Vibration control of sensitive manufacturing facilities

J.M.W. Brownjohn
University of Sheffield, United Kingdom

ABSTRACT: As demands increase for reducing feature sizes in computer processors, display units and media, the requirements for controlling vibration levels become more severe and begin to govern structural design. Design guidance is so far limited or non-existent and vibration control exercises are not standardised but case-specific. This paper presents experiences in vibration control of micro-electronics fabrication plants or ‘fabs’ subject to dynamic loading from pedestrians, wind, vehicles and other machinery, the lessons learnt and some suggestions on design.

1 INTRODUCTION

Trends in increased power and miniaturization for personal computers and other IT and electronics products push technology for economic mass production at nano-scale to greater challenges and there now appear other difficulties to deal with as demands increase for ever smaller ‘feature sizes’.

Manufacture to very tight dimensional tolerances requires extreme stability of equipment in order to machine and then check the finished product; feature sizes such as media track widths and connections are now specified in nanometers, and at 10Hz, 1 nanometer (10^{-9}m) is equivalent to 40 μm/sec^2, detectable by only the most sensitive accelerometers and seismometers.

The acceptable levels of machine support vibration depend on the type of machine and the type of operation and it is a practical impossibility to cater individually to machine requirements, even when adequately specified, so generic design criteria have evolved along with means to assess structures a-priori and as-built.

1.1 *Specification of vibration tolerance*

A case study indicates the problems in satisfying poorly specified equipment vibration tolerances. DRAM manufacturer ‘A’ had installed scanning electron microscopes from supplier ‘B’ to check the tracks on the chips. The SEMs were installed on the first floor (above ground level) in a low rise purpose-built factory. The SEMs appeared to malfunction as the image wobbled, moving around by one or two microns (μm), the same order as the track size. B had vibration tolerance specifications in the form of ‘x-microns at frequency x’ rather than in the form of a power spectral density value and while A could argue mathematically that vibrations at frequency x vanished, the problem clearly lay in the poor vibration performance (sway) of A’s building.

There were problems both with vibration control and with unambiguous specification of acceptable vibration levels for equipment. The letter difficulty is now commonly dealt with using ‘generic vibration criteria’.

1.2 *Generic vibration criteria*

Due to the wide range of machine vibration tolerances and the differing and ambiguous methods of specifying them, a de-facto standard has evolved for specifying acceptable vibration levels. These generic criteria (Gordon, 1991) use $1/3^{rd}$ octave RMS velocity levels VC-A (least severe) to VC-E (most severe) which can be specified to apply globally or locally (to different areas of a structure). Figure 1 shows how vertical vibrations due to walking in a car park translate to velocity levels in a range of frequencies. The lowest curve, 3.125μm/sec is VC-E, the highest is VC-A, at 50μm/sec. If this is the strongest signal recorded during the assessment, the structure is VC-B for vertical vibrations.

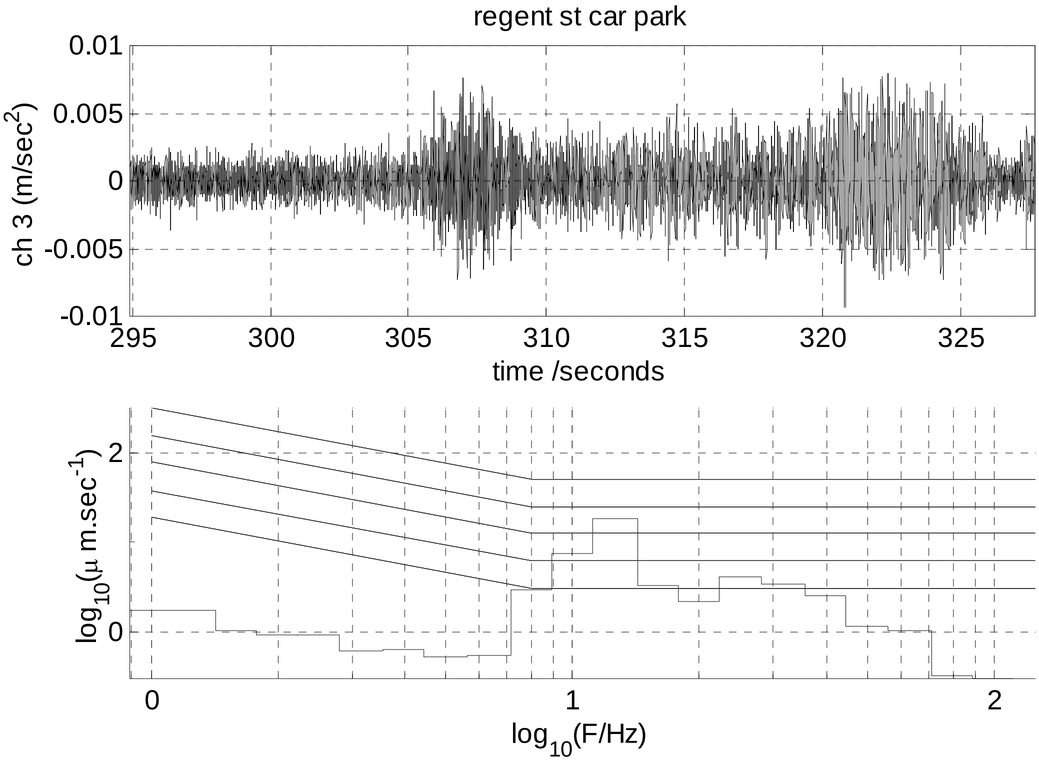

Figure 1 Acceleration time series and corresponding $1/3^{rd}$ octave velocity spectrum

The record used has duration of over 30 seconds. Due to time dependent variations in RMS levels, higher $1/3^{rd}$ octave velocity values could be indicated using shorter averaging times. There is no guidance available on averaging times, although record length should be enough too resolve the lowest frequency band. Below 8Hz, the VC-bands are constant acceleration and, arguably, are limited to more than 4Hz although in theory there is no reason to limit the range.

The criteria provide a useful target for design, and the exercise of ensuring that production and test machines mounted in a building designed to a ‘VC’ function without detrimental effect of vibration is termed vibration control.

2 DESIGN FOR VIBRATION CONTROL

Prediction of vibration levels in a structure requires a good understanding of the remaining variables in the vibration serviceability chain, i.e. source and path.

2.1 *Vibration source*

External vibrations sources of concern in fab design are roads and railways, nearby construction activities and machinery and turbulent wind. Earthquakes are unlikely to be considered a threat due to rare occurrence. Turbulent wind generates a horizontal *load* on the structural envelope while the other sources generate *vibrations* in three axes rather than forces. The vibration are transmitted via the building foundations, and result in mass-dependent 'body forces'. While forces due to wind can be estimated via loading codes, the procedure for predicting vibration levels transmitted from a vehicle to the structure is, at best, 'inexact'.

Internally, pumps and air handling facilities generate narrow band vibrations, while movement of workers and to a lesser extent wheeled carriers are likely to be most significant in the design process. Each of these sources generate vertical forces that are transmitted to the floors of the structures. Horizontal internal forces are not a concern as they need to engage the very large mass of the whole building.

There is a growing body of literature describing forces generated by pedestrians, particularly with respect to low frequency floors where resonance is a factor, but these do not reflect very well the conditions in a fab clean room for example. In such an environment, at least in Asia, workers are predominantly female and movement is severely restricted by garments worn to maintain the low particulate levels. Hence median pedestrian weights and pacing rates are significantly reduced with respect to, for example, western open office environments, yet there is no guidance on this and no precedents to defend a decision on a representative pedestrian loading function. A variant on ARUP's high frequency floor forcing function (Young, 2001) may be appropriate but this still leaves the question of how (and if) to considering effects of multiple pedestrians.

Forces generated by internal machinery are notoriously difficult to quantify partly due to reluctance on the part of manufacturers to provide such data, compounded by minimal published literature (Bachmann and Ammann, 1987). Air handling machinery typically generates forces at distinctive discrete frequencies which are only an issue for vibration control of fixed machines susceptible to high frequency forces. There is even less information (i.e. none) about forces due to trolleys and other internal sources.

2.2 *Vibration path*

For forces applied directly to the structure (wind, footfall forces, out of balance machinery forces) the problem now shifts to simulating the response of the structure to a specific load. For ground-borne vibrations due to external sources there is a significant problem of predicting not only how the vibrations (not forces) propagate and attenuate through from the source to the foundation but also how the presence of the building itself affects the received vibration levels.

The mechanism of ground-borne vibration transmission is complex and poorly understood and often it is taken that 'free field' measurements will be replicated when the fab is built. Hence is it common to conduct a thorough survey of vibration levels at the empty site and then translate these as input motions to the structure without any filtering or mitigation. These vibrations are then input to the structure in the same way as for a seismic analysis.

2.3 *Modelling procedures*

A prerequisite for analysis to predict response to the various forms of loading is a reliable mathematical model, typically a finite element (FE) representation.

For horizontal vibration (wind load or ground borne vibration) detailed modeling of the floor is unnecessary except insofar as it contributes to sway stiffness and to total mass. Empirical formulae or simple lumped mass models may be just as accurate, but far less costly to create and study than a full representation of the structure.

For vertical response analysis a detailed model of the floor will be necessary and modeling a single bay is unlikely to be adequate. Figure 2 shows an upper floor of a fab, comprising over 50 bays split into two nominally separate areas by an expansion joint. How many bays should be modeled? In addition, how should the contribution of the columns be included? Modeling experience (Pavic et al., 2002) has shown that even with fixity at the columns, the rotational stiffness of the columns can make a significant difference. Guidance by Amick and Byatt (1998) also suggests that axial flexibility of columns be included.

Figure 3 shows a model of a 3x3 bay section of a proposed fab floor design with each bay having dimension 9m by 8m. The columns support deep beams in the short spanning direction

Figure 2 Mutli-bay fab floor

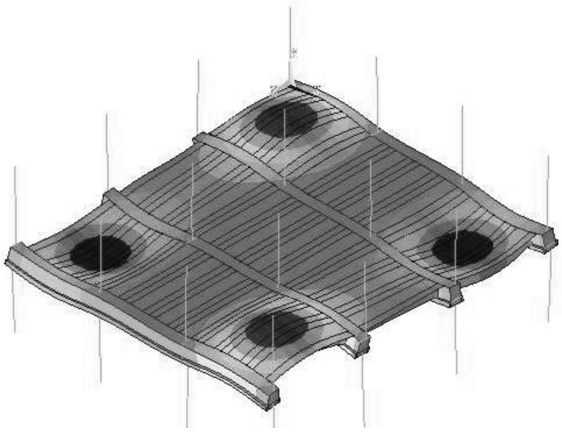

Figure 3 FE model representing 9 bays and columns

which in turn support transverse deep inverted T-beams with integral slab. Columns having dimension 1m square by 8m tall are continuous through the five levels of the building. The mode shape shows one vibration mode, predicted to occur at 21Hz and having modal mass 115 tonnes. This is just one of the many closely spaced modes starting from 20Hz and having variations of relative phase and symmetry between the various bays.

What such models do not show is the axial vibration modes of the columns, a surprising effect of the massive and massively stiff floors, typically having webs or waffles over 1m deep.

2.4 *Analysis procedure -wind*

Each loading type leads to a choice of analysis procedures; for wind the choice should be relatively simple since there are design codes, although not all explicitly cover vibration serviceability. The latest Australian wind code, AS1170:2 (2002) relates maximum acceleration $\ddot{x}_{\max}$ to resonant component of wind induced moment M_{res} on the building via: $\ddot{x}_{\max} = \left(3M_{res}/m_oH^2\right)$, where m_o is average mass per unit height and H is building height. The clear origins of this result indicate that the formula may not represent squat buildings, but the results are in line with more elaborate predictions. The code provides a formula for M_{res} in terms of turbulence, statistical peak factor, wind spectrum value, shape coefficients, areas and of course design wind speeds and the peak acceleration can be converted to RMS, assumed to occupy the single 1/3rd octave band around the building fundamental frequency, by dividing by the statistical peak factor (typically given as 3.7).

2.5 *Analysis procedure –ground borne vibration*

Given a modal solution for the floor, the choice lies between frequency domain analysis using a representative spectrum of ground vibrations or time history analysis using worst case time series. The input spectra of time series would typically be obtained from site measurements before construction e.g. during passing of a train or heavy vehicles.

In either case, the analysis treats the ground vibration as an inertial load and the response in a given vibration mode, measured in time or frequency domain, depends on the participation factor $\Gamma = \phi^T\mathbf{Mg}/\phi^T\mathbf{M}\phi$ where $\mathbf{M}$ is mass matrix, ϕ is mode shape (unit normalized) and $\mathbf{g}$ is a vector of ones for vertical degrees of freedom. Participation factors can reduce where modes, such as shown in Figure 2, have symmetry leading to a relatively small numerator in the expression.

2.6 *Analysis procedure –machinery*

This is a relatively simple exercise since the force is well described. A transfer function is created from the FE model and the peak value multiplied by the specified rotating out of balance force (for that frequency). This assumes the worst case of machinery running at the frequency for maximum transfer function.

2.7 *Analysis procedure –footfalls*

There are essentially three approaches to predicting response to footfall forces. Time series analysis using a representative walking time history, application of a new walking load model for high frequency floors based on impulsive response, or applying an old but widely accepted empirical formula requiring knowledge only of floor natural frequency and static stiffness.

For low frequency floors the concern is resonance at multiples of pacing rate. For high frequency floors, having frequencies above 10Hz, the imperfect timing of walking leads to leakage of energy from higher harmonics of pacing rate, resulting a spread frequency spectrum resembling that of an impulse. Figure 4 illustrates this in the footfall forcing function for a 65kg male walking at a leisurely 3.6km/hour. The first five harmonics are clear, but in the frequency range of interest (20Hz and above) these harmonics are buried.

The first approach simply applies this walking time history to the floor FE model, either assuming walking is on the spot, or moving the force. The letter is cumbersome and the former leads to a worst case prediction so is preferable. Figure 5 shows floor displacement and acceleration estimated this way. The highest 1/3rd octave velocity value is 8mm/sec, qualifying the floor as VC-C.

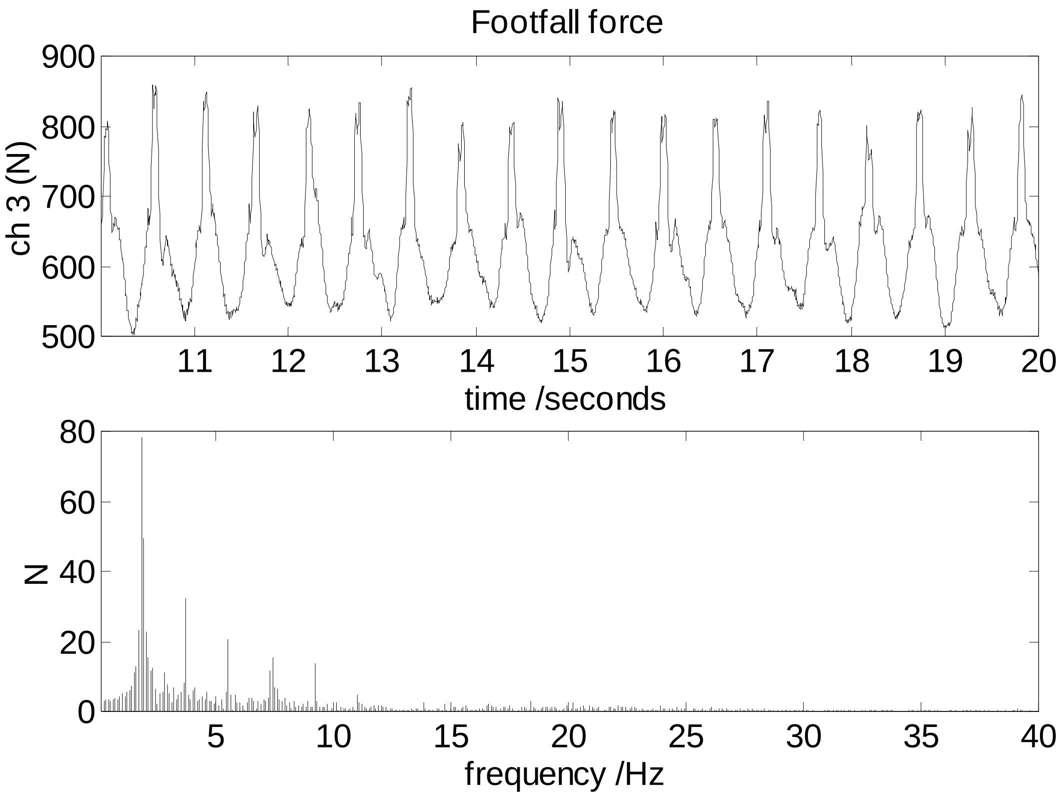

Figure 4 Example footfall force and spectrum

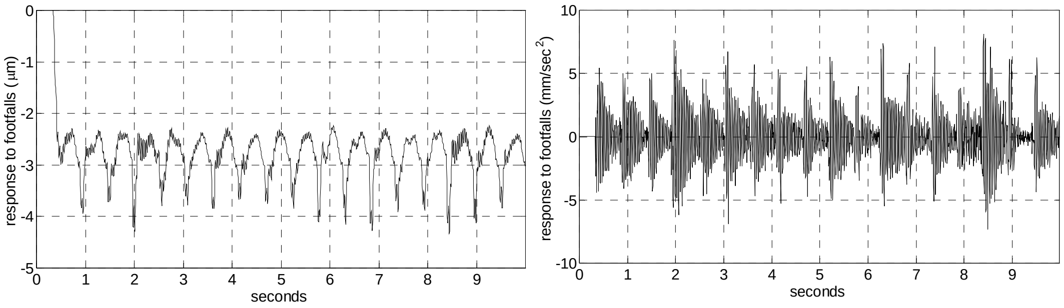

Figure 5 Floor response displacement and acceleration

The second approach uses the ARUP model (Young, 2001) which specifies an effective impulse I_{eff} depending on floor frequency f_n and pacing rate f as follows via $I_{eff} = 42 f^{1.43} / f_n^{1.3}$.

This semi-empirical approach is simple to apply if the floor responds in a single mode, otherwise modal contributions must be summed. Peak velocities can be derived by dividing by unit-scaled modal mass, while RMS values are obtained with averaging time logically taken as a multiple of interval between footfalls. For the example floor studied, comparison with results for real walking show that this model predicts much larger responses; in this case 12.4μm/sec results from just one mode, and is invariably conservative with respect to full simulations.

The last method is derived from the work of Colin Gordon & Associates (Amick and Byatt, 1998). From regression analysis on an ensemble of experimental data for fabs, they have shown that 1/3rd octave RMS values can be estimated using the formula $V_w = C_w / k f_n$ where C_w is a constant, approximately 7×10^4N.s^{-2} for this type of structure. The origins of this formula are obscure, but it has to be said that it fits and is very simple to use. Again, a single frequency value is used, and RMS is taken to be the peak 1/3rd octave RMS level. With a point stiffness of 220MN/m, a value of 17.4μm/sec is returned.

2.8 *Damping*

For harmonic response (to machinery) response is inversely proportional to damping. For ground borne vibration, assuming a broad-band excitation, response is inversely proportional to square root of damping, with a similar result for horizontal response to wind. For response to internal transient forces, particularly footfalls, damping is a relatively unimportant parameter as resonance is not an issue and the peak values occurring directly due to impulses dominate. Nevertheless, values for damping have to be taken, and a range of 1.5% to 3% is reasonable, assuming the facilities are concrete structures. In practice, with false floor, ceiling attachments and other fittings, a less-conservative figure of 3% is often argued.

3 STRUCTURE DESIGN CONSIDERATIONS

With some knowledge of the loading, some general observations can be made about overall design philosophy. Subject to requirement on usage of the facility, such as headroom and other clearances, vibration is the principal design criterion for structural form.

3.1 *Stiffness and mass control*

The prime concern is vibration control of the floors which need to have frequencies high enough to avoid resonant excitation by footfall forces. In addition, frequencies have to be high enough to avoid the range of ground borne vibration frequencies. Trucks typically generate significant energy at frequencies up to 14Hz (the upper limit of truck axle hop frequencies). Mere frequency control is not enough, however, since response to (footfall) impulses is inversely proportional to mass, hence the massive and stiff floor designs used in fabs.

Up to a point, massive and deeper beams can add both stiffness and mass, but it is an exercise of diminishing returns as flexibilities of cross beams and columns begin to contribute. Engaging more mass (without drop in frequency) or increasing stiffness, e.g. via boundary conditions can be useful approaches.

When designing a floor arrangement for vertical stiffness, the horizontal stiffness may be overlooked and one-way spanning beams such as in the example of Figures 2 and 3 may compromise lateral stiffness in the transverse direction and render the structure wind-sensitive.

3.2 *Isolation and shielding*

Numerous tricks are used to control vibration transmission from external or internal sources to vibration-sensitive areas. One method is structural isolation (Amick et al 1999), as shown in Figure 2 where two adjacent column lines are intended to split the building into structurally separate halves. Structural isolation breaks are also used so that surrounding parts of the structure shield internal vibration-sensitive areas at least from wind but also from activities in the non-sensitive areas. It is less straightforward to isolate structures from ground-borne vibration but it has been suggested (with no evidence) that piles installed in the vibration path can mitigate response. Trenches are also commonly suggested as vibration barriers, at least to surface waves, but there is no guidance on sizing or even effectiveness for such large structures.

The presence of the structure itself provides a strong mitigation effect, Figure 6 shows 1/3rd octave spectra recorded at the same location in a vibration sensitive structure during and after construction, due to passing of the same express train. The reduction is by a factor of at least two along with reduction in the frequency levels.

4 EXPERIMENTAL QUALIFICATION

Given the heavy investment in vibration control in the design stage, a vibration serviceability check on the as-built structure under representative conditions is advised. This serves as a feedback for future exercises and may reveal surprises about overlooked or underestimated effects.

Response to ground borne vibration can be tested by ambient vibration measurements: simply recording response in various locations and attempting to correlate with occurrence of external vibration activities such as passage of trains.

Response to wind can only be checked on a windy day but response to footfall forces can be checked objectively; it should be done under representative but worst case conditions e.g. a person in the upper quartile of body weights walking at a pace that is no faster than physically possible in a clean room suit and preferably a sub-harmonic of the strongest and probably lowest mass floor vibration mode. To check for the latter requires expensive forced vibration testing, but this is strongly recommended .

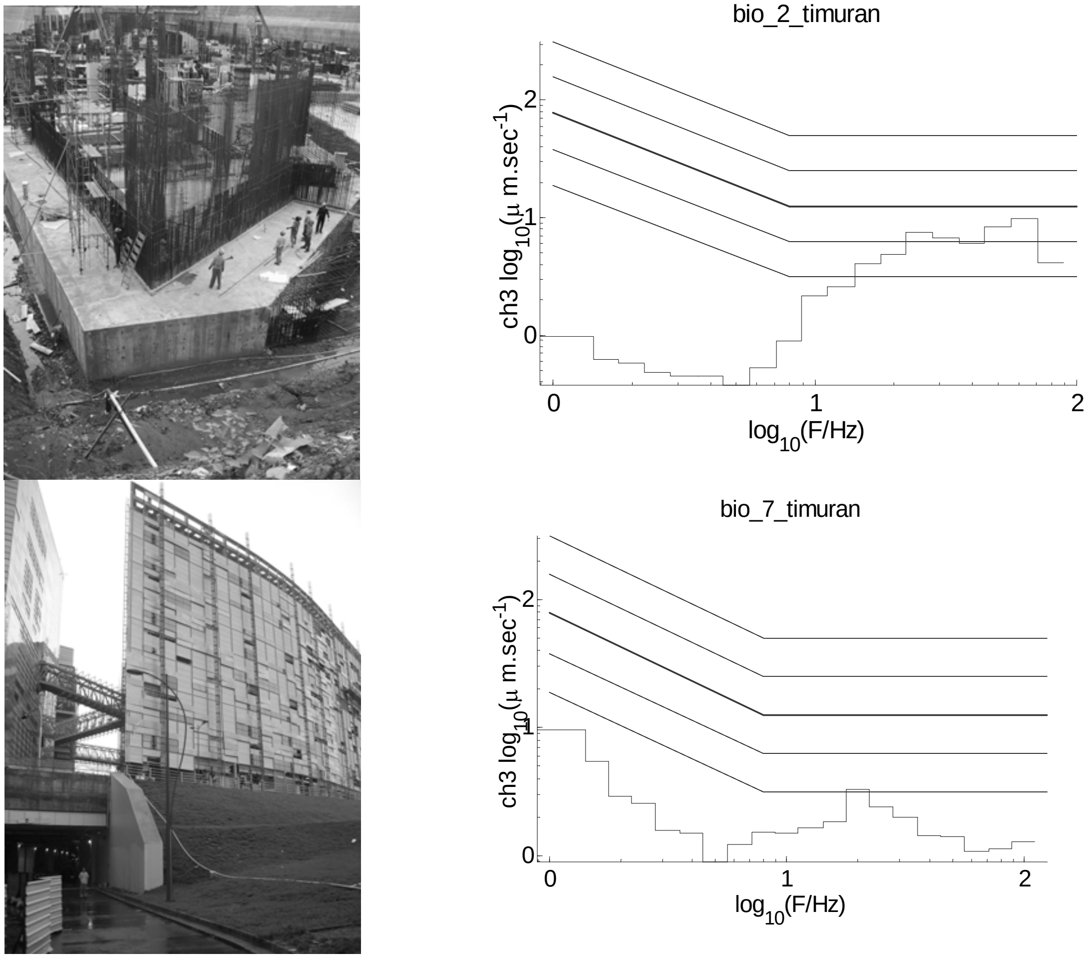

Figure 6 Effect of building on received ground borne vibration due to identical source

Experience has shown some surprises about as-built performance compared to a-priori analysis. Specifically,

- Footfall-induced response is likely to be lower than predicted and vibrations are do not propagate as far as in simulations, so cross-transmission is unlikely to be an issue.
- Effects of ground borne vibration are likely to be reduced in line with findings of Figure 6.
- Structural isolation breaks may not be so effective at lower frequencies, below 10Hz
- Low frequency sway vibrations may be a possible concern in string winds
- Axial vibration modes of the entire building may occur at frequencies below floor modes.

5 SUGGESTIONS FOR DESIGN PROCEDURE

This subject appears to be not as well researched and published as traditional studies on floors and bridges, but the commercial concerns are just as real with large cost implications for under- or over-conservative design and a number of observations can be made.

- Ground borne vibrations present a significant challenge to determine in-situ vibration levels with the as-built structure. There is no convincing evidence of a reliable analytical approach with low cumulative error over the many stages and variables in the chain from vehicle to building floor.
- Ground borne vibrations may be the governing concern for larger spans.
- Effects of footfall forces can be modeled in several ways, but the most convincing and reliable method will use reliable FE modeling of the floor rather than empirical formulae.
- Wind effects that result in low frequency sway should not be underestimated.
- Close the loop by using any opportunity for post-construction experimental qualification.

There is demand for research in a number of areas such as:

- Modeling propagation of low level (non-seismic) ground borne vibration
- Investigation of damping mechanisms in multi-bay extended structures
- Modeling footfall forces under fab-like working conditions
- Developing rules for scaling individual pedestrian effects to groups of workers
- Providing clear evidence on the efficacy of some proposed vibration mitigation measures (shield piles, trenches, structural isolation breaks)
- Validating commonly used empirical formulae

6 REFERENCES

Gordon CG, Generic criteria for vibration-sensitive equipment, (1991). SPIE Vol. 1619, San Jose, CA p71-85. http://www.cganda.com/pdf/Gordon-SPIE91.pdf

Bachmann H, Amman W, (1987). Vibrations in structures induced by man and machines. Structural engineering documents 3e, IABSE Switzerland 1987.

Young P, Improved floor vibration prediction methodologies, (2001). Arup vibration seminar on engineering for structural vibration –current developments in research and practice. IMechE London.

Amick H, Gendreau M, Byatt A, (1999). Dynamic characteristics of structures extracted from in-situ testing. Proceedings of SPIE - The International Society for Optical Engineering, Vol. 3786, p40-63

Pavic A, Reynolds P and Waldron, P, (2002). Modal Testing and FE Model Correlation and Updating of a Long-Span Prestressed Concrete Floor. Proceedings of the Institution of Civil Engineers: Structures and Buildings, Vol. 152, No. 2, p 97-110.

AS/NZS 1170.2, (2002) Structural design actions, Part 2: Wind actions

Amick H, Byatt A, Dynamics of stiff floors for advanced technology facilities, (1998). Proceedings, 12th ASCE EM conference, La Jolla, CA, p318-321