Design Aids for Walking Vibrations in Steel Framed Floors

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ABSTRACT

Floor system vibration due to occupant activity is often ignored by designers; however, floor system vibration is an increasingly important serviceability criterion for occupant comfort and building owner satisfaction. Vibration occurs when the floor system design has: (1) inadequate stiffness; (2) low damping; or (3) low mass. When the floor system vibration response due to normal activity causes the occupants to become uncomfortable or annoyed, the successful use of the building is severely impaired. After-the-fact attempts to correct floor vibration problems are difficult, expensive, and usually not successful. This paper briefly reviews design criteria for floor systems, studies of human response to vibration, current code requirements, and the American Institute of Steel Construction (AISC) Steel Design Guide Series 11 for determining floor system vibration acceptability criteria. Several design aids are developed herein to promote the expedient verification of concrete slab on steel beam floor system acceptability as a general serviceability check during the design stage. An example is provided to demonstrate the application of the included design aids.

INTRODUCTION

To varying degrees, all floor systems exhibit an inherent flexibility and will respond dynamically to an exciting force. Building occupant activity as routine and benign as walking can be sufficient to excite a floor system so as to cause discomfort to other occupants within the immediate area. This phenomenon is problematic to the structural engineer in that the loading is transitory and neither the source nor the respondent can be isolated, unlike the routinely isolated dynamic machine loading causing steady state motion. In addition, several aspects of the building floor vibration problem result in this design criterion being overlooked: (1) the loading parameters are not easily or readily defined; (2) the structural response to the load is dynamic in nature; (3) the serviceability criterion for acceptance or rejection is not easily or precisely defined; and (4) the analysis procedure is often perceived to require advanced tools beyond the designer. Simply put, floor vibration serviceability is a separate and primarily psychological issue apart from the major concern of providing a safely designed structure with sufficient strength to resist wind, earthquake, snow, and other external loads.

Excessive floor vibration occurs when the floor system design has inadequate stiffness, low damping, and/or low mass. Several researchers have contributed to the refinement of the analytical model defining interaction and importance of these three critical parameters in evaluating the building floor system dynamic response. Transient floor vibrations in commercial buildings is the subject of this paper, including a brief discussion of past research to determine human response to vibration, an historical overview of the analytical development of dynamic floor models, a review of code criteria, and the development of design aids based on the state-of-the-art to promote the rapid verification of floor vibration serviceability criteria.

HUMAN RESPONSE TO VIBRATION

Floor motion, or vibration, is often caused by common human activities ranging from walking to running, dancing, and aerobics. Successful structural dynamic analytical models have been developed by several researchers for the typically encountered building floor systems; however, the human response to vibrations is not easily predicted. In addition, the characterization of the floor vibration to determine the physical phenomenon that humans are responsive to (e.g., frequency, displacement amplitude, velocity amplitude, accelerations) is not well understood. Many studies have been undertaken to quantitatively evaluate the human response to structural floor vibrations. Studies by the Building Research Establishment (1983), Goldman and Von Gierke (1961), Grether (1971), Guignard (1971), Lenzen (1968, 1971), Reiher and Meister (1931), Wiss and Parmelee (1974), Wright and Green (1969) have all contributed significantly to the understanding of human tolerance to structural floor vibrations in various environments. These studies indicate that response of building occupants to structural floor vibrations is a function of many

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parameters and considerations:

1. Steady state motion tends to be more objectionable than transitory vibrations.
2. The vibration acceptability is sensitive to the degree of damping in the floor system.
3. The activities of the occupants subjected to vibrations affects the perception of vibration.
4. Sensitivity of individual occupants is highly variable.
5. Vibration accompanied by observable and audible vibrations is perceived as more severe.
6. Perception and tolerance is highly dependent on occupant expectations of performance.

Several researchers have developed graphs to define domains of human response to vibrations as a function of frequency and amplitude. A commonly accepted graph was developed (Lenzen, 1971) by modifying the original Reiher-Meister (1931) human response curves to account for damping effects. Human response is categorized into one of four levels: (1) vibration not perceived; (2) vibration perceived but no annoyance; (3) vibration is disturbing; and (4) vibration not tolerable. Floor systems with first natural frequencies in the range of 5-8 Hz can result in discomfort due to a correspondence with natural frequencies of internal human organs (Hanes, 1970); therefore, care must be taken when designing floor systems in this frequency range.

Different criteria must be considered for the various building situations such as residential environments, office environments, commercial environments, and gymnasium environments. The discussion contained herein pertains to office and commercial type buildings, or buildings with similar occupant activities and construction. For further studies of human response, see literature reviews by Galambos et al. (1973), Hanes (1970), and Pool and Murray (1972).

CODE REQUIREMENTS AND GUIDELINES

A number of design specifications and guides provide guidance and design requirements for the minimization of floor vibrations. These include ASCE 7-95, *Minimum Design Loads for Buildings and Other Structures* (1995), AISC *Manual of Steel Construction, LRFD,* (1994), AISC Steel Design Guide Series 11 (Murray et al., 1997), and the Steel Joist Institute *Technical Digest No. 5* (1988). Each of these documents specifies limitations for floor vibrations and guidelines. The following is a brief review of these documents.

ASCE 7-95, Appendix B, Serviceability Considerations, specifies that:

> Floor systems supporting large open areas free of partitions or other sources of damping, where vibration due to pedestrian traffic might be objectionable, shall be designed with due regard for such vibration.

The Appendix B commentary of ASCE 7-95, B.1.3, *Vibrations,* notes that floor vibrations inhibit the serviceability of the building and that occupant complaints of disturbing vibrations have been increasing in recent years. The commentary suggests a simple screening method to identify floor systems that require a more in-depth analysis of floor vibrations. In the ASCE 7-95 procedure it is suggested that the natural frequency of floor systems be kept above 8 Hz to minimize the probability of vibration problems. The ASCE 7-95 procedure is useful for quickly determining whether objectionable floor vibrations *may* affect the design of the floor system, but is not rigorous enough to use as a basis for final design decisions that will affect the overall economy of the structure.

The Steel Joist Institute (SJI) *Technical Digest No. 5,* (1988) addresses issues specific to floor vibrations in systems incorporating open web steel joists as the secondary members. This type of structural framing system, while very economical, is somewhat more susceptible to floor vibrations than rolled sections due to higher slab and joist flexibility and the typically lower mass associated with this type of construction. The SJI *Technical Digest No. 5* approaches floor vibrations of open web steel joists as a two-way plate system, accounting for differing stiffness in the two orthogonal directions, that of the joist and that of the slab. The theoretical presentation of SJI *Technical Digest No. 5,* prepared by Galambos, is largely based on the experimental verification conducted by Lenzen (1968, 1971). The procedure determines: (1) an effective number of floor joists; (2) the natural frequency of the effective floor; and (3) the amplitude of the vibrations. After obtaining frequency and amplitude for the joist floor system, the two variables are plotted on a displacement versus frequency, human response graph to determine the acceptability of the system. Predictions of vibrations and the corresponding human response for this method were verified both in the laboratory and in the field with good results.

AISC (1994) also identifies floor vibrations as an important serviceability design consideration. Due to the use of higher strength steels and composite construction, floor systems contain less mass, which results in increased vibration due to human activity. Because of this, beam designs are increasingly governed by vibration considerations. AISC, (1994), Part 6, *Load and Resistance Factor Design Specification for Structural Steel Buildings,* Chapter L, *Serviceability Design Considerations,* states that:

> Vibration shall be considered in designing beams and girders supporting large areas free of partitions or other sources of damping where excessive vibration due to pedestrian traffic or

other sources within the building is not acceptable.

AISC (1994), Part 4, provides floor vibration design criteria and guidance based on the earlier research by Murray (1991, 1975).

AISC has published a comprehensive Steel Design Guide Series 11 (Murray, Allen, and Ungar, 1997) for the assessment of floor vibrations due to human activities. This guide discusses human comfort and sensitive equipment criteria for a wide range of structures in addition to remedial measures for floors. This guide forms the basis for the design aids presented herein and is discussed in the following section.

AISC Steel Design Guide Series 11

The current state-of-the-art for steel structures, contained in AISC Design Guide Series 11 (Murray et al., 1997) is briefly reviewed in the following for vibrations due to walking.

Allen and Murray (1993) have studied floor system vibrations extensively for many years and propose a design criterion based on wide experience, theoretical studies, laboratory studies, and field studies. Based on this study, the following acceptability criterion for walking vibrations in a structural floor system was published in the AISC Design Series 11:

$$\frac{a_p}{g} = \frac{P_o e^{(-0.35 f_n)}}{\beta W} \leq \frac{a_o}{g} \tag{1}$$

where:

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

P_o is a constant given in Table 1 representing the magnitude of the walking force, β = the modal damping ratio of the structural system given in Table 1, W is the effective mass weight of the floor, a_0 is the acceleration limit given in Table 1, g = acceleration due to gravity (386 in./sec^2), and Δ_j and Δ_g are the joist and girder mid-span deflections respectively due to the weights they support. The mass weight of the floor system to be used in Equation 1 is determined as a weighted average based on joist and girder deflections:

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

where $W_i = w(B_i \times L_i)$, w is the average unit dead and live load present, L is the length of the member (joist or girder), and B_i, the effective width, is given as:

$$B_j = C_j \left(\frac{D_s}{D_j}\right)^{1/4} L_j \tag{4}$$

$$B_g = C_g \left(\frac{D_j}{D_g}\right)^{1/4} L_g \tag{5}$$

A factor of 1.5 is applied to W_i for rolled steel beams shear-connected to the girder on both sides, and the adjacent beam span is > 70% of the span under consideration. The factors C_j and C_g are taken from Table 2. D is the flexural rigidity per unit width of the slab, joist, or girder as indicated by s, j, or g. For floor systems where $L_g < B_j$ the effect is to stiffen the entire system. To account for this effect, AISC Design Guide 11 recommends the following modification of the girder deflection:

$$\Delta'_g = \frac{L_g}{B_j} (\Delta_g) \tag{6}$$

Table 1
Recommended Values of Parameters (AISC, 1997)

Application	Constant Force P_o	Damping Ratio β	Acceleration Limit $a_o/g \times 100\%$
Offices, residences, churches	0.29 kN (65 lb)	0.02–0.05*	0.5%
Shopping malls	0.29 kN (65 lb)	0.02	1.5%
Footbridges—indoor	0.41 kN (92 lb)	0.01	1.5%
Footbridges—outdoor	0.41 kN (92 lb)	0.01	5.0%

* 0.02 for floors with few non-structural components
0.03 for floors with non-structural components and furnishings
0.05 for full height partitions between floors

The method consists of the following steps to complete the evaluation of the beam and girder design:

1. Determine the section properties of the joist and the girder (composite unless the upper flange is separated from the concrete slab).
2. Determine the static weight tributary to each beam and each girder.
3. Determine the deflection of the beam and the girder due to the static weight.
4. Determine the moment of inertia per unit width for the floor slab, beam, and the girder.
5. Calculate the mass weight contributing to the beam and the girder.
6. Calculate the combined mode properties for frequency and mass weight.
7. Calculate the walking acceleration (Equation 1) and compare it to the acceleration limit in Table 1.

Parameters Influencing Vibration

The selection of the damping ratio of the structural floor system and the contribution from non-structural features is a decision that will significantly affect the outcome of the vibration analysis. Vibration evaluations are very sensitive to the damping ratio, however, this parameter is the most difficult to predict. Considerable effort has been focused on the damping ratio and contribution by various non-structural components found in buildings. Many researchers have studied this important aspect of the determination of damping ratio. The summary below includes both recommendations from past studies to be used in determining the damping ratio for a given system and factors having little to no effect on the damping:

1. Ceilings increase the damping somewhat.
2. Ductwork, electrical conduits, and lighting increase the damping somewhat.
3. Partitions significantly increase the damping in proportion to the size and spacing in plan.
4. Adding dead weight does not significantly improve damping.
5. Adding bridging does not improve the damping characteristics.

The AISC Guide Series 11 contains recommendations for estimating modal damping in buildings. These recommendations are shown in Table 1.

DESIGN AIDS

Design aids (Figures 1 through 12) have been developed based on AISC Guide Series 11 for typically encountered concrete slab on steel composite beam systems and various span lengths with the first natural frequency less than 9 Hz. Use of these design aids significantly reduces the computation time to evaluate a given floor system for acceptability of floor system vibrations.

The following assumptions were made in developing the design aids:

1. Concrete strength = 4000 psi.
2. Ambient, or average, live load = 11 psf.
3. E_c is 1.35 times E_c determined by the standard ACI formula.
4. Δ_g is reduced by $\frac{L_g}{B_j}(\geq 0.5)$ when $L_g < B_j$.
5. Floors of at least 3 bays in each direction.
6. Does not apply for interior openings.
7. Average dead load of the mechanical, electrical, flooring, and ceiling is taken as 4 psf.
8. Normal weight concrete is used.

Although the design aids are based on a concrete strength of 4000 psi, the deflection calculations dependent on this parameter ($E_c = 57{,}000\sqrt{f'_c}$) do not differ from that presented herein by more than 3% when a concrete strength of 3000 psi to 5000 psi is used. The design aids may, therefore, be safely used for concrete with a strength between 3000 psi and 5000 psi. It is important to note that ambient, or average, service live load should be used in floor vibration acceptability calculations, not *design* live loads or factored live loads. Design or factored live loads will result in a significant error in estimating mass weight and natural frequency. In general, the evaluation is not sensitive to small errors in the estimation of the dead load contribution from mechanical, electrical, flooring, and ceilings as the dominant floor dead load is the concrete,

Table 2
Effective Floor Width Factor

Component or Condition	C_j	C_g
Beams or joists in most areas	2.0	
Beams or joists parallel to an interior edge	1.0	
Girders supporting joists without extended chords		1.6
Girders supporting joists with extended chords or hot-rolled beams		1.8

deck, and steel, which were calculated directly for each case. If a lightweight concrete floor is used, the design aid mass weights and deflections should be multiplied by 85% to account for the reduced weight of concrete. The following procedure is to be used with the design aids:

1. Identify the material and loading design parameters and specifications.
2. Determine the applicability of the design aids.
3. Calculate the beam mode Δ_j and W_j using Figures 1 to 8.
4. Determine the girder mode Δ_g/S_g and $W_g/(I_j \times S_g/S_j)^{0.25}$ using Figures 9 to 12.
5. Calculate the combined mode frequency and mass weight using Equations 2 and 3.
6. Calculate the walking acceleration, $\frac{a_p}{g}$ and compare with the limit, $\frac{a_o}{g}$ from Table 1.

A floor system evaluation example is provided in Appendix II to illustrate the use of the design aids.

SUMMARY AND CONCLUSIONS

Floor system vibration due to occupant activity is often ignored by designers; however, floor system vibration is an important serviceability criterion and is important for occupant comfort and building owner satisfaction. This paper reviews vibration design criteria for floor systems, studies of human response to vibration, and current code requirements for determining floor system vibration acceptability criteria. Design aids are developed to promote the expedient verification of floor acceptability as a general serviceability check during the design stage. An example is provided to demonstrate the application of the included design aids. It is anticipated that, through the availability of design aids such as those included here, floor system vibration evaluations will become routine and part of the normal design process.

REFERENCES

Allen, D. E. and Rainer, J. H. (1976), "Vibration Criteria for Long-Span Floors," *Canadian Journal of Civil Engineering,* Vol. 3, No. 2, June, pp. 165-173.

Allen, D. E., Rainer, J. H., and Pernica, G. (1985), "Vibration Criteria for Assembly Occupancies," *Canadian Journal of Civil Engineering,* Vol. 12, No. 3, pp. 617-623.

Allen, D. E. (1974), "Vibrational Behavior of Long-Span Floor Slabs," *Canadian Journal of Civil Engineering,* Vol. 1, No. 1, September.

Allen, D. E. (1990a), "Floor Vibrations from Aerobics," *Canadian Journal of Civil Engineering,* Vol. 19, No. 4, pp. 771-779.

Allen, D. E. (1990b), "Building Vibrations from Human Activities," *Concrete International,* Vol. 12, No. 6, pp. 66-73.

Allen, D. E. and Murray, T. M. (1993), "Design Criterion for Vibrations Due to Walking," *Engineering Journal* AISC, Vol. 30, No. 4, pp. 117-129.

ANSI (1983), *American National Standard Guide to the Evaluation of Human Exposure to Vibration in Buildings,* ANSI S3.29-1983, American National Standards Institute, New York.

ASCE (1995), *Minimum Design Loads for Buildings and Other Structures,* ASCE 7-95, American Society of Civil Engineers, New York.

Bachmann, H. (1992), "Case Studies of Structures with Man-Induced Vibrations," *Journal of Structural Engineering,* ASCE, Vol. 118, No. 3, pp. 631-647.

Becker, R. (1980), "Simplified Investigation of Floors under Foot Traffic," *Journal of the Structural Division,* ASCE, Vol. 106, No. ST11, November, pp. 2221-2234.

BRS (1983), "Vibrations of Buildings and Human Response," *Building Research Establishment Digest* 278, Building Research Station, Garston, Watford, England, October.

CSA (1989), *Canadian Standard CAN3-S16. 1-M89: Steel Structures for Buildings—Limit States Design, Appendix G: Guide for Floor Vibrations,* Canadian Standards Association, Rexdale, Ontario.

Ellingwood, B. and Tallin, A. (1984), "Structural Serviceability: Floor Vibrations," *Journal of Structural Engineering,* ASCE, Vol. 100, No. 2, February, pp. 401-418.

Galambos, T. V. et al. (1973), "Structural Deflections: A Literature and State-of-the-Art Survey," U.S. Department of Commerce, SD Catalog No. C13.29-2:47, October.

Goldman, D. E. and Von Gierke (1961), *Effects of Shock and Vibration on Man,* McGraw-Hill, New York, Vol. 3.

Greimann, L. F. and Klaiber, F. W. (1978), "Dynamic Forces Induced by Spectators," *Journal of the Structural Division,* ASCE, Vol. 104, No. ST2, February, pp. 348-351.

Grether, W. F. (1971), "Vibration and Human Performance," *Human Factors,* Vol. 13, No. 3, pp. 203-216.

Guignard, J. C. (1971), "Human Sensitivity to Vibration," *Journal of Sound and Vibration,* Vol. 15, No. 1, pp. 11-16.

Hanes, R. M. (1970), *Human Sensitivity to Whole-Body Vibration in Urban Transportation Systems: A Literature Review,* Silver Springs, MD, Applied Physics Laboratory, The John Hopkins University.

Harper, F. C., Warlow, W. J., and Clarke, B. L. (1961), "The Forces Applied to the Floor by the Foot in Walking," Building Research Station, *National Building Studies Research Paper No.* 32, HMSO, London, U.K.

Hatfield, F. J. (1992), "Design Chart for Vibration of Office and Residential Floors," *Engineering Journal,* AISC, Vol. 29, No. 4, p. 141.

Huggins, M. W., and Barber, J. D. (1982), "Building Deflections, Distortions and Vibrations—A Survey," *Canadian Journal of Civil Engineering,* Vol. 9, No. 1., March, pp. 133-137.

ISO (1992), *International Standards ISO 10137, Basis for the Design of Structures—Serviceability of Buildings Against Vibration,* International Standards Organization.

ISO (1989), *International Standard ISO 2631-2, Evaluation of Human Exposure to Whole-Body Vibration—Part 2: Human Exposure to Continuous and Shock-Induced Vibrations in Buildings (1 to 80 Hz),* International Standards Organization.

Irwin, A. W. (1978), "Human Response to Dynamic Motion of Structures," *Structural Engineer,* Vol. 56, No. 9, September, pp. 237-244.

Lenzen, K. H., Dorsett, L., and Sokolowski, M. (1971), "The Variation of Vibrational Characteristics of Steel Joist-Concrete Floor Systems with Changes in the Structural Parameters," Engineering Archives of the Polish Academy of Sciences, Vol. XVII A, March.

Lenzen, K. H., and Dorsett, L. (1968), "Effect of the Variation of Structural Parameters on the Vibrational Characteristics of Steel Joist-Concrete Floor and Suggested Designs," SEM 32, August 1968.

Lenzen, K.H. (1966), "Vibration of Steel Joist Concrete Slab Floors," *Engineering Journal,* AISC, Vol. 3, No. 3, pp. 133-136.

Murray, T. M. (1991), "Building Floor Vibrations," *Engineering Journal,* AISC, Vol. 28, No. 3, pp. 102-109.

Murray, T. M. (1981), "Acceptability Criterion of Occupant-Induced Floor Vibration," *Engineering Journal,* AISC, Vol. 18, No. 1, pp. 62-70.

Murray, T. M. (1975), "Design to Prevent Floor Vibrations," *Engineering Journal,* AISC, Vol. 12, No. 3, pp. 82-87.

Murray, T. M., Allen, D. E., and Ungar, E. E. (1997), *Floor Vibrations Due to Human Activity,* Design Guide Series 11, American Institute of Steel Construction, Chicago, IL.

National Research Council of Canada (1990), *Commentary A, Serviceability Criteria for Deflections and Vibrations,* National Building Code of Canada-1990, Ottawa, Ontario.

Nelson, F. C. (1974), "Subjective Rating of Building Floor Vibration," *Journal of Sound and Vibration,* October, pp. 34-37.

Ohlsson, S. V. (1988), "Ten Years of Floor Vibration Research—A Review of Aspects and Some Results," *Proceedings of the Symposium/Workshop on Serviceability of Buildings. Vol. I,* Ottawa, pp. 435-450.

Osborne, K. P. and Ellis, B. R. (1990), "Vibration Design and Testing of a Long-Span Lightweight Floor," *The Structural Engineer,* Vol. 68, No. 10, pp. 181-186.

Pernica, G. and Allen, E. E. (1982), "Floor Vibration Measurements in a Shopping Centre," *Canadian Journal of Civil Engineering,* Vol. 9, No. 2, pp. 149-155.

Pool, T. W. and Murray, T. M. (1972), "Measurement and Analysis of Floor Vibrations," School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, OK, April, (unpublished).

Reiher, H. and Meister, F. J. (1931), "Sensitivity of Humans to Vibration," (German Language), *Forschung auf dem Febeite des Ingenieurwesens,* Vol. 2, No. 11, November.

SJI (1988), *Vibration of Steel Joist-Concrete Slab Floors,* Steel Joist Institute Technical Digest No. 5, Steel Joist Institute, Myrtle Beach, SC.

Wiss, J. F. and Parmelee, R. A. (1974), "Human Perception of Transient Vibrations," *Journal of the Structural Division,* ASCE, Vol. 100, No. ST4, April, pp. 773-787.

Wright, D. T. and Green, R. (1969), *Human Sensitivity to Vibration,* Ontario Joint Highway Research Program, Report No. 7, February.

Wyatt, T. A. (1989), "Design Guide on the Vibration of Floors," *Steel Construction Institute Publication 076,* London.

APPENDIX I. NOTATION

The following symbols are used in this paper:

- B_j = Effective joist panel width
- B_g = Effective girder panel width
- C_g = Factor modifying girder panel width (see Table 2)
- C_j = Factor modifying joist or beam panel width (see Table 2)
- D = Estimated % critical damping of the floor system
- D_a = Flexural rigidity of secondary member per unit width
- D_b = Flexural rigidity of primary member per unit width
- D_j = Flexural rigidity of floor joist or beam per unit width
- D_g = Flexural rigidity of girder per unit width
- E_c = Young's modulus of elasticity for concrete
- E_s = Young's modulus of elasticity for steel

f_n = Floor system frequency considering the combined mode
g = Acceleration due to gravity
I_j = Moment of inertia of the floor joist or beam
I_g = Moment of inertia of the girder
L_j = Length of the floor joist or beam
L_g = Length of the girder
P_o = A constant force representing the excitation
S_j = Spacing of the floor joists or beams
S_g = Spacing of the girder
W = Total mass weight of the floor system
W_j = Effective panel weight supported by the floor joist or beam
W_g = Effective panel weight supported by the floor girder
δ = deflection of supporting member
β = Modal Damping Ratio for the floor system
Δ_j = Deflection of floor joist or beam due to ambient dead and live loads
Δ_g = Deflection of girder due to dead and ambient, or average, live loads
Δ'_g = Modified girder deflection (see Equation 6)
γ_{conc} = Unit weight of concrete

APPENDIX II. EXAMPLE

The following example of a floor vibration evaluation for a typical commercial office building illustrates the use of graphs and tables provided in this article. The calculations are completed in customary U.S. units for clarity and because this is currently the system used throughout the industry (material and product specifications).

1. Design specifications:

Steel strength: $F_y = 50$ ksi

Concrete strength: $f'_c = 4000$ psi, $\gamma_{conc} = 145$ pcf

Deck: 2″ composite with 2″ concrete (4″ total)

Dead load: Flooring	1 psf
Concrete	39 psf
Metal deck	2 psf
W16×26 beam	4 psf
Mech. and elect	3 psf
Ceiling	1 psf
Total	50 psf

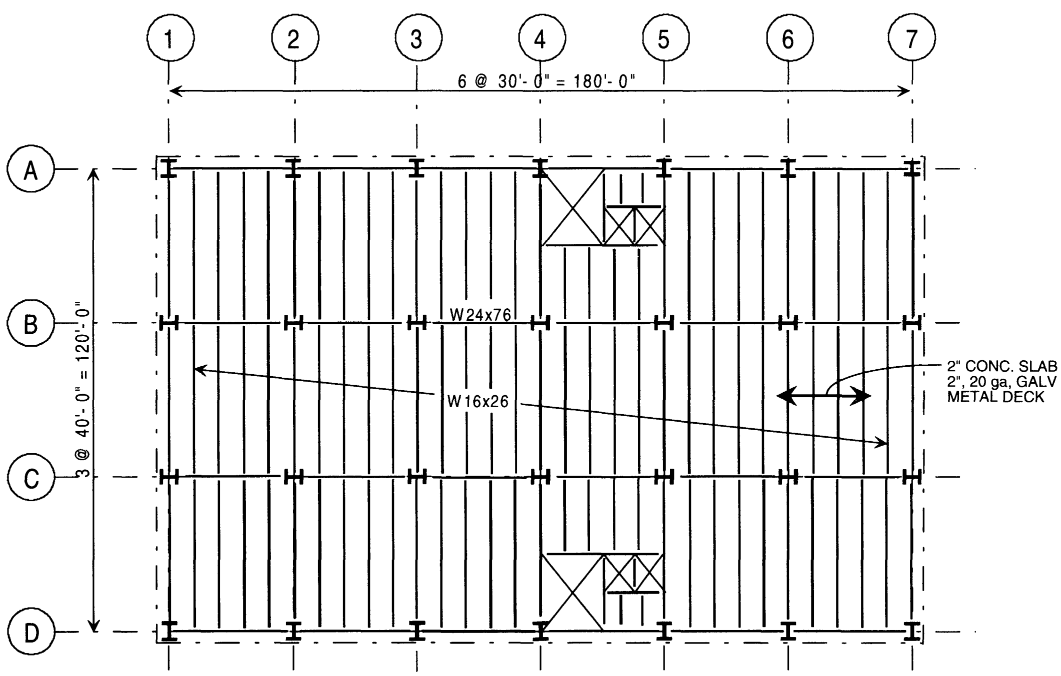
Live Load: Design live load = 75 psf, Ambient live load = 11 psf

2. Applicability

The design parameters are all within an acceptable range of the typical values used as a basis for the provided design aids.

3. Beam Mode

From Figure 5 (2″ concrete, 2″ metal deck, S_j = 6′- 0″), enter with beam span, L_j, equal to 40′- 0″ and a beam size



Example. Concrete slab on composite steel framing for typical office building.

of W16×26:

Δ_j = 0.72 in.
W_j = 78.7 kips × 1.5 (beams shear connected to girder) = 118 kips

$$B_j = \frac{W_j}{wL_j} = \frac{78{,}700 \text{ lb}}{(50 + 11) \text{ psf} \times 40 \text{ ft}} = 32.3 \text{ ft}$$

4. Girder Mode

From Figure 11, (2″ concrete, 2″ metal deck), enter with girder span equal to 30′ - 0″ and a girder size of W24×76:

$$\frac{\Delta_g}{S_g} = 0.0070 \qquad \frac{W_g}{\left(\frac{I_j S_g}{S_j}\right)^{0.25}} = 6.4$$

S_g = 40′−0″, S_j = 6′−0″, I_j = 996 in.^{4} (from Table 3).
Δ_g = 0.0070 in./ft (40 ft) = 0.28 in.

$$W_g = 1.8 \text{ (beams connected to girder web)} \times 6.4 \times \left(\frac{(996 \text{ in.}^4)(40 \text{ ft})}{6 \text{ ft}}\right)^{0.25} = 104 \text{ kips.}$$

$$\text{Since } L_g < B_j,\ \Delta_g = 0.28 \text{ in.} \times \frac{30.0 \text{ ft.}}{32.3 \text{ ft.}} = 0.26 \text{ in.}$$

5. Combined Model

$$f_n = 0.18\sqrt{\frac{386}{\Delta_j + \Delta_g}} = 0.18\sqrt{\frac{386}{0.72 + 0.26}} = 3.6 \text{ Hz}$$

$$W = \frac{\Delta_j}{\Delta_j + \Delta_g} W_j + \frac{\Delta_g}{\Delta_j + \Delta_g} W_g = \frac{0.72}{0.72 + 0.26} 118 + \frac{0.26}{0.72 + 0.26} 104 = 114 \text{ kips}$$

6. Acceptability

Apply Equation (1) with f_n = 3.6 and W = 114 kips, taking β = 0.03 for open floor plan:

$$\frac{a_p}{g} = \frac{P_0 e^{(-0.35 \times f_n)}}{\beta W} = \frac{65 e^{(-0.35 \times 3.6)}}{0.03 \times 114{,}000} = 0.53\% > 0.5\% \text{ from Table 1}$$

therefore, the floor system could be expected to experience floor vibrations at a level unacceptable to the typical occupant. An evaluation of potential revisions to the original design should include: (1) analysis of increased beam and/or girder stiffness, considering which member will have the largest influence on the vibrations; (2) analysis of increased concrete slab thickness; and (3) careful review of the anticipated system damping and possible refinements (see previous discussion). Each of these three factors will improve the vibration characteristics of the floor system and reduce the probability of occupant discomfort.

Table 3
Moments of Inertia (in.^{4}) of Common Composite Floor Beams, I_j, f'_c = 4000 psi

Beam Size	Spacing = 4′-0″		Spacing = 6′-0″				Spacing = 8′-0″	
	1½″ Deck		1½″ Deck		2″ Deck		2″ Deck	
	2″ Conc	2½″ Conc	2″ Conc	2½″ Conc	2″ Conc	2½″ Conc	2″ Conc	2½″ Conc
W12×16	372	406	396	431	431	468	447	485
W12×19	441	482	472	513	512	556	533	578
W14×22	612	665	657	710	707	763	737	793
W16×26	865	938	934	1006	996	1072	1043	1118
W16×31	1018	1105	1107	1193	1178	1270	1239	1329
W18×35	1328	1441	1451	1562	1536	1654	1620	1735
W18×40	1514	1645	1663	1793	1756	1895	1860	1995
W21×44	2038	2211	2248	2419	2359	2540	2505	2681

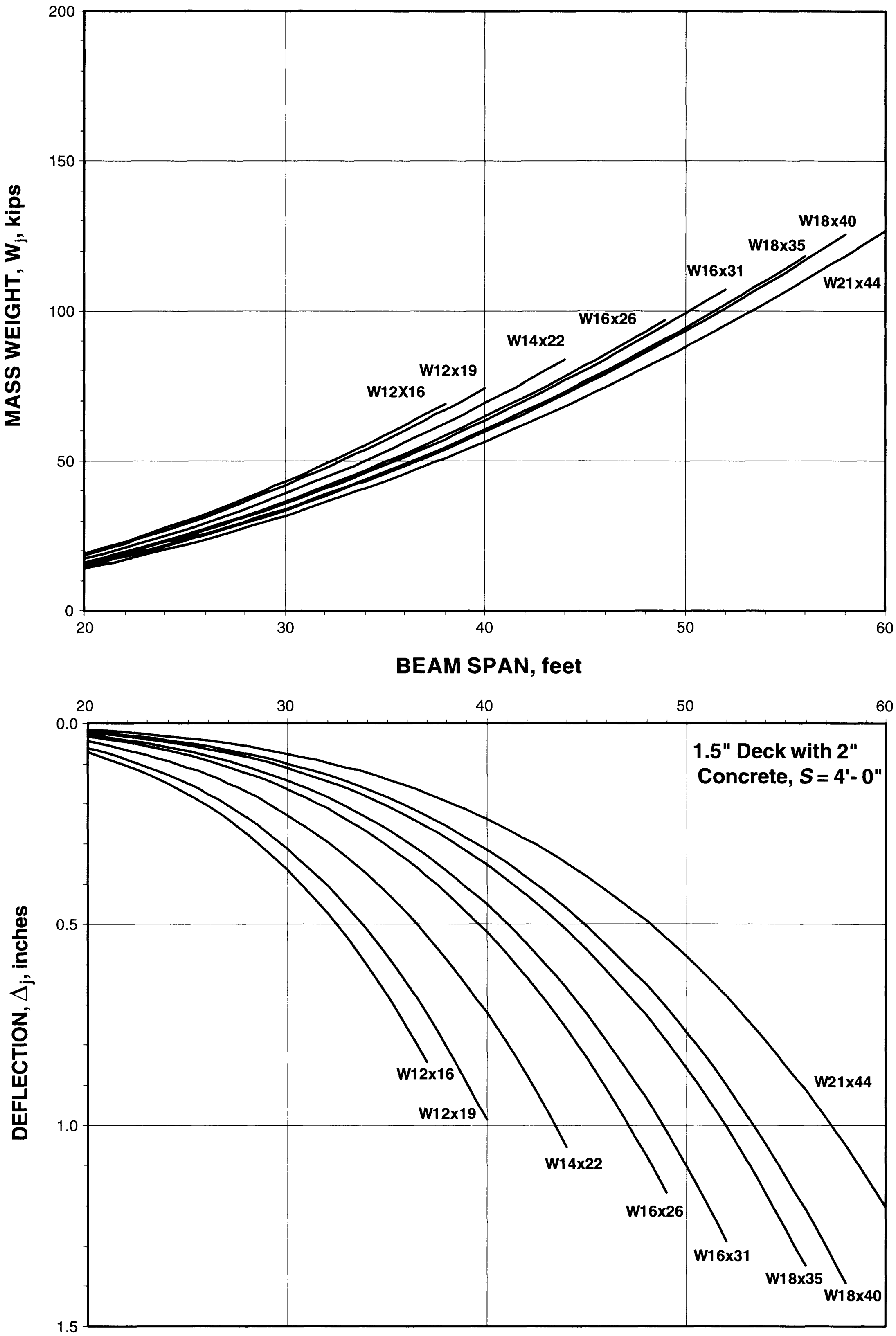


Fig. 1 Deflection and mass weight, 1½" deck, 2" concrete, S = 4'-0"

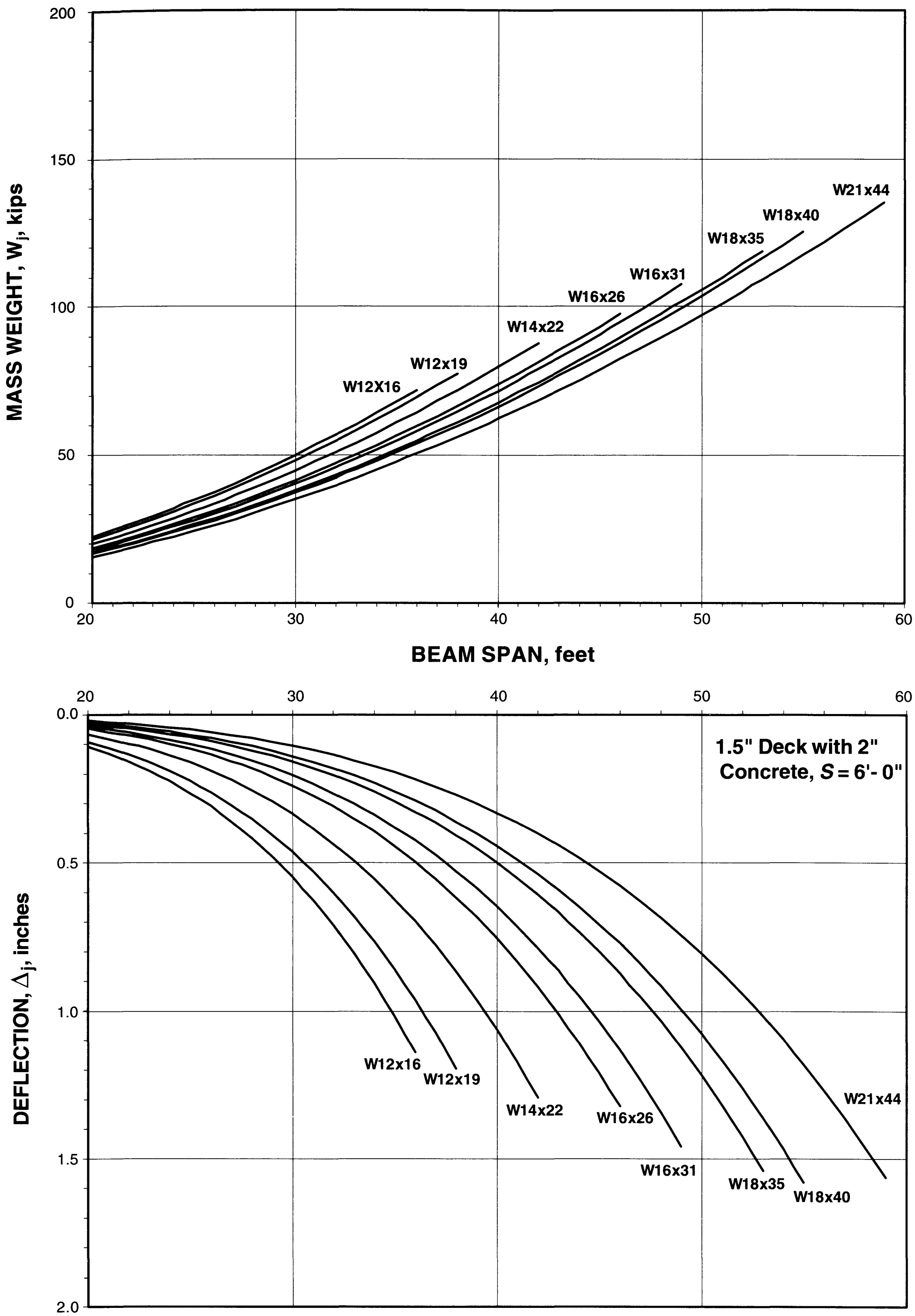


Fig. 2 Deflection and mass weight, 1½″ deck, 2″ concrete, S = 6′-0″

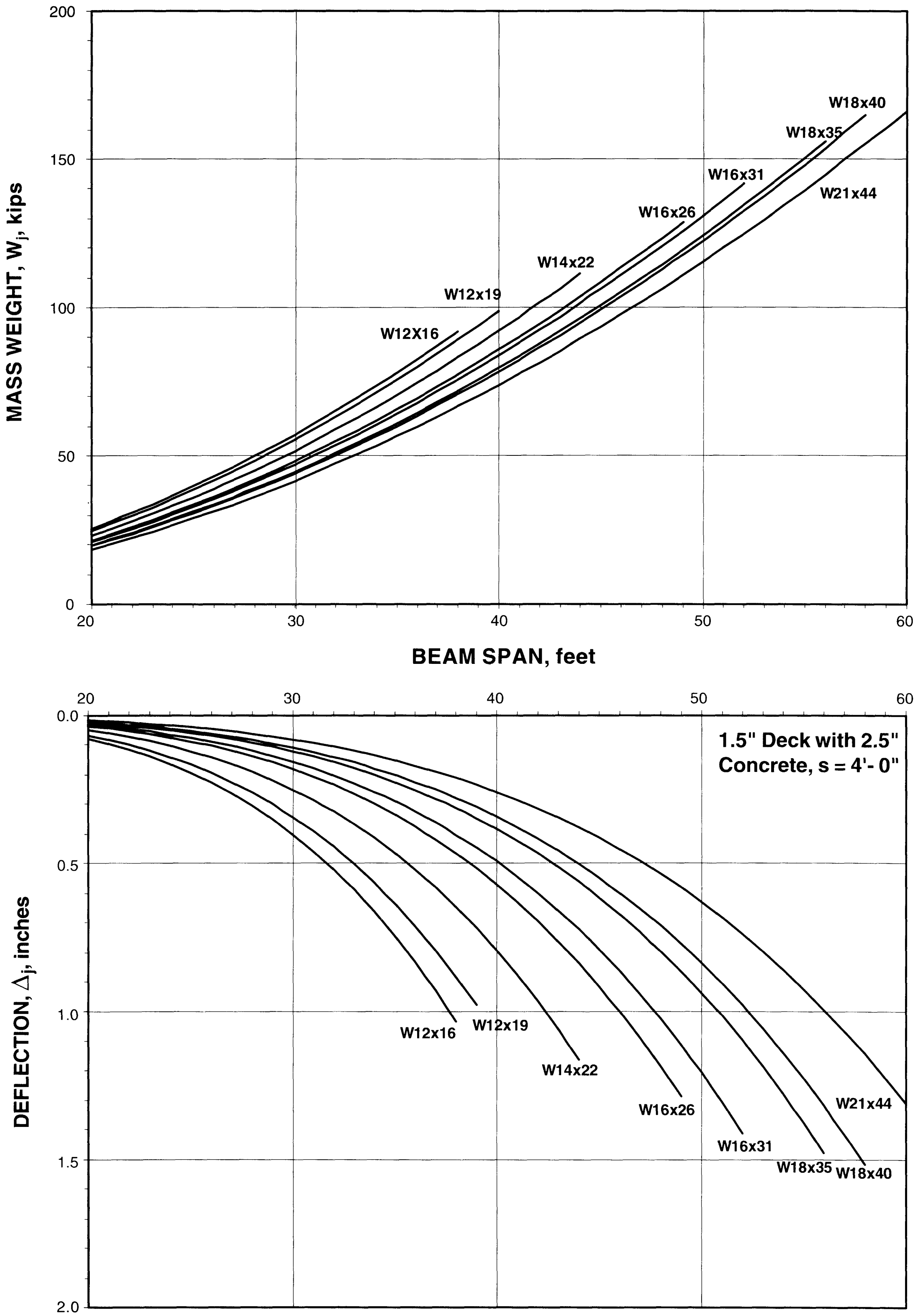


Fig. 3 Deflection and mass weight, 1½" deck, 2½" concrete, S = 4'-0"

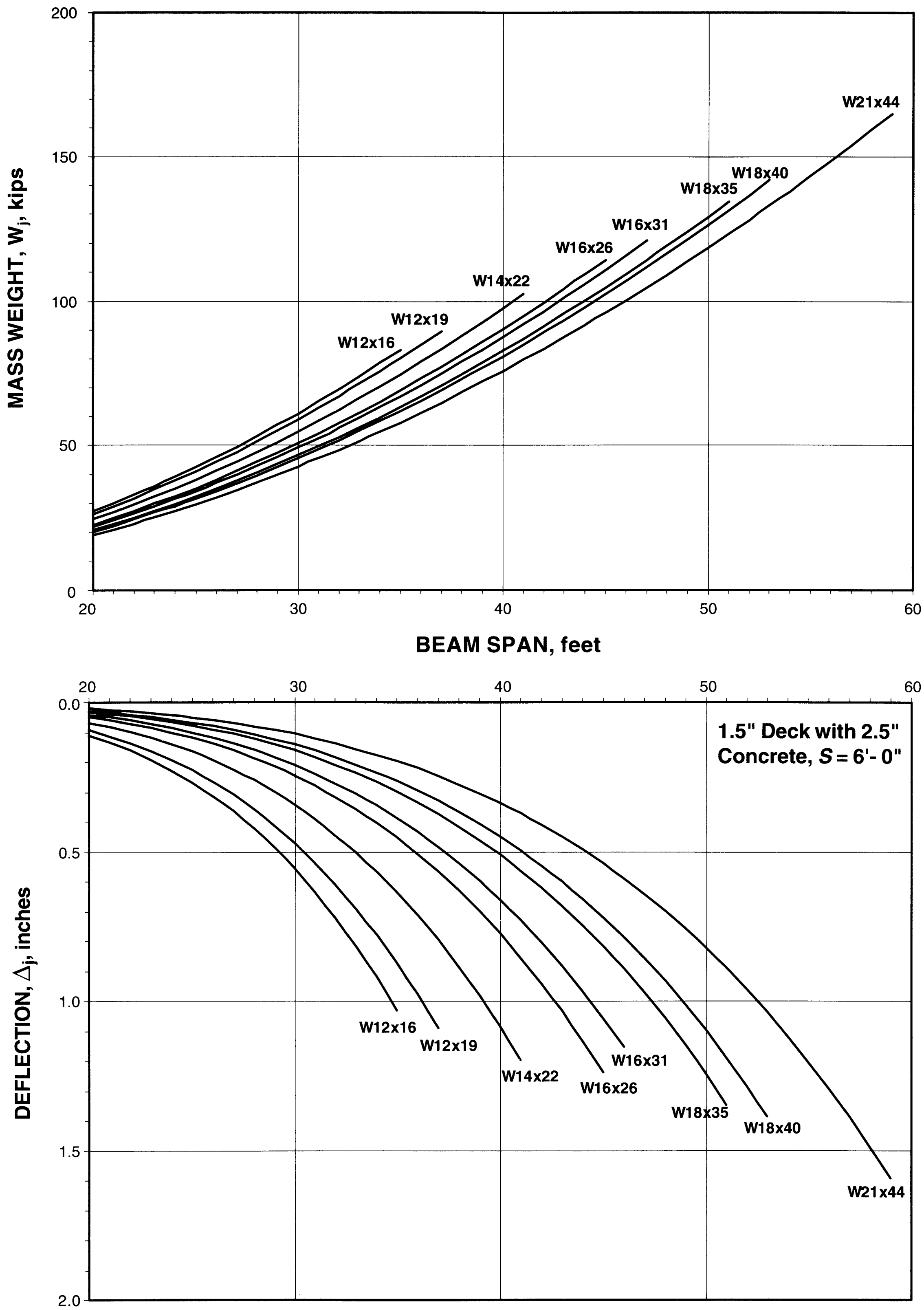


Fig. 4 Deflection and mass weight, 1½" deck, 2½" concrete, S = 6'-0"

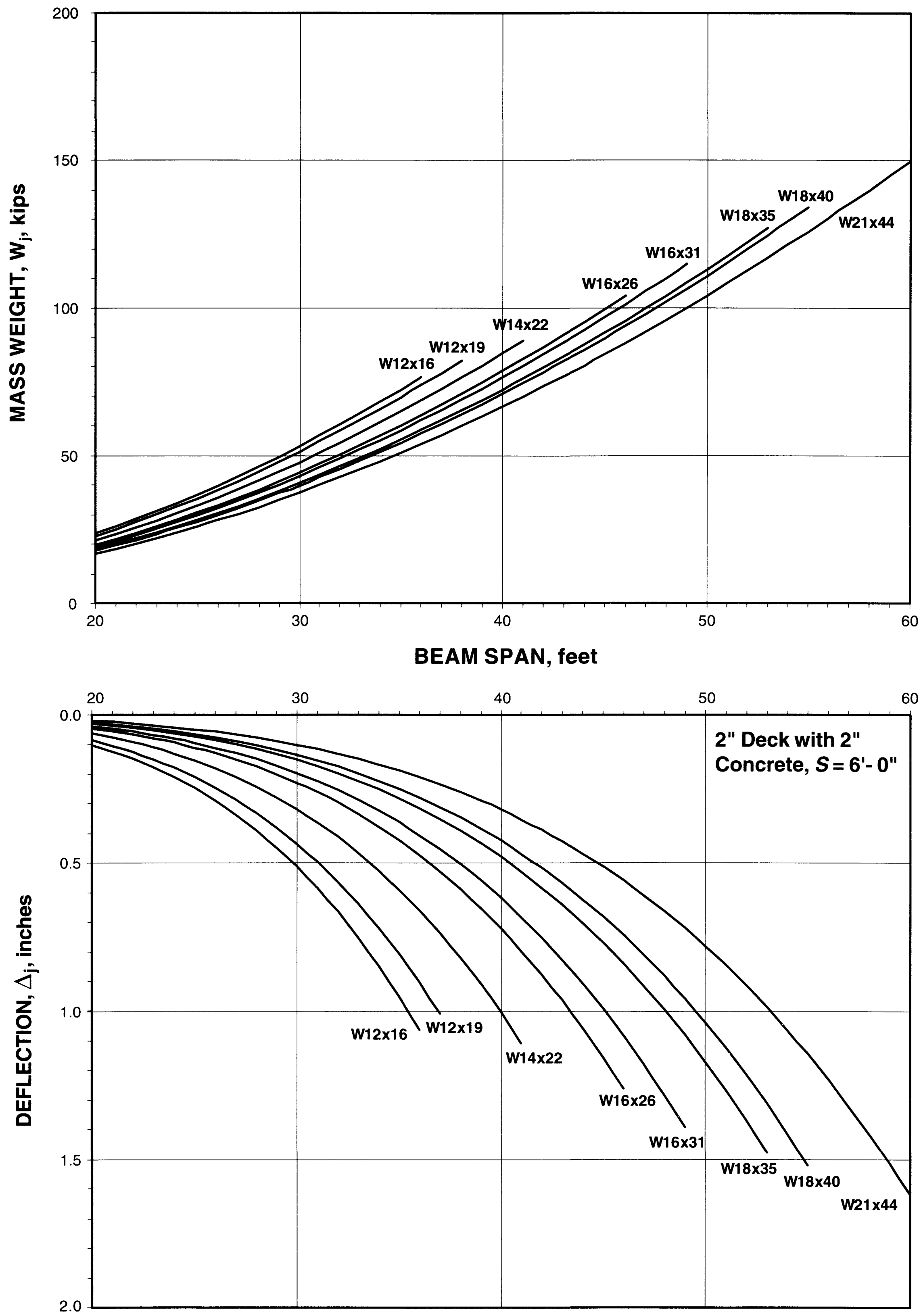


Fig. 5 Deflection and mass weight, 2″ deck, 2″ concrete, S = 6′-0″

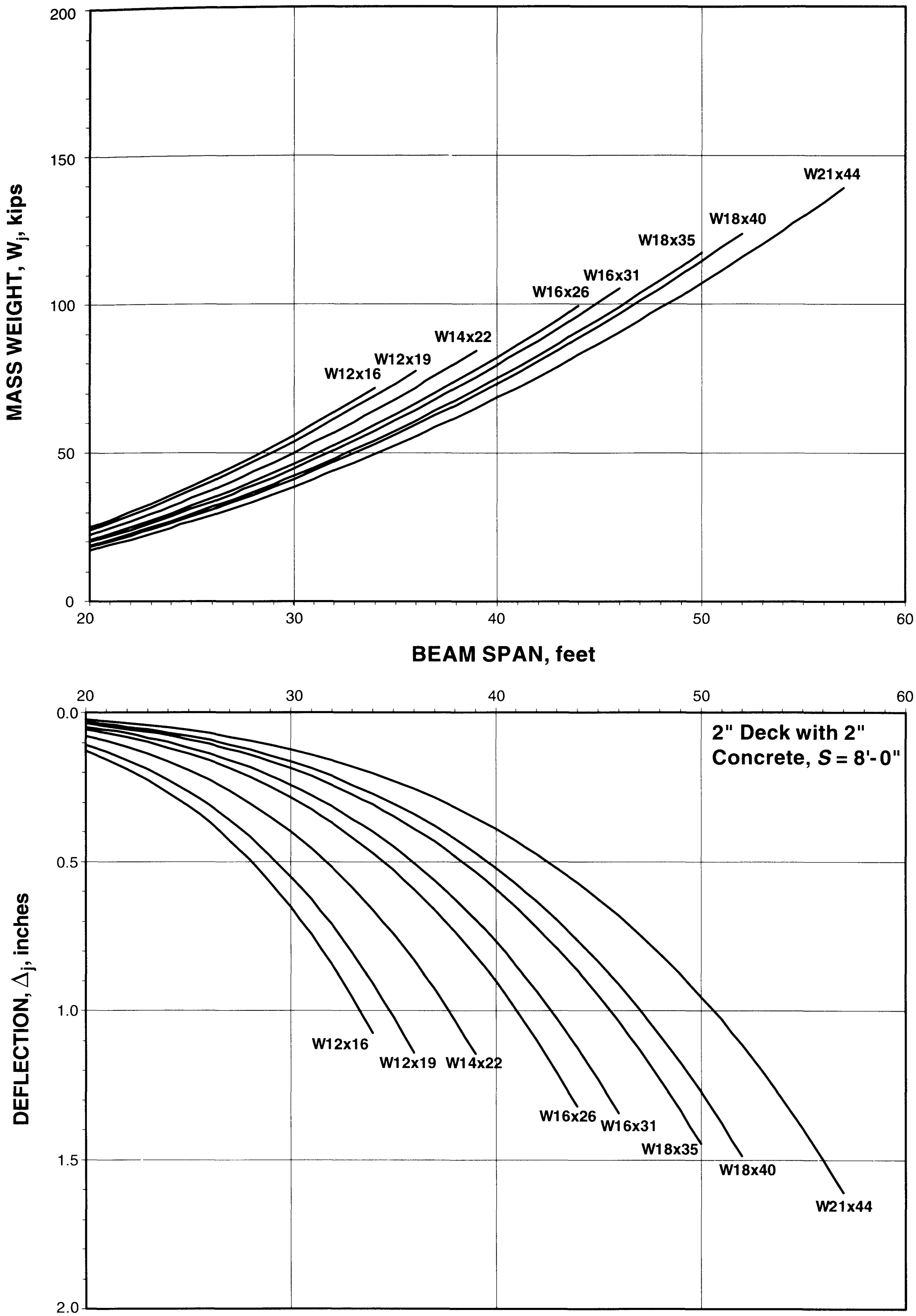


Fig. 6 Deflection and mass weight, 2" deck, 2" concrete, S = 8′-0″

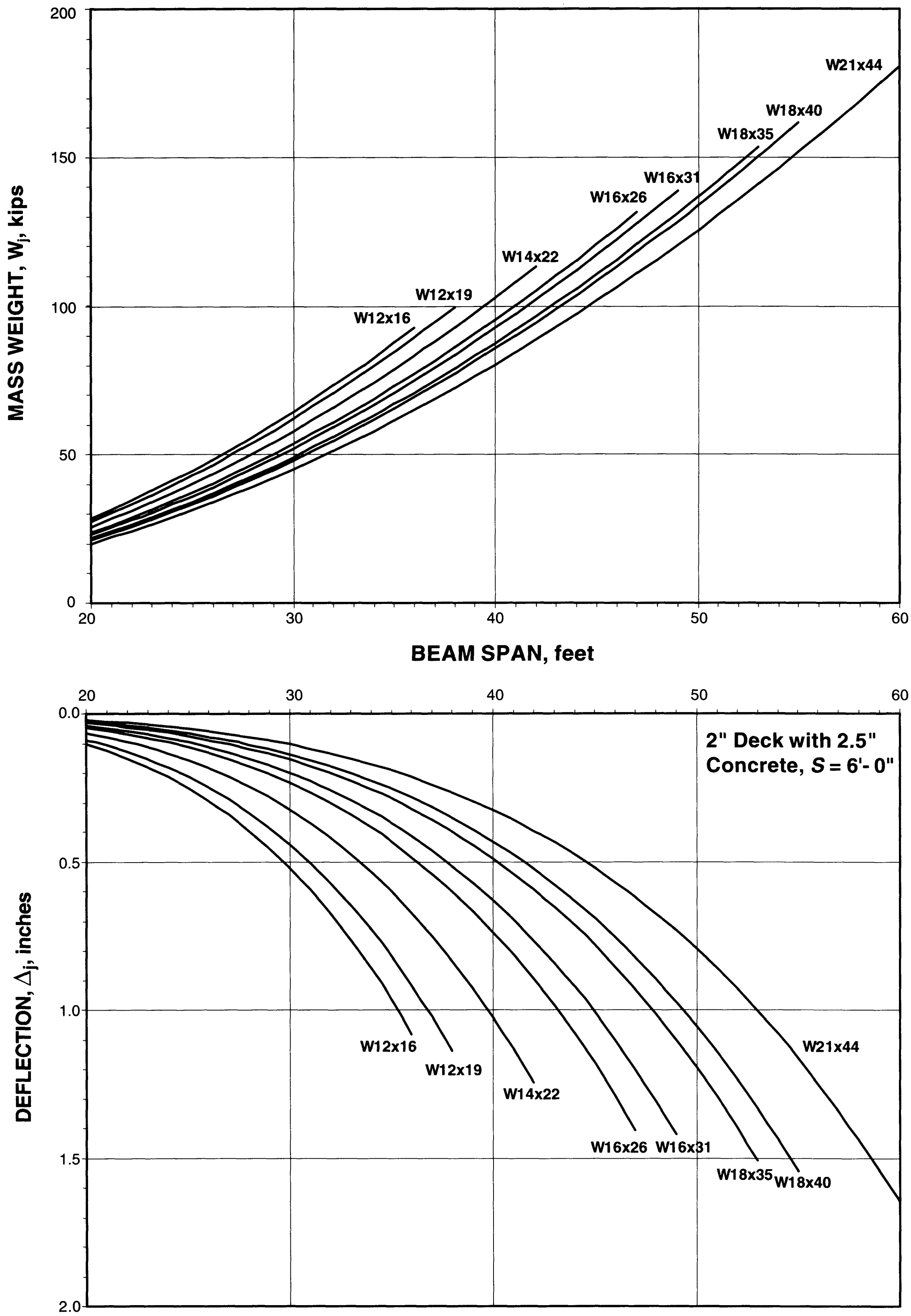


Fig. 7 Deflection and mass weight, 2″ deck, 2½″ concrete, S = 6′-0″

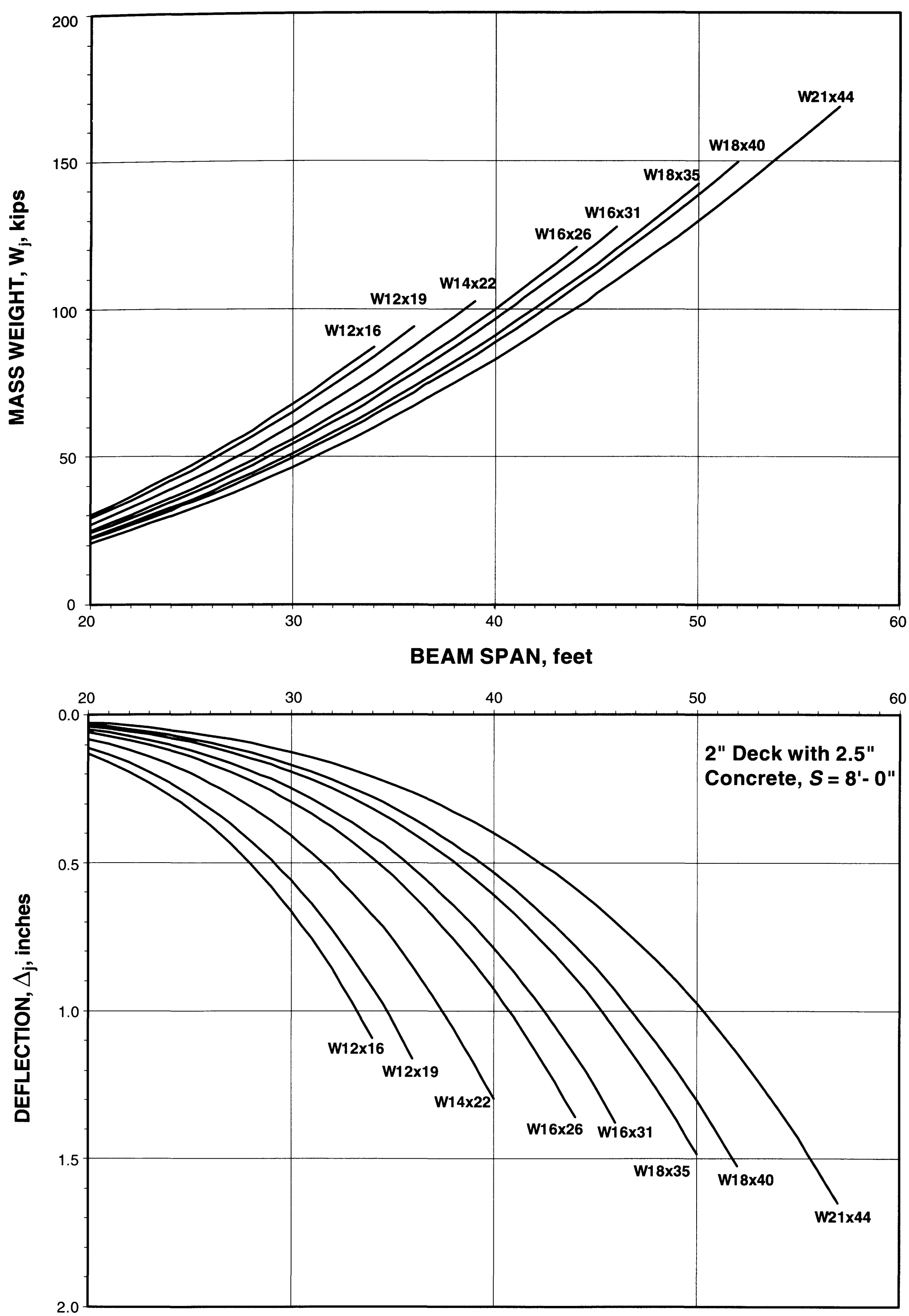


Fig. 8 Deflection and mass weight, 2" deck, 2½" concrete, S = 8'-0"

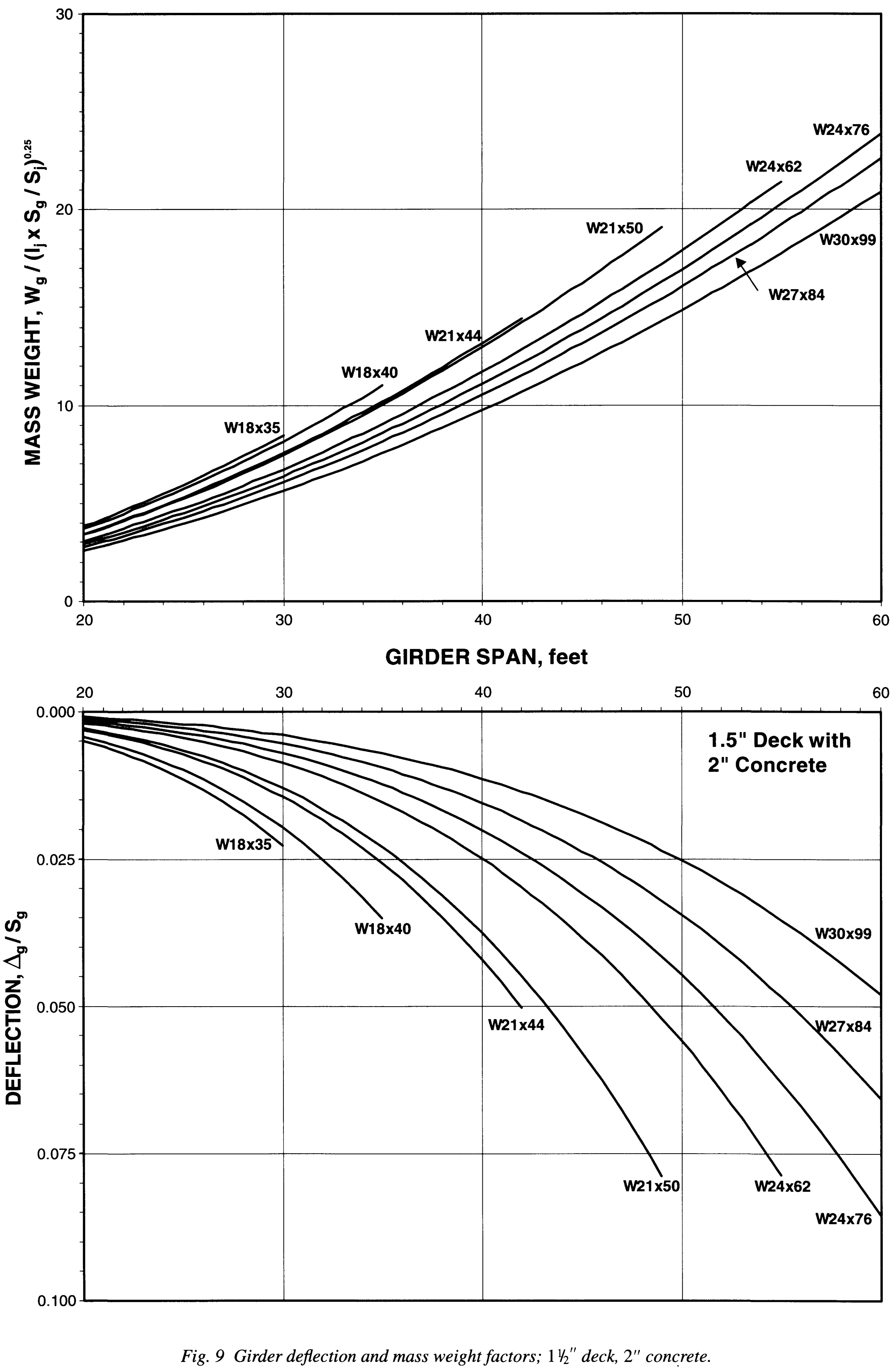


Fig. 9 Girder deflection and mass weight factors; 1½" deck, 2" concrete.

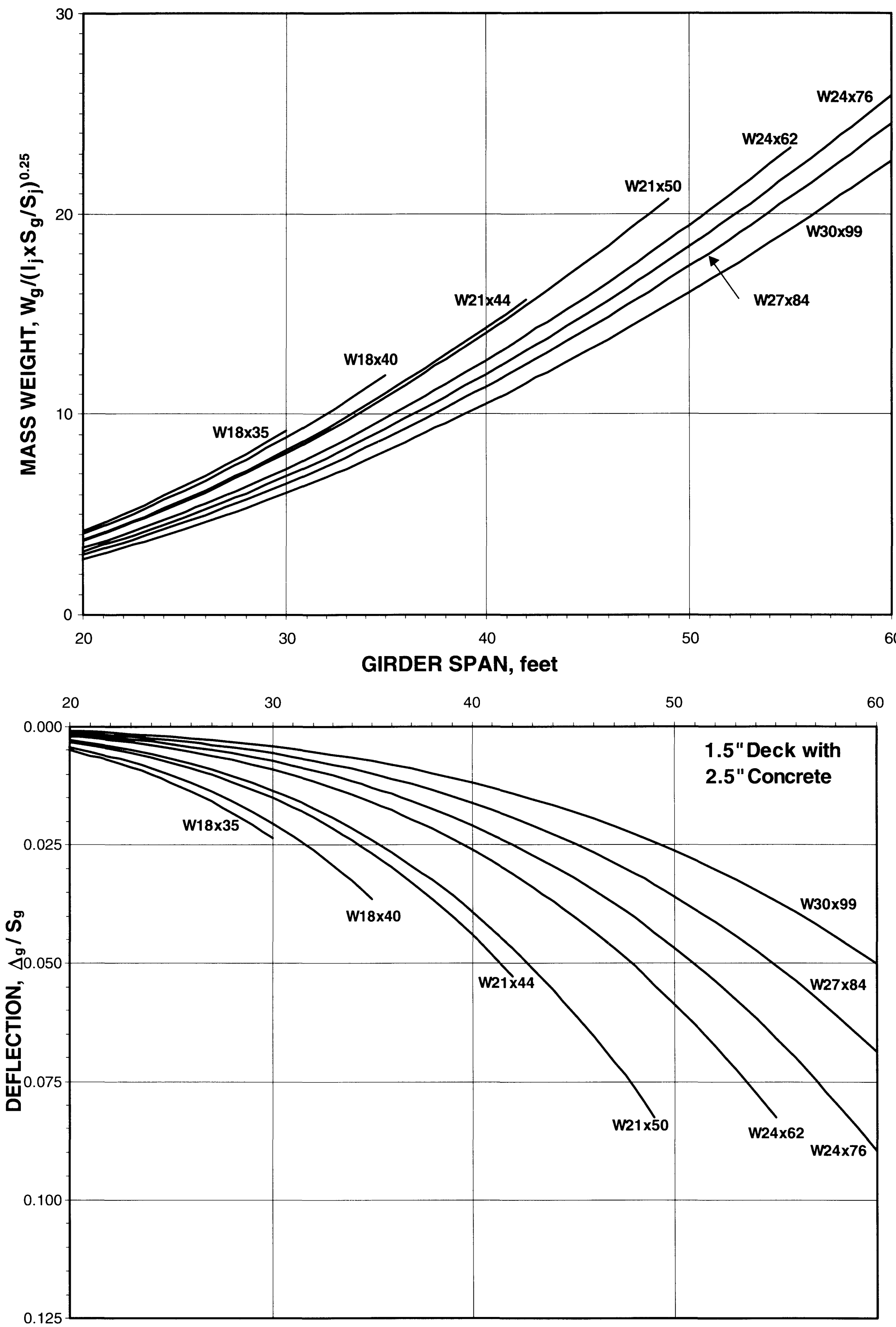


Fig. 10 Girder deflection and mass weight factors; 1½" deck, 2½" concrete.

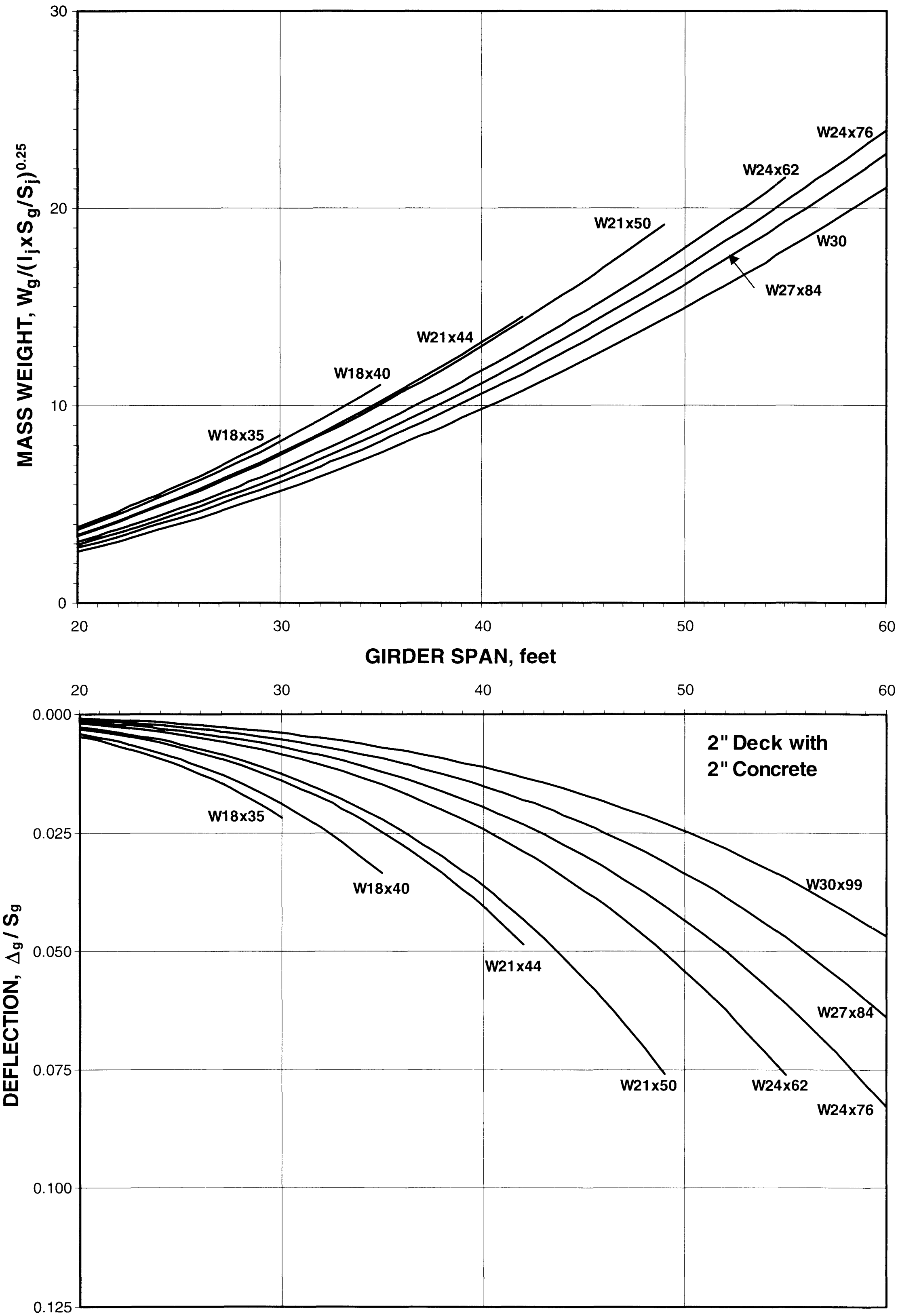


Fig. 11 Girder deflection and mass weight factors; 2" deck, 2" concrete.

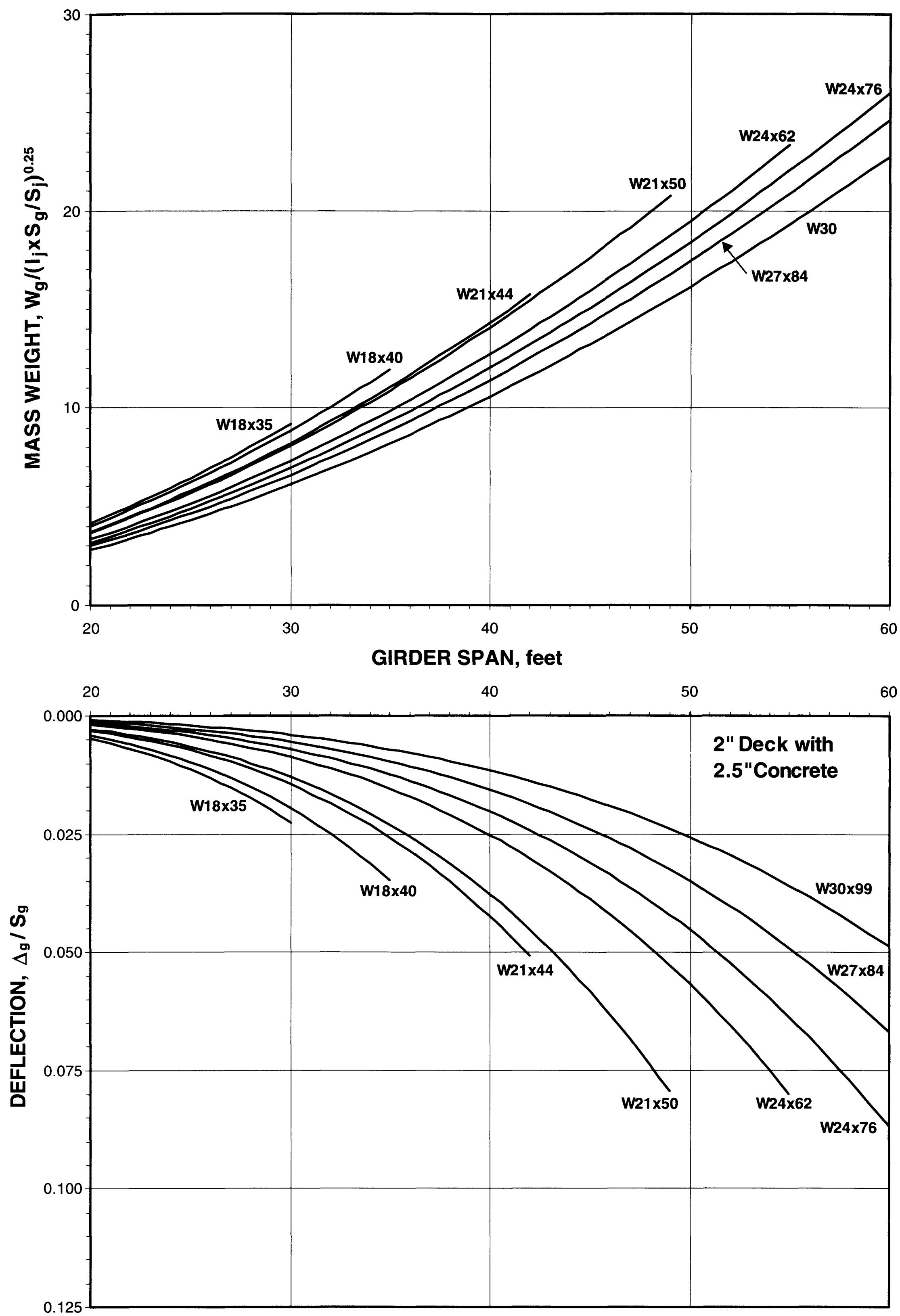


Fig. 12 Girder deflection and mass weight factors; 2" deck, 2½" concrete.