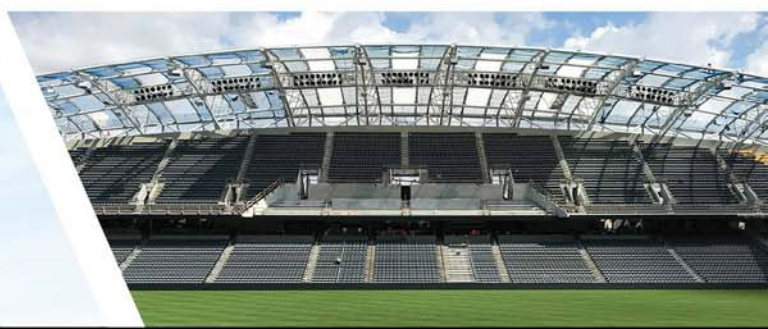
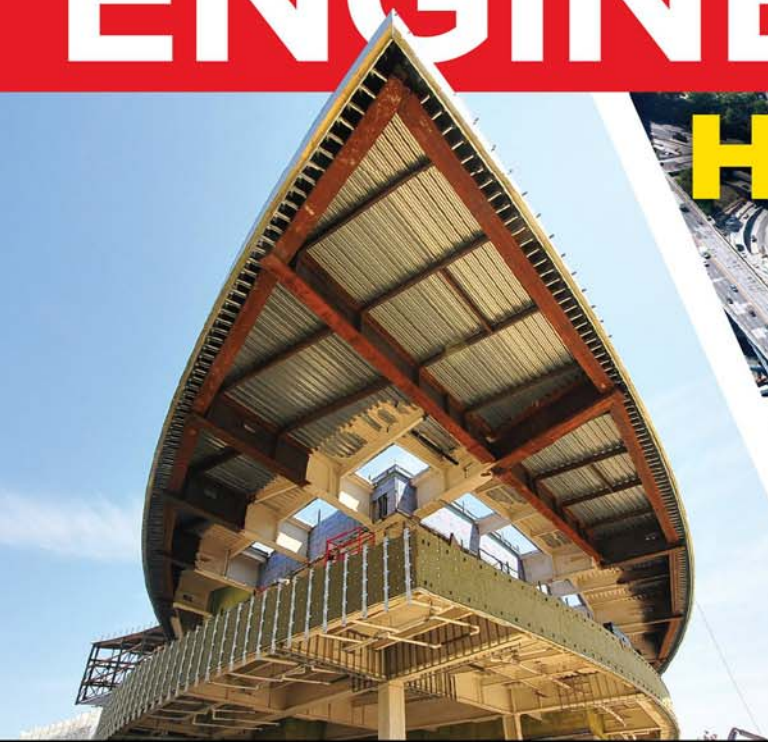




# STRUCTURAL ENGINEERING

# HANDBOOK

FIFTH EDITION



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

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**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*



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

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# Contents

Contributors xv  
Preface xix

<b>Chapter 1. Structural Loads</b> <i>Mustafa Mahamid, David A. Fanella</i> . . . . .	<b>1</b>
1.1 Introduction . . . . .	1
1.2 Dead Loads . . . . .	1
1.3 Live Loads . . . . .	1
1.4 Rain Loads . . . . .	7
1.5 Soil Lateral Loads . . . . .	8
1.6 Snow and Ice Loads . . . . .	9
1.7 Wind Loads . . . . .	20
1.8 Earthquake Loads . . . . .	49
1.9 Flood and Tsunami Loads . . . . .	49
1.10 Load Combinations . . . . .	57
References . . . . .	60
<b>Chapter 2. Structural Analysis</b> <i>Aly M. Said, Anas S. Issa, M. Shahria Alam</i> . . . . .	<b>61</b>
<b>PART A FUNDAMENTALS AND APPLICATIONS TO STRUCTURAL FRAMEWORKS</b> . . . . .	<b>61</b>
2.1 Introduction . . . . .	61
2.2 Fundamentals of Analysis . . . . .	61
2.3 Energy Principles . . . . .	63
2.4 Analysis of Statically Determinate Structures . . . . .	67
2.5 Analysis of Statically Indeterminate Structures . . . . .	72
2.6 Force Method . . . . .	74
2.7 Displacement Method . . . . .	77
<b>PART B ARCHES AND RIGID FRAMES</b> . . . . .	<b>91</b>
2.8 Introduction . . . . .	91
2.9 Analysis of Arches . . . . .	93
2.10 Design of Arches . . . . .	94
2.11 Design of Frames . . . . .	101
2.12 Special Topics . . . . .	111
2.13 Construction and Details . . . . .	112
References . . . . .	116
<b>Chapter 3. The Finite-Element Method</b> <i>Craig D. Foster, Sheng-Wei Chi</i> . . . . .	<b>119</b>
3.1 Overview of Theory of Finite-Element Analysis . . . . .	119
3.2 Outline of Steps in a Finite-Element Analysis . . . . .	122
3.3 Types of Structural and Mechanical Analyses . . . . .	122
3.4 Elements and Nodes . . . . .	124
3.5 Meshing . . . . .	125
3.6 Applying Loads and Displacement Boundary Conditions . . . . .	126
3.7 Material Models and Other Properties . . . . .	126
3.8 Solving the Quasi-Static Problem . . . . .	126

3.9	Postprocessing—Solving for Strain, Stress, and Other Quantities .....	126
3.10	Dynamic Finite-Element Analysis .....	126
3.11	Nonlinear Finite-Element Analysis .....	128
3.12	Verification and Validation .....	128
3.13	Issues and Pitfalls in Finite-Element Analysis .....	128
3.14	Introduction to Finite Elements for Thermal, Thermomechanical, and Other Problems .....	130
	References .....	131
<b>Chapter 4. Computer Applications in Structural Engineering</b>		
	<i>Raoul Karp, Bulent N. Alemdar, Sam Rubenzer</i> .....	<b>133</b>
4.1	Introduction .....	133
4.2	Computer Structural Analysis Simulation .....	133
4.3	Structural Finite Elements .....	135
4.4	Foundations .....	139
4.5	Verifying Analysis Results .....	142
4.6	Building Information Modeling and Interoperability .....	142
4.7	Summary .....	143
	References .....	143
<b>Chapter 5. Earthquake-Resistant Design S. K. Ghosh</b> .....		
	<i>S. K. Ghosh</i> .....	<b>145</b>
5.1	Overview .....	145
5.2	Nature of Earthquake Motion .....	145
5.3	Design Philosophy .....	146
5.4	Seismic Design Requirements of the 2018 IBC/ASCE 7-16 .....	147
	References .....	162
<b>Chapter 6. Fracture and Fatigue Kedar S. Kirane, Zdeněk P. Bažant, J. Ernesto Indacocha, Vineeth Kumar Gattu</b> .....		
	<i>Kedar S. Kirane, Zdeněk P. Bažant, J. Ernesto Indacocha, Vineeth Kumar Gattu</i> .....	<b>165</b>
PART A CONCRETE AND COMPOSITES .....		165
6.1	Introduction to Quasibrittle Fracture .....	165
6.2	Concrete .....	166
6.3	Fiber-Reinforced Composites .....	169
	References .....	173
PART B STRUCTURAL STEELS .....		175
6.4	Fracture of Structural Steels .....	175
6.5	Fatigue of Structural Steels .....	182
	References .....	193
<b>Chapter 7. Soil Mechanics and Foundations Joseph W. Schulenberg, Krishna R. Reddy</b> .....		
	<i>Joseph W. Schulenberg, Krishna R. Reddy</i> .....	<b>195</b>
7.1	Soil Behavior .....	195
7.2	Shallow Foundation Analyses .....	199
7.3	Deep Foundations .....	204
7.4	Retaining Structures .....	210
7.5	Investigations .....	218
7.6	Soil Improvement .....	219
7.7	Monitoring .....	221
	References .....	221
<b>Chapter 8. Design of Structural Steel Members Jay Shen, Bulent Akbas, Onur Seker, Charlies J. Carter</b> .....		
	<i>Jay Shen, Bulent Akbas, Onur Seker, Charlies J. Carter</i> .....	<b>225</b>
8.1	Design of Steel and Composite Members .....	225
8.2	Seismic Design of Steel Members in Moment and Braced Frames .....	264
8.3	Concluding Remarks .....	303
	References .....	303
<b>Chapter 9. Design of Cold-Formed Steel Structural Members</b>		
	<i>Nabil A. Rahman, Helen Chen, Cheng Yu</i> .....	<b>305</b>
9.1	Shapes and Applications .....	305
9.2	Materials .....	306

9.3 Corrosion Protection.....	308
9.4 Member Design Methodology.....	309
9.5 Structural Stability in Determining Member Forces.....	311
9.6 Member Design .....	311
9.7 Assemblies and Systems .....	315
9.8 Connections.....	317
References .....	320

<b>Chapter 10. Aluminum Structural Design</b> <i>J. Randolph Kissell</i> .....	<b>321</b>
10.1 Introduction .....	321
10.2 Design Overview .....	322
10.3 Determining Required Forces .....	322
10.4 Axial Tension .....	323
10.5 Axial Compression.....	324
10.6 Flexure.....	325
10.7 Shear and Torsion.....	326
10.8 Combined Forces .....	328
10.9 Connections.....	328
10.10 Serviceability.....	331
10.11 Fabrication and Erection.....	331
10.12 Fatigue .....	331
References .....	331

<b>Chapter 11. Design of Reinforced-Concrete Structural Members</b> <i>Mustafa Mahamid, David A. Fanella</i> .....	<b>333</b>
11.1 Concrete .....	333
11.2 Reinforcement.....	333
11.3 Specifications, Codes, and Standards .....	334
11.4 General Requirements for Strength and Serviceability .....	334
11.5 General Principles of the Strength Design Method .....	338
11.6 General Principles and Requirements.....	339
11.7 One-Way Slabs, Two-Way Slabs, and Beams .....	340
11.8 Columns.....	352
11.9 Tension Members.....	354
11.10 Members Subjected to Flexure and Axial Load .....	354
11.11 Walls .....	356
11.12 Footings.....	360
11.13 Two-Way Slab Systems .....	365
11.14 Seismic.....	367
References .....	368

<b>Chapter 12. Design of Prestressed-Concrete Structural Members</b> <i>Sri Sritharan, Maryam Nazari</i> .....	<b>369</b>
Notation .....	369
12.1 Introduction.....	370
12.2 Prestress Losses .....	371
12.3 Analysis Concepts .....	374
12.4 Design for Flexure .....	380
12.5 Design for Shear, Bond, and Bearing.....	386
12.6 Design of Continuous Beam.....	389
12.7 Design for Torsion .....	393
12.8 Design for Seismic Loads .....	396
References .....	397

<b>Chapter 13. Masonry Construction</b> <i>Richard Bennett, Sam Rubenzer</i> .....	<b>399</b>
Notation .....	399
13.1 Masonry Materials.....	400
13.2 Masonry Analysis.....	401
13.3 Unreinforced Masonry .....	402
13.4 Reinforced Masonry .....	403

13.5 Seismic Design .....	407
13.6 Specifying Masonry and Testing Masonry.....	409
13.7 Masonry Fire Walls.....	409
References .....	410

**Chapter 14. Timber Structures** *Thomas Williamson, Mustafa Mahamid.* ..... **411**

14.1 Wood as an Engineering Material.....	411
14.2 Allowable Stress Design (ASD) vs. Load and Resistance Factor Design (LRFD).....	413
14.3 Structural Wood Products.....	413
14.4 Member Design .....	422
14.5 Connection Design .....	425
14.6 Lateral Load Resistance .....	430
References .....	435

**Chapter 15. Bridge Engineering** *Soliman Khudeira, Tony Shkurti, Eric Stone, James Carter III, Jamshid Mohammadi, Bora Jang* ..... **437**

<b>PART A STEEL AND CONCRETE BRIDGES</b> .....	<b>437</b>
15.1 General .....	437
15.2 Loads .....	437
15.3 Steel Bridges .....	453
15.4 Bearing and Expansion Details .....	459
15.5 Beam and Plate-Girder Bridges.....	462
15.6 Truss Bridges .....	469
15.7 Concrete Bridges .....	470
15.8 Slab Bridges .....	471
15.9 T-Beam Bridges .....	473
15.10 Box-Girder Bridges .....	483
15.11 Prestressed-Concrete Bridges .....	493
15.12 Bridge Railings .....	505
15.13 Administration of a Bridge System .....	506
References .....	507
<b>PART B STEEL BOX-GIRDER BRIDGES.</b> .....	<b>508</b>
15.14 Benefits .....	508
15.15 Internal Elements.....	509
15.16 Limit States and Combinations .....	509
15.17 Analysis of Box Girders .....	511
15.18 Design of Box-Section Members.....	512
15.19 Internal Element Design .....	512
15.20 Concluding Remarks.....	512
References .....	513
<b>PART C CURVED STEEL I-GIRDER BRIDGES</b> .....	<b>514</b>
15.21 General.....	514
15.22 Design Considerations .....	514
15.23 Curved Girder Mechanics .....	517
References .....	524
<b>PART D CURVED STEEL BOX-GIRDER BRIDGES.</b> .....	<b>525</b>
15.24 General .....	525
15.25 Design Considerations .....	526
15.26 Box-Girder Mechanics .....	529
References .....	531
<b>PART E CURVED CONCRETE BOX-GIRDER BRIDGES</b> .....	<b>532</b>
15.27 General.....	532
15.28 Concrete Box-Girder Bridge Types .....	532
15.29 Significance of Structural Configuration and Details.....	533
15.30 Review of Theory .....	535
15.31 Design Considerations .....	539
References .....	547

<b>Chapter 16. Railroad Bridge Design</b> <i>Mohsen Issa,</i>	
<i>Ahmad Hammad</i> .....	549
16.1 Introduction.....	549
16.2 General Requirements.....	549
16.3 Loading.....	549
16.4 Timber.....	550
16.5 Steel.....	551
16.6 Concrete.....	552
References.....	557
<b>Chapter 17. Industrial Buildings</b> <i>Jules Van de Pas, John Rolfes</i> .....	559
17.1 Planning Industrial Buildings.....	559
17.2 Code Requirements and Industrial Loads.....	563
17.3 Framing Systems.....	566
References.....	573
<b>Chapter 18. Tall Buildings</b> <i>Charles Besjak, Brian McElhatten,</i>	
<i>Preetam Biswas</i> .....	575
18.1 Definition of Tall Building.....	575
18.2 General Design Considerations.....	575
18.3 Structural Design Considerations.....	576
18.4 Serviceability Considerations.....	577
18.5 Structural Systems for Tall Buildings.....	577
18.6 System Conceptualization.....	579
18.7 System Parameters and Choices.....	581
18.8 Analysis Parameters and Techniques.....	591
18.9 Performance-Based Design for Wind.....	595
18.10 Performance-Based Design for Seismic.....	599
18.11 Creep and Shrinkage.....	600
18.12 High-Rise Building Glossary.....	601
18.13 Additional Credits.....	601
Acknowledgments.....	601
References.....	601
<b>Chapter 19. Thin-Shell Concrete Structures</b> <i>Edmond Saliklis,</i>	
<i>Mustafa Mahamid, David P. Billington, Julian A. Dumitrescu</i> .....	603
19.1 Introduction and Historical Overview.....	603
19.2 Shells of Rotation.....	609
19.3 Domes.....	613
19.4 Cylindrical Barrel Shells.....	626
19.5 Folded Plates.....	632
19.6 Translation Shells of Double Curvature.....	638
19.7 Dimensioning.....	647
19.8 Stability and Safety.....	647
19.9 Construction.....	649
19.10 Appearance.....	649
References.....	649
<b>Chapter 20. Cable-Supported Roofs</b> <i>Paul A. Gossen,</i>	
<i>Keith M. MacBain</i> .....	651
20.1 Introduction.....	651
20.2 Cable Materials and Construction.....	651
20.3 Structural Systems.....	656
20.4 Dynamics.....	658
20.5 Analysis and Design.....	658
20.6 Erection.....	661
References.....	661

<b>Chapter 21. Reinforced-Concrete Silos</b> <i>Ramez B. Gayed, Mustafa Mahamid, Amin Ghali</i> .....	<b>663</b>
21.1 General .....	663
21.2 Design of Walls .....	676
21.3 Design of Bottoms .....	681
References .....	695
<b>Chapter 22. Design of Steel Tanks</b> <i>Leslie D. Scott</i> .....	<b>697</b>
22.1 Introduction .....	697
22.2 Design Considerations .....	701
22.3 Design of Reservoirs and Standpipes .....	707
22.4 Elevated Tanks .....	717
22.5 Accessories .....	723
22.6 Materials .....	726
22.7 Commercially Available Computer Programs .....	726
22.8 The Engineer's Role .....	727
References .....	727
<b>Chapter 23. Electrical Transmission and Substation Structures</b> <i>Michael D. Miller, Robert E. Nickerson</i> .....	<b>729</b>
23.1 Introduction .....	729
23.2 Referenced Standards and Manuals of Practice .....	729
23.3 Transmission Line Structures .....	729
23.4 Substation Structures .....	737
References .....	740
<b>Chapter 24. Chimneys</b> <i>Shu-Jin Fang, Victor Bochicchio</i> .....	<b>741</b>
24.1 Introduction .....	741
24.2 Design Loads .....	741
24.3 Steel Stacks .....	745
24.4 Reinforced-Concrete Chimneys .....	750
24.5 Liners and Linings .....	752
24.6 Foundations .....	754
References .....	754
<b>Chapter 25. Health Monitoring and Nondestructive Testing</b> <i>Didem Ozevin, Farhad Ansari</i> .....	<b>757</b>
25.1 Introduction .....	757
25.2 Components of NDE Methods .....	757
25.3 Waveform-Based NDE Methods and Applications .....	760
25.4 The Applications of Waveform-Based NDE Methods to Infrastructure Systems .....	765
References .....	767
<b>Chapter 26. Building Information Modeling (BIM) for Structural Engineering</b> <i>Nawari O. Nawari</i> .....	<b>771</b>
26.1 Introduction .....	771
26.2 BIM Fundamentals .....	771
26.3 BIM Processes in Practice .....	776
26.4 Structure and Architecture Synergy (SAS) Framework .....	778
26.5 Conclusions .....	786
References .....	786
<b>Chapter 27. Structural Fire Engineering</b> <i>V. K. R. Kodur, M. Z. Naser</i> .....	<b>789</b>
27.1 General .....	789
27.2 Designing Structures for Fire Safety .....	789
27.3 Fire Growth and Development .....	789
27.4 Properties of Construction Materials at Elevated Temperatures .....	791
27.5 Fire Resistance Evaluation .....	796
27.6 Prescriptive-Based Approaches .....	796

27.7 Rational Design Approaches .....	798
27.8 Summary .....	800
References .....	800
<b>Chapter 28. Disproportionate Collapse and Blast-Resistant Design</b> <i>Shalva Marjanishvili, Robert Smilowitz</i> .....	<b>801</b>
<b>PART A STRUCTURAL ROBUSTNESS AND DISPROPORTIONATE COLLAPSE</b> .....	<b>801</b>
28.1 Introduction .....	801
28.2 Disproportionate Collapse Mitigation Strategies .....	802
28.3 Progressive Collapse Modeling .....	802
28.4 Progressive Collapse Analysis Example .....	806
References .....	809
<b>PART B BLAST-RESISTANT DESIGN</b> .....	<b>809</b>
28.5 Introduction .....	809
28.6 Blast Phenomena .....	810
28.7 Dynamic Design Approach .....	812
28.8 Structural Behavior .....	813
28.9 Primary Structure: Material Selection and Design for Blast Resistance .....	814
28.10 Secondary Structure: Material Selection and Design for Blast Resistance .....	815
28.11 Conclusion .....	815
References .....	815
<b>Chapter 29. FRP Strengthening of Reinforced-Concrete Members</b> <i>Hayder A. Rasheed</i> .....	<b>817</b>
29.1 FRP Properties for Strengthening Applications .....	817
29.2 Flexural Strengthening Design for Beams and Slabs .....	818
29.3 Shear Strengthening Design for Beams .....	822
29.4 Confinement Strengthening Design for Circular Columns .....	827
References .....	831
<b>Chapter 30. Structural Glass and Glazing</b> <i>Rui de S. Camposinhos</i> .....	<b>833</b>
30.1 Introduction .....	833
30.2 Glass: Production and Properties .....	834
30.3 Glass as a Structural Material .....	835
30.4 Actions .....	839
30.5 Codes and Standards .....	842
30.6 Plate Buckling .....	850
30.7 Lateral-Torsional Buckling .....	854
30.8 Glass Columns .....	856
References .....	858
<b>Chapter 31. Machine Foundations</b> <i>O. Salem Ali</i> .....	<b>861</b>
31.1 Background .....	861
31.2 Classification of Machine Based on Machine Type .....	861
31.3 Classification of Machine Based on Type of Excitation Force .....	861
31.4 Classification of Machine Based on Foundation Type .....	861
31.5 Classification of Machine Load Transfer Mechanism .....	861
31.6 Design Limits for Machine Foundations .....	862
31.7 Effect of the Supporting Soil .....	862
31.8 Energy Transfer Mechanism .....	863
31.9 Effect of Embedment of Foundation .....	863
31.10 Reduction in Permissible Soil Stress .....	864
31.11 Damping in Soil .....	864
31.12 Modeling Techniques for Machine Foundations .....	865
31.13 Block-Type Foundation .....	865
31.14 Mat Foundations .....	866
31.15 Elevated Machine Foundation .....	867

31.16	Three-Dimensional Finite-Element Modeling .....	868
31.17	Soil Modeling.....	868
31.18	Current Approach of Soil Modeling .....	869
31.19	Methods to Compute Dynamic Impedance Functions .....	870
31.20	Foundations Supported on Piles.....	870
31.21	Piles Subjected to Lateral Vibrations.....	871
31.22	Elastic Continuum .....	872
31.23	Piles Subjected to Vertical Vibrations .....	875
31.24	Pile Group Effect.....	881
	References .....	882

**Chapter 32. Value Methodology** *Muthiah Kasi,*

<i>Charles A. Bartlett.</i> .....	<b>885</b>	
32.1	Introduction.....	885
32.2	VM Job Plan .....	885
32.3	The Key Features of VM Job Plan: Function Analysis .....	889
32.4	Example 1: Parapet Joint Detail .....	890
32.5	Evaluation Phase .....	893
32.6	Implementation .....	894
32.7	Summary.....	894
	References .....	894

**Chapter 33. Stone Cladding** *Rui de S. Camposinhos*..... **895**

33.1	Introduction: Natural Stone Cladding.....	895
33.2	Natural Stone Depiction .....	896
33.3	Mechanical Properties .....	898
33.4	Cladding Systems and Methods .....	899
33.5	Limit States Design .....	901
33.6	Dowel Anchorage.....	905
33.7	Kerf Anchorage.....	909
33.8	Undercut Anchorage.....	911
	References .....	915



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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*

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**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<sup>2</sup>) 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<sup>2</sup>) must be included for movable partitions if the nominal uniform floor live load is less than 80 psf (3.8 kN/m<sup>2</sup>).

IBC Table 1607.1 prescribes a minimum roof live load of 20 psf (0.96 kN/m<sup>2</sup>) 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<sup>2</sup> (37.2 m<sup>2</sup>):

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

$\geq 0.50L_o$  for members supporting one floor  
 $\geq 0.40L_o$  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.

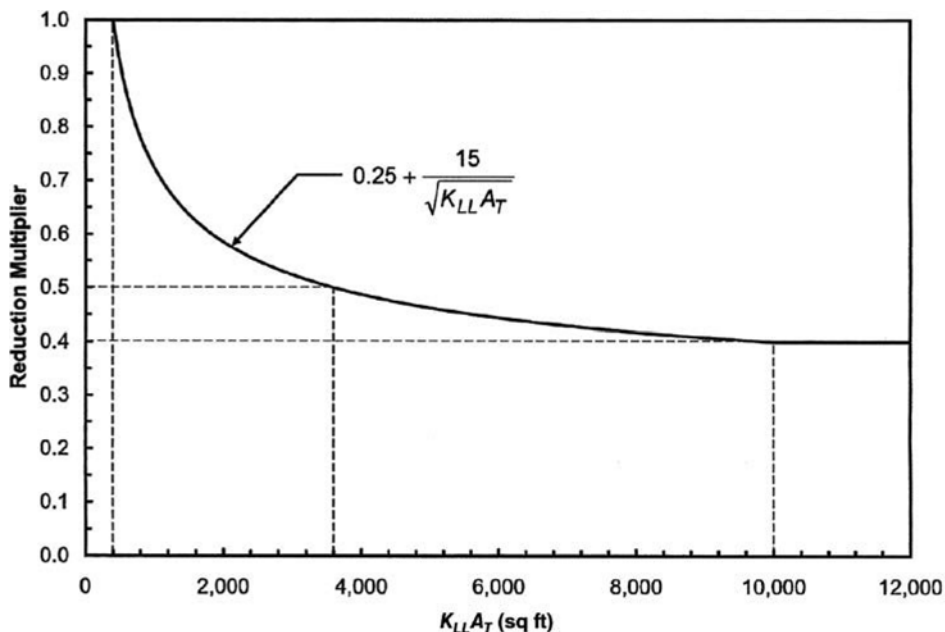


Figure 1.1 Reduction multiplier for live load in accordance with IBC 1607.11.1.

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.

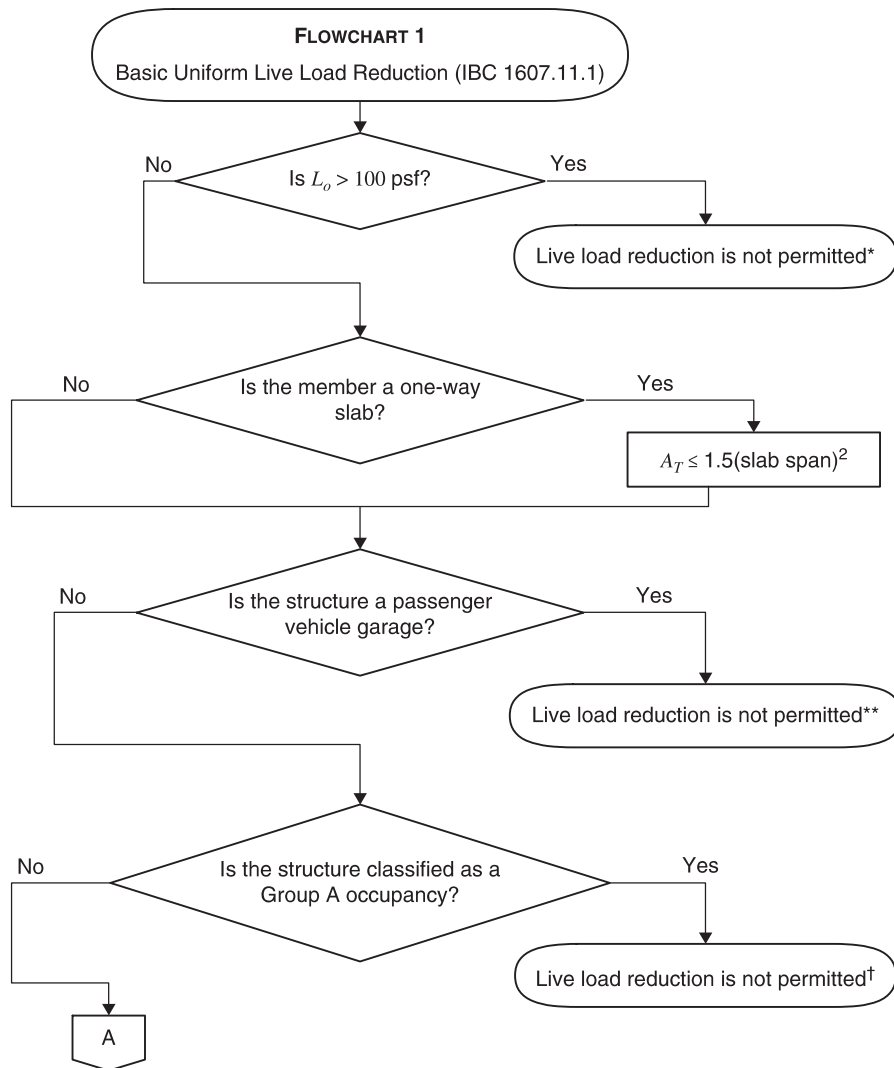
GROUP A (ASSEMBLY) OCCUPANCIES

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).

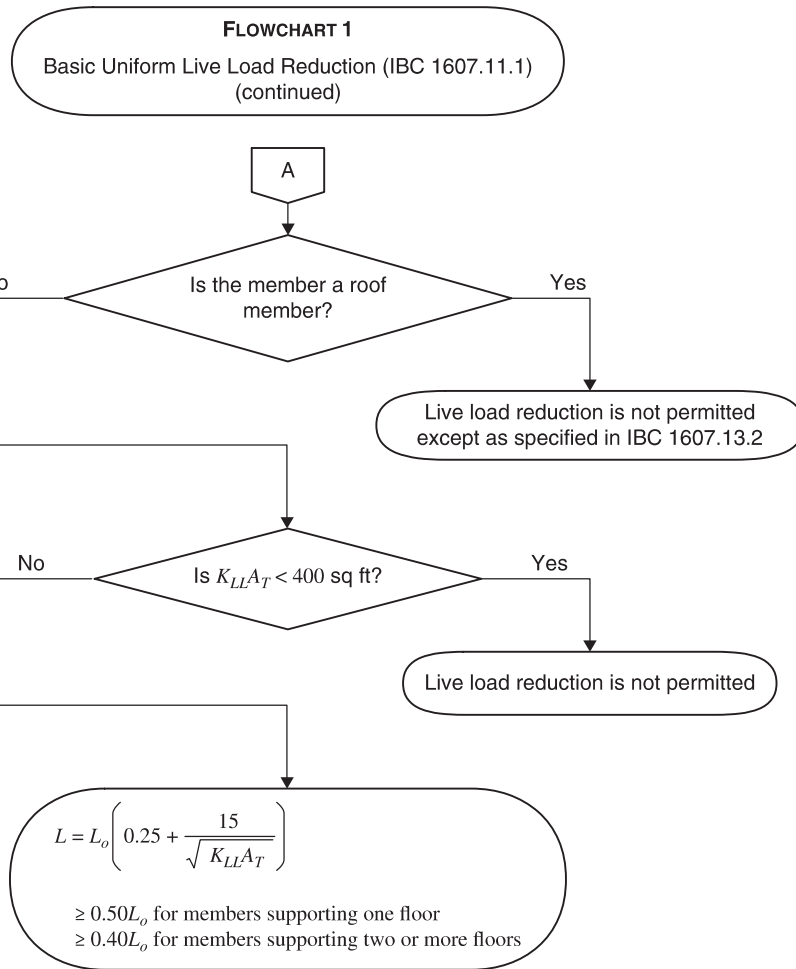


Figure 1.2 (Continued)

$R$  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

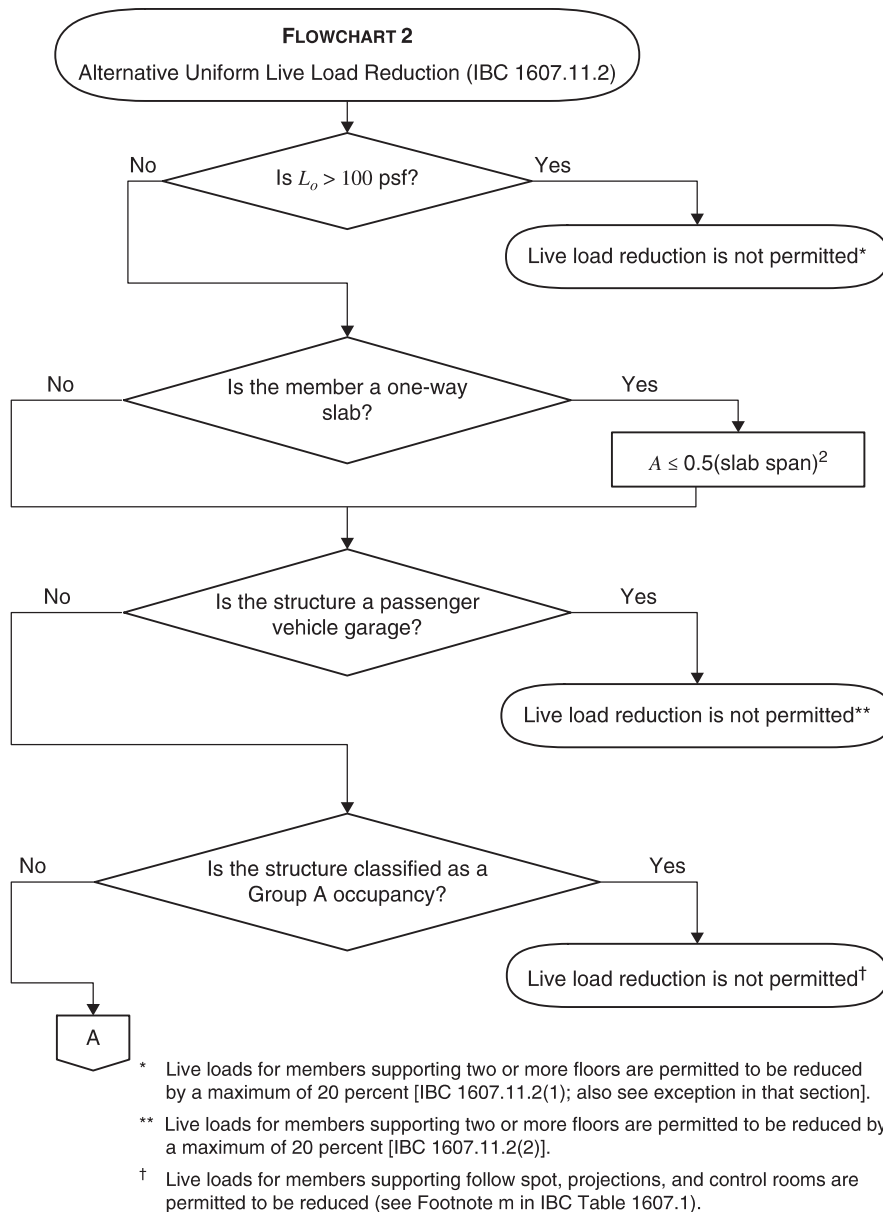
$$R_1 = \begin{cases} 1 & \text{for } A_t \leq 200 \text{ square feet} \\ 1.2 - 0.0001A_t & \text{for } 200 \text{ square feet} < A_t < 600 \text{ square feet} \\ 0.6 & \text{for } A_t \geq 600 \text{ square feet} \end{cases}$$

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

$A_t$  = 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.



**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

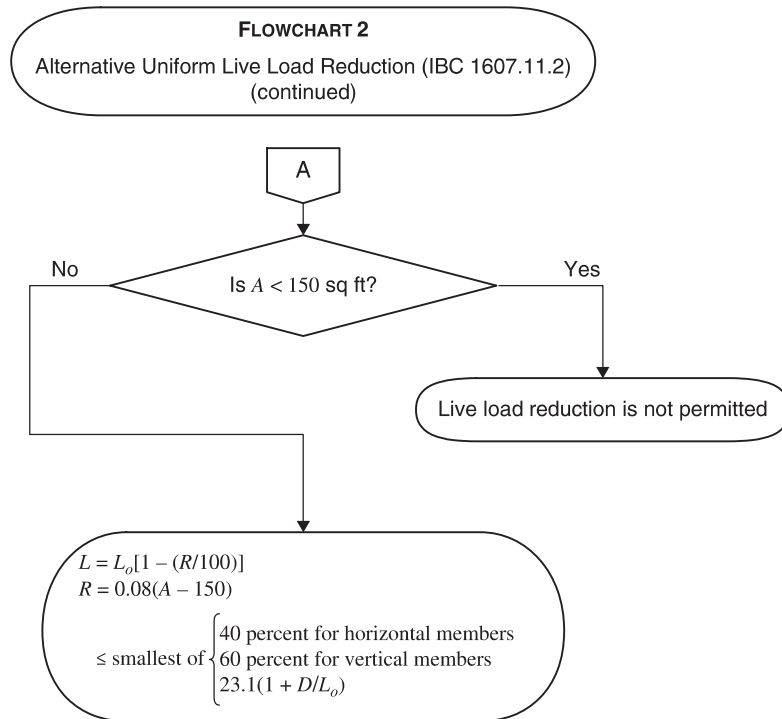


Figure 1.3 (Continued)

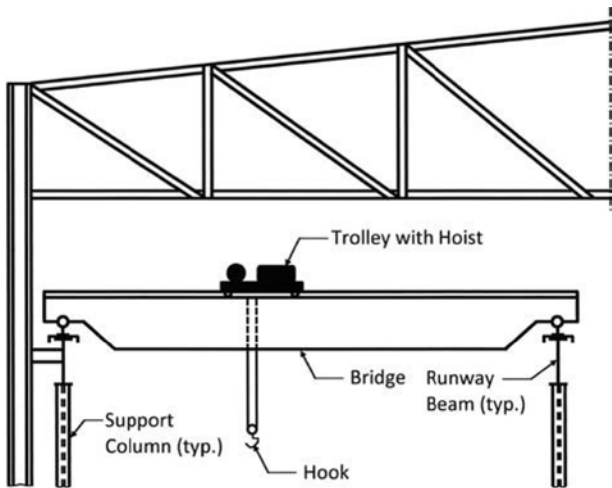


Figure 1.4 Top-running bridge crane.

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

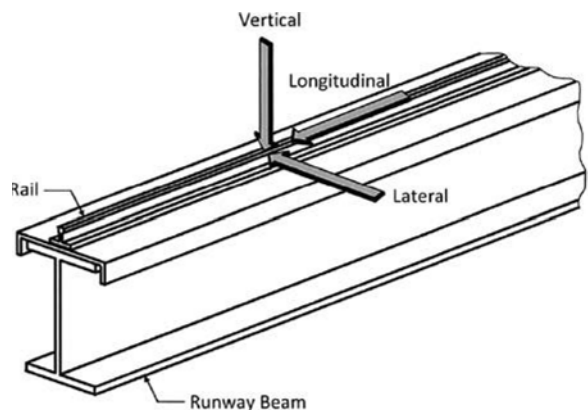


Figure 1.5 Crane loads on a runway beam.