Walking Criterion for Floor Vibration Analysis.

Floor Vibration Due to Human Activity with the RAM Structural System

AISC/CISC Design Guide 11, by L. Allen Adams, S.E. and Thomas M. Murray, Ph.D., P.E.

Executive Overview

The **RAM™ Structural System** is now linked to **FloorVibe**, a software product developed by Tom Murray, Structural Engineers, Inc., Radford, Virginia. Using FloorVibe, a designer can analyze floor framing for Walking and Rhythmic Excitations and for suitability to support Sensitive Equipment. The calculation procedures and criteria are from the AISC/CISC Design Guide 11, Floor Vibrations Due to Human Activity (DG11), which has become the de facto standard for floor vibration analysis in North American.

Art, in the form of engineering judgment, is necessary to correctly apply the criterion for Walking Excitation in Chapter 4 of DG11. Consequently, it is very difficult, if not impossible, to develop software that can consistently and reliably apply the criterion correctly without human input, except for the simplest of framing plans. The framing plan shown in Figure 1 is a real example of how adjacent framing can affect floor response. The structural engineer reported that during design they checked typical Bays A, but did not consider Bay B. Upon occupancy, complaints were immediately received from office personnel in Bay B. The predicted acceleration for Bays A, assuming paper offices, is 0.5%g and for Bay B, 0.63%g. The former just satisfies the DG11 criterion and the latter does not. Why? The Floor Length, as defined in DG11 for the Bays A is 81 ft and for Bay B is 48.5 ft. Simply looking at individual beams and girders or individual bays is not sufficient; effects of adjacent framing must be considered.

The purpose of this White Paper is to explain and demonstrate with examples how to make good engineering judgments when analyzing office and residential floors for vibration, particularly with complex framing. It is assumed that the reader is familiar with Design Guide 11.

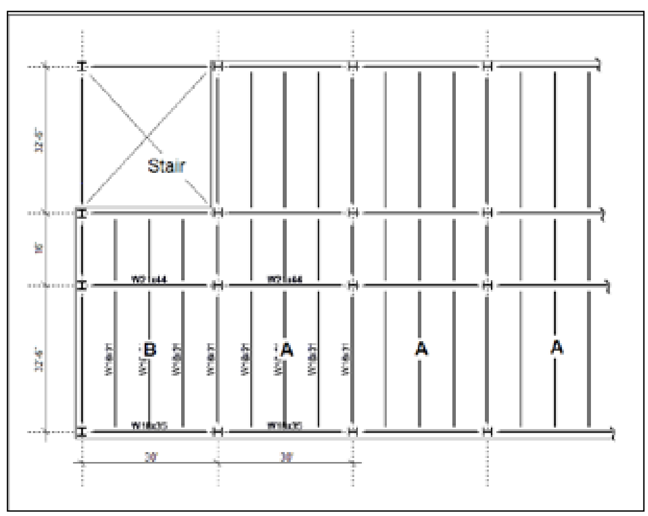

Figure 1: Example Framing

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Bay Classification

The RAM Structural System identifies bays as 'Perfect Bays', 'Imperfect Bays', or 'Irregular Bays'. A Perfect Bay "perfectly matches" DG11 bays, that is the bay is rectangular, all beams are identical, beam spacing is uniform, etc. Bays with some minor deviations may still be categorized as Perfect Bays if those deviations are "close enough" to Perfect, that is, within some tolerances. An Imperfect Bay is one for which the bay generally exhibits characteristics of a Perfect Bay but has one or more geometric features that deviate from such. An Irregular Bay is one that deviates significantly from the bays described in DG11. Also, miscellaneous beams that are not part of a bay are designated as 'Irregular'.

Acceptance Criteria

In DG11, it is recommended that office residential and similar floor systems satisfy:

$$\frac{a_p}{g} = \frac{P_o \exp(-0.35 f_n)}{\beta W} \leq \frac{a_o}{g} \quad (1)$$

where a_p / g is the predicted peak acceleration of the floor due to walking as a fraction of gravity, a_o /g is the tolerance acceleration for the environment, P_o is a constant force representing the excitation, f_n is the fundamental frequency of the floor system, ß is the modal damping in the floor system, and W is the combined mode effective weight that is determined from the weight of so-called beam and girder "panels". P_o is 65 lb for office floors, and a_o /g is 0.005g or 0.5%g for office environments. The terms f_n and W require an estimate of the actual live loading, but the predicted peak acceleration is not particularly sensitive if the estimate is reasonable. The Design Guide recommends 11 psf for paper offices and 6-8 psf for electronic offices, which have been found to be adequate. Damping, ß, must also be estimated. The Design Guide recommends between 0.02 and 0.05 (2% to 5% of critical damping), depending primarily on the presence of nonstructural components such as partitions, for floors supporting quiet areas like offices, churches, and residences.

Frequency.

The frequency, fn, is the fundamental frequency of the system, not that of an individual beam or girder. DG11 recommends the use of a form of Dunkerley's equation to estimate the frequency of a rectangular bay,

$$f_n = 0.18 \sqrt{\frac{g}{\Delta_b + \Delta_g}} \quad (2)$$

where Δ_b and Δ_g are the beam and girder deflections due to uniformly distributed actual expected loads, not design loads, respectively. DG11 does not have provisions for non-rectangular bays as they are too complex for manual calculations. Fortunately, most irregular bays rarely if ever exhibit vibration problems. For bays with a low skew angle, say less than 10-15 degrees, using the average beam or girder span, as appropriate, may be an acceptable approximation.

When calculating Δ_b and Δ_g, full composite action should always be assumed unless the floor deck is not in direct contact with the top flange or chord of the supporting member. Vertical amplitudes of 0.004-0.010 in. cause annoying floor vibrations. Such small deflections result in very small shear forces at the flange or chord and floor deck interface and therefore the member will vibrate as if a fully composite cross-section. If the floor deck is not in continuous contact with the supporting member, for example a girder supporting joists, full composite action is not achieved. DG11 and FloorVibe have procedures for determining the effective moment of inertia for such members.

When analyzing floors supported by trusses, shear deformation of the web must be considered. If joists or joist girders are the supporting members, both web shear deformations and eccentricity at the chord panel points must be considered. Again, DG11 and **FloorVibe** have procedures for both.

Modal Damping.

Lightly damped, modern floors are sensitive to vibration because of possible resonance with a multiple of the walking pace. Resonance can occur when one, two, or three times the walking pace is at or near the fundamental frequency of the floor system and the damping is low. (Multiples of the walking pace are referred to as "harmonics" in DG11). Consequently, the predicted peak acceleration, ap/g, is very sensitive to the damping value.

Offices can be classified depending on the fit out, as (1) with dry wall partitions, (2) a paper office, or (3) an electronic office. The corresponding recommended damping values are 5%, 3%, or 2-2.5% if there is typical ductwork and suspended ceiling below the floor. If ductwork or a suspended ceiling is not present, the damping values should be reduced by 0.5-1%. Care is needed when assessing damping provided by dry wall partitions. If the partitions are only above the girder(s), their contribution to damping is not significant; if the dry wall partitions are in the bay and perpendicular to the beam span, their contribution is very significant and the 5% damping estimate is reasonable. A paper office is an office with demountable partitions, desks, file cabinets, etc., as in a typical engineering office. An electronic office is one with very light and widely spaced furniture, no file cabinets, etc., as in a call center.

Figure 2 is a photograph of a paper office. There are ductwork and a hung ceiling below; therefore a damping value of 3% is justified. Figure 3 shows an electronic office, again with ductwork and hung ceiling below. Therefore the damping is estimated to be between 2 and 2.5%.

Figure 2: Photograph of a Paper Office

Figure 3: Photograph of an Electronic Office (courtesy of Steelcase

If the predicted acceleration is say 0.4% of gravity based on an estimate of 3% damping assuming a paper office, the actual acceleration may be as high as 0.6% of gravity if the actual damping is only 2% as for an electronic office. The 0.4% value predicts an acceptable floor; the 0.6% value represents an unacceptable floor. Complaints will not be received if the fit-out is a paper office, but complaints are expected if it is an electronic office. So, what should the design engineer do? First determine the intended office fit-out. If known, estimate the damping ratio. If the intended fit-out is other than electronic offices, warn the architect and owner that a future change in fit-out may result in occupant complaints. If office fit-out is not known, discuss with the owner consequences of damping estimates. Using tolerance criterion recommended in the Design Guide, the required damping can be back calculated for a proposed framing scheme and an acceptable office fit-out determined. Once a decision has been made, a change in office fit out that reduces damping should be considered the same as a change in fit out that results in an increased live loading, e.g. retrofit may be required. The bottom line is that assumed fit out can affect initial cost as well as possible retrofit costs over the life of the building.

Combined Mode Effective Weight.

The combined mode effective weight, W, in Equation (1) is obtained from

$$W = \frac{\Delta_b}{\Delta_b + \Delta_g} W_b + \frac{\Delta_g}{\Delta_b + \Delta_g} W_g$$

(3)

where Wb and Wg are the beam and girder panel weights from

$$W_b = C_j B_j L_j$$

(4)

$$W_g = C_g B_g L_g$$

(5)

where C_j and C_g are coefficients, L_j and L_g are the beam (joist) and girder spans, and B_j and B_g are the effective panel widths that are determined from anisotropic plate theory.

The coefficients C_j and C_g have the following definitions in DG11:

C_j = 2.0 for joists or beams in most areas

= 1.0 for joists or beams parallel to an interior edge

C_g = 1.6 for girders supporting joist connected to the girder flange (e.g. joist seats)

= 1.8 for girders supporting beams connected to the girder web

FloorVibe defaults to C_j = 2.0 as "in most areas" means in bays where there is an adjacent bay, a wall, or relatively stiff external cladding support along the edge beam(s). For a balcony, mezzanine, or when the exterior cladding connection is very flexible, the "Mezzanines" option in **FloorVibe** should be invoked by the user.

FloorVibe defaults to C_g = 1.6 if joists are specified and to 1.8 for any other type of member. If the bottom chords of joists are extended and connected before the concrete is poured, C_g = 1.8 may be justified. The higher value of C_g is obtained by checking "Joist Extended Bottom Chords".

The effective beam and girder panel widths, Bj and Bg are limited to 2/3 of the floor width or 2/3 of the floor length, respectively. Determining the floor width and floor length requires judgment on the part of the designer.

Floor Width represents the portion of the floor perpendicular to the beam span that is associated with the fundamental frequency (mode) of the beams. When floor framing is excited, there is an associated mode shape. Figure 4 shows a typical fundamental mode shape for a series of beams supported by a wall, that is, a rigid support. A finite element analysis of this system would show movement of every beam, regardless of the width of the framing. Because of energy dissipation, such movement will not occur in a real structure. The provisions for determining B_j take into account this fact with

(6) $$B_j = C_j(D_s/D_j)^{1/4}L_j \leq 2/3 \times \text{Floor Width}$$

For a series of perfect bays, the Floor Width is the sum of the supporting girder spans perpendicular to the beam span. Non-perfect framing will reduce the Floor Width and engineering judgment is required.

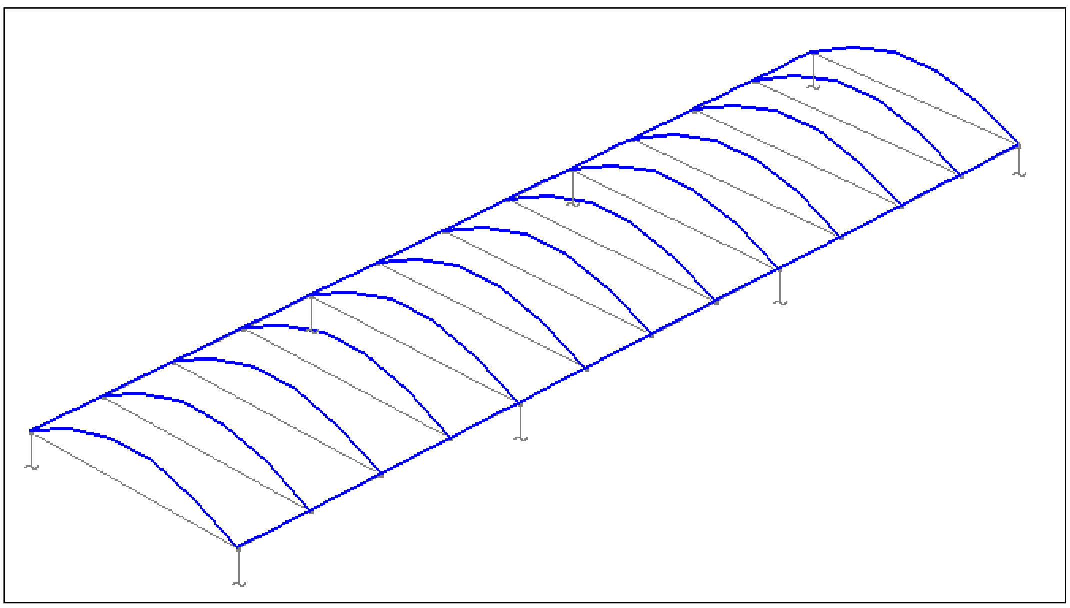

Figure 4: Mode Shape Associated with Beams from a Finite Element Analysis

Similarly, there is a mode shape associated with girder movement as shown in Figure 5 and for the same reasons as for beams the Floor Length is limited by

(7) $$B_g = C_{gj}(D_{js}/D_g)^{1/4}L_{gj} \leq 2/3 \times \text{Floor Length}$$

For a series of Perfect Bays, the Floor Length is the sum of the beam spans perpendicular to the girder spans of the bay being analyzed. Again, non-perfect framing will reduce the Floor Length and engineering judgment is required.

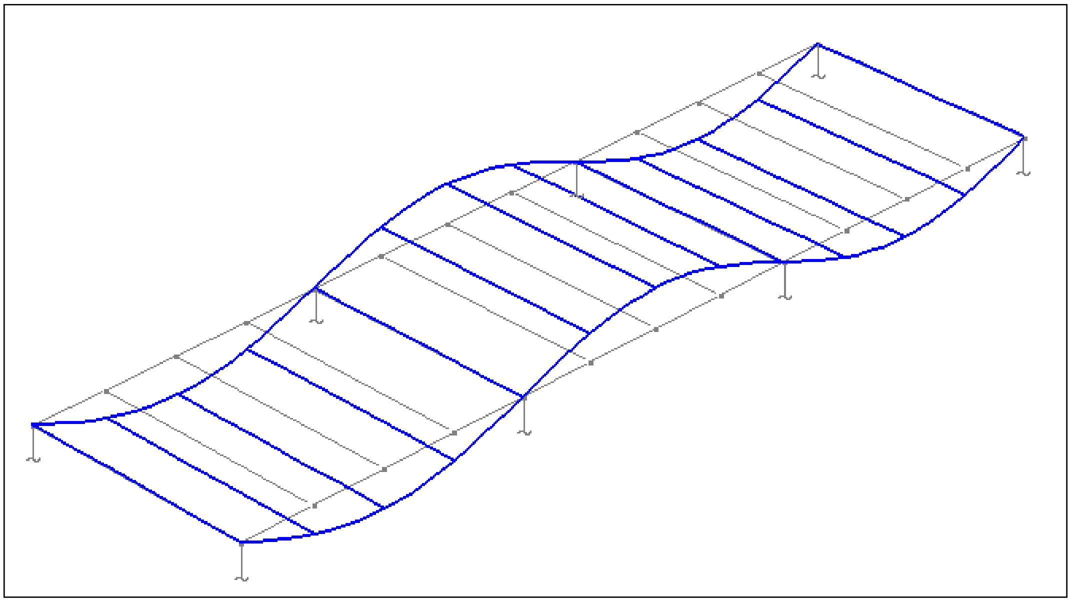

Figure 5: Mode Shape Associated with Girders from a Finite Element

Bays in the RAM Structural System

The floor framing shown in Figure 6 is used to illustrate how Floor Width and Floor Length are determined for complex framing. The bays with the beams shown in Blue are RAM Structural System Perfect Bays. Yellow indicates Imperfect Bays and Gray, Irregular Bays. The numbers in each Perfect Bay are the values reported to FloorVibe by the RAM Structural System for Floor Width (upper number) and Floor Length (lower number) for that bay. The FloorVibe user must verify the suitability of these dimensions, and modify them if necessary, before completing an analysis.

The Floor Widths shown are distances perpendicular to the beam span of the bay based on the adjacent Perfect Bays. For example, the Floor Width of the three bays between grids C-F and 3-4 is 90 ft. The width of Bays B/C and F/G are not included in the floor Width dimensions because they are either Imperfect or Irregular Bays. The same rule applies for the other Perfect Bays in the center portion of the framing, that is, Imperfect and Irregular bay widths are not included in the Floor Width dimensions.

The Floor Lengths shown are distances perpendicular to the girder span of the bay, again, based on adjacent perfect bays having beam spans of at least 50% of the beam span of the bay under consideration and subsequent adjacent bays having beam spans of at least 50% of that of the previous bay.

For example the Floor Length of the bays between grids C-E and 2-5 is 120 ft. Bays between grids 1-2 and 5-6 are not included in the reported Floor Lengths because of their short beam spans. The Floor Length for the bays between grids C-E and 1-2 and 5-6 is 135 ft because the spans in the successive adjacent perfect bays are at least 50% of these bays. It is noted that the Floor Lengths of the other Perfect Bays between grids B-G are restricted in length by adjacent Imperfect or Irregular Bays.

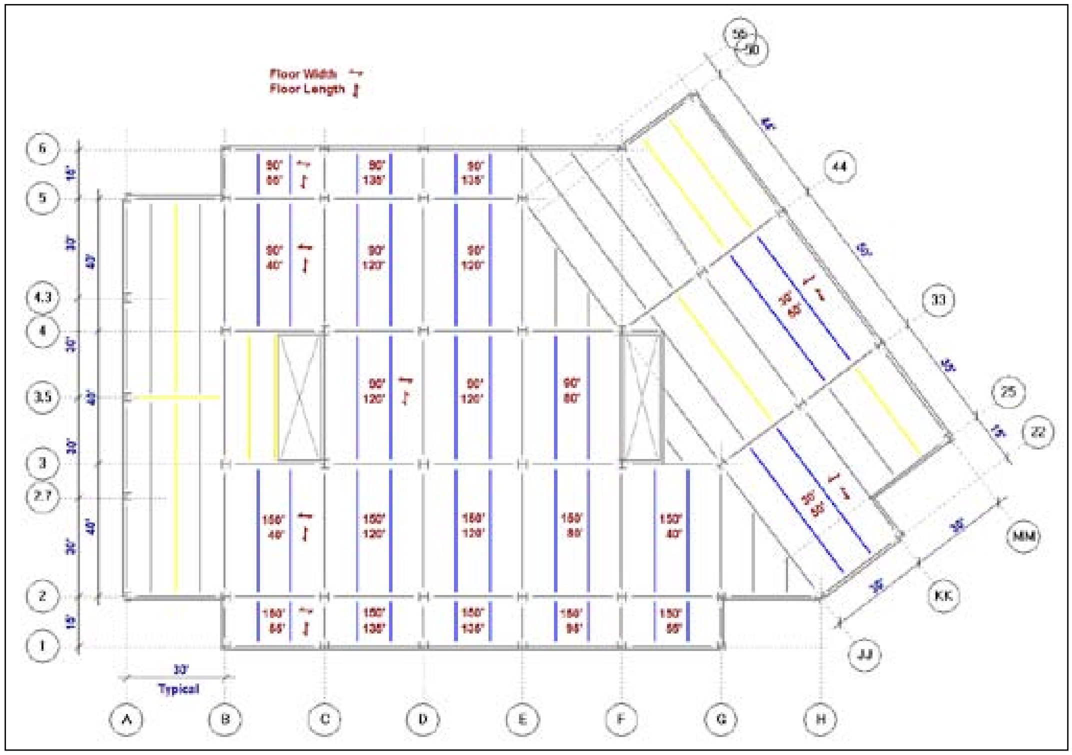

Figure 6. Example Framing Plan

Bays between grids A and B are imperfect bays because the interior girder is supported by a second girder at the intersection of grids B and 3.5. If the girder along grid 3.5 is very stiff for vibration purposes, for instance, if it supports a wall, these bays can be analyzed using FloorVibe. If this is done, the Floor Width and Floor Length for the two bays are 30 ft and 120 ft, respectively. Note that if there was a column at B-3.5, the Floor Width and Floor Length dimensions would likewise be 30 ft and 120 ft, respectively.

Bay B-C/3-4 is an Imperfect Bay because of the opening. If there are walls around the opening and they are sufficiently stiff to restrain vibration, the bay could be analyzed using FloorVibe with the girder span and Floor Width taken as 15 ft, and the Floor Length as 40 ft. However, it is unlikely that walking will cause significant accelerations in this area and analysis may not be required, because it is a single bay surrounded by totally dissimilar bays.

Bay KK-MM/44-50 is an Imperfect Bay because of the slight skew of the beam along column line KK between grids 44 and50. Engineering judgment allows this bay to be analyzed by FloorVibe with a Floor Width of 30 ft and a Floor Length of 94 ft.

Bay JJ-KK/33-44 is obviously an Imperfect Bay and is not a vibration concern because of the irregular framing along grid JJ. Bay KK-MM/25-33 is an Imperfect Bay because of the adjacent framing in Bay JJ-KK/22-33. Since the girder along grid 25 is supported by a beam along grid KK, the bay cannot be analyzed by FloorVibe.

The remaining triangular and multi-sided bays are designated as Irregular Bays by the RAM Structural System. They are not of concern as, to our knowledge, there has never been a reported floor vibration problem for such bays.

Mezzanines in the RAM Structural System

Design Guide 11 procedures require consideration of "interior floor edges, as in mezzanine areas or atria" because of the reduced effective mass due to the free edge or edges. Unless the beam or joist along a free edge is stiffened, the coefficient Cj in Equation (4) is taken as 1.0. For bays with a girder along a free edge, the girder panel width is taken as 2/3 times the supported beam or joist span. For bays with beam or joist and girder free edges, both requirements are invoked by FloorVibe. According to DG11, if the free edge beam or joist has a moment of inertia 50% greater than the interior beams or joists, Cj in Equation (4) can be taken as 2.0. In general, walls built over edge members at mezzanine areas or atria provide sufficient stiffness such that interior floor edge considerations are not needed. However, neither the RAM Structural System nor FloorVibe has provisions to detect a stiffened edge beam or joist.

It is also stated in DG11 that "experience so far has shown that exterior floor edges of buildings do not require special consideration as do interior floor edges. Reasons for this include stiffening due to exterior cladding and walkways generally not being adjacent to exterior walls. If these conditions do not exist, the exterior floor edges should be given special consideration." This statement was written in 1995 before the proliferation of electronic offices, which generally do not have well defined walkways. The reader is cautioned that, when the exterior cladding is not firmly attached in the vertical direction to the spandrel framing members, to consider using the free edge option(s) in FloorVibe.

The RAM Structural System assumes: (1) Exterior edge members (spandrel members) are not exterior floor edges, so the mezzanine option in FloorVibe is not tagged, and conservatively, that (2) all interior floor edges are mezzanines, so the mezzanine option in FloorVibe is tagged. For example, Bays C-D/3-4 and E-F/3-4 are tagged as a Mezzanine with a "Beam Parallel to Open Side", that is, this option is invoked in FloorVibe when it is launched from the RAM Structural System. The FloorVibe user must verify that this is a correct assumption and, if necessary, activate or deactivate the Mezzanine designation before an analysis is done.

Conclusion

Even for complicated framing configurations, the RAM Structural System can be very helpful in interpreting the geometric conditions of floor framing that, when appropriately confirmed by the engineer, can be used in FloorVibe to assess the vibration sensitivity of floor framing.

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