Preliminary Assessment for Walking-Induced Vibrations in Office Environments

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Floor vibration serviceability is an increasingly important issue in the design of steel-framed office floor systems. Economic realities have driven increased use of lighter, higher strength steel members and thinner slabs. More importantly, the changing work place has resulted in a trend toward more open office plans that support less weight and have fewer non-structural elements to absorb vibration. As a result, there are many more complaints concerning unacceptable levels of floor vibration due to walking excitation (Murray, 1998, 2001).

To combat this problem, AISC published Design Guide 11, *Floor Vibrations Due to Human Activity* (Murray, Allen, and Ungar, 1997) in which a criterion for walking excitation and a procedure by which a design can be evaluated are offered. This procedure is widely accepted as an accurate tool to assess this serviceability condition. A review of this procedure is presented in the next section of this paper. A negative aspect of this procedure is that it requires a long manual calculation that, in most cases, could not be undertaken by anyone other than a structural engineer. Because of the nature of the calculation required, the assessment of a floor system for vibration serviceability is often delayed until the final stages of design when most decisions important to floor serviceability, such as the selection of spans, slab thickness, concrete weight, and use of composite action, have already been made. Conversely, an early, easy assessment of vibration serviceability could result in a better selection of floor system properties to provide the most economical solution without sacrificing serviceability.

This paper presents the development and use of a preliminary assessment procedure to assess the most common office floor configurations for walking induced vibration serviceability. The value of a somewhat approximate, but greatly simplified, means of evaluation is that it could be employed in the early stages of design development when changes to the structural system, impacting other disciplines, can still be made.

To develop a simplified procedure for floor vibration assessment of office floors subjected to walking vibrations, statistical methods were employed. More specifically, a database of more than 70,000 floor system configurations was formulated. The formulation of the database is discussed in detail in Kim and Hanagan (2002). Using the results of this database, a multiple regression analysis was performed yielding a set of "simplified equations." These simplified equations were then integrated into a short, preliminary evaluation procedure that relies on tabulated values. After a brief overview of the AISC Design Guide 11 walking vibration criterion, the preliminary evaluation procedure is presented, followed by a discussion of its development and accuracy.

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WALKING VIBRATION CRITERION

The AISC Design Guide 11 (Murray and others, 1997) presents a procedure "Design for Walking Excitation." This particular serviceability criterion was established to evaluate a panel (or bay) of a steel floor framing system with respect to unacceptable levels of floor vibration. It is limited to structures subjected to walking excitations and the following occupancy uses: offices, residences, churches, shopping malls, and footbridges. A brief review of the criterion follows; however, the reader should be cautioned that this review is provided for contextual purposes and not as a substitute for the detailed discussion provided in the referenced document. The criterion states that a floor system design is acceptable if the following inequality is satisfied.

$$\frac{a_o}{g} \geq \frac{a_p}{g} = \frac{P_o \exp(-0.35\, f_n)}{\beta W} \tag{1}$$

where

a_o/g = 0.5 to 5.0 percent, depends on the occupancy;
P_o = 65 lb to 92 lb, depends on occupancy;
β = 0.01 to 0.05, depends on occupancy and presence of non-structural elements;
f_n = fundamental natural frequency of the bay, Hz, and W is the effective panel (bay) weight.

Table 1. Summary of Database Classes

Class	Steel framing type	Construction type	Deck type	Concrete weight
1	Rolled beams/ girders	Non-Composite	Form or Composite	Normal weight
2	Rolled beams/ girders	Non-Composite	Form or Composite	Lightweight
3	Rolled beams/ girders	Composite	Composite	Normal weight
4	Rolled beams/ girders	Composite	Composite	Lightweight
5	Steel joist/rolled girders	Non-Composite	Form deck	Normal weight
6	Steel joist/rolled girders	Non-Composite	Form deck	Lightweight

Before continuing, one should note that in Equation 1, a_p/g is the peak steady-state acceleration amplitude of a single-degree-of-freedom system subjected to a resonant sinusoidal force with a frequency dependent magnitude. Recommendations are made in the criterion to evaluate f_n and W as follows:

$$f_n = 0.18\sqrt{\frac{g}{\Delta_j + \Delta_g}} \tag{2}$$

$$W = \frac{\Delta_j}{\Delta_j + \Delta_g} W_j + \frac{\Delta_g}{\Delta_j + \Delta_g} W_g \tag{3}$$

where subscript j refers to beams or joists and subscript g refers to girder properties;

$$\Delta_j = \frac{5 w_j L_j^4}{384 E_s I_j} \text{ and } \Delta_g = \frac{5 w_g L_g^4}{384 E_s I_g}; \tag{4-5}$$

I_j = composite moment of inertia of beam or joist, regardless of mechanical connection;

I_g = composite moment of inertia of girder, regardless of mechanical connection;

W_j = $w_j B_j L_j$ (x 1.5 if continuous) and $W_g = w_g B_g L_g$ (x 1.5 if continuous); (6-7)

B_j = $C_j (D_s / D_j)^{0.25} L_j \leq 2/3$ (floor width); (8)

B_g = $C_g (D_j/D_g)^{0.25} L_g \leq 2/3$ (floor length for interior panels); (9)

B_g = $2/3\ L_j$ for edge panels; (10)

C_j = 2.0 for interior panels and edge stiffened exterior panels and 1.0 for exterior panels with unstiffened edges; (11)

C_g = 1.8 for shear-connected girders, 1.6 if not; (12)

$D_s = \frac{d_e^3}{12n}$ effective slab stiffness, (n is the modular ratio); (13)

$D_j = I_j/S$, effective joist stiffness, (S is the joist spacing); (14)

$D_g = I_g/L_j$ (15)

After a review of the procedure above, it is easy to see the benefit of a simplified procedure to evaluate common office floor configurations. Using the procedure above, a database containing evaluations of common floor system configurations was formulated. The parameters and assumptions defining the cases included in the database are described later in this paper.

PRELIMINARY ASSESSMENT PROCEDURE

The following preliminary assessment procedure applies to steel-framed office floors where the framing is the result of a strength design utilizing the most economical cross section. Additionally, framing members should meet a live load deflection limitation of $L/360$. The primary use of this evaluation is to determine whether a floor system that has been designed to meet strength and live load deflection requirements, should be altered to meet walking vibration serviceability requirements.

Limitations and Assumptions

The limitations expressed below are the result of the strength design assumptions used in developing the database from which the preliminary assessment procedure is derived. More details on the formulation of the database can be found in Kim and Hanagan (2002). Acceptable deviations from the stated assumptions are noted below; however, the reader should be cautioned that the accuracy of the results, discussed in the Appendix of this paper, are based on floors that satisfy the assumptions below.

1. Floor system must be defined by one of the six classes in Table 1.

2. Strength design based on LRFD methods except for K-series joist systems, which are based on ASD. Since LRFD design usually results in the same, lighter, or shallower members, ASD designs can be conservatively evaluated with this procedure.

3. Grade 50 steel. Because this procedure will produce very conservative results for ASTM A36 steel, systems using A36 steel that are evaluated as being unacceptable should be re-evaluated by the Design Guide 11 procedure before any changes are considered.

4. Design loads are 15 psf superimposed dead load, 145 pcf for normal weight concrete, 110 pcf for lightweight concrete, 50 psf live load, and 20 psf partition live loads with no live load reduction applied. Systems designed for heavier loads can be conservatively evaluated. If heavier live loads were used, some live load reduction can be conservatively considered.

5. Specified concrete strength is 3000 psi. Concrete strengths in the range of 2500–5000 psi can be considered with little loss in accuracy.

6. All members are assumed to be simply supported. The procedure will yield a conservative result for moment-connected members.

7. Composite steel framing is designed for unshored construction.

8. For non-composite beam/steel joist and girder designs, the most economical cross section is used unless a live load deflection limit of L/360 controls member selection. When several beam depths exist for a particular beam weight, the deepest cross-section is selected.

9. Floors have at least three bays in each direction and the beam span is the same on each side of the girder. Systems where beam/joist spans differ on either side of the girder can be reasonably evaluated for each beam/joist span.

10. Common architectural elements are attached, thus assuming a damping value of 0.03. The evaluation assumes that a hung ceiling, ductwork, etc. are suspended below and that some paper files or books exist in the office cubicles. When office areas are very lightly loaded, as in electronic offices, or when few attachments are made below, the preliminary assessment procedure should not be used. Extensive full-height partitions enclosing offices are assumed not to exist.

11. Beam/joist spans range from 20 ft to 40 ft and girder spans range from 15 ft to 40 ft. Shorter spans can be conservatively considered by assuming the minimum span noted. Longer spans should not be considered using this procedure.

12. Beam spacing is assumed to be equal within a bay and is assumed to be less than the deck span allowed for the 20 ga., 3 span, unshored condition.

Preliminary Evaluation Procedure

1. Define design class from Table 1.

2. Select C_1 from Table 2 according to class, deck thickness, and topping thickness. If a "U" is noted, all floors were found to be unacceptable for the spans studied. If an "A" is noted, all floors were found to be acceptable for the spans studied when damping is assumed to be 3 percent of critical. See assumption #10 above.

3. If step 2 did not result in a "U" or "A" rating, select C_2 according to class determined in step 1 from Tables 3–8.

4. Evaluate:

   For $C_1 + C_2 \leq 0.5$, floor should be acceptable for normal office environments.

   For $C_1 + C_2 > 0.5$, floor may be found unacceptable for office environments.

It should be reiterated that the assessment procedure above is to determine whether a floor system that has been designed to meet strength and live load deflection requirements, should be altered to meet walking vibration serviceability requirements. An example illustrating the strength design assumptions and limitations and the application of the preliminary evaluation is presented in the next section. The statistical derivation of the regression equations and the evaluation of the accuracy of the preliminary assessment procedure are presented in the Appendix.

Table 2. Values for C_1

Deck Height (in.)	Total Slab Thickness (in.)	Class 1 NC/NW	Class 2 NC/LW	Class 3 C/NW	Class 4 C/LW	Class 5 J/NW	Class 6 J/LW
0.5625	2	U	U	n/a	n/a	U	U
0.5625	2.5	0.476	U	n/a	n/a	U	U
0.5625	3	0.392	0.473	n/a	n/a	U	U
0.5625	3.5	A	0.400	n/a	n/a	U	U
0.5625	4	A	A	n/a	n/a	0.496	U
0.5625	4.5	A	A	n/a	n/a	0.434	U
0.5625	5	A	A	n/a	n/a	0.371	U
1	2.5	U	U	n/a	n/a	U	U
1	3	0.424	0.495	n/a	n/a	U	U
1	3.5	A	0.422	n/a	n/a	U	U
1	4	A	A	n/a	n/a	U	U
1	4.5	A	A	n/a	n/a	0.454	U
1	5	A	A	n/a	n/a	0.392	U
1	5.5	A	A	n/a	n/a	0.329	0.459
1.5	3.5	0.377	0.448	U	U	n/a	n/a
1.5	4	A	0.375	U	U	n/a	n/a
1.5	4.5	A	A	U	U	n/a	n/a
1.5	4.75	n/a	A	n/a	U	n/a	n/a
1.5	5	A	A	0.422	U	n/a	n/a
1.5	5.5	A	n/a	0.339	n/a	n/a	n/a
1.5	5.75	n/a	A	n/a	0.413	n/a	n/a
1.5	6	A	n/a	A	n/a	n/a	n/a
2	4	A	0.402	U	U	n/a	n/a
2	4.5	A	A	U	U	n/a	n/a
2	5	A	A	0.451	U	n/a	n/a
2	5.25	n/a	A	n/a	U	n/a	n/a
2	5.5	A	n/a	0.368	0.472	n/a	n/a
2	6	A	n/a	A	n/a	n/a	n/a
2	6.25	n/a	A	n/a	0.367	n/a	n/a
2	6.5	A	n/a	A	n/a	n/a	n/a
3	5	A	A	U	U	n/a	n/a
3	5.5	A	A	0.426	U	n/a	n/a
3	6	A	A	0.343	0.449	n/a	n/a
3	6.25	n/a	A	n/a	0.414	n/a	n/a
3	6.5	A	A	A	0.379	n/a	n/a
3	7	A	A	A	0.309	n/a	n/a
3	7.25	n/a	A	n/a	A	n/a	n/a
3	7.5	A	n/a	A	n/a	n/a	n/a

A: Acceptable for all spans studied when damping is assumed to be 3 percent of critical.
U: Unacceptable for all spans studied. Modification to meet vibration serviceability is suggested.
n/a: Configuration not studied
NC: Non-composite, rolled beams and girders
C: Composite, rolled beams and girders
J: K series joists with non-composite, rolled girders
NW: Normal weight concrete
LW: Lightweight concrete

Table 3. Non-Composite Beam and Non-Composite Girder Framed Floor Systems, Normal Weight Concrete

	CLASS 1: C_2 Values																				
	L_j (ft)																				
L_g (ft)	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
15	0.043	0.044	0.046	0.047	0.048	0.049	0.050	0.050	0.051	0.051	0.051	0.050	0.050	0.049	0.047	0.046	0.044	0.042	0.039	0.036	0.033
16	0.066	0.067	0.069	0.070	0.071	0.071	0.072	0.072	0.072	0.072	0.071	0.070	0.069	0.068	0.066	0.063	0.060	0.057	0.053	0.049	0.045
17	0.085	0.086	0.088	0.089	0.089	0.090	0.090	0.090	0.090	0.089	0.088	0.087	0.085	0.083	0.081	0.078	0.074	0.070	0.066	0.061	0.055
18	0.101	0.102	0.103	0.104	0.104	0.105	0.105	0.105	0.104	0.103	0.102	0.101	0.099	0.096	0.093	0.090	0.086	0.081	0.076	0.071	0.064
19	0.113	0.114	0.115	0.115	0.116	0.116	0.116	0.116	0.115	0.114	0.113	0.111	0.109	0.106	0.103	0.100	0.095	0.090	0.085	0.079	0.072
20	0.122	0.122	0.123	0.124	0.124	0.124	0.124	0.124	0.123	0.122	0.121	0.119	0.117	0.114	0.111	0.107	0.103	0.098	0.092	0.085	0.078
21	0.128	0.128	0.129	0.129	0.129	0.130	0.129	0.129	0.128	0.128	0.126	0.124	0.122	0.120	0.116	0.113	0.108	0.103	0.097	0.091	0.083
22	0.131	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.131	0.130	0.129	0.128	0.125	0.123	0.120	0.116	0.112	0.107	0.101	0.094	0.087
23	0.133	0.133	0.133	0.133	0.133	0.133	0.133	0.132	0.132	0.131	0.130	0.129	0.127	0.124	0.121	0.118	0.114	0.109	0.103	0.097	0.089
24	0.133	0.132	0.132	0.131	0.131	0.131	0.131	0.131	0.130	0.130	0.129	0.128	0.126	0.124	0.121	0.118	0.114	0.110	0.104	0.098	0.091
25	0.131	0.130	0.129	0.128	0.128	0.128	0.128	0.127	0.127	0.127	0.126	0.125	0.124	0.122	0.120	0.117	0.113	0.109	0.104	0.098	0.091
26	0.127	0.126	0.125	0.124	0.123	0.123	0.123	0.123	0.122	0.122	0.122	0.121	0.120	0.119	0.117	0.114	0.111	0.107	0.102	0.097	0.090
27	0.123	0.121	0.119	0.118	0.117	0.117	0.117	0.116	0.116	0.116	0.116	0.116	0.115	0.114	0.113	0.110	0.108	0.104	0.100	0.095	0.088
28	0.119	0.116	0.113	0.112	0.110	0.110	0.109	0.109	0.109	0.110	0.110	0.110	0.109	0.109	0.107	0.106	0.103	0.100	0.096	0.091	0.086
29	0.114	0.110	0.107	0.105	0.103	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.102	0.101	0.100	0.098	0.095	0.092	0.087	0.082
30	0.109	0.104	0.100	0.097	0.095	0.094	0.093	0.093	0.093	0.094	0.094	0.095	0.095	0.095	0.095	0.094	0.092	0.090	0.087	0.083	0.077
31	0.104	0.098	0.093	0.090	0.087	0.086	0.085	0.085	0.085	0.085	0.086	0.086	0.087	0.087	0.087	0.087	0.086	0.084	0.081	0.077	0.072
32	0.100	0.093	0.087	0.083	0.080	0.078	0.077	0.076	0.076	0.077	0.077	0.078	0.079	0.080	0.080	0.080	0.079	0.077	0.075	0.071	0.066
33	0.096	0.088	0.082	0.077	0.073	0.070	0.069	0.068	0.068	0.068	0.069	0.070	0.071	0.072	0.072	0.072	0.072	0.070	0.068	0.065	0.060
34	0.094	0.085	0.077	0.071	0.067	0.063	0.061	0.060	0.060	0.060	0.061	0.062	0.063	0.064	0.065	0.065	0.064	0.063	0.061	0.057	0.053
35	0.094	0.083	0.074	0.067	0.062	0.058	0.055	0.053	0.053	0.053	0.053	0.054	0.055	0.056	0.057	0.057	0.057	0.056	0.053	0.050	0.045
36	0.096	0.083	0.072	0.064	0.058	0.053	0.050	0.048	0.046	0.046	0.047	0.047	0.048	0.049	0.050	0.050	0.049	0.048	0.046	0.042	0.037
37	0.099	0.085	0.073	0.063	0.056	0.050	0.046	0.043	0.041	0.041	0.041	0.041	0.042	0.043	0.043	0.043	0.042	0.041	0.038	0.034	0.028
38	0.105	0.089	0.075	0.064	0.055	0.049	0.044	0.040	0.038	0.037	0.036	0.036	0.036	0.037	0.037	0.037	0.035	0.033	0.030	0.025	0.019
39	0.114	0.096	0.080	0.068	0.058	0.049	0.043	0.039	0.036	0.034	0.033	0.032	0.032	0.032	0.032	0.031	0.029	0.027	0.023	0.017	0.010
40	0.126	0.106	0.088	0.074	0.062	0.053	0.045	0.040	0.036	0.033	0.031	0.030	0.029	0.028	0.027	0.026	0.023	0.020	0.015	0.008	0.000

*L_j = Beam span length, ft
*L_g = Girder span length, ft

Table 4. Non-Composite Beam and Non-Composite Girder Framed Floor Systems, Lightweight Concrete

	CLASS 2: C_2 Values																				
	L_j (ft)																				
L_g (ft)	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
15	0.000	0.004	0.009	0.012	0.016	0.019	0.022	0.024	0.026	0.028	0.029	0.030	0.031	0.031	0.030	0.029	0.028	0.026	0.023	0.020	0.016
16	0.028	0.032	0.036	0.040	0.043	0.045	0.048	0.050	0.051	0.053	0.053	0.054	0.053	0.053	0.051	0.050	0.047	0.044	0.041	0.037	0.032
17	0.052	0.056	0.059	0.062	0.065	0.067	0.069	0.071	0.072	0.073	0.073	0.073	0.072	0.071	0.069	0.067	0.064	0.060	0.056	0.051	0.045
18	0.071	0.075	0.078	0.081	0.083	0.085	0.087	0.088	0.089	0.090	0.090	0.089	0.088	0.086	0.084	0.081	0.078	0.074	0.069	0.063	0.057
19	0.087	0.090	0.093	0.095	0.097	0.099	0.101	0.102	0.103	0.103	0.103	0.102	0.101	0.099	0.096	0.093	0.089	0.085	0.079	0.073	0.067
20	0.099	0.102	0.104	0.106	0.108	0.110	0.111	0.112	0.113	0.113	0.113	0.112	0.110	0.108	0.106	0.102	0.098	0.094	0.088	0.082	0.075
21	0.108	0.110	0.112	0.114	0.116	0.117	0.119	0.119	0.120	0.120	0.120	0.119	0.117	0.115	0.113	0.109	0.105	0.100	0.095	0.089	0.081
22	0.114	0.116	0.118	0.119	0.121	0.122	0.123	0.124	0.124	0.124	0.124	0.123	0.122	0.120	0.117	0.114	0.110	0.105	0.100	0.093	0.086
23	0.118	0.119	0.120	0.122	0.123	0.124	0.125	0.126	0.126	0.126	0.126	0.125	0.124	0.122	0.120	0.117	0.113	0.108	0.103	0.097	0.090
24	0.120	0.120	0.121	0.122	0.123	0.124	0.125	0.125	0.126	0.126	0.126	0.125	0.124	0.123	0.120	0.118	0.114	0.110	0.105	0.099	0.092
25	0.119	0.119	0.120	0.120	0.121	0.121	0.122	0.123	0.123	0.124	0.124	0.123	0.122	0.121	0.119	0.117	0.114	0.110	0.105	0.099	0.093
26	0.118	0.117	0.117	0.117	0.117	0.117	0.118	0.119	0.119	0.120	0.120	0.120	0.119	0.118	0.117	0.115	0.112	0.108	0.104	0.099	0.092
27	0.115	0.113	0.112	0.112	0.112	0.112	0.113	0.113	0.114	0.114	0.115	0.115	0.115	0.114	0.113	0.111	0.109	0.106	0.102	0.097	0.091
28	0.111	0.109	0.107	0.106	0.106	0.106	0.106	0.106	0.107	0.108	0.108	0.109	0.109	0.109	0.108	0.107	0.105	0.102	0.098	0.094	0.088
29	0.107	0.104	0.101	0.100	0.099	0.098	0.098	0.099	0.100	0.100	0.101	0.102	0.102	0.102	0.102	0.101	0.100	0.097	0.094	0.090	0.085
30	0.102	0.098	0.095	0.093	0.091	0.091	0.091	0.091	0.091	0.092	0.093	0.094	0.095	0.095	0.095	0.095	0.094	0.092	0.089	0.085	0.080
31	0.098	0.093	0.089	0.086	0.084	0.083	0.082	0.082	0.083	0.084	0.085	0.086	0.087	0.088	0.088	0.088	0.087	0.086	0.083	0.080	0.075
32	0.095	0.088	0.083	0.079	0.077	0.075	0.074	0.074	0.074	0.075	0.076	0.078	0.079	0.080	0.080	0.080	0.080	0.079	0.077	0.073	0.069
33	0.092	0.084	0.078	0.073	0.070	0.067	0.066	0.066	0.066	0.067	0.068	0.069	0.070	0.072	0.073	0.073	0.073	0.072	0.070	0.067	0.062
34	0.090	0.081	0.074	0.068	0.064	0.061	0.059	0.058	0.058	0.059	0.060	0.061	0.062	0.064	0.065	0.065	0.065	0.064	0.062	0.059	0.055
35	0.090	0.079	0.071	0.064	0.059	0.055	0.053	0.051	0.051	0.051	0.052	0.053	0.055	0.056	0.057	0.058	0.058	0.057	0.055	0.052	0.047
36	0.092	0.079	0.069	0.061	0.055	0.051	0.047	0.046	0.045	0.045	0.046	0.047	0.048	0.049	0.050	0.051	0.050	0.049	0.047	0.044	0.039
37	0.096	0.082	0.070	0.060	0.053	0.048	0.044	0.041	0.040	0.040	0.040	0.041	0.042	0.043	0.043	0.044	0.043	0.042	0.040	0.036	0.031
38	0.102	0.086	0.073	0.062	0.053	0.047	0.042	0.039	0.037	0.036	0.035	0.036	0.036	0.037	0.038	0.038	0.037	0.035	0.032	0.028	0.022
39	0.111	0.093	0.078	0.066	0.056	0.048	0.042	0.038	0.035	0.033	0.033	0.032	0.033	0.033	0.033	0.032	0.031	0.029	0.025	0.020	0.013
40	0.124	0.103	0.086	0.072	0.061	0.052	0.045	0.039	0.036	0.033	0.032	0.031	0.030	0.030	0.029	0.028	0.026	0.023	0.018	0.012	0.004

*L_j = Beam span length, ft
*L_g = Girder span length, ft

Table 5. Composite Beam And Composite Girder Framed Floor Systems, Normal Weight Concrete

	CLASS 3: C_2 Values																				
	L_j (ft)																				
L_g (ft)	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
15	0.018	0.023	0.027	0.031	0.035	0.038	0.041	0.044	0.047	0.050	0.052	0.054	0.056	0.057	0.059	0.060	0.061	0.061	0.062	0.062	0.062
16	0.037	0.040	0.042	0.044	0.046	0.047	0.049	0.050	0.051	0.052	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.052	0.051	0.050	0.049
17	0.056	0.056	0.057	0.057	0.057	0.057	0.057	0.056	0.056	0.055	0.054	0.053	0.052	0.051	0.049	0.047	0.046	0.044	0.042	0.039	0.037
18	0.074	0.073	0.071	0.070	0.068	0.067	0.065	0.063	0.061	0.059	0.056	0.054	0.051	0.049	0.046	0.043	0.040	0.037	0.034	0.031	0.027
19	0.091	0.088	0.085	0.082	0.079	0.076	0.073	0.070	0.066	0.063	0.059	0.056	0.052	0.048	0.044	0.040	0.036	0.032	0.028	0.024	0.019
20	0.107	0.103	0.099	0.095	0.090	0.086	0.081	0.077	0.072	0.068	0.063	0.058	0.053	0.049	0.044	0.039	0.034	0.029	0.023	0.018	0.013
21	0.123	0.117	0.112	0.106	0.101	0.095	0.089	0.084	0.078	0.073	0.067	0.061	0.055	0.049	0.044	0.038	0.032	0.026	0.020	0.014	0.008
22	0.137	0.130	0.124	0.117	0.111	0.104	0.097	0.091	0.084	0.078	0.071	0.064	0.058	0.051	0.045	0.038	0.031	0.024	0.018	0.011	0.004
23	0.150	0.143	0.135	0.128	0.120	0.113	0.105	0.098	0.090	0.083	0.076	0.068	0.061	0.053	0.046	0.039	0.031	0.024	0.016	0.009	0.002
24	0.162	0.154	0.145	0.137	0.129	0.121	0.113	0.104	0.096	0.088	0.080	0.072	0.064	0.056	0.048	0.040	0.032	0.024	0.016	0.008	0.000
25	0.172	0.163	0.155	0.146	0.137	0.128	0.119	0.111	0.102	0.093	0.085	0.076	0.067	0.059	0.050	0.042	0.033	0.025	0.017	0.008	0.000
26	0.181	0.172	0.162	0.153	0.144	0.135	0.125	0.116	0.107	0.098	0.089	0.080	0.071	0.062	0.053	0.044	0.035	0.027	0.018	0.009	0.000
27	0.188	0.179	0.169	0.159	0.150	0.140	0.131	0.121	0.112	0.102	0.093	0.084	0.075	0.065	0.056	0.047	0.038	0.029	0.020	0.011	0.002
28	0.194	0.184	0.174	0.164	0.155	0.145	0.135	0.126	0.116	0.106	0.097	0.087	0.078	0.068	0.059	0.050	0.040	0.031	0.022	0.013	0.004
29	0.197	0.187	0.178	0.168	0.158	0.148	0.139	0.129	0.119	0.110	0.100	0.090	0.081	0.071	0.062	0.053	0.043	0.034	0.025	0.015	0.006
30	0.199	0.189	0.179	0.170	0.160	0.150	0.141	0.131	0.122	0.112	0.103	0.093	0.084	0.074	0.065	0.055	0.046	0.037	0.027	0.018	0.009
31	0.198	0.189	0.179	0.170	0.161	0.151	0.142	0.132	0.123	0.114	0.104	0.095	0.086	0.077	0.067	0.058	0.049	0.039	0.030	0.021	0.012
32	0.195	0.186	0.177	0.168	0.159	0.150	0.141	0.132	0.123	0.114	0.105	0.096	0.087	0.078	0.069	0.060	0.051	0.042	0.033	0.024	0.015
33	0.190	0.182	0.173	0.165	0.157	0.148	0.140	0.131	0.123	0.114	0.105	0.097	0.088	0.079	0.071	0.062	0.053	0.045	0.036	0.027	0.019
34	0.183	0.175	0.167	0.160	0.152	0.144	0.136	0.128	0.120	0.112	0.104	0.096	0.088	0.080	0.072	0.063	0.055	0.047	0.039	0.030	0.022
35	0.172	0.166	0.159	0.152	0.145	0.138	0.131	0.124	0.117	0.109	0.102	0.095	0.087	0.079	0.072	0.064	0.057	0.049	0.041	0.033	0.025
36	0.159	0.154	0.148	0.142	0.136	0.130	0.124	0.118	0.111	0.105	0.098	0.092	0.085	0.078	0.071	0.064	0.057	0.050	0.043	0.035	0.027
37	0.144	0.139	0.135	0.130	0.125	0.120	0.115	0.110	0.104	0.099	0.093	0.087	0.082	0.076	0.069	0.063	0.057	0.050	0.044	0.037	0.030
38	0.125	0.122	0.119	0.115	0.112	0.108	0.104	0.100	0.096	0.091	0.087	0.082	0.077	0.072	0.067	0.061	0.056	0.050	0.044	0.038	0.032
39	0.103	0.102	0.100	0.098	0.096	0.093	0.091	0.088	0.085	0.082	0.078	0.075	0.071	0.067	0.063	0.058	0.053	0.049	0.044	0.038	0.033
40	0.078	0.078	0.078	0.078	0.077	0.076	0.075	0.074	0.072	0.070	0.068	0.066	0.063	0.060	0.057	0.054	0.050	0.046	0.042	0.038	0.033

*L_j = Beam span length, ft
*L_g = Girder span length, ft

Table 6. Composite Beam and Composite Girder Framed Floor Systems, Lightweight Concrete

	CLASS 4: C_2 Values																				
	L_j (ft)																				
L_g (ft)	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
15	0.000	0.008	0.016	0.023	0.030	0.036	0.041	0.046	0.051	0.054	0.057	0.060	0.062	0.063	0.064	0.064	0.064	0.063	0.061	0.059	0.057
16	0.022	0.028	0.033	0.038	0.043	0.046	0.050	0.053	0.055	0.057	0.058	0.059	0.060	0.059	0.059	0.058	0.056	0.054	0.051	0.048	0.044
17	0.043	0.047	0.050	0.053	0.055	0.057	0.059	0.060	0.061	0.061	0.060	0.060	0.059	0.057	0.055	0.053	0.050	0.046	0.043	0.038	0.034
18	0.063	0.065	0.066	0.067	0.068	0.068	0.068	0.067	0.066	0.065	0.063	0.061	0.059	0.056	0.053	0.049	0.045	0.041	0.036	0.031	0.025
19	0.083	0.083	0.082	0.082	0.081	0.079	0.077	0.075	0.073	0.070	0.067	0.064	0.060	0.056	0.051	0.047	0.042	0.036	0.031	0.025	0.018
20	0.102	0.100	0.098	0.095	0.093	0.090	0.087	0.083	0.080	0.076	0.071	0.067	0.062	0.057	0.051	0.046	0.040	0.033	0.027	0.020	0.013
21	0.119	0.116	0.113	0.109	0.105	0.101	0.096	0.092	0.087	0.081	0.076	0.071	0.065	0.059	0.052	0.046	0.039	0.032	0.024	0.017	0.009
22	0.136	0.131	0.127	0.122	0.117	0.111	0.106	0.100	0.094	0.088	0.081	0.075	0.068	0.061	0.054	0.047	0.039	0.031	0.023	0.015	0.007
23	0.151	0.146	0.140	0.134	0.128	0.121	0.115	0.108	0.101	0.094	0.087	0.079	0.072	0.064	0.056	0.048	0.040	0.031	0.023	0.014	0.005
24	0.165	0.158	0.152	0.145	0.138	0.130	0.123	0.116	0.108	0.100	0.092	0.084	0.076	0.068	0.059	0.051	0.042	0.033	0.024	0.015	0.005
25	0.177	0.170	0.162	0.155	0.147	0.139	0.131	0.123	0.115	0.106	0.098	0.089	0.080	0.071	0.062	0.053	0.044	0.035	0.025	0.016	0.006
26	0.188	0.180	0.172	0.164	0.155	0.147	0.138	0.130	0.121	0.112	0.103	0.094	0.085	0.075	0.066	0.057	0.047	0.037	0.027	0.018	0.008
27	0.197	0.188	0.180	0.171	0.162	0.153	0.145	0.136	0.126	0.117	0.108	0.099	0.089	0.079	0.070	0.060	0.050	0.040	0.030	0.020	0.010
28	0.203	0.195	0.186	0.177	0.168	0.159	0.150	0.141	0.131	0.122	0.112	0.103	0.093	0.083	0.073	0.063	0.053	0.043	0.033	0.023	0.013
29	0.208	0.199	0.190	0.181	0.172	0.163	0.154	0.145	0.135	0.126	0.116	0.107	0.097	0.087	0.077	0.067	0.057	0.047	0.037	0.026	0.016
30	0.210	0.201	0.193	0.184	0.175	0.166	0.157	0.148	0.138	0.129	0.119	0.110	0.100	0.090	0.080	0.070	0.060	0.050	0.040	0.029	0.019
31	0.210	0.202	0.193	0.185	0.176	0.167	0.158	0.149	0.140	0.131	0.122	0.112	0.103	0.093	0.083	0.073	0.063	0.053	0.043	0.033	0.023
32	0.207	0.199	0.192	0.183	0.175	0.167	0.158	0.150	0.141	0.132	0.123	0.114	0.105	0.095	0.086	0.076	0.066	0.056	0.046	0.036	0.026
33	0.202	0.195	0.187	0.180	0.172	0.164	0.157	0.148	0.140	0.132	0.123	0.114	0.106	0.097	0.087	0.078	0.069	0.059	0.049	0.039	0.029
34	0.194	0.188	0.181	0.174	0.167	0.160	0.153	0.145	0.138	0.130	0.122	0.114	0.106	0.097	0.088	0.079	0.070	0.061	0.052	0.042	0.032
35	0.183	0.177	0.172	0.166	0.160	0.154	0.147	0.141	0.134	0.127	0.120	0.112	0.104	0.096	0.088	0.080	0.071	0.063	0.053	0.044	0.035
36	0.169	0.164	0.160	0.155	0.150	0.145	0.140	0.134	0.128	0.122	0.115	0.109	0.102	0.095	0.087	0.079	0.071	0.063	0.055	0.046	0.037
37	0.151	0.148	0.145	0.142	0.138	0.134	0.130	0.125	0.120	0.115	0.110	0.104	0.098	0.091	0.085	0.078	0.070	0.063	0.055	0.047	0.038
38	0.130	0.129	0.128	0.126	0.123	0.121	0.118	0.114	0.111	0.106	0.102	0.097	0.092	0.087	0.081	0.075	0.068	0.061	0.054	0.047	0.039
39	0.106	0.107	0.107	0.106	0.106	0.104	0.103	0.101	0.098	0.096	0.092	0.089	0.085	0.080	0.076	0.070	0.065	0.059	0.052	0.045	0.038
40	0.078	0.081	0.083	0.084	0.085	0.085	0.085	0.085	0.084	0.083	0.081	0.079	0.076	0.072	0.069	0.065	0.060	0.055	0.049	0.043	0.036

*L_j = Beam span length, ft
*L_g = Girder span length, ft

Table 7. Non-Composite Open Web Steel Joist And Non-Composite Rolled Girder Framed Floor Systems, Normal Weight Concrete

	CLASS 5: C_2 Values																				
	L_j (ft)																				
L_g (ft)	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
15	0.099	0.096	0.093	0.090	0.088	0.086	0.084	0.083	0.082	0.081	0.080	0.079	0.079	0.078	0.078	0.078	0.078	0.078	0.078	0.079	0.079
16	0.120	0.116	0.112	0.109	0.105	0.102	0.100	0.097	0.095	0.092	0.090	0.088	0.086	0.084	0.082	0.080	0.079	0.077	0.075	0.073	0.071
17	0.139	0.134	0.129	0.125	0.121	0.117	0.113	0.110	0.106	0.103	0.099	0.096	0.093	0.090	0.086	0.083	0.080	0.076	0.073	0.069	0.065
18	0.155	0.150	0.144	0.139	0.134	0.130	0.125	0.121	0.116	0.112	0.108	0.103	0.099	0.095	0.090	0.086	0.081	0.076	0.071	0.066	0.061
19	0.170	0.163	0.157	0.152	0.146	0.141	0.135	0.130	0.125	0.120	0.115	0.110	0.105	0.100	0.094	0.089	0.083	0.077	0.071	0.065	0.058
20	0.182	0.175	0.168	0.162	0.156	0.150	0.144	0.138	0.133	0.127	0.121	0.116	0.110	0.104	0.098	0.092	0.085	0.079	0.071	0.064	0.056
21	0.192	0.185	0.177	0.171	0.164	0.157	0.151	0.145	0.139	0.133	0.127	0.121	0.114	0.108	0.102	0.095	0.088	0.080	0.072	0.064	0.055
22	0.201	0.193	0.185	0.177	0.170	0.163	0.157	0.150	0.144	0.138	0.131	0.125	0.118	0.112	0.105	0.097	0.090	0.082	0.074	0.065	0.056
23	0.207	0.199	0.190	0.183	0.175	0.168	0.161	0.154	0.148	0.141	0.135	0.128	0.121	0.115	0.107	0.100	0.092	0.084	0.076	0.066	0.057
24	0.212	0.203	0.194	0.186	0.178	0.171	0.164	0.157	0.150	0.144	0.137	0.131	0.124	0.117	0.110	0.102	0.095	0.086	0.077	0.068	0.058
25	0.216	0.206	0.197	0.188	0.180	0.173	0.166	0.159	0.152	0.145	0.139	0.132	0.126	0.119	0.112	0.104	0.096	0.088	0.079	0.070	0.060
26	0.218	0.207	0.198	0.189	0.181	0.173	0.166	0.159	0.152	0.146	0.139	0.133	0.126	0.120	0.113	0.106	0.098	0.090	0.081	0.072	0.062
27	0.218	0.207	0.197	0.188	0.180	0.172	0.165	0.158	0.151	0.145	0.139	0.133	0.127	0.120	0.114	0.107	0.099	0.091	0.083	0.074	0.063
28	0.217	0.206	0.196	0.186	0.178	0.170	0.163	0.156	0.149	0.143	0.137	0.132	0.126	0.120	0.114	0.107	0.100	0.092	0.084	0.075	0.065
29	0.215	0.203	0.193	0.183	0.174	0.166	0.159	0.153	0.146	0.141	0.135	0.130	0.124	0.119	0.113	0.107	0.100	0.093	0.085	0.076	0.066
30	0.212	0.200	0.188	0.179	0.170	0.162	0.155	0.148	0.142	0.137	0.132	0.127	0.122	0.117	0.111	0.106	0.099	0.093	0.085	0.076	0.067
31	0.208	0.195	0.183	0.173	0.164	0.156	0.149	0.143	0.137	0.132	0.127	0.123	0.118	0.114	0.109	0.104	0.098	0.092	0.084	0.076	0.067
32	0.203	0.189	0.177	0.166	0.157	0.149	0.142	0.136	0.131	0.126	0.122	0.118	0.114	0.110	0.106	0.101	0.096	0.090	0.083	0.075	0.066
33	0.197	0.182	0.170	0.159	0.150	0.142	0.135	0.129	0.124	0.120	0.116	0.112	0.109	0.105	0.101	0.097	0.092	0.087	0.080	0.072	0.063
34	0.190	0.175	0.162	0.151	0.141	0.133	0.126	0.121	0.116	0.112	0.109	0.105	0.102	0.099	0.096	0.092	0.088	0.082	0.076	0.069	0.060
35	0.183	0.167	0.153	0.142	0.132	0.124	0.117	0.112	0.107	0.103	0.100	0.098	0.095	0.092	0.089	0.086	0.082	0.077	0.071	0.063	0.055
36	0.175	0.158	0.144	0.132	0.122	0.113	0.107	0.101	0.097	0.094	0.091	0.089	0.087	0.084	0.082	0.079	0.075	0.070	0.064	0.057	0.048
37	0.166	0.149	0.134	0.121	0.111	0.102	0.096	0.091	0.086	0.083	0.081	0.079	0.077	0.075	0.073	0.070	0.066	0.062	0.056	0.048	0.039
38	0.157	0.139	0.123	0.110	0.099	0.091	0.084	0.079	0.075	0.072	0.070	0.068	0.066	0.065	0.063	0.060	0.057	0.052	0.046	0.038	0.028
39	0.148	0.129	0.112	0.098	0.087	0.078	0.072	0.066	0.062	0.059	0.057	0.056	0.054	0.053	0.051	0.049	0.045	0.040	0.034	0.026	0.015
40	0.139	0.118	0.101	0.086	0.075	0.066	0.058	0.053	0.049	0.046	0.044	0.043	0.041	0.040	0.038	0.035	0.032	0.027	0.020	0.011	0.000

*L_j = Joist span length, ft
*L_g = Girder span length, ft

Table 8. Non-Composite Open Web Steel Joist and Non-Composite Rolled Girder Framed Floor Systems, Lightweight Concrete

	CLASS 6: C_2 Values																				
	L_j (ft)																				
L_g (ft)	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
15	0.048	0.049	0.050	0.051	0.051	0.052	0.051	0.051	0.050	0.049	0.047	0.045	0.043	0.041	0.038	0.035	0.031	0.028	0.023	0.019	0.014
16	0.068	0.069	0.069	0.068	0.068	0.067	0.066	0.065	0.063	0.061	0.059	0.056	0.053	0.050	0.047	0.043	0.039	0.035	0.030	0.025	0.020
17	0.087	0.086	0.085	0.084	0.083	0.081	0.079	0.077	0.075	0.072	0.069	0.066	0.063	0.059	0.055	0.051	0.046	0.041	0.036	0.031	0.025
18	0.104	0.102	0.101	0.099	0.097	0.094	0.091	0.089	0.085	0.082	0.079	0.075	0.071	0.066	0.062	0.057	0.052	0.047	0.041	0.036	0.030
19	0.119	0.117	0.115	0.112	0.109	0.106	0.102	0.099	0.095	0.091	0.087	0.082	0.078	0.073	0.068	0.063	0.058	0.052	0.046	0.040	0.034
20	0.133	0.130	0.127	0.123	0.120	0.116	0.112	0.108	0.103	0.099	0.094	0.089	0.084	0.079	0.073	0.068	0.062	0.056	0.050	0.044	0.038
21	0.146	0.142	0.138	0.133	0.129	0.125	0.120	0.115	0.110	0.105	0.100	0.095	0.089	0.084	0.078	0.072	0.066	0.060	0.054	0.047	0.041
22	0.156	0.152	0.147	0.142	0.137	0.132	0.127	0.122	0.116	0.111	0.105	0.099	0.094	0.088	0.082	0.076	0.069	0.063	0.057	0.050	0.043
23	0.165	0.160	0.155	0.149	0.144	0.138	0.133	0.127	0.121	0.115	0.109	0.103	0.097	0.091	0.085	0.078	0.072	0.065	0.059	0.052	0.045
24	0.173	0.167	0.161	0.155	0.149	0.143	0.137	0.131	0.125	0.118	0.112	0.106	0.099	0.093	0.087	0.080	0.074	0.067	0.060	0.054	0.047
25	0.178	0.172	0.166	0.159	0.153	0.146	0.140	0.134	0.127	0.121	0.114	0.108	0.101	0.094	0.088	0.081	0.075	0.068	0.061	0.055	0.048
26	0.183	0.176	0.169	0.162	0.155	0.149	0.142	0.135	0.128	0.122	0.115	0.108	0.101	0.095	0.088	0.081	0.075	0.068	0.062	0.055	0.049
27	0.185	0.178	0.171	0.164	0.156	0.149	0.142	0.135	0.128	0.121	0.115	0.108	0.101	0.094	0.088	0.081	0.074	0.068	0.061	0.055	0.049
28	0.186	0.178	0.171	0.163	0.156	0.149	0.141	0.134	0.127	0.120	0.113	0.106	0.100	0.093	0.086	0.080	0.073	0.067	0.060	0.054	0.048
29	0.185	0.178	0.170	0.162	0.154	0.147	0.139	0.132	0.125	0.118	0.111	0.104	0.097	0.091	0.084	0.077	0.071	0.065	0.059	0.053	0.047
30	0.183	0.175	0.167	0.159	0.151	0.144	0.136	0.129	0.121	0.114	0.107	0.101	0.094	0.087	0.081	0.075	0.069	0.063	0.057	0.051	0.045
31	0.179	0.171	0.163	0.155	0.147	0.139	0.131	0.124	0.117	0.110	0.103	0.096	0.089	0.083	0.077	0.071	0.065	0.059	0.054	0.048	0.043
32	0.174	0.165	0.157	0.149	0.141	0.133	0.125	0.118	0.111	0.104	0.097	0.091	0.084	0.078	0.072	0.066	0.061	0.055	0.050	0.045	0.041
33	0.167	0.158	0.150	0.141	0.133	0.126	0.118	0.111	0.104	0.097	0.091	0.084	0.078	0.072	0.067	0.061	0.056	0.051	0.046	0.042	0.037
34	0.158	0.149	0.141	0.133	0.125	0.117	0.110	0.103	0.096	0.089	0.083	0.077	0.071	0.065	0.060	0.055	0.050	0.046	0.041	0.037	0.034
35	0.148	0.139	0.130	0.122	0.115	0.107	0.100	0.093	0.086	0.080	0.074	0.068	0.063	0.058	0.053	0.048	0.044	0.040	0.036	0.033	0.030
36	0.136	0.127	0.119	0.111	0.103	0.096	0.089	0.082	0.076	0.070	0.064	0.059	0.054	0.049	0.045	0.041	0.037	0.033	0.030	0.027	0.025
37	0.122	0.113	0.105	0.098	0.090	0.083	0.076	0.070	0.064	0.058	0.053	0.048	0.044	0.039	0.035	0.032	0.029	0.026	0.024	0.021	0.020
38	0.107	0.098	0.091	0.083	0.076	0.069	0.063	0.057	0.051	0.046	0.041	0.037	0.033	0.029	0.026	0.023	0.020	0.018	0.016	0.015	0.014
39	0.090	0.082	0.074	0.067	0.060	0.054	0.048	0.042	0.037	0.032	0.028	0.024	0.021	0.018	0.015	0.013	0.011	0.009	0.008	0.008	0.008
40	0.071	0.064	0.056	0.049	0.043	0.037	0.032	0.027	0.022	0.018	0.014	0.011	0.008	0.005	0.003	0.002	0.001	0.000	0.000	0.000	0.001

*L_j = Joist span length, ft
*L_g = Girder span length, ft

EXAMPLE OFFICE FLOOR DESIGN

This section presents an example illustrating the use of the preliminary assessment procedure in the design of an acceptable office floor. The numbered assumptions and limitations, as presented in an earlier section, noted throughout this example, are given to illustrate their impact on design decisions and conditions.

Given:

- The floor to be designed is comprised of six bays in one direction and three bays in the other. All bays have the same beam and girder spans. This satisfies limitation #9.
- The floor framing is to be comprised of a 3000 psi concrete slab on a composite metal deck, supported by noncomposite, Grade 50, steel wide flange sections utilizing typical shear connections. This satisfies limitation #1, #5 and #6.
- The floor framing will support an open plan office that meets the description in assumption #10.
- Beam span = 30'-0" (This satisfies limitation #11.)
- Girder span = 28'-0" (This satisfies limitation #11.)

Select slab/deck configuration:

Try 1.5VLI20 deck, where the 20 ga. deck satisfies assumption #12, with 2 in. lightweight topping (3.5 in. total slab thickness)

- Preliminary evaluation of vibration serviceability assuming 3 percent damping:

  1. Select class from Table 1: Class 2
  2. Select C_1 from Table 2: 0.448
  3. Select C_2 from Table 4: 0.108
  4. Evaluate: $C_1 + C_2 = 0.448 + 0.108 = 0.556 > 0.5 \therefore$ not OK

     Options:

     a) Proceed with the strength design with an understanding that the beam sizes will probably need to be increased to meet vibration serviceability requirements.

     b) Select a different slab/deck configuration so that the strength design will most likely meet vibration serviceability requirements without increasing member sizes beyond those required for the strength design.

- Proceed with Option b (changes are shown in bold): Try 1.5VLI20 deck with 2 in. normal weight topping.
- Preliminary evaluation of vibration serviceability:

  5. Select class from Table 1: Class 1
  6. Select C_1 from Table 2: 0.377
  7. Select C_2 from Table 3: 0.110
  8. Evaluate: $C_1 + C_2 = 0.377 + 0.110 = 0.49 < 0.5 \therefore$ OK

     Proceed with the strength design with an understanding that the beam sizes will probably be satisfactory to meet vibration serviceability requirements. Since the evaluation indicates a borderline floor and there is some error in the preliminary evaluation procedure, it is possible that the Design Guide 11 procedure will result in an unacceptable floor evaluation.

Strength Design:

The strength design portion of this example is presented to further illustrate the assumptions and limitations applied in formulating the database from which the preliminary evaluation procedure was derived. The preliminary assessment procedure is only valid for designs that satisfy all assumptions and limitations.

Design Beam:

- From deck catalog (applying assumption #12):

  Maximum beam spacing = 8'-4"; slab/deck weight = 33 psf

  For 28' girder span, maximum beam spacing = 28'/4 = 7.0' = s

- Compute the factored beam load and design moment (applying assumptions #2 and #4):

w_u = [1.2D+1.6L] × beam spacing
= [(33 psf+15 psf)(1.2)+(50 psf +20 psf)(1.6)](7.0 ft)
= 1187 plf

$M_u = w_u l^2/8$ = 1.19 plf (30 ft)^2/8 = 134 kip-ft (applying assumption #6)

- Select member:

  Try W16×26 where $\phi_b M_{px}$ = 166 kip-ft; I_x = 301 in.^{4} (To properly apply assumption #8, a W16×26 was chosen even though a W12×26 will work for the moment due to the loads.)

  Add beam self weight: M_u = 134 + 0.026(30^2)/8 = 137 kip-ft < 166 kip-ft $\therefore$ OK

- Check deflection (applying assumption #8):

$$I_{req} = \frac{5w_{LL}l^4}{384E\Delta_{LL\max}} = \frac{5(0.07\times 7)(30^4)(1728)}{384(29000)(30\times 12/360)}$$
$$= 308 \text{ in.}^4 > 301 \text{ in.}^4 \therefore \text{ increase size.}$$

- Use W16×31, A992 beams spaced at 7’-0” on center.

Design Girder:

- Compute the factored girder loads, three loads spaced at 7 ft, and design moment (applying assumptions #2 and #4):

  $P_u =$ w_{ubeam} × beam span = (1.19 + 0.031)(30) = 36.6 k (applying assumptions #2 and #4)
  $M_u =$ $1.5P_u l/2 - P_u l/4$ = 1.5(36.6 k)(14 ft)–36.6 k (7.0 ft)
  = 512 ft-k (applying assumption #6)

- Select member:

  Try W24×62 where $\phi_b M_{px}$ = 578 kip-ft; I_x = 1560 in.^{4} (To properly apply assumption #8, a W24×62 was chosen even though a W21×62 will work for the moment due to the loads.)

  Add beam self weight:

  M_u = 512 kip-ft + 0.062 klf (28 ft)^2/8 = 515 kip-ft < 578 kip-ft ∴ OK

- Check deflection (applying assumption #8):

$$\Delta_{LL}\,(\text{estimated}) = \frac{5(P_u\,/\,beam\ spacing)\lambda^4}{384EI}$$
$$= \frac{5(0.07\times 30)(28^4)(1728)}{384(29000)(1560)}$$
$$= 0.642'' < \lambda/360 = 0.93 \therefore OK$$

- Use W24×62, A992 girders.

Design Guide 11 Evaluation (not shown):
a_p/g = 0.465 percent g < 0.5% g ∴ OK

Design Summary:

1.5VLI20 composite deck with 2 in. normal weight concrete topping (3½ in. total slab thickness)

W16×31, A992 beams spaced at 7’-0” on center

W24×62, A992 girders

CONCLUSIONS

Floor vibrations that annoy or disturb office workers are a growing concern. AISC Design Guide 11 offers a procedure to evaluate steel floor systems for walking-induced vibration. While this procedure has an excellent track record for identifying problem floors, it requires extensive calculations to arrive at a conclusion. Because of the calculation complexities, the evaluation is often performed late in the design process when changes to beam depth, slab/deck thickness, and concrete weight are difficult.

This paper presents a preliminary assessment procedure to evaluate steel office floor designs for susceptibility to excessive walking induced vibrations. Because the preliminary assessment procedure is very short, it is easier to incorporate into the early design process when many of the important decisions affecting vibration serviceability are made. An additional benefit of the preliminary assessment procedure is it makes clear that the slab/deck configuration has a great influence on walking-induced vibration serviceability. It is an even better indicator of when serviceability is going to control the design instead of strength. As shown in the example, switching from lightweight to normal weight concrete improves vibration performance. This is logical since a strength design using normal weight concrete results in a larger effective mass and a larger beam than a similar configuration using lightweight concrete. Finally, it cannot be overstated that the preliminary assessment procedure is not meant to replace the Design Guide 11 procedure, but rather to give insight as to whether the strength design might need to be modified to provide acceptable vibration behavior.

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APPENDIX

Statistical Derivation

This section presents the statistical derivation of the linear regression equations that resulted in the preliminary assessment procedure presented in the previous section. The multivariate method used for analyzing the database under this study was multiple linear regression analysis. Regression analyses are a set of statistical techniques for assessing the relationship between one random variable and several fixed independent variables (Tabachnick and Fidell, 1996). In this data analysis, the acceleration ratio is a dependent variable, while floor properties such as beam and girder span, slab and deck thickness are explanatory variables (also called independent variables). The mathematical equation is generally represented by

$$y = \mathrm{f}(x, b) + \varepsilon \tag{16}$$

where y is the dependent variable, b contains the regression parameters, x is a set of independent variables, and ε is randomness or error of the estimated function. Ordinary least squares method for the estimation of the regression parameters was applied. This method minimizes the sum of the squares of the differences between the predicted and the actual values of the dependent variable. The applicability of this method relies on the following assumptions:

1. Stability of the regression model. That is, the value of the dependent variable y is an additive combination of the independent predictor variables, x. This also implies that, if there is interaction effect, taken in the statistical sense that the value of one explanatory variable depends on one or more other explanatory variables, the estimates of the regression coefficients are unreliable.

2. Constancy of error variance. The formulation assumes that the error terms (ε) are uncorrelated with the independent variables and they have constant variability over the range of the variables. The dependent variable, y, is also assumed to hold a constant variance; in other words, the dependent variables are independent of each other.

3. Normality of the response variable, y. In multiple regression, the estimated regression parameters (β) are most often determined through the statistical rules of least squares method, thus requiring normality.

4. Normality of the error terms, ε. The least squares approach for estimating the regression parameters is the most efficient when the residuals or errors also have a normal probability distribution.

In summary, the validity of a multiple regression model rests on the classical assumptions described above: linearity or additivity, homoscedasticity, and normality.

To satisfy the basic assumptions, several remedies for the individual variables are applied. Transformations of variables are necessary to simplify (straighten) relationships, stabilize variances, and to improve normality (Rawlings, Pantula, and Dickey, 1998). Some of the explanatory variables have a nonlinear trend with the value of the acceleration ratio. For example, girder span has a curvilinear relationship with the value of the acceleration ratio, so a quadratic term relating to the girder length was used to convert the nonlinear relationship into a linear one. Similarly, the data interpretation showed that the beam span has a nonlinear relationship with the response variable and the relationship was straightened by a transformation on the beam and girder span variable.

When the classical assumptions of constant variance and normality are violated, a nonlinear transformation of the response may improve the regression fit. Evaluation of the data revealed normal distributions of the residuals, indicating that no transformation would be necessary to satisfy this assumption (Kim and Hanagan, 2002).

When the effects of the independent variables on the response variable are not additive, the effect of one independent variable depends on the levels of the other predictor variables (Neter, Wasserman, and Kutner, 1996). In this study, the polynomial regression models required to simplify the relationships between floor properties and acceleration ratio contain interaction effects, resulting in non-constant variance. A simple and commonly used means of modeling the interaction effect of two predictor variables on the response variable is by a cross-product term that is called an interaction term (Neter and others, 1996). Consequently, the interaction terms of girder span and beam span were included in the regression equations.

After considering the potential regression problems and taking their remedies, regression models were generated using ordinary least squares method. Because the independent variables are reasonably orthogonal, ordinary least squares results remain almost the same regardless of which other variables are in the model. All possible subset regressions were computed and evaluated to yield the best statistical model. This method is feasible because the number of independent variables is not large; in this case, the variable number is 4.

Stepping through the model selection process, the best statistical model was developed for each class. The resulting regression equations are expressed as six mathematical equations as follows:

$$\begin{aligned} \text{1. } a_p = {} & 0.372 - 0.0541\,L_j + 0.00142\,L_j^2 + 0.0552\,L_g \\ & - 0.00234\,L_g^2 + 0.0000576\,L_g^3 \\ & + 0.00729\,L_j L_g - 0.000190\,L_j^2 L_g \\ & - 0.000243\,L_j L_g^2 + 0.00000677\,L_j^2 L_g^2 \\ & - 0.000000000754 L_j^3 L_g^3 - 0.169\,t_c - 0.0952\,t_d \end{aligned} \tag{17}$$

$$\begin{aligned} \text{2. } a_p = {} & -0.0313 - 0.0374\,L_j + 0.00119\,L_j^2 \\ & + 0.0824\,L_g - 0.00291\,L_g^2 + 0.0000614\,L_g^3 \\ & + 0.00642\,L_j L_g + 0.00000659\,L_j^2 L_g^2 \\ & - 0.000000000750 L_j^3 L_g^3 - 0.000177\,L_j^2 L_g \\ & - 0.000231\,L_j L_g^2 - 0.146\,t_c - 0.0939\,t_d \end{aligned} \tag{18}$$

$$\begin{aligned} \text{3. } a_p = {} & -0.425 + 0.0804\,L_j - 0.000657\,L_j^2 + 0.121\,L_g \\ & - 0.00124\,L_g^2 - 0.0000195\,L_g^3\ 0.00647\,L_j L_g \\ & + 0.0000497\,L_j^2 L_g + 0.000115\,L_j L_g^2 \\ & - 0.00000115\,L_j^2 L_g^2 - 0.166\,t_c - 0.108\,t_d \end{aligned} \tag{19}$$

$$\begin{aligned} \text{4. } a_p = {} & -0.939 + 0.113\,L_j - 0.00116\,L_j^2 + 0.148\,L_g \\ & - 0.00152\,L_g^2 - 0.0000228\,L_g^3 - 0.00838\,L_j L_g \\ & + 0.000146\,L_j L_g^2 + 0.0000788\,L_j^2 L_g \\ & - 0.00000139\,L_j^2 L_g^2 - 0.140\,t_c - 0.0925\,t_d \end{aligned} \tag{20}$$

$$\begin{aligned} \text{5. } a_p = {} & 0.730 - 0.0512\,L_j + 0.00177\,L_j^2 \\ & + 0.0368\,L_g - 0.000563\,L_g^2 + 0.0000220\,L_g^3 \\ & + 0.00561\,L_j L_g - 0.000200\,L_j^2 L_g - 0.000207\,L_j L_g^2 \\ & + 0.00000701\,L_j^2 L_g^2 - 0.000000000820\,L_j^3 L_g^3 \\ & - 0.125\,t_c - 0.0776\,t_d \end{aligned} \tag{21}$$

$$\begin{aligned} \text{6. } a_p = {} & 0.0239 + 0.0395\,L_j - 0.000394\,L_j^2 \\ & + 0.0893\,L_g - 0.00136\,L_g^2 - 0.00251\,L_j L_g \\ & + 0.0000154\,L_j^2 L_g + 0.0000274\,L_j L_g^2 - 0.126\,t_c \\ & - 0.0808\,t_d \end{aligned} \tag{22}$$

where

a_p = acceleration response in % g;
L_j = length of floor beam or joist span in ft;
L_g = length of floor girder span in ft;
t_c = concrete slab topping in in.;
t_d = deck thickness in in.

The mathematical equations shown above represent the regression model for the six classes defined in Table 1. Since these equations are very cumbersome for direct use in evaluating an office floor system, the tables presented in the previous section were developed. It should be noted that only the data for slab/deck configurations showing a numeric coefficient for C_1 in Table 2 were included in developing Equations 17–22. Where Table 2 notes a “U” or “A” designation, the assessment of acceptable or unacceptable did not vary for that slab/deck configuration for the spans studied.

Evaluation of Accuracy

Ensuring the effectiveness of the preliminary walking vibration assessment procedure is an essential part of this contribution. In this section, the resultant outcomes of the preliminary assessment procedure are described and evaluated to determine its validity for design purposes. Validation of a fitted regression equation is the demonstration or confirmation that the model is sound and effective for the purpose for which it was intended (Rawlings and others, 1998). The intended purpose of the regression analysis in this work is to predict the values of the response variable precisely enough for a preliminary assessment of office floor acceptability.

Table 9 summarizes the results of the preliminary assessment procedure for each of the six classes as defined in Table 1. The first line in Table 9 indicates the total number of floors designed and evaluated for the database. The next line indicates the number and percent of floors evaluated correctly. That is, the assessment of acceptable or unacceptable, as determined by Equations 1-15, is the same as the assessment of the preliminary assessment procedure. With an overall success rate of 97 percent, this procedure provides a relatively accurate tool for assessing floor vibration serviceability.

Within each class, only a subset of the total number of floors needed to be estimated by the regression equation. These floors are indicated by a numeric entry for C_1 in Table 2. For this subset of floors, the beam and girder spans needed to be considered before an assessment could be made. For the purpose of evaluation, the data for the floors estimated by regression fit are broken into four conditions as follows:

1. Actual predicted response value and response value predicted by the regression equation are less than or equal to 0.5 percent g. (in other words, both evaluations predict an acceptable floor)

Table 9. Evaluation of Data

	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Total number of floors evaluated	17472	17472	9828	10374	7644	7644
Floors evaluated correctly	17123 (98%)	16723 (96%)	9412 (96%)	9927 (96%)	7404 (97%)	7559 (99%)
Floors evaluated incorrectly	349 (2%)	749 (4%)	416 (4%)	447 (4%)	240 (3%)	85 (1%)
Number of floors estimated by regression fit	2184	3822	3276	4368	3276	1092
Condition 1	1096 floors	1385 floors	1545 floors	1909 floors	1172 floors	58 floors
Condition 2	122 floors	328 floors	142 floors	196 floors	73 floors	36 floors
Max error*	0.073%g	0.090%g	0.105%g	0.109%g	0.061%g	0.084%g
Avg error*	0.032%g	0.031%g	0.030%g	0.034%g	0.023%g	0.028%g
Condition 3	195 floors	390 floors	207 floors	214 floors	167 floors	47 floors
Max error*	-0.104%g	-0.126%g	-0.080%g	-0.089%g	-0.067%g	-0.063%g
Avg error*	-0.045%g	-0.041%g	-0.030%g	-0.033%g	-0.022%g	-0.026%g
Condition 4	771 floors	1719 floors	1382 floors	2043 floors	1864 floors	951 floors

* The error noted is the actual value – fitted value in units of percent g.

2. Actual predicted response value is more than 0.5 percent g and the response value predicted by the regression equation is less than or equal to 0.5 percent g (in other words, an unacceptable floor is predicted as acceptable by the regression equation).

3. Actual predicted response value is less than or equal to 0.5 percent g and the simplified predicted response value is more than 0.5 percent g (in other words, an acceptable floor is predicted as unacceptable by the regression equation).

4. Actual predicted response value and simplified predicted response value are more than 0.5 percent g (in other words, both evaluations predict an unacceptable floor).

A summary of the conditions observed for each of the six classes is presented in Table 9. For structural design purposes, conditions 2 and 3 are of particular interest, because they result in a different assessment from the actual predicted response. In these cases, the magnitude of the error is very important. From Equation 16, y is the actual value for the predicted response, $f(x, b)$ is the fitted value and ε is the error. The prediction error, ε, was computed for each floor estimated by the regression equations. The average and maximum errors for conditions 2 and 3 are shown in Table 9.

The accuracy of the fitted data, for each of the six classes of floors, can be better understood by inspection of Figures 1-6. These figures plot the fitted versus the actual values for the cases included where the values resulting from the regression equations, as determined by $C_1 + C_2$, are noted as the "fitted values" and the results from the Design Guide 11 procedure, as determined by Equations 1-15, are noted as the "actual values." The diagonal line represents a perfect fit and the distance a point lies from this line represents the error. Additionally, these graphs are broken up into quadrants representing conditions 1-4. Points that lie in quadrants 1 and 4 represent correct predictions for the preliminary assessment procedure. Points that lie in quadrants 2 and 3 represent incorrect predictions. As noted previously, large errors in these quadrants would be of the greatest concern. The conclusions from these graphs are that the fitted values provide a reasonable estimate of the actual values and the preliminary assessment procedure is a good starting point for addressing serviceability concerns.

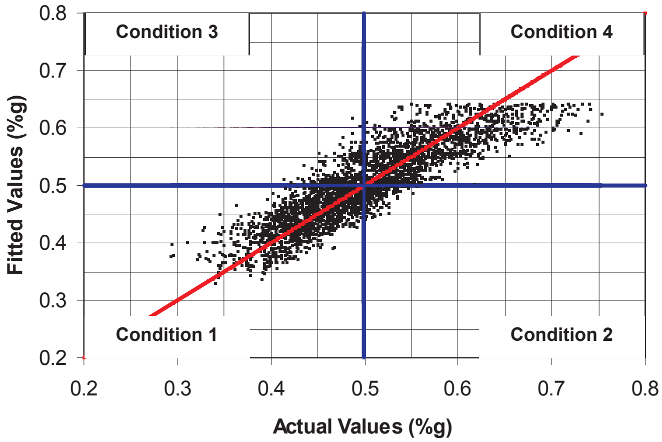

Fig. 1. Comparison of Actual values vs. Fitted Values for Class 1.

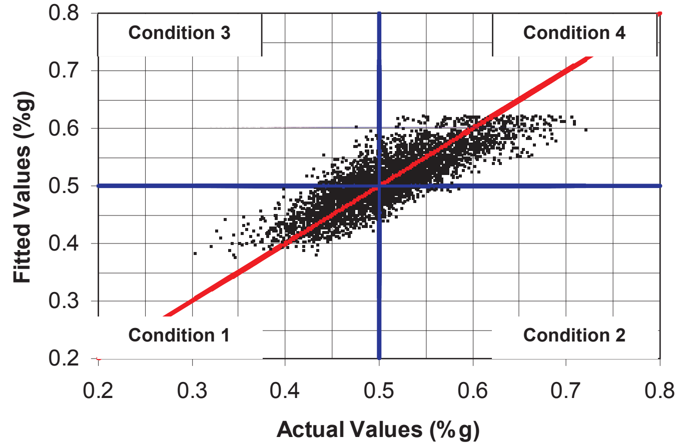

Fig. 2. Comparison of Actual values vs. Fitted Values for Class 2.

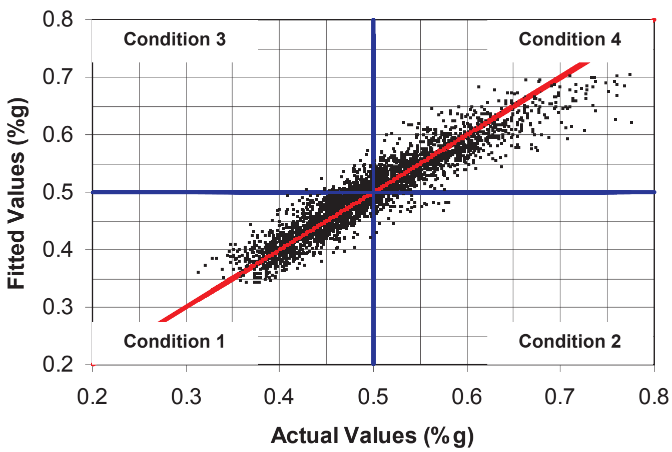

Fig. 3. Comparison of Actual values vs. Fitted Values for Class 3.

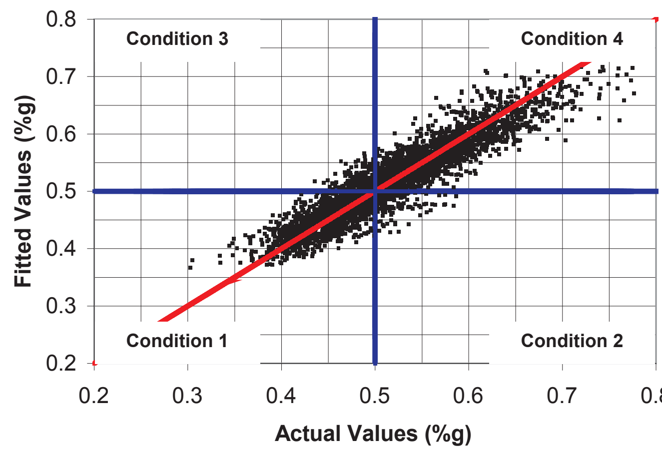

Fig. 4. Comparison of Actual values vs. Fitted Values for Class 4.

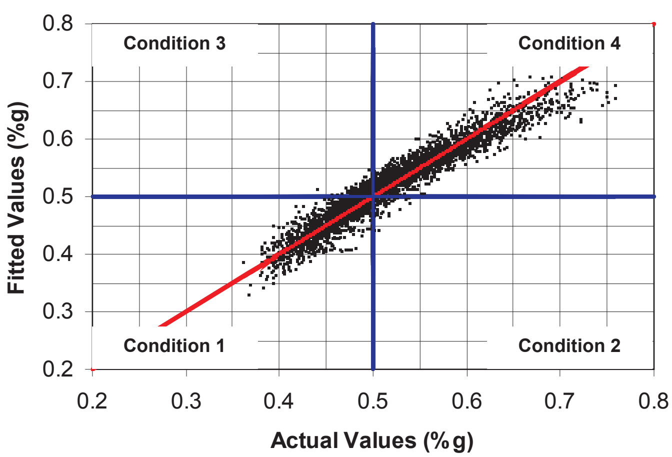

Fig. 5. Comparison of Actual values vs. Fitted Values for Class 5.

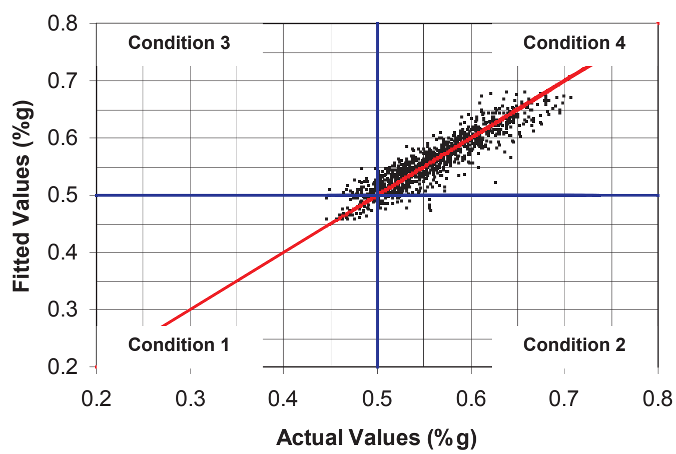

Fig. 6. Comparison of Actual values vs. Fitted Values for Class 6.