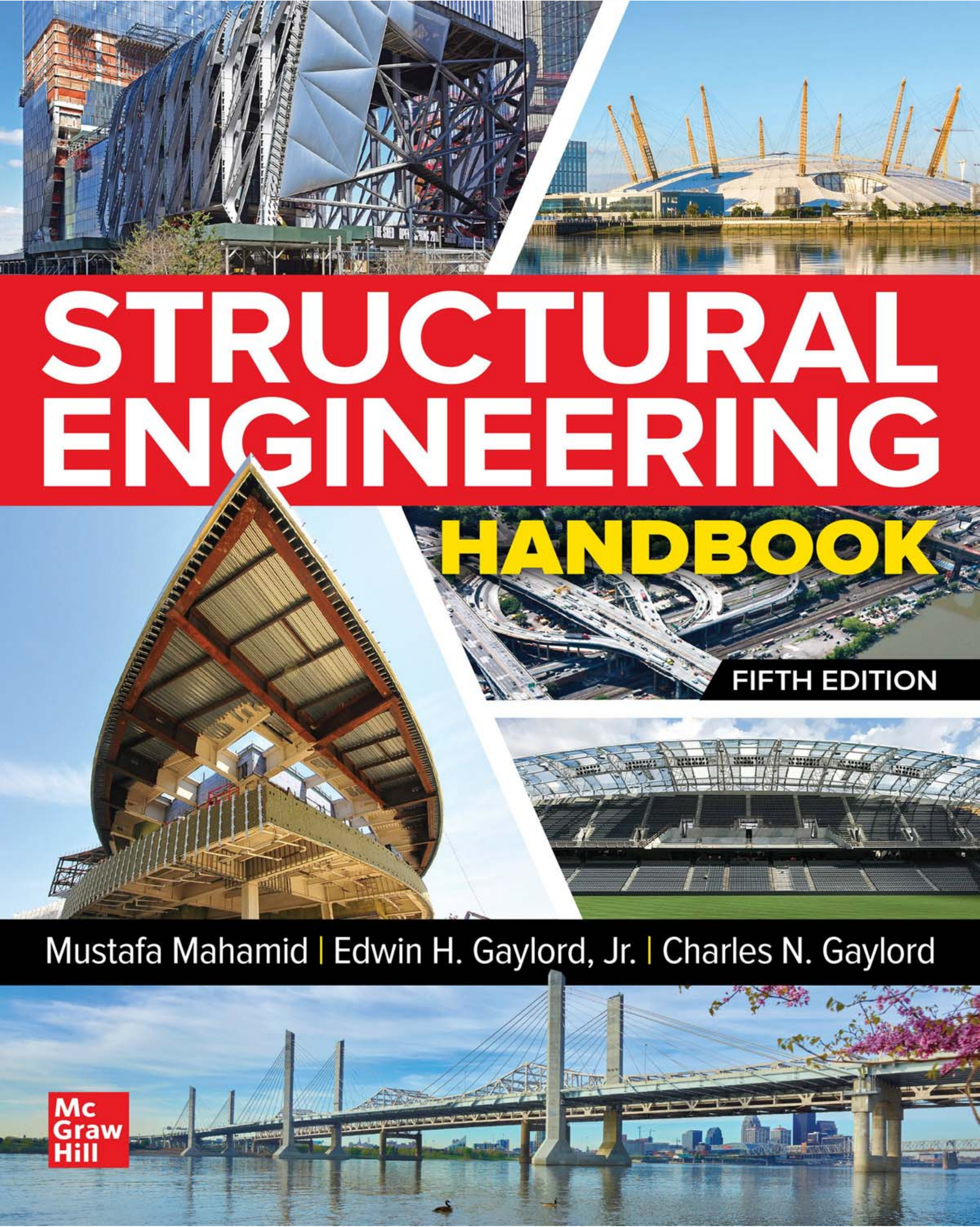

STRUCTURAL ENGINEERING HANDBOOK

FIFTH EDITION

Mustafa Mahamid | Edwin H. Gaylord, Jr. | Charles N. Gaylord

Mc
Graw
Hill

Structural Engineering Handbook

The photos on the front cover are courtesy of Thornton Tomasetti (Chicago office) and Jacobs (New York office). Mustafa Mahamid is grateful to the two firms for their contributions.

Structural Engineering Handbook

MUSTAFA MAHAMID
EDWIN H. GAYLORD, JR.
CHARLES N. GAYLORD

Fifth Edition

Mc Graw Hill

New York Chicago San Francisco Athens London
Madrid Mexico City Milan New Delhi
Singapore Sydney Toronto

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The late **Charles N. Gaylord** was a professor of civil engineering at the University of Virginia.

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Preface

As a practicing structural engineer and as an educator, I have always believed that structural engineers and architects should have knowledge of the design of the various types of structures and of their components, various analysis and design methods, the technologies used in this analysis, and the design and production of engineering drawings. The *Structural Engineering Handbook* provides established engineers, young engineers preparing for license exams, architects, and civil engineering students a comprehensive reference on the planning and design of a variety of engineered structures. It also gives the designer the information likely needed for all design phases.

The handbook covers various types of structures, such as tall buildings, industrial buildings, bridges including railroad bridges, thin-shell structures, arches, cable-supported roofs, steel tanks for liquids, retaining structures, blast-resistant structures, bins and silos for granular material, steel transmission towers and poles, and chimneys. Structural loads for the various types of structures are also covered, and there is comprehensive coverage of classical structural analysis methods, finite-element analysis, and computer applications in structural engineering. Additionally, earthquake-resistant design has been covered based on the most recent codes and standards. Design of reinforced concrete, prestressed concrete, structural steel, cold-formed steel, masonry, wood, and aluminium are covered. A chapter on soil mechanics, soil exploration, and foundation design is also provided. Design against fatigue and fracture is covered for concrete, composites, and steel.

In this fifth edition, all chapters have been rewritten, some chapters in previous versions of the handbook have been removed due to recent developments in design or construction practices, and 12 new chapters have been added. The new chapters cover structural loads, fracture mechanics of concrete and composites, railroad bridges, health monitoring of structures, building information modeling (BIM), structural fire engineering, progressive collapse and blast-resistant design, strengthening of concrete using fiber-reinforced polymer (FRP), structural glass, design of foundations for machines, value engineering, and stone cladding.

The 33 chapters of the handbook have been written by 66 contributors. They have presented their material in a ready-to-use form with flowcharts to show step-by-step procedures wherever possible. Therefore, derivations of formulas are omitted in all but a few instances, and many worked-out examples are given. Background information, descriptive matter, and explanatory material have been condensed or omitted. Because each chapter treats a subject that is broad enough to fill a book by itself, the contributors have had to select the material that, in their judgment, is likely to be the most useful to the greatest number of users. References and sources of additional material are noted for most of the topics that could not be treated in sufficient detail.

I am very grateful to the contributors for their tremendous efforts in writing, reviewing, and editing their work, and for their patience during the time it has taken to complete the fifth edition.

Mustafa Mahamid, Ph.D., S.E., P.E., P.Eng.
University of Illinois at Chicago

Structural Engineering Handbook

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Chapter 1

Structural Loads

BY
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1.1 INTRODUCTION

Applicable nominal loads on a structure are determined from the general building code under which the project is to be designed and constructed. Chapter 16 of the IBC (Ref. 1) contains the minimum magnitudes of some nominal loads and references ASCE/SEI 7 (Ref. 2) for others. For a specific project, the governing local building code should be consulted for any variances from the IBC or ASCE/SEI 7.

It is common for nominal loads to be referred to as service loads. These loads are multiplied by load factors in the strength design method. Exceptions are the wind load effect W and the earthquake load effect E: Both are defined to be strength-level loads where the load factor is equal to 1.0.

Table 1.1 contains a list of loads from the IBC and ASCE/SEI 7. Comprehensive information on the determination of structural loads can be found in Ref. 3.

1.2 DEAD LOADS

Nominal dead loads D are the actual weights of construction materials and fixed service equipment that are attached to or supported by the building or structure. Specific examples of such loads are listed under the definition of "dead load" in IBC 202.

Dead loads are considered to be permanent loads because their magnitude remains essentially constant over time.

Superimposed dead loads are permanent loads other than the weights of the structural members and include the following: floor finishes and/or topping; walls; ceilings; heating, ventilating, and air-conditioning (HVAC) and other service equipment; fixed partitions; and cladding.

Minimum design dead loads for various types of common construction components are provided in ASCE/SEI Table C3.1-1a, and minimum densities for common construction materials are given in ASCE/SEI Table C3.1-2. In cases where information on dead load is unavailable, values of dead loads used in design must be approved by the building official (IBC 1606.2).

1.3 LIVE LOADS

1.3.1 General

Live loads are transient in nature and vary in magnitude over the life of a structure. These loads are produced by the use and occupancy of a building or structure and do not include construction loads, environmental loads (such as wind loads, snow loads, rain loads, earthquake loads, and flood loads), or dead loads (IBC 202).

IBC Table 1607.1 contains nominal design values of uniformly distributed and concentrated live loads L_o as a function of occupancy or use. The occupancy description listed in the table is not necessarily group-specific (occupancy groups are defined in IBC Chapter 3). For example, an office building with a Business Group B classification may

Table 1.1 Summary of Loads Addressed in the IBC and ASCE/SEI 7

Notation	Load	Code section
D	Dead load	IBC 1606
D_i	Weight of ice	Chap. 10 of ASCE/SEI 7
E	Combined effect of horizontal and vertical earthquake-induced forces as defined in ASCE/SEI 12.4.2	IBC 1613 and ASCE/SEI 12.4.2
E_m	Maximum seismic load effect of horizontal and vertical forces as set forth in ASCE/SEI 12.4.3	IBC 1613 and ASCE/SEI 12.4.3
F	Load due to fluids with well-defined pressures and maximum heights	-------
F_a	Flood load	IBC 1612
H	Load due to lateral earth pressures, ground water pressure, or pressure of bulk materials	IBC 1610 (soil lateral loads)
L	Live load, except roof live load, including any permitted live load reduction	IBC 1607
L_r	Roof live load including any permitted live load reduction	IBC 1607
R	Rain load	IBC 1611
S	Snow load	IBC 1608 and Chapter 7 of ASCE/SEI 7
T	Cumulative effects of self-straining forces and effects	See ASCE/SEI 2.3.4 and 2.4.4
W	Load due to wind pressure	IBC 1609 and Chapters 26 to 31 of ASCE/SEI 7
W_i	Wind-on-ice load	IBC 1614 and Chapter 10 of ASCE/SEI 7

also have storage areas that may warrant live loads of 125 or 250 psf (6.0 or 12.0 kN/m^2) depending on the type of storage, which are greater than the prescribed office live loads. Structural members are designed on the basis of the maximum effects due to application of either a uniform load or a concentrated load and need not be designed for the effects of both loads applied at the same time. The building official must approve live loads that are not specifically listed in the table.

Partitions that can be relocated (i.e., those types that are not permanently attached to the structure) are considered to be live loads in office and other buildings. A live load equal to at least 15 psf (0.72 kN/m^2) must be included for movable partitions if the nominal uniform floor live load is less than 80 psf (3.8 kN/m^2).

IBC Table 1607.1 prescribes a minimum roof live load of 20 psf (0.96 kN/m^2) for typical roof structures; larger live loads are required for roofs used as gardens or places of assembly.

ASCE Table 4.3-1 also contains minimum uniform and concentrated live loads, and some of these values differ from those in IBC Table 1607.1. ASCE Tables C4.3-1 and C4.3-2 can be used as a guide in establishing live loads for some commonly encountered occupancies.

1.3.2 Reduction in Live Loads

Because live loads are transient in nature, the probability that a structural member will be subjected to the full effects from nominal live loads decreases as the area supported by the member increases. Except for uniform live loads on roofs, the minimum uniformly distributed live loads L_o in IBC Table 1607.1 are permitted to be reduced in accordance with the methods in IBC 1607.11.1 or 1607.11.2. The general method of live load reduction in IBC 1607.11.1 is also given in ASCE/SEI 4.7. Reduction of roof live loads must conform to IBC 1607.13.2.

1.3.3 General Method of Live Load Reduction

IBC Equation (16-23) can be used to obtain a reduced live load L for members that support an area $K_{LL}A_T \geq 400$ ft^2 (37.2 m^2):

$$L = L_o\left(0.25 + \frac{15}{\sqrt{K_{LL}A_T}}\right)$$

$$\geq 0.50L_o \text{ for members supporting one floor}$$

$$\geq 0.40L_o \text{ for members supporting two or more floors}$$

In SI Units

$$L = L_o\left(0.25 + \frac{4.75}{\sqrt{K_{LL}A_T}}\right)$$

In this equation, K_{LL} is the live load element factor given in IBC Table 1607.11.1, and A_T is the tributary area supported by the member in square feet (square meters).

The live load element factor K_{LL} converts the tributary area A_T into an influence area, which is considered to be the adjacent floor area from which the member derives its load. In other words,

$$K_{LL} = \text{influence area/tributary area}$$

Figure 1.1 illustrates how the reduction multiplier $0.25 + 15/(\sqrt{K_{LL}A_T})$ varies with respect to the influence area $K_{LL}A_T$. Included in the figure are the minimum influence area of 400 square feet and the limits of 0.5 and 0.4, which are the maximum permitted reductions for members supporting one floor and two or more floors, respectively.

One-Way Slabs

Live load reduction on one-way slabs is permitted provided that the tributary area, A_T, does not exceed an area equal to the slab span times a width normal to the span of 1.5 times the slab span (i.e., an area with an aspect ratio of 1.5). The live load will be somewhat higher for a one-way slab with an aspect ratio of 1.5 than for a two-way slab with the same aspect ratio. This recognizes the benefits of higher redundancy that results from two-way action.

ASCE/SEI 4.7.6 has the same requirements for live load reduction on one-way slabs as that in IBC 1607.11.1.1.

Heavy Live Loads

According to IBC 1607.11.1.2, live loads that are greater than 100 psf must not be reduced except for the following:

1. Live loads for members supporting two or more floors are permitted to be reduced by a maximum of 20 percent, but L must not be less than that calculated by IBC 1607.11.1.
2. In occupancies other than storage, additional live load reduction is permitted if it can be shown by a registered design professional that such a reduction is warranted.

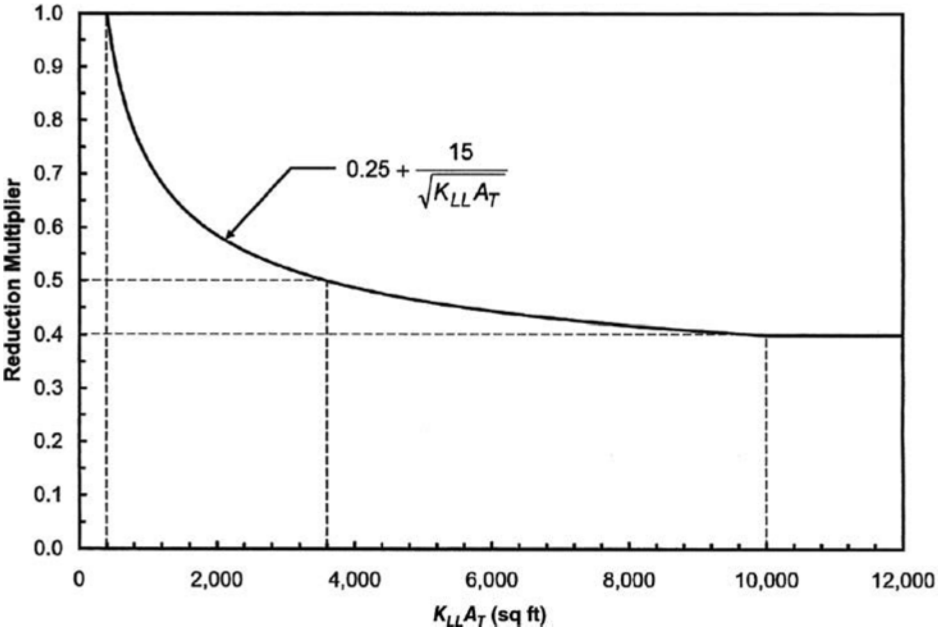


Figure 1.1 Reduction multiplier for live load in accordance with IBC 1607.11.1.

In buildings that support relatively large live loads, such as storage buildings, several adjacent bays may be fully loaded; as such, live loads should not be reduced in those situations. Data in actual buildings indicate that the floor in any story is seldom loaded with more than 80 percent of the nominal live load. Thus, a maximum live load reduction of 20 percent is permitted for members that support two or more floors, such as columns and walls.

Passenger Vehicle Garages

The live load in passenger vehicle garages is not permitted to be reduced, except for members supporting two or more floors; in such cases, the maximum reduction is 20 percent, but L must not be less than that calculated by IBC 1607.11.1 (IBC 1607.11.1.3). Thus, live load reduction is not permitted except for members that support two or more floors.

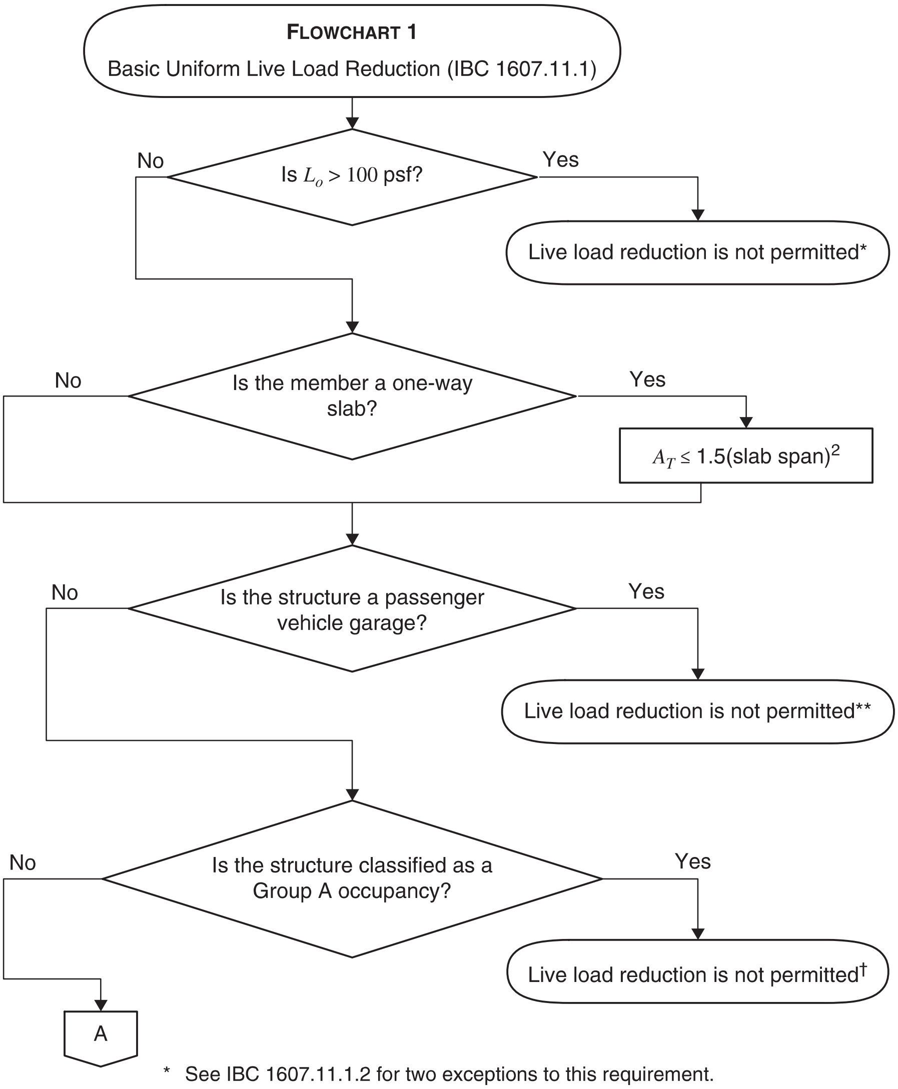
Group A (Assembly) Occupancies

Due to the nature of assembly occupancies, there is a high probability that the entire floor is subjected to full uniform live load. According to Footnote m in IBC Table 1607.1, live load reduction is not permitted in assembly areas, except for follow spot, projection, and control rooms, unless specific exceptions of IBC 1607.11 apply.

Flowchart 1 shown in Fig. 1.2 can be used to determine basic uniform live load reduction in accordance with IBC 1607.11.1.

1.3.4 Alternative Uniform Live Load Reduction

An alternative method of uniform live load reduction, which is based on provisions in the 1997 Uniform Building Code (Ref. 4), is given in IBC 1607.11.2. IBC Equation 16-24 can be used to obtain a reduction factor



* See IBC 1607.11.1.2 for two exceptions to this requirement.

** Live loads for members supporting two or more floors are permitted to be reduced by a maximum of 20 percent (IBC 1607.11.1.3).

† Live loads for members supporting follow spot, projections, and control rooms are permitted to be reduced (see Footnote m in IBC Table 1607.1).

Figure 1.2 Basic uniform live load reduction in accordance with IBC 1607.11.1 (Flowchart 1).

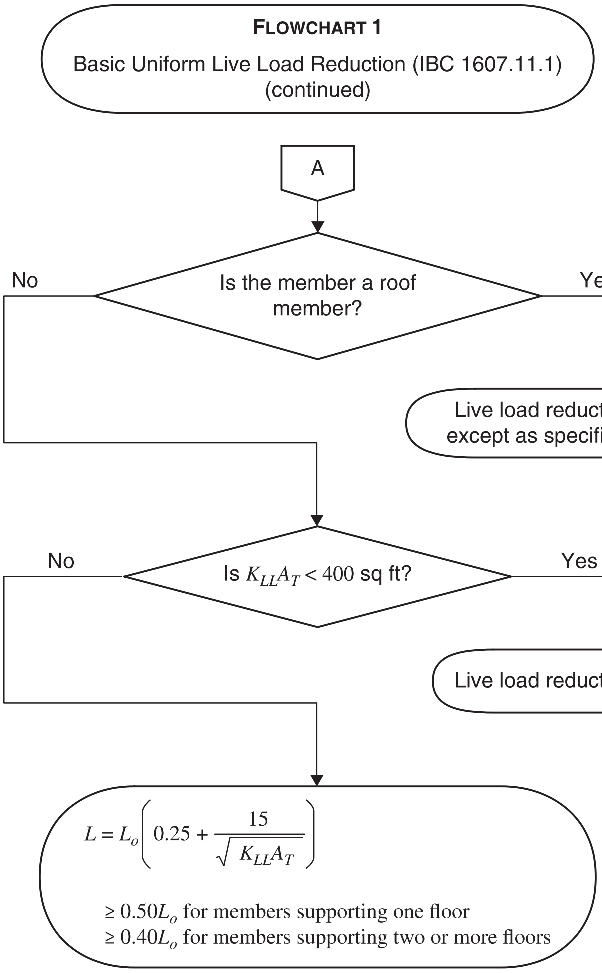


Figure 1.2 (*Continued*)

R for members that support an area greater than or equal to 150 square feet where the live load is less than or equal to 100 psf.

Flowchart 2 shown in Fig. 1.3 can be used to determine alternative uniform live load reduction in accordance with IBC 1607.11.2.

1.3.5 Roof Loads

In general, roofs are to be designed to resist dead, live, wind, and, where applicable, rain, snow, and earthquake loads. A minimum roof live load of 20 psf is prescribed in IBC Table 1607.1 for typical roof structures, while larger live loads are required for roofs used as gardens or places of assembly.

IBC 1607.13.2 permits nominal roof live loads on flat, pitched, and curved roofs and awnings and canopies other than fabric construction supported by a skeleton frame to be reduced in accordance with IBC Equation 16-26:

$$L_r = L_o R_1 R_2; \quad 12 \leq L_r \leq 20$$

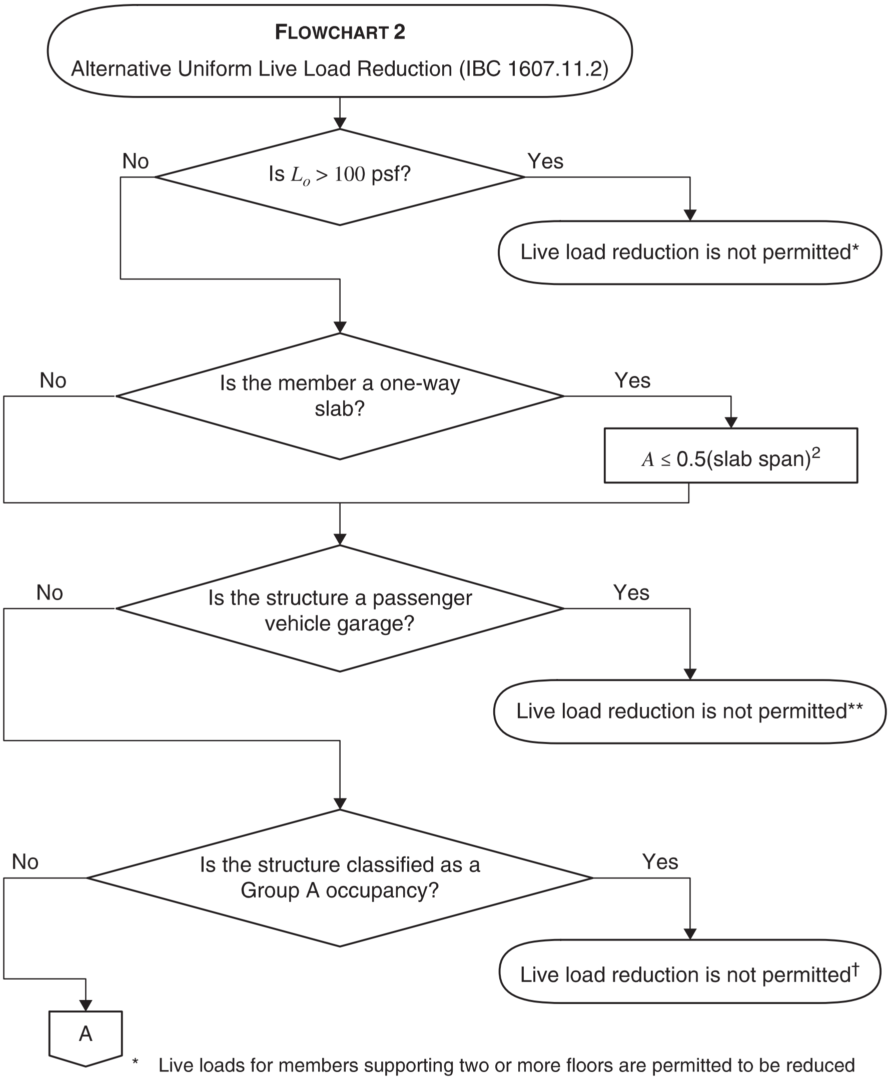
where L_o = unreduced roof live load per square foot of horizontal roof projection supported by the member
L_r = reduced roof live load per square foot of horizontal roof projection supported by the member

$$R_1 = \begin{cases} 1 & \text{for } A_t \leq 200 \text{ square feet} \\ 1.2 - 0.0001A_t & \text{for } 200 \text{ square feet} < A_t < 600 \text{ square feet} \\ 0.6 & \text{for } A_t \geq 600 \text{ square feet} \end{cases}$$

$$R_2 = \begin{cases} 1 & \text{for } F \leq 4 \\ 1.2 - 0.05F & \text{for } 4 < F < 12 \\ 0.6 & \text{for } F \geq 12 \end{cases}$$

A_t = tributary area (span length multiplied by effective width) in square feet supported by a member
F = the number of inches of rise per foot for a sloped roof
= the rise-to-span ratio multiplied by 32 for an arch or dome

No live load reduction is permitted for members supporting less than or equal to 200 square feet as well as for roof slopes less than or equal to 4:12. In no case is the reduced roof live load to be taken less than 12 psf. The minimum load determined by this equation accounts for occasional loading due to the presence of workers and materials during repair operations.



* Live loads for members supporting two or more floors are permitted to be reduced by a maximum of 20 percent [IBC 1607.11.2(1); also see exception in that section].

** Live loads for members supporting two or more floors are permitted to be reduced by a maximum of 20 percent [IBC 1607.11.2(2)].

† Live loads for members supporting follow spot, projections, and control rooms are permitted to be reduced (see Footnote m in IBC Table 1607.1).

Figure 1.3 Alternative uniform live load reduction in accordance with IBC 1607.11.2 (Flowchart 2).

Live loads are permitted to be reduced on areas of occupiable roofs using the provisions of IBC 1607.11 for floor live loads (IBC 1607.13.3). Live loads that are greater than or equal to 100 psf at areas of roofs that are classified as Group A (assembly) occupancies are not permitted to be reduced unless specific exceptions of IBC 1607.11 apply (see Footnote m in IBC Table 1607.1).

A minimum roof live load of 20 psf is required in unoccupied landscaped areas on roofs (IBC 1607.13.3.1). The weight of landscaping material is considered a dead load and must be determined based on the saturation level of the soil.

A minimum roof live load of 5 psf is required for awnings and canopies in accordance with IBC Table 1607.1 (IBC 1607.13.4). Such elements must also be designed for the combined effects of snow and wind loads in accordance with IBC 1608 and 1609.

1.3.6 Crane Loads

Design provisions for runway beams that support moving bridge cranes and monorail cranes are given in IBC 1607.14. In general, the support structure of the crane must be designed for the maximum wheel load, vertical impact, and horizontal impact as a simultaneous load combination.

A typical top-running bridge crane is depicted in Fig. 1.4. The trolley and hoist move along the crane bridge, which is supported by the

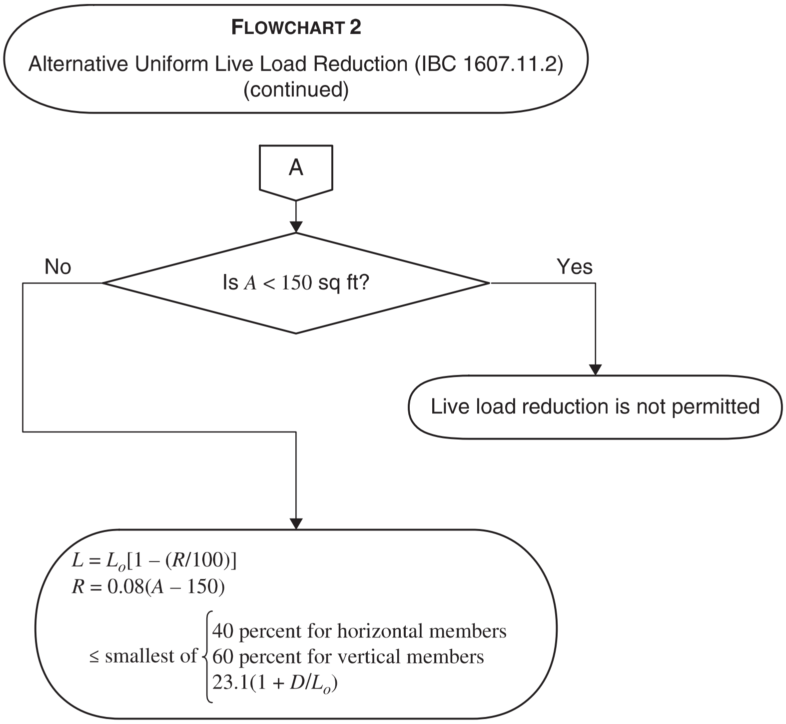


Figure 1.3 (*Continued*)

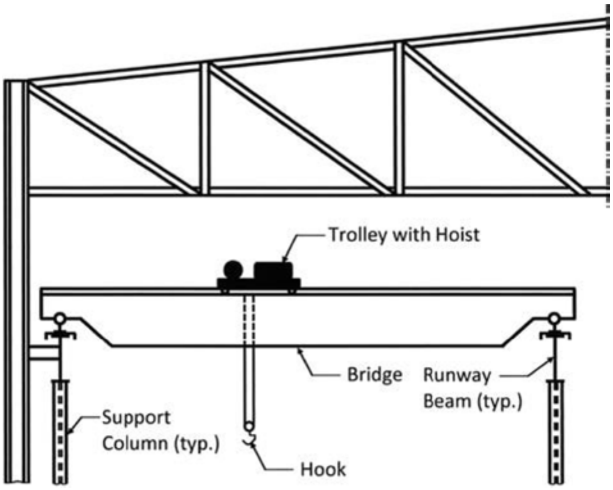


Figure 1.4 Top-running bridge crane.

runway beams and support columns. The entire crane assemblage can also move along the length of the runway beams.

The maximum wheel loads that are to be used in the design of the supporting members are due to the weight of the bridge plus the sum of the rated capacity and the weight of the trolley. The trolley is to be positioned on its runway at the location where the resulting load effect is maximum; generally, this occurs when the trolley is moved as close to the supporting members as possible.

The maximum wheel loads must be increased by the percentages given in IBC 1607.14.2 to account for the vertical impact force that is caused by the starting and stopping movement of the suspended weight from the crane and by the movement of the crane along the rails.

A lateral force that acts perpendicular to the crane runway beams is generated by the transverse movement of the crane, that is, by movement that occurs perpendicular to the runway beam (see Fig. 1.5). According to IBC 1607.14.3, the magnitude of this load on crane

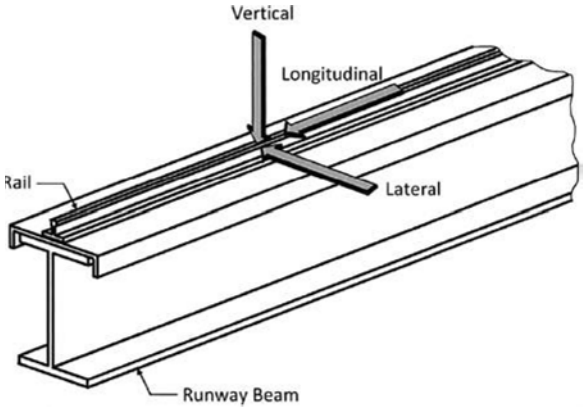


Figure 1.5 Crane loads on a runway beam.