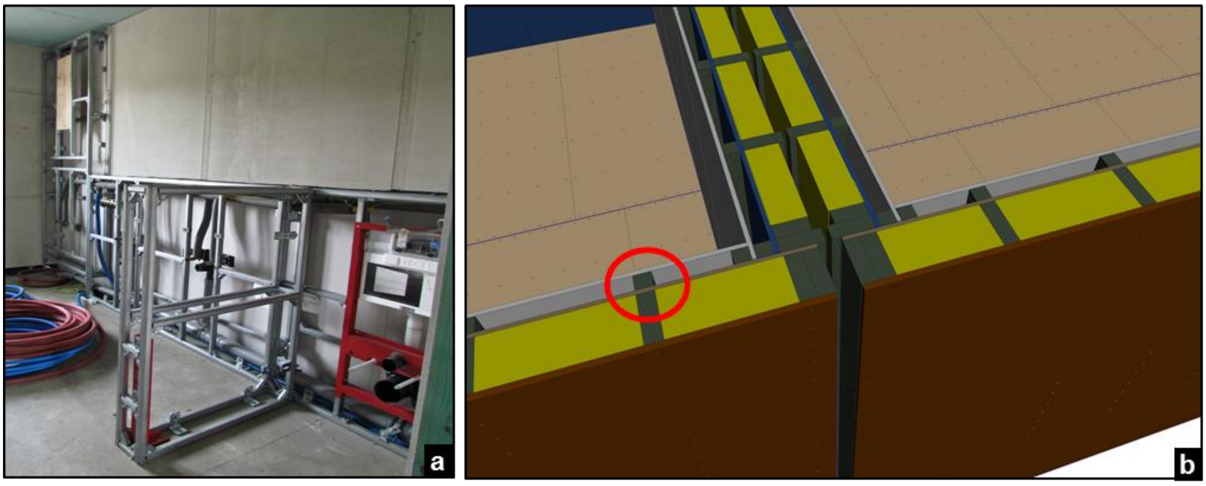


Figure 24: technical lining can be beneficial (picture b) but can present dangers such as the heavy technical lining for bathrooms with thick, very rigid steel studs, to which vibration sources (sinks, toilet…) will be attached (picture a).

Specific rigid metallic technical linings are sometimes used in bathrooms and kitchens. Typical terraced houses have a limited width, and in typical plans, the staircase and bathroom are next to the party wall. There are specific technical linings for bathrooms, lavatories and kitchens which have a reinforced frame so as to be able to cope with the weight of sinks, cupboards etc. Pipes too are fixed into this rigid frame. As this reinforced frame of course needs to be fixed to the lightweight timber frame construction, it can be a dangerous source of vibrational energy. If possible, the easiest way to avoid problems is to adapt the plan of the bathroom/kitchen… so that this rigid frame is connected to a non-common, internal wall. The alternative is the elastic decoupled fixing of this technical rigid lining to the floor and ceiling next to the party wall.

For the same obvious reasons, it is strongly recommended not to fix stairs directly to the party wall. Even 'elastic fixations' are insufficient to avoid acoustic discomfort in the neighbouring dwelling. Ideally, stairs should only be fixed in the floors and/or internal walls of the dwelling. Even in these cases elastic fixations using washers are necessary to obtain enhanced acoustic comfort in the neighbouring dwelling. An even better solution is a stair case with an independent carrying construction.

3.3.4 - Junction of the party walls with the façades and roofs

Light weight party wall constructions need to use 'acoustic double wall' technology to attain sufficient airborne sound insulation. Optimized width of cavities as a function of the surface masses of both wall partitions is one aspect here. Another is avoiding structural connections between the constituting walls if the maximum insulation possible is to be attained. Structural vibration transmission *can* indeed dramatically limit the airborne sound insulation. Even contacts at the edges of the double wall construction can limit the maximum attainable sound insulation. So attention is needed at the edges of the party wall, i.e. in its junctions with the roof and the façade. In the drawings below, one can see the interruptions in the boards in these junctions. The interruption in the façade masonry, useful in heavy constructions, is not really necessary in light-weight timber frame constructions, at least not for acoustic reasons.

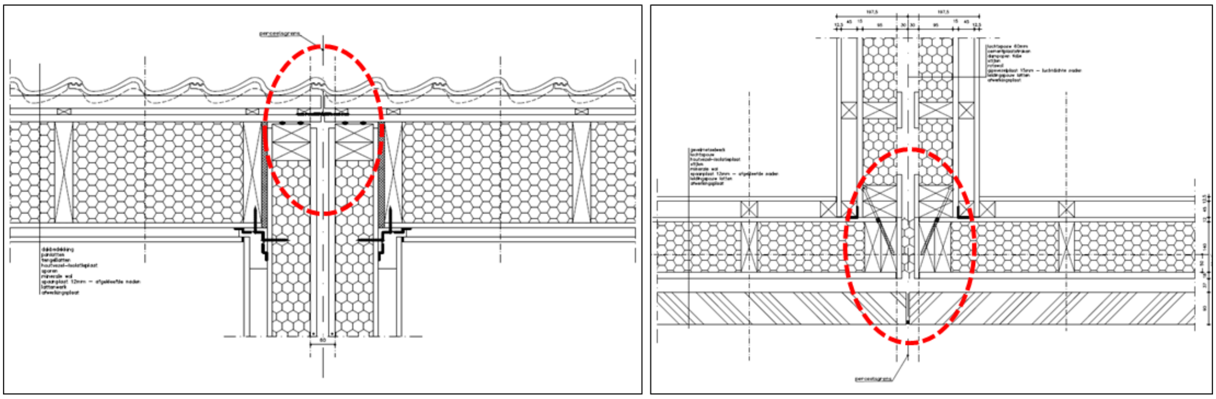


Figure 25: the decoupling should also be respected at the borders of the party wall (junction with the roof to the left, junction with the façade to the right)

3.3.5 - Junction of the party walls with the foundation or lowest floor

Depending on the condition of the building plot, i.e. its load carrying possibility versus the weight of the new construction, the depth of the phreatic surface, the nature of the layers of which it is composed and the risks of differential settings, the strategy of thermal insulation etc. or even the building technique used, many types of foundations can be found. Some examples are given below.

The junction at the foundation can influence the direct sound insulation of the party wall. In the figures 26 'c' and 'd' both wall portions are connected by the continuous concrete from respectively the concrete beam and concrete slab. This will diminish the maximum possible sound insulation of the party wall. The separation of the concrete slabs in figures 26 'a' and 'b' is more favourable for optimal "acoustic double wall effect" and clearly interrupts a possible transmission path between the two wall portions. Even rigid thermal insulation as EPS or XPS will do as a separating element to obtain this positive disconnection effect.

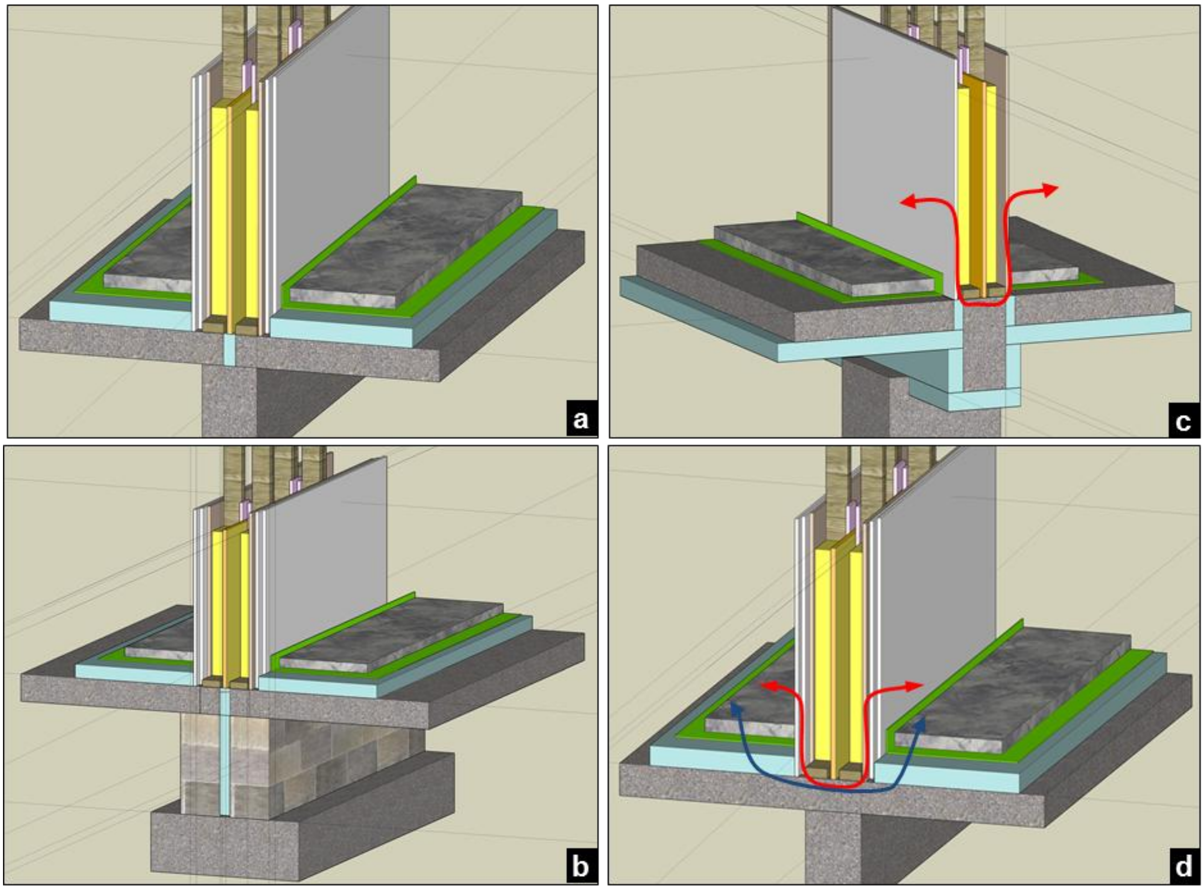
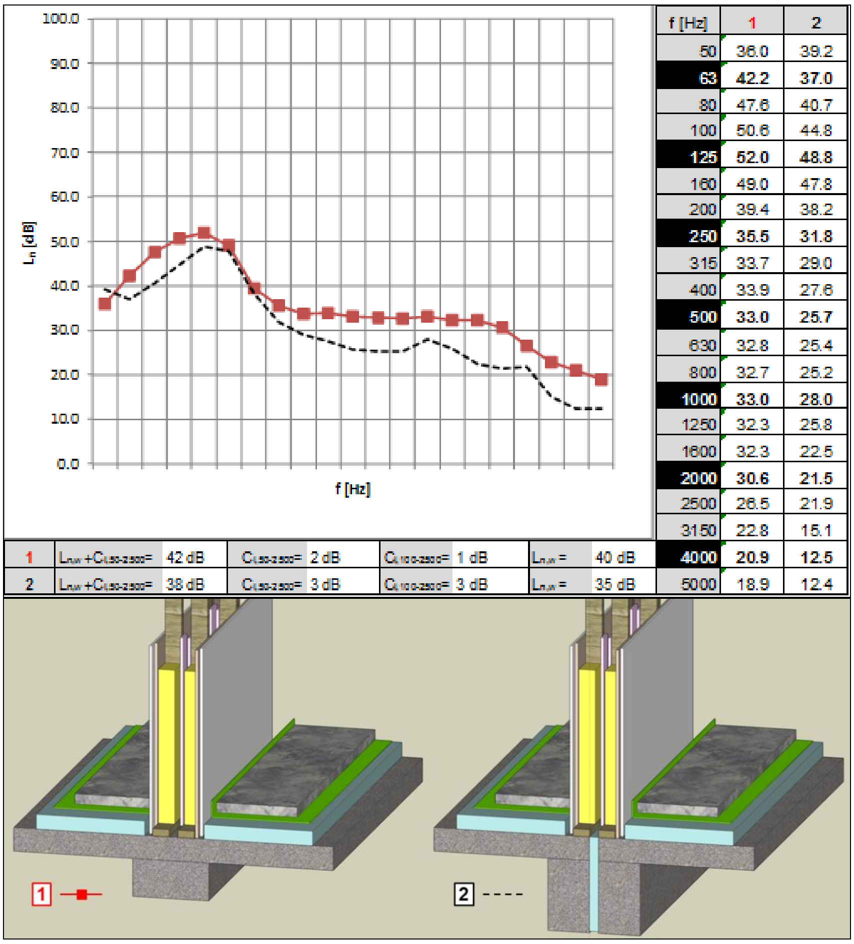


Figure 26: some possible foundations and junctions with the party wall. The use of floating floors is everywhere recommended to avoid impact sound. In figures 'c' and 'd' the maximum possible sound insulation that can be obtained with the party wall will not be attained due to a connecting path between both wall portions via the concrete slab/ beam.

In figure 26 'd' there is more to worry about: first there is the risk of excessive impact sound transmitted through the continuous concrete slab and secondly important flanking transmission is something to worry about. Although a good floating floor in both dwellings could reduce the impact and airborne flanking sound transmission, this is a risky solution we would certainly not recommend. There is always the risk of a not perfectly executed floating floor and of course this solution certainly limits the direct sound insulation of the party wall. Imagine the case with this solution with no floating floor or a badly executed one. The light weight party wall will only have a very low vibrational reduction effect on the transmission path ‘Ff’ (floor to floor) and even other flanking transmissions paths (‘Fd’, ‘Df’) might influence the sound reduction between both adjacent dwellings.

The vibration gaps in figures ‘a’, ‘b’ and ‘c’ certainly diminish the impact sound transmission and eliminates most of the airborne flanking transmission. The installation of a floating floor is still highly recommended for optimal comfort against impact sound. In figures 26 ‘a’, ‘b’ and ‘d’, the thermal insulation has been placed on top of the concrete floor. When this thermal insulation is rigid, a supplementary resilient layer needs to be placed on top of the thermal insulation.



f [Hz]	1	2
50	36.0	39.2
63	42.2	37.0
80	47.6	40.7
100	50.6	44.8
125	52.0	48.8
160	49.0	47.8
200	39.4	38.2
250	35.5	31.8
315	33.7	29.0
400	33.9	27.6
500	33.0	25.7
630	32.8	25.4
800	32.7	25.2
1000	33.0	28.0
1250	32.3	25.8
1600	32.3	22.5
2000	30.6	21.5
2500	26.5	21.9
3150	22.8	15.1
4000	20.9	12.5
5000	18.9	12.4

1	$L_{n,w}+C_{I,50-2500}$= 42 dB	$C_{I,50-2500}$= 2 dB	$C_{I,100-2500}$= 1 dB	$L_{n,w}$ = 40 dB
2	$L_{n,w}+C_{I,50-2500}$= 38 dB	$C_{I,50-2500}$= 3 dB	$C_{I,100-2500}$= 3 dB	$L_{n,w}$ = 35 dB

Figure 27: comparison avec the impact sound insulation with well executed floating floors. Both results are excellent, but the interrupted concrete slabs have a 4 dB better performance and offers some additional ‘insurance’ for the case when something goes wrong with the floating floor. (Measurements BBRI-MBS RE Hechtel-Eksel liv23liv21 for case 2 and liv19liv21 for case 1)

Last but not least: absolutely to be avoided is a continuous wooden floor on a concrete foundation between two dwellings. Indirect sound transmission, the coupling of both party wall portions, very important airborne and impact flanking transmission are disastrous for the acoustic comfort.

3.3.6 - Remark: indirect sound transmission to the adjacent house via façades and ventilation ducts

Thanks to the above discussed concept of the party wall, no structural flanking transmission is possible between the two terraced dwellings. But problems can arise with indirect airborne sound transmission.

A very classical problem is the transmission path across ventilation grids that lack or have insufficient acoustic damping. This is also a frequently encountered problem in heavy constructions. Even in very calm environments, if natural ventilation using ventilation grids is chosen, ventilation grids should have a minimal sound transmission loss both for privacy reasons and to avoid indirect sound transmission to adjacent houses/apartments. The same reasoning is valid for all weak points in the sound insulation of the façades.

Typically for light weight timber frame constructions, two further paths for these indirect airborne transmissions are possible as well in the horizontal (terraced houses) as in the vertical direction (to be avoided in the case of apartment constructions):

- TRANSMISSION PATH 1: Across the internal visible wall of the emission room to the exterior cavity (a gap 2 to 3 cm between the façade cladding and the 'wind screen panel'), propagation throughout this cavity and finally across the internal visible wall to the room at the reception side.
- TRANSMISSION PATH 2: Across the façade/roof of the emission room to the outside and finally across the façade/roof of the reception room.

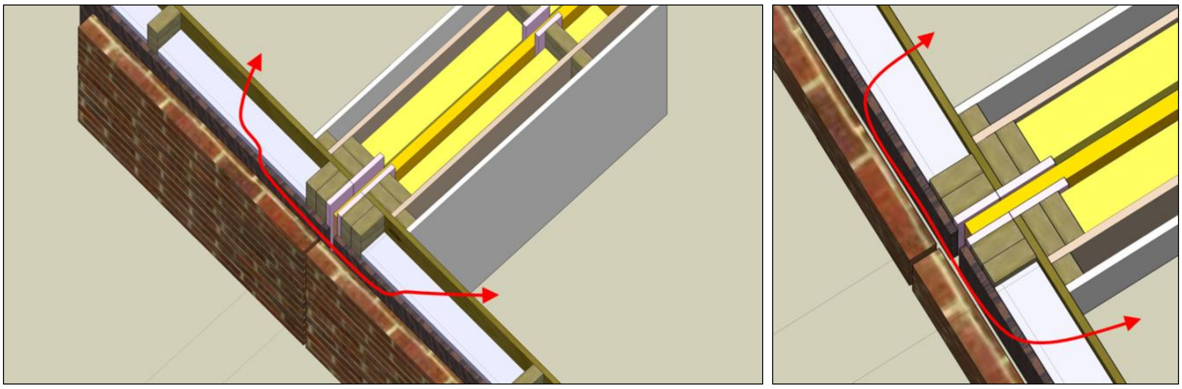


Figure 28: transmission path 1 for the indirect sound transmission, this transmission path is important when thermal insulation is used with no acoustic absorbent characteristics.

This needs some explanation: the inside façade wall is normally a stud wall construction with the typical traditional board fixed at the side of the room, giving strength (also laterally) to the construction. On the outside though, very often a low density (200 to 250 kg/m³) wood fibre panel of 18 mm is used, adding to the thermal insulation and fulfilling the task of windscreen but still allowing for vapour permeability. The use of these light panels results in a rather low direct sound insulation of the stud wall construction. This is even worse when PU or EPS (see figures above and below) is used to optimize the thermal performances. Sound penetrates across this construction and - depending on the exterior finishing - both above-mentioned transmission paths are possible.

When the exterior finishing is made of a heavy material (brick finishing, cement boards with stucco finishing…), only the first indirect airborne transmission path will occur in the cavity (if present, which is normally the case) between the exterior finishing and the low density board.

In the case of a light-weight (wooden planking…) or non-acoustically tight finishing (tiles…) the second path also will occur.

The indirect airborne transmission path in the cavity inside the stud construction is normally negligible due to the studs of the façade wall that connect this wall with the studs of the party wall

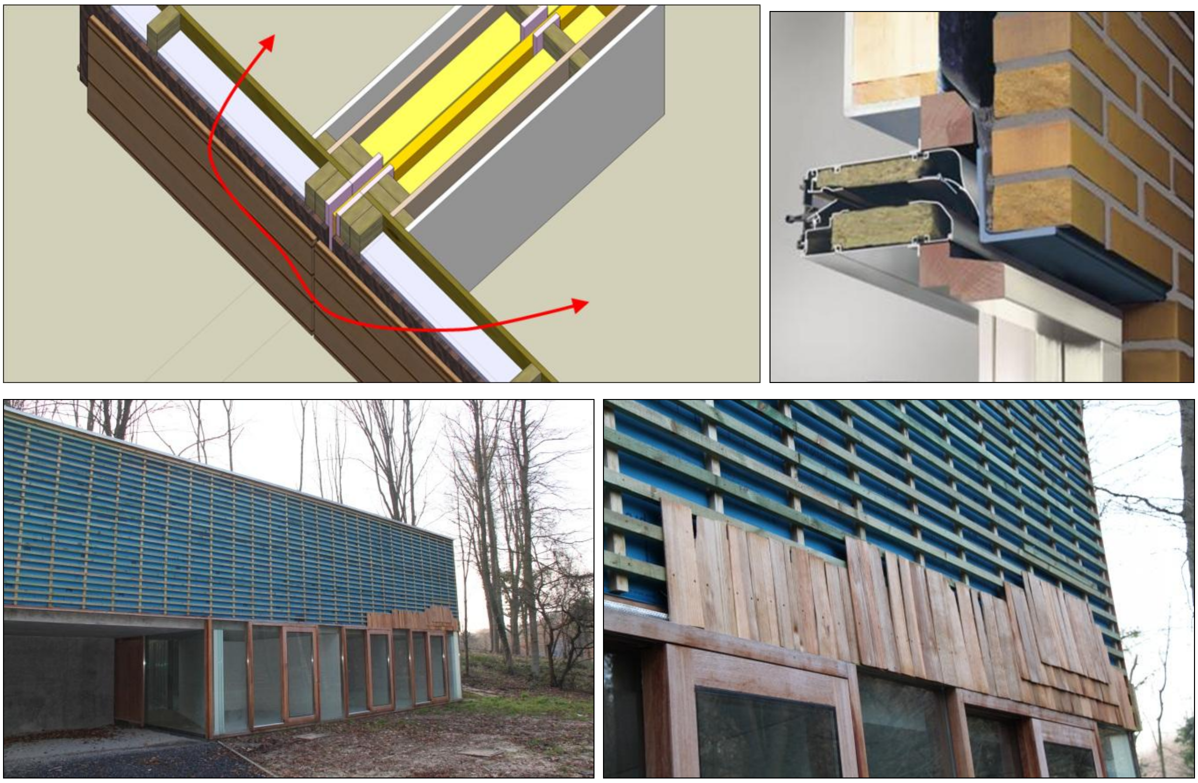


Figure 29: transmission path 2 when the sound façade insulation is low (rigid thermal insulation with closed cells, cladding, cedar tiles,…). Ventilation grids should have a minimal acoustic sound insulation to avoid indirect sound transmission

3.4 - Floors

Most acoustic requirements in European countries for the sound insulation between rooms of the same dwelling are rather low or even inexistent.

For minimal comfort reasons, $D_{nT,w}$ > 35 dB and $L'_{nT,w}$ < 60 dB are often imposed or advised.

Many solutions comply with these requirements. In some countries, resilient floor coverings or floating floors are standard tradition not only in apartment constructions but even in terraced houses. This increases the acoustic comfort for the inhabitant.

But if your country has low or no requirements for the sound insulation between rooms in the same dwelling, are these floating floors or resilient coverings necessary for the impact sound insulation to the adjacent dwelling? Or can parquet be glued or nailed straight into the boards of the load carrying floor, saving height and money? Indeed if a floating floor is necessary and parquet is desired, a resilient interlayer and an extra board (or lattices) are necessary to be able to nail/glue the parquet…. increasing as such the cost of labour and materials.

In *traditional party walls (boards-studs-boards/cavity/ boards-studs-boards)*, there is also a perfect structural disconnection from the foundations to the roof. The vibrational power injected by footsteps (or the impact machine) can propagate to the first partial wall of the party wall where it can radiate sound (and transmit vibrations via mass-spring-mass coupling to the second wall). The second partial wall is a double wall (though with rigid wooden studs) and a sufficient barrier against the radiated sound of the first wall. So, with this kind of party walls, floating floors are eventually not necessary (but still highly recommendable) in countries where no acoustic requirements exist between rooms/floor levels of the same dwelling. We do advice, though, to have a floating floor on the lowest level. The disconnection between the two dwellings is always weaker or inexistent at the lowest level (sometimes a continuous concrete slab) and acoustic discomfort due to impact sound or non-compliance with acoustic requirements is a major risk if no floating floors are applied.

Using the same simplified (and definitely incorrect for lower frequencies) reasoning of a 3 room-model approach, one can understand that the situation is different for *the party wall construction with a single large cavity*. The partial wall at the reception side consists of an ‘acoustic single wall’ composed of boards, offering a rather weak sound barrier especially in the low frequencies. When no technical linings are applied (to be avoided, one is well advised to provide them, see above), there is a major risk that transmitted impact levels are too high and not comply with local requirements for the sound insulation between terraced dwellings. Even when technical linings are applied, this could still generate problems. As technical linings have rigid stud connections with the party wall, have a mass-spring-mass resonance frequency around 125 Hz and have no absorption material in the cavity, it is unclear how much the technical lining can improve the impact sound insulation. Unfortunately, no measurements of these situations are available, so it is a safe precaution to have floating floors on all levels. This is indeed different in the case of heavy tie-less constructions. Here, floating floors are necessary only on the lowest floor (for these countries which do not have requirements covering internal impact sound insulation within the same dwelling).

4 - APARTMENT CONSTRUCTIONS

4.1 - General

For terraced dwellings, the acoustic problems have mainly to do with the horizontal airborne and impact sound transmission.

Multifamily constructions imply in most cases dwellings on top of each other. Total structural decoupling is then of course not possible any more. This implies a direct impact sound transmission path (which we did not have with terraced houses), numerous flanking transmission paths and greater difficulty in obtaining direct airborne sound insulation in the vertical direction. For countries using the D_{nT} quantity, the relation with R' also becomes less favourable as the term 10.lg(V/3.S) is much less advantageous (V/S≈average height) than in a horizontal direction (V/S≈average depth perpendicular to the separating wall) for larger rooms.

Sound insulation in a vertical direction is crucial for the experienced acoustic comfort, but is unfortunately rather complicated to optimize. The lack of acoustic comfort most complained about is low frequency impact noise.

Larger lightweight timber frame apartment constructions are a relatively recent phenomenon. Smaller constructions, of the kind of terraced units with one or two apartments on top of each other in each unit, are more frequently met. Standard constructions of this type all over Europe pretty much look structurally alike and are largely determined by Eurocode 5 structural calculations. Façade finishings, section of joists and studs and layers of thermal insulation differ, but real acoustic optimisation can only be seen in more recent projects. Lots of details (floors, walls, façades and even some junctions) and corresponding acoustic, thermal and fire data can be found in the excellent database www.dataholz.com and in many different publications (see literature list) such as 'Robust Details', 'Acoustic performance of party floors and walls in timber framed buidlings', etc. (see literature list). Some innovative systems (the use of elastic joints to reduce flanking transmission, special damping constructions within floors, etc..) will be shown later on.

In many countries, technical building guidelines covering lightweight timber frame constructions exist, but the acoustic information mostly remains scarce and limited to single ratings based upon the frequency range down to 100 Hz. Moreover, building guidelines stick to solutions that comply with building regulations. As these requirements are suitable to guarantee acoustic comfort for heavy constructions, but not necessarily for lightweight constructions, there still are quite a lot of problems to be solved and improvements to be made.

In the figure below, a Finnish construction (Ylojärvi apartments) is presented with an overall great acoustic performance. In the charts, spectral information of normalized impact sound levels and apparent sound reduction indices are compared with the average results in heavy apartment constructions with floating floors (see discussion in chapter 2). Both impact and airborne sound insulation of the Finnish construction are more than ‘respectable’ but remain in the low frequency bands below the traditional heavy constructions.

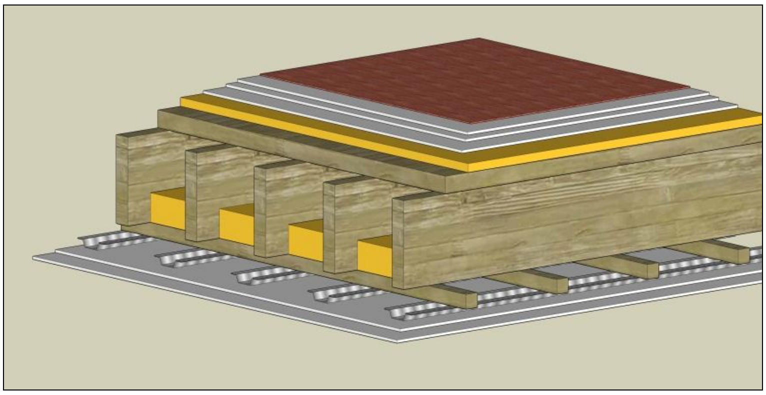
Outline of this section 4:

In the next sections, we will first have a quick look in 4.2. at the party wall construction, being quite similar as to the party walls discussed in the part of this text about terraced houses. Next, compartment floors are being examined in 4.3. The impact sound insulation is extensively treated with topics such as:

(1) the choice between resilient floor coverings and floating floor;
(2) some words explaining how floating floors acoustically work and how this can be different compared to floating floors with heavy floors;
(3) possible errors with the characterisation of the efficiency of floating floors;
(4) current craftmanship errors in the field;
(5) types of floating floors in LWTF construction;
(6) the effectiveness of dry floating floor systems used in LWTF constructions
(7) the necessity of false ceilings

Section 4.3. also gives some information about the airborne sound insulation and some basic information about comfort against vibrations. A series of solutions / examples with the acoustic performance closes this chapter.

Section 4.4. takes a closer look at junctions and the flanking transmission that occurs in these. Techniques to reduce the flanking transmission are being discussed. In the report of WG 1, a methodology to estimate the flanking transmission has been described. In this document, measurements give some indication about the importance of the flanking transmission for some junctions.



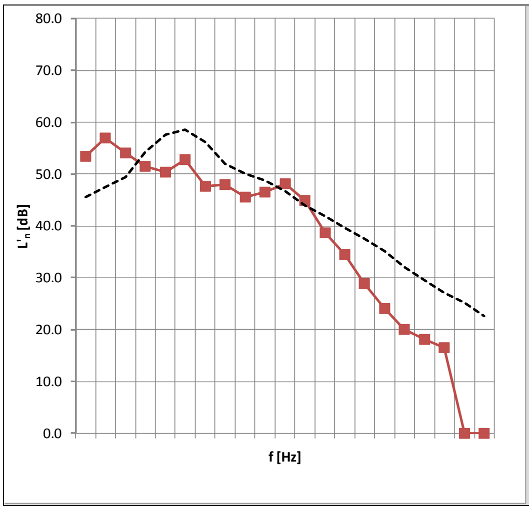
*REF.: Sound insulation structures of beam-to-column framed wooden apartment buildings *** Asko Keronen – Mikko Kylliäinen *** Tampere University of Technology (1997) *** ISBN 951-722-776-0 *** Ylöjärvi apartments, appendix 3 page 1 (L'n) and appendix 5 page 1*

Topping: *Vinyl *** 3x12.5 mm fibre gypsum boards (30.8 kg/m²)*** mineral wool 30 mm (100 kg/m³)*

Floor: *ribbed slab (thickness 6 cm), joists ca. 30 x 6 cm²*

Cavity: *mineral wool 100 mm (30 kg/m³)*

Ceiling: *wooden spacers 5x5 cm² *** resilient channels *** 2x12.5 mm gypsum boards(ca. 2x9.4 kg/m²)*



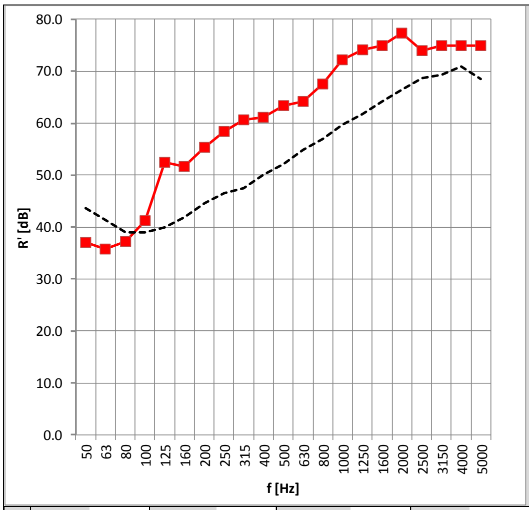
f [Hz]	1	2
50	53.4	45.6
63	**56.9**	**47.5**
80	54.1	49.4
100	51.5	54.2
125	**50.3**	**57.6**
160	52.8	58.5
200	47.6	56.1
250	**47.9**	**52.0**
315	45.6	50.1
400	46.6	48.8
500	**48.2**	**46.6**
630	45.0	44.0
800	38.7	41.9
1000	**34.5**	**39.7**
1250	28.9	37.6
1600	24.0	35.2
2000	**20.0**	**32.1**
2500	18.2	29.5
3150	16.6	27.0
4000	**0.0**	**25.1**
5000	0.0	22.6

1	$L_{n,w}+C_{I,50}$	47 dB	$C_{I,50-2500}$=	3 dB	$C_{I,100-2500}$=	dB	$L_{n,w}$=	44 dB
REF	$L_{n,w}+C_{I,50}$	49 dB	$C_{I,50-2500}$=	2 dB	$C_{I,100-2500}$=	2 dB	$L_{n,w}$=	47 dB

1 —■— **LWTF construction described above**

2 ------ **Average performance heavy floor constructions with floating floors in Belgium (see chapter 2)**

(part of Figure 30)



f [Hz]	1	2
50	37.1	43.6
63	**35.7**	**41.3**
80	37.3	39.0
100	41.2	39.0
125	**52.4**	**39.9**
160	51.7	41.9
200	55.3	44.7
250	**58.4**	**46.5**
315	60.6	47.5
400	61.2	50.0
500	**63.3**	**52.1**
630	64.1	54.9
800	67.6	57.0
1000	**72.2**	**59.6**
1250	74.2	61.7
1600	75.0	64.2
2000	**77.3**	**66.4**
2500	73.9	68.6
3150	75.0	69.3
4000	**75.0**	**70.8**
5000	75.0	68.6

1	R'_{living}= 64 dB	$C_{50-5000}$= -3 dB	$C_{100-3150}$= -2 dB	R'_w= 67 dB
2	R'_{living}= 56 dB	$C_{50-5000}$= -1 dB	$C_{100-3150}$= -2 dB	R'_w= 57 dB

1 **LWTF construction described above**

2 ------ **Average performance heavy floor constructions with floating floors in Belgium (see chapter 2)**

Figure 30: comparison of normalized impact sound levels and apparent sound reduction indices between an acoustically very well performing Finnish LWTF floor construction and the average result in heavy apartment constructions with floating floors (see discussion in section 2).

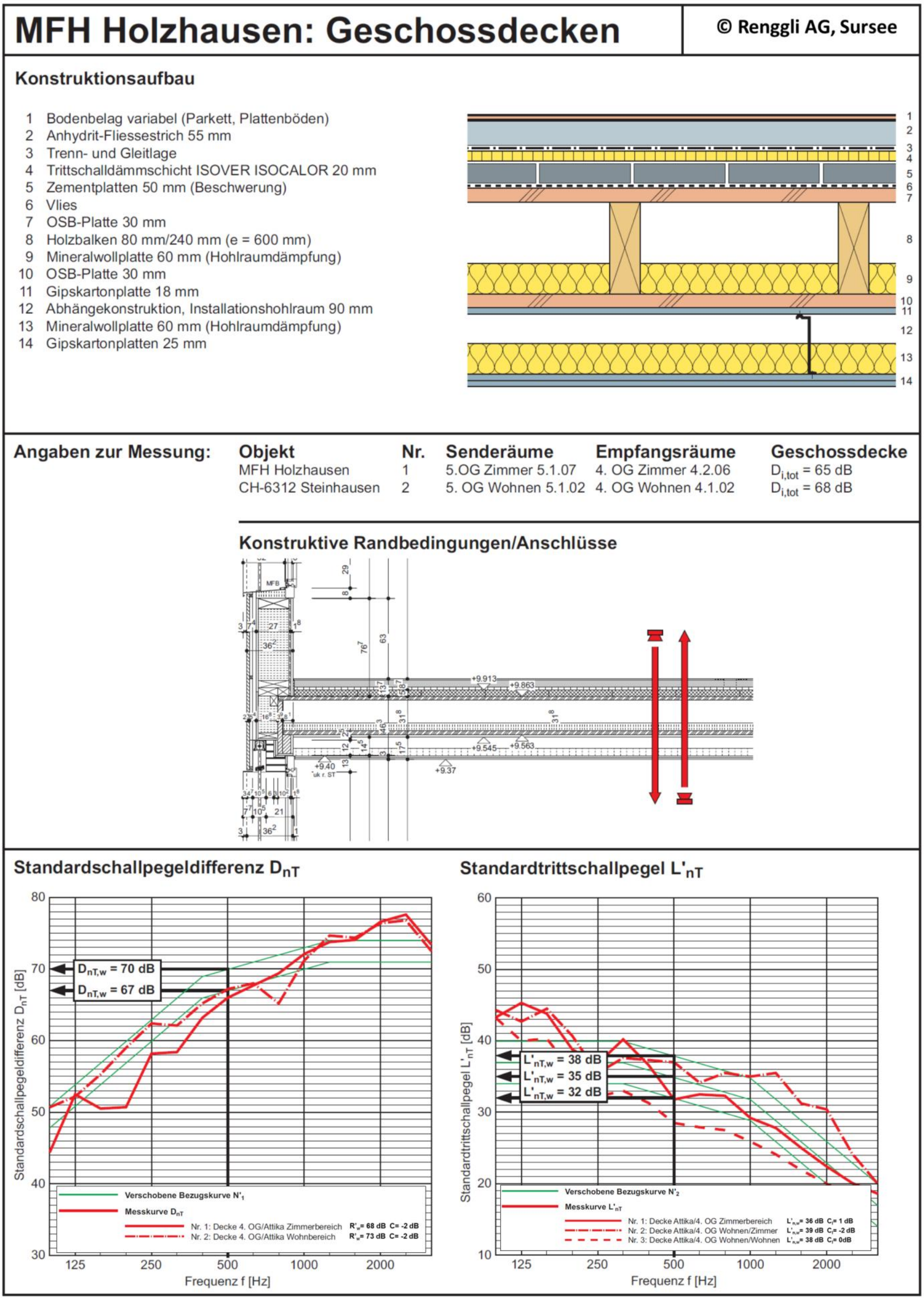


Figure 31: floor construction in the first 6 floors high LWTF project in Steinhausen, Switzerland (MFZ Holzhausen, © Renggli AG, Sursee).

4.2 - Party walls

In the horizontal direction, we can refer to the discussion of party walls in terraced houses, at least for small scale buildings. For larger projects, the required horizontal stability under wind load or earthquake resistance might mean that using the same total separation construction is just not feasible. But in different projects in Europe, we have seen that this problem in large-scale projects is often solved by having a rigid concrete or steel core inside the building containing staircases and lifts (necessary in any case for lifts), although this increases building time. All horizontal forces of the LWTF construction are then brought to bear on this steel or concrete core (e.g. Limnologen Växjö).

Another problem can be penthouses whose floor plans can stretch out over several apartments situated below. No particular details and measurements as a solution for this are available, though one could imagine a locally elastically coupling of the load-carrying floors each time at the party walls of the apartments below. The floating floor could then continue above these party walls so that visually no gap occurs, while acoustically no real structural coupling occurs between the two constituent walls of the lower party walls.

4.3 - Compartment floor constructions (incl. ceilings)

4.3.1 - Introduction

Before considering the junctions and the problems with the numerous flanking transmission paths, it is useful to study in detail the direct insulation against airborne and impact sound. Particularly impact sound, mainly in the low frequencies (drumming sound) can be a major problem in LWTF constructions.

Most compartment floor systems (separating two apartments) consist of 3 structured layers: a floating floor or resilient floor covering is built up on top of the load carrying floor (a combination of joists and boards) and a ceiling mostly made of gypsum boards. A problem could be the thickness (exceeding standard thicknesses of 30 cm to 35 cm in heavy weight constructions) and the weight of these floors when really high performances are required.

4.3.2 - Impact sound insulation

A basic structure without any kind of resilient floor covering or floating floor just will not offer sufficient acoustic comfort against impact sound.

Using floating floors to reduce impact sound has some additional benefits compared with resilient floor coverings; this is discussed in point (1) here below.

It is important to understand how floating floors reduce impact sound (paragraph 2) and how it is correctly characterized to avoid mistakes and to optimize constructions or to look for innovations. But the choice of kind of floating floor is less easy than for heavy constructions and design mistakes are quickly made (paragraph 3).

Next (paragraph 4) we will look at the professional placing of the floating floor so as to avoid frequently-made errors. As small errors almost entirely eliminate the benefits of the floating floor, good craftsmanship is absolutely necessary. Finally (paragraph 5), we will take a closer look at the different families of floating floor concepts and their acoustic performances.

4.3.2.1 - ***Reducing impact noise: the choice between resilient floor coverings and floating floors***

Resilient floor coverings such as carpets and laminate floors on elastic underlays are sometimes used in LWTF constructions. These solutions work out fine in terraced houses where the obtained impact sound reduction can be sufficient. Applying these in apartment constructions is also feasible but presents certain disadvantages: solutions with resilient floor coverings require a much better performance of the rest of the construction of the floor. In some countries, the necessary impact sound insulation must be attained even without the resilient floor covering (e.g. Belgium) owing to legal concerns and discussions: the change of carpets towards parquet or tiling is sometimes considered as an interior decoration change and the concept of the building should be such that these changes have no impact on the building physics of the construction. Floating floors are in this case not only an advantage but a must.

Last but not least, floating floors are very interesting for limiting flanking sound transmission, an advantage resilient floor coverings do not offer. There exist constructions with resilient floor coverings showing sufficient impact reduction in the laboratory to allow one to hope that they will comply with acoustic requirements in situ. But there is the problem of the flanking transmission 'Df'[2]. Without the floating floor, the load-carrying floor and especially the boards will be excited directly by the tapping machine (or walking persons…) and this energy will be transmitted to the load-bearing walls below where it will radiate as impact noise and added to the directly transmitted impact noise ('Dd'). There are four of these flanking paths 'Df' and that can add up quite a lot of sound. Two of these flanking paths 'Df' can be more important than the remaining ones. Indeed the propagation of the vibrational energy injected by the tapping machine will be more rapidly attenuated by distance in the direction perpendicular to the load-bearing joists (at each crossing of a joist an extra attenuation happens). So using linings in front of the floor-carrying walls could possibly be of some help (though we have to take into account perverse effects of the mass-spring-mass-resonances of the linings). But the best way to cope with these flanking transmissions is to install optimised floating floors.

4.3.2.2 - ***How do floating floors reduce impact noise?***

Floating floors are mass-spring-mass systems (see figure below). They may reinforce vibrations at the resonance frequency of the system, but above this frequency, the

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[2] An international convention is to indicate transmission ways using capitals for the start of the flanking path at the emission room (with 'D' indicating the direct separating floor or wall between the two rooms seen from the emission side, 'F' represents a flanking wall in the emission room most of the time perpendicular to the direct separating wall or floor). Minuscules are used for the end of the flanking path at the reception side. (with 'd' indicating the direct separating floor or wall between the two rooms seen from the reception side, 'f' represents a flanking wall in the reception room most of the time perpendicular to the direct separating wall or floor').

transmission of vibrations (and the afterwards radiated impact sound) is ever more reduced with increasing frequency (see figure below). Good floating floors are designed in such a way that the resonance frequency is as low as possible (where the sensitivity of the human ear is lower or inexistent) generating an important reduction of the impact sound in the greatest part of the audible spectrum.

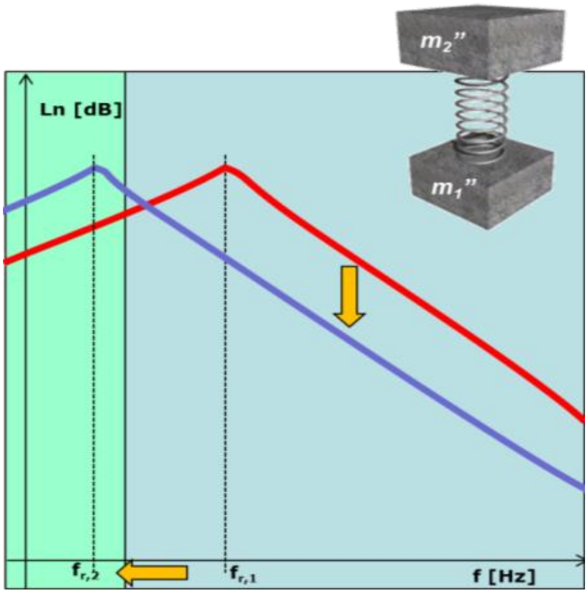


Figure 32: Shifting the resonance frequency in the figure from $f_{r,1}$ to $f_{r,2}$ reduces considerably the impact noise. Although we try to avoid formulas in this WG 4 report, the following simple formula is very useful to calculate the mass-spring-mass resonance frequency f_r. It allows for a better understanding of how the floating floor system works. The resonance frequency f_r resulting from the system composed of the load bearing floor with surface mass m''_1 [kg/m²], the spring with dynamic stiffness s [MN/m³] (normally an elastic interlayer) and the floating floor with surface mass m''_2 (surface mass refers to the mass that acts per surface unit of the spring), can be calculated by:

$$f_r = \frac{1}{2\pi}\sqrt{s.\left(\frac{1}{m''_1}+\frac{1}{m''_2}\right)}\ [Hz]$$

Other mechanisms such as internal and surface damping will also influence the final impact reduction obtained with the system.

Unfortunately, this model is only so simple and valid for rigid concrete constructions. For less rigid light weight timber frame floors, the behaviour can be unexpectedly slightly different. Dynamic impacts on the topping can sometimes be unable to cause the interlayer to compress but instead cause the direct deformation of the supporting subfloor. As such, subfloor and topping are not sufficiently decoupled and the resonance frequency can be less influenced by changing for instance the stiffness of the elastic interlayer. This effect has been noticed in measurements in the National Research Council Canada[3] and in the measurements by BBRI discussed in chart 10 in this section 4.3.2.

4.3.2.3 - *<u>Floating floors to be used in LWTF-construction are often wrongly characterized, leading to wrong concepts and too much impact noise. Moreover most floating floors are often less efficient when applied in LWTF constructions than identical ones used in heavy constructions.</u>*

The efficiency of a floating floor system is expressed by ΔL_w (see EN ISO 717-2). One could describe this quantity as a *single rating that expresses the reduction of the impact sound of*

[3] On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012)

a floor system due to the use of the floating floor. Owing to the still dominant heavy way of building, most products used in floating floors have been characterized for use on heavy floors of ca. 14 cm thick concrete (EN ISO 10140 parts 3 and 5), though these standards also permit a characterization for three types of lightweight timber floors. *One has to be careful not to use the ΔL_w (the weighted reduction of impact sound level) determined on the reference concrete floor in applications with lightweight timber frame constructions!* The correct ΔL_w of the floating floor applied on lightweight timber floors can be quite a bit smaller. One should always keep in mind that the ΔL_w characterizes the total mass-spring-mass system (load-carrying floor – resilient interlayer –floating floor) and not the resilient interlayer alone. So the same elastic interlayer applied on and under different masses and types of materials will have a totally different efficiency in reducing impact sound! There are two reasons for this:

Floating floors equally work as a mass-spring (here the elastic interlayer)-mass system, with the mass of the concrete load-bearing floor being considerably different from the lightweight constructions. Moreover, typical screed like solutions (6 to 8 cm at a density of 1800 kg/m³) put on top of the resilient layer in heavy constructions are often much heavier than the classical floating floor types (e.g. boards) installed in LWTF constructions. That means that the mass-spring-mass resonance frequency for the same elastic interlayer is much lower for the heavy type of construction than for LWTF construction. The lower the mass-spring-mass resonance frequency, the better the impact sound insulation will be. This is therefore a problem from the outset for LWTF constructions.

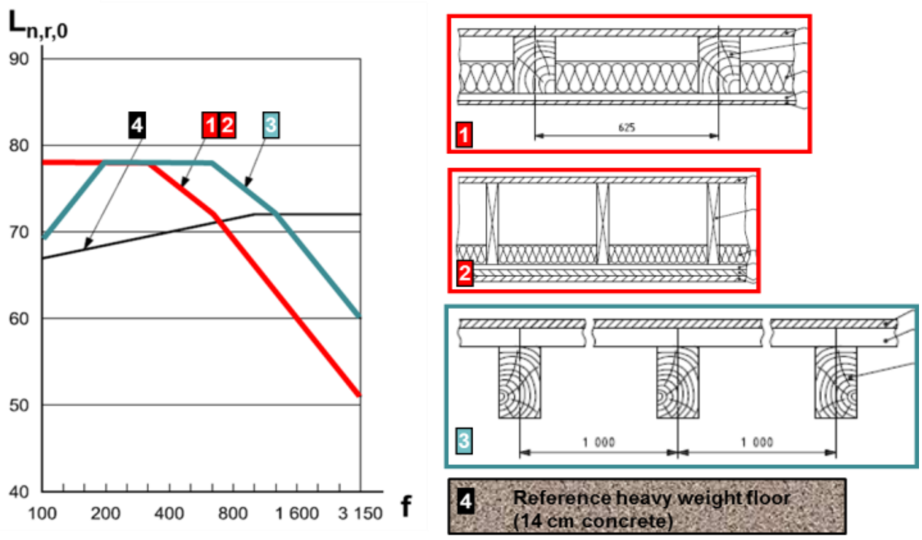


Figure 33: impact sound on reference floors as specified in EN ISO 10140-5. The improvement of the impact sound represents the difference between the impact sound measured directly on the reference floor and measured with the floating floor.

But there is another reason why it is more difficult to reduce impact sound with a lightweight basic floor than with the heavy concrete reference floor. When the tapping machine is positioned on the concrete floor, it generates more sound in the higher frequencies than in the lower frequencies. For the same tapping machine placed on the bare wooden floor (without a ceiling finishing), the opposite is true: more sound power is radiated in the lower frequencies than in the higher frequencies (see figure here above). The attenuation effect of a mass-spring-mass system increases with the frequency above its resonance frequency. Even if one had floating floor systems with the same mass-spring-mass resonance frequencies, the above reasoning explains why the reduction of the impact sound offered by the floating floor will still be much larger for heavy floors than for LWTF constructions.

All this means that one has to be very careful with ΔL_w –values proposed in technical documentation. Most of them were measured on standard concrete floors and show an efficiency that is way above what can be attained with lightweight wooden floors. There are two possible options if one has to choose a floating floor system (or for manufacturers to characterize their product): one could ask manufacturers for the ΔL_w-value measured on the most suitable type of reference wooden floor described in EN ISO 10140-5 represented in the figure above; the even better alternative is to measure the impact noise level $L_{n,w}$ of the complete floor with its ceiling in a laboratory construction.

4.3.2.4 - ***Of course floating floors should 'float' and execution errors must be avoided. No hard contacts should link the floating floor to the adjacent walls or to the load-carrying floor. Even small hard contacts will almost entirely eliminate all beneficial effects of the floating floor. In general, the same rules apply as for the placing of floating floors in heavy constructions.***

Resilient strips should be placed between the floating floor and the adjacent walls so as to avoid a hard connection. Where foils are used as an elastic interlayer, this can simply be done by folding the foils up to the wall (figures 34 'a' and 'b'). Especially when working with screeds and concrete floating floors, these resilient border strips should be placed with extreme care. They should only be cut off after the tiling or the parquet has been placed so as to avoid any hard contact with the wall through the floor finishing. Architects and work surveyors should check that the border strips are still visible after placing the floor finishing and before placing the plinths (see figure 34 'e'). Plinths should be fixed to the walls and make no hard contact with the floating floor. If desired, an elastic joint filling (silicones…) can be applied between plinths and floors.

Pipes passing through the floating floor should be detached from the floating floor using again resilient strips around the pipes. Fixations of whatever equipment (radiators, etc.) should not make any hard bridges between the floating and the basic floor (see figure 34 c).

The surface on which the elastic interlayer is to be placed should be horizontal. If electric tubes or water pipes are fixed on top of the load-carrying floor and foils or mats are used as an elastic interlayer, then a levelling layer should be installed so as to provide a flat surface for the correct placement of the elastic interlayer. Before placing the foils or mats, the surface should be cleaned and free of all objects (nails, screws, debris,…).

Elastic interlayers placed as mats should connect well without gaps in between them. Foils should have sufficient overlap and are ideally taped together (see figure 34 'a'). If two superposed elastic interlayers are used, it is recommended to superpose them in crossed orientations (see figure 34 ‘a’). All of this is especially important when screed or concrete is used for the floating floor. Its ‘liquid placing’ is most sensitive to even small gaps as it does not have the advantage of bridging gaps as boards do. Small perforations are again no problem for boards, but can be catastrophic for screeds. Work project leaders should pay attention to all manipulations that could create holes in the elastic interlayer before the placing of the screed. This latter should be done as soon as the elastic interlayer is in place and all other actions in between should be avoided (perforations created by ladders, wheelbarrows, falling objects….). Care should also be taken during the placing of the screed (shovels!), using elastic foil around the tripod to avoid punctuating the foils (see figure 34‘d’).

When porous mats in glass wool, rock wool, cellulose fibres or similar materials are used as elastic interlayers, a plastic foil should be placed on top of these materials to avoid the liquid screed or concrete penetrating inside the pores and producing a hard contact between the two floors (figure 34 ‘f’).

The correct placing of the floating floor is not only crucial for impact but also for airborne direct and flanking insulation!

Figure34: the correct placing of the floating floor is vital. Even small hard contacts will eliminate all positive effects! If a material with open cells is used as an elastic interlayer (e.g. mineral wool, see right picture), a plastic foil should be applied before installing the screed.

4.3.2.5 - ***Types of floating floor systems used in LWTF constructions***

Paragraph (2) explained how floating floors reduce impact sound. The lower the mass-spring-mass resonance frequency, the better the impact sound reduction due to the floating floor in general will be (though some internal and surface damping mechanism will also be a significant parameter). The simple formula that calculates the resonance frequency shows us two possible strategies to optimize the floating floor for impact sound insulation.

We can try to reduce the dynamic stiffness 's' in the formula. This will indeed reduce the resonance frequency, but we cannot do this indefinitely: beyond an optimization value of this dynamic stiffness practical reasons quickly limit the possibilities of this strategy. First of all, the static stiffness should be such that the resilient layer is not overly compressed locally under the influence of furniture or even persons (otherwise the floor wouldn't be a horizontal surface anymore), secondly walking on a too resilient floor can give a strange heaving feeling!

The second strategy is to lower the resonance frequency by adding mass (more boards, screed), preferably both symmetrically below and on top of the elastic interlayer. Increasing the weight of only the basic floor or only of the floating floor will soon become inefficient as the formula for the mass-spring-mass resonance frequency shows. (It is only in heavy constructions that increasing the weight of the floating floor leads to a lower resonance frequency and hence a better performance. This is of course due to the considerably higher surface mass of the load-carrying floor in these constructions, so that $1/m_1''$ becomes negligible compared to $1/m_2''$ in the resonance frequency formula.)

Good floating floors display an optimization of the surface masses and the dynamic stiffness of the elastic interlayer. Lots of products exist that serve as elastic interlayers.

Increasing surface mass for the load-carrying floor can be done by adding extra boards, by using or adding extra heavy boards (fibre cement boards, extra heavy fibre reinforced gypsum board,…), by using sand fillings between the joists (a typical German technique) or on top of the boards (National Research Council of Canada), by grit fillings in honey comb elements on top of the boards (Fermacell), sand or concrete in case elements (Lignatur), dry concrete blocks in case elements (Lignatur) with optimization of the damping (to limit drum sound)…

Similar actions can be undertaken to increase the mass of the floating floor itself. Very often though, a screed of 6 to 8 cm thickness of concrete is used as this is a relatively cheap and very efficient way to increase the surface mass. Moreover, this also gives the possibility to install floor heating.

Up to now, we have always been considering that in a section of 1 m² of the floating floor system that 1 m² of elastic interlayer covers 1m² of the basic load-carrying floor and supports 1 m² of the floating top floor. Let's call this SYSTEM 1 -solutions.

By reducing the surface of the spring, we can also increase the total mass per surface of the spring (m_1'' and m_2''), lowering as such the mass-spring-mass resonance frequency of the system and improving the impact sound insulation. This can be done by concentrating mass so that it bears down line- or point-wise on the elastic pad/interlayer, resulting in a lower resonance frequency and thus to a better performance. The obvious advantage is that with existing reasonable masses of load-carrying and floating floors, quite low resonance frequencies can be obtained. In this e-book we will call the line-wise solutions SYSTEM 2-solutions and the point-wise solutions SYSTEM 3-solutions. The figure below shows some of these SYSTEM 2- and SYSTEM 3-solutions.

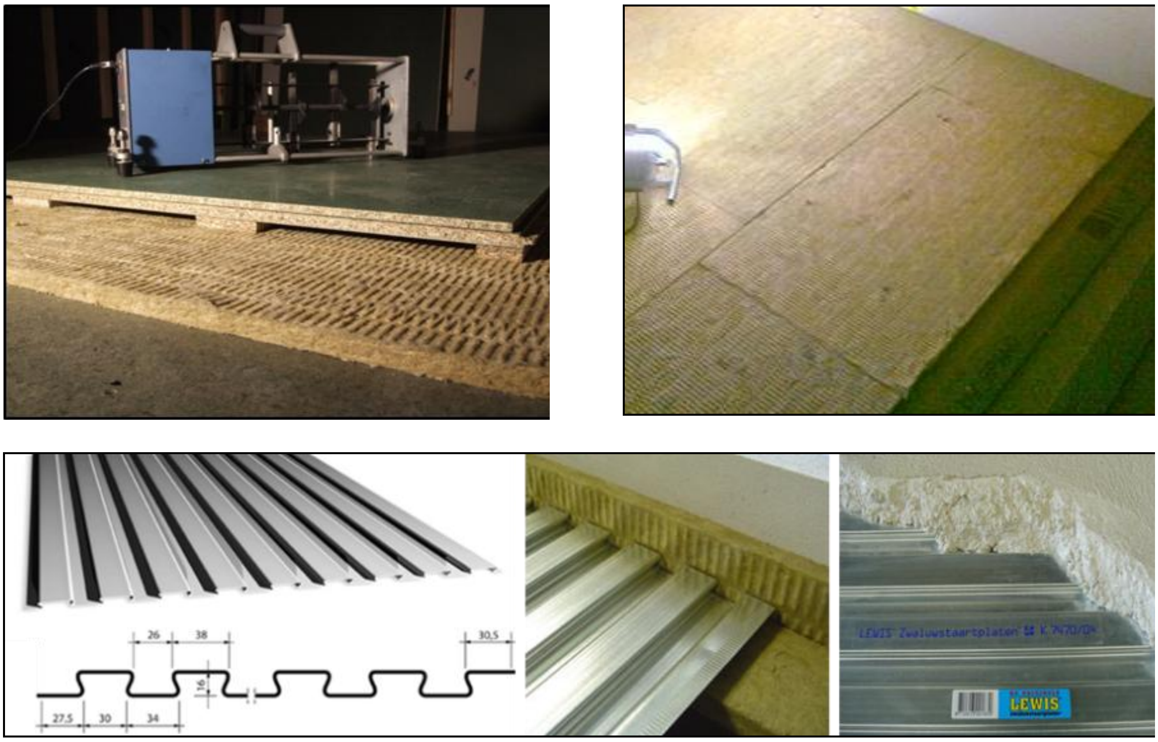
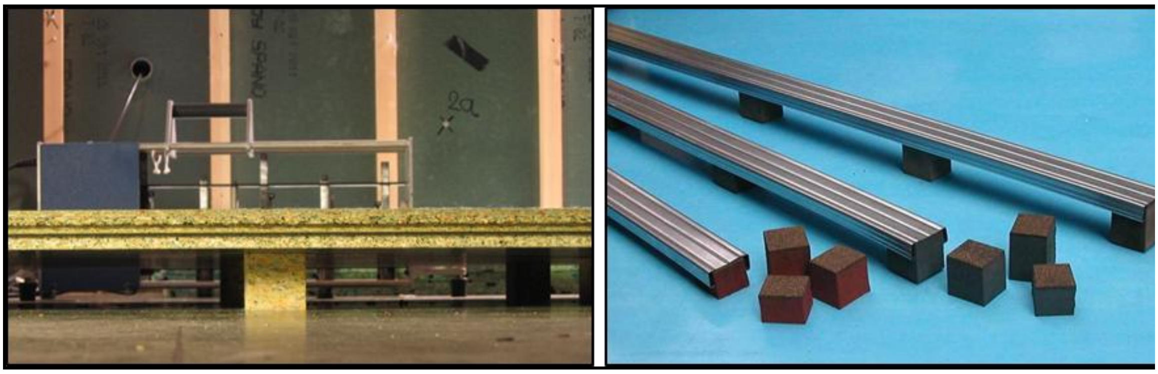


Figure 35: illustrations of floating floors SYSTEM 2 solutions based upon the principle of concentrating mass carrying line-wise on an elastic interlayer.

<u>Picture a:</u> Using the extra 100 mm wide board strips (18 mm high) on centre every 400 mm instead of placing the 2 particle-boards (Spano 12 mm +18 mm) straight on the rock wool (Rockwool 504, 140 kg/m³) reduces the impact sound by 4 dB ($L'_{nT,w} + C_{I,50-2500}$) . In order to 'robotize' the prefabrication of the floor elements, the alternative way <u>(picture c)</u> of fixing the 100 mm wide boards directly on the basic floor (putting the rock wool and boards on top of these strips) was examined and showed identical gains (which is logical in a mass-spring-mass system).

<u>Pictures b:</u> Lewis steel plates have a ribbed surface less than 20 mm high and are placed perpendicular to the joists of the load-carrying floor upon high density mineral wool (140 kg/m³) fixed itself on top of the joists and boards system. A concrete mortar is poured on top of these ribbed plates resulting in a thin layer of concrete (normally around 100 kg/m²). The steel ribs are specifically shaped so as to act as reinforcement steel for the concrete. The ribbed structure perpendicular to the joists channels the load partly line-wise and partly point-wise (dominant mass at the points of crossing with the joists) onto the mineral wood. ***www.reppel.nl***



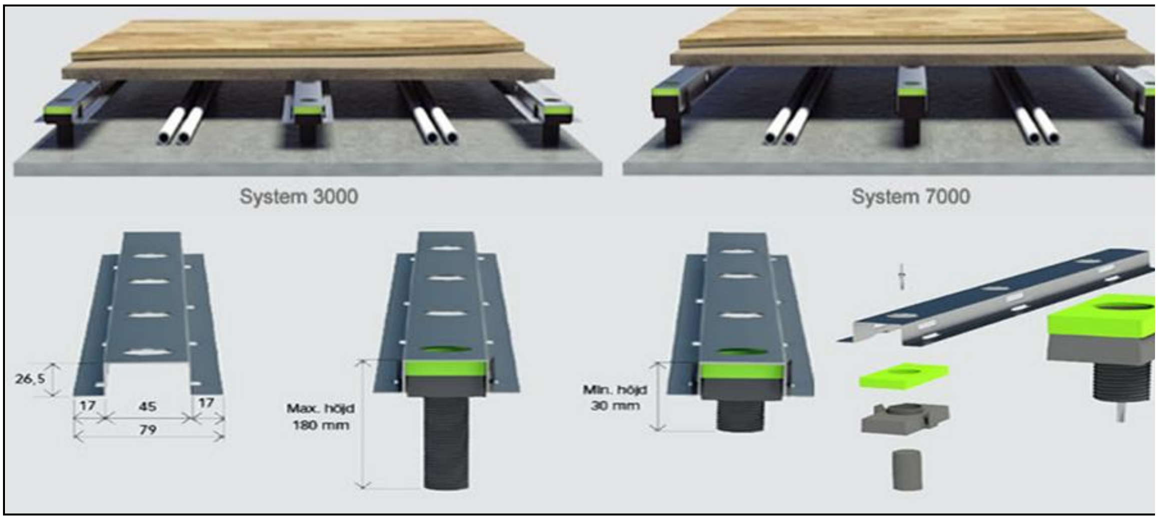


*Figure 36: illustrations of SYSTEM 3-solutions based upon the principle of concentrating mass carrying point-wise on elastic pads. Pictures c is from from CDM company (pads and iso-lats) see **www.cdm.be**. Pictures d is from Granab Subfloorsystems **www.granab.se***

4.3.2.6 - ***Effectiveness of dry floating floor systems used in LWTF constructions***

Field measurements with the standard tapping machine were carried out in a two-storey timber frame mock-up construction. The goal was to compare different dry floating floor systems on the same reference floor. The mock-up contained a reference timber floor construction separating two transmission rooms. From top to bottom the basis floor construction was composed as follows (see figure below): 18 mm particle board, timber joists (section: 240 mm x 45 mm, centre-to-centre distance: 400 mm), timber battens (section: 45 mm x 22 mm, centre-to-centre distance: 400 mm), 12.5 mm gypsum boards, directly screwed on the timber battens. A mineral wool filling (90 mm, 16 kg/m³) was applied in the cavity between the timber joists.

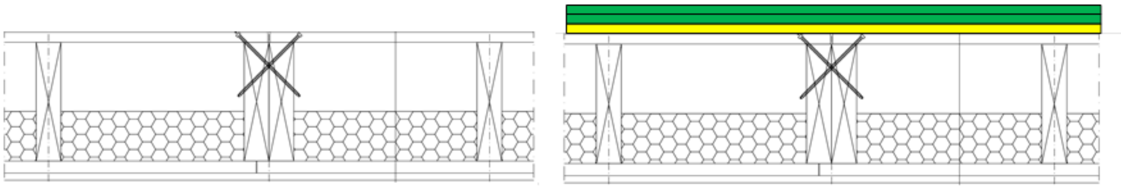


Figure 37: LEFT: construction of the reference timber floor. RIGHT: example of a floating floor on top of the reference floor.

Different (dry) floating floor systems were installed on this reference floor and examined for their impact sound reduction capacity. The examined flooring complexes consisted of a resilient layer loaded with one or two flooring boards (see figure RIGHT). Different types of resilient layers and board materials were tested in this set-up.

For reasons of time and cost savings, more than 40 different samples were tested on a limited surface, defined by typical board dimensions, e.g. 120 cm x 260 cm, 122 cm x 244 cm. In this phase of the study, only impact sound insulation measurements were made. For certain high performing complexes, airborne transmission of the radiated impact noise in the upper room became noticeable in the high frequencies (but without influence on the single ratings).

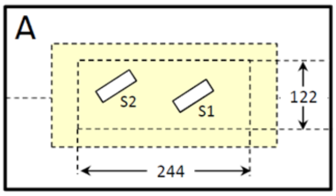


Figure 38: setup of the comparative measurements

First we examined the influence of the different board materials. Tests were carried out on different combinations and types of boards using the same 20 mm mineral wool (140 kg/m³). The following types were examined: particle boards (720 kg/m², 12 mm and 18 mm), OSB boards (600 kg/m³, 12 mm and 18 mm), wood fibre cement boards (1250 kg/m³, 18 mm), fibre cement boards (1180 kg/m³, 12 mm) and fibre reinforced gypsum boards (1140 kg/m³, 2x 10 mm).

Eight different complexes were tested in this way. In terms of $L'_{nT,w}$ the results are situated between 58 dB and 63 dB, while the surface mass of the top layers varies from 11 kg/m² to 45 kg/m². This indicates that surface mass is not the only influence parameter, and certainly internal and surface damping mechanisms need to be taken into account. For this reason we did not necessarily find worse results for boards with lower surface mass. Ranking the tested complexes by their surface mass (see figure chart 1 below), we observe only slightly higher impact noise levels (1 to 2 dB) for simple OSB and particle boards (11 to 13 kg/m², 63 dB) compared to nearly twice as heavy complexes such as an additional 12 mm board (18 to 22 kg/m²) or 18 mm wood fibre cement boards (23 kg/m²). On the other hand, for the same surface mass (23 kg/m²) we observe a difference of 2 dB between the 18 mm wood fibre cement board and the double layer of fibre reinforced gypsum board, in favour of the latter. This indicates clearly the importance of the nature of the board material. The lowest impact noise level (58 dB) was found for the heaviest complex (45 kg/m²) being a double layer of 18 mm wood fibre cement board. Though compared to the double layer of 10 mm fibre reinforced gypsum board, one had to double the surface mass to obtain a negligible improvement of only 1 dB in terms of $L'_{nT,w}$.

Of course, in order to maximise the gain using more and/or heavier boards, this mass should be equally/symmetrically distributed to both masses in the mass-spring-mass system as we explained earlier. For comparison reasons this was not done here, maintaining always the same reference floor.

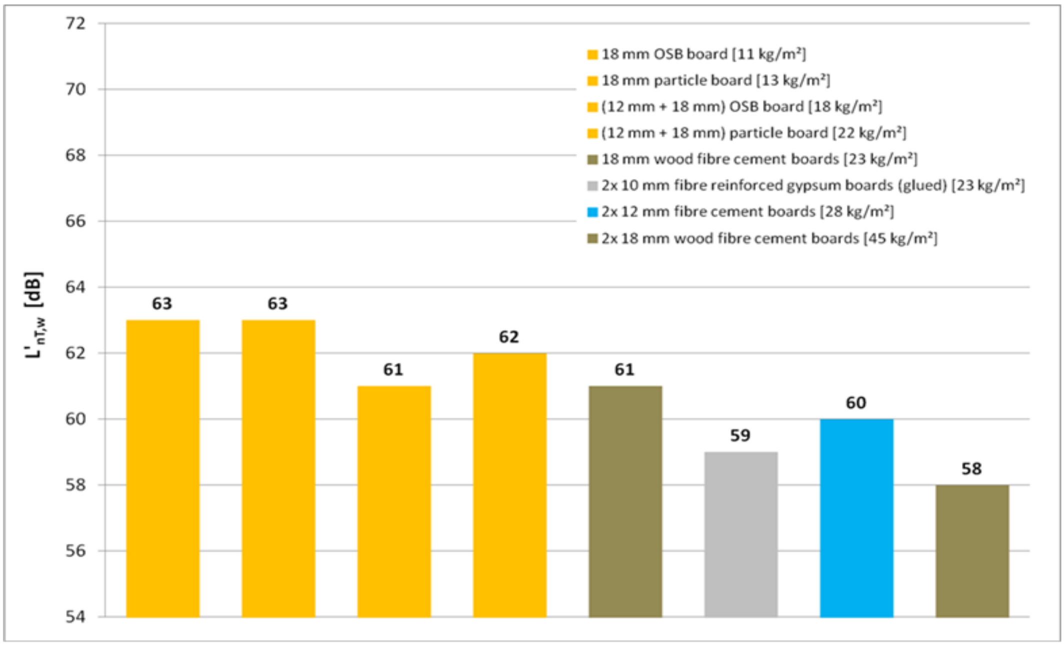


Chart 1: different board types tested on top of a 20 mm thick mineral wool layer (140 kg/m³)

Staying with one type of material, in this case particle boards and OSB boards, the single isolated influence of the surface mass could be observed (see chart 2 below). Tests were carried out on the mineral wool layer loaded with an 18 mm board and with an additional 12 mm board, screwed to the first board. Although important improvements are found between 1250 Hz and 2500 Hz, hardly any improvement of the low frequent efficiency is obtained. In terms of $L'_{nT,w}$ the improvements are confined to 1 or 2 dB. So adding boards is a sure way to improve the impact sound reduction, but not the most efficient one if no equivalent mass increase is applied to the load-carrying floor.

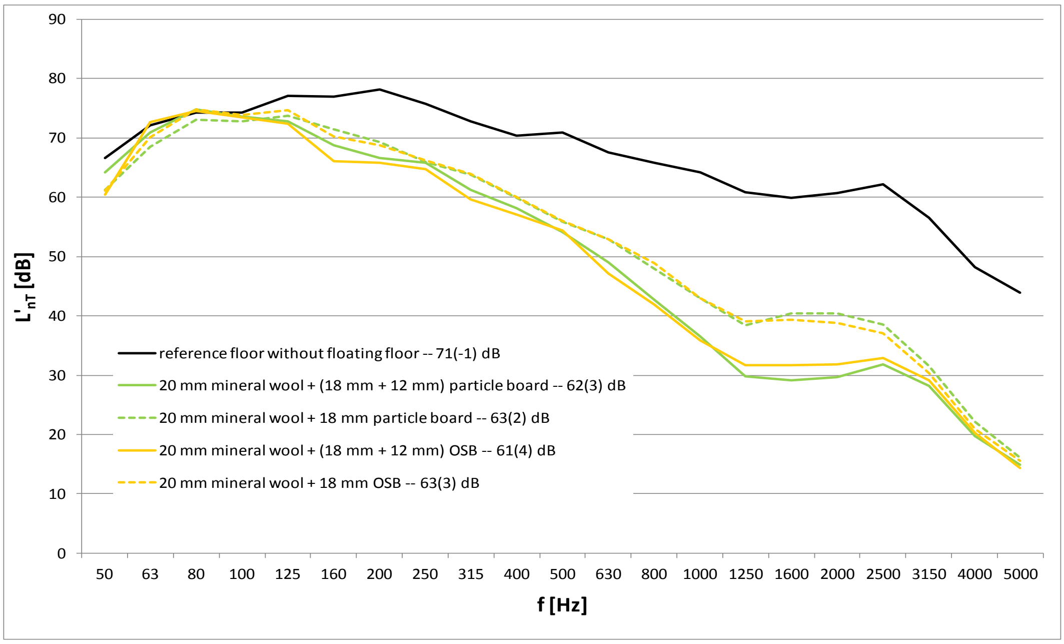


Chart 2: loading effect on 20 mm mineral wool for two different board types

In order to increase the loading effect, an experimental set-up was put into place consisting of 100 mm wide particle board strips (c-t-c distance 400 mm) screwed underneath the top layer so as to obtain a SYSTEM 2-construction. An important performance gain was now observed for the low and mid frequency range (below 1250 Hz, see figure chart 3). This tells us that combining both measures, extra boards and intermediate strips, permits a considerable overall improvement of the impact sound insulation. In terms of $L'_{nT,w}$ a gain of 5 dB due to the intermediate strips is found. Compared to the initial single value of 71 dB for the 'naked' floor, a considerably lower impact sound level of 57 dB is now obtained.

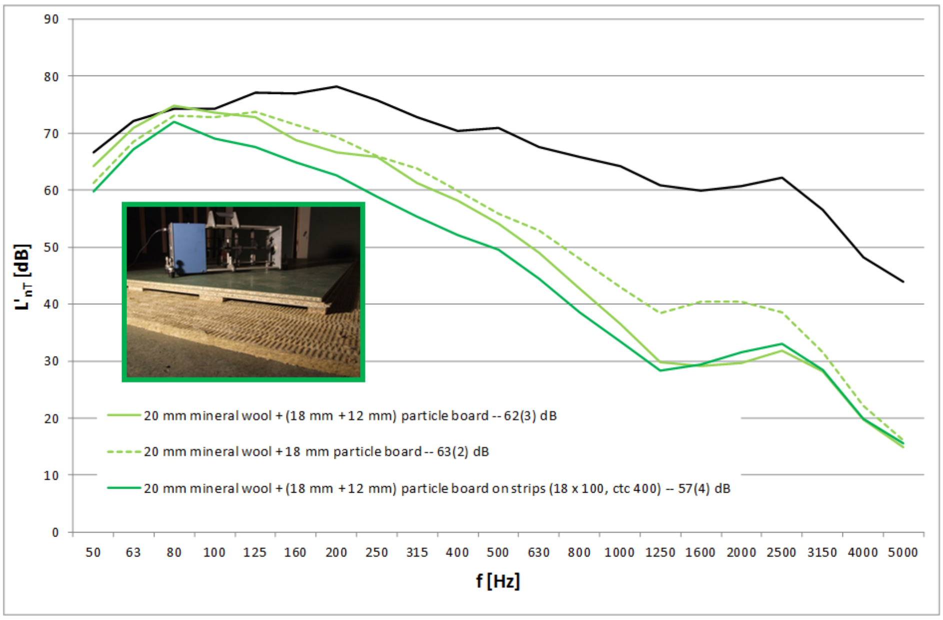
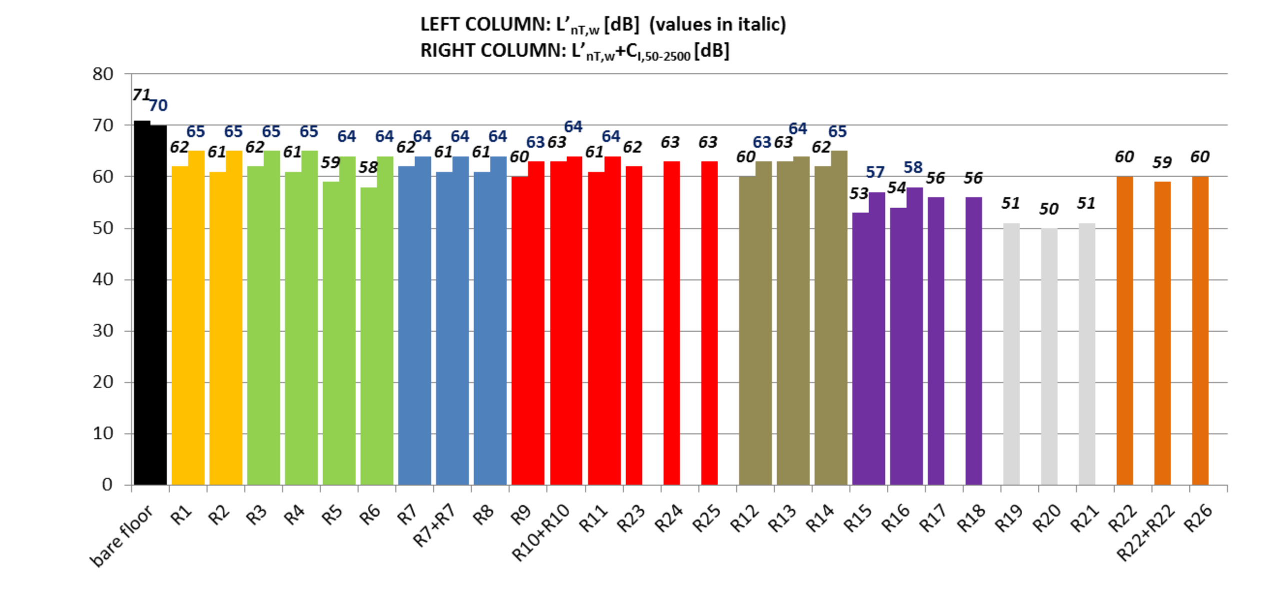


Chart 3: effect of concentrating load by means of wooden strips between boards and resilient layer

Focusing now on the nature of the resilient layer, tests were carried out on several materials, classified into eight different 'material groups'. The following colour codes were used to indicate them:

- Yellow: mineral wool layers (20 mm) – 140 kg/m³, 100 kg/m³
- Green: rubber flake foams (10, 20, 30, 40 mm) – 120 kg/m³
- Blue: PU flake foams (10, 2x10 mm) – 80 kg/m³, 100 kg/m³
- Red: (multi-layered) PE foam membranes (2x 3.5 mm, 4x 2 mm, 2x 3 mm, 5 mm, 6 mm, 9 mm)
- Brown: resin-bound rubber membranes (corrugated 8/4 mm, 3 mm, 4.5 mm)
- Purple: elastomer pads (30 mm, 50 mm)
- Grey: PU flake foam pads (50 mm)
- Orange: Wood fibre insulation boards (18 mm, 36 mm) – 270 to 250 kg/m³

Almost 40 different resilient layers were tested under a complex of 12 mm and 18 mm particle boards, in order to compare their effectiveness regarding impact noise. A brief look at the single value results ($L'_{nT,w}$), shows rather small differences between the tested samples, except for the 'purple' and 'grey' group, containing all the 'pads-based' solutions (SYSTEM 3) (see figure chart 4). Again this indicates that effective solutions have to be looked for in 'discrete' applications, such as strips or pads, optimizing the mass-spring-mass effect for the floating floor. In this way, values in the range of 50-56 dB are obtained for $L'_{nT,w}$, still with a rigidly connected gypsum board ceiling as described above. However, the PU flake pads solutions were found to be too resilient to be used in practice. For the other, more traditional resilient layers, impact noise values ranging from 58 to 63 are found.

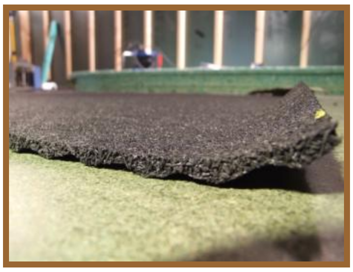


Mineral wool sample

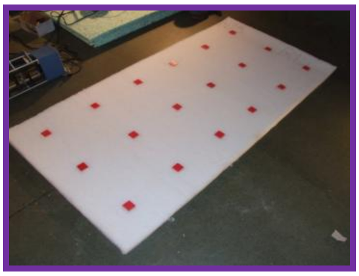
Rubber flake foam

PU flake foam

PE foam membrane



resin-bound rubber membrane



elastomeric pads in polyester wool

Sample of PU flake foam pad

wood fibre insulation boards (under particle fibre boards

Chart 4: $L'_{nT,w}$ results for different type of resilient layers combined loaded with a double layer particle boards (12 mm + 18 mm)

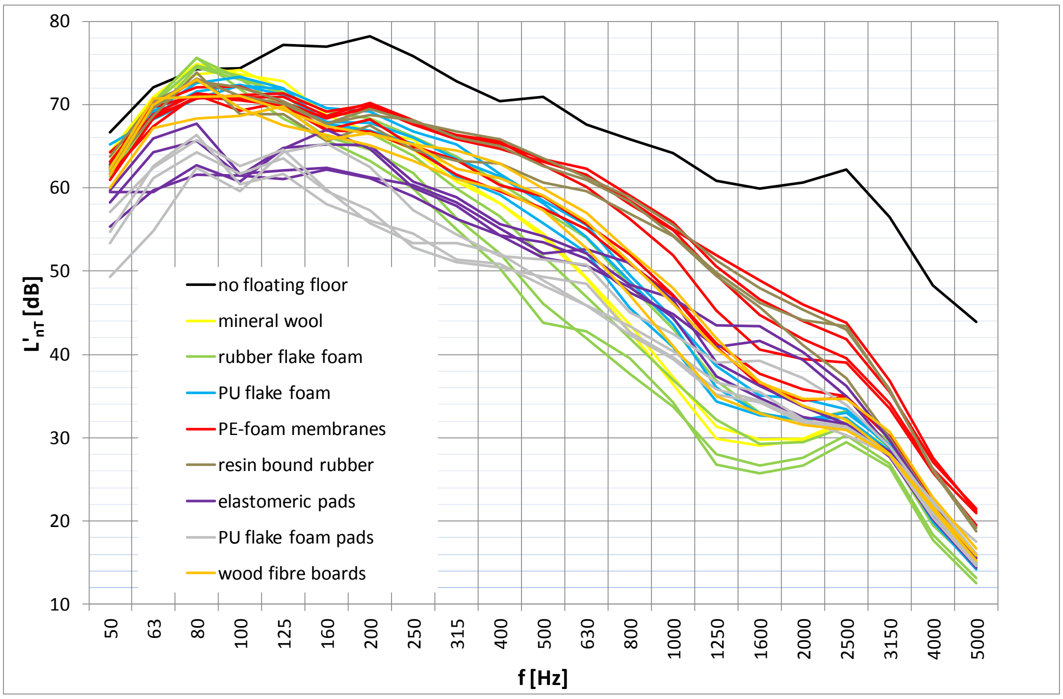


Chart 5: spectral comparison for different type of resilient layers tested under (12 mm + 18 mm) particle boards

A comparison based on spectral information (see figure chart 5) indicates a mainly low and mid frequency improvement in the case of the pad solutions (SYSTEM 3 solution).

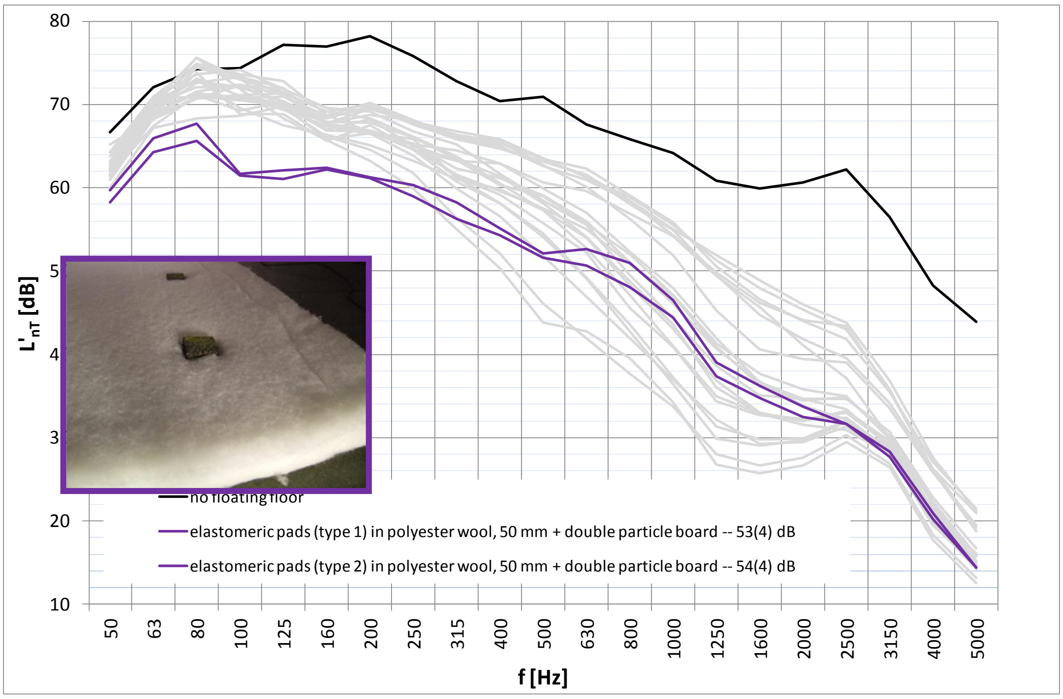


Chart 6: two different types of elastomeric pads tested in polyester wool

Two different types of elastomeric pads (both 50 mm) were tested. When embedded in a polyester fibre wool layer, suppressing standing waves in the cavity, 53 dB and 54 dB were reached in terms of single values. It should be noted that in spite of certain other samples leading to higher gains in the 200-2000 Hz frequency range, the pad solutions remain the best-scoring solutions due to their effectiveness below 200 Hz (figure chart 6). In this frequency range, even for the most effective (thick) membrane (SYSTEM 1), the spectral values remain in the region of 70 dB, leading to relatively high $L'_{nT,w}$ values in spite of their effectiveness in the higher frequencies.

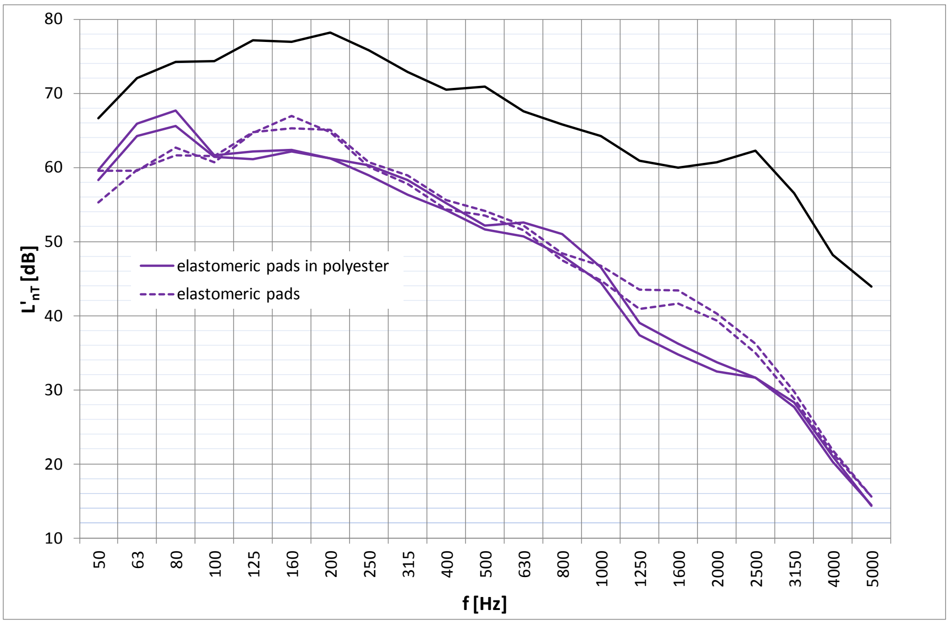
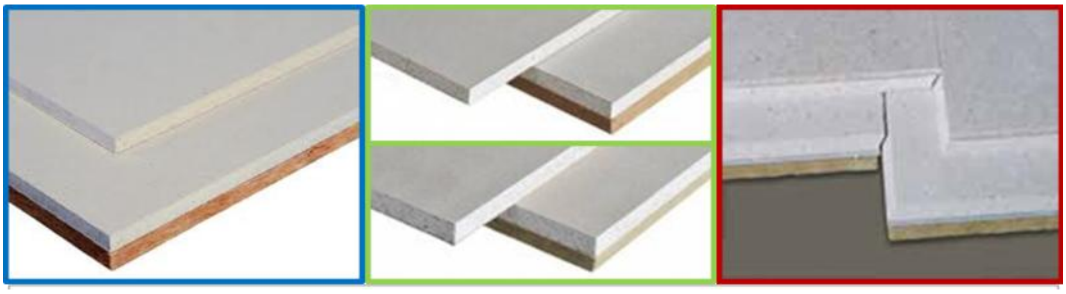


Chart 7: influence of polyester wool layer as cavity absorption with pad solutions (SYSTEM 3 solution)

When no sound absorbent cavity filling surrounds the elastomeric pads (and steel channels are used to support the floating floor), a shift of the resonance peaks is observed in the low frequency region as well as an increase of the impact noise levels in the high frequencies (cavity standing waves, see figure chart 7). In terms of single values, a loss of 2 to 3 dB is recorded ($L'_{nT,w}$ = 56 dB) compared to the pads solutions with cavity filling.

Considering again the more traditional resilient layers tested under a 12 mm + 18 mm complex of particle boards (see figures chart 4 and chart 5), the lowest value (58 dB) was found with the thickest solutions, 40 mm rubber flake foam. The least effective solutions (63 dB) turned out to be the thinnest PE foam membrane solutions. Nevertheless, a value of 60 dB was recorded for a specific 2x3.5 mm PE foam membrane, while comparable results (single values) are obtained for the 18 to 36 mm thick wood fibre insulation boards and a 2 dB higher (!) single value was found for the 20 mm thick mineral wool layer (140 kg/m³). In spite of their impressive performances in the high frequencies, the mineral wool layers do not seem to be well adapted to the relatively small load from the boards resulting in rather high levels at low frequencies (resonance zone). Comparable results (61-62 dB) were found for equivalent thicknesses of PU and rubber flake foams.

A second series of samples was tested for impact noise insulation in the above described mock-up, using commercially available preassembled floating floor systems. The 8 different samples were examined with different kinds of resilient layers: mineral wool (10 mm), wood fibre board (10 mm) or felt (9 mm). All systems consist of fibre-reinforced gypsum boards of different thicknesses: 2x 10 mm, 2x 12.5 mm or 18 mm. Depending on the manufacturer of the specific system, the nature of the fibres used to reinforce the gypsum boards may differ (same colour indicates same manufacturer).



Large deviations are recorded in the high frequency range when comparing systems with similar top layer but different resilient layer (figure chart 8). Felt and wood fibre board seem to be less effective sub layers, in favour of the more resilient mineral wool.

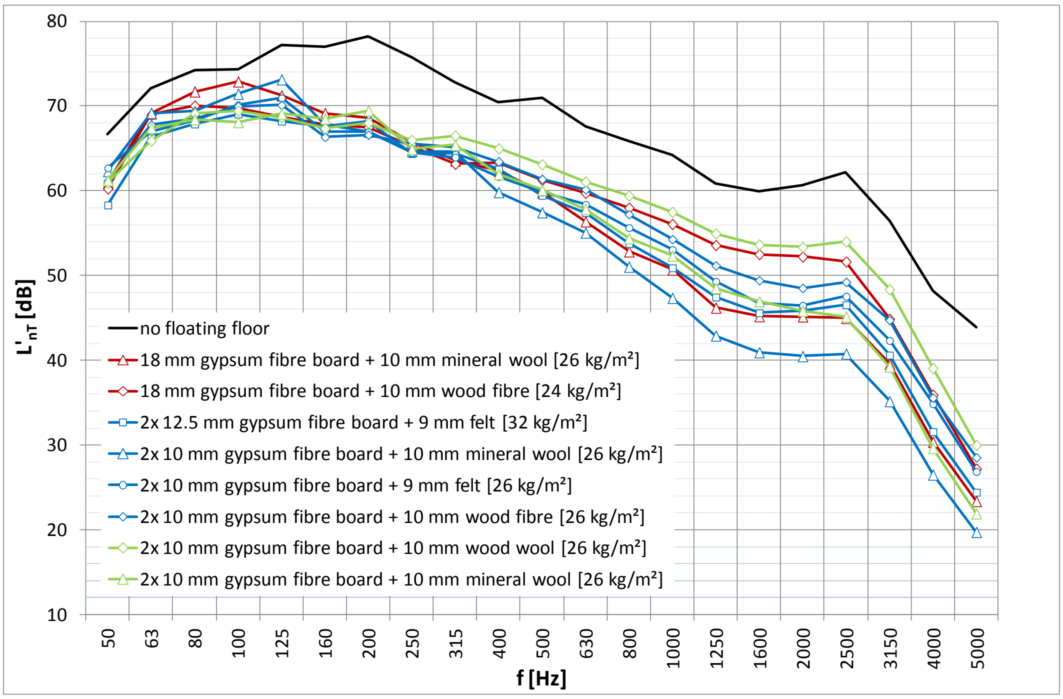


Chart 8: spectral comparison of different pre-assembled dry floating floor systems on reference floor

In spite of the large high frequency spectral deviations, the single values differ only slightly and are situated between 61 dB and 63 dB (figure chart 9). The similar, rather poor effectiveness of these 'ready made' systems in the low frequencies, limits the results in term of single values.

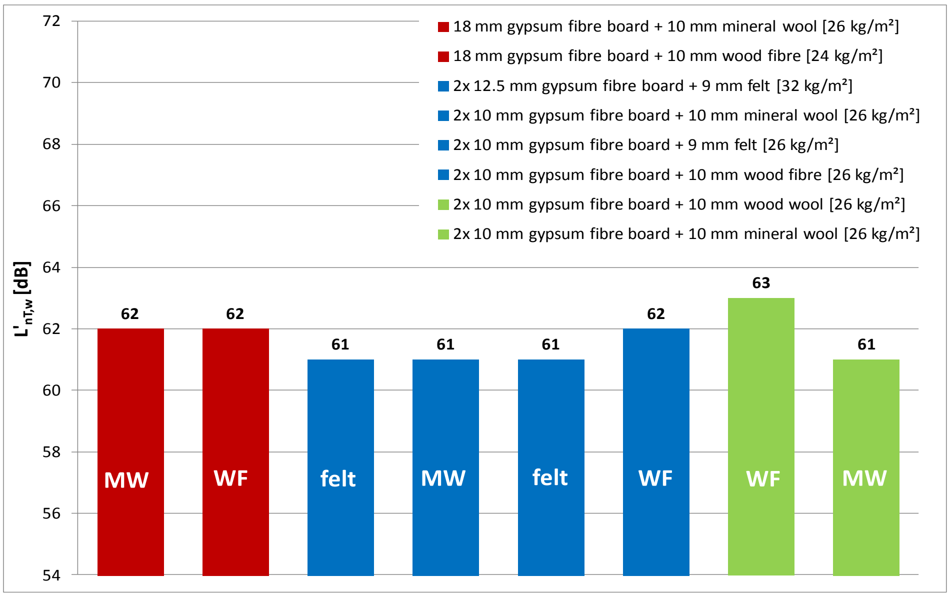


Chart 9: single value results for different pre-assembled dry floating floor systems tested on reference floor

The limits of the mass-spring-mass model for lightweight timber frame floors can be seen in chart 10. Reducing the stiffness 's' of the elastic interlayer by increasing its thickness does not lead towards a downward shift of the resonance frequency. The explanation for this is to be found in the lack of rigidness of the subfloor and was already mentioned with the introduction of the mass-spring-mass model. Dynamic impacts on the topping can sometimes be unable to cause the interlayer to compress but instead cause the direct deformation of the supporting subfloor. As such, subfloor and topping are not sufficiently decoupled and the resonance frequency can be less influenced by changing for instance the stiffness of the elastic interlayer. Creating rigid load-bearing subfloors is not only a good idea for vibration comfort (see section 4.3.4.), it will also improve the impact sound insulation with floating floors due to the above mentioned effect.

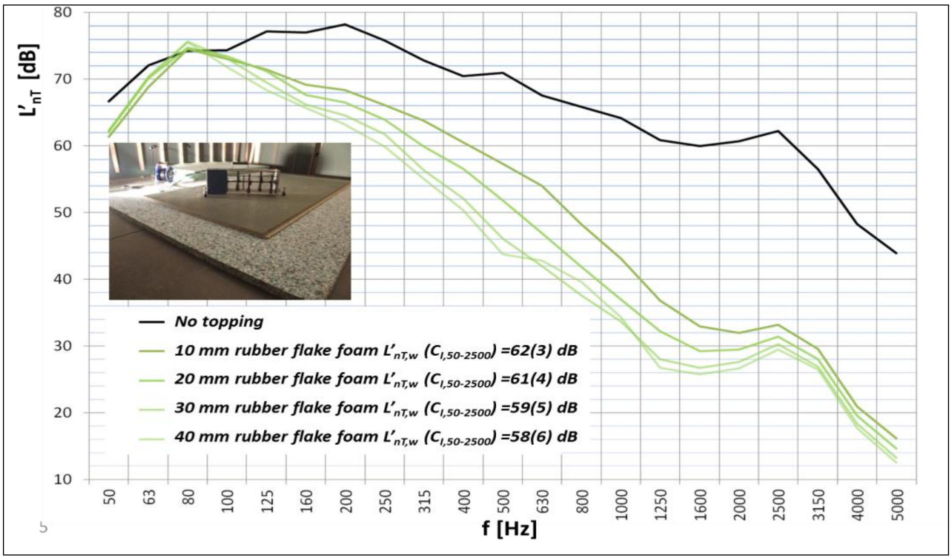


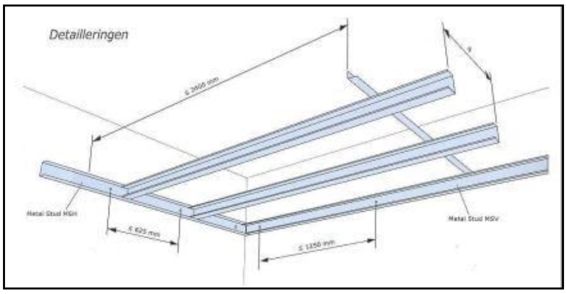
Chart 10: influence of the thickness of the elastic interlayer. Increasing the thickness of the rubber flake foam diminishes its stiffness. Doubling the thickness from 10 mm to 20 mm reduces the stiffness with 2; 40 mm thick foam only has a quarter of the stiffness of 10 mm foam. One would expect a downwards shift of the mass-spring-mass resonance with diminishing stiffness, but this was not noticeable in the measurements.

4.3.2.7 - ***The necessity of false ceilings***

We have seen in paragraph (3) that the same floating floor placed on top of a lightweight timber floor offers a less efficient reduction than installed upon a heavy (concrete) floor. This lack of efficiency explains also why impact sound in most solutions cannot be solved only with a floating floor on top of a light joist/boards system: an additional suspended ceiling will be almost always necessary.

In single family houses, ceilings are often fixed directly on wooden battens (wood furring strips) identical to the reference floor in the previous paragraph. This is not such a problem within the same dwelling, but if the floor separates two apartments (compartment floor), then this solution might not be such a good idea. Although there is some decoupling by the wood furring strips fixed perpendicularly to the joists, reducing the structural coupling to point contacts, too much structural sound transmission still occurs.

The ideal solution is a suspended ceiling that has no structural contacts at all with the load-carrying floor. This is possible to achieve with metal stud systems (see technical manuals of manufacturers), but only for limited spans. For spans above 4 m, stud heights of 15 cm are necessary. As this all comes below the joists, very quickly important floor thicknesses are the consequence (at least when the joists are perpendicular to the metal profiles). One possibility for increasing the span is to subdivide the span into two or more smaller spans using wooden beams (on which the metal studs are fixed just as if it were a wall) that can be placed between the joists of the load-carrying floor. The alternative is a wooden joist system from wall to wall and completely independent from the load-bearing floor joists.



KNAUF	Knauf CW double profile as ceiling profile					
	Maximum room width with max. axial spacing of ceiling profiles b: 500 mm				625 mm	
Metal thickness 0.6 mm	Cladding thickness in mm: 12.5	+ extra load 1)	2x 12.5	+ extra load 1)	18	+ extra load 1)
CW 50	**3**	2.75	**2.5**	2.25	**2.75**	2.25
CW 75	**3.75**	3.5	**3.25**	3	**3.25**	3
CW 100	**4.25**	4	**3.75**	3.5	**4**	3.5
CW 125	**5**	4.5	**4.25**	4	**4.5**	4
CW 150	**5.5**	5	**4.75**	4.5	**5**	4.5

GYPROC Plafonds (code)		Dubbele beplating Gyproc A			
		MS 75P/ 50.2(A)	MS 100P/ 75.2(A)	MS 125P/ 100.2(A)	MS 150P/ 125.2(A)
Plafondsamenstelling					
Hoogte constructie in mm		75	100	125	150
Opbouw frame:	Metal Stud MSH	50	75	100	125
	Metal Stud MSV	50	75	100	125
Aantal & dikte platen		2 x 12,5 mm Gyproc A			
Gewicht in kg/m²		23	24	24	24
Maximale overspanningen					
H.o.h.-afstand van de plaatdragende Metal Stud MSV-profielen in mm	300	2200	3000	3750	4350
	400	2000	2750	3400	3900
	500	1900	2550	3200	3650

*Figure 39: maximum room widths of free-spanning fireboard ceilings are limited (see documentation **www.gyprocplafonds.nl** and **www.knauf.de**)*

The alternative of a completely independent ceiling is the use of resilient metal channels that are fixed directly in the joists of the load-carrying floor (see figures 40 'a-f' below).

Figure 40: (a) Wood furring strips fixed directly and perpendicular to the joists of the floor, this is only suitable for floors within the same building. (b) Mounting device to fix any heavy boards (c) (d) Ceiling metal profiles (Knauf) allowing a resilient connection with the joists (e) The finishing of the joint between wall and ceiling has an influence on the direct and flanking insulation. (f) Another type of fixation of metal ceiling profiles allowing for a larger cavity (Gyproc).

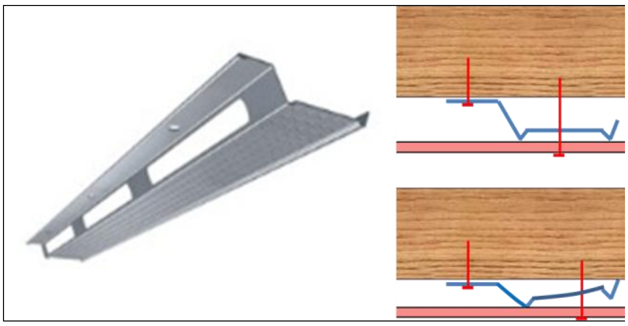


Figure 41: So-called resilient Z-channels (picture from PrimeWall® Resilient Channel). Possible mistakes can deteriorate the acoustic performance. Using the wrong screws that are too long and enter the joists can block the resiliently hung ceiling (this can also happen with the channels in the above picture d). Especially the first screws fixed through the gypsum board can push the 'free end' of the Z-profile against the joists. Even well-dimensioned screws can then enter in the joists, blocking the resilient system.

There are still other alternatives of rigid, ‘punctual’ fixation clips fixed to the channels (in which finally the gypsum boards are screwed).

Research work in NRCC showed the very beneficial effect of increasing the spacing of resilient channels from 406 mm to 610 mm. The improvement is quite large and ranges from 4 to 6 points in all cases (see table below). This large increase occurs, because by reducing the number of resilient channels, the overall stiffness of the connection decreases, meaning the resonance frequency shifts downwards also. This means that the improvement due to adding resilient channels starts earlier.[4]

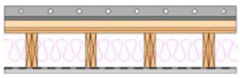
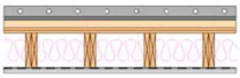
Floor ID	Sketch (not to scale)	Heavy impact (Ball)		Light Impact (Hammer)	
		$L_{iFavg,Fmax}$ (63-1k Hz)	$L_{i,Fmax,AW}$	$L_{n,W}+C_I$ (50-2500 Hz)	$L_{n,W}$
NRC-K23	2G + RC406 	**46**	**49**	**50**	**47**
NRC-K15	2G + RC610 	**42**	**44**	**44**	**43**
NRC-K23 – NRC-K15	Difference	**4**	**5**	**6**	**4**

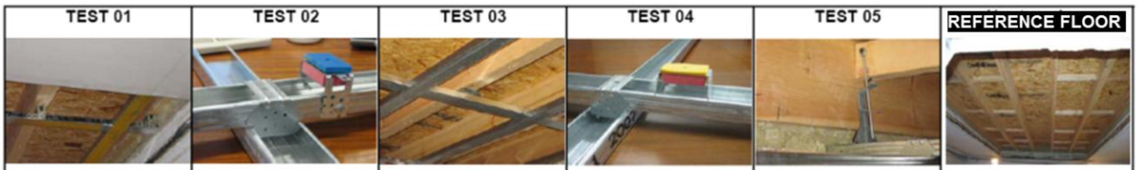
Table 1: increasing the spacing between the resilient channels results in large improvements of the impact sound insulation (data from table 5 of the article referenced to in the footnote).

Specially developed clips with elastic fixations are also available although the possible gain in insulation remains more limited than when used with concrete floors (see figures and tables below).

The impact sound insulation will improve with the surface mass of the ceiling. In practice this means more (fire resistant) gypsum boards or fire resistant gypsum boards combined with heavier boards. The added mass will lower the resonance frequency and hence increase the sound insulation.

Inside the cavity, flexible porous material should be added to avoid standing waves and to help increase the sound insulation. Taking into account fire requirements, very often rock wool and cellulose fibres are used. The effect of adding these materials inside the cavity will increase with thickness only if the decoupling from the load-carrying floor is sufficient (if not, the structural transmission path will be dominant).

[4] On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012)



	TEST 01				TEST 02				TEST 03				TEST 04				TEST 05				REFERENCE FLOOR	
	L_n	ΔL	R	ΔR	L_n	ΔL	R	ΔR	L_n	ΔL	R	ΔR	L_n	ΔL	R	ΔR	L_n	ΔL	R	ΔR	L_n	R
100	68.3	13.7	34.3	12.3	69.8	12.2	35.4	13.4	70.9	11.1	35.8	13.8	69	13	35.1	13.1	69.9	12.1	34.2	12.2	82	22
125	73.6	15.6	33.4	13.6	73.2	16	34.8	15	74.9	14.3	33.7	13.9	74.2	15	36	16.2	73.7	15.5	36.3	16.5	89.2	19.8
160	74.7	15.8	31.1	13.1	72.6	17.9	33.8	15.8	74.5	16	32.9	14.9	73	17.5	32.7	14.7	73.7	16.8	32.3	14.3	90.5	18
200	74.7	18	35	16.7	73.5	19.2	34.9	16.6	74.8	17.9	34.2	15.9	73.9	18.8	34.7	16.4	74	18.7	34.1	15.8	92.7	18.3
250	74.8	19.8	37.5	17.6	72.9	21.7	38.5	18.6	73.9	20.7	38.6	18.7	73.3	21.3	37.8	17.9	73.6	21	37.7	17.8	94.6	19.9
315	70.9	21.8	41.6	20	69.4	23.3	43.8	22.2	70.1	22.6	43.7	22.1	69.8	22.9	42.9	21.3	71.2	21.5	41.5	19.9	92.7	21.6
400	70.9	19.8	45.5	21.2	69.6	21.1	46.5	22.2	70.7	20	46.2	21.9	69.9	20.8	46.5	22.2	70.9	19.8	45.6	21.3	90.7	24.3
500	72	20.6	45.6	21.3	71.3	21.3	47.3	23	72.1	20.5	46	21.7	71.3	21.3	46.8	22.5	71.7	20.9	44.9	20.6	92.6	24.3
630	70.6	23.4	47.6	24.1	70.1	23.9	48.6	25.1	70.6	23.4	48.2	24.7	71.2	22.8	47.1	23.6	70.9	23.1	47.1	23.6	94	23.5
800	70.7	20.1	46.6	21.1	69.3	21.5	48.5	23	70.1	20.7	47.4	21.9	69.9	20.9	47	21.5	70.5	20.3	46.7	21.2	90.8	25.5
1000	67.3	22.6	47.9	22.8	66.1	23.8	50.1	25	66.4	23.5	49.8	24.7	66.6	23.3	49.1	24	66.2	23.7	49.2	24.1	89.9	25.1
1250	64.2	23	49.8	24.7	62.7	24.5	51.9	26.8	63.4	23.8	51.2	26.1	63.7	23.5	50.7	25.6	64.1	23.1	50.2	25.1	87.2	25.1
1600	59.6	25.5	52.8	27	59.2	25.9	54	28.2	59.3	25.8	53.3	27.5	59.9	25.2	53.3	27.5	60.1	25	52.7	26.9	85.1	25.8
2000	55.1	27.2	54.6	28	55.2	27.1	55.6	29	54.8	27.5	54.9	28.3	56	26.3	54.6	28	55.7	26.6	54.6	28	82.3	26.6
2500	53	25.3	54	25.6	53.5	24.8	54.9	26.5	53.5	24.8	54	25.6	54.5	23.8	54.2	25.8	54.1	24.2	54	25.6	78.3	28.4
3150	49	24.5	55.4	24.7	49	24.5	56.8	26.1	49.6	23.9	56.2	25.5	50.5	23	56.1	25.4	50.3	23.2	55.7	25	73.5	30.7
4000	41.3	26.9	60.2	28	41.1	27.1	61.2	29	43.6	24.6	60.8	28.6	42.8	25.4	60.2	28	42.8	25.4	60	27.8	68.2	32.2
5000	34.2	28.1	61.7	26.9	32.9	29.4	62.2	27.4	36.9	25.4	62.5	27.7	34.3	28	62.1	27.3	36.1	26.2	61.6	26.8	62.3	34.8
	69	25	48	22	68	25	50	24	69	25	49	23	69	23	49	23	69	24	48	22	91	26
	-1	-5	-1		-1	-4	-2		-1	-5	-1		-2	-3	-2		-2	-4	-1		-4	-1
			-5				-5				-5				-5				-5			-2

Table 2: direct airborne insulation of different resilient ceiling suspension systems and profiles. The reference floor is a simple wooden floor made of joists and a single OSB panel of 18 mm. Although no measurements are available below 100 Hz, as a conclusion one can say that the difference between all the systems (carrying two gypsum boards of 12.5 mm) is rather negligible. The last two lines represent the single ratings and the spectrum adaptation terms for the frequency area between 100-3150 Hz (airborne sound insulation) and between 100 H-2500 Hz (impact sound).

Where the suspended ceiling touches the walls, a hard connection can arise between the load-carrying floor and the suspended ceiling. Moreover, extra flanking transmission paths will occur. So the use of an elastic joint between ceiling and wall is from an acoustic point of view preferable. Unfortunately problems might arise with fire requirements. In some countries, the use of an elastic junction is allowed in combination with rock wool in the cavity (forming an extra fire barrier), but in other countries, this is not the case.

4.3.3 - Direct airborne sound insulation

The direct airborne sound insulation of floors is very similar to what can be said about party walls. Due to the height of the floor joists and the need for an independent or resilient fixing of the false ceiling (creating extra cavity height), large cavities that can be filled up with flexible porous materials are present, allowing for a very low mass-spring-mass resonance frequency. For the lower frequencies, this is of course ideal.

In party walls, all structural coupling can be avoided except near the foundations. The same perfect structural decoupling cannot be attained with floors. So the ultimate performance of the direct airborne sound insulation will always be slightly influenced by some form of structural sound transmission. In order to obtain ever better performances, cavity width can be increased and the surface masses of the composing mass-spring-mass system can be increased (heavier ceilings, heavier complex of basic floor and floating floor). These strategies have already been commented on above in terms of further increasing impact sound insulation.

In well-structured decoupled systems, adding thicker porous flexible materials (rock wool, cellulose fibres,…) will further increase the direct airborne sound insulation. In general, it is not the direct airborne sound insulation that causes the major worries. Impact sound, vibrations and flanking airborne sound transmission are the topics in LWTF apartment constructions that are most difficult to master

4.3.4 - Floors and comfort against vibrations

Not only impact sound is a worry, also vibrations can be experienced in the same and adjacent rooms when someone is walking around or when children are playing and jumping around (cups starting to tremble, …). In accordance with EC5 'Serviceability under vibrations of wooden floors', an accurate design and calculation of lightweight constructions such as wooden floors is most important. Calculation aspects and requirements are treated in the reports of WG2 and WG3.

Lightweight constructions are far more sensitive to vibrations than heavy constructions: For a given vibratory energy, the amplitude of vibration will increase for the lightweight structural parts of the building. So for a given induced energy, coming either from normal users of the floor or from external sources, the vibration velocity will be much greater than in the case of a normal concrete floor.

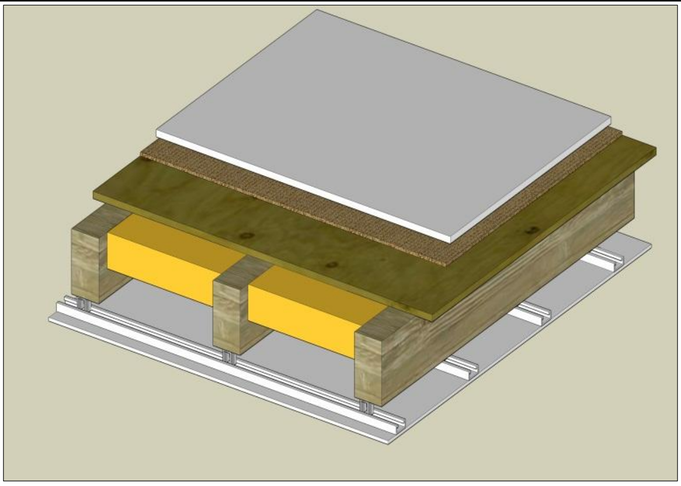
The second drawback of wooden floors is the anisotropy coming from the great contrast between the flexural rigidity in the two directions of the floor. There is a direct mathematical link between the contrast of rigidity and the number of flexural modes of the floors under 40 Hz. From this number of flexural modes, the accelerance of the floor, which is the ratio of acceleration and induced force, can directly be deduced. The accelerance expresses a kind of 'deformability' or 'flexibility' and is a good parameter for the quantification of discomfort for users. If the number of flexural modes is low, the floor will be in compliance with EC5 and users will not experience any kind of vibration inconvenience. For example, in the case of an isotropic concrete floor of classical size there is only one mode lower than 40 Hz. A wooden floor which fails to respect the rules of good design will reveal up to 7 modes!

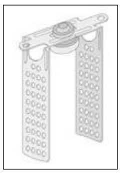
Good rules of design in accordance with EC5 are:

- creating floors that are as rigid as possible (especially reinforcing the flexural rigidity perpendicular to the joists (diminishing the effects of orthotropic behaviour that otherwise exists);
- keeping the first mode of vibration as high as possible in the frequency domain in which vibration energy is induced by normal walking of users. The stipulated minimal limit in EC5 is 7 Hz;
- calculation is always necessary, given that simple building guidelines are just not enough.

Vibratory energy from walking, dancing etc. is well known in terms of induced force and in terms of frequency content. In this way the rules of good design have been established in Eurocode 5. But there can also be problems with exterior sources of vibrations induced by traffic (especially near places where speed bumps are installed or in the proximity of deteriorated road infrastructure). In the case of external sources of vibration, frequency content and amplitude depend on the environment and possibly cannot be met by the calculation design of EC 5. So discomfort can be experienced by people, even when the rules of good design of EC 5 have been respected.

4.3.5 - Complete floor systems and their direct airborne and impact insulation: examples



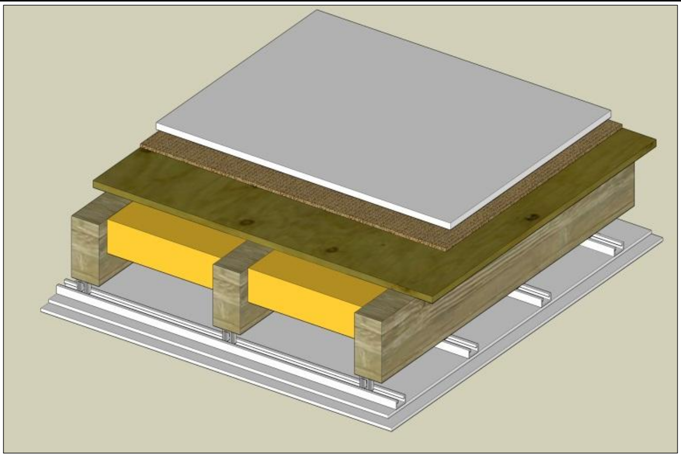


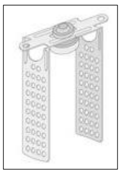
R'_{w}=	67.5 dB
R'_{living}=	57 dB
$C_{50-5000}$=	-10.6 dB
$C_{100-3150}$=	-2.5 dB
$C_{tr,100-3150}$	-8.4 dB

$L_{n,w}$=	49.4 dB
$L_{n,w}+C_{I,50-2500}$=	57.5 dB
$C_{I,50-2500}$=	8.1 dB
$C_{I,100-2500}$=	0.4 dB

Ref. SDH 08098-03-R (Anlage 9), Bauphysik Iphofen

Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 22 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: 100 mm mineral wool
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating a space of 70 mm between joists and ceiling. *** 1x12.5 mm 'K diamant board' (ca. 13 kg/m²)



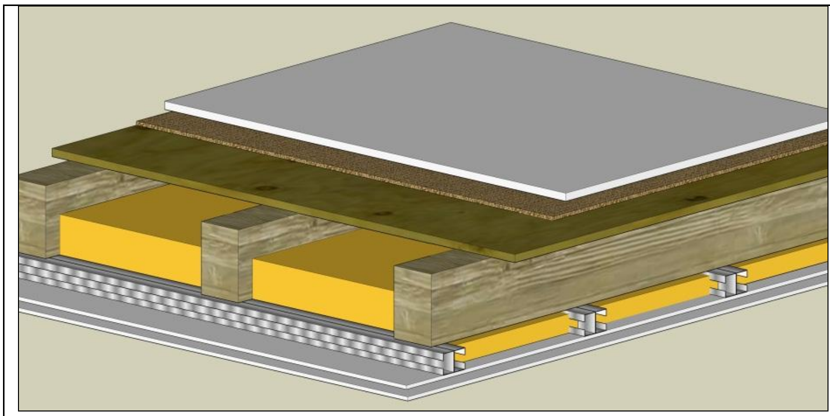


R'_{w}=	71.0 dB
R'_{living}=	62.2 dB
$C_{50-5000}$=	-8.8 dB
$C_{100-3150}$=	-2.3 dB
$C_{tr,100-3150}$	-7.8 dB

$L_{n,w}$=	45.0 dB
$L_{n,w}+C_{I,50-2500}$=	51.7 dB
$C_{I,50-2500}$=	6.7 dB
$C_{I,100-2500}$=	-0.1 dB

Ref. SDH 08098-03-R (Anlage 16), Bauphysik Iphofen

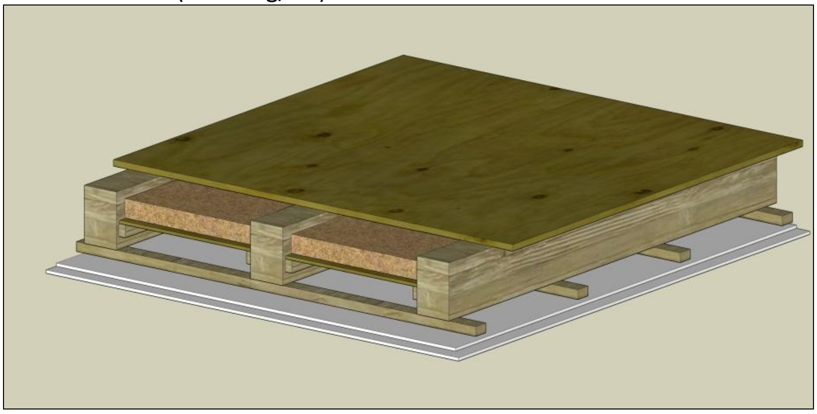
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 22 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: 100 mm mineral wool
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating a space of 70 mm between joists and ceiling board. *** 2x12.5 mm 'Knauf diamant board' (ca. 13 kg/m²)



$R'_{w}=$	74.6 dB
$R'_{living}=$	70.1 dB
$C_{50\text{-}5000}=$	-4.5 dB
$C_{100\text{-}3150}=$	-2.1 dB
$C_{tr,100\text{-}3150}$	-6.7 dB
$L_{n,w}=$	37.8 dB
$L_{n,w}+C_{I,50\text{-}2500}=$	43.9 dB
$C_{I,50\text{-}2500}=$	6.1 dB
$C_{I,100\text{-}2500}=$	1.3 dB

Ref. SW 07024-10R, Bauphysik Iphofen

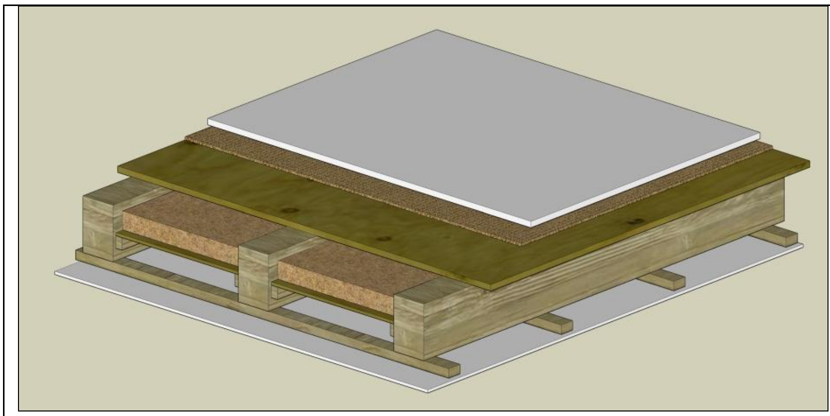
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 22 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: 100 mm mineral wool
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 25 mm below the joists *** 2x12.5 mm 'Knauf diamant board' (ca. 13 kg/m²)



$R'_{w}=$	not avail.
$R'_{living}=$	not avail.
$C_{50\text{-}5000}=$	not avail.
$C_{100\text{-}3150}=$	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}=$	71 dB
$L_{n,w}+C_{I,50\text{-}2500}=$	71 dB
$C_{I,50\text{-}2500}=$	0 dB
$C_{I,100\text{-}2500}=$	0 dB

Ref. 01 011-T-48, Bauphysik Iphofen

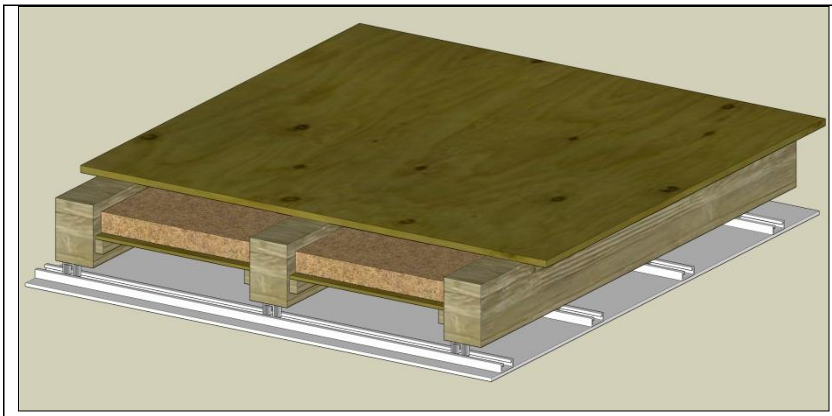
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: wooden battens 50 x 30 mm² (o.c. 50 cm) rigidly fixed to joists*** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



$R'_{w}=$	not avail.
$R'_{living}=$	not avail.
$C_{50\text{-}5000}=$	not avail.
$C_{100\text{-}3150}=$	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}=$	68 dB
$L_{n,w}+C_{I,50\text{-}2500}=$	70 dB
$C_{I,50\text{-}2500}=$	2 dB
$C_{I,100\text{-}2500}=$	1 dB

Ref. 03 026-T-12, Bauphysik Iphofen

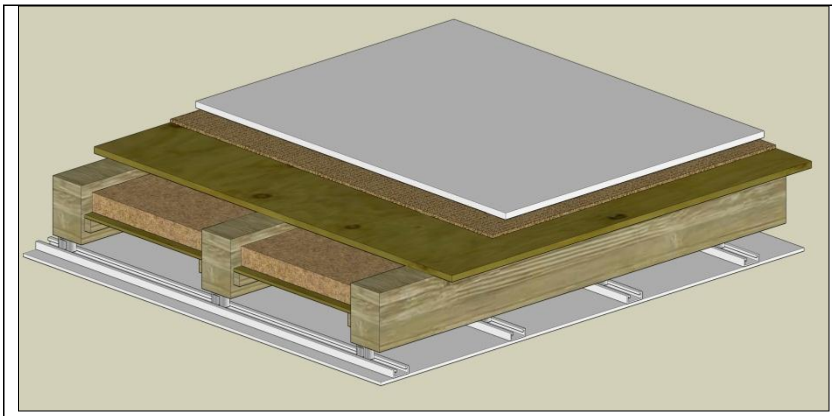
Topping: 20 mm fibre gypsum board (Gipsfasern Integral) + 10 mm wood fibre insulation (Steico)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: wooden battens 50 x 30 mm² (o.c. 50 cm) rigidly fixed to joists*** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	62 dB
$L_{n,w}+C_{I,50-2500}$=	63 dB
$C_{I,50-2500}$=	1 dB
$C_{I,100-2500}$=	0 dB

Ref. 06 026-T-43, Bauphysik Iphofen

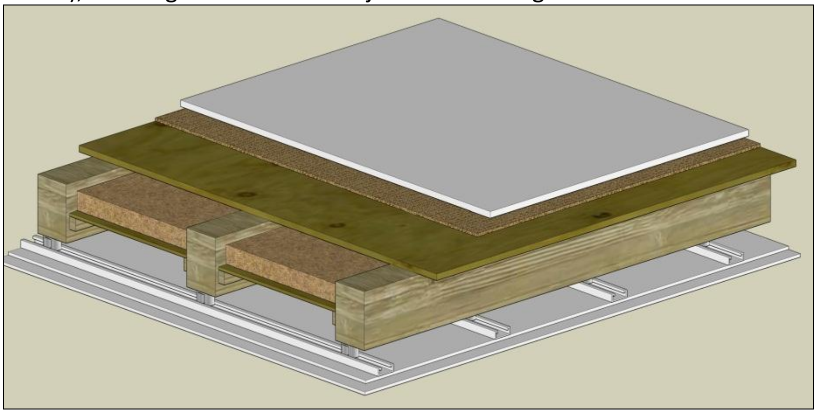
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating a 35 mm between joists and ceiling board. *** 1x12.5 mm 'GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	55 dB
$L_{n,w}+C_{I,50-2500}$=	60 dB
$C_{I,50-2500}$=	5 dB
$C_{I,100-2500}$=	3 dB

Ref. 06 026-T-43, Bauphysik Iphofen

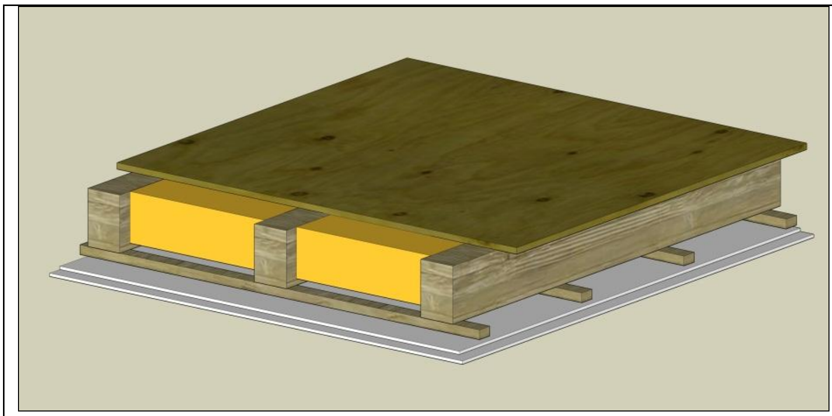
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 35 mm between joists and ceiling board. *** 1x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	49 dB
$L_{n,w}+C_{I,50-2500}$=	56 dB
$C_{I,50-2500}$=	7 dB
$C_{I,100-2500}$=	1 dB

Ref. 06 026-T-43, Bauphysik Iphofen

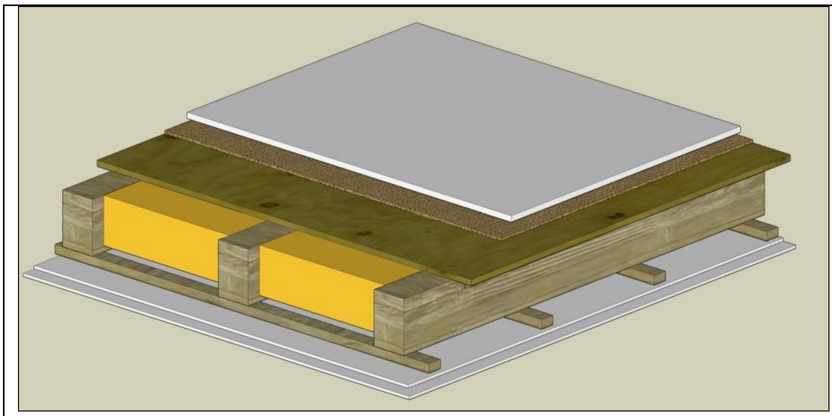
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating a space of 35 mm between joists and ceiling board. *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_{w}=	not avail.
R'_{living}=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	74 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	75 dB
$C_{I,50\text{-}2500}$=	1 dB
$C_{I,100\text{-}2500}$=	0 dB

Ref. 03 026-T-17, Bauphysik Iphofen

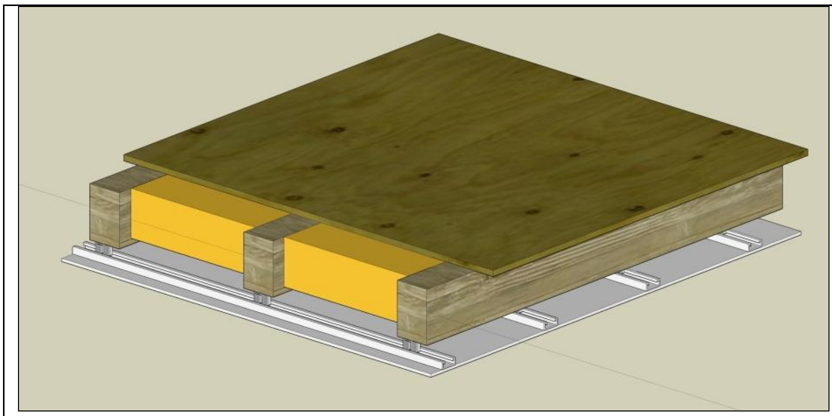
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: wooden battens 50 x 30 mm² (o.c. 50 cm) rigidly fixed to joists*** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_{w}=	not avail.
R'_{living}=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	65 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	67 dB
$C_{I,50\text{-}2500}$=	2 dB
$C_{I,100\text{-}2500}$=	1 dB

Ref. 03 026-T-11, Bauphysik Iphofen

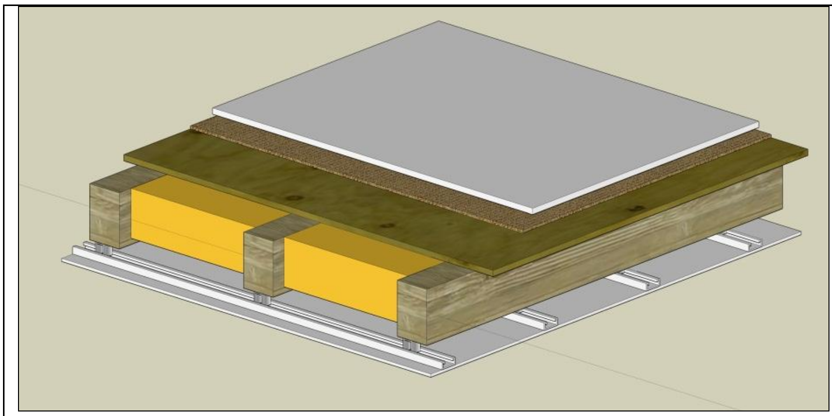
Topping: 20 mm fibre gypsum board (Gipsfasern Integral) + 10 mm wood fibre insulation (Steico)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: wooden battens 50 x 30 mm² (o.c. 50 cm) rigidly fixed to joists*** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_{w}=	not avail.
R'_{living}=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	60 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	69 dB
$C_{I,50\text{-}2500}$=	9 dB
$C_{I,100\text{-}2500}$=	2 dB

Ref. 05 007-T-43, Bauphysik Iphofen

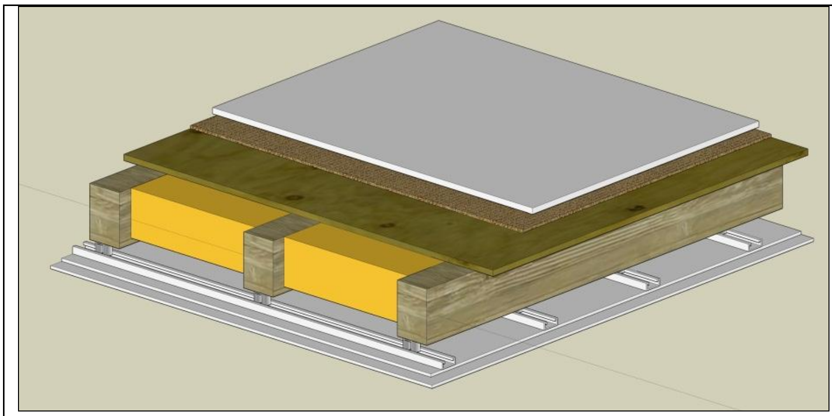
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 30 mm between joists and ceiling board. *** 1x12.5 mm 'Knauf GKB' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	54 dB
$L_{n,w}+C_{I,50-2500}$=	63 dB
$C_{I,50-2500}$=	9 dB
$C_{I,100-2500}$=	2 dB

Ref. 05 007-T-44, Bauphysik Iphofen

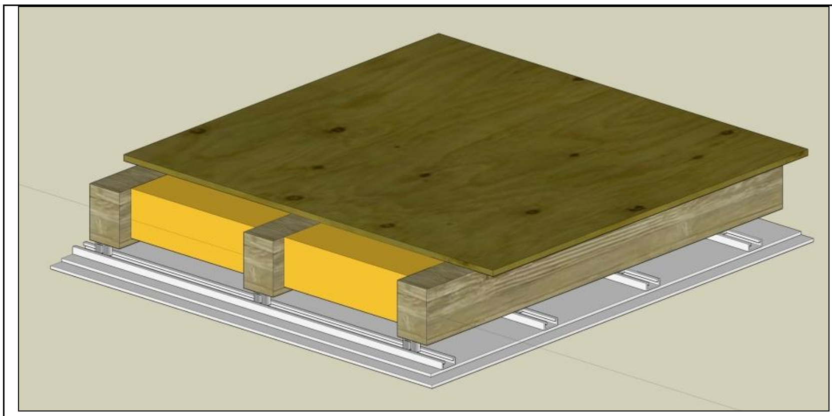
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 30 mm between joists and ceiling board. *** 1x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	49 dB
$L_{n,w}+C_{I,50-2500}$=	60 dB
$C_{I,50-2500}$=	11 dB
$C_{I,100-2500}$=	1 dB

Ref. 05 007-T-45, Bauphysik Iphofen

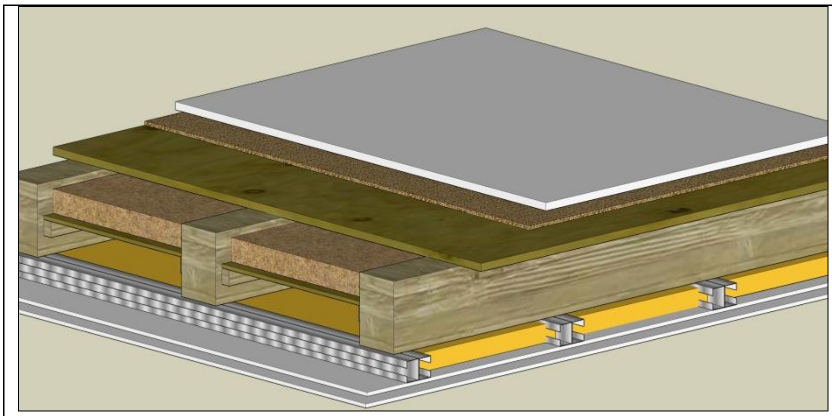
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 30 mm between joists and ceiling board. *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	55 dB
$L_{n,w}+C_{I,50-2500}$=	65 dB
$C_{I,50-2500}$=	10 dB
$C_{I,100-2500}$=	2 dB

Ref. 05 007-T-46, Bauphysik Iphofen

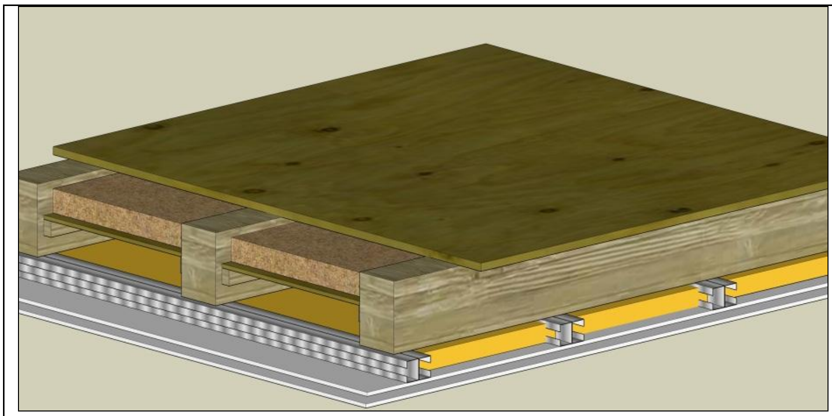
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm 35 kg/m³
Ceiling: channels 60 mmx27 mm fixed with 'Knauf Direktschwingabhänger' (vibration isolated fastener, see above), creating 30 mm between joists and ceiling board. *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	38 dB
$L_{n,w}+C_{I,50-2500}$=	48 dB
$C_{I,50-2500}$=	10 dB
$C_{I,100-2500}$=	0 dB

Ref. 06 026-T-06, Bauphysik Iphofen

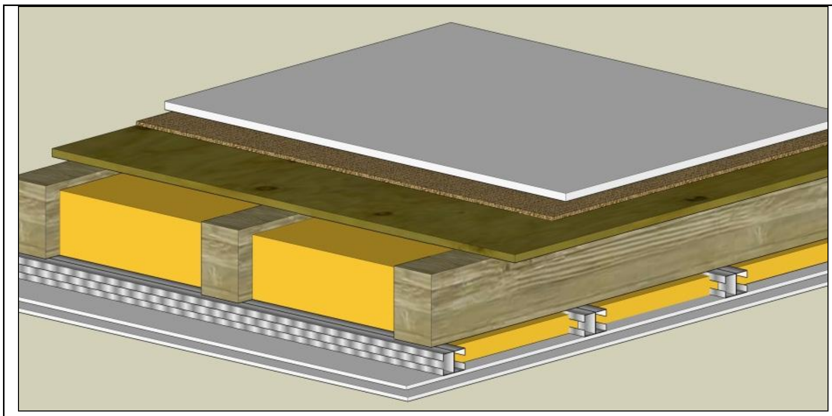
Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board and mineral wool 60 mm
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 100 mm below the joists *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	45 dB
$L_{n,w}+C_{I,50-2500}$=	50 dB
$C_{I,50-2500}$=	5 dB
$C_{I,100-2500}$=	-1 dB

Ref. 06 026-T-05, Bauphysik Iphofen

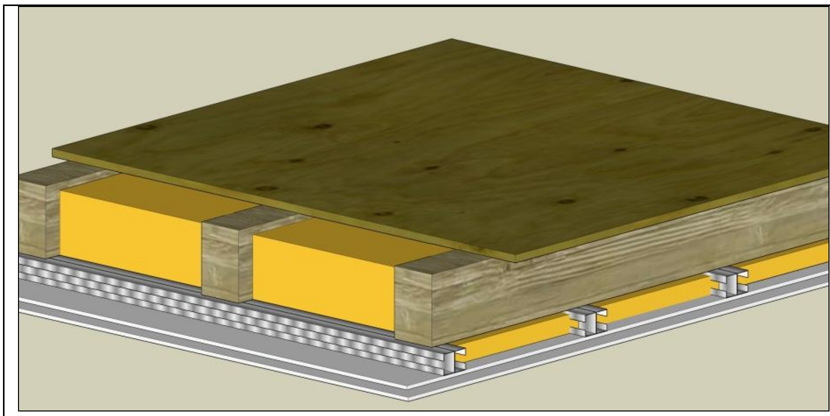
Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: ca. 100 kg/m² sand (ca. 6 cm) on OSB board and mineral wool 60 mm between channels
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 100 mm below the joists *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)



R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	41 dB
$L_{n,w}+C_{I,50-2500}$=	50 dB
$C_{I,50-2500}$=	9 dB
$C_{I,100-2500}$=	1 dB

Ref. 05 007-T-6, Bauphysik Iphofen

Topping: KNAUF BRIO WF (complex of 10 mm wood fibre insulation and 18 mm gypsum fibre board)
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm and mineral wool 60 mm between channels
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 100 mm below the joists *** 2x12.5 mm 'Knauf GKB board' (ca. 720 kg/m³)

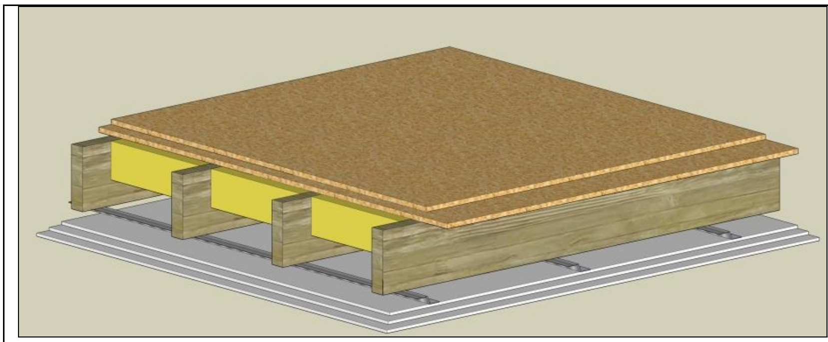


R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.

$L_{n,w}$=	51 dB
$L_{n,w}+C_{I,50-2500}$=	56 dB
$C_{I,50-2500}$=	5 dB
$C_{I,100-2500}$=	1 dB

Ref. 05 007-T-5, Bauphysik Iphofen

Topping: none
Floor: Particle board 24 mm *** joists 180x120 mm² o.c. 625 mm
Cavity: mineral wool 160 mm and mineral wool 60 mm between channels
Ceiling: completely free hanging ceiling on 2X CW-75 channels, 100 mm below the joists *** 2x12.5 mm ‘Knauf GKB board’ (ca. 720 kg/m³)



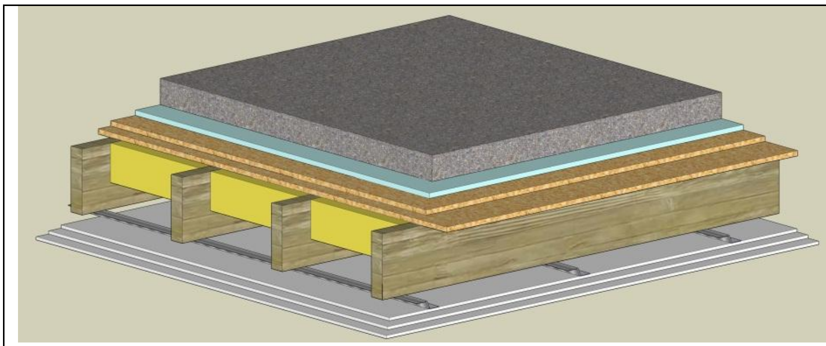
R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.

$L_{n,w}$=	54 dB
$L_{n,w}+C_{I,50-2500}$=	56 dB
(1) $L_{iFavg,Fmax}$=	59 dB
(1) $L_{i,Fmax,AW}$=	57 dB

(1) *Heavy impact Ball measurement*

REF.: On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K01 NRCC

Topping: none
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2”x10”) o.c. 406 mm
Cavity: mineral wool 150 mm
Ceiling: RC spaced 610 mm o.c.! 3 x 12.5 fire rated gypsum boards.



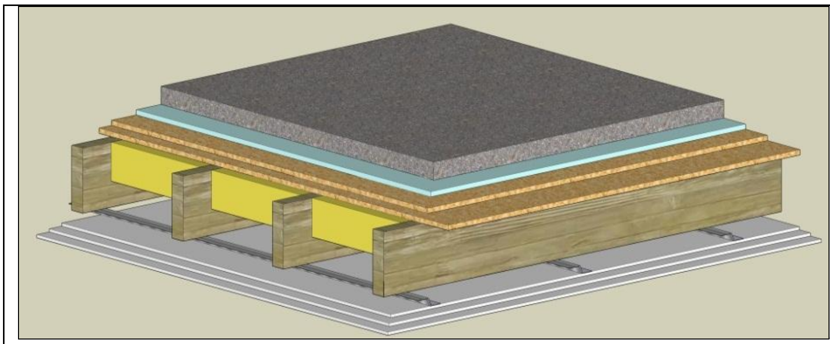
R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.

$L_{n,w}$=	43 dB
$L_{n,w}+C_{I,50-2500}$=	44 dB
(1) $L_{iFavg,Fmax}$=	42 dB
(1) $L_{i,Fmax,AW}$=	39 dB

(1) *Heavy impact Ball measurement*

REF.: On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K12 NRCC

Topping: Prefab concrete slab(100 mm) *** 20 mm closed cell foam resilient (no more information available)
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2”x10”) o.c. 406 mm
Cavity: mineral wool 150 mm
Ceiling: RC spaced 610 mm o.c.! 3 x 12.5 fire rated gypsum boards.

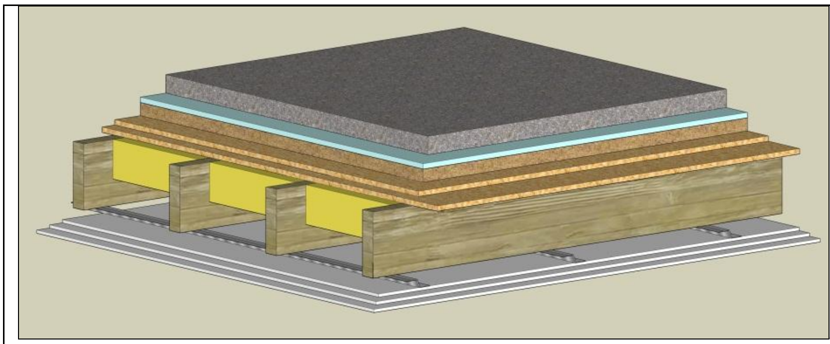


R'_{w}=	not avail.
R'_{living}=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	44 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	44 dB
(1) $L_{iFavg,Fmax}$=	44 dB
(1) $L_{i,Fmax,AW}$=	41 dB

(1) *Heavy impact Ball measurement*

***REF.:* On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K11 NRCC**

<u>Topping:</u> Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient (no more information available)
<u>Floor</u>: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2”x10”) o.c. 406 mm
<u>Cavity:</u> mineral wool 150 mm
<u>Ceiling:</u> RC spaced 610 mm o.c.! 3 x 12.5 fire rated gypsum boards.

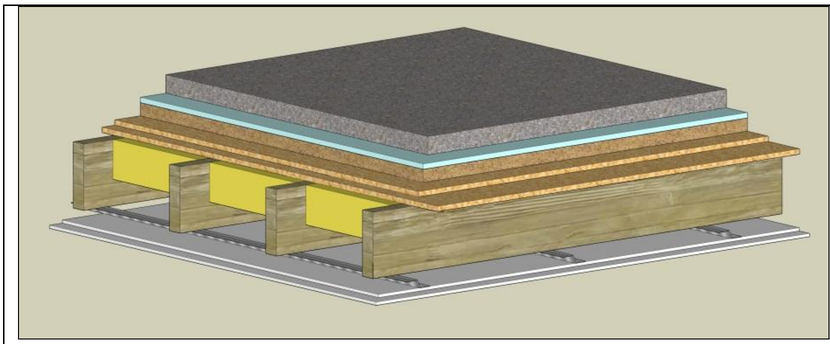


R'_{w}=	not avail.
R'_{living}=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	40 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	42 dB
(1) $L_{iFavg,Fmax}$=	41 dB
(1) $L_{i,Fmax,AW}$=	41 dB

(1) *Heavy impact Ball measurement*

***REF.:* On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K14 NRCC**

<u>Topping:</u> Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient *** 50 cm sand (ca. 80 kg/m²)
<u>Floor</u>: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2”x10”) o.c. 406 mm
<u>Cavity:</u> mineral wool 150 mm
<u>Ceiling:</u> RC spaced 610 mm o.c.! 3 x 12.5 fire rated gypsum boards.

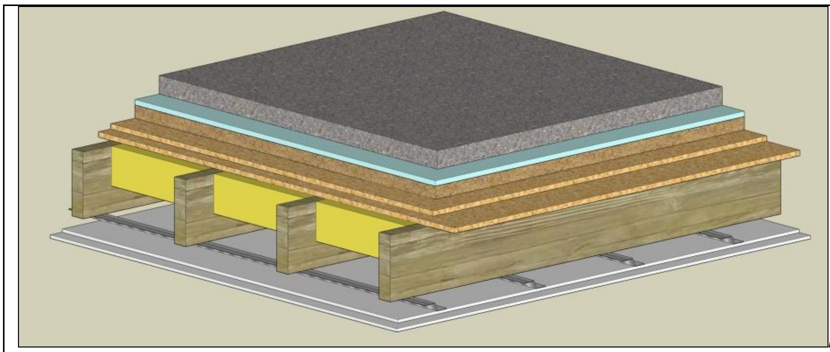


R'_{w}=	not avail.
R'_{living}=	not avail.
$C_{50\text{-}5000}$=	not avail.
$C_{100\text{-}3150}$=	not avail.
$C_{tr,100\text{-}3150}$	not avail.
$L_{n,w}$=	43 dB
$L_{n,w}+C_{I,50\text{-}2500}$=	44 dB
(1) $L_{iFavg,Fmax}$=	42 dB
(1) $L_{i,Fmax,AW}$=	44 dB

(1) *Heavy impact Ball measurement*

***REF.:* On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K15 NRCC**

<u>Topping:</u> Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient (no more information available) *** 50 cm sand (ca. 80 kg/m²)
<u>Floor</u>: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2”x10”) o.c. 406 mm
<u>Cavity:</u> mineral wool 150 mm
<u>Ceiling:</u> RC spaced 610 mm o.c.! 2 x 12.5 fire rated gypsum boards.

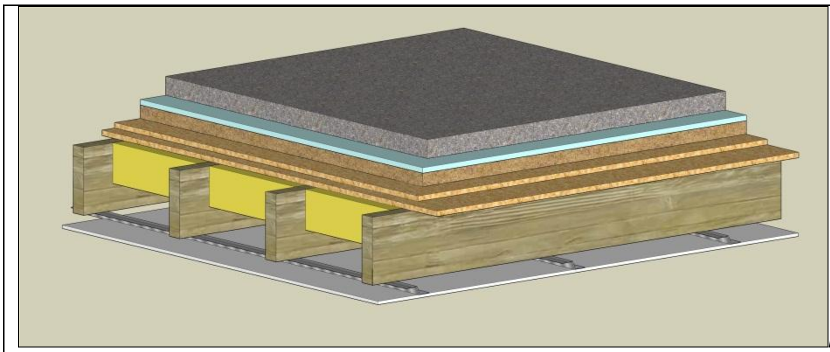


R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	47 dB
$L_{n,w}+C_{I,50-2500}$=	50 dB
(1) $L_{iFavg,Fmax}$=	46 dB
(1) $L_{i,Fmax,AW}$=	49 dB

(1) *Heavy impact Ball measurement*

***REF.:* On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K23 NRCC**

Topping: Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient *** 50 cm sand (ca. 80 kg/m²)
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2"x10") o.c. 406 mm
Cavity: mineral wool 160 mm and mineral wool 60 mm between channels
Ceiling: RC spaced 403 mm o.c.! 2 x 12.5 fire rated gypsum boards.

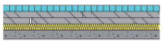
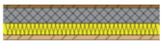
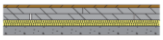
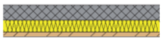
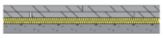
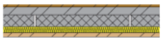
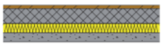
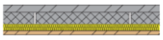
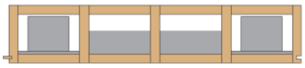
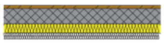
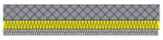
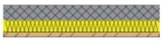
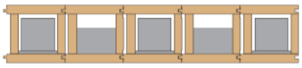
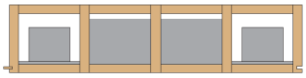
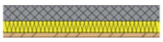
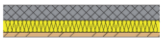
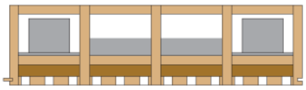
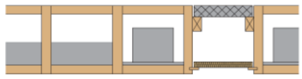


R'_w=	not avail.
R'_{living}=	not avail.
$C_{50-5000}$=	not avail.
$C_{100-3150}$=	not avail.
$C_{tr,100-3150}$	not avail.
$L_{n,w}$=	47 dB
$L_{n,w}+C_{I,50-2500}$=	48 dB
(1) $L_{iFavg,Fmax}$=	46 dB
(1) $L_{i,Fmax,AW}$=	48 dB

(1) *Heavy impact Ball measurement*

***REF.:* On reducing low frequency impact sound transmission in wood framed construction - Berndt Zeitler, Ivan Sabourin, Stefan Schoenwald, Erik Wenzke - National Research Council Canada (Inter.noise 2012) - Ref. NRC-K16 NRCC**

Topping: Prefab concrete slab(70 mm) *** 20 mm closed cell foam resilient *** 50 cm sand (ca. 80 kg/m²)
Floor: 2 x 19 mm OSB *** joists ca. 5x 25 cm (2"x10") o.c. 406 mm
Cavity: mineral wool 160 mm and mineral wool 60 mm between channels
Ceiling: RC spaced 610 mm o.c.! 1 x 12.5 fire rated gypsum boards.

		$R_{w,P}$	$L_{n,w,P}$	$C_{I,50-2500}$ $C_{I,100-2500}$			$R_{w,P}$	$L_{n,w,P}$	$C_{I,50-2500}$ $C_{I,100-2500}$
1 3 4 8 13			37 dB	+12 dB +1 dB	2 7 10 14			44 dB	+2 dB ±0 dB
2 3 4 8 13			37 dB	+17 dB +1 dB	7 10 14		71 dB	52 dB	-3 dB -5 dB
3 4 8 13		69 dB	46 dB	+7 dB -3 dB	2 5 6 11 14			45 dB	+5 dB -1 dB
2 7 9 13			40 dB	+8 dB ±0 dB	5 6 11 14		68 dB	50 dB	+1 dB -2 dB
7 9 13		75 dB	44 dB	+5 dB -1 dB			II 		
2 7 9 12			47 dB	+7 dB -1 dB					
7 9 12		69 dB	56 dB	-1 dB -6 dB	7 10 14		73 dB	50 dB	-3 dB -5 dB
		I 					III 		
7 10 14		68 dB	52 dB	-1 dB -5 dB	7 10 14		72 dB	51 dB	±0 dB -2 dB
		IV 					V 		

1 Parquet flooring laid floating
2 Fermacell Powerpanel 20mm glued
3 Fermacell Powerpanel 20mm unitised
4 Fermacell screed element 25mm
5 Wood chipboard 28mm
6 Isover EP2, 20 mm, s'<20MN/m³
7 Gutex Thermofloor, 20mm, s'<30MN/m³
8 Isover EP2, 30mm, s'<15MN/m³
9 Fermacell honeycomb fill 30mm

I LIGNATUR box element (LKE)
II LKE with fill 45kg/m² (possible as of element height h = 160mm)
III LKE with fill 90 kg/m² (possible as of element height h = 200mm)

11 Parquet flooring laid floating
12 Cement screed 50mm
13 Isover PS81, 30mm, s'<6MN/m³

IV LIGNATUR surface element (LFE)
V LFE with 50kg/m² fill (possible as of element height h = 160mm)
VI LFE with 100kg/m² fill (possible as of element height h = 200mm)

Figure: the Swiss company 'Lignatur' has some specific solutions for compartment floors. Box and surface elements constitute the load-bearing floor. Different types of toppings allow attaining a wide variety of acoustic performances. The picture down left shows a highly damped solution with dry concrete blocks and grit fillings, optimizing the low frequency sound insulation and acoustic comfort (damping the modal peaks and resonances). Source: http://www.lignatur.ch/2011/en/planning/workbook/

4.4 - Junctions and flanking transmission

4.4.1 - Techniques used to reduce the flanking transmission

In the optimized acoustic concept for party walls of a continuous cavity from foundations to roofs, no flanking transmission between horizontally adjacent apartments is possible. But for apartments one above the other, flanking transmission is definitely present and will limit the overall airborne sound insulation. The main questions are: '*how important is this flanking transmission (see section 4.4.2) and how can we reduce it?*'

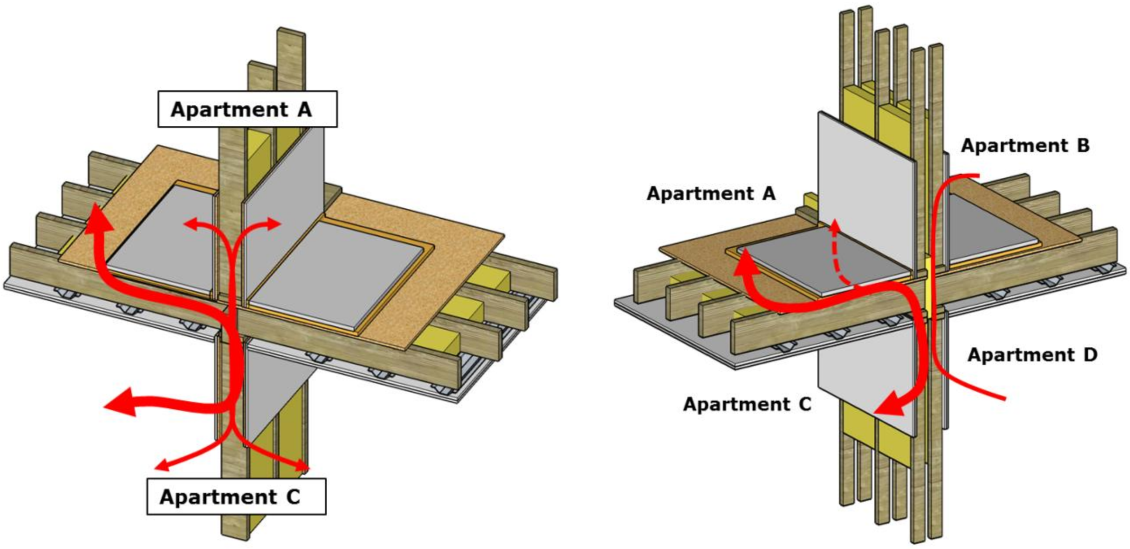


Figure 42 a: flanking transmission paths exist vertically in all junctions, so also through room dividing walls of an apartment (left) or via the façades. In the horizontal direction, the flanking transmission to the adjacent apartment can be eliminated by a party wall such as described in section 3.

1) The most obvious technique to reduce the flanking transmission is to make a disconnection / vibration interruption

We have seen this technique being applied to its full extent in the party wall (see above figure 42 'a'), reducing flanking transmission to the adjacent apartment almost totally.

But also smaller disconnections like the use of an elastic joint between the ceiling boards and the walls (see figure 42 'b') will reduce the flanking transmission from the walls and floor from the apartment above to the ceiling and walls below. Caution: we were told that there can be problems with fire safety acceptance in several European countries, making it necessary to still have a rigid joint.

If the sound insulation is important between two rooms, boards should never continue from one room to the adjacent room to avoid flanking transmission. This is illustrated in figure 42 'c' with an evaluation of the flanking transmission through a metal stud wall with gypsum boards/

Figure 42 b: creating an elastic joint between the ceiling and the walls can reduce the flanking transmission 'Fd' and 'Df', but can create problems with the fire safety requirements in some countries.

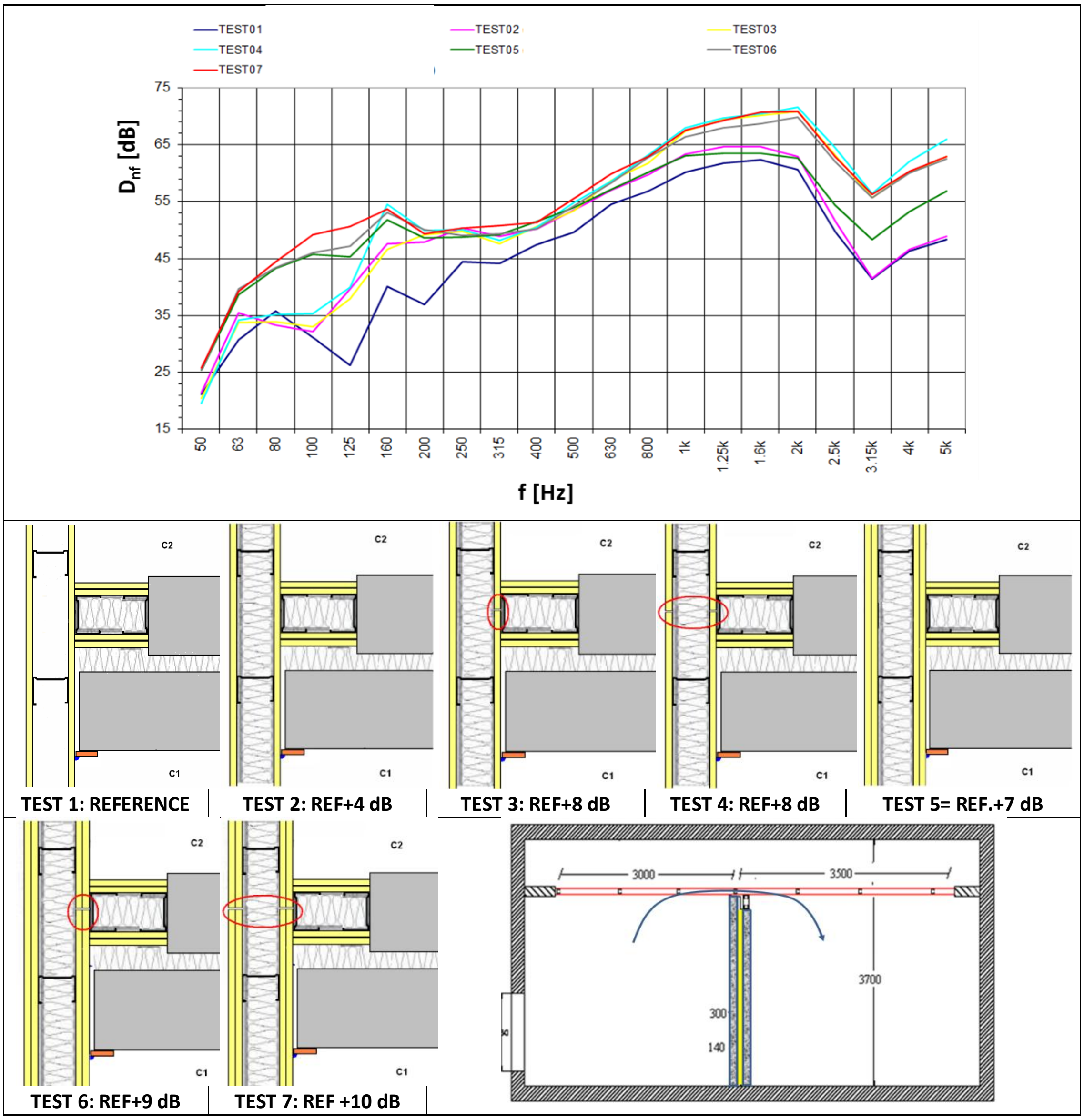


Figure 42 c: evolution of the flanking sound insulation for different constructions. The basic construction was a T junction. The flanking wall was composed of a single layer gypsum board (12.5 mm) on a single Metal frame (75 mm thick). The cavity was empty in the reference setup (Test 1). In test 2, the cavity was filled up with mineral wool. In test 3, the inner leaf was interrupted. The same was done with the outer leaf in test 4. In the tests 5, 6 and 7, the same interventions were made but on a flanking wall consisting of 2x12.5 mm gypsum boards.

2) Linings will have some effect. We already discussed the effect floating floors can have on the 4 flanking transmission paths ‘Df’. Technical linings before the walls in the emission and the reception rooms will have some effect if fixed with resilient bars, preferably perpendicular to the wooden studs (see figure 42 ‘d’). Unfortunately no measurements are known to us to quantify this effect. The empty cavity (necessary to allow the passage of electric wiring or piping) and the limited width of the cavity will unfortunately limit the possible benefits, especially in the low frequency bands.

Figure 42 d: technical linings using resilient studs fixed perpendicular to the wood studs can also diminish some flanking transmission. We do not dispose of any measurements quantifying this, but we expect the improvement to be only in the mid and higher frequencies.

3) Using more ‘wood mass’ in the junction apparently also has some effect. In Canada a ‘heavy’ junction with a concentration of wooden beams, showed some improvement even in the low frequencies (see figure 42 ‘e’). Unfortunately no measurement data is available that isolates this aspect from other influences. So this hypothesis still has to be verified with a dedicated setup.

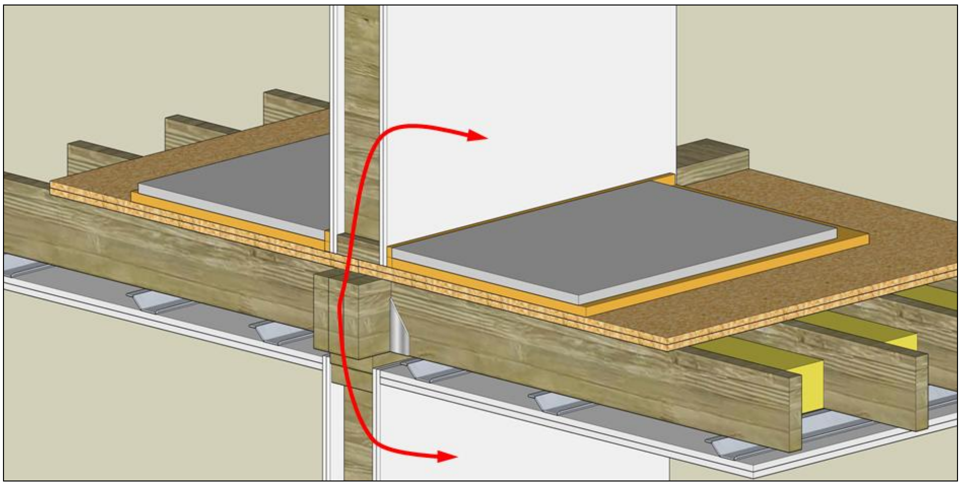


Figure 42 e: creating heavier junctions apparently reduces the flanking transmission. Unfortunately no measurement data is available to verify this statement (information from Zeitler Berndt, National Research Council Canada).

4) Apparently several research groups and consulting offices have tried to use elastic interlayers to reduce the flanking transmission. Two 'families of solutions' can be seen: the first uses continuous linear elastic interlayers on top of walls and below floors (or just only below the floors and not interrupting the walls in the project Limnologen in Växjö, Sweden, figure 42 'g'), a second solution uses discontinuous fixations on top of the load bearing floors (figure 42 'h'). This last solution is apparently only possible with cross laminated timber, the load pressure with punctual charges being too high for the wood fibres in the horizontal beams of timber frame constructions. A pragmatic research (figure 42 'f') showed only a small improvement above 200 Hz that even became negligible when screws were fixed every 40 cm (necessary to take on the horizontal forces within the construction). The inefficient behaviour in the low frequencies can be explained by a too small disruption for the long structural wavelengths of low frequency bending and transversal waves. In the construction in Limnologen (figure 42 'g'), the linear elastic interlayer seems to have a beneficial effect on the flanking impact sound. Unfortunately, no measurement results or additional information about this was communicated.

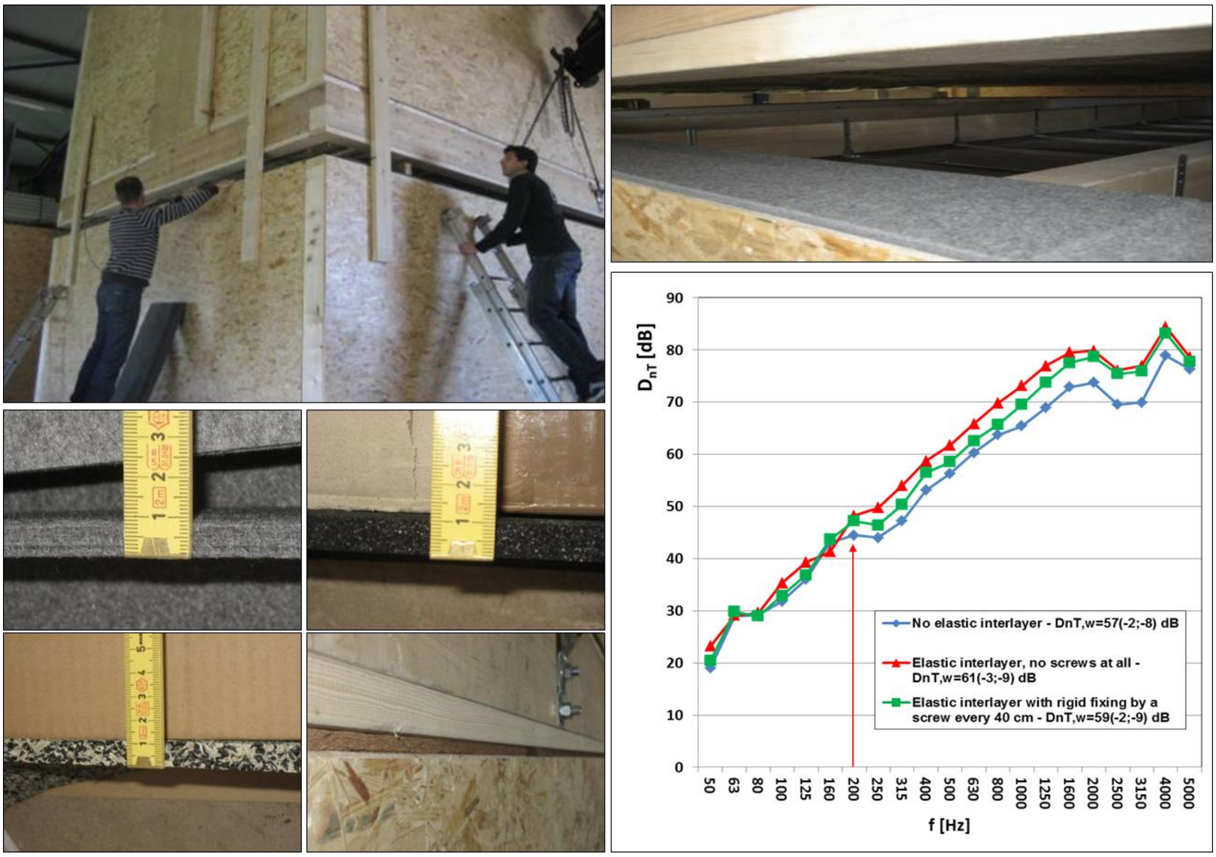


Figure 42 f: a pragmatic research examined the effect on the airborne standardised sound insulation D_{nT} of different linear and continuous elastic interlayers on the walls just below the floor of the room above. The system proved to be only effective above 200 Hz, showing no difference at all for the low frequencies.

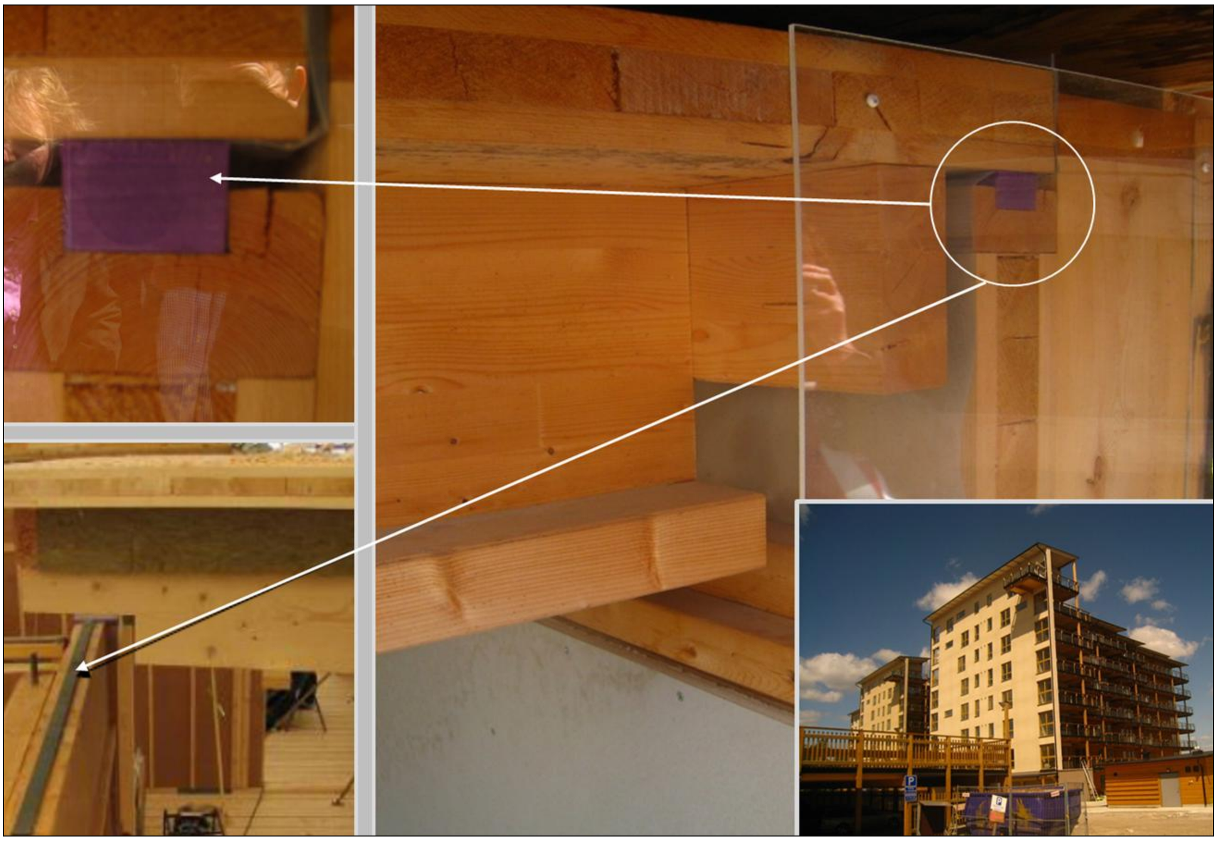


Figure 42 g: a huge multi-storey lightweight timber frame apartment building in Limnologen Växjö, Sweden, also uses linear continuous elastic interlayers to reduce flanking impact sound transmission. All floors bear on the purple elastic interlayer.

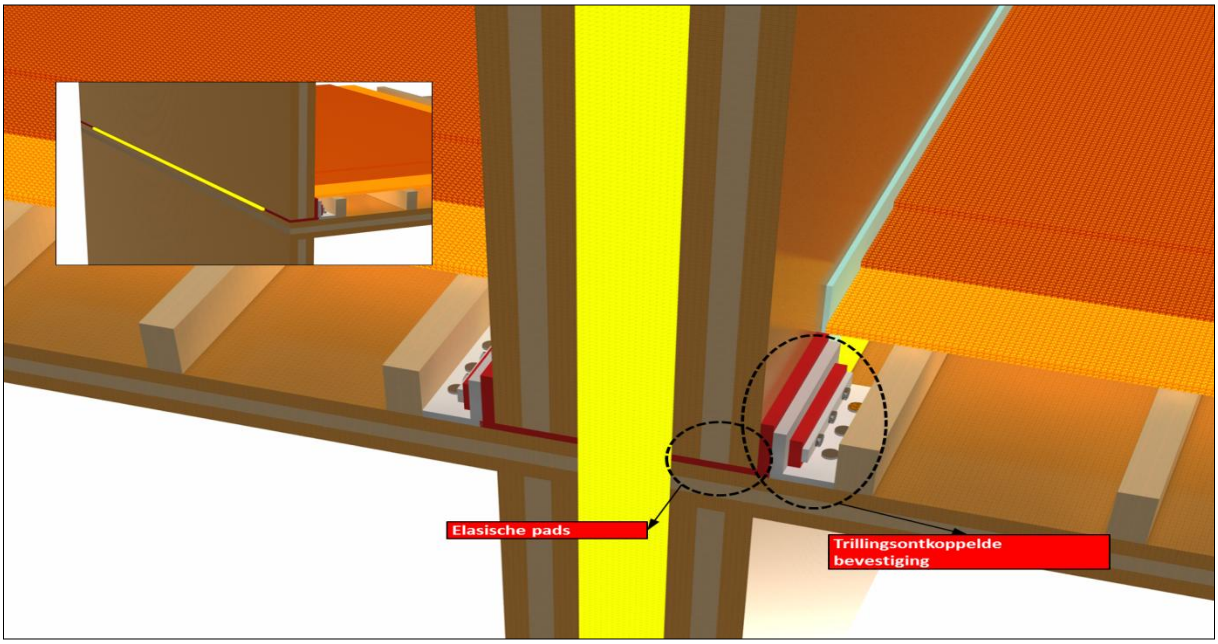


Figure 42 h: the use of elastic pads, creating only discontinuous elastic contact points every 150 cm appears to have a better effect in the low frequencies (BBRI-La Maison Idéale Project).

4.4.2 - Quantifying the flanking transmission

(1) Example 1: quantifying the flanking insulation of some lightweight timber frame junctions in a laboratory setup with and without elastic joints.

Methods to predict the total sound transmission (and the insulation against it) have been developed. A more detailed description can be found in the report of WG 1.

In this chapter some measurements results are given that quantify this flanking transmission (and vice versa the flanking sound insulation).

Special setups have been built in the BBRI's laboratories allowing the following measurements: R, σ, R_{ij}, δ, T_s, D_{nf}. The measurement of the $D_{n,f}$ was carried out with the intensity technique. The sound generated in the source room (C1) was steady and had a continuous spectrum in the considered frequency range. The radiated power by the reception wall was measured with an intensity probe. In order to avoid the background noise from the acoustic hall, we had to use a semi-anechoic box which disrupted the values below 350 Hz. The D_{nf} and R_{ij} were then obtained by the following formulas: $D_{nf,I} = (L_{p1} - 6) - \left(\overline{L_{In,f}} + 10lg\left(\frac{S_{mf}}{A_0}\right)\right)$ and $R_{ij} = D_{nf} + 10lg\,\frac{S_s l_{ij,lab}}{A_0 l_{ij}}$

Figure 43: LEFT: laboratory setup; MIDDLE and RIGHT: a semi-anechoic box (protecting against the noise influence from the acoustic hall) was used to measure the radiated sound of the wall via the intensity technique

The measurement procedures and the result analysis are reported in other documents. This report here summarizes the results measured on (1) lightweight timber frame constructions in the laboratory, (2) on a research mock-up (built to comply with the EOTA-testing procedure) and (3) on cross laminated timber constructions.

The first setup to get an idea of the importance of the flanking transmission, was built in the (former) acoustic laboratory facility in Limelette. Figures 44 'a' to 'c' first give a description of the separating floor and the acoustic performances going from its basic load-bearing construction (figure 44 'a') to the finished construction in figure 44 'c'. Next (figure 44 'd'), a wall is constructed upon this floor creating a L-junction for which the flanking sound insulations have been determined. In figure 44 'e', the construction has been extended to a T-junction with a wall on top and below the floor, rigidly connected to the load-bearing construction and the ceiling. In figure 44 ‘f’, the effect of an elastic interlayer (reducing the linear rigid contact to punctual rigid contacts) on the flanking transmission is examined.

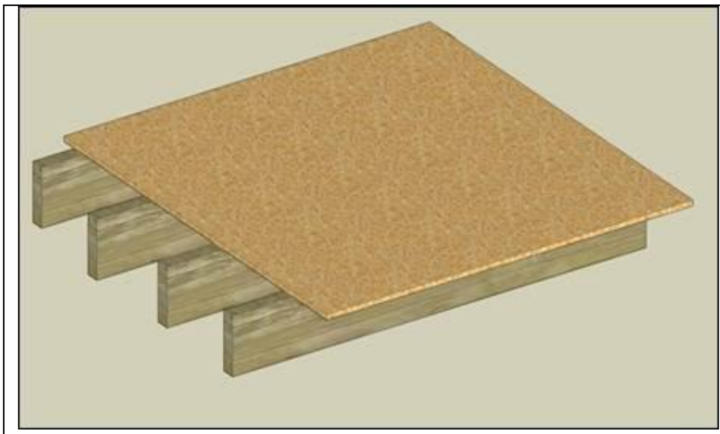
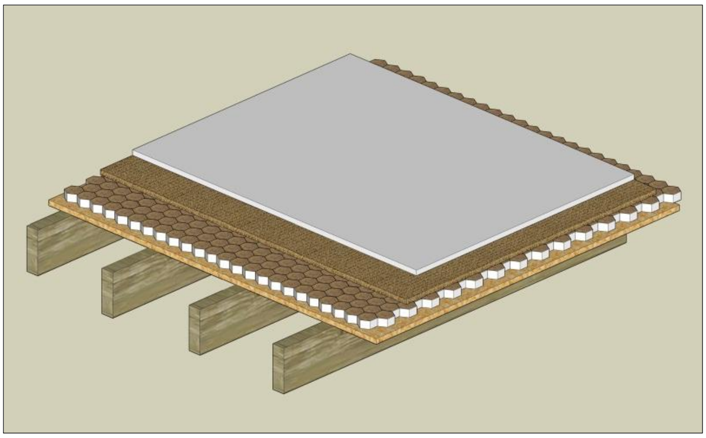
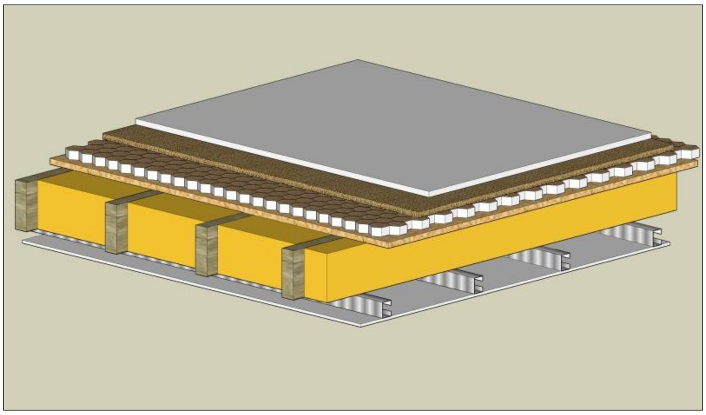
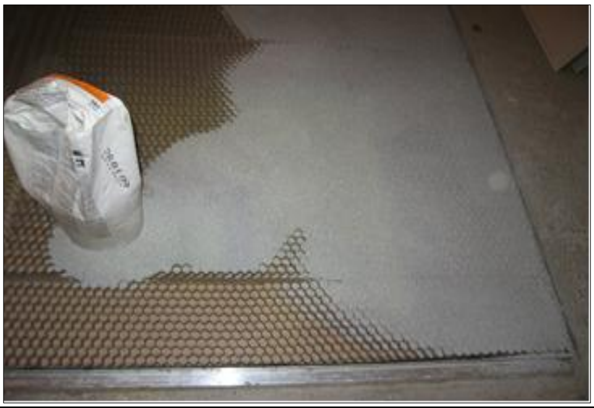
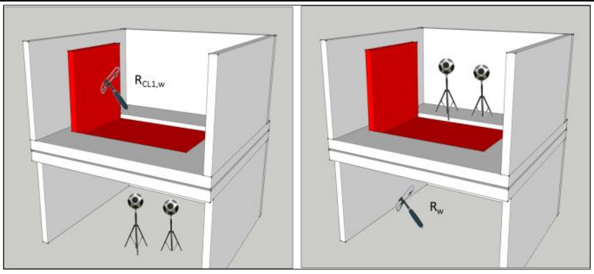
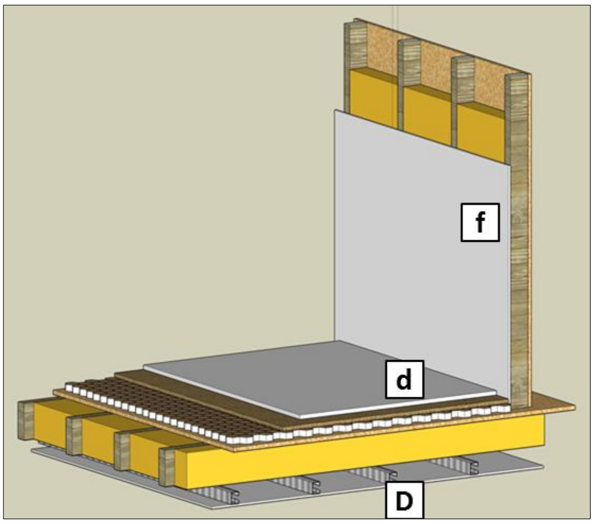
 *Figure a: load carrying floor*	**Reference floor** 3750 x 2400 mm²: OSB 22 mm (13 kg/m²) *** joists 165x65 mm², 40 cm o.c. **Topping: /** **R_w (C;C_{tr})=28 (-1;-2) dB** **$L_{n,w}$ (C_I)=92(-5) dB** Ref. BBRI – OSABOIS TEST0
 *Figure b: with topping of honeycomb boards filled with gravel*	**Floor** 3750 x 2400 mm²: OSB 22 mm (13 kg/m²) *** joists 165x65 mm², 40 cm o.c. **Topping:** honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board) **R_w (C;C_{tr})=52 (-2;-8) dB** **$L_{n,w}$ (C_I)=59(1) dB** Ref. BBRI –OSSABOIS TEST1
 *Figure c: with an independent ceiling (1 board of 10 mm Fermacell)*	**Floor** 3750 x 2400 mm²: OSB 22 mm (13 kg/m²) *** joists 165x65 mm², 40 cm o.c. **Topping:** honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board) **Ceiling:** totally independent MS channels,10 mm Fermacell board (7.7 kg/m²), total cavity width 235 mm filled with 150 mm MW (32 kg/m³) **R_w (C;C_{tr})=68 (-3;-9) dB** (intensity measurement, side ceiling) **$L_{n,w}$ (C_I)=43(1) dB** Ref. BBRI –OSSABOIS TEST2

Figure 44: Floors a, b and c







$R_{w,Dd}$ = R_w ($C;C_{tr}$)=68 (-3;-9) dB
(direct sound insulation, measured in the situation corresponding with figure 'c', BBRI – OSSABOIS TEST2)
$R_{w,Df}$ > 73 dB (flanking sound insulation for the transmission from the ceiling 'D' to the flanking wall 'f', determined via intensity measurement on the gypsum board side of the 'f' wall, Ref. BBRI –OSSABOIS TEST4)

Figure d: L-junction with the studwall rigidly fixed on top of the floor

Floor 3750 x 2400 mm²:
OSB 22 mm (11.7 kg/m²) *** joists 165x65 mm², 40 cm o.c.
Topping 'd': honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board)
Ceiling 'D': totally independent MS channels,10 mm Fermacell board (7.7 kg/m²), total cavity width 235 mm filled with 150 mm MW (32 kg/m³)
Wall 'f' 12.5 mm gypsum board, studs 90x40 mm² 60 cm o.c., MW 90 mm, OSB 18 mm

Figure 44: junction d

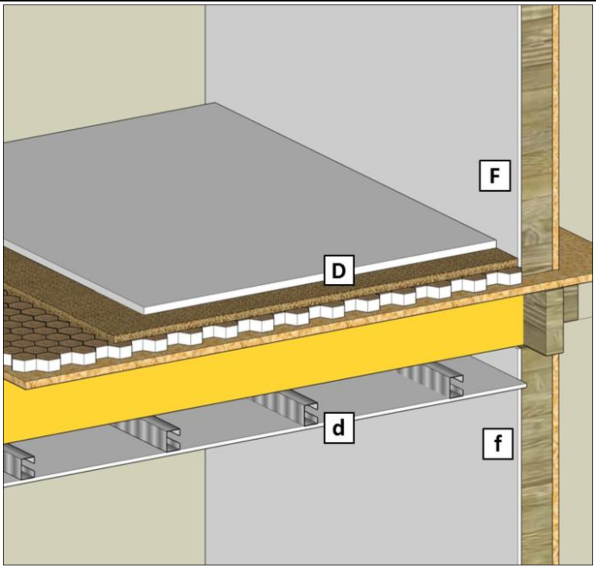


Figure e: T-junction with the studwall rigidly fixed on top of and below the floor

$R_{w,Dd}$ = R_w ($C;C_{tr}$)=68 (-3;-9) dB
(direct sound insulation, measured in the situation corresponding with figure 'c', BBRI – OSSABOIS TEST2)
$R_{w,Fd}$> 76 dB (flanking insulation for the flanking transmission from the flanking wall 'F' to the ceiling 'd', value obtained by the energetic subtraction of the value determined by the intensity measurement result on the ceiling minus $R_{w,Dd}$. Ref. BBRI –OSSABOIS TEST11)
$R_{w,L1L2}$ > 69 dB (flanking insulation for the flanking transmission from the flanking wall 'F' to the flanking wall 'f', value obtained by the intensity measurement result on the wall 'f', we supposed that the shielding of the floor by its topping is effective enough not to take in account the transmission path 'Df'. Ref. BBRI –OSSABOIS TEST11)

Floor 3750 x 2400 mm²:
OSB 22 mm (11.7 kg/m²) *** joists 165x65 mm² 40 cm o.c.
Topping 'D': honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board)
Ceiling 'd': totally independent MS channels,10 mm Fermacell board (7.7 kg/m²), total cavity width 235 mm filled with 150 mm MW (32 kg/m³)
Wall 'F' and 'f': 12.5 mm gypsum board, studs 90x40 mm² 60 cm o.c., MW 90 mm, OSB 18 mm

Figure 44: junction e

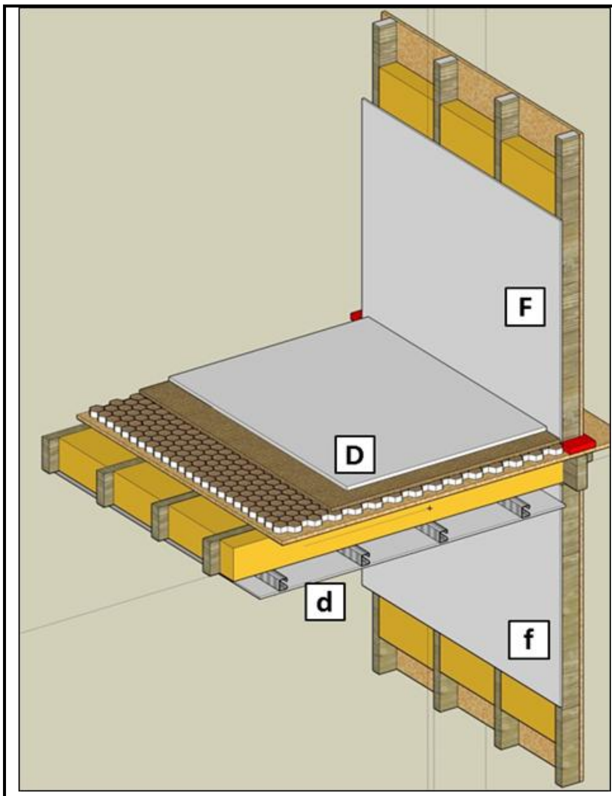


Figure f: similar as in figure 'e' but with an elastic junction: T-junction with the stud wall rigidly fixed below the floor. The stud wall on top of the floor stands on an elastic interlayer (CDM 41010, see red strip in drawing). A screw fixes the top wall every 60 cm through the elastic interlayer to the floor, resulting in a punctual rigid connection. The effect of the resilient interlayer appears to be negligible.

Floor 3750 x 2400 mm²:
OSB 22 mm (11.7 kg/m²) *** joists 165x65 mm², 40 cm o.c
Topping 'D': honeycomb boards filled with gravel (Fermacell) 45 kg/m²*** Fermacell boards 2E32 26 kg/m² (complex of 10 mm MW and 20 mm gypsum fibre board)
Ceiling 'd': totally independent MS channels,10 mm Fermacell board (7.7 kg/m²), total cavity width 235 mm filled with 150 mm MW (32 kg/m³)
Wall 'F' and 'f': 12.5 mm gypsum board, studs 90x40 mm² 60 cm o.c., MW 90 mm, OSB 18 mm

$R_{w,Dd}$ = R_w ($C;C_{tr}$)=68 (-3;-9) dB
(direct sound transmission, measured in the situation corresponding with figure 'c', BBRI – OSSABOIS TEST2)
$R_{w,Fd}$> 78 dB (flanking insulation for the flanking transmission from the flanking wall F to the ceiling d, value obtained by the energetic subtraction of the value determined by the intensity measurement result on the ceiling minus $R_{w,Dd}$. Ref. BBRI –OSSABOIS TEST06)
$R_{w,Ff}$ > 71 dB (flanking insulation for the transmission from the flanking wall 'F' to the flanking wall 'f', value obtained by the intensity measurement result on the wall 'f', we supposed that the shielding of the floor by its topping is effective enough not to take in account the transmission path 'Df'. Ref. BBRI – OSSABOIS TEST06)

Figure 44 : junction f

(2) Example 2: quantifying the flanking insulation of some lightweight timber frame junctions in an experimental mock-up (Beringen, MBS).

A major lightweight timber frame manufacturer wants to expand its activities to apartment constructions. They agreed to cooperate in a research project aiming to generate building guidelines for lightweight timber frame apartment constructions. A mock-up has been built that complies with the setup instructions as stipulated by EOTA (see figure a). One of the experiments was to study the flanking sound transmission in a simple 3-cell timber frame mock-up and to confront the measurements with the prediction methods as developed by WG1 (results are discussed in a research report)

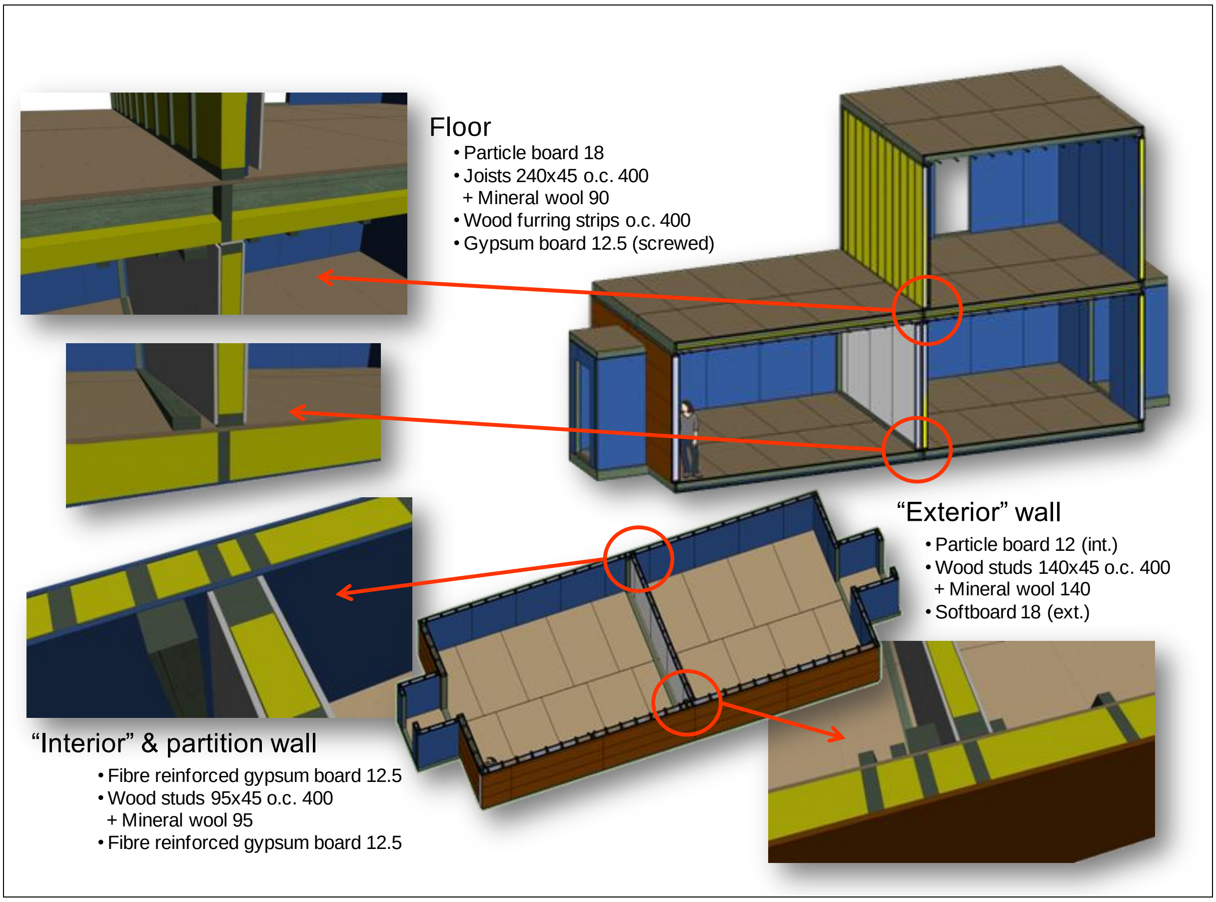


Figure 45 a: Timber frame mock-up at Machiels Building Solutions at Beringen (Belgium) (all dimensions in mm)

Both vibration reduction indices $D_{v,ij,n}$ using structural excitation and flanking sound reduction indices R_{ij} using airborne excitation have been measured. In the further analysis, we will focus only on the flanking sound reduction indices. These have been measured using the sound intensity technique (using both 50 mm and 12 mm microphone spacers) with appropriate shielding (see figure b). Only the vertical sound transmission is studied along 2 junctions: the cross junction and the T-junction involving the "exterior" wall. The measurement results are displayed in figures c and d. Since the direct sound reduction index - estimated at $R_w(C;C_{tr};C_{50-5000};C_{tr,50-5000})$ = 40(-1;-3;0;-6) dB - is much lower than all the flanking sound reduction indices measured(see figure e), it is clear that, in this case (very basic floor construction), flanking is not important. However, when the floor construction is improved considerably, flanking sound transmission may become important.

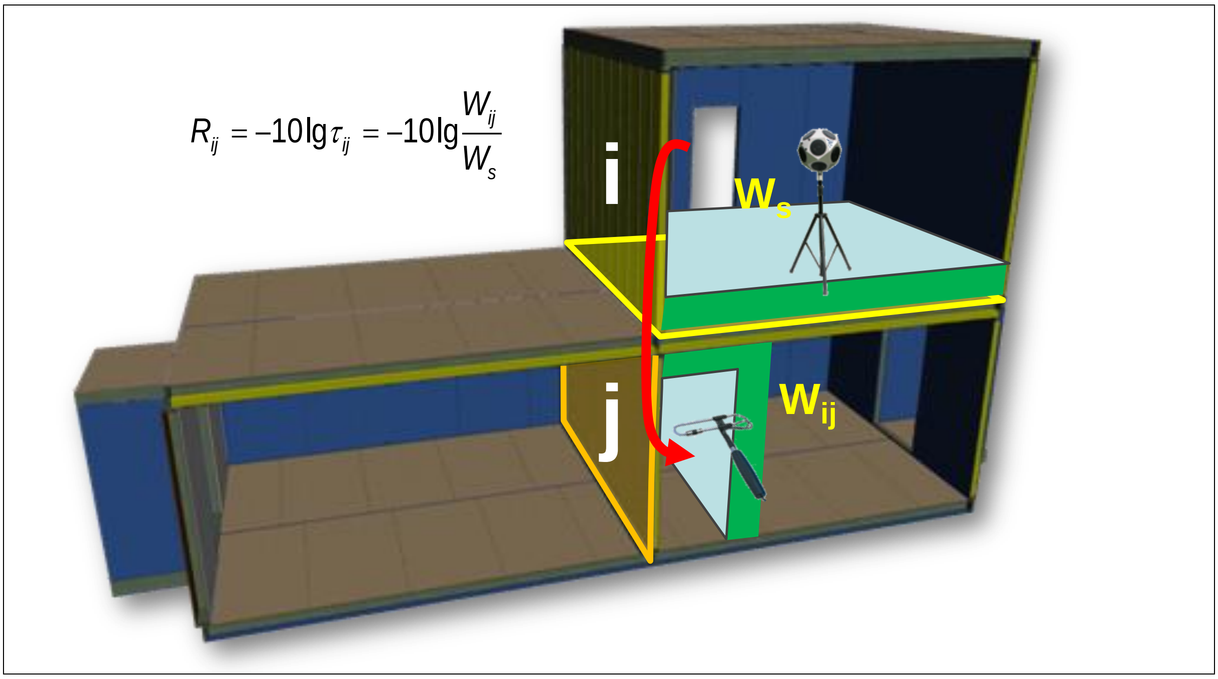


Figure 45 b: Test setup example for measuring the flanking sound reduction index

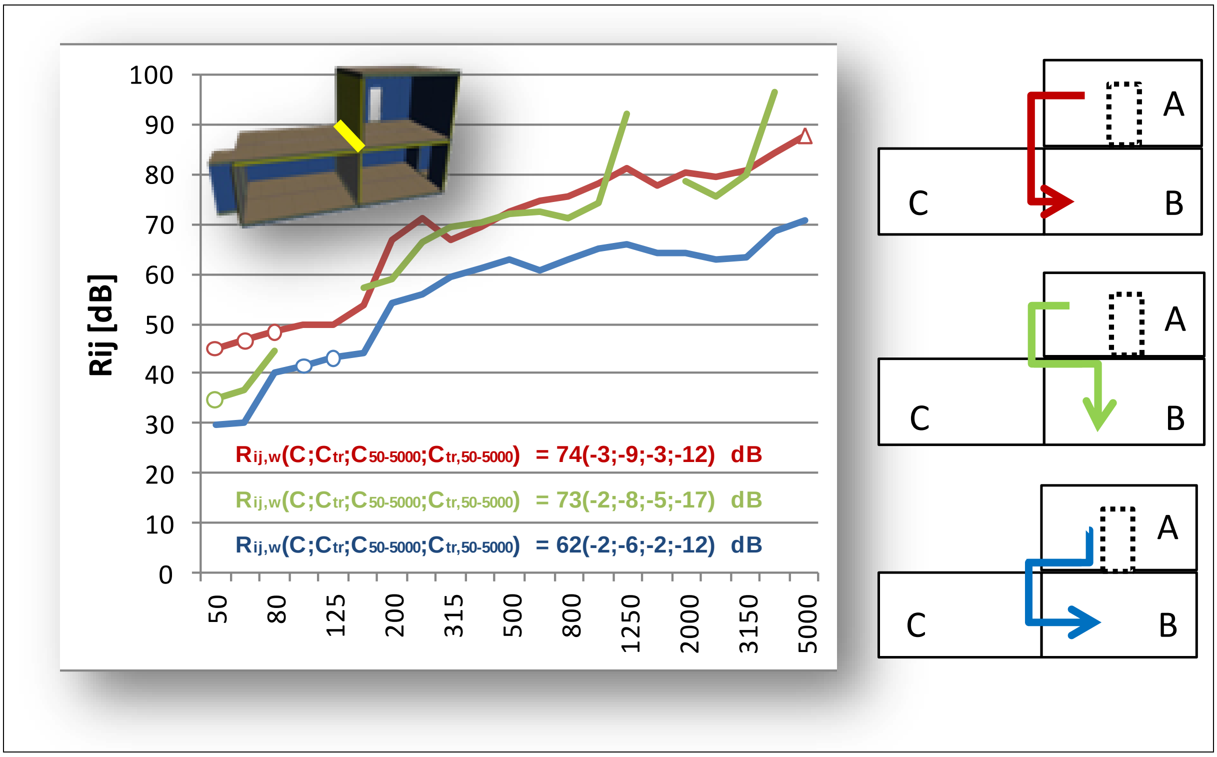


Figure 45 c: Measured flanking sound reduction indices on the cross junction for the 3 paths Ff, Fd and Df. Values indicated with a triangle are minimal values, whereas values indicated with a circle are interpolated or extrapolated values (-5 dB/octave going down at low frequencies).

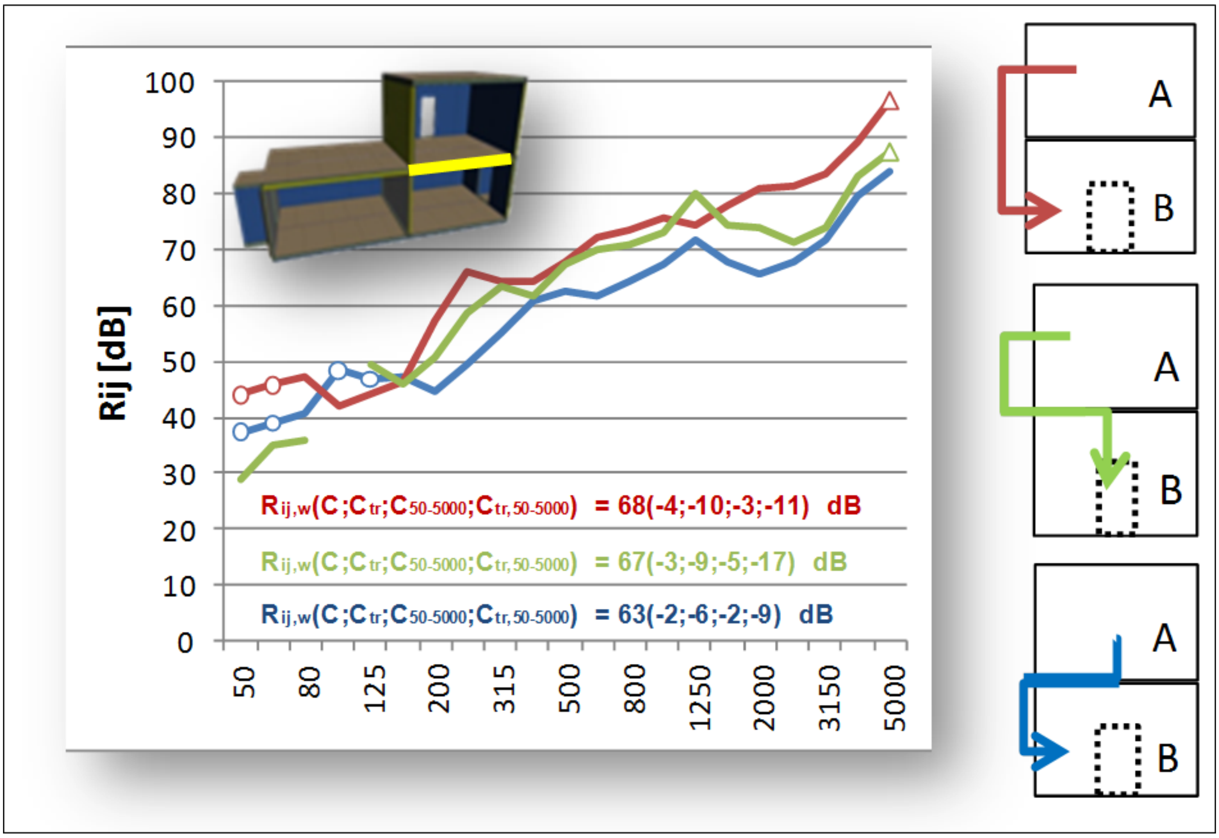


Figure 45 d: Measured flanking sound reduction indices on the T junction for the 3 paths Ff, Fd and Df. Values indicated with a triangle are minimal values, whereas values indicated with a circle are interpolated or extrapolated values (-5 dB/octave going down at low frequencies).

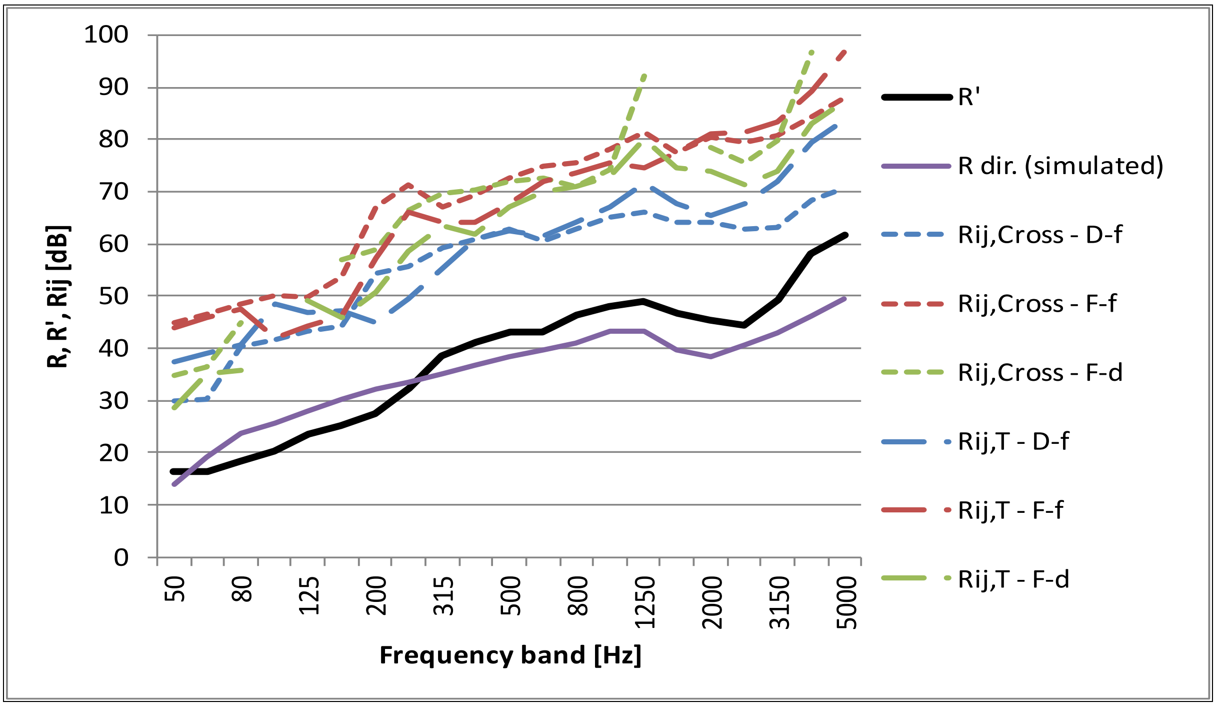


Figure e: Comparison of the (simulated) direct sound reduction index R, the measured overall sound reduction index R′ and the measured flanking sound reduction indices R_{ij}.

(3) Example 3: Quantifying the flanking insulation of some cross laminated timber junctions with and without elastic joints in a laboratory setup

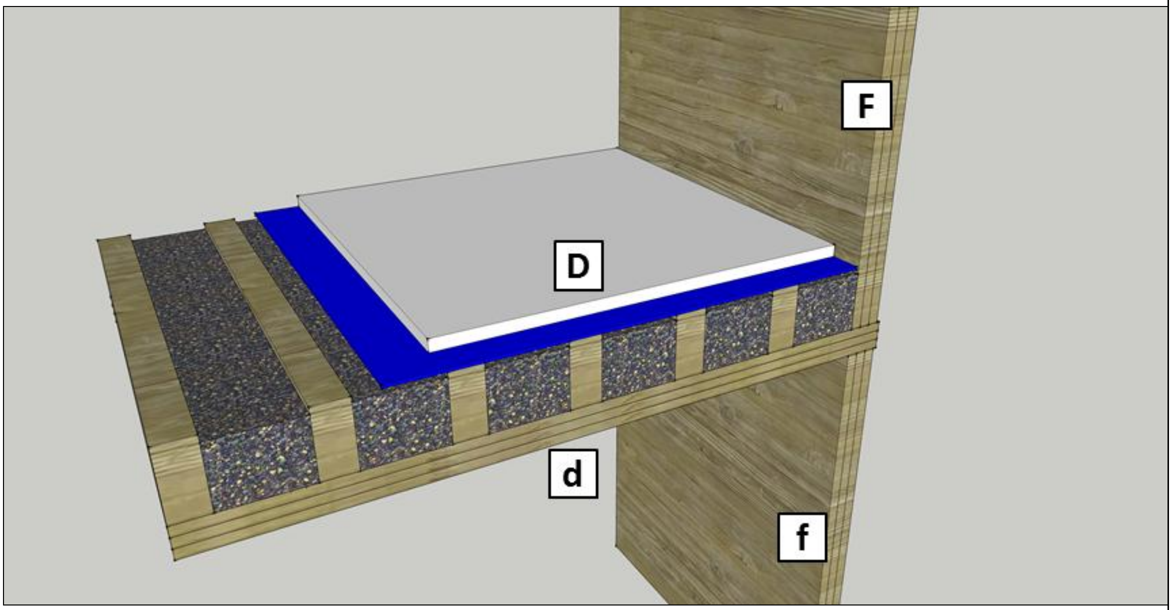


Figure a: T-junction with cross laminated timber (RE GT Wal)

__Floor 'd'__ *cross laminated timber 9.4 cm thick, with wooden 'ribs' (see drawing) of 9.5x20 cm², interdistance 25 cm. The space between the 'ribs' is filled with gravel (1400 kg/m³).*

__Topping 'D':__ *9 mm thick elastic latex lining Isopack, with a Fermacell dryfloor (fibre gypsum) system 'Maxifloor' of 38 mm thickness (1100 kg/m³ or 41.8 kg/m²)*

__Wall 'F' and 'f':__ *9.4 cm cross laminated timber 9.4 cm thick, connected with 3 steel connecting hooks (see picture left) for each wall.*

__Floor element alone__

$R_{w,Dd}$= R_w ($C;C_{tr}$)=65 (-3;-9) dB

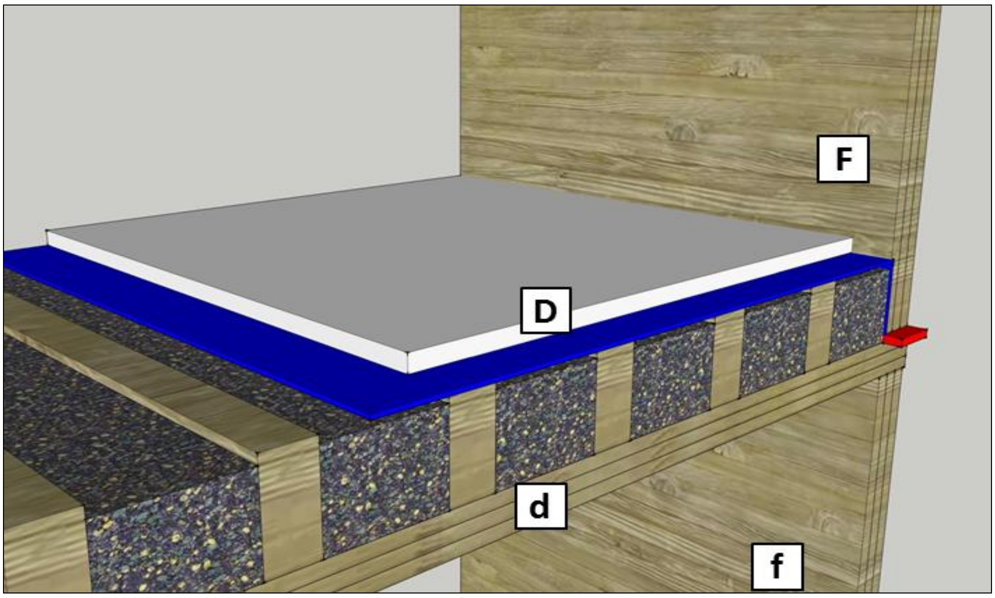
(direct sound transmission through the floor alone, BBRI –AC5126)

$L_{n,w}$ (C_I)= 50 (-1) dB *(BBRI-AC5068)*

__Flanking sound insulation__

$R_{w,\,Dd\oplus Fd}$=61(-2;-8) dB *(total insulation for the transmission paths Dd and Fd determined by intensity measurement result on the ceiling minus $R_{w,Fd}$. Ref. BBRI –AC5127)*

$R_{w,Ff}$ = 61 dB *(determined by intensity measurement on f, we supposed that the shielding of the floor by its topping is effective enough not to take in account the transmission path Df. Ref. BBRI –AC5127)*



Floor 'd' *cross laminated timber 9.4 cm thick, with wooden 'ribs' (see drawing) of 9.5x20 cm², interdistance 25 cm. The space between the 'ribs' is filled with gravel (1400 kg/m³).*

Topping 'D': *9 mm thick elastic latex lining Isopack, with a Fermacell dryfloor (fibre gypsum) system 'Maxifloor' of 38 mm thickness (1100 kg/m³ or 41.8 kg/m²)*

Wall 'F' and 'f': *9.4 cm cross laminated timber 9.4 cm thick, connected with 3 steel connecting hooks (see picture left) for each wall.*

Floor element alone

$\boldsymbol{R_{w,Dd} = R_w\ (C;C_{tr}) = 65\ (-3;-9)\ dB}$

(direct sound transmission through the floor alone, BBRI –AC5126)

$\boldsymbol{L_{n,w}\ (C_I) = 50\ (-1)\ dB}$ *(BBRI-AC5068)*

Flanking sound insulation

$\boldsymbol{R_{w,\ Dd\oplus Fd} = 60(-3;-8)\ dB}$ *(total insulation for the transmission paths Dd and Fd determined by intensity measurement result on the ceiling minus $R_{w,Fd}$. Ref. BBRI –AC5128)*

$\boldsymbol{R_{w,Ff} = 60\ dB}$ *(determined by intensity measurement on f, we supposed that the shielding of the floor by its topping is effective enough not to take in account the transmission path Df. Ref. BBRI –AC5128)*

4.5 - REFERENCES

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[27] Jean-Luc Kouyoumji ; Sylvain Gagnon, 'Experimental approach on sound transmission loss of Cross Laminated Timber floors for building', Inter.noise 2010, Lisbon, Portugal

[28] Anders Ågren, Acoustic highlights in Nordic light weight building tradition - focus on on-going development in Sweden', BNAM 2010, Bergen, Norway

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[30] Heinz J. Ferk, Sound insulation evaluation results of lightweight and massive built multi-family houses in Austria, power point presentation, 2009, TU Graz, Austria

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[35] Lieven De Geetere, 'Experimental Investigations on Flanking Sound Transmission in Lightweight Timber Frame Constructions.',Euronoise 2012, Prague, Chechia

CHAPTER 5
OVERVIEW OF RESEARCH ACTIVITIES AT THE MAIN INSTITUTES MEMBERS OF COST FP0702

COST Action FP0702

Net-Acoustics for Timber based Lightweight Buildings and Elements

CONTENTS

In order for the reader of this e-book to have a better idea about the research activities on timber based lightweight buildings at the main institutes participating in COST Action FP0702, an "overview of research" document has been created giving the current (and previous) research topics and the associated available papers and presentations.

The following institutes (in order of presentation) have given information on their research activities:

- **TNO, The Netherlands**
- **Lulea University of Technology, Sweden**
- **Liverpool University, UK**
- **CSTB, France**
- **Hochschule Rosenheim, Germany**
- **PTB, Germany**
- **Holzforschung, Austria (HFA) in cooperation with Technical University, Vienna, Austria**
- **TECNALIA Spain**
- **BBRI, Belgium**
- **SINTEF, Norway**
- **University of Canterbury, Christchurch New Zealand**
- **RMIT and CSIRO, Australia**
- **NTNU, Trondheim, Norway**
- **FCBA, France**
- **Center for Timber Engineering, Edinburgh Napier University, Scotland**

1 - RESEARCH ACTIVITIES AT TNO

Eddy Gerretsen, Susanne Bron-v.d.Jagt, Arnold Koopman, Sven Lentzen relevant for WG1 and partly WG2

1.1 - Current research

- research project with industry on characterising junctions of light weight building systems, also timber based, sound and vibration down to 0 Hz; measurements and modelling (FEM, SEA) of junctions and incorporation in total transmission model like EN12354; 2005-2010; reports only in Dutch, see papers on Acoustics'08 and others
- TNO-research project on understanding and solving problems in the combination of equipment sound and light weight buildings; 2007-ongoing; see Acoustics'08 paper, EN 12354-5
- TNO-research project on developing an analytical/numerical analysis tool for structural vibration and low-frequency noise ("Uil"); 2009-ongoing; no documents publicly available yet.
- TNO-research project on low frequency noise: perception, measurements en modeling; 2010-ongoing; see paper on Forum Acusticum '11.

1.2 - Previous research

- PhD-study on sound transmission through lightweight walls, Stefan Schoenwald; 2003-2008; see various papers and thesis
- ECSC research on vibrations Hivoss in which a European guideline (criteria, assessment methods) is written about walking-induced vibrations on floors and bridges; 2007-2008; see website
- various consultancy projects and/or trouble shooting on light weight building systems, both steel- and timber based; 1995 till now, both sound and vibration and, besides focusing on sound insulation, often focussing on walking induced vibrations (<20 Hz)

1.3 - Available papers / presentations

[1] G. Susanne Bron-van der Jagt, A. Koopman, C.C.J.M. Hak, *Sound transmission through cross-joints in multi-family houses with lightweight, double structures and steel supporting structures – measurements* -, Forum Acusticum 2002, Sevilla, september 2002 (paper and presentation)

[2] Koopman, W. van Gogh, G. Susanne Bron-van der Jagt, *Sound transmission through cross-joints in multi-family houses with lightweight, double structures and steel supporting structures – transmission models* -, Forum Acusticum 2002 – Sevilla, september 2002 (paper and presentation)

[3] Susanne Bron-van der Jagt e.a., *Sound transmission through junctions between lightweight floors and walls - comparison of FEM-, SEA- and measurement results*, Euronoise 2006, mei 2006 (paper and presentation)

[4] Gerretsen, E., *Possibilities to improve the modelling in EN 12354-1 for lightweight elements*, Euronoise, Tampere, 30 mei- 1 juni 2006

[5] Schoenwald, S. e.a., *Measurement of flanking transmission through gypsum board walls with a modified SEA method*, Internoise 2007, Istanbul, August 2007

[6] Gerretsen, E., *Some aspects to improve sound insulation prediction models for lightweight elements*, Internoise 2007, Istanbul, August 2007,

[7] HIVOSS documents, see www.stb.rwth-aachen.de/projekte/2007/HIVOSS/download.php

[8] Gerretsen, E., *Various acoustic aspects of buildings with lightweight elements*, CIB bijeenkomst W51, 216 mei 2008, Boras, Zweden

[9] Gerretsen, E., *Some practical aspects of the prediction of structure-borne sound caused by house-hold equipment*, Acoustics'08, Paris, 2008

[10] Gerretsen, E., *Prediction models for building performance – European need and world wide use*, Acoustics'08, Paris, 2008

[11] Gerretsen, E. *State of the art and future developments of the Eurpopean standard EN 12354,* AIA Building Acoustic conference, 11-12 March 2009, Ferrara

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Abstract

The development of the building acoustic prediction models in EN 12354 started twenty years ago, since the CPD made it necessary within Europe to link the acoustic performance of building products and elements to the performance of buildings. It concerned six acoustic aspects: airborne sound insulation, impact sound insulation, façade insulation, sound radiation to the outside, sound due to service equipment and reverberant sound in enclosed spaces. So these became the six parts of the standard, drafted by working group 2 of CEN Technical Committee 126 'Building Acoustics'. For various building elements the product quantities and their measurement methods were well established so these could be used as input to the prediction (estimation) of the building performance. But drafting these prediction models made clear what type of input data was still missing and what type of product quantities and measurement methods should be added. This generated activities in other working groups to define methods and in various countries to collect the product performances appropriate for the local building situations. An overview will be presented of these developments so far and the items still to be covered or improved.

[13] Lentzen, S., Koopman, A and Salomons, E. *Assessment of impact noise at 31.5Hz*, 27. June – 1. July 2011, Aalborg.

Summary

Due to the increasing popularity of lightweight building methods, vibrations and low frequency noise have become a greater challenge. This work deals with the assessment of impact noise at the 31.5 Hz octave band. Three possible impact sound sources to determine the sound insulation have been tested and compared in laboratory measurements. It is concluded that the excitation using the rubber ball, as described in Annex F of ISO/DIS 140 part 11, is comparable to that from using the heel-drop method. The latter is described in the Dutch SBR guidelines for walking induced floor vibrations. It is further concluded that the standard hammerbox excitation method, generally used for the assessment of impact sound insulation above 50Hz, is not suitable for the lower frequency range. Due to the possible pronounced modal character of the sound field in the receiving room, it is recommended to introduce the L10 sound level: the sound level that is only exceeded in 10% of the room volume. As it has been proven with extensive tests on human subjects, the A-weighted sound level can be used for the assessment of most sound sources. However, in particular cases penalty factors have to be taken into account.

2 - RESEARCH ACTIVITIES AT LULEA UNIVERSITY OF TECHNOLOGY, DIV OF ENGINEERING ACOUSTICS

Anders Ågren, Fredrik Ljunggren

Relevant for WG1, WG2, WG3 and WG4 - Research during the COST FP0702 action

2.1 - Previous research

Development of a prediction model for impact sound in timber buildings. A three-year PhD student project with national funding. A PhD student has developed the impact sound prediction model of Jonas Brunskog et.al. Moments as well as a de-coupling of floor and ceiling have been added to the model. The project ended during 2011 with a licentiate thesis and two Journal papers, where one is published and one is to be published soon.

Sound insulation variations among nominally identical light weight timber houses. During the COST FP0702 period a nationally funded project has been conducted where variations in impact sound level and airborne sound insulation has been carefully measured in a large number of nominally identical apartments. The project ended 2011-01 and has resulted in two Journal papers and three conference proceedings.

2.2 - Current research

Development of an extended measurement and evaluation scheme for light weight floors. Within AkuLite an extended measurement series is developed and applied on a number of light weight and a couple of concrete structures. The purpose with the measurements, apart from the standardized measurement procedure of impact sound level and airborne sound insulation, is to give more thorough information about the floors like: information about the low frequency behavior, the damping properties, static stiffness, resonance frequencies as well as the vibration propagation in the floor and the flanking transmission over the boundaries.

Low frequency sound and vibrations in light weight timber buildings. Part of AkuLite, a large Swedish national program that is running for three years and ending in the beginning of 2013. Experimental data will be compared to modeled data. Some experimental research at LTU, but the FE modeling research is at Lund TH.

Correlation between extended sound and vibration measurements data and subjective evaluations by the tenants. Within the AkuLite project correlations are being done between objective data and subjective data from written surveys among tenants. The data is measured in matching buildings in order to be comparable. The sound insulation measurements are done according to the extended measurement procedures mentioned above.

Development of improved sound insulation in industrially prefabricated light weight timber houses. A regionally funded project driven together with three house and building part manufacturers. The objective has been to develop the constructions in a cost effective way so that they can stand the Swedish class B level and also perform well at low frequencies. The project has resulted in buildings that fulfill the class B levels. The work is ongoing towards reducing the low frequency sound and reaching the class A level. The project has delivered one Journal paper an two conference proceedings.

2.3 - References with content related to COST FP0702

2.3.1 - Journal papers:

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[2] Ökvist R., Ljunggren F., Ågren A. Variations in sound insulation in nominally identical prefabricated light weight timber constructions. Journal of Building Acoustics, Volume 17 (2010) No 2, 91-103.

[3] Mosharrof, Md.S., Brunskog J., Ljunggren F., Ågren A.,. An improved prediction model for the impact sound level of lightweight floors: introducing decoupled floor-ceiling and beam-plate moment. (2011) Vol 97, No 2., 2011, pp. 254-265 Acta Acoustica with Acoustics.

[4] Öqvist,R., Ljunggren,F., Ågren,A. On the uncertainty of building acoustic measurements - Case study of a cross laminated timber construction. Applied Acoustics, Accepted and resubmitted (Jan 2012).

2.3.2 - Book publication

F. Ljunggren, A. Ågren. Dynamic and Subjective Analysis of a Lightweight/Semi-heavyweight Floor in Laboratory. Paper selected to be included in the book: *Collected papers in building Acoustics: Sound Transmission.* Edited by Barry Gibbs, John Goodchild, Carl Hopkins, David Oldman. Multi science publications, 2009.

2.3.3 - Theses

[1] C. Simmons. Managing uncertainty in building acoustics – Comparisons of predictions using the EN 12354 standards to measurements. PhD thesis LTU 2009.

[2] M.S. Mosharrof. Study and modelling of lightweight floor structure regarding is acoustic properties. Licentiate thesis LTU 2010.

[3] R. Öqvist.Variations in sound insulation in lightweight timber constructions. Licentiate thesis. Licentiate thesis LTU 2010.

2.3.4 - Conference proceedings

[1] Ljunggren, F. Ågren, A., How to improve impact sound insulation in a lightweight module based building system.; ICA, 2007, Madrid, Spain

[2] Ljunggren, F. Improved sound insulation on module based timber framed buildings. BNAM – Joint Baltic-Nordic Acoustics Meeting, 2008, Reykjavik, Iceland.

[3] Ljunggren, F. Changed sound properties due to minor construction changes in a lightweight building. Acoustics´08, 2008, Paris, France.

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[6] Ökvist R., Ågren A., F.Ljunggren. Variations in sound insulation in multi-storey lightweight timber constructions Inter Noise 2009, Ottawa. Invited.

[7] Ågren A. *Acoustic highlights in Nordic light weight building tradition*- focus on ongoing development in Sweden. Keynote speaker BNAM Bergen, May 2010.

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[9] Ljunggren, F. Sound insulation in a six-storey volume based timber building equipped with elastic layers. ICSV 17 – International Congress on Sound & Vibration, 2010, Cairo, Egypt.

[10] Ågren A., Ökvist R., Ljunggren F., Variations in Sound Insulation in Cross Laminated Timber Housing Construction. Forum Acusticum, Aalborg, June 2011. Invited

[11] Ljunggren, F. Long-term effects of elastic glue in lightweight timber constructions. Forum Acusticum, 2011, Aalborg,

3 - RESEARCH ACTIVITIES AT LIVERPOOL UNIVERSITY

Carl Hopkins

Relevant for WG1 and WG2

3.1 - Current research

Supervision of four PhD students who are studying topics with potential application to timber-frame structures. Matthew Robinson is studying the practicalities of using a transient form of SEA to predict maximum sound pressure levels in spaces due to transient structure-borne sound sources (started 2008, finishes 2012). Jianfei Yin is studying how ribbed plates can be incorporated into SEA models (started 2009, finishes 2013). Claire Churchill is studying direct and flanking transmission across hybrid lightweight-heavyweight floor systems (started 2010). Wang Xing is studying the prediction of vibration transmission across complex networks of beams with point-connected plates (started 2012, finishes 2015).

EPSRC funding (2010-2013): Reception Plate Method for Structure-Borne Sound Sources. This project will investigate the characterisation of structure-borne sound sources using the reception plate and its application to lightweight structures.

Previous research

Primarily on prediction and measurement relating to sound transmission in buildings.

3.2 - Available papers / presentations

[1] Hopkins C (2002) Laboratory measurement of the sound reduction index improvement by acoustical linings due only to resonant transmission. Forum Acusticum 2002. Forum Acusticum, Seville.

[2] Carl Hopkins, “Sound Insulation”, Elsevier / Butterworth-Heinemann (622 pages). ISBN 978-0-7506-6526-1 (2007)

[3] J. Yin and C. Hopkins. Determination of coupling loss factors between L-junctions of coupled homogenous and periodic plates using finite element models. ICSV, Cairo, Egypt.

[4] Hopkins C (2009) Sound insulation in timber-framed buildings - Improving the reliability and relevance of field measurements in the low-frequency range. Acoustics for Timber-based Lightweight Buildings and Elements. COST Action FP0702, Vaxjo, Sweden.

[5] Hopkins C (2009) Influence of the physical test set-up and in-plane waves on the measurement of flexural wave coupling parameters between heavyweight building elements. Proceedings of Euronoise. Edinburgh.

[6] Hopkins C (2009) Spatial sampling of sound pressure in rooms using manual scanning paths. Proceedings of Euronoise. Edinburgh.

[7] Hopkins C (2009) Sound insulation in timber-framed buildings - Improving the reliability and relevance of field measurements in the low-frequency range. Acoustics for Timber-based Lightweight Buildings and Elements. COST Action FP0702, Vaxjo, Sweden.

[8] Yin J and Hopkins C (2010) Determination of coupling loss factors between L-junctions of coupled homogenous and periodic plates using finite element methods. Proceedings of ICSV. International Congress on Sound and Vibration, Cairo.

[9] Hopkins C (2010) The effectiveness of manual scanning measurements to determine the spatial average sound pressure level in rooms. Internoise 2010. I-INCE, Lisbon.

[10] Robinson M and Hopkins C (2010) Prediction of maximum sound pressure and vibration levels in heavyweight building structures using Transient Statistical Energy Analysis. Internoise 2010. I-INCE, Lisbon.

[11] Hopkins C (2011) Revision of ISO Standards on field sound insulation testing. EU COST Networks FP0702 and TU0901. EMPA, Zurich.

[12] Yin J and Hopkins C (2011) Using the framework of Statistical Energy Analysis to incorporate tunnelling mechanisms for bending wave transmission across a ribbed periodic plate. Proceedings of Internoise 2011. I-INCE, Osaka.

[13] Hopkins C and Robinson M (2011) Using Transient Statistical Energy Analysis to assess errors in the total loss factor determined from measured structural reverberation times in building acoustics. Proceedings of Internoise 2011. I-INCE, Osaka.

[14] Robinson M, Hopkins C (2011) Predicting the effect of coupled spaces and structures on structural decay curves of building elements using Transient Statistical Energy Analysis. Proceedings of ICSV 2011. International Congress on Sound and Vibration, Brazil.

[15] Robinson M, Hopkins C (2011) Signal processing errors associated with the measurement of maximum sound pressure levels. Proceedings of ICSV 2011. International Congress on Sound and Vibration, Brazil.

[16] Robinson M, Hopkins C (2011) Transient Statistical Energy Analysis: A two-subsystem model to assess the validity of using steady-state coupling loss factors for plate radiation. Proceedings of ICSV 2011. International Congress on Sound and Vibration, Brazil.

[17] Churchill C, Hopkins C, Krajci L (2011) Modelling airborne sound transmission across a hybrid heavyweight-lightweight floor using Statistical Energy Analysis. Proceedings of Forum Acusticum 2011. Forum Acusticum, Denmark.

[18] Wilson D, Hopkins C (2011) Prediction of low frequency structure-borne sound transmission between non-adjacent rooms in buildings using SEA and FEA. Proceedings of Forum Acusticum 2011. Forum Acusticum, Denmark.

[19] Hopkins C (2011) On the efficacy of spatial sampling using manual scanning paths to determine the spatial average sound pressure level in rooms. Journal of the Acoustical Society of America vol 129 issue 5 pp 3027-3034.

4 - RESEARCH ACTIVITIES AT CSTB

Michel Villot, Catherine Guigou-Carter

Relevant for WG1 and WG2

4.1 - Current research

CSTB study planned for 3 years (2008-2010), and financially supported by DHUP (French Ministry of Housing) on simplified prediction model for estimating lightweight building performances at design stage. Because of the great variety of wall type, floor type and junction type, the main idea is to group all the elements and junction between elements into a few categories represented by characteristic (mean) parameters such as R index, radiation efficiency or vibration level difference … obtained with the use of combined measured / calculated data.

CSTB, financially supported by DHUP (French Ministry of Housing) in 2011 focused on noise from service equipment installed in timber based lightweight buildings.

Acoubois project: partners: CSTB, FCBA (French center for wood construction) and QUALITEL; financially supported by ADEME, DHUP, CODIFAB (wood manufacturer organization) and the various industrial partners. Phase 1 of the project in 2010: gathering and categorizing the different building elements and junctions between elements used in France in timber based lightweight buildings; identification of missing data. From 2011 to 2013, laboratory components acoustic performance measurements as well as junctions characterization measurements and in-situ building acoustic performance measurements, are being and planned to be performed. These measurements are to be used in validating, updating the prediction method for lightweight construction, as well as the development of a simplified method for QUALITEL. A survey based on questionnaire will also be carried out to evaluate the perception and acceptability of such lightweight buildings.

4.2 - Previous research

Study on prediction and measurement methods based on European standards (140 and 12354 series) and adapted to wood frame lightweight constructions, financially supported by ADEME (French Agency for Environment and Energy) and DHUP (French Ministry of Housing).

CSTB partner of the European project ACOUSVIBRA on the acoustics and low frequency vibration of steel frame lightweight constructions.:

- CSTB has developed a new calculation model for the acoustic performance of single frame lightweight walls, based on a combination of wave approach and SEA
- CSTB has adapted standard EN 12354 - 1 and 2 to the prediction of flanking transmission in steel frame lightweight constructions

4.3 - Available papers / presentations

[1] "Measurement methods adapted to wood frame lightweight constructions", M. Villot and C. Guigou, Building Acoustics, volume 13, number 3, 2006

Abstract

When building elements of wood-frame lightweight constructions are considered, laboratory acoustic measurement methods have to be rethought. Indeed, because lightweight elements are often highly damped, the vibrational fields are no longer reverberant and existing standards often lose relevance, particularly in the case of mechanical excitation (such as in impact noise measurements or in vibration reduction index measurements of junctions). In this paper, standardized methods are identified or new methods are proposed for characterizing lightweight elements in order to obtain input data for prediction models such as that adapted from the standards EN 12354-1 and -2 and described in a companion paper. Moreover, it is shown that a new parameter (the radiation efficiency) is required when predicting the performance of lightweight buildings. Measurement results are shown for both wall and floor elements and the results are discussed, particularly in comparison with heavy building elements

[2] "Prediction methods adapted to wood frame lightweight constructions", C. Guigou and M. Villot, Building Acoustics, volume 13, number 3, 2006

Abstract

When wood frame lightweight constructions are considered, both the standardized methods, EN 12354-1 and -2, for predicting building performances from the performances of building elements and the related standardized laboratory measurement methods for characterizing building elements and their junctions have to be reconsidered. In this paper, a prediction method based on Statistical Energy Analysis and adapted to lightweight constructions, is presented. It was applied to a two-storey four-room building where an analysis of the different transmission paths was required in order to understand and improve the acoustic performances of the building. Comparisons between results, expressed in terms of airborne and impact sound insulation between rooms, either directly measured or calculated using the prediction method, are given in the three cases of vertical, horizontal and diagonal transmission. A satisfactory agreement between calculated and measured results is obtained.

[3] Research Program of the Research Fund for Coal and Steel, Technical Group TGS 8, "High Quality Acoustic and Vibration Performance of Lightweight Steel Constructions", Final report of project RFS-CR-03025 (published in 2007)

[4] "Predicting sound insulation in wood frame buildings", M. Villot and C. Guigou, Internoise09, Ottawa Canada, proceedings

Abstract

The vibration response of wood frame lightweight constructions is different from the response of heavy structures, particularly because of the presence of non-uniform vibration fields, relatively high attenuation (high internal loss factors) and non-resonant fields; these particularities have to be taken into account in predicting sound insulation and require more input data than for heavy structures. There is also another difficulty: the variety of building elements (using different types of boards, studs, joist…) and of junctions between elements is so great that it is impossible to measure the performance of all the possible elements and junctions. This paper deals with this difficulty by grouping building elements and junctions between elements into a smaller number of categories represented by characteristic parameters such as the known

sound reduction index R or the vibration level difference Dv,ij (or related junction invariant), but also the less known radiation efficiency σ, all obtained with the use of combined measured and calculated data. A few practical examples are present

[5] "Comparison between measured and predicted sound insulation in wood frame lightweight buildings", C. Guigou, M. Villot and R. Wetta, Internoise10, Lisbon Portugal, proceedings

Abstract

When wood frame lightweight constructions are considered, the standardized methods, EN 12354-1 and -2, for predicting building performances from the performances of building elements have to be modified. A prediction method based on SEA and adapted to lightweight constructions requiring more input data than for heavy structures has been introduced by CSTB. Recently, some simplifications have been introduced by grouping building elements and junctions between elements, into a small number of categories represented by characteristic parameters. Laboratory and in-situ measurements have been carried out on a wood frame lightweight building and some of its elements. Comparisons between results expressed in terms of airborne and impact sound insulation between rooms, either directly measured or calculated using the prediction method are presented; these results, including or not the simplified approach, are given in the cases of vertical and horizontal transmissions.

[6] "Predictions and measurements for lightweight constructions and low frequencies ", C. Guigou and M. Villot, Euronoise10, Prague Czech Republic, proceedings

Abstract

In this work, a prediction method based on the EN 12354-1 and -2 approach and adapted to lightweight construction is presented. The measurement procedures to evaluate the different model input parameters such as the radiation efficiency of elements and the vibration level difference associated to junction between elements are introduced and discussed. The use of the finite element method to estimate the vibration level difference associated to junctions is also investigated. The prediction method to evaluate the building acoustic performance is tested with some simplifications to limit the number of measurements of the input parameters. Comparisons between measurement and prediction results in terms of airborne and impact sound insulation down to low frequencies (below 100 Hz) are given to access the relevance of the prediction model for vertical and horizontal transmission.

[7] "Prediction of structure borne noise in heavyweight and lightweight constructions", M. Villot and S. Bailhache, 19th ICSV, Vilnius Lithuania, proceedings

Abstract

This work aims at predicting and comparing the structure-borne noise due to building ser-vice equipment, installed in heavyweight or lightweight buildings, taking waste water pipes as an example. The structural power injected into the supporting structure is estimated using a source and receiver mobility approach; this part of the work is presented in a companion paper. For heavy constructions, the structure borne noise prediction is made according to standard EN 12354-5. For lightweight constructions, a modified approach is proposed according to the recent work performed in the frame of COST Network FP0702 and using two new quantities: the sound reduction index referring to resonant transmission only and a junction invariant expressed as normalized direction average velocity level difference. Comparisons between heavy and lightweight constructions are made in terms of injected structural power (companion paper), supporting structure velocity field, velocity level difference at junctions and structure borne sound pressure level radiated.

[8] “Prediction of structure borne noise in heavyweight and lightweight constructions”, S. Bailhache and M. Villot, 19th ICSV, Vilnius Lithuania, proceedings

Abstract

The purpose of this work is to compare the structure-borne sound power injected into build-ing elements due to building service equipment, in heavyweight or lightweight construction. The case of waste water pipes rigidly fixed to a separating wall is considered, this wall being made either of concrete or of gypsum boards on wood frame. The structure-borne sound power injected into the supporting structure is calculated using a source and receiver mobility approach. Characterization measurements are carried out to determine the duct free velocity under various water flows as well as the source and receiver mobilities determined using an electrodynamic shaker excitation. Different expressions for the injected power are used, de-pending on the source receiver mobility conditions. Calculation results, given in 1/3 octave bands, are discussed. The estimated values of structural power are used in a companion paper as input data for a prediction model leading to radiated noise in adjacent rooms.

4.4 - Network on lightweight wood constructions

An horizontal network of CSTB agents working on lightweight wood constructions in different domains (structural stability, fire, thermal insulation, acoustics, air and water proofing…) has been created; common meetings should contribute to a better mutual information within CSTB.

There is an agreement between CSTB and FCBA (both members of Action FP0702) in order to improve the coordination / collaboration between the two institutes ; meetings will be regularly organized in acoustics.

5 - RESEARCH ACTIVITIES IN GERMANY, ROSENHEIM

Joachim Hessinger

Relevant for WG1 and WG4

5.1 - Current research

Vibration behaviour of timber-floors in frequency range below 100 Hz, TU Munich and Hochschule Rosenheim, started in 2010

5.2 - Previous research

- revision of collection of construction examples of timber building elements for DIN 4109, PTB 2005
- Flanking transmission of impact sound in timber floors, ift Centre for Acoustics, 2005
- Calculation model for timber wall constructions, ift Centre for Acoustics, 2006
- Construction principles for the application of lightweight construction elements in the interior construction, Hochschule Rosenheim, 2008
- Timber joist floors in renovation of buildings – part 1, ift Centre of Acoustics, 2008
- Vibration and attenuation behaviour of timber-floors and timber-concrete-composite floors, TU Munich, 2009
- FEM based prediction model for the impact sound level of floors, TU Munich, 2009
- Application of Helmholtz resonator for improvement of sound insulation between rooms in timber buildings, Hochschule Rosenheim, 2010
- Timber joist floors in renovation of buildings – part 2: Flanking transmission, Hochschule Rosenheim, ift Centre of Acoustics, 2012

5.3 - Planned research

- Integrated design of the vibro-acoustical performance of multi-storey buildings based on solid wood
- Elements, TU München, Hochschule Rosenheim, ift Centre of Acoustics, application in 2012

5.4 - Available papers / presentations

[1] Rabold, A., Düster, A., Hessinger, J., Rank, E., “Optimization of lightweight floors in the low frequency range with a FEM based prediction model”, Tagungsband DAGA 2009

Abstract

The impact noise transmission at low frequencies is a well known problem of lightweight floors, which is treated in many publications. A satisfying solution, considering the different construction principles of lightweight floors, could not be found so far. To overcome this problem a FEM based prediction model for the optimization of the floor construction and the improvement of the impact sound insulation has been developed and applied in a current research project at the TU München. The overall approach of the prediction model consists of the three-dimensional modelling of the structure and the excitation source (standard tapping machine), the subsequent modal- and spectral analysis and the computation of radiated sound from the ceiling. The validation of the prediction model has been carried out by comparing the evaluated impact sound pressure levels with results from measurements on 25 different floor constructions. In the next step the prediction model was used for the improvement of established lightweight timber floors. Finally these constructions were tested in a laboratory test stand according to ISO 140-6 at ift Rosenheim centre for acoustics and the ibp Stuttgart. This contribution shows the results of the computations and the construction rules developed for optimized lightweight floors.

[2] Rabold, A., Hamm, P., “Schall- und schwingungsoptimierte Holzdecken”, bauen mit holz, 4, 2009, 38-43

[3] Rabold, A., Hessinger, J., Bacher, S., Schallschutz, Holzbalkendecken in der Altbausanierung, Mikado plus, 3, 2008

[4] Rabold, A., Wissel, C., Schanda, U., Hessinger, J., Prognose der Schalldämmung von leichten Trennwänden, Tagungsband DAGA 2010

[5] Schramm, M., Dolezal, F., Rabold, A., Schanda U., Stoßstellen im Holzbau – Planung, Prognose und Ausführung, Tagungsband DAGA 2010

[6] Otto, J., Schanda, U., Schramm, M., Wolf, M., Helmholtzresonatoren zur Absorption tieffrequenten Trittschalls, Tagungsband DAGA 2010

[7] Hessinger, J., Rabold A., Saß, B., Schallschutz im Holzbau, in: Fouad, N.A., Bauphysik Kalender 2009, Ernst und Sohn Verlag, 2009

6 - RESEARCH ACTIVITIES IN GERMANY, PTB

Heinrich Bietz

Relevant for WG1 and WG4

6.1 - Previous research

6.1.1 - - Installation Noise test facility [1]

Discussions with the German association of manufacturers of prefabricated houses (BDF) showed a growing concern towards the behaviour of installation noise generated by sanitary equipment in lightweight buildings. At PTB, a test facility which represents a two-storey prefab house, was created. Its main objectives are a) to enable companies organized in BDF to test the acoustic behaviour of their sanitary installations and b) give PTB the opportunity to do basic research on this topic with the long-term aim of defining a prediction method for installation noise and also a standardised laboratory test setup. The test facility started operation in 2004. Until today, 11 companies have performed tests in the facility. The results are collected and interpreted by PTB. They show that it is basically possible to meet the German requirements on installation noise in a lightweight building, though there is a wide spread in the results. Furthermore, the wastewater-pipe showed up as a major sound source, thus making it subject of further research.

6.1.2 - Characterisation of a waste water pipe as a sound source [4]

As the waste water pipe presented itself as a major sound source, closer attention was given to it. First the point mobility was measured with different fixtures and also with the pipe filled with different amounts of water. Results showed that the influence of water in the pipe is not very significant with respect to point mobility.

In a second step, a wastewater pipe was characterised as a sound source using the 2-stage-method recently suggested by Gibbs et al..

Furthermore, research was done on the influence of different fixture systems on the transmitted sound power, the final report still has to be finished.

In all, it turned out that the waste water pipe has a source mobility which is in the same range as the input impedances of lightweight walls, thus enabling a good power transfer into these structures.

6.1.3 - General measurements on lightweight structures [2]

Numerous mobility and transfer function measurements were performed on lightweight structures, including those of the Installation Noise Test Facility, selected prefab houses and a plasterboard / metal stud configuration (T-junction). One major outcome of this is that the point mobilities of the investigated structures are comparable with a reasonable spread, as long as they are lightweight.

The aforementioned topics are well compiled in a report for the German federal building agency. Unfortunately, it is available only in German. I will try to get permission to publish it on the action website anyway.

6.1.4 - Verification of the two-stage-method (TSM) [3], [4]

This method, proposed by Gibbs et al., can be a valuable tool to characterise the source quantities of complex structure-borne sound sources. One of its possible drawbacks is that it employs certain simplifications to have it implemented properly. Research was done at PTB to validate this method by characterising sources with known characteristics. Major outcomes are that the method works with reasonable accuracy, but selection of the proper receiving plates may be critical, depending of the source characteristics. Future research will be an attempt to characterise a human walker with help of the TSM.

6.2 - Current research

6.2.1 - - Characterisation of the human walker as a sound source [4]

Based on previous research, first attempts have been done to characterise the human walker as a sound source using the two-stage-method. The initial results are promising, and research is currently focusing on the selection of suitable receiving plates.

6.2.2 - Collection of data related to installation noise and structure-borne sound parameters in lightweight buildings

Parallel to the research in the installation noise test facility, several measurements in finished prefab house are performed, with more to come. The measurements include installation noise as well as structure-borne sound parameters like point mobilities and transfer functions. One of the aims of these measurements is to find out whether transfer functions can be used for a prediction of installation noise. In addition to these measurements there is a cooperation with researchers from Weimar university with the focus on the assessment of transfer functions

6.2.3 - Compact measurement setup for the determination of impact noise reduction

A compact measurement setup for the determination of impact noise reduction (COMET) has been developed in PTB. Until now, it works successfully for concrete floors and locally reacting coverings. PTB has applied for a research project with the aim to extend the applicability of this device to wooden floors and plate-like floor coverings like parquet floors etc..

6.2.4 - Research on walking noise emission and impact noise reduction of laminate floorings [5]

PTB is currently conducting a round robin test on the assessment of walking noise emission and noise transmission reduction of laminate floorings. The major objective is the establishment of a standardized procedure for the measurement of walking noise. Actually, the test samples are sent to the participants. 21 laboratories from Germany, France, Poland, Sweden, Denmark, Spain, The Netherlands, Belgium and Switzerland will take part in the round robin.

6.3 - Available papers / presentations

[1] Bietz, H., Wittstock, V., Scholl, W., Prüfstand zur Bestimmung von Installationsgeräuschen im Holz- Fertigbau- Neue Messergebnisse und Entwicklungen - , Proceedings DAGA 2006, Braunschweig March 2006

[2] Kling, C., Wittstock, V., Bietz, H., Studie zur Anwendbarkeit des Prognoseverfahrens nach prEN 12354-5 und damit zusammenhängender Labormessverfahren (CEN TC 126/WG 7) im Leichtbau, Abschlussbericht BBR-Projekt Z6-10.07.03-06.18 / II 2-800106-18

[3] Wittstock, V., Bietz, H., Characterising sources of structure-borne sound by the Two Plate Method; Proceedings NOVEM 2009, Oxford, April 2009

Abstract

The assessment of the ability of a vibratory source to inject sound power into a receiver is a major task in different fields of acoustics. Recently, Gibbs et. al. proposed to characterise structure-borne sound sources by two properties, an activity and a mobility quantity. They are determined by connecting the source under test to two different receiving plates with different point mobilities. From the different sound powers injected into the different receiving plates, source quantities can be calculated. At PTB, this method has been used to determine the source characteristics of an electrodynamic shaker. This source has the advantage that it can be modelled by electromechanic analogies and, thus, source properties can be determined by a second method. Additionally, the power input into the receiving plates can be measured by an impedance head and the electric power input is also known. Furthermore, impulse signals can be used as well as stationary ones and the mechanical structure can be manipulated very easily. The results presented will include comparisons between sound powers and source quantities determined by different methods for stationary and impulse signals for different sources.

[4] Wittstock, V., Characterisation of structure-borne sound sources in buildings by the two-stage reception plate method, Proceedings InterNoise 2010, Lisbon, April 2010

Abstract
Structure-borne sound sources must usually be described by at least two source properties, an activity and a mobility quantity. The two-stage reception plate method was proposed as a practical means to determine these source quantities. The method requires the determination of structure-borne sound powers in two receiving plates, one with a higher and one with a lower mobility than the source mobility. The contribution gives an overview of recent applications of the two-stage method to realistic structure-

borne sound sources in buildings such as waste water systems with different clamps, walking persons and free water jets.

[5] Scholl, W., Messung von Gehgeräuschen, Proceedings DAGA 2010, Berlin, March 2010

7 - RESEARCH ACTIVITIES IN AUSTRIA, HFA AND TGM

Franz Dolezal, Herbert Müllnerrelevant for WG1

7.1 - Current research

7.2 - Previous research

7.2.1 - Flanking transmission of impact noise at solid wood structures

3-years research project on predictions and measurements of direct and flanking transmission with solid wood floors and wooden floors with flexibel interlayers (Holzforschung Austria (HFA) in cooperation with TU-Vienna) 2006-2008:

Since solid wood constructions are more frequently applied for multy-storey residential buildings, demand for reliable prediction of sound insulation is increasing. Prediction is generally carried out following EN 12354 which, however, does not contain any input data for solid wood constructions.

For creating an extensive collection of data for direct and flanking transmission in solid wood structures, planning and construction of test facilities was required. Three different types of solid wooden floors and four different flexible interlayers were investigated. Additional measurements were carried out with additional load to simulate the situation of multy storey buildings and with different types of fasteners.

Therefore, sound- and vibration measurements are realized on solid wood test facilities where flanking transmission and input data for standardized predictions are acquired. The normalized impact sound pressure level is calculated for different flexible interlayers and compared to the results of the measurements. Single number quantities show satisfactory accordance between measurement and prediction with deviations between 0 and 2 dB. Considering frequency dependent values major deviations, which can be detected in a certain frequency range, require more accurate modelling.

Hence, the impact of flexible interlayers is highly affected by installation of required metal fasteners, in a further step, application of gathered results to the building situation by the use of fasteners had to be investigated. By means of sound and vibration measurements the acoustic impact of fasteners was quantified and assigned to the particular type of connection. Optimized fasteners were verified in respect of their acoustical and load bearing performance.

Considering former expertise of measurements carried out in test facilities, a prediction model was developed. In this model the junction is defined only by properties of flexible interlayers, load and fasteners. Comparing measurement and calculation leads to satisfying results.

A catalogue of verified constructions was published ("Deckenkonstruktionen für den mehrgeschossigen Holzbau – Schall- und Brandschutz, Detailkatalog" – Holzforschung Austria) to enable quick estimation of acoustic parameters of selected constructions, including flanking transmission.

7.2.2 - Feasibility Study on low frequencies in light weight constructions.

Short study with international partners guided by TGM Vienna 2009-2011.

The reason for this study is that acoustical development is based on knowledge for heavy weight mode of construction. Because of this fact, the aim to consider the extended frequency range down to 50 Hz to become an established part of standards and legislations. The sound insulation properties between dwellings and between apartments are currently a vivid discussed topic in many European countries. The study will deliver basics and proposals based on the conclusions of the state-of-the-art and the supposed future situation regarding the effect on the "building with wood sector" and actions which have to be taken into consideration to face the upcoming challenges well prepared and to keep the

concerned industry sector competitive. To avoid a loss of sympathy for light weight mode of construction and to keep the building with wood industry competitive action is needed.

A feasibility study should clarify the current situation, the intermediate as well as long term prospects

to get a basic knowledge what actions have to be done, to keep the building with wood industry competitive.

Experts from different European countries were invited to work on this study.

1. Round robin test (organized by TGM Vienna 2008-2010) into impact sound of light weight floors – solid wood and joist floor - with special attention to low frequencies in small receiving rooms.
2. Analysis of structure-borne sound transmission in solid wooden constructions – master thesis carried out at TU Vienna

7.3 - Planned research

7.4 - Available papers / presentations

[1] Dolezal, Franz; Bednar, Thomas: Schall-Längsleitung bei Massivholzkonstruktionen. Proceedings DAGA 2008, Dresden.

[2] Dolezal, Franz; Bednar, Thomas: Einfluss von Befestigungsmitteln auf die Schall-Längsleitung von Massivholzkonstruktionen. Proceedings DAGA 2010, Berlin.

[3] Dolezal, Franz; Teibinger, Martin; Bednar, Thomas: Flanking Transmission of Impact Noise at Solid Wood Structures. Proceedings World Conference on Timber Engineering WCTE 2010, Bd. 3. Riva del Garda, Trento, Italy.

[4] Dolezal, Franz; Bednar, Thomas; Teibinger, Martin: Flankenübertragung bei Massivholzkonstruktionen, Teil 1. Verbesserung der Flankendämmung durch Einbau elastischer Zwischenschichten und Verifizierung der Anwendbarkeit von EN 12354. *Bauphysik* 30 (3), 2008.

[5] Dolezal, Franz; Bednar, Thomas; Teibinger, Martin (2008): Flankenübertragung bei Massivholzkonstruktionen, Teil 2. Einfluss von Befestigungsmitteln auf die Verbesserung durch den Einbau elastischer Zwischenschichten. *Bauphysik* 30 (5), 2008.

[6] Müllner, Herbert; et.al.: Sound Insulation in the Low Frequency Range Prospects and Recommendations to keep the Building with Wood Industry competitive. TGM 2011, Vienna.

[7] Müllner, Herbert; Stani, Mathias: Ringversuch Teil 2 - Messung des Luft- und Trittschallschutzes von Decken in Holzbauweise mit besonderem Fokus auf dem erweiterten Frequenzbereich unter 100 Hz. Bericht zum Ringversuch Teil 2, Messungen an einer Holzbalkendecke. TGM 2010, Vienna.

[8] Müllner, Herbert; Stani, Mathias: Ringversuch Teil 1 - Messung des Luft- und Trittschallschutzes von Decken in Holzbauweise mit besonderem Fokus auf dem erweiterten Frequenzbereich unter 100 Hz. Bericht zum Ringversuch Teil 1, Messungen an der Brettstapeldecke. TGM 2010, Vienna.

[9] Hanic, Radoslav: Analysis of structure-borne sound transmission in solid wooden constructions. TU Vienna. Zentrum für Bauphysik und Akustik 2009, Vienna.

8 - RESEARCH ACTIVITIES AT TECNALIA

Marta Fuente González

Relevant for WG1 and partly WG2

8.1 - Current research

EGOSOINU: Industrialised constructive system for timber based multistory dwellings. EUREKA project "ECO-HOUSE". (2011-2014). Acoustic design of a constructive system based on cross laminated timber (CLT) products with enhanced acoustic performances with a Spanish wood panel manufacturer EGOIN. The project will focus on in situ acoustic performances of CLT systems taking into account laboratory measurements, vibration behaviour of joints and technical problems related to lightweight constructions. The objective is fulfilling Spanish and French acoustics requirements, and without forgetting other characteristics as fire protection, seismic behaviour, etc.

8.2 - Previous research

- CETICA (2007-2011): a big project of **lightweight construction based on steel** which is leaded by **Arcelor Mittal** and co-financed by Ministry of Science and Innovation. The objective of the project is to design and to develop new and advanced materials and constructive systems, based on steel, for a new model of building efficient echo energetically, inside a sustainable development with a clear orientation towards the final user. This project will allow to **industrialize the construction sector in a steel base**. In this project the acoustic performance was a very important task. (www.arcelormittal.com/cetica , in Spanish).
- BALI (2009-2011): Comprehensive design of acoustically efficient systems and buildings in a health-giving environment. Improvement in the acoustic characteristics of architectural products and greater efficiency from the acoustic comfort point of view and without neglecting other aspects to do with sustainability, in particular to do with energy saving. It is leaded by **FCC** and financed by Ministry of Science and Innovation. There are two projects inside about: lightweight facades and polymeric composites façade panels.
- ERAHONTEK (2008-2009): Development of multimaterial facade panels based on plastic and stony waste from building and demolition. Developed prototypes have been characterized mechanically, thermally and acoustically. It has been financed by Diputación Foral de Bizkaia.
- In Spain, nowadays the construction of buildings is heavy weight. Even in single-family houses light weight construction is practically nonexistent. Although mixed construction (light and heavy weight) is more usual than in the past, but only with

some light weight elements for facades, walls or roofs. The floors are still being heavy weight.

- The acoustical quality of dwellings in Spain is going to be guaranteed with the compliance of the new Spanish Building Regulation (CTE-DB HR). Searching a higher level of comfort in dwellings the CTE is increasing its requirements and is considering the building as a product itself. This new Regulation is compulsory since April 2009.
- Manufacturers of the constructive sector in Spain are launching many innovative research strategies for the development of better products, addressing key factors for the energy efficiency of buildings and the acoustic improvement.
- So our previous researches in building acoustics have been focused on improve the more usual and traditional Spanish construction elements, for example: on the optimization of ceramic brick double walls with peripheral resilient layers, to be used to separate dwellings (2003-2009).

8.3 - Available papers / presentations

[1] Perez, M.; Fuente, M.; Guigou-Carter, C. Predicting and measuring the acoustic performances of lightweight based buildings. Congrès Français d'Acoustique 2012, Nantes.

[2] Fuente, M.; Arines, S.; Elguezabal P.; de Rozas, M.J.; Perez, M. Industrialized lightweight floors for multi-storey dwellings in Spain. FORUM ACUSTICUM. Aalborg (Dinamarca), 2011.

[3] Arines, S.; Fuente, M. Modelling the acoustic behaviour of ceramic brick double walls with peripheral resilient layers. Euronoise 2009, Edinburgh, 2009.

[4] Arines, S.; Cortés, A.; Fuente, M.; Guigou-Carter, C., Claude, M.; Villot, M. Optimization of ceramic brick double walls with peripheral resilient layers. ICA, Madrid, 2007.

8.4 - Additional information

- Now we are Tecnalia, as a result of the merger of 8 technological centres. We have combined our capabilities to work in different areas of construction: acoustic, thermal, energy saving, fire protection, wood technology, nanotechnology… www.tecnalia.com
- We have designed and built a new building for tests, trials and monitoring. It is intended to enhance knowledge not only in acoustics, but also in thermal behaviour and energy efficiency. http://edificacionindustrializada.com/multimedia/

9 - RESEARCH ACTIVITIES AT BBRI

Bart Ingelaere

Relevant for WG1 and partly WG2

9.1 - Current research

The current researches are financed by the DGTRE and IWT for the projects OSSABOIS and AH+ respectively. The research runs for 2 years.

- Development of building guidelines for wooden construction
  The challenge is to reduce the flanking transmissions in an as economic as possible way. We study here the applicability of resilient joints at junctions to improve the reduction of the structural transmission. The application of resilient joints at junctions was studied in the case of lightweight masonry walls and has shown a very good improvement of the sound insulation between rooms. Different joints (rubber, felt,..) are (and will) tested in laboratory and insitu.

- Development of procedures to measure the attenuation of the vibrational power flow through a junction joining lightweight walls
  As we have found earlier, lightweight walls with a large damping factor show an important attenuation of the vibration level with distance. Moreover, these complex wall systems (e.g. gypsum boards on a wooden or metallic frame) don't behave as homogeneous monolithic walls, making it difficult to interpret the attenuation of the vibration level. Hence, the use of the « VLD » method for these kinds of walls is not appropriate. At the BBRI acoustic laboratory, we have developed a test setup destined to measure in particular the influence of a junction on the attenuation of the vibrational power flow by using sound intensity measurements (method 1). Subsequently, we have developed another method (method 2), more simple to implement, which is inspired by the work of E. Gerretsen. This second method is in fact an adaptation of the « VLD » method. A short description of these two methods can be found on the cost-website.
  These new methods will be validated by experimental measurements in laboratory and by FEM models (ACTRAN 2007.3).

9.2 - Previous research

MEZ/MAE 2006-2008 : a prenormative research financed by the ministry of economics affairs (Belgium). In this research we have developed the new measurement methods of Kij for lightweight construction. Report in French.

9.3 - Available papers / presentations

[1] C. Crispin, B. Ingelaere and G. Vermeir. Innovative building systems to improve the acoustical quality in lightweight masonry constructions: Application of resilient joints at junctions - PART 1: analysis of the experimental results, Acoustics08, Paris

[2] C. Crispin, B. Ingelaere and D. Wuyts. Innovative building systems to improve the acoustical quality in lightweight masonry constructions: Application of resilient joints at junctions - PART 2: Study cases modelled according to the standard 12354-1 (2000). Acoustics08, Paris

[3] MEZ/MAE 2006-2008 – report only in French

10 - RESEARCH ACTIVITIES AT SINTEF BUILDING & INFRASTRUCTURE

Anders Homb

Relevant for WG1 and WG2

10.1 - Current research:

A research project funded by NFR (The Research Council of Norway) and an industry partner named "Modern timber floor constructions" is running. The project period is from 2011 to 2012. The scope is on static and dynamic properties of beam constructions with open web joist timber beams. The project also contains activities related to fire and sound insulation challenges when installing technical installations in the beam construction. The project is organized with different Work Packages and contains measurements, simulations and support to secure quality of buildings in progress. The overall objective of the project is to develop methods and gain knowledge and competence to design constructions with double span with solutions and integrated installations.

10.2 - Previous research:

A research project funded by NFR (The Research Council of Norway) and the industry called "Comfort properties of timber floor constructions" is finished. The project period was from 2006 to 2010. The scope was on the vibration response of floor constructions exposed to human activities and common vibration sources in relevant building categories. The project is organized with different Work Packages. One PhD student is working on numerical modeling, but with connection to an experimental program. We have also assigned M.Sc. students to this project at the involved universities, NTNU and UMB. The overall objective of the project was to develop methods and gain knowledge and competence to design timber floor constructions with increased span width compared with existing, common solutions.

Research work have been carried out with NFR and relevant industry concerning sound transmission in buildings with cross-laminated timber floors and walls. The project period was from 2009 to 2011. The scope is especially on the sound transmission at junctions between floor and wall elements. The project is organized with work packages concerning existing knowledge, calculations and measurements. The objective of the project is to develop solutions reducing the flanking transmission at the junctions.

Different research projects with the Norwegian industry on characterizing sound transmission of light weight building systems in general, mainly timber based solutions. Both calculations and measurements have been carried out. The main focus has been on practical application.

10.3 - Planned research

Research project together with different industry partners. We want to develop timber beam constructions with improved impact sound insulation properties at low frequencies. The scope is on acceptable perception of the floors compared with common solutions used so far in Norway.

We are also trying to establish a larger project with funding from NFR related to timber construction and urban buildings. The approval will contain a wide range of items, for instance architecture, building technology and structures (load bearing, vibrations, acoustics, fire and moisture) and implementation.

10.4 - Available papers and reports (ver. may 2012):

- Homb, A (1998). *Ball method for combined low frequency sound insulation and vibration measurements.* Conference proceedings ”Acoustic Performance of Medium-Rise Timber Buildings ”. Cost Action E5 Workshop, Dublin, Ireland, December 3-4, 1998.
- Homb, A. (2000a). *Floor vibrations using a rubber ball impact method.* Proceedings Nordic Acoustical Meeting, NAM 2000, 5-7. may 2000, Røros, Norway.
- Homb, A. (2000b). *Floor vibrations and low frequency sound pressure levels using a rubber ball impact method*. Proceedings Inter.noise 2000, session 8; Assessment and improvement of floor impact sound in buildings. Nice 27-30. august 2000, France.
- Hveem, S. & al. (2000). *Trehus i flere etasjer. Lydteknisk prosjektering - nordisk samarbeid (Multistorey wood buildings. Designing sound insulation – a nordic cooperation)*. NBI Anvisning 37, 2000 (in Norwegian).
- Stenstad, V. & al. (2003). *Fleretasjes trehus. Hefte 2: Lyd (Multistorey wood buildings. Part 2: Acoustics).* A. Homb og S. Hveem. NBI Håndbok 51, 2003 (in Norwegian).
- Homb, A. (2005a). *Experiences with spectrum adaptation term and extended frequency range from field and laboratory measurements*. Proceedings Forum Acousticum, Budapest Hungary, 29.august – 2. september 2005.
- Homb, A. (2005b). Byggforsk informerer; *Lydisolerende gitterbjelkelag (Sound insulating open web joist timber floor constructions)*. Byggeindustrien nr. 9, 2005 (in Norwegian).
- Homb, A. (2006a). *Excitation methods and impact sound insulation of timber floor constructions*. 2nd Inernational Symposium on advanced Timber and Timber-Composite Elements for Buildings. Acoustic performance and low frequency vibration, 27th April, 2006 Biel – Switzerland, proceedings p. 107-116.

- Homb, A. (2006b). *Low frequency sound and vibrations from impacts on timber floor constructions*. Doctoral theses at NTNU, 2006:132. IME Faculty, Dep. of Electronics and Telecommunications. Trondheim, Norway 2006.
- Homb, A. (2007). *Kriterier for opplevde vibrasjoner i etasjeskillere (Criteria for vibration performance of floor constructions)*. Project report SINTEF Byggforsk, serienr. 8, Oslo 2007 (in Norwegian).
- Homb, A. (2008). *Vibrasjonsegenskaper til dekker av massivtre (Vibration properties of cross laminated timber floors)*. Project report SINTEF Byggforsk, serienr. 24, Oslo 2008 (in Norwegian).
- Homb, A. , Austnes, J.A. *Experiences with sound insulation for cross-laminated timber floors.* Proceedings, Baltic Nordic Acoustical Meeting, Bergen Norway, 10-12. May 2010.
- Kolstad, S.T., Homb, A. *Beregning av nedbøyning til trebjelkelag. Vurdering av parametre og beregningsresultater (Calculation of deflections in timber beam constructions*. *Evaluation of parameters and results)*. Project report SINTEF Byggforsk, serienr. 37, Oslo 2009 (in Norwegian).
- Homb, A. *Nedbøyning og vibrasjoner til bjelkelag (Deflections and vibrations of beam constructions)*. Project report SINTEF Byggforsk, serienr. 49, Oslo 2009 (in Norwegian).
- Homb, A., Hveem, S. *Lydoverføring i byggesystemer med massivtreelementer (Sound transmission in building constructions with cross laminated timber elements) .* Project report SINTEF Byggforsk, serienr. 80, Oslo 2011 (in Norwegian).

11 - RESEARCH ACTIVITIES AT THE UNIVERSITY OF CANTERBURY, CHRISTCHURCH NEW ZEALAND

Jeffrey Mahn

Relevant for WG1 and WG4

11.1 - Current research

- Sound transmission through roofing systems inclusive of the cladding, joists and ceiling. The purpose of the industry funded study is to determine the influence of the different components of the roofing system on the transmission of traffic and aircraft noise into a dwelling. The study will include both laboratory testing and field testing in a dedicated test house. The laboratory testing includes both the evaluation of the intensity sound reduction index of just the claddings and of the roofing system in compliance with ISO 15186-1. The study will also include the evaluation of prediction methods for the transmission of noise through roof systems and the sound reduction index of corrugated metal claddings. Project start May 2010 and planned stop April 2012.
- Prediction of the sound reduction index of corrugated panels based on laboratory measurements.
- Prediction of the sound reduction index of metal tiles based on laboratory measurements.
- Prediction of the sound reduction index of complete roof systems.
- Development of a new acoustics section of the New Zealand Building Code based on field testing rather than the laboratory testing of building elements.
- Development of a library of the acoustic properties of lightweight building elements for the approved solutions of the New Zealand Building Code.
- Sound transmission through facades.
- Evaluation of the calculation of the resonant component of the sound reduction index for use in the EN12354-1 standard for lightweight building elements.
- The uncertainty of the measured sound reduction index in the 1/3 octave bands below 100 Hz.

11.2 - Previous research

- PhD study on the application of EN12354-1 to lightweight building constructions.
- Evaluation of the uncertainty of the EN12354-1 method.

11.3 - Available papers / presentations

[1] Mahn, J. and Pearse, J., Uncertainty of the Direction-Averaged Velocity Level Difference, Proceedings of 15th International Conference on Sound and Vibration, Daejeon, Korea, 2008.

[2] Mahn, J. and Pearse, J., Reciprocity and the Prediction of the Apparent Sound Reduction Index for Lightweight Structures According to EN12354, Proceedings of Acoustics'08, Paris, 2008.

[3] Mahn, J. and Pearse, J., Separation of Resonant and Non-Resonant Components Part I: Sound Reduction Index, Building Acoustics, 2008, 15(2), 95-115.

[4] Mahn, J. and Stevenson, D. C., Separation of Resonant and Non-Resonant Components Part II: Surface Velocity, Building Acoustics, 2008, 15(2), 117-135.

[5] Mahn, J. and Pearse, J., On the Probability Density Functions of the Terms Described by the EN12354 Prediction Method, Building Acoustics, 2008, 15(4), 263-287.

[6] Mahn, J. and Pearse, J., The Probability Density Functions and the Uncertainty of the EN12354 Prediction Method, Proceedings of Inter-Noise 2008, Shanghai China, 2008.

[7] Mahn, J., Prediction of Flanking Noise Transmission in Lightweight Building Constructions: A Theoretical and Experimental Evaluation of the Application of EN12354-1, PhD Thesis, University of Canterbury, 2009.

[8] Mahn, J. and Pearse, J., The Propagated Uncertainty of EN12354-1 for Lightweight Building Constructions, Proceedings of Inter-Noise, Ottawa, Canada, 2009.

Abstract

This paper describes the calculation of the uncertainty of the EN12354 estimate of the flanking sound reduction index due to the uncertainty of the input data. The propagated uncertainty was derived using the method described by the ISO Guide to the Expression of Uncertainty in Measurement (GUM). The number of effective degrees of freedom was also derived so that the confidence intervals of the EN12354 estimate may be calculated. The propagated uncertainty of the EN12354 estimate of the flanking sound reduction index of lightweight constructions is shown to be dependent on the uncertainty of the calculated resonant component of the sound reduction index of the elements and the variance of the surface velocity measured on the elements according to ISO10848-1. Lightweight constructions which may not support diffuse vibratory fields will result in a larger propagated uncertainty of the EN12354 estimate than elements which do support diffuse vibratory fields.

[9] Mahn, J. and Pearse, J., On the Uncertainty of the EN12354-1 Estimate of the Flanking Sound Reduction Index Due to the Uncertainty of the Input Data, Building Acoustics, 2009, 16(3), 199-231.

Abstract

Equations to calculate the uncertainty of the EN12354-1 estimate of the flanking sound reduction index due to the uncertainty of the input data are derived using the method of the ISO Guide to the Expression of Uncertainty in Measurement (GUM). The uncertainty equations have been validated using Monte Carlo

simulations. It is shown that the magnitude of the uncertainty depends on the uncertainty of the resonant sound reduction indices of the elements, the uncertainty of the vibration reduction index and the uncertainty of the equivalent absorption lengths and areas of the elements. However, equations could not be derived to calculate the uncertainty of the EN12354 estimate of the apparent sound reduction index which has a log-normal probability density function and is therefore outside of the scope of the method of GUM. Monte Carlo simulations must be used to calculate the uncertainty of the apparent sound reduction index. It is recommended that guidance for calculating and declaring the uncertainty is included in future versions of EN12354, ISO10848 and ISO15712.

[10] Mahn, J. and Pearse, J., Evaluation of the EN12354 Method through Field Testing Using Sound Intensity, Proceedings of Inter-Noise, Lisbon, Portugal, 2010.

Abstract

The accuracy of the EN12354 method of predicting the apparent sound reduction index in building constructions which include lightweight elements was evaluated through field testing. This evaluation differed from most prior studies because the intensity sound reduction index of each of the flanking elements in the receiving room was measured in addition to the apparent sound reduction index. The measurement of the intensity flanking sound reduction index allowed for the assessment of the EN12354 prediction of the flanking sound reduction index of each element in the source room. The study found that the use of the apparent sound reduction index alone was not sufficient to evaluate the accuracy of the EN12354 predictions. Sound intensity measurements were needed to fully evaluate the accuracy of the predictions. The use of sound intensity is a promising method to evaluate future changes to the EN12354 method for application to lightweight building constructions.

[11] Mahn, J. and Pearse, J., Evaluation of the Sound Insulation of Roofing Systems, Proceedings of Twentieth International Congress on Acoustics (ICA 2010), Sydney, Australia, 2010.

Abstract

The transmission of noise from the outside environment into dwellings is often a concern for the inhabitants. However, the transmission of the noise through the roof is often overlooked when the sound insulation of the dwelling is being assessed unless the dwelling is located near an airport. The transmission of noise through the roof system depends not only on the performance of the roof cladding, but also on the structure-borne noise attenuation of the trusses, the ceiling and the ceiling insulation. In this investigation, the sound insulation of different configurations of roofing systems were evaluated in the laboratory. The configurations tested included variations in the cladding, the sarking installed under the cladding, the thickness of the insulation installed between the ceiling joists and the ceiling construction. The outcome of the study will help to improve the acoustic performance of roofing systems as well as to assist architects in the selection of roofing systems.

[12] Mahn, J., Davy, J. L., and Pearse, J., The Acoustic Requirements of Dwellings in New Zealand, Proceedings of Forum Acusticum 2011, Aalborg, Denmark, 2011.

Abstract

With a growing number of New Zealanders living in medium and higher density housing, it has become important to ensure that household units have appropriate levels of noise insulation. Revisions to the New Zealand Building Code Clause G6 - Protection from Noise are currently under consideration by the New Zealand Department of Building and Housing. The revisions to the Building Code mark a shift from laboratory based testing to field testing for compliance. In this paper, the current and the proposed sound insulation requirements in New Zealand as well as the requirements in Australia are compared to the requirements currently in use in Europe. The paths to compliance in New Zealand are also examined

including the proposed database of acceptable construction solutions to meet the new regulatory requirements.

[13] Mahn, J. and Pearse, J., The Sound Insulation of Lightweight Roofing Systems, Proceedings of Inter-Noise 2011, Osaka, Japan, 2011.

Abstract

The transmission of noise from the outside environment into dwellings is often a concern when the dwellings are to be built in an area where background noise levels are an issue. A transmission path which is often overlooked during the planning phase unless the dwelling is near an airport is that through the roof system inclusive of the cladding, the trusses, the ceiling insulation and the ceiling. Little is currently known or published about the sound reduction index of the claddings or the lightweight roof systems commonly used in New Zealand. In this investigation, the intensity sound reduction indices of different configurations of lightweight roofing systems were measured in the laboratory. The configurations evaluated included variations in the cladding, the underlay installed under the cladding, the thickness of the thermal insulation above the ceiling and the ceiling plasterboard. The outcome of the evaluation will assist in the selection of the optimal roofing system for dwellings built where the outside noise levels are a concern.

[14] Mahn, J., "Evaluation of the Methods to Calculate the Resonant Sound Reduction Index," COST Action FP0702, Zurich, Switzerland, Report WG1-N23, 2011.

Abstract

The methods of calculating the resonant sound reduction index which were presented in WG1-N19 are evaluated by comparing predictions of the flanking sound reduction index measured values for single and double leaf panels. The CSTB Correction factor and the CSTB Method are shown to result in the best predictions for the double leaf and single leaf panels, respectively.

[15] Mahn, J. and Pearse, J., Revising the EN12354 Method of Calculating the Flanking Sound Reduction Index of Lightweight Building Elements, Proceedings of Acoustics 2012 Hong Kong, Hong Kong, 2012.

Abstract

There is great interest worldwide in using the standard, EN12354 to predict the flanking sound reduction index of lightweight building constructions. However, there are several problems which must be overcome before the prediction method can be accurately applied to lightweight building elements. One problem is that the resonant component of the sound reduction index of lightweight elements must typically be determined for the predictions. Three methods of determining the resonant component which are being considered by COST Action FP0702 have been evaluated. The evaluation was conducted by comparing the predicted flanking sound reduction indices which were calculated using the different methods of calculating the resonant sound reduction index to the measured flanking intensity sound reduction index for a series of elements. The elements included single, homogeneous elements and double leaf elements. The determination of the resonant sound reduction index using a correction factor proposed by CSTB based on the radiation efficiencies of the elements is recommended.

[16] Mahn, J. and Pearse, J., The Calculation of the Resonant Sound Reduction Index for Use in EN12354, Proceedings of Euronoise 2012, Prague, Czech Republic, 2012.

Abstract

Lightweight constructions typically have critical frequencies in or above the frequency range of interest. Since EN12354 only considers resonant transmission for the calculation of the flanking sound reduction

index, the resonant component of the sound reduction indices used in the predictions must be calculated theoretically or from measurement data. Several methods of calculating the resonant sound reduction index have been proposed with several being considered by the COST Action FP0702. These methods include Method Gerretsen, Method CSTB and the CSTB correction factor. This paper evaluates the proposed methods of calculating the resonant sound reduction index by comparing the flanking sound reduction index predicted using the different resonant sound reduction indices to measured data.

12 - RESEARCH ACTIVITIES AT RMIT AND CSIRO, AUSTRALIA

John Davy

Relevant for WG1

12.1 - Current research

1. Prediction of flanking transmission below the critical frequency.
2. Prediction of the directivity of sound insulation.
3. Prediction of the direct sound transmission of single walls and cavity walls.
4. Prediction of the direct sound insulation of steel stud walls and walls with resilient furring channels

12.2 - Available publications

[1] Davy, J.L. (2009). Predicting the sound insulation of walls. Journal of Building Acoustics 16(1):1-20. doi:10.1260/135101009788066546 .

Abstract

Between 1990 and 1998, the author published five conference papers which described the gradual development of a simple theoretical model for predicting the sound insulation of building partitions. The first aim was to extend Sharp's model for cavity walls to cavities without sound absorption. The second aim was to remove the reported over prediction of Sharp's model for cavity walls. The third aim was to explain the five decibel empirical correction in Sharp's model for stud walls. The fourth aim was to produce a more theoretically valid model than Gu and Wang's steel stud wall model. Although the simple theoretical model has been reasonably successful, several concerns have since arisen. This paper describes how these concerns have been addressed and gives the current version of this theoretical model for predicting sound insulation. The theoretical model is compared with a number of experimental measurements and produces reasonable agreement.

[2] Davy, J.L. (2009). The directivity of the sound radiation from panels and openings. Journal of the Acoustical Society of America 125(6):3795-3805. doi:10.1121/1.3117687 .

Abstract

This paper presents a method for calculating the directivity of the radiation of sound from a panel or opening, whose vibration is forced by the incidence of sound from the other side. The directivity of the radiation depends on the angular distribution of the incident sound energy in the room or duct in whose wall or end the panel or opening occurs. The angular distribution of the incident sound energy is predicted using a model which depends on the sound absorption coefficient of the room or duct surfaces. If the sound source is situated in the room or duct, the sound absorption coefficient model is used in conjunction with a model for the directivity of the sound source. For angles of radiation approaching 90 ° to the normal to the panel or opening, the effect of the diffraction by the panel or opening, or by the finite baffle in which the panel or opening is mounted, is included. A simple empirical model is developed to predict the diffraction of sound into the shadow zone when the angle of radiation is greater than 90 ° to the normal to the panel or opening. The method is compared with published experimental results.

[3] Davy, J.L. (2009). The forced radiation efficiency of finite size flat panels which are excited by incident sound. Journal of the Acoustical Society of America 126(2):694-702. doi:10.1121/1.3158820 .

Abstract

The radiation efficiency of an infinite flat panel which is radiating a plane wave into a half space is equal to the inverse of the cosine of the angle between the direction of propagation of the plane wave and the normal to the panel. The fact that this radiation efficiency tends to infinity as the angle tends to 90 ° causes problems with simple theories of sound insulation. Sato has calculated numerical values of radiation efficiency for a finite size rectangular panel in an infinite baffle whose motion is forced by sound incident at an angle to the normal from the other side. This paper presents a simple two dimensional analytic strip theory which agrees reasonably well with Sato's numerical calculations for a rectangular panel. This leads to the conclusion that it is mainly the length of the panel in the direction of radiation, rather than its width that is important in determining its radiation efficiency. A low frequency correction is added to the analytic strip theory. The theory is analytically integrated over all angles of incidence, with the appropriate weighting function, to obtain the diffuse sound field forced radiation efficiency of a panel.

[4.] Davy, J.L. (2009). Predicting the sound insulation of single leaf walls - extension of Cremer's model. Journal of the Acoustical Society of America 126(4):1871-1877. doi:10.1121/1.3206582 .

Abstract

In his 1942 paper on the sound insulation of single leaf walls, Cremer made a number of approximations in order to show the general trend of sound insulation above the critical frequency. Cremer realised that these approximations limited the application of his theory to frequencies greater than twice the critical frequency. This paper removes most of Cremer's approximations so that the revised theory can be used down to the critical frequency. The revised theory is used as a correction to the diffuse field limp panel mass law below the critical frequency by setting the nonexistent coincidence angle to ninety degrees. The diffuse field limp panel mass law for a finite size wall is derived without recourse to a limiting angle by following the average diffuse field single sided radiation efficiency approach. The shear wave correction derived by Heckl and Donner is applied to the revised theory in order to cover the case of thicker walls. The revised theory predicts the general trend of the experimental data, although the agreement is usually worse at low frequencies and depends on the value of damping loss factor used in the region of and above the critical frequency.

[5] Davy, J.L. (2010). The improvement of a simple theoretical model for the prediction of the sound insulation of double leaf walls. Journal of the Acoustical Society of America 127(2):841-849. doi:10.1121/1.3273889 .

Abstract

This paper presents a revised theory for predicting the sound insulation of double leaf cavity walls that removes an approximation which is usually made when deriving the sound insulation of a double leaf cavity wall above the critical frequencies of the wall leaves due to the airborne transmission across the wall cavity. This revised theory is also used as a correction below the critical frequencies of the wall leaves instead of a correction due to Sewell [(1970). J. Sound Vib. 12, 21-32]. It is found necessary to include the "stud" borne transmission of the window frames when modelling wide air gap double glazed windows. A minimum value of stud transmission is introduced for use with resilient connections like steel studs. Empirical equations are derived for predicting the effective sound absorption coefficient of wall cavities without sound absorbing material. The theory is compared with experimental results for double glazed windows and gypsum plasterboard cavity walls with and without sound absorbing material in their cavities. The overall mean, standard deviation, maximum and minimum of the differences between experiment and theory are -0.6 dB, 3.1 dB, 10.9 dB at 1250 Hz and – 14.9 dB at 160 Hz respectively.

[6] Davy, J. L., Guigou-Carter, C., and Villot, M. (2010). The equivalent translational stiffness of steel studs. Proceedings of 20th International Congress on Acoustics, ICA 2010, 23-27 August 2010, Sydney, Australia, Paper No. 21, edited by Burgess, M., Davy, J., Don, C. and McMinn, T., refereed conference paper only available on CD-ROM, ISBN: 978-0-646-54052-8.

Abstract

The effect of the resilience of the steel studs on the sound insulation of steel stud cavity walls can be modelled as an equivalent translational stiffness in simple models for predicting the sound insulation of walls. Numerical calculations (Poblet-Puig et al., 2009) have shown that this equivalent translational stiffness varies with frequency. Vigran (2010a) has derived a best-fit third order polynomial approximation to the logarithm of these numerical values as a function of the logarithm of the frequency for the most common type of steel stud. This paper uses an inverse ex-perimental technique. It determines the values of the equivalent translational stiffness of steel studs which make Davy's (2010) sound insulation theory agree best with experimental sound insulation data from the National Research Council of Canada (NRCC) (Halliwell et al., 1998) for 126 steel stud cavity walls with gypsum plasterboard on each side of the steel studs and sound absorbing material in the wall cavity. These values are approximately constant as a function of frequency up to 400 Hz. Above 400 Hz they increase approximately as a non-integer power of the fre-quency. The equivalent translational stiffness also depends on the mass per unit surface area of the cladding on each side of the steel studs and on the width of the steel studs. Above 400 Hz, this stiffness also depends on the stud spac-ing. The equivalent translational stiffness of steel studs determined in this paper and the best-fit approximation to that data are compared with that determined numerically by Poblet-Puig et al. (2009) and with Vigran's (2010a) best-fit approximation as a function of frequency. The best-fit approximation to the inversely experimentally determined values of equivalent translational stiffness are used with Davy's (2010) sound insulation prediction model to predict the sound insulation of steel stud cavity walls whose sound insulation has been determined experimentally by NRCC (Halliwell et al., 1998) or CSTB (Guigou-Carter and Villot, 2006).

[7] Davy, J. L., Guigou-Carter, C., and Villot, M. (201X). An empirical model for the equivalent translational compliance of steel studs. Submitted to Journal of the Acoustical Society of America on 10 May 2010. Revised version submitted on 4 September 2011. Being refereed.

Abstract

The effect of the resilience of the steel studs on the sound insulation of steel stud cavity walls can be modelled as an equivalent translational compliance in simple models for predicting the sound insulation of walls. Recent numerical calculations have shown that this equivalent translational compliance varies with frequency. This paper determines the values of the equivalent translational compliance of steel studs which make a simple sound insulation theory agree best with experimental sound insulation data for 126 steel stud cavity walls with gypsum plaster board on each side of the steel studs and sound absorbing material in the wall cavity. These values are approximately constant as a function of frequency up to 400 Hz. Above 400 Hz they decrease approximately as a non-integer power of the frequency. The equivalent translational compliance also depends on the mass per unit surface area of the cladding on each side of the steel studs and on the width of the steel studs. Above 400 Hz, this compliance also depends on the stud spacing. The best fit approximation is used with a simple sound insulation prediction model to predict

the sound insulation of steel stud cavity walls whose sound insulation has been determined experimentally.

[8] Davy, J. L., Mahn, J., Guigou-Carter, C., and Villot, M. (201X). The prediction of flanking sound transmission below the critical frequency. Submitted to the Journal of the Acoustical Society of America on 29 July 2011. Revised version submitted on 9 January 2012. Being refereed.

Abstract

Although reliable methods exist to predict the apparent sound reduction index of heavy, homogeneous isotopic building constructions, these methods are not appropriate for use with lightweight building constructions which typically have critical frequencies in or above the frequency range of interest. Three main methods have been proposed for extending the prediction of flanking sound transmission to frequencies below the critical frequency. The first method is the direct prediction which draws on a database of measurements of the flanking transmission of individual flanking paths. The second method would be a modification of the existing EN 12354 (ISO 15712) standard. This method requires the calculation of the resonant sound transmission factors. However, most of the approaches proposed to calculate the resonant sound transmission factor work only for the case of single leaf homogeneous isotropic building elements and therefore are not readily applicable to complex building elements. The third method is the measurement or prediction of the resonant radiation efficiency and the airborne diffuse field excited radiation efficiency which includes both the resonant and the non-resonant radiation efficiencies. The third method can currently deal with complex building elements if the radiation efficiencies can be measured or predicted. This paper examines these prediction methods.

13 - RESEARCH ACTIVITIES AT NTNU, TRONDHEIM, NORWAY

Nathalie Labonnote

Relevant for WG2

13.1 - Previous research

Validation of an experimental protocol to evaluate damping

- ***Experimental protocols***

The driving point method estimates the fundamental frequencies and the associated damping ratios from one single impact, whereas the roving hammer method estimates the mode shapes, and the associated fundamental frequencies and damping ratios from several impacts located on a selected mesh on the structure. For both methods, transient accelerations due to modal hammer impact are processed in order to build the Frequency Response Function (FRF). Experimental modal analysis is then used to curve fit an analytical FRF, from which the dynamic characteristics of the structure are estimated.

- ***Investigation of consistency and robustness***

Repeatability and reproducibility were studied using a panel of 10 operators. Parametric studies were conducted in order to check the reciprocity principle. It was concluded that the method provides reliable damping ratio evaluations, which do not depend on strength or skills of the operator.

- ***Experimental evaluations of material damping***

Timber beam specimens were subjected to flexural vibrations through the impact test method described in section 2. The material damping was evaluated in 11 solid wood beams and 11 glulam beams, both types made out of Norway Spruce, whose cross-sections were representative of common timber floor structures. The beams were simply supported with a symmetric overhang, and were tested at different spans and orientations. A total of 420 material damping evaluations were performed. The results are presented as mean values for each configuration along with important statistical indicators to quantify their reliability.

13.2 - Current research

13.2.1 - Analytical prediction of material damping

Complex elastic moduli and complex global stiffness were defined to derive a relationship between the equivalent viscous damping for the whole structure (which is a system quantity depending on the boundary conditions) and the bending and shear damping parameters and (which are intrinsic material properties). Physical interpretations of the derived model were given, and the different contributions from shear and pure bending were discussed. Shear damping and bending damping were defined accordingly. Fitting of the model was performed using the experimental results described in section 3.1. The good agreement of the derived model with experimental data reveals an efficient approach to the prediction of internal damping.

13.2.2 - Measurement and prediction of material damping in sheathing panels

The same protocol is currently being applied to different types of wooden panels. Damping is evaluated through the impact method for isotropic timber panels (fiberboard panels), transversely isotropic timber panels (OSB panels), and orthotropic timber panels (Structural LVL). Three different boundary conditions and two different thicknesses are investigated for each type of panel. A similar derivation as in section 3.2, extended to various plate theories, is currently being developed to predict material damping in wood sheathing panels.

13.3 - Planned research

Experimental evaluations of damping are intended to be performed first in assemblies formed by two timber beams (joists) and sheathing panels, and then to complete portion of floors. From the joist/sheathing panel experimental data, it is expected that the damping due to connectors is evaluated and discussed. From the complete section of floor, it is expected that the damping due to friction in-between components is evaluated and discussed. Prediction models for both connector damping and friction damping are expected to be developed.

14 - RESEARCH ACTIVITIES AT FCBA

Jean-Luc Kouyoumji

For WG1 and partly WG4

14.1 - Current research

- Bois-AcouTherm Collaborative Project with FCBA, InterAC, EFIA, Finnforest, ISOVER, Bouygues.: Acoustic – Thermal Interaction in lightweight constructions. Testing and predicting new generation of timber buildups, when design is controlled by Building Energy Efficiency. Database of about 110 tested configurations of wall, floors and roofs. Creation of SEA-Wood a design tool for timber building acoustics. Predicting walls and junctions' behavior, see papers 1, 2 & 6.
- Prediction and in-situ measurement of usual wall in zero-energy timber buildings.
- Collaborative project with FCBA and FPInnovations Canada, Acoustics of Cross Laminated Timber floors, see papers 2 & 3, and presentations.
- PhD-study on Objective and subjective qualification of acoustic and thermal comfort in timber framed houses, Sylvain Boulet, 2006-2010. Paper 4.
- Silent Wall : observation, description and modelling of heterogeneity, physical model development, design and elaboration of material, experimental validation, and optimisation, 2006-2011.
- Acoubois project: partners: CSTB, FCBA and QUALITEL; financially supported by DHUP, CODIFAB (wood manufacturer organization), the wood industry, and the building industry. Phase 1 of the project in 2010: gathering and categorizing the different building elements and junctions between elements used in France in timber based lightweight buildings; identification of missing data.

14.2 - Previous research

- PhD-study on "Characterization of lightweight walls and junctions for acoustical prediction of timber construction", Jean-Luc Kouyoumji; 1997-2000; see various papers and thesis,
- Two Projects on "Panacoustique : Characterization panels and timber walls", 2001-2006,
- Collaborative project "Acoustics of flooring" FCBA, CSTB, CEBTP and Flooring industry, 2001-2004
- Other projects on wooden windows, stairs, floors, walls, since 1997,
- Various consultancy projects on acoustics of lightweight buildings,

14.3 - Available papers / presentations

[4] Kouyoumji J.L, Borello G., Vernois L., Prediction of Flanking Transmission in light weight timber framed construction with SEA-Wood, a SEA software 40th Internoise Congress, September 4-7, 2011, Osaka, Japan.

[5] Kouyoumji J.L., Gagnon S., Experimental approach on sound transmission loss of, Cross Laminated Timber floors for building, 39th Internoise International Congress, June 13-16, 2010, Lisbon, Portugal.

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15 - RESEARCH ACTIVITIES AT THE CENTRE FOR TIMBER ENGINEERING, EDINBURGH NAPIER UNIVERSITY, EDINBURGH, UK

Binsheng Zhang

For WG3

15.1 - Current research

- Tall Timber Buildings: This is a joint research initiative with Bath University, Strathclyde University and Edinburgh University. This project aims to bring the UK's timber research community together with apposite expertise in a whole systems approach to address the structural engineering challenge of constructing safe and serviceable timber buildings over 30 stories high within the next 15-20 years. One of the many objectives for this project is to develop building forms and optimum structural arrangements and solutions needed to achieve safe and serviceable timber structures 30-45 stories high. Focusing on strategies for dynamic building responses under both service and ultimate wind loading, this will be achieved through structural modelling using non-linear structural finite element method, large-scale testing and monitoring of real structures. Solutions for dealing with structural movements and seismic loadings using quantifiable performance based metrics are also considered.
- Investigations of dynamic performance of attic room floors in timber framed houses: This project allows using commercial finite element software to analyse the dynamic performance of the flooring systems in the attic room of duo-pitch timber frame houses. The vibrational serviceability parameters include the mid-span deflections of the bottom chord under dead loads and unit point load and the modal frequencies and shapes. The influence of geometric configurations is systematically studied, including bracing members, floor span and roof pitch angle. The composite effect is also to be investigated. Thus, a design equation for predicting the fundamental frequency can be proposed.
- Engineered timber wall panels subjected to combined vertical and lateral loading: This PhD project allows engineered timber wall panels being subjected to lateral loading together with varied vertical loading until failure to examine the performance of these panels under service and ultimate loading. The dynamic and acoustic performance of the wall panels will be looked into in later stage.
- UK National Annexes to Eurocode 5: The centre has been largely involved in the UK timber design committee for the development of UK National Annexes and other technical documents to Eurocode 5 and much research work has been included in the design codes.

- Consultant work on testing timber materials, members and structures and designing timber structures on static, dynamic and acoustic performance.

15.2 - Previous research

- PhD study on "Dynamic response of structural timber flooring systems", Jan Weckendorf; 2005-2009; see various papers and thesis.
- PhD study on "Development and evaluation of composite insulated beams", Ali Bahadori Jahromi; 2002-2005; see various papers and thesis.
- Project on "Testing to Evaluate the Vibration/Deflection of Metal Web Joist Floors & the Enhanced Floor Flexural Rigidity by the Introduction of Strongback Bracing", collaborated with the Metal Web Working Group comprising ITW Alpine, Gang Nail Systems, MiTek Industries Ltd and Wolf Systems., 2008.
- CPD courses to practical engineers on the design of timber structures to Eurocodes.
- Various consultant projects on testing timber materials, members and structures, and carrying out design of timber structures, since 2003.

15.3 - Available papers / presentations

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[3] Zhang B., Weckendorf J. and Kermani A. Vibrational performance of metal-webbed timber floors, The 11th World Conference on Timber Engineering (WCTE-11), Riva del Garda, Trentino, Italy, June 2010.

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