Vibration Characteristics and Acceptability of Cold-formed Steel Joists

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Abstract

Metal building manufacturers have developed proprietary steel joists (e.g., truss purlins) made of cold-form steel for use as roof systems in long-bay buildings. The question has been raised: Is it reasonable to use such members to support concrete floor systems where vibration due to human activity prevails? This study investigated analytically a number of steel framed floor systems with cold-formed steel trusses with the dual objectives: (1) To gain a better understanding on the vibration characteristics of cold-form steel joists; (2) To examine if the floor joist system meets the current vibration acceptability criteria as specified in AISC Design Guide 11. The ultimate goal of this study was to provide guidelines to the industry and professionals on the proper use of cold-form steel joists in vibratory environment and their serviceability requirements.

Introduction

In an effort to achieve long-bay building solutions some metal building manufacturers have developed proprietary cold-formed truss purlins. These members are formed of chords and webs of cold-formed steel joined together at the panel points with either welds, screws, or bolts. Since the truss purlin provides the metal building manufacturer with a product that is comparable with K-series bar joist in the roof, it would be reasonable to try to use them in floor systems. Design of the truss for gravity loading is rather straightforward. However, vibration of floor systems has increasingly become a problem over the years. Therefore manufacturers should be aware of this serviceability issue and understand whether their product meets current vibration standards.

Traditional methods of limiting floor joist live load-deflection to L/360 or joist depth-to-span ratios to 24 or less may not adequately address vibration problems. Load and resistance factor design, the use of lightweight concrete and lighter design loads have allowed designers to increase member spans with lighter weight members further increasing the chances of annoying floor vibrations due to human activity. In today's office buildings, lightweight cubicles have replaced heavy steel desks and computers with electronic data storage have replaced heavy filing cabinets of paper records. The lack of full height partitions and reduction in weight of office equipment reduces the natural damping of the floor system thus magnifying potential floor vibration problems.

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In 1997 the American Institute of Steel Construction (AISC) published a design guide[1] addressing floor vibration due to human activity to provide design engineers the latest information regarding dynamic analysis of steel framed floor systems. The design guide also provides provisions for dynamic analysis of floor systems consisting of K-series bar joist and steel girders. Nevertheless, that document did not specifically address cold-formed steel joists. This study examined the suitability and adequacy of the AISC procedure for floor systems consisting of cold-formed steel trusses and wide flange steel girders. The primary objective of this study was to analyze non-composite floor systems consisting of cold-formed steel trusses, a cast-in-place concrete slab, and wide flange steel girders for floor vibrations due to walking excitation. Variables such as floor slab thickness, truss span, and live loads were varied to study the floor system's susceptibility to floor vibration. It should be noted that although the floor systems of this study do not have shear studs for a full structural composite action, the system does behave as partially composite for vibration purposes.

Truss Specimen

The cold-formed steel truss to be analyzed became available in the 1960's. It is a constant depth member where both the top and bottom chords are cold-formed hat shapes of varying thickness with flange lips (Figs. 1 & 2). The webs are made from continuous tubes bent and flattened at 30 in (76.2 cm) on centers where they are welded to the chords. The section depth and member profile is fixed with only the material thickness varying with the loading. This truss purlin system is capable of supporting typical static floor loads at similar spans as K-series bar joists. However, it has never been analyzed for the dynamic loads due to human activity that is found in floor systems.

Human Activity

Human activity such as walking, jumping, or dancing excites floor systems causing them to vibrate. These are transient vibrations, which cannot be isolated; therefore they must be controlled by the structure. Excessive floor vibration typically occurs when floor systems have inadequate stiffness, low damping and/or low mass.[2] However, vibration perception is highly subjective and not a well defined or measured phenomena. Vibration is not a structural problem, but rather a serviceability issue that generally isn't well addressed in building codes or design specifications.

Floor systems can be modeled as a simple mass connected to the ground by a spring and damper. A person walking across the floor exerts a vertical sinusoidal force on the floor system. Resonance occurs when the frequency of the sinusoidal forces is the same as the natural frequency of the floor system. The natural frequency of concrete floor slabs supported by structural steel can be close to or match a harmonic forcing frequency, so resonant amplification is commonly associated with floor vibration problems. Interestingly, floor systems with first natural frequencies between 5-8 Hz correspond with natural frequencies of human internal organs which most likely will result in occupant discomfort.[2]

Repeating forces can be modeled by a combination of sinusoidal forces with frequencies, f, which are harmonics, or multiples, of the repeating force's basic frequency. Eqn (1) represents the Fourier series of the time-dependent repeating force.

$$F = P\,[1 + \Sigma\alpha_i\cos(2\pi i f_{step} t + \varphi_i)] \qquad (1)$$

where P = person's weight, α_i = dynamic coefficient for the harmonic force, i = harmonic multiple (1,2,3.. ..), f_{step} = step frequency of the activity, t = time, and φ_i = phase angle for the harmonic motion.

The dynamic coefficient typically decreases with increasing harmonics resulting in harmonic forces that are smaller than the lowest mode of vibration. Therefore, only the lower modes are of interest when considering vibration due to human activity.

Literature Review

The readers are reminded to refer to the available literature for more comprehensive review including the research reported by Aswad and Chen.[3]

Among other researchers, Hanagan and Murray[4] conducted several studies on floor system vibration which form the basis of the AISC Design Guide 11.[1] He reported that system frequency, f_n (Hz), can be approximated by the Dunkerly relationship: Among other researchers, Hanagan and Murray[4] conducted several studies on floor system vibration which form the basis of the AISC Design Guide 11.[1] He reported that system frequency, f_n (Hz), can be approximated by the Dunkerly relationship:

$$1/f_n^2 = 1/f_j^2 + 1/f_g^2 \qquad (2)$$

where f_j = the beam or joist panel mode frequency (Hz) and f_g = the girder panel mode frequency (Hz).

Their research demonstrates the importance of floor damping and recommends a minimum damping ratio for floor systems. Their approach was found to be suitable for floor systems with natural frequencies between 5-8 Hz, as had been reported in Aswad and Chen.[3]

The AISC Design Guide presents a procedure where the mode properties of the individual components (beams, girders, and columns) including effective panel weights and natural frequencies are calculated. The combined mode frequency is calculated using eqn (2) and a combined mode weight is established based upon the relationship of the deflection of the components to the deflection of the combined mode. The acceleration expressed as a ratio of gravity is then compared to allowable maximum values shown in Table 1. The peak acceleration due to walking, a_p, can be expressed in terms of the gravity acceleration (g) as:

$$a_p/g = P_0 e^{-0.35 f_n}/(\beta W) \qquad (3)$$

where P_0 = a constant force representing the excitation, f_n = the fundamental natural frequency of a structural element or the system, β = modal damping ratio, and W = the effective weight of a structural component or the system.
If the floor system has a natural frequency greater than 9 Hz the floor system stiffness

must be greater than 5.7 kips/inch (1.0 kN/mm).

Table 1Recommended Values of Parameters in Eqn (3) and Acceleration Limits

	Constant Force P_0, lbs (N)	Damping Ratio β	Acceleration Limit
Offices, Residences & Churches	65 (289)	0.02-0.05	0.005 g
Shopping Malls	65 (289)	0.02	0.015 g
Indoor Footbridges	92 (409)	0.01	0.015 g

Parametric Studies and Analysis Procedures

Floor systems

This study analyzed floor systems with four square grid systems having the following sizes of 20 ft (6.096 m), 25 ft (7.620 m), 30 ft (9.144 m), and 35 ft (10.668 m). The floors were assumed to be typical interior bays without openings in the floor slab so the influence of edge conditions were not included in this study. For each floor system the joists are spaced at 2 ft 6 in (76.2 cm) on centers typically. A 28 gage thick floor deck was assumed for all floor systems.

The floor slab thickness varies between 2 ½ in (64 mm) and 4 in (102 mm) in ½ in (13 mm) increments. Both lightweight concrete with the unit weight of 115 pcf (1842.1 kg/m^3) and normal weight concrete with the unit weight of 145 pcf (2322.7 kg/m^3) were used. The live loads used in the gravity design of the floor systems are 80 psf (3830 Pa), 100 psf (4788 Pa) and 125 psf (5985 Pa), respectively. These live loads are typical for mezzanines or floors above ground level for offices, schools, light manufacturing or light storage.[5] See Fig. 3 for the typical floor layout.

Analysis and model

The floor systems were modeled and designed for gravity loads using a commercially available software. Both the beams and truss members were designed for L/360 deflection under live load and L/240 under combined dead load and live load, where L = span length. The floor system was then analyzed for vibration according to the procedures and criteria outlined in the AISC Design Guide[1] using a developed spreadsheet.

Seven different cold-formed truss configurations were designed for the various floor systems in this study. The chord thickness varies from 0.060 in (1.5 mm) to 0.124 in (3.1 mm). The web members were neglected in the calculation of the truss center of gravity and the moment of inertia (I_x). The truss depth is kept at constant at 29½ in (74.9 cm). I_x varies from 183.09 in^4 (7620.8 cm^4) to 372.17 in^4 (15490.9 cm^4).

Recommended modal damping ratios for the typical uses of these floor systems ranges from 2% to 5%.[1] The use of 2% is recommended for floors with few non-structural components such as ceilings, ducts, and partitions. A value of 3% is recommended for floors with non-structural components and furnishings, but with only small demountable partitions that are typical of many modular office areas. A damping ratio of 5% is recommended for floor systems that have full height partitions. A damping ratio of 3% was used is this study as there is likely sufficient damping in most uses to justify this value while at the same time not being too unconservative.

Joist and girder panel mode properties

The fundamental mode frequency of both the joist and the girder are calculated separately and then combined using eqn (2) to calculate the fundamental mode frequency for the floor system. The combined fundamental mode frequency is used in eqn (3) to determine the floor system's peak acceleration as a percentage of gravity. This value is compared to the acceptable values shown in Table 1.

Due to the actual composite action between the concrete slab floor and the joist, a transformed moment of inertia may be calculated considering the effective slab width supported by the floor joist. The joist fundamental frequency, f_j (Hz), is then calculated by:

$$f_j = 0.18\sqrt{g/\Delta_j} \tag{4}$$

where Δ_j = the midspan deflection of the member due to the weight supported.

The calculations of the girder mode properties begin with calculating a transformed moment of inertia based upon an effective slab width. The transformed moment of inertia must then be reduced due to the greater flexibility of the joist ends as compared to the rest of the joist per the following equation:[1]

$$I_g = I_{nc} + (I_c - I_{nc})/4 \tag{5}$$

where I_g = girder moment of inertia reduced for joist ends flexibility, I_{nc} = girder non-composite moment of inertia, and I_c = girder composite moment of inertia.

Note that Eqn (5) was based on steel joist bearings and further study may indicate less composite action. The girder fundamental mode frequency is calculated using eqn (4) by substituting the girder properties into the equation in lieu of the joist properties.

Combined mode properties and walking evaluation

The fundamental mode properties of the individual components are combined according eqn (2) as shown in the following equation:

$$f_n = 0.18\sqrt{g/(\Delta_j + \Delta_g)} \tag{6}$$

where Δ_g = the midspan deflection of the girder member due to the weight supported. Columns in tall buildings can have vertical frequencies low enough to create resonance problems. For those cases eqn (6) is modified to include the axial shortening of the column due to the supported weight,

$$f_n = 0.18\sqrt{g/(\Delta_j + \Delta_g + \Delta_c)} \qquad (7)$$

where Δ_c = the axial shortening of the column due to the weight supported.

The effects of columns, generally negligible in most buildings, are not included in this study. The equivalent panel weight for the combined mode is calculate using the following equation:

$$W = (\Delta_j W_j)/(\Delta_j + \Delta_g) + (\Delta_g W_g)/(\Delta_j + \Delta_g) \qquad (8)$$

where W_j = the effective panel weight for the joist and W_g = the effective panel weight for the girder.

Using eqn (3), the constant force, Po, and damping ratio, β from Table 1 the floor acceleration can be calculated and compared to the limit in Table 1. If the floor system fundamental frequency is greater than 9 Hz the floor should have a minimum stiffness of 5.7 kip/in (1 kN/mm).

Analysis Results and Discussions

The calculated floor system acceleration was compared to the acceptable values to determine whether the floor vibration was satisfactory.

Floor system acceleration

For each floor system, the acceleration, expressed as a percentage of the acceleration of gravity is summarized in Tables 5 and 6. The value must be less than or equal to 0.50 to be considered acceptable for walking excitation. The tables show only 19 (shown in boldface in the tables) out of the 96 floor systems studied meet this vibration acceptance criterion. Though the majority of the floor systems are not satisfactory for walking excitation, none of them had a fundamental frequency greater than 9 Hz which would have required additional analysis of the floor stiffness.

Table 2 Floor System Acceleration with Light-Weight Concrete, a_p/g, (%)

Span (ft)	Live Load					
	80 psf	100 psf	125 psf			
	Slab Thk., in.	Slab Thk., in.	Slab Thk., in.			
	2½-4	2½-4	2½	3	3½	4
20	> 0.50	> 0.50	**0.41**	**0.40**	**0.39**	**0.38**
25	> 0.50	> 0.50	0.58	0.56	0.54	0.52
30	> 0.50	> 0.50	0.66	0.62	0.54	0.51
35	> 0.50	> 0.50	0.64	0.60	0.56	**0.47**

1 ft = 0.3048 m; 1 in = 25.4 mm; 1 psf = 47.88 Pa.

Table 3 Floor System with Normal-Weight Concrete, a_p/g, (%)

Span (ft)	Live Load								
	80 psf		100 psf			125 psf			
	Slab Thk., in.		Slab Thk.			Slab Thk., in.			
	2½-3½	4	2½&3	3½	4	2½	3	3½	4
20	OK	**0.50**	OK	**0.38**	0.60	**0.41**	**0.40**	**0.39**	**0.34**
25	OK	0.51	OK	0.52	**0.49**	0.57	0.54	0.54	**0.41**
30	OK	0.67	OK	0.55	0.51	0.57	0.54	0.51	**0.45**
35	OK	**0.50**	OK	**0.50**	**0.49**	0.61	**0.49**	**0.49**	**0.45**

1 ft = 0.3048 m; 1 in = 25.4 mm; 1 psf = 47.88 Pa.

Representative floor system acceleration percentages are summarized in Tables 4 to 7. In general, the floor system acceleration ratio decreases between 5% and 34% as the floor slab thickness increased for a given uniform live load and span. These changes are to be expected due to the additional dead load of the thicker floor slab which increases the total equivalent panel weight, W in eqn (3).

The floor acceleration tends to increase by as much as 56% with increasing span lengths for the same slab thickness and live load. Interestingly the acceleration percentage often appears to peak between 25 ft (7.62 m) and 30 ft (9.144 m) spans. This may indicate that trusses at those spans may be more likely to experience annoying vibration. As the frequency decreases, such as it does with increasing floor slab thickness and truss span length, the value of this term increases thereby increasing the acceleration ratio.

Table 4 Acceleration Percentage of C-Series Floors (Light-weight Conc; LL = 125 psf)

Span (ft)	Acceleration Percentage, a_0/g							
	2½-in slab		3-in slab		3½-in slab		4-in slab	
20	C1	**0.41**	C2	**0.40**	C3	**0.39**	C4	**0.39**
25	C5	0.58	C6	0.56	C7	0.54	C8	0.52
30	C9	0.66	C10	0.62	C11	0.54	C12	0.51
35	C13	0.64	C14	0.60	C15	0.56	C16	**0.47**

1 ft. = 0.3048 m; 1 in. = 25.4 mm; 1 psf = 47.88 Pa.

Table 5 Acceleration Percentage of D-Series Floors (Normal-weight Conc; LL = 80 psf)

Span (ft)	Acceleration Percentage, a_0/g							
	2½-in slab		3-in slab		3½-in slab		4-in slab	
20	D1	0.66	D2	0.54	D3	0.52	D4	**0.50**
25	D5	0.70	D6	0.66	D7	0.54	D8	0.51
30	D9	0.70	D10	0.65	D11	0.67	D12	0.52
35	D13	0.69	D14	0.64	D15	0.59	D16	**0.50**

1 ft. = 0.3048 m; 1 in. = 25.4 mm; 1 psf = 47.88 Pa.

Table 6 Acceleration Percentage of E-Series Floors (Normal-weight Conc; LL = 100 psf)

Span (ft)	Acceleration Percentage, a_0/g							
	2½-in slab		3-in slab		3½-in slab		4-in slab	
20	E1	0.56	E2	0.55	E3	**0.43**	E4	**0.38**
25	E5	0.60	E6	0.57	E7	0.52	E8	**0.49**
30	E9	0.63	E10	0.58	E11	0.55	E12	0.51
35	E13	0.65	E14	0.60	E15	**0.50**	E16	**0.49**

1 ft. = 0.3048 m; 1 in. = 25.4 mm; 1 psf = 47.88 Pa.

Table 7 Acceleration Percentage of F-Series Floors (Normal-weight Conc; LL = 125 psf)

Span (ft)	Acceleration Percentage, a_0/g							
	2½-in slab		3-in slab		3½-in slab		4-in slab	
20	F1	**0.41**	F2	**0.40**	F3	**0.39**	F4	**0.34**
25	F5	0.57	F6	0.54	F7	0.54	F8	**0.41**
30	F9	0.57	F10	0.54	F11	0.51	F12	**0.45**
35	F13	0.61	F14	**0.49**	F15	**0.48**	F16	**0.45**

1 ft. = 0.3048 m; 1 in. = 25.4 mm; 1 psf = 47.88 Pa.

Floor system frequency

The fundamental frequencies of the trusses, floor beams and system as a whole are shown in Figs. 4-9. Initially, the truss fundamental frequencies are much greater than both the floor beam and overall floor system frequencies. Then they trend down toward the overall system fundamental frequency. The frequencies of the floor beams do not exhibit the same range as the trusses. Generally, the line representing floor beam frequencies is parallel to the line representing the overall floor system frequency.

The floor system fundamental frequency decreases by up to a maximum of 9.2% with increasing floor slab thickness, under a given uniform live load and span. The floor system fundamental frequency decreases between 41.1 % and 48.3% with increasing span lengths given a uniform live load and floor slab thickness. This change is primarily a function of the span length alone and is an indication of decreasing floor stiffness with span. This is to be expected since eqn (4) can be re-written by substituting $\Delta_j = 5wL^4/(384E_sI_T)$ as:

$$f_n = (\pi/2)\sqrt{gE_sI_T/(wL^4)} \quad (9)$$

where E_s = Young's modulus, I_T = transformed moment of inertia, w = loading, and L = span length.

As noted, f_n is inversely proportional to w and L.

Conclusions and Recommendations

Overall floor system evaluation

Further investigation of floor systems that failed the walking vibration criteria shows that increasing the truss chord thicknesses does very little to improve the system acceleration percentages. Typically those values only come down by 1-3% points. Combining the heavier trusses with reduced truss spacing may reduce the overall system acceleration between 1-8% points. Using heavier floor beams appears to be the most effective at significantly reducing the system acceleration. This indicates the floor system acceleration is more influenced by the beams than the truss, as shown in Figs. 4-9. This is in line with the AISC recommendation which states that stiffening the structural components with the lowest fundamental frequency are the ones which should be stiffened to remedy floor vibration problems.[1]

Since the cold-formed trusses have a higher fundamental frequency than the supporting beams, the trusses can be used in floor systems provided the vertical acceleration is computed and compared to the procedures and criteria as described in the AISC Design Guide[1]. According to the Steel Joist Institute, few steel joist-concrete slab floors exhibit annoying vibrations. The Steel Joist Institute also notes multiple sizes and types of joist will not improve the vibration characteristics of floor systems and recommends increasing the floor slab thickness as an effective way of improving the floor system's dynamic response.[6]

It is worth repeating that vibration perception is highly subjective and not a well defined or measured phenomenon. The evaluation criterion of 0.5 g is not an absolute value. Sound engineering judgment combined with the procedures and criteria as specified in the AISC Design Guide[1] will aid engineers in the design of an acceptable floor system.

Suggestions for further research

- Further parametric studies of these floor systems to compare the floor system performance with those floors with K-series bar joist to determine if there is a structural advantage for using either type of floor secondary members.
- In this study, the sections were assumed fully effective since the assumed load for vibration was less than 18% of the total design live load. However, the section properties of cold-formed steel sections vary with the stresses in the individual plate elements that make up the section. A more refined method such as the finite element analysis would be necessary to validate the assumption that the sections are fully effective.

Acknowledgement

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References

1. American Institute of Steel Construction, *Steel Design Guide Series* 11, *Floor Vibrations Due to Human Activity*, Chicago, IL 1997.
2. Laman, Jeffrey A., "Design Aids for Walking Vibrations in Steel Framed Floors", *Engineering Journal,* American Institute of Steel Construction, 2nd Qtr, 1999, pp 83-101.
3. Aswad, A. and Chen, Y, "Vibration Properties of Precast Building Floors," Pennsylvania State University, Harrisburg, PA, 1993.
4. Hanagan, Linda M. and Murray, Thomas M., "Experimental Implementation of Active Control to Reduce Annoying Floor Vibrations", *Engineering Journal,* American Institute of Steel Construction, 4th Qtr, 1998, ppI23-127.
5. *International Building Code,* International Code Council, 2003, pp. 275.
6. Steel Joist Institute, *Vibration of Steel Joist-Concrete Slab Floors*, Myrtle Beach, South Carolina, 1988.

Appendix- Notation

a_p = the peak acceleration due to walking
E_s = Young's modulus
f_j = the beam or joist panel mode frequency
f_g = the girder panel mode frequency
f_n = the fundamental natural frequency of a structural element or a system
f_{step} = step frequency of the activity
g = the gravity acceleration
i = harmonic multiple (1,2,3.. ..)
I_g = girder moment of inertia reduced for joist ends flexibility
I_{nc} = girder non-composite moment of inertia, and I_c = girder composite moment of inertia
I_T = transformed moment of inertia
I_x = moment of inertia about x (strong) axis.
L = span length
P = weight or force
P_0 = a constant force representing the excitation
t = time
w = loading
W = the effective weight of a structural component or a system
W_g = the effective panel weight for the girder
W_j = the effective panel weight for the joist
y_c = centroid of truss section measured from the top chord
α_i = dynamic coefficient for the harmonic force
β = modal damping ratio
φ_i = phase angle for the harmonic motion
Δ_c = the axial shortening of the column due to the weight supported
Δ_j = the midspan deflection of the member due to the weight supported
Δ_g = the midspan deflection of the girder member due to the weight supported

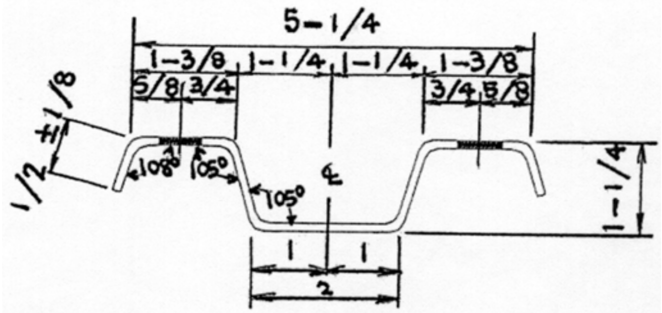

Fig. 1. Typical chord cross-section of the cold-formed steel truss (Dimensions in inches; 1 inch = 25.4 mm)

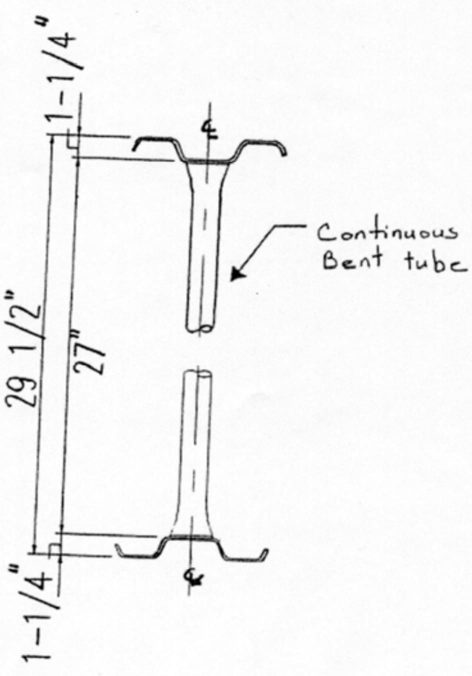

Fig. 2. Cross-section of the cold-formed steel truss (1 inch = 25.4 mm)

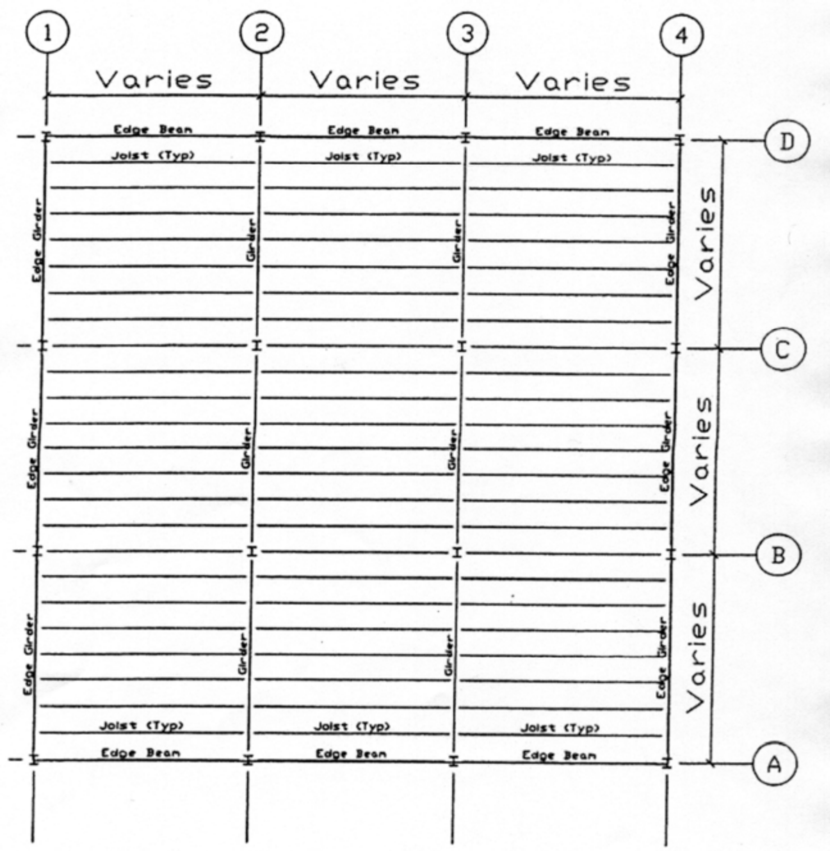

Fig. 3. Typical floor framing

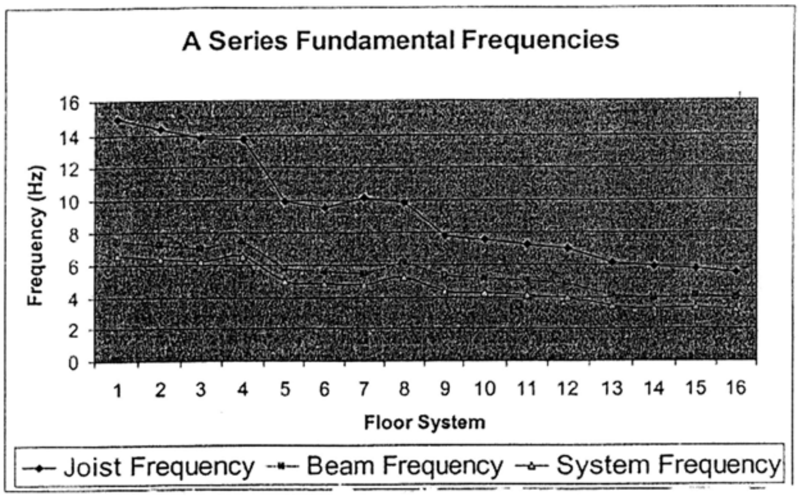

Fig. 4. Fundamental frequencies of A-series floor system
[Light-weight conc.; LL = 80 psf (3.830 kPa)]

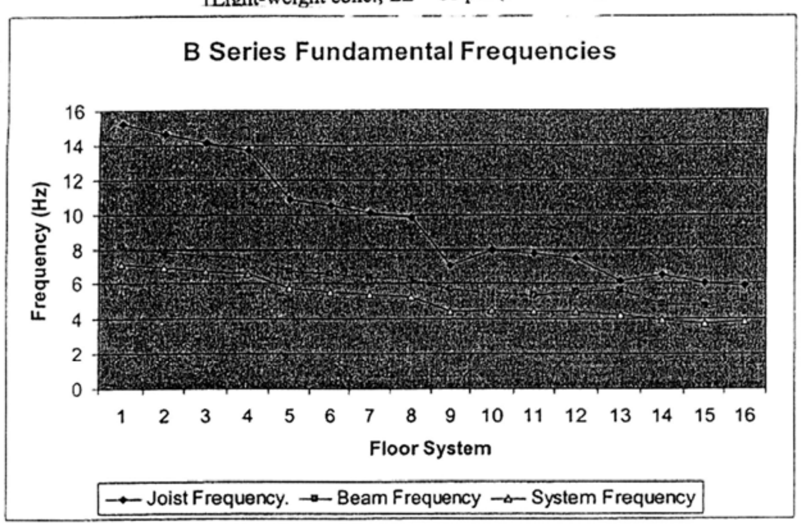

Fig. 5. Fundamental frequencies of B-series floor system
[Light-weight conc.; LL = 10 psf (4.780 kPa)]

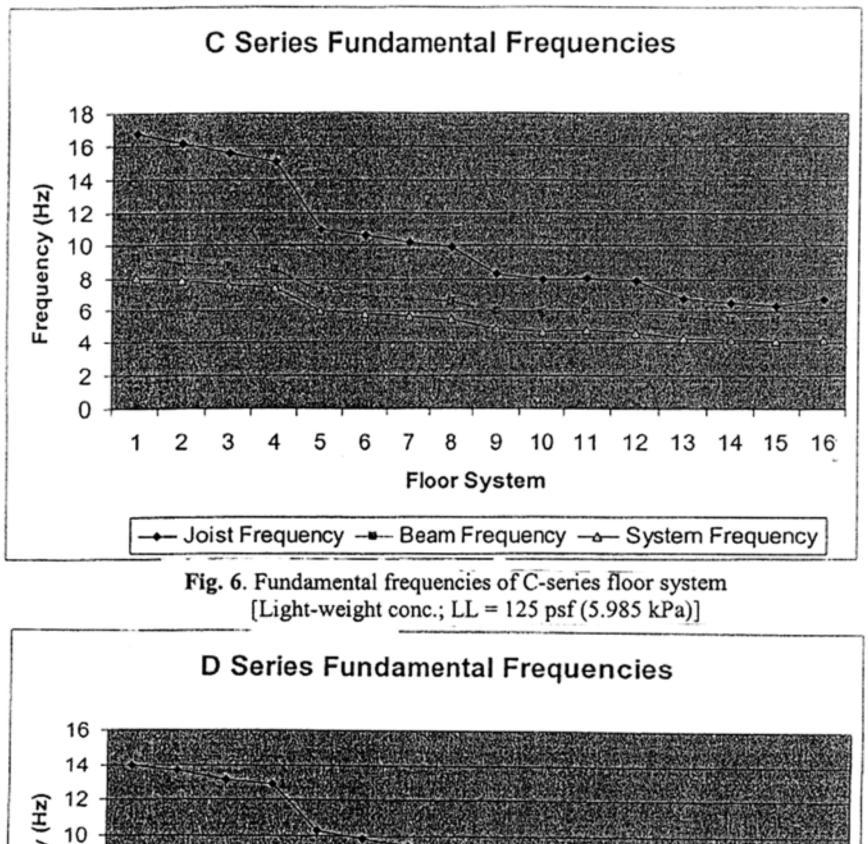

Fig. 6. Fundamental frequencies of C-series floor system
[Light-weight conc.; LL = 125 psf (5.985 kPa)]

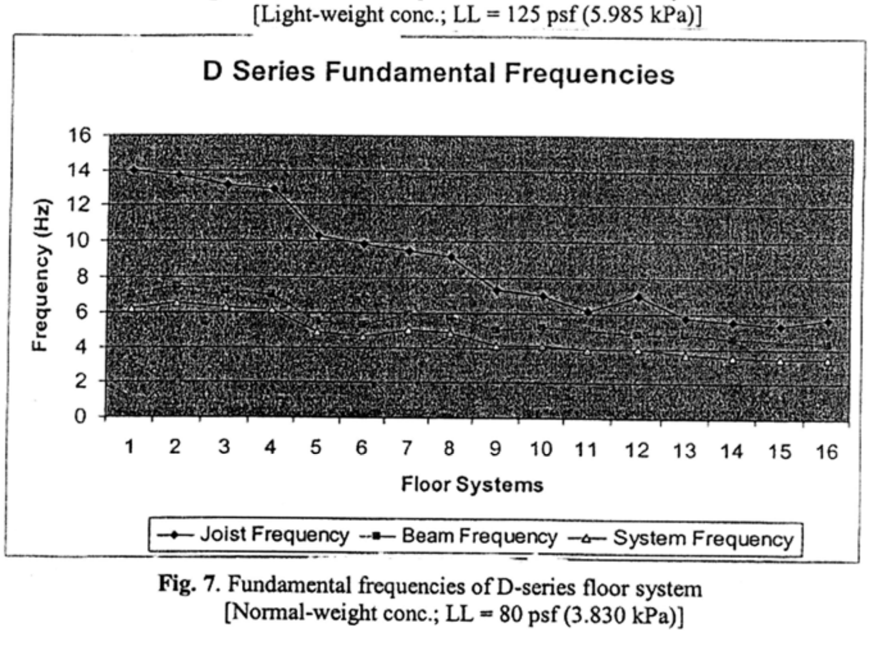

Fig. 7. Fundamental frequencies of D-series floor system
[Normal-weight conc.; LL = 80 psf (3.830 kPa)]

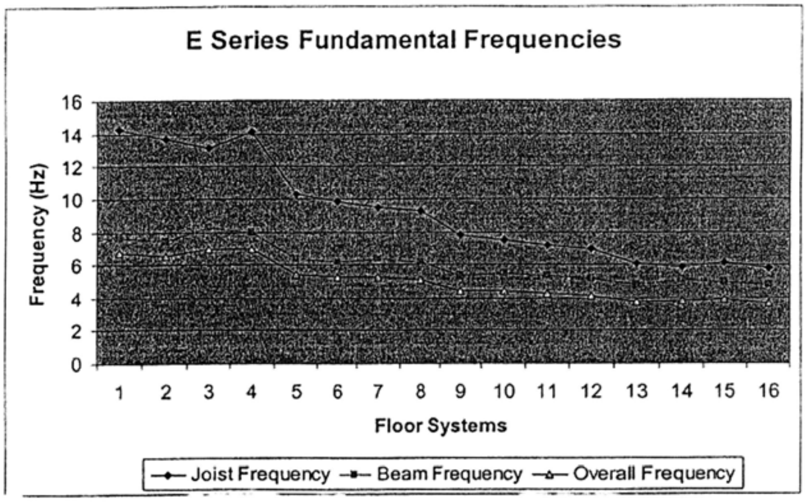

Fig. 8. Fundamental frequencies of E-series floor system [Normal-weight conc.; LL = 100 psf (4.780 kPa)]

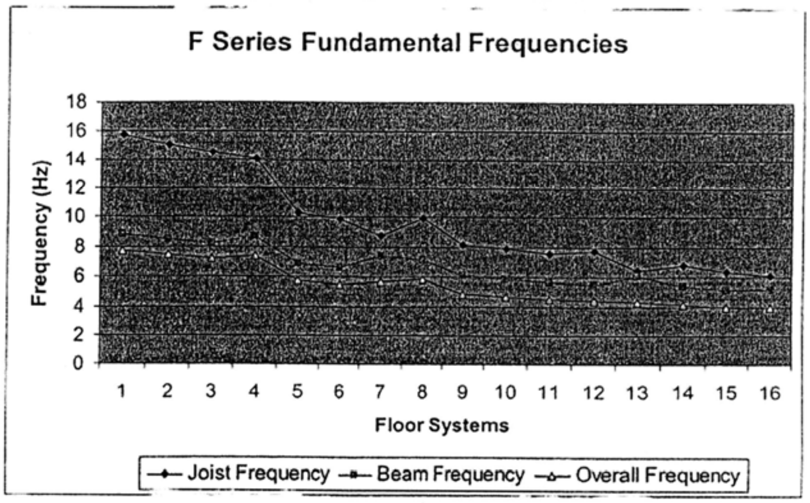

Fig. 9. Fundamental frequencies of F-series floor system [Normal-weight conc.; LL = 125 psf (5.985 kPa)]