The Cost Equation
when designing for floor vibrations

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When it comes to selecting floor framing systems for vibration serviceability, consider more than than just structural costs.

CHOOSING FLOOR FRAMING FOR A STEEL OFFICE BUILDING IS OFTEN BASED ON STRUCTURAL COST, with some consideration for floor vibration serviceability. In essence, a lowest structural cost vs. vibration performance decision is made. When lowest structural cost wins, the result can be a floor system that is susceptible to walking-induced vibration that occupants find disturbing. By looking beyond structural cost and examining the other construction costs that are impacted by floor system selection, the perceived cost savings of choosing a lightweight system might not be as favorable as one might think. In this paper, we'll examine three steel-framed floor systems for other associated costs to show that if a seemingly inexpensive floor system is, in fact, susceptible to vibration problems, it may not be so inexpensive after all. We'll evaluate these three prototype designs, representing typical structural framing, for vibration performance, structural cost, fire protection cost, and façade cost.

Floor System Designs Evaluated

A typical bay layout was developed and used for the three floor system designs, and is shown in Fig. 1. The three floor systems designed were as follows:

1. Open-web steel joists supported by rolled steel girders with a 1-in.-deep steel form deck supporting a 2½-in. lightweight concrete topping slab (total slab depth is 3½ in.).
2. Composite steel beams and girders with a 2-in.-deep composite steel deck supporting 3¼-in. lightweight concrete topping slab (total slab depth is 5¼ in.).
3. Non-composite steel beams and girders with a 3-in.-deep composite steel deck supporting a 4½-in. normal weight concrete topping slab (total slab depth is 7½ in.).

Details of the designs and governing assumptions can be found in Chattoraj (2005), and a summary of the design results is presented in Table 1. In all of the designs, the girders run along the lettered column lines, and the beams or joists run along the numbered column lines. Other system characteristics presented in this table are described in subsequent sections.

Evaluation for Vibration Serviceability

The three floor system designs described were evaluated for floor vibration serviceability using the walking vibration criterion in the AISC *Design Guide 11* (Murray, et al. 1997). The criterion for offices requires that the following inequality be met:

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

where a_o/g = 0.5% for offices; P_o = 65 lb for offices; β = 0.03 for regular offices with hung ceilings below; f_n is the fundamental natural frequency of bay, Hz; and W is the effective panel (bay) weight.

The details of this analysis can be found in Chattoraj (2005), and the results of this evaluation are presented in Table 2. The composite and non-composite systems are found acceptable for both bay sizes with the non-composite system having the best vibration performance. The joist system was found unacceptable for vibration performance with the 30-ft by 30-ft bay being most susceptible to objectionable vibration levels due to people walking in the space. This system was redesigned two different ways to result in an acceptable design. The first redesign changed only the joist size to yield acceptable performance; the second redesign changed the slab, deck, concrete, joists, and girders to offer a less expensive redesign. Summaries of the redesign results and vibration evaluation are also included in Tables 1 and 2, respectively.

Design for Fire Protection

Floor system configuration has an impact on the fire protection design to meet the required two-hour fire ratings in the code. Several configurations meeting fire protection requirements were studied for each floor system. The least expensive option was selected for use in the cost

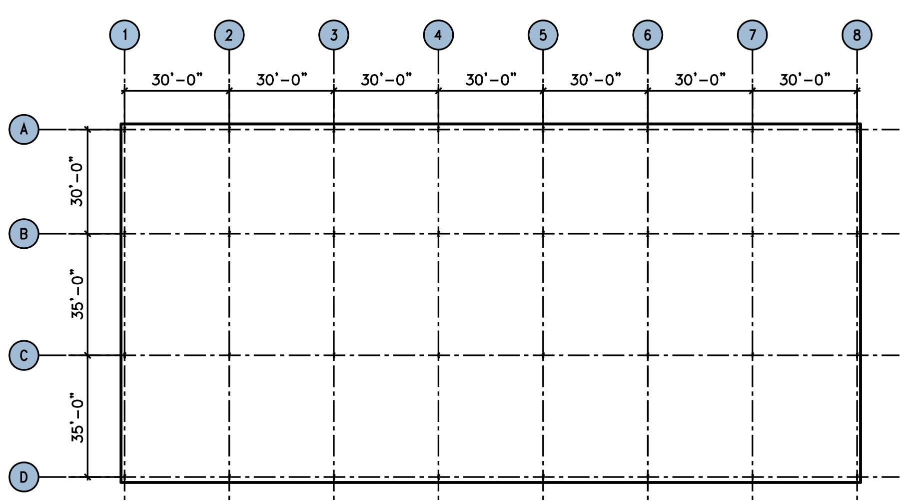

Figure 1. Prototype building floor plan.

Table 1. Summary of Floor System Characteristics

	Joist System	Non-Composite System	Composite Beam System	Redesign No. 1	Redesign No. 2
Topping Slab (in.)	2.5	4.5	3.25	2.5	4
Deck Depth (in.)	1	2	2	1	1.5
Concrete Type	Lightweight	Normal-Weight	Lightweight	Lightweight	Normal-Weight
Beam (30 ft span)	20LH6	W18x35	W16x26	28LH11	24LH9
Beam (35 ft span)	24LH6	W18x40	W18x35	28LH13	28LH9
Beam Spacing	4′-3⅜″	7′-6″	10′-0″	4′-3⅜″	5′-0″
Composite/Non-Composite	Non-Composite	Non-Composite	Composite	Non-Composite	Non-Composite
Girder	W24x76	W27x84	W24x55	W24x76	W27x84
Column Type	Wide-Flange	Wide-Flange	Wide-Flange	Wide-Flange	Wide-Flange
Vibration Susceptibility	Susceptible	Not Susceptible	Not Susceptible	Not Susceptible	Not Susceptible
Story Height	13′-2″	13′-0″	12′-10″	13′-6″	13′-8″
Structure weight (tons)	453	967	600	480	805
Fire Protection Type	Rated Ceiling	Unprotected Deck	Unprotected Deck	Rated Ceiling	Rated Ceiling
Column Protection	Spray	Spray	Spray	Spray	Spray
Sprinklers / No Sprinklers	No Sprinklers	No Sprinklers	No Sprinklers	No Sprinklers	No Sprinklers
Façade Type	Curtain wall	Curtain wall	Curtain wall	Curtain wall	Curtain wall

comparison presented in the next section. Other options and more details on the selected options are presented in Chattoraj (2005). For the joist system, a rated ceiling is required to achieve adequate fire protection without using sprinklers (a more expensive option). This is primarily because the slab has insufficient thickness to act as a fire barrier. The steel framing members in the composite and non-composite systems require spray-on fireproofing to achieve the two-hour fire rating. In the composite system a 3¼-in. lightweight topping slab on composite deck was selected because this is the minimum thickness that can be used without adding spray fireproofing to the deck. Similarly, the non-composite system was configured with a 4½-in. normal-weight topping slab to avoid the need for spray fireproofing on the deck to achieve a two-hour fire rating.

Cost Comparison

The cost per square foot of floor area was calculated using RS Means (2004) for the structural system, the curtain wall system, and the fire protection system. These are the primary costs affected by the selection of the floor system. The percentages noted in Fig. 2 are the cost differences for the various systems with the joist floor system as the basis. Assuming a constant finished ceiling height, the curtain wall cost is a function of the depth of the floor construction. The composite system produced a shallower depth and, therefore, reduced cost for the curtain wall. This differential will vary with individual designs. Since the non-composite and composite systems were designed with adequate slab thickness to achieve a two-hour fire rating without spraying the deck, the cost of protecting these floor system structures is less than protecting a joist system. Rated ceilings are more expensive and only the increased cost of the ceiling system was included as a cost in fire protection.

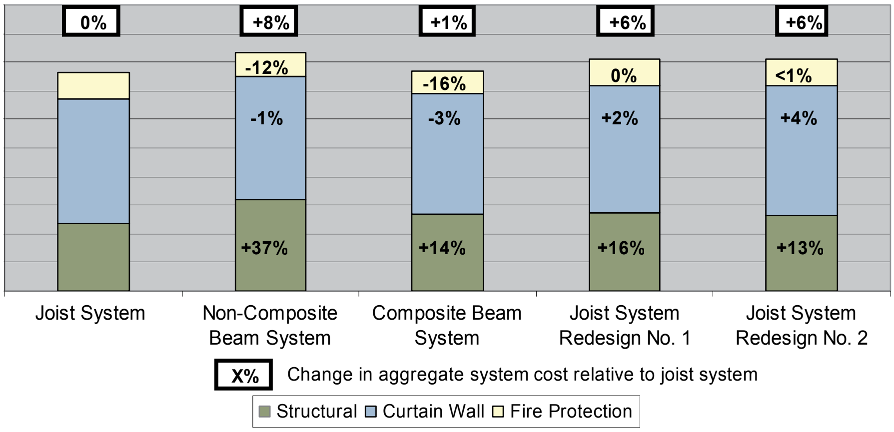

Figure 2. Relative cost differences using the joist system as a basis.

Conclusion

All of the floor system structural members in this case study are designed for the same purpose and loads, and the costs vary by as much as 37%. Each lighter-weight system in this paper is less costly than the heaviest system, the non-composite beam system. Therefore, lighter-weight systems can be economical from a strength, deflection, and vibration serviceability standpoint. However, the lowest cost option here is not the best option overall because it is susceptible to excessive vibration. As a result, the building must be examined as a whole to find the best option.

To obtain the lowest-cost building for the given bays and loads, the least-weight wide-flange beams with a large spacing

Table 2. Summary of Vibration Evaluation

	Joist System	Non-Composite Beam System	Composite Beam System	Joist Redesign No. 1	Joist Redesign No. 2
			30-ft by 35-ft Bay		
f_n (Hz)	4.4	6.0	5.1	4.7	4.3
W (kips)	63.1	179.0	123.4	83.0	109.2
a_p/g (%)	0.73	0.15	0.29	0.50	0.40
Limit, a_o/g (%)	0.50	0.50	0.50	0.50	0.50
Susceptible to Excessive Vibration?	Yes	No	No	No	No
			30-ft by 30-ft Bay		
f_n (Hz)	3.7	4.8	4.2	5.2	3.5
W (kips)	72.9	204.8	123.1	70.9	130.8
a_p/g (%)	0.81	0.20	0.40	0.50	0.49
Limit, a_o/g (%)	0.50	0.50	0.50	0.50	0.50
Susceptible to Excessive Vibration?	Yes	No	No	No	No

and a 3¼-in. lightweight topping slab or a 4½-in. normal-weight topping slab should be used. With these slab configurations, the fire protection costs will be kept to a minimum. In addition, the strength design should meet the vibration susceptibility criteria from the beginning. If the strength design leads to a vibration-susceptible floor system in lieu of changing one component of the system, the entire system should be redesigned. Furthermore, the depth of the floor system should be as shallow as possible to allow for reduced exterior skin costs.

Several general conclusions can be drawn that are applicable to buildings outside of this case study. One conclusion is that the strength design of a floor can meet the vibration susceptibility criteria without greatly increasing the overall building cost. Another is that the floor system has an effect on the remainder of the building and cannot be viewed successfully as an independent feature. The most important conclusion, however, is that the building must be evaluated as a whole to determine the cost-effectiveness of the floor system. MSC

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References

Chattoraj, Melissa C., *Lightweight Steel Floor Systems: The Cost Implications of Minimizing Floor Vibrations*, MS Thesis, Department of Architectural Engineering, Pennsylvania State University, August 2005.

Murray, T.M., Allen, D.E. and Ungar E.E., "Floor Vibrations Due to Human Activity," *Steel Design Guide 11*, AISC, Chicago, 1997.

RSMeans Building Construction Cost Data, 62nd Edition, Reed Construction Data, 2004.

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