Engineering Notes

Dynamic Loads on Dance Floors

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Building structures are designed for static, immobile loads. For design purposes, even wind and seismic loads are usually considered static. However buildings are exposed to genuine dynamic forces. Examples are vibrating machinery, blast loads, impact forces, and dancing. A structure responds differently to dynamic forces than to static loads. Sometimes the difference can be dramatic--even catastrophic.

The conversion of old downtown buildings into dance clubs has been a source of concern. In Springfield, Missouri, some venues have suffered damage and required repairs. This has sparked interest in how structures respond to dancing loads.

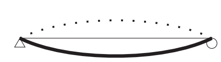
Dance floors are similar to aerobic exercise floors. Basically, its just people jumping up and down. The beat of the music and people's natural jumping pace is approximately 150 beats per minute. Now this is not a 100% coherent load, meaning some people (engineers especially) are dancing out of sync. Mathematically, this type of loading can be easily represented as a sinusoidal function.

The maximum intensity of the load is not immediately obvious. It should be higher than the static weight of the occupants. The International Building Code require 100 psf for this type of assembly area and already includes an allowance for ordinary impact forces.

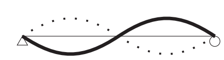
The average weight per person is about 160 lbs. (remember that most patrons are in their 20's!). The static 100 psf load is equivalent to one person in each 15" square box. That's pretty packed. Code occupancy calculations are based on one person per 5 square feet. Therefore, I consider it adequate to use an applied forcing function of 100 psf maximum intensity at a frequency of 2.5 Hz (150 beats per minute).

Natural Frequency and Resonance

Every object has a natural frequency of vibration. In fact, there are an infinite number of higher modes of vibration that are integer multiples of the first mode.



First Mode
of Vibration



Second Mode
of Vibration

Skipping the derivation, the natural frequency of a simple-span beam is:

$$\omega = \sqrt{\frac{EI}{mL^4}}$$

Resonance is when the applied load closely matches this natural frequency. In this case, the amplitude (maximum deflection) and the corresponding internal stresses can continue to grow until failure. It is critically important that the applied dancing force not resonate with any of the structure's natural frequencies.

Equation of Motion

Damping and transient vibrations are not relevant to this analysis. Only the steady-state vibrations are of interest. The equation of motion for the beam becomes:

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$$EI\frac{\partial^4 v}{\partial x^4} + m\frac{\partial^2 v}{\partial x^2} = P_0 \sin \Omega t$$

The terms should be recognizable. This non-homogeneous differential equation can be solved by separation of variables and modal superposition. It's a rather involved process.

Dynamic Amplification

Intuitively, one would expect that a single factor could be derived that could be multiplied by the static shear and moment--like an impact factor. However, this is not the case. The reason is that the shape of the beam under dynamic load is not like the static shape.

Static Deflection

Dynamic Deflection

A dynamic amplification factor can be calculated for each mode of vibration. This is a fairly simple process, and for a generalized single degree of freedom system, the DAF is:

$$\mathrm{DAF} = \frac{1}{\left(1 - \left(\frac{\Omega}{\omega}\right)^2\right)}$$

For the dance floor analysis, several modes of vibration need to be considered. The first mode contributes the most to the deflected shape, and the effects of subsequent modes decay rapidly. It is possible that the dancing load could excite some of the higher modes. This needs to be considered. For a simple span beam, only odd numbered modes contribute. This is not the case for other boundary conditions. In its final form, the equation for the deflection of a simple-span beam is:

$$v_{(x,t)} = \sum_{n=1}^{\infty} \left[\frac{4P_0}{\omega_n^2 mn\pi \left(1 - \left(\frac{\Omega}{\omega_n}\right)^2\right)} \right] \left[\sin \frac{n\pi x}{L} \right]$$

From this equation, the shear and bending moments can be derived.

Conclusion

For normal spans, dynamic amplification is not likely to be a problem. But it is a condition that needs to be evaluated on a case-by-case basis. Each joist, girder, or header responds differently to the load. It is difficult to predict the response.

I recently analyzed a low-mass, timber-framed floor system. On spans ranging from 10 to 25 feet, stresses increased from 10% to 20% over static.

Most downtown venues are timber-framed. The National Design Specification for Wood Construction permits allowable stresses to be increased for short-duration loads. This load duration factor is 1.6 for wind/earthquake loads and 2.0 for impact. Since the dancing force is cyclical, I typically use the 1.6 factor as being more conservative. The allowable stress increase usually exceeds the dynamic amplification factor. Thus, static loads frequently govern the dance floor design.

Connections are critical. Reactions are amplified, but increasing the allowable stresses is usually not permitted. Deterioration of old structures combined with poor workmanship during myriad remodels is the most serious concern to me. Nails rusted away and crumbling masonry can only be discovered by careful observation during construction.

The full derivation of the dynamic analysis is available on our website at www.wsengineer.com. This analysis gives equations for finding the deflection, shear, and bending moment at any point along the beam's span. It also provides the basis to calculate other span conditions and load configurations.

- *Robust connections between joists-to-girders; girders-to-columns; and floor structure to bearing walls is most important.*
- *Only certain spans will be sensitive to dancing loads.*

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