Footfall Vibration and Finite Element Analysis

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With more efficient design utilizing stronger materials leading to lighter structures, the problem of human-induced vibrations on floors is increasing. Conventional methods of predicting floor accelerations are only suitable for a narrow range of floor layouts and materials. Originally developed for internal use in Arup, Oasys GSA is a structural analysis program commercially available to other consultants. One of the most popular features added within the past five years is the ability to calculate the vibrations caused by footfall and other human activities on any type of structure, including floors, bridges and stadia.

The possibility of human footfall loading leading to excessive vibration of structures has long been recognized. In 1831, soldiers marching across a cast iron bridge generated vibrations that caused the bridge to collapse, thus the reason why some bridges now display notices instructing soldiers to break step when crossing (see Figure 1). There have been other collapses of floors and stadium structures induced by crowds dancing or jumping in unison.

The introduction of lightweight, long-span, composite construction and open-plan offices in North America in the 1960s led to concerns that normal walking caused uncomfortable vibrations for occupants of the buildings. Until this time, serviceability was checked using only simple stiffness-based criteria, such as limiting imposed-load deflections to a ratio of the span or ensuring that the natural frequency was higher than a certain limit.

Market Drivers

There are now numerous market forces causing clients to insist on floor vibration checks:

- *Design codes* – AISC and IBC recommend that floor vibrations be checked.
- *Commercial* – on lively floors, computer users complain because their screens wobble, making it difficult to work.
- *Bridges* – need to comply with bridge codes.
- *Laboratories* – equipment, such as optical and electron microscopes and laser research systems, are very sensitive to vibrations. Floors for such equipment floors must comply with the BBN or ASHRAE standards.
- *Hospitals* – operating theaters require the utmost stability for delicate operations, and the latest scanning technologies require even lower vibration levels.
- *Airports* – Airport owners are concerned that floor vibrations in heavily trafficked waiting areas can upset seated travelers.
- *Retail* – many major retailers require assurance that vibrations on display floors, such as a display of glasses on glass shelves, will not be excessive. If the floor is too lively, then the glasses will rattle

Vibration Problem

For many years, serviceability requirements have been a part of structural design. Initially, these were just deflection limits to prevent finishes from cracking and building occupants noticing floors sagging. These proved adequate for decades, until advances began to be made into more efficient, lighter structures, such as composite beam or post-tensioned slab floors, and open-plan rather than cellular offices became more common. Unfortunately, users of some of these buildings found that the floors could be rather lively.

The first proposed remedy to this problem was to restrict the natural frequency of the floor beams, since it was thought that if this were kept above walking pace, then resonance should not occur. For simple floor layouts, the fact that this frequency could be found by a simple hand calculation encouraged this approach.

Figure 1. Albert Bridge, London.

However, a number of problems emerged with this solution. The first was that floors can be excited into resonance at higher harmonics of a pedestrian's footstep frequency. The second was that while shorter spans had higher natural frequencies, they also had lower mass, making them easier to excite. This, combined with the modern trend for irregular floor bays, open plan offices and electronic storage rather than filing cabinets (reducing the mass and damping of floors) made the vibration problem more difficult to assess and solve.

Floor vibration problems are not restricted to steel/composite floors. While most reinforced concrete floors, such as shown in Figure 2, are adequate for office and residential use, vibration must still be checked for more sensitive occupancies such as laboratories. Post-tensioned slabs, such as shown in Figure 3, are thinner and lighter than those of conventional reinforced concrete, and are thus more susceptible. Therefore, what the industry needed was a reliable design method for all construction forms, materials and framing layouts.

Industry Solutions

Industry experts recognized that floor frequency was not the crucial issue, but how much the floor responds to the footsteps of a person walking over it – a footfall response calculation. Various trade organizations, such as the American Institute of Steel Construction (AISC),[1] the Steel Construction Institute (SCI),[2] and the Concrete Society[3] have produced guides to assist engineers in predicting this floor response.

Measuring the Vibration Problem. Human comfort is often the key design objective for footfall-induced vibration, but in research, medical, microelectronics and other "vibration-sensitive" occupancies, vibration may need to be restricted to levels well below the threshold of human perception.

Response Factors for Humans. Setting simple criteria for human acceptance, such as shown in Figure 4, is complicated by the fact that human tolerance of vibration varies with the direction, frequency and duration of vibration. To account for direction and frequency dependencies, the response factor R is defined as a multiplier of the level of vibration, at the average threshold of human perception, in the direction of concern at any frequency. Therefore, a response factor of 1 represents the magnitude of vibration that is just perceptible by a typical human, while a response

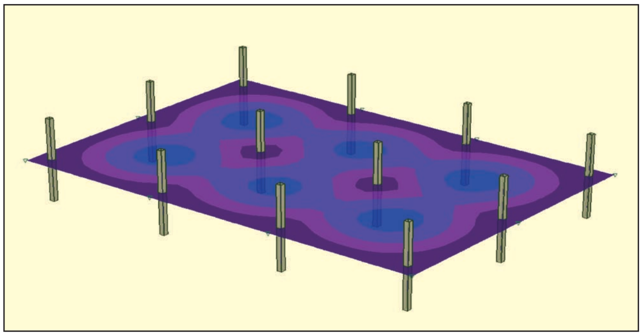

Figure 2. Eight-meter bay, reinforced concrete flat slab.

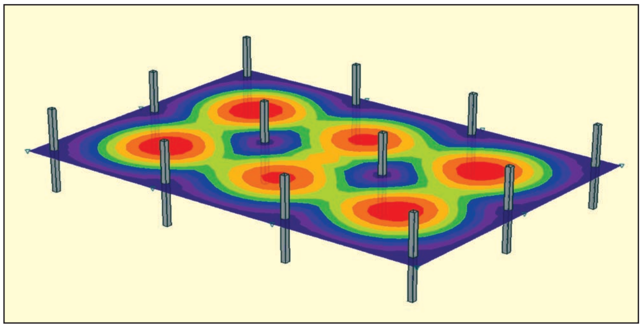

Figure 3. Eight-meter bay, post tensioned slab.

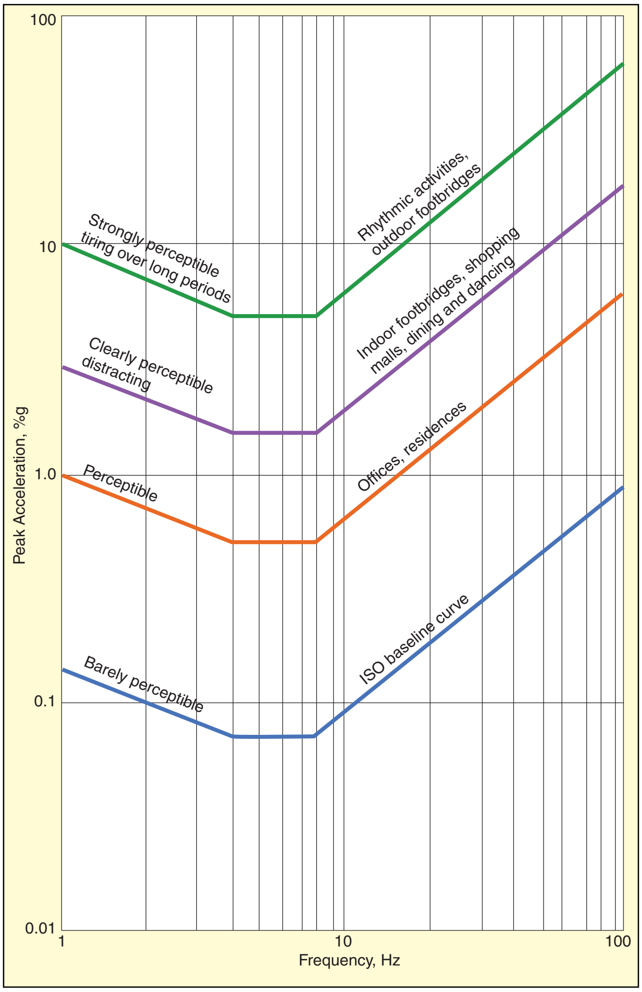

Figure 4. Building vibration z-axis curves for acceleration (RMS baseline, peak criteria) after AISC.

factor of 2 is twice that, and a response factor of 8 is eight times that. In this way, each of the colored lines in Figure 4 represents the vibration level corresponding to a particular response factor.[2] For sensitive equipment, different types of criteria (BBN, ASHRAE,

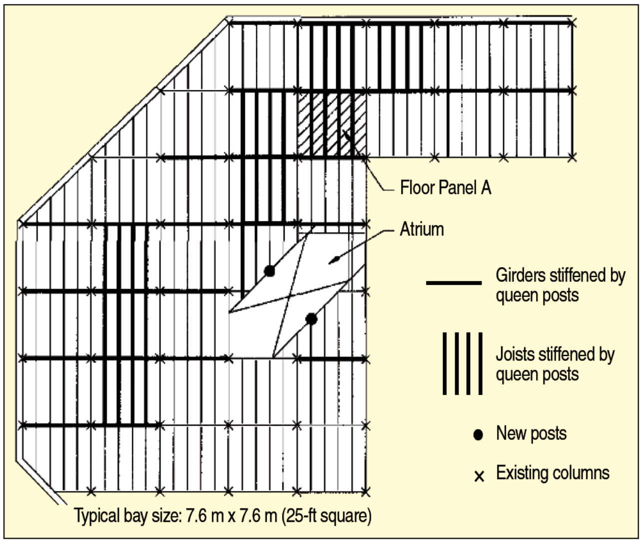

Figure 5. Floor vibrations due to human activity; example from AISC.

or equipment-specific) apply.

Regular and Irregular Structural Layouts. The difficulty with some floor vibration guidelines is that they offer procedures only for regular rectangular floor layouts. While this simplicity enables calculations to be carried out by hand, many modern buildings do not have simple and uniform floor bays. While some software suppliers have suggested that irregular frames cannot experience resonant problems, this is not the case in practice. This is supported by an example in the AISC design guide (shown in Figure 5) where "unacceptable walking vibrations occur throughout most of the floor, particularly adjacent to the atrium."

In fact, floors with irregular bays can be livelier than regular ones, because susceptible vibration modes are sometimes localized to small areas. This means that the modes have low modal mass and can be more easily excited to high acceleration responses under footfalls. This can be predicted with GSA Footfall as shown in Figure 6.

If we then add the posts under the atrium beams using staged analysis, the floor in this area does improve. But there is some knock-on effect to adjacent bays (see Figure 7).

The Ideal Solution

The ideal methodology for assessing the susceptibility of a structure to footfall vibration would be:

- Applicable to as many structural forms as possible, whether simple or complex.
- Straightforward to use, enabling the consequences of various design iterations to be readily and quickly assessed.
- Applicable to structures whose structural properties may be ascertained by: hand calculation undertaken early in the design (or to verify more complex analyses); finite-element analysis; and measurement.

Most existing methods rely heavily on "rules" that classify different structural forms, thus the details of the analysis to be used. If the structure does not readily fit into one of these classifications, then approximations must be made. If the underlying assumptions for the basis of these empirical rules are not fully understood, then the assumptions made are likely to be inaccurate.

A new set of methods was developed by Arup in the 1990s and is based on extensive fundamental research into the nature of footfall forces and the manner in which structures respond to them. In the past 10 years, these methods have been very extensively validated against measurements on completed structures and have been adopted in several of the most recent industry design guides.[2,3]

The research confirmed that when the walking frequency (or a multiple of it) coincides with a natural frequency of the floor, then vibrations will build up in a resonant manner. Resonant vibrations tend to dominate on low-frequency floors (<10 Hz), when modal frequencies fall below four times the footfall rate (resonance to the first four harmonics of the footfall force).

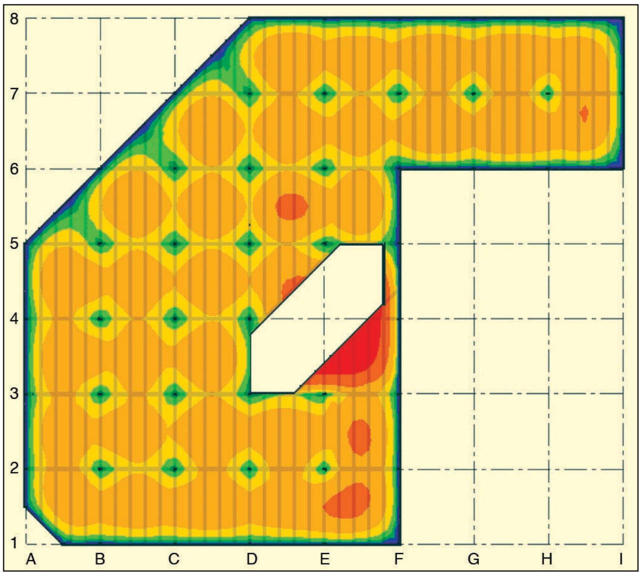

Figure 6. Floor response before remedial work.

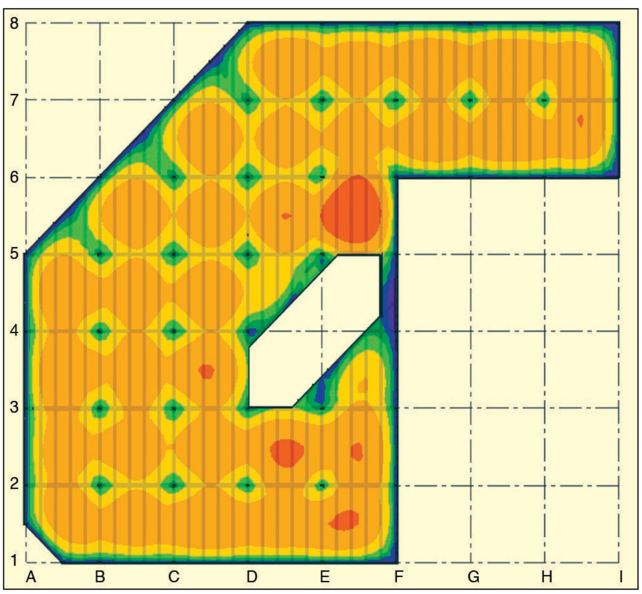

Figure 7. Floor response after addition of new posts.

On higher-frequency floors (>10 Hz), vibration induced by each footstep tends to decay substantially before the next footstep occurs, and transient vibrations due to each individual footstep dominate the response.

GSA Footfall

For many years, GSA has been one of the leading PC-based packages for structural analysis. Developed by Arup to meet its own demanding and diverse requirements as one of the world's leading firms of international consulting engineers, GSA's capabilities are proven on thousands of complex and prestigious projects worldwide.[4,5]

GSA Footfalls analyzes structures using extensively validated Arup methods. Appropriate dynamic loading functions for walking and other human activities as recommended by Arup research and the American Institute of Steel Construction (AISC) are automatically available, including forces for use with stairs.

A properly conducted finite-element analysis (FEA) is the only reliable way to predict the footfall response of any floor that is not part of a regular rectangular frame (see Figure 8). Even with a regular frame, FEA is often quicker than using hand calculations. Using GSA, you get quick and accurate predictions of floor's resonant and transient response to footfall forces, including response factors, peak and RMS accelerations and velocities.

GSA analysis enables you to locate regions of high and low re-

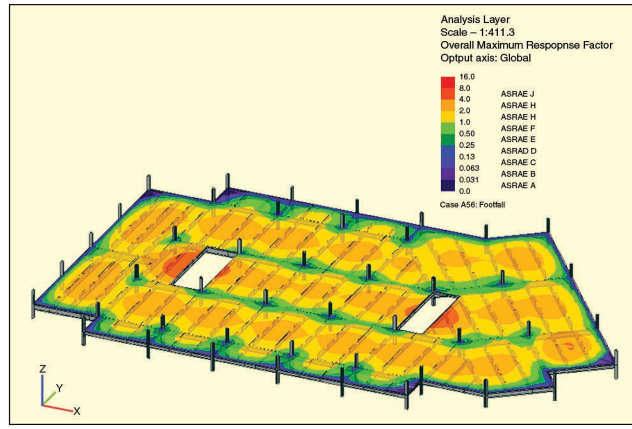

Figure 8. Finite element analysis of irregular floor frame.

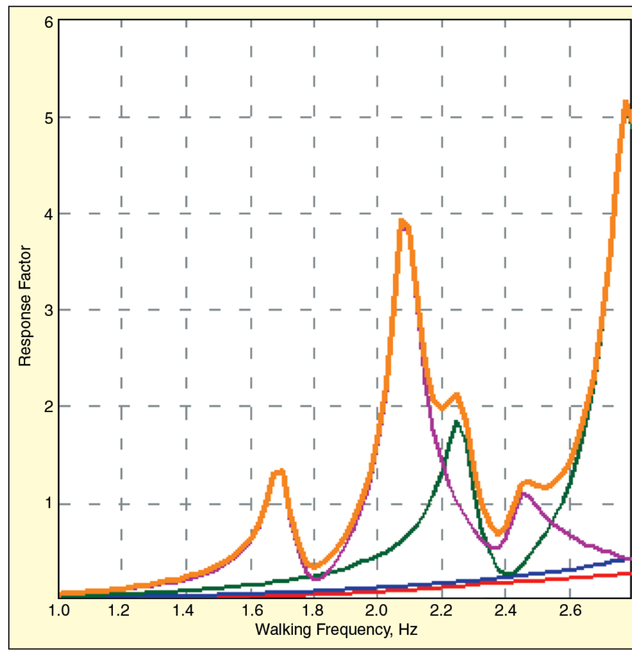

Figure 9. Response factor vs. walking frequency.

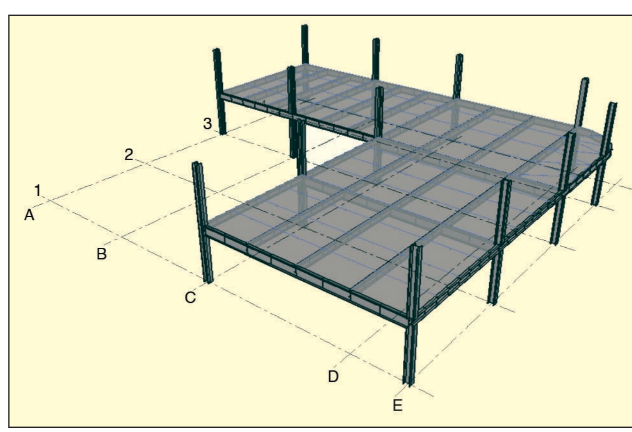

Figure 10. Composite frame.

sponse to determine sensible locations for sensitive equipment or activities. It also allows you to assess quickly the cost effectiveness of localized modifications to floor structures to meet the design criteria for humans or sensitive equipment. Also, because GSA is based on the first principles of structural dynamics, not empirical formulae to specific layouts, you can calculate the footfall response of any floor, bridge or other structure constructed of steel, composite, reinforced, pre- or post-tensioned concrete or timber.

Because you can define exactly where to examine a model, you can check particular areas, such as the effect of running down a corridor next to an operating theatre. You can also examine the

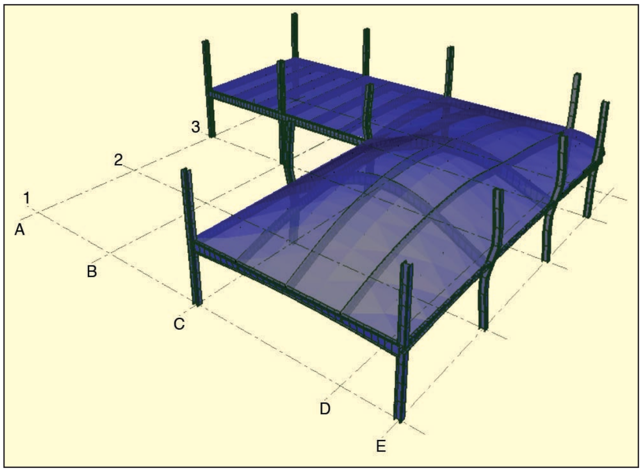

Figure 11 Mode 1 of composite frame.

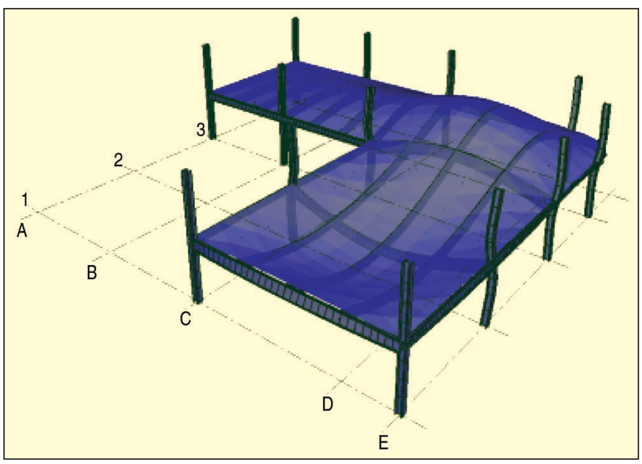

Figure 12. Mode 2 of composite frame.

resonance of a structure to vibrating machinery and dance loads using harmonic analysis, define your own dynamic load factors, or conduct a linear response analysis.

Dynamic Features of GSA

Modal Analysis: choice of eigenvalue analysis (modal, modal P-delta, Ritz, Ritz P-delta); chose number of vibration modes and start mode; include additional horizontal or vertical restraints; specify mass or derive mass from applied loads and self weight; and include stiffening effects of loads.

Footfall Analysis: check full model or selected areas; damping by user input values, modal damping or table; vary number of footfalls for resonant response; vary weight of walker; choice of excitation force methods (Arup/Concrete-Centre, Steel Construction, American Institute of Steel Construction, floor or stair); adjust minimum and maximum walking frequencies (footfall rates); detailed chart views of results; and contour plots of vibration levels on floor.

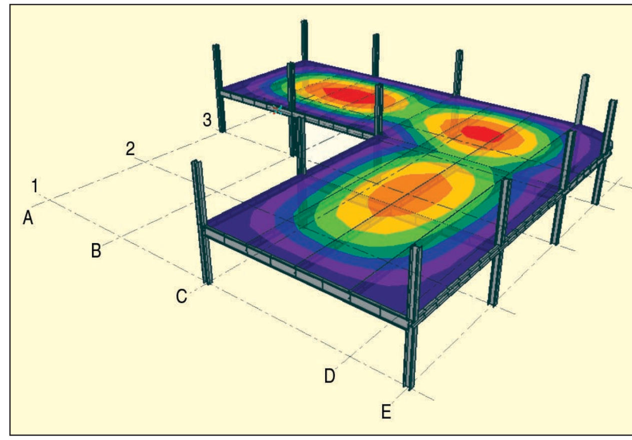

Figure 13. Footfall vibration response contours.

Other Vibration Analyses: harmonic analysis; response spectrum; linear time history; and periodic excitation (see Figure 9).

Step-by-Step Guide

1. *Sub-Frame Model* – Create a model of the floor in question using beams and/or shells as shown in Figure 10.
2. *Modal Analysis* – Run a modal analysis to find the modes up to the limit specified in the relevant design guide. These are typically 10 Hz, 15 Hz or twice the fundamental frequency (see Figures 11 and 12).
3. *Footfall Analysis* – Run a footfall response analysis as shown in Figure 13. Options include selection of harmonic or impulsive forces, the area of excitation, footfall rates and damping.

Summary

GSA Footfalls is for structural engineers who need to predict reliably the response of a structure to footfall-induced loading. It is a FEA program that provides the ability to analyze any structure for footfall response, whether steel or concrete, bridge, floor or stair. Unlike other programs or manual methods, it gives you the tools to assess your structure using the AISC, Concrete Centre and SCI methods.

References

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