FLOOR Vibration AND THE ELECTRONIC OFFICE

By Thomas M. Murray, Ph.D., P.E.

Serviceability concerns are a growing issue for many designers. Modern design specifications, coupled with today's stronger steel, allow for lighter sections when strength is the governing factor. However, in most offices—especially today's electronic offices—vibration requirements are often more important.

Virtually paperless, the electronic office is lighter and therefore provides less inherent damping than conventional offices with large file cabinets, heavy desks and bookcases. Adding to the problem are modern floor layouts, which often are very open, with few fixed partitions, widely spaced demountable partitions, or, in some cases, no partitions whatsoever. Finally, atrium type areas are more common and curtain wall construction is less stiff, both of which can increase floor liveliness.

As a result, the structural engineer must pay much more attention to floor serviceability and must carefully critique the floor vibration analysis procedure that is being used—whether the analysis is being performed by hand or with a computer program. Fortunately, the procedures for designing comfortable offices are available. This article provides information on evaluating modern floor systems supporting electronic offices.

HISTORICAL PERSPECTIVE

Analysis procedures for floor vibration have two components: a human tolerance criterion and a method to predict the response of the floor system. Analysis procedures are calibrated by measuring the response of floor due to a standard impact and then recording the response of the building occupants. Adjustments are then made to effect good results. Obviously, human perception is subjective and any procedure cannot ensure that no one will ever complain about floor movement. The aim of the calibration procedure is to be sure that movement of the floor due to human activity will not annoy the great majority of the floor users.

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Since the mid-1960s, four procedures have been commonly used in North American. The first was the Modified Reiher-Meister scale proposed by Professor Kenneth H. Lenzen. This scale has regions of "perceptibility"—from "not" to "strongly" perceptible. The engineer is required to calculate the first natural frequency and amplitude due to a heel-drop impact and then from the scale determine if the proposed floor system is satisfactory or not. The procedure does not include damping. However, because the procedure was calibrated between about 1966 and 1970 when floor construction and occupancies were very different than what is found today, between 4% and 8% critical log decrement damping is inherently assumed.

In the early '70s, both the Murray Criterion and a Canadian Standards Association procedure were proposed. Both of these procedures include floor system damping. The Murray Criterion states that a floor system is satisfactory if

$$D > 35\,A_o\,f_n + 2.5$$

where D is the required log decrement damping in the floor system in percent of critical damping, Ao is the amplitude in inches due to a heel-drop impact, and fn is the fundamental natural frequency of the floor system. This procedure was calibrated with data gathered in the late 1960s and early 1970s, again with steel framing and office occupancies very different than are found today. Generally, if the required damping is less than 4-4.5% of critical log decrement damping, the floor system for a conventional office will be satisfactory. However, this level must be adjusted down if the procedure is used for office buildings constructed today.

Because of the construction and office configurations used to calibrate them, these procedures are not recommended for evaluating floor systems designed using LRFD with A572 Gr 50 steel and supporting electronic offices.

RECOMMENDED PROCEDURE

The 1997 AISC Design Guide Floor Vibrations Due to Human Activity has a new procedure for evaluating floor designs. The procedure is based on avoiding resonance from walking. The criterion is satisfied if

$$a_p/g = 65 \exp(-0.35 f_n)/bW < a_o/g$$

where ap/g is the predicted acceleration ratio due to human activity, is the modal damping ratio for the floor system, W is the equivalent floor panel weight, and ao/g is the acceleration limit taken as 0.5%g for offices. This procedure was calibrated using measurements made in buildings constructed in the 1980s before the advent of the electronic

Useful References

"Minimum Design Loads for Buildings and Other Structures", ASCE Standard 7-93, American Soceity of Civil Engineers, New York, NY, 1993.

Murray, Thomas M., David E. Allen and Eric E. Ungar, "Floor Vibrations Due to Human Activity", Steel Design Guide Series 11, American Institute of Steel Construction, Chicago, IL, 1997

FLOORVIB2, User's Manual, Structural Engineers, Inc., Radford, VA, 1997

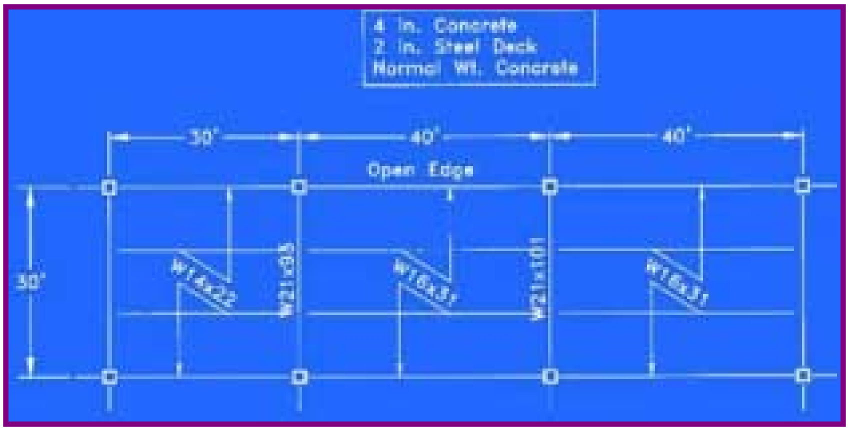

Figure 1: Mezzanine are with 2" of normal weight concrete on a 2" metal deck for a total floor depth of 4"

office. However, the procedure is quite general and allows the evaluation of other than the standard bay in a sea of standard bays. Effects of adjacent bays, including different geometry, as well as mezzanine construction, can be accounted for in the calculations.

The Design Guide recommends that the modal damping ratio, b, be taken as "0.05 for offices with full height partitions between floors, 0.03 for floors with non-structural components and furnishings, but with only small demountable partitions, typical of many modular office areas, and 0.02 for floors with few non-structural components (ceilings, ducts, partitions, etc.) as can occur in open work areas and churches". These damping values will seem very low to engineers experienced with heel-drop based procedures. The reason is that modal damping is associated only with energy loss; whereas log decrement damping, which is used with heel-drop criteria, is associated with both energy loss and transmission of vibrational energy to other structural components. Modal damping is approximately two thirds to one half of log decrement damping. For the electronic office, the modal damping ratio should be taken as 0.02 – 0.025.

The criterion requires a close estimate of the natural frequency of the floor system under everyday loadings. The Guide recommends that the fundamental natural frequency of the floor system be calculated using where b and g are the beam (or joist) and girder deflections due to the weight supported. The dead and live loads used to calculate these deflections will significantly affect the estimated natural frequency. Strength design dead and live loads should not be used for vibration analysis. A floor system will not exhibit annoying vibrations when fully loaded; problems occur when the system is lightly loaded. (For example, a number of problem floors have been reported in schools, not during the day when the children were there, but after school when only one or two people were in the classroom.) The Guide recommends the dead load should be estimated as 4 psf plus the weight of the floor deck and supporting members, unless a heavy ceiling and/or unusual ductwork is present. For live load, the Guide recommends 11 psf for offices and 6 psf for residences. These values are found in an Appendix of ASCE-7-95 "Minimum Design Loads for Buildings and Other Structures" and were determined by the National Bureau of Standards during calibration of LRFD. This calibration was done during the late 1970s when electronic offices were only just beginning to be envisioned. The live load for an electronic office may be less than 7 psf, depending on the number of demountable partitions and desk spacing.

EXAMPLES

The following examples are used to illustrate the concepts discussed above.

Example 1. The partial framing plan shown in Figure 1 is a mezzanine area of a proposed building. The proposed floor deck is 2 in. of normal weight concrete on 2 in. steel deck (total depth is 4 in.). The composite design provisions of the AISC LRFD Specification and A572 Gr. 50 steel were used. The floor will support an office with closely spaced demountable partitions. All of the building occupants use computers; paper record storage is minimal; and the estimated actual live load is 7 psf.

The floor framing was analyzed using the software FLOORVIB2 and the Modified Reiher-Meister Scale, the Murray Criterion, and the procedure in the 1997 AISC Design Guide. The former two procedures do not have provisions to account for the additional flexibility because of the mezzanine construction; thus, results from this analysis will tend to be unconservative. A dead load of 4 psf plus the weight of the floor deck and supporting members and a live load of 7 psf were used in the analysis.

The floor framing plots in the "Slightly Perceptible" range of the Modified Reiher-Meister Scale, which means that the floor framing satisfies that criterion. However, the implied damping in this criterion is 4%-8%, which does not exist in the floor system and, therefore, the evaluation is in error.

Using the Murray Criterion, the required damping is 4%. This requirement is usually satisfied for conventional offices. But, for this floor system, the loading is very light and the damping probably does not exceed 3% and it is a mezzanine.

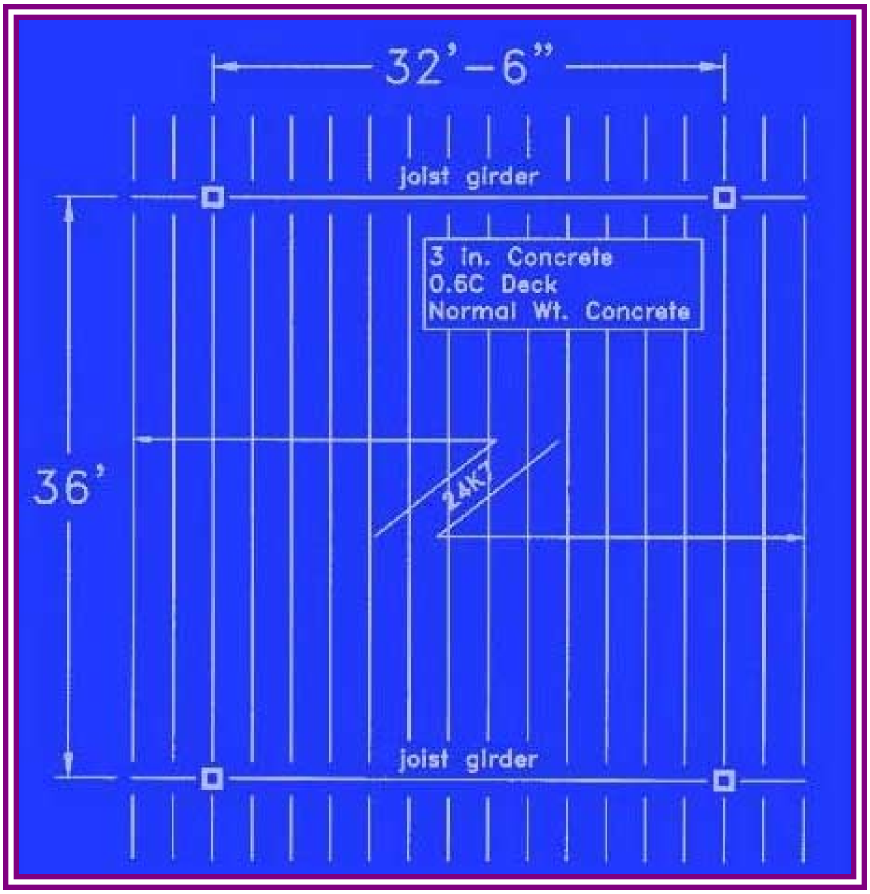

Figure 2: Building housing electronic offices with no fixed partitions and only a few demoutable partitions; workstations are widely spaced.

The AISC Design Guide procedure predicts a peak acceleration of 1.05%of gravity for 2.5% modal damping. The beam, girder, and combined mode frequencies are 4.1 Hz, 5.4 Hz and 3.2 Hz, respectively. The tolerance acceleration criterion for offices is 0.50% of gravity. Obviously, the system does not satisfy the criterion and occupant complaints would be expected.

The Design Guide recommends that “where the edge member is a joist or beam, a practical solution is to stiffen the edge by adding another joist or beam, or by choosing an edge beam with moment of inertia 50 percent greater than for the interior beams”. When either option is used, the bay is analyzed as an interior bay. Increasing the edge beam to a W16x45 and reanalyzing as an interior bay, the predicted acceleration is 0.75% gravity, which is still not acceptable.

Since the natural frequency of the beams is lower than the girder, the beams should be stiffened before stiffening the girders. If the floor beams are increased to W21x57 with a W21x83 edge beam, the predicted peak acceleration is 0.48% gravity. This solution requires a significant increase in steel weight; however, part of the cost is offset because composite construction would not be required for strength.

An alternate solution is to increase the floor deck depth to 5 in. by adding 1 in. of concrete. With W18x40 beams, a W21x50 edge beam, and W21x101 girders, the predicted acceleration is 0.50% gravity, an acceptable solution.

Example 2. The partial framing plan in Figure 2 is for a proposed office building which will house electronic offices. There will be virtually no paper at the computer workstations and the workstations will be widely spaced. No fixed partitions and few demountable partitions are anticipated. The proposed floor is 3 in. of normal weight concrete on 0.6C deck. The proposed framing plan is shown in Figure 2; the framing meets ASD stress criteria and the live load deflection is less than span/360.

The floor framing was analyzed using the software FLOORVIB2 and the Modified Reiher-Meister Scale, the Murray Criterion, and the procedure in the 1997 AISC Design Guide. A dead load of 4 psf plus the weight of the floor deck and supporting members and 7psf live load was used for the analysis. The area and moment of inertia of the joist girder were taken as 17.3 in2 and 3585 in.4, respectively.

The amplitude and frequency plot in the lower half of the “Distinctly Perceptible” region of Modified Reiher-Meister scale. Therefore, the floor is considered acceptable by this procedure. As in Example 1, the inherent damping in the procedure is assumed to be 4-8% of critical log decrement damping which would not be realized for the conditions given

The required damping from the Murray Criterion is 4.5%. Damping of this magnitude would not be realized and redesign is necessary.

Using a modal damping value of 2.5%, the predicted peak acceleration from the AISC Design Guide procedure is 0.90% gravity which exceeds the criterion limit of 0.50% gravity and redesign is necessary. The joist, joist girder, combined mode frequencies are 5.7 Hz, 6.1 Hz, and 4.2 Hz, respectively.

Increasing the concrete depth to 5 in., the deck height to 1.0 in., the joists to 30K7, and the joist girder properties to an area of 21.4 in.2 and moment of inertia to 4440 in.4, results in a predicted acceleration of 0.52% gravity. This acceleration value is marginally acceptable for the proposed office building.

SUMMARY.

In summary, electronic offices are lighter and have less damping than traditional offices in the past. Floor vibration provisions developed and calibrated in the 1960s and 1970s are generally not valid for office floors constructed in the 1990s. Instead, it is recommended that engineers follow the design procedure in the 1997 AISC Design Guide 11 for new office buildings that will house electronic offices.

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