Structural Practices

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Bad Vibrations

Designing for Floor Vibrations Caused by Concerts

By Charles DeVore, Ph.D., P.E.

*Charles DeVore is a Senior Engineer at Exponent, Inc. and is an Adjunct Professor at New York University where he teaches structural dynamics. He can be reached at **cdevore@exponent.com**.*

Concerts tend to create a worst case loading scenario for floor vibrations. Large groups of people are concentrated together, and the musical performance provides a synchronization signal for the audience to sway, bounce, or jump along with the music. This synchronized excitation creates a harmonic load on the floor which often can be near the natural frequency of the floor structure, resulting in resonance. When this happens, dynamic amplification occurs that may result in an unacceptably large acceleration response.

This article describes the process used to evaluate floor structures subjected to harmonic loading from a concert crowd. The International Organization for Standardization (ISO), American Institute of Steel Construction (AISC), and Concrete Reinforcing Steel Institute (CRSI) vibration standards are used to model harmonic loading parameters and estimate the peak acceleration response for various structural stiffness and damping parameters. With this data, the range of natural frequencies and damping ratios that meet the various acceptance criteria can be determined.

Structural Model

Floor structures are composed of a variety of structural systems with diverse materials and configurations. Using the materials, geometry, and loading, the floor structure can be analyzed in terms of its vertical vibration modes. For simple and regular structures, the individual spans can be separated into single degree of freedom (SDOF) models (independent systems with one dominant mode).

When the overall floor structure is separated into individual SDOF models, the dynamic model can be described as a set of independent mass-damper-spring systems. This dynamic model combines the effects of the distributed mass, damping, and stiffness into a simplified model. In this model, the mass is the tributary dead load supported by the beam divided by the constant of gravity. The damping is assumed to be viscous, characterized by a percentage of critical damping, and the spring behavior is equivalent to the vertical stiffness of the floor structure. Employing these parameters, the natural frequency of the SDOF model can be computed using the properties of the floor structure (dead load, bending stiffness, and span length). Likewise, the dynamic model can be expressed using the mass, natural frequency, and damping ratio if these parameters are determined through other means such as experimental testing.

Just like the properties of the continuous floor structure are represented by single parameter values, the crowd force can be represented by a simplified model. In this case, it is assumed that the crowd is distributed along the entire span of the beam and that the crowd acts in unison to apply a harmonic load. With this simplification, the crowd is described by a harmonic forcing function with an amplitude scale factor and an excitation frequency.

Design Factors

For floor vibrations, engineers are primarily concerned with the peak acceleration response of the structure. Each standard has a different way of calculating the peak acceleration response, but there are many similarities and commonalities.

This article separates the different components into three non-dimensional design factors: the crowd load factor, the structural amplification factor, and the harmonic load factor. These quantities are themselves functions of the properties of the structure and values given by the vibration standards. When used in the scope of this article, the peak acceleration response is given by the product of the non-dimensional design factors and g, the constant of gravity. The peak acceleration is commonly expressed in units of gravity, in which case the peak acceleration is just the product of the non-dimensional design factors.

Crowd Load Factor

The first design factor is the crowd load factor. This is simply the ratio of the static crowd weight divided by the total service load (dead load plus static crowd weight). For coordinated crowds in open areas, ISO 10137 specifies that a typical value of the static crowd weight is approximately

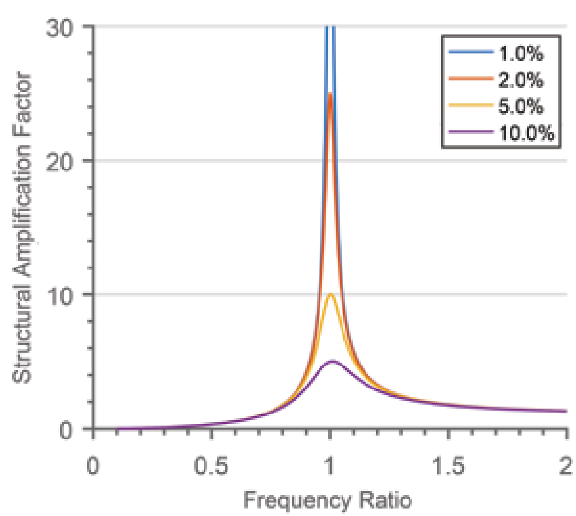

Figure 1. Structural amplification factor versus frequency ratio for various damping ratios.

11 pounds per square foot (psf) and the maximum value can be as high as 84 psf, using a 150-pound average person weight. AISC Design Guide 11, *Floor Vibrations Due to Human Activity*, assumes a static crowd weight of 31 psf for a seated concert. This standard does not provide a static crowd weight for standing room concerts. The CRSI vibration standard contains the same values as Design Guide 11.

As the static crowd weight is increased, the total dynamic mass of the structure changes which, in turn, causes the structure's natural frequency to decrease.

Structural Amplification Factor

The structural amplification factor is the response amplification from a harmonic load applied to a flexible structure. In this case, the crowd is providing a time-varying load at a particular frequency. You can see this behavior in *Figure 1*, which shows the dynamic amplification versus the frequency ratio (the crowd force frequency divided by the structure's natural frequency). Several values of the structure's damping ratio are shown and, as the frequency ratio approaches a value of 1.0, the dynamic amplification can be quite significant as a result of resonance (i.e., the harmonic load is applied at the natural frequency).

Designers are specifically interested in designing for the worst-case scenario, which occurs when the crowd force frequency is the same as the structure's natural frequency. Under this resonant condition, the structural amplification factor is a function of the structure's damping, as shown in *Figure 1*. For low values of damping (<2%), the structural amplification is over 25x, which indicates that even a low level of crowd force may cause a large acceleration response.

Most civil structures are lightly damped structures (<5%) which can result in high structural amplification factors. Also, the damping ratio used for vertical floor vibrations is often different from the damping ratio used for lateral seismic forces because vertical vibrations do not commonly result in inelastic deformations. ISO provides recommendations for design damping ratios based on the specific structural system used, with preliminary design values between 1.3–2.0%. AISC and CRSI allow for a damping ratio of 6% to be used for rhythmic activities because human occupants will act as shock absorbers which have an effect similar to damping.

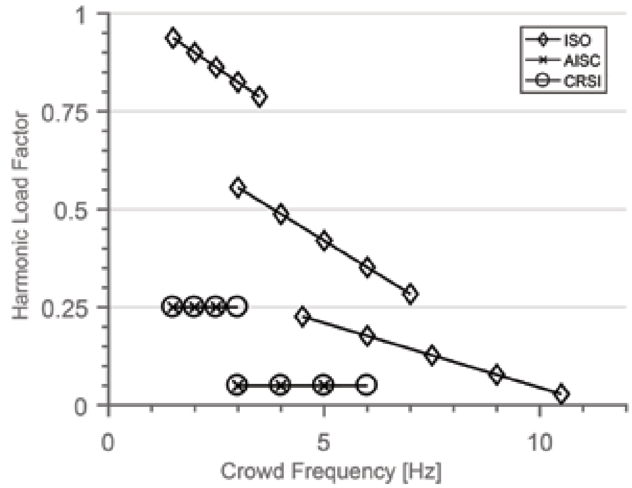

Figure 2. Harmonic load factor versus crowd excitation frequency for ISO, AISC, and CRSI vibration standards. Note that CRSI follows AISC identically, except for two additional data points.

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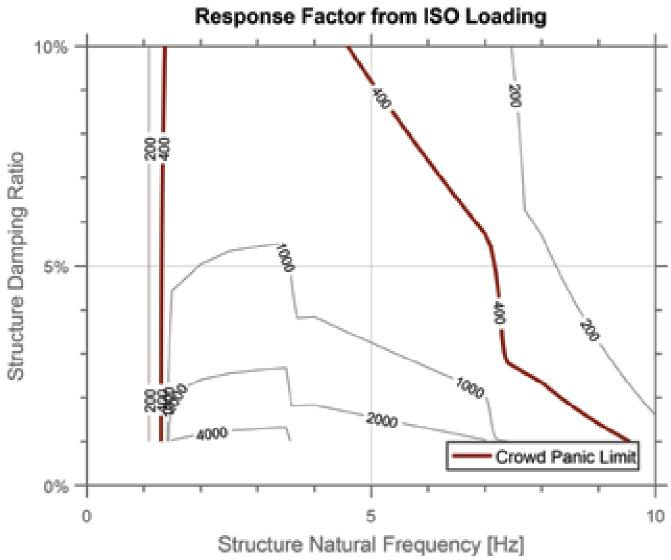

Figure 3. Response factor for various levels of structure natural frequency and damping ratio using ISO 10137 loading parameters.

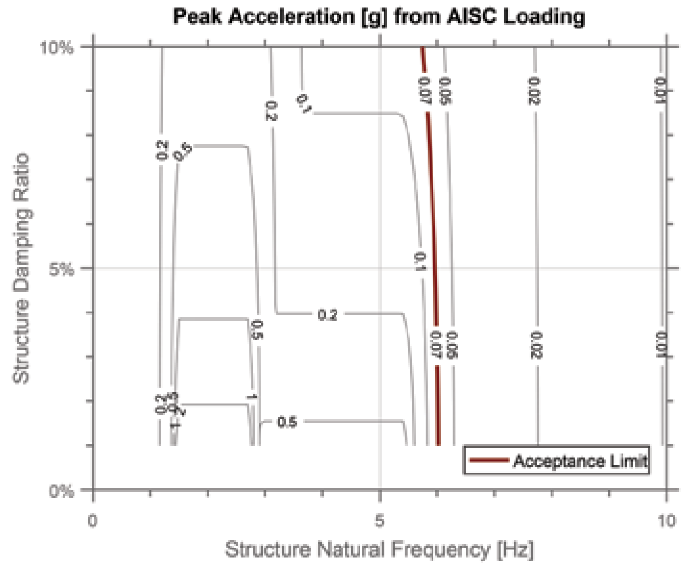

Figure 4. Peak acceleration for various levels of structure natural frequency and damping ratio using AISC Design Guide 11 loading parameters.

Harmonic Load Factor

The harmonic load factor is computed based on the design guides and takes into consideration the crowd load frequency to compute the load factor. ISO assumes that the crowd can apply a harmonic load between 1.5–3.5 Hertz (Hz), which is equivalent to 90–210 beats per minute (bpm). A frequency dependent factor is applied for the first three harmonics. The standard also includes a crowd coordination reduction factor to account for the relative ability of crowds to act in unison. AISC assumes that the crowd can apply a fundamental harmonic load between 1.5 Hz and 2.7 Hz (90–162 bpm) and applies a factor for the first two harmonics. CRSI uses the same values as AISC but extends the upper limit of the crowd frequency to 3 Hz (180 bpm). The harmonic load factor is shown for each standard in *Figure 2*.

Acceptance Criteria

Each design standard provides its own specific acceptance criteria. However, the two basic types of criteria are the peak acceleration and the response factor. The peak acceleration is the maximum acceleration associated with the harmonic crowd load and is the primary engineering design parameter of interest. The response factor relates to the intensity of vibration felt by human occupants and is defined as the number of times above the baseline of human perception to vibration, which is approximately 0.0005*g* for frequencies from 4 – 8 Hz. As a relative measure, the response factor is the ratio of acceleration response to the level of human vibration perception at a specific frequency.

Different acceptance criteria are used by different standards. At a basic level, the goal is to limit the intensity of the vibrations in the frequency range where humans are sensitive to such vibrations. As a result, each design standard provides similar restrictions even though different acceptance criteria are used.

Design Example

To illustrate the design guidance of each standard, a design example is offered where a floor structure with a 100 psf dead load is analyzed for a variety of stiffness and damping ratios. The results are presented in *Figures 3*, *4* and *5* for each design standard and using the recommended crowd and harmonic load factors.

ISO recommends that the static crowd weight is 11.5 psf for rhythmic activities in areas without seats. Assuming the structure has a natural frequency of 2.5 Hz and damping ratio of 6%, the peak acceleration response is 0.82*g*, and the response factor is 900. ISO recommends that the vibration should not exceed a response factor of 200 for crowd comfort or 400 for crowd panic, which is not met for this example. It is necessary to increase the natural frequency to 7 Hz or greater or increase the damping ratio to 10% and the natural frequency to 5 Hz or greater, to meet the crowd panic acceptance criterion.

AISC recommends a static crowd weight of 31 psf for a lively concert with fixed seating but does not provide guidance for standing crowds. The peak acceleration is estimated to be 0.51*g*, and the response factor is 560, assuming the same structure as before. AISC recommends that the peak acceleration not exceed 0.07*g* for rhythmic activities, which is not met for this example. It is necessary to increase the structure's natural frequency to 6 Hz or greater to meet the criterion.

CRSI recommends the same static crowd weight as AISC and calculates the same peak acceleration response. However, CRSI recommends an acceptance limit of 0.05*g*, which is also not met for this example. It is necessary to increase the structure's natural frequency to 7 Hz or greater to meet the criterion.

Design/Remediation Options

There are three basic solutions available to the structural engineer to solve a floor vibration problem: change the natural frequency, increase damping, or add a structural control device.

The first option is to change the natural frequency of the structure so that the structure's response is outside the frequency range of the crowd's excitation. The structure's natural frequency can be raised by increasing the floor's stiffness or lowered by increasing the floor mass (dead load). Theoretically, both options can achieve the goal of limiting peak accelerations to an acceptable level. However, in practice, adding mass to achieve a low enough natural frequency that is outside the crowd's excitation range can result in a structure that does not meet deflection or strength requirements. As a result, structural modifications usually aim to add stiffness with the goal of raising the structure's natural frequency above the crowd excitation frequency's upper range.

The second option is to increase the damping in the structural system. As previously discussed, damping is difficult to estimate, and there can be mixed guidance as to what damping ratio is appropriate for a specific scenario. However, while it may be difficult to estimate the structure's damping ratio

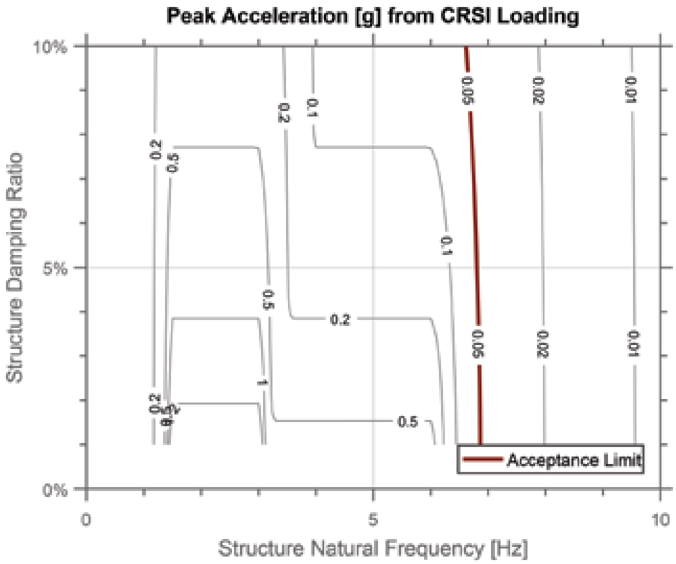

Figure 5. Peak acceleration for various levels of structure natural frequency and damping ratio using CRSI vibration standard loading parameters.

accurately, increased damping has a positive effect by decreasing the peak response at resonance. As a result, a structural engineer can design the support structure to include supplemental damping as a way to increase the total damping of the system. This can be accomplished by using linear damping devices as part of the support structure.

The third option available is to utilize a structural control device such as a tuned mass damper (TMD) or an active mass damper (AMD). A TMD is a secondary mass that is suspended from the floor by a system of springs and linear damping devices. The mass, damping, and stiffness of the TMD are specifically designed to tune the secondary mass to a frequency near the structure's natural frequency so that it provides out of phase forces to decrease the total response of the floor. An AMD is like a TMD except that an actuator is used to control the motion of the secondary mass based on the measured structural response, allowing more efficient use of a smaller mass over a wider range of frequencies. Both options can be effective for retrofit as they take up a small amount of space and do not require extensive structural modifications.

Conclusions

Concerts often provide a worst-case loading scenario for flexible floor structures. Audience members can bounce, sway, and jump along with the music in such a way that the crowd is synchronized to apply a harmonic load at the same frequency as the music's tempo. When this excitation frequency corresponds to the natural frequency of the floor structure, significant structural response can occur due to resonance, which may result in unacceptable vibration levels and affect occupants' comfort.

To prevent unacceptable floor vibrations from occurring during concerts, structural engineers should ensure that the vertical, natural frequency of the floor structure is above 7 Hz. Where this is not feasible, structural engineers can decrease the vibration intensity by adding supplemental damping or including a structural control device.▪

The online version of this article contains references. Please visit **www.STRUCTUREmag.org**.

References

1. ISO (International Organization for Standardization). 2007. *Bases for Design of Structures – Serviceability of Buildings and Walkways Against Vibrations*. ISO 10137:2007(E), Geneva, Switzerland.
2. Murray, T.M. et al. 2016. *Vibrations of Steel-Framed Structural Systems Due to Human Activity*. Steel Design Guide Series, 2nd Ed., American Institute of Steel Construction, Chicago, IL.
3. CRSI (Concrete Reinforcing Steel Institute). 2014. *Design Guide for Vibrations of Reinforced Concrete Floor Systems*. Schaumberg, IL.