About the Author
Alan Williams, Ph.D., S.E., F.I.C.E., C. Eng., is a registered structural engineer in California who has had extensive experience in the practice and teaching of structural engineering. In California, he has worked as a Senior Transportation Engineer in the Department of Transportation and as Principal for Structural Safety in the Division of the State Architect. His prior positions include Professor of Structural Analysis at Ahmadu Bello University, Nigeria, and consulting structural engineer in South Africa and the United States. Dr. Williams’ practical experience includes the design and construction of bridges, schools, and commercial and industrial structures.

The author obtained his bachelor of science degree and doctorate from Leeds University and has published 13 papers and nine books on structural engineering topics. Dr. Williams is a member of the Structural Engineers Association of Southern California; Fellow and Life Member of the Institution of Civil Engineers, and a Chartered Engineer in the United Kingdom.

About the International Code Council
The International Code Council (ICC), a membership association dedicated to building safety, fire prevention, and energy efficiency, develops the codes and standards used to construct residential and commercial buildings, including homes and schools. The mission of ICC is to provide the highest quality codes, standards, products, and services for all concerned with the safety and performance of the built environment. Most U.S. cities, counties, and states choose the International Codes, building safety codes developed by the ICC. The International Codes also serve as the basis for construction of federal properties around the world, and as a reference for many nations outside the United States. The ICC is also dedicated to innovation and sustainability and Code Council subsidiary, ICC Evaluation Service, issues Evaluation Reports for innovative products and reports of Sustainable Attributes Verification and Evaluation (SAVE).

Headquarters: 500 New Jersey Avenue, NW,
6th Floor, Washington, DC 20001-2070
District Offices: Birmingham, AL; Chicago, IL;
Los Angeles, CA
1-888-422-7233
www.iccsafe.org
## Contents

Preface ......................................................... xv
Nomenclature ............................................. xvii

1 Steel Buildings and Design Criteria ......................... 1
   1.1 Introduction .......................................... 1
   1.2 Types of Steel Buildings ............................... 5
   1.3 Building Codes and Design Criteria ................. 8
   1.4 ASD and LRFD Concepts ............................... 9
   References .................................................. 12
   Problems .................................................. 12

2 Design Loads .................................................. 15
   2.1 Introduction ........................................... 15
   2.2 Dead Loads ........................................... 16
      Tributary Area ......................................... 16
      Slab Supports .......................................... 16
      Dead Load Applied to Beams ......................... 17
      Dead Load Applied to Girders ....................... 19
      Dead Load Applied to Columns ...................... 21
      Two-Way Slabs ......................................... 24
   2.3 Live Loads ............................................... 25
      Continuous Beam Systems ............................ 25
      Influence Area ......................................... 26
      Reduction in Floor Live Load ....................... 27
      Reduction in Roof Live Load ......................... 31
      Combined Dead and Live Load ....................... 33
   2.4 Snow Loads .............................................. 34
      Flat Roof .............................................. 34
      Ground Snow Load ..................................... 34
      Flat Roof Snow Load .................................. 34
      Exposure Factor ....................................... 35
      Thermal Factor ......................................... 35
      Importance Factor ..................................... 35
      Rain-on-Snow Surcharge Load ....................... 36
      Snow Drifts on Lower Roofs ......................... 38
      Leeward Snow Drifts .................................. 38
      Windward Snow Drifts ................................ 42
      Sloped Roof Snow Load ................................ 44
      Slope Factor ........................................... 45
      Warm Roof Slope Factor .............................. 45
      Cold Roof Slope Factor .............................. 45

Copyrighted Material
Unbalanced Snow Load for Hip and Gable Roofs  46
Unbalanced Snow Load for Gable Roof with
  \( W \leq 20 \text{ ft} \)  47
Unbalanced Snow Load for Gable Roof with
  \( W > 20 \text{ ft} \)  48
Sliding Snow  51
Snow Load on Continuous Beam Systems  54
2.5 Soil Lateral Load  55
Earth Pressure at Rest  55
2.6 Flood Loads  55
  Loads during Flooding  55
  Hydrostatic Loads  55
  Hydrodynamic Loads  55
  Wave Loads  56
Impact Loads  56
2.7 Rain Loads  56
  Design Rain Loads  56
  Ponding Instability  57
2.8 Wind Loads  57
  Exposure Category  59
  Basic Wind Speed  59
  Low-Rise Building  61
  Regular Building  61
  Simple Diaphragm Building  61
  Velocity Pressure Exposure Coefficient  61
  Site Topography  61
  Directionality Factor  62
  Velocity Pressure  62
ASCE 7 Chapter 28 Part 1—Envelope Procedure  63
Rigidity of the Structure  64
Gust Effect Factor  64
Enclosure Classifications  64
Design Wind Pressure on MWFRS for Low-Rise, Rigid Buildings  65
Design Wind Pressure on Components and Cladding  67
Design of Components and Cladding Using ASCE 7 Sec. 30.4  68
IBC Alternate All-Heights Method  71
Velocity Pressure Exposure Coefficient  72
Topography Factor  72
Wind Stagnation Pressure  72
Wind Importance Factor  73
Net-Pressure Coefficient  73
Design Wind Pressure on MWFRS: IBC Alternate All-Heights Method  75
Design Wind Pressure on Components and Cladding: IBC Alternate All-Heights Method  77
2.9 Seismic Loads .............................................. 78
  Ground Motion Parameters ................................ 80
  Site Classification Characteristics ...................... 80
  Site Coefficients ........................................ 80
  Adjusted Earthquake Response Accelerations ............ 81
  Design Response Acceleration Parameters .............. 81
  Occupancy Category and Importance Factors .......... 83
  Seismic Design Category .................................. 83
  Seismic Force-Resisting System ......................... 85
  Response Modification Coefficient .................... 86
  Fundamental Period of Vibration ....................... 89
  Seismic Response Coefficient ......................... 89
  Effective Seismic Weight ................................ 92
  Seismic Base Shear ...................................... 93
  Vertical Distribution of Seismic Forces .............. 93
  Diaphragm Loads ........................................ 95
  Flexible Diaphragms ................................... 96
  Anchorage of Structural Walls to Diaphragms ......... 99
  Rigid Diaphragms ...................................... 104
  Lateral Design Force on Structural Walls .......... 109
  Lateral Design Force on Parapets ..................... 109
  Redundancy Factor .................................... 110
2.10 Load Combinations ................................... 114
  Strength Design Load Combinations .................... 115
  Allowable Stress Load Combinations .................. 117
  Strength Design Special Load Combinations .......... 119
  Allowable Stress Design Special Load Combinations .. 120
2.11 Serviceability Criteria ................................ 120
  Deflection ........................................... 121
  Drift ................................................ 121
  Vibration ............................................ 122
  Durability ............................................ 122
References .................................................. 122
Problems .................................................. 123

3 Behavior of Steel Structures under Design Loads .... 129
  3.1 Introduction .......................................... 129
  3.2 Gravity Load-Resisting Systems .................... 129
    Simple Connections .................................... 129
    Fully Restrained (FR) Moment Connections ............ 135
    Partially Restrained (PR) Moment Connections ......... 140
  3.3 Lateral Load-Resisting Systems ..................... 144
    Diaphragms .......................................... 144
    Collectors .......................................... 145
    Steel Deck Diaphragms ................................ 151
    Frames Subjected to Lateral Forces .................. 156
3.4 Approximate Methods for Laterally Loaded Frames 160
   Portal Method 160
   Cantilever Method 163
References 167
Problems 168

4 Design of Steel Beams in Flexure 171
   4.1 Introduction 171
   Flexural Limit States 171
   Lateral Bracing of Beams 172
   Design Flexural Strength and Allowable Flexural Strength 173
   4.2 Plastic Moment of Resistance 175
   Shape Factor and ASD 176
   Built-Up Sections 177
   4.3 Compact, Noncompact, and Slender Sections 179
   Compact Section 179
   Noncompact Section 181
   Slender Section 182
   4.4 Lateral-Torsional Buckling Modification Factor 182
   4.5 Lateral-Torsional Buckling 185
   Plastic Mode Lb < Lp ≤ Lm 185
   Plastic Mode Extended: Lb < Lp ≤ Lm 187
   Inelastic Mode: Lb < Lp ≤ Lr 188
   Elastic Mode: Lb > Lr 190
   4.6 Weak Axis Bending 191
   Compact Flanges 191
   Noncompact Flanges 192
   4.7 Biaxial Bending 194
   Overhead Traveling Bridge Crane 195
   4.8 Singly Symmetric Sections in Bending 198
   Plastic Mode 199
   Lateral-Torsional Buckling 199
   Flange Local Buckling 199
   Stem Local Buckling 200
   4.9 Redistribution of Bending Moments in Continuous Beams 201
   4.10 Deflection Limits 204
References 204
Problems 204

5 Design of Steel Beams for Shear and Torsion 209
   5.1 Introduction 209
   Shear in Beam Webs 211
   Web Yielding 212
   Inelastic Buckling 214
   Elastic Buckling 216
   5.3 Weak Axis Shear 218
   5.4 Longitudinal Shear in Built-Up Sections 219
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>Block Shear</td>
<td>221</td>
</tr>
<tr>
<td></td>
<td>Block Shear Strength for Bolted Connections</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>Effective Bolt Hole Diameter and Net Area</td>
<td>223</td>
</tr>
<tr>
<td></td>
<td>Block Shear Strength for Welded Connections</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>Block Shear Strength for Coped Beams</td>
<td>226</td>
</tr>
<tr>
<td>5.6</td>
<td>Web Local Yielding</td>
<td>228</td>
</tr>
<tr>
<td></td>
<td>Bearing on Concrete</td>
<td>229</td>
</tr>
<tr>
<td></td>
<td>Web Yielding at Support</td>
<td>231</td>
</tr>
<tr>
<td></td>
<td>Web Yielding at Girder Interior</td>
<td>233</td>
</tr>
<tr>
<td>5.7</td>
<td>Web Crippling</td>
<td>234</td>
</tr>
<tr>
<td>5.8</td>
<td>Web Sidesway Buckling</td>
<td>235</td>
</tr>
<tr>
<td>5.9</td>
<td>Design for Torsion</td>
<td>237</td>
</tr>
<tr>
<td></td>
<td>Torsion in Closed Sections</td>
<td>237</td>
</tr>
<tr>
<td></td>
<td>Torsion in Open Sections</td>
<td>238</td>
</tr>
<tr>
<td></td>
<td>Specification Provisions</td>
<td>239</td>
</tr>
<tr>
<td></td>
<td>Round HSS Subject to Torsion</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>Rectangular HSS Subject to Torsion</td>
<td>241</td>
</tr>
<tr>
<td></td>
<td>W-Shape Subject to Torsion</td>
<td>244</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>249</td>
</tr>
<tr>
<td>Problems</td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>6</td>
<td>Design of Compression Members</td>
<td>255</td>
</tr>
<tr>
<td>6.1</td>
<td>Introduction</td>
<td>255</td>
</tr>
<tr>
<td></td>
<td>Compression Limit State</td>
<td>255</td>
</tr>
<tr>
<td>6.2</td>
<td>Effective Length</td>
<td>257</td>
</tr>
<tr>
<td></td>
<td>Tabulated Factors</td>
<td>257</td>
</tr>
<tr>
<td>6.3</td>
<td>Alignment Charts</td>
<td>259</td>
</tr>
<tr>
<td></td>
<td>Alignment Chart for Braced Frame</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>Alignment Chart for Sway Frame</td>
<td>261</td>
</tr>
<tr>
<td></td>
<td>Stiffness Reduction Factors</td>
<td>263</td>
</tr>
<tr>
<td>6.4</td>
<td>Axially Loaded Compression Members</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>Flexural Buckling of Members without Slender Elements</td>
<td>264</td>
</tr>
<tr>
<td></td>
<td>Torsional and Flexural-Torsional Buckling of Members without Slender Elements</td>
<td>268</td>
</tr>
<tr>
<td></td>
<td>Single Angle Compression Members without Slender Elements</td>
<td>271</td>
</tr>
<tr>
<td></td>
<td>Members with Slender Elements</td>
<td>273</td>
</tr>
<tr>
<td>6.5</td>
<td>Built-Up Sections</td>
<td>279</td>
</tr>
<tr>
<td>6.6</td>
<td>Column Base Plates</td>
<td>282</td>
</tr>
<tr>
<td></td>
<td>Concrete Footing Capacity</td>
<td>282</td>
</tr>
<tr>
<td></td>
<td>Base Plate Thickness</td>
<td>285</td>
</tr>
<tr>
<td>6.7</td>
<td>Column Flanges with Concentrated Forces</td>
<td>287</td>
</tr>
<tr>
<td></td>
<td>Introduction</td>
<td>287</td>
</tr>
<tr>
<td></td>
<td>Flange Local Bending</td>
<td>287</td>
</tr>
<tr>
<td></td>
<td>Web Compression Buckling</td>
<td>290</td>
</tr>
<tr>
<td></td>
<td>Web Panel Zone Shear</td>
<td>292</td>
</tr>
</tbody>
</table>
## Contents

Transverse Stiffener Requirements ........................................ 296
Doubler Plate Requirements ............................................. 300
References ................................................................. 302
Problems ................................................................. 302

7 Stability of Frames ...................................................... 307
   7.1 Introduction ......................................................... 307
   Beam-Columns ......................................................... 307
   Second-Order Effects ................................................. 308
   7.2 Design for Combined Forces ....................................... 310
   7.3 Stability Analysis .................................................. 312
      Approximate Second-Order Analysis ................................ 312
      Stability Analysis Procedures .................................... 316
References ................................................................. 329
Problems ................................................................. 329

8 Design by Inelastic Analysis ............................................ 333
   8.1 Introduction ......................................................... 333
      General Principles .................................................. 333
      Ductility ............................................................ 334
   8.2 Plastic Moment of Resistance ....................................... 334
   8.3 Plastic Hinge Formation ............................................ 336
   8.4 Design Requirements ................................................ 337
      Local Buckling ..................................................... 337
      Unbraced Length .................................................. 338
      Limiting Axial Load .............................................. 338
   8.5 Analysis Requirements ............................................. 339
      Geometric Imperfections ........................................... 339
      Residual Stress and Partial Yielding Effects .................... 339
      Material Properties and Yield Criteria .......................... 340
   8.6 Statical Method of Design .......................................... 340
   8.7 Mechanism Method of Design ....................................... 344
      Linear Elastic-Plastic Response Curve ............................ 347
   8.8 Static Equilibrium Check .......................................... 349
   8.9 Beam-Column Design ............................................... 351
References ................................................................. 356
Problems ................................................................. 357

9 Design of Tension Members ............................................. 359
   9.1 Introduction ......................................................... 359
   9.2 Tensile Strength .................................................... 359
   9.3 Effective Net Area .................................................. 360
      Plates with Bolted Connection ................................... 361
      Plates with Welded Connection .................................. 364
      Rolled Sections with Bolted Connection ......................... 365
      Rolled Sections with Welded Connection ......................... 368
# Contents

Round Hollow Structural Sections with Welded Connection .......................... 369

9.4 Pin-Connected Members .................................................. 372
  Dimensional Requirements ............................................. 372
  Limit States ............................................................... 373

9.5 Design of Eyebars .......................................................... 375
  Dimensional Requirements ............................................. 375

9.6 Design for Fatigue .......................................................... 378
  Design Procedure ......................................................... 379

References ................................................................. 380
Problems ................................................................. 381

10 Design of Bolted Connections ............................................ 387

10.1 Introduction ............................................................... 387
  Bolt Types ................................................................. 387
  Bolt Installation .......................................................... 387
  Connection Types .......................................................... 388

10.2 Snug-Tight Bolts in Shear and Bearing ..................................... 390
  Bolt Spacing ............................................................... 390
  Shear Strength ........................................................... 391
  Bearing Strength .......................................................... 392

10.3 Snug-Tight Bolts in Shear and Tension ..................................... 397
  Bolts in Tension Only ..................................................... 397
  Bolts in Combined Tension and Shear .................................. 397

10.4 Slip-Critical Bolts in Shear and Tension .................................. 400
  Bolts in Shear Only ....................................................... 400
  Bolts in Combined Shear and Tension .................................. 404

10.5 Prying Action ............................................................... 406

10.6 Bolt Group Eccentrically Loaded in Plane of Faying Surface ............... 410
  Elastic Unit Area Method ................................................. 410
  Instantaneous Center of Rotation Method ................................. 413

10.7 Bolt Group Eccentrically Loaded Normal to the Faying Surface ............... 415

References ................................................................. 418
Problems ................................................................. 418

11 Design of Welded Connections ............................................... 423

11.1 Introduction ............................................................... 423
  The Welding Process ....................................................... 423
  Welding Applications ..................................................... 423
  Quality Assurance .......................................................... 424
  Weld Metal Strength ....................................................... 424

11.2 Weld Types ............................................................... 425
  Complete Joint Penetration Groove Welds ................................ 425
  Partial Joint Penetration Groove Welds ................................ 425
  Fillet Welds ............................................................... 427
## Contents

11.3 Available Strength of Fillet Welds ................................. 432
   Summary ................................................. 432
   Linear Weld Group Loaded through the Center of Gravity ... 432
   Weld Group with Concentric Loading ....................... 433

11.4 Weld Group Eccentrically Loaded in Plane of Faying
   Surface .................................................... 435
   Elastic Vector Analysis .................................. 435
   Instantaneous Center of Rotation Method .................. 439

11.5 Weld Group Eccentrically Loaded Normal to Faying
   Surface .................................................... 442
   Elastic Vector Analysis .................................. 442
   Instantaneous Center of Rotation Method .................. 445

References ..................................................... 446
Problems ....................................................... 447

12 Plate Girders .................................................. 451

12.1 Introduction .................................................. 451
12.2 Girder Proportions ............................................ 452
   Girder Depth ............................................... 452
   Flange Area ................................................ 452
   Flange Width .............................................. 453
   Flange Thickness .......................................... 453
   Web Thickness ............................................. 453
   Intermediate Transverse Stiffeners ....................... 453

12.3 Postbuckling Strength of the Web .............................. 454
12.4 Design for Shear with Unstiffened Web ....................... 455
12.5 Design for Shear with Stiffened Web: Tension Field
   Action Excluded .......................................... 457
12.6 Design for Shear with Stiffened Web: Tension Field
   Action Included ........................................... 459
12.7 Design of Transverse Stiffeners .............................. 460
   Tension Field Action Excluded ............................ 460
   Tension Field Action Included ............................ 462
12.8 Flexural Design of Plate Girders ............................ 464
   Compression Flange Yielding ............................. 464
   Lateral-Torsional Buckling ................................ 465
   Compression Flange Local Buckling ....................... 466
   Tension Flange Yielding .................................. 467

12.9 Design of Bearing Stiffeners ................................. 469
References ..................................................... 473
Problems ....................................................... 473

13 Composite Members .............................................. 477

13.1 Introduction .................................................. 477
13.2 Encased Composite Columns ................................. 479
   Limitations ............................................... 479
   Compressive Strength ..................................... 479
   Load Transfer ............................................. 483
Contents

13.3 Filled Composite Columns .................................................. 486
    Limitations ............................................................. 486
    Slenderness Limits ...................................................... 487
    Compressive Strength ................................................ 487
    Load Transfer .......................................................... 490
13.4 Encased Composite Beams ................................................ 493
13.5 Composite Beam with Flat Soffit Concrete Slab ....................... 494
    Effective Slab Width .................................................. 495
    Nominal Strength ...................................................... 495
    Fully Composite and Partially Composite Beams ...................... 495
    Nominal Strength of Fully Composite Beam with PNA in
    Concrete Slab .......................................................... 497
    Design Tables ............................................................ 500
    Shored and Unshored Construction ..................................... 502
    Composite Beam Deflection .......................................... 505
    Negative Flexural Strength .......................................... 506
    Steel Headed Stud Anchors in Composite Beam with
    Flat Soffit Concrete Slab .............................................. 508
    Steel Headed Stud Anchors in Composite Section
    with Concentrated Loads .............................................. 512
13.6 Formed Steel Deck with Ribs Perpendicular to Beams ............... 514
    Requirements ............................................................ 514
    Steel Headed Stud Anchors in Formed Steel Deck with
    Ribs Perpendicular to Beam .......................................... 516
13.7 Formed Steel Deck with Ribs Parallel to Beams ...................... 519
    Requirements ............................................................ 519
    Steel Headed Stud Anchors in Formed Steel Deck
    with Ribs Parallel to Beam ........................................... 520
References ................................................................. 522
Problems ................................................................. 523
Index ................................................................. 529
The purpose of this book is to introduce engineers to the design of steel structures using the International Code Council’s 2012 International Building Code (IBC). The International Building Code is a national building code which has consolidated and replaced the three model codes previously published by Building Officials and Code Administrators International (BOCA), International Conference of Building Officials (ICBO), and Southern Building Code Congress International (SBCCI). The first Code was published in 2000 and it has now been adopted by most jurisdictions in the United States.

In the 2012 IBC, two specifications of the American Institute of Steel Construction are adopted by reference. These are Specification for Structural Steel Buildings (AISC 360-10) and Seismic Provisions for Structural Steel Buildings (AISC 341-10). This book is based on the final draft of AISC 360-10. Where appropriate, the text uses the 13th edition of the AISC Steel Construction Manual, which includes AISC 360-05, as the 14th edition of the Manual was not available at the time of this publication. The design aids in the Manual are independent of the edition of the Specification.

Traditionally, structural steel design has been based on allowable stress design (ASD), also called working stress design. In ASD, allowable stress of a material is compared to calculated working stress resulting from service loads. In 1986, AISC introduced a specification based entirely on load and resistance factor design (LRFD) for design of structures. In 2005, AISC introduced a unified specification in which both methods were incorporated, both based on the nominal strength of a member, and this principle is continued in the 2010 Specification. In accordance with AISC 360 Sec. B.3, structural steel design may be done by either load and resistance factor design or by allowable strength design. Allowable strength design is similar to allowable stress design in that both utilize the ASD load combinations. However, for strength design, the specifications are formatted in terms of force in a member rather than stress. The stress design format is readily derived from the strength design format by dividing allowable strength by the appropriate section property, such as cross-sectional area or section modulus, to give allowable stress. In the LRFD method, the design strength is given as the nominal strength multiplied by a resistance factor and this must equal or exceed the required strength given by the governing LRFD load combination. In the ASD method, the allowable strength is given as the nominal strength divided by a safety factor and this must equal or exceed the required strength given by the governing ASD load combination. This book covers both ASD and LRFD methods and presents design problems and solutions side-by-side in both formats. This allows the reader to readily distinguish the similarities and differences between the two methods.
The 2012 IBC also adopts by reference the American Society of Civil Engineers’ Minimum Design Loads for Buildings and Other Structures (ASCE 7-10). This Standard provides live, dead, wind, seismic, and snow design loads and their load combinations. The examples in this text are based on ASCE 7-10.


This publication is suitable for a wide audience including practicing engineers, professional engineering examination candidates, undergraduate, and graduate students. It is also intended for those engineers and students who are familiar with either the ASD or LRFD method and wish to become proficient in the other design procedure.

I would like to express my appreciation and gratitude to John R. Henry, PE, Principal Staff Engineer, International Code Council, Inc., for his helpful suggestions and comments. Grateful acknowledgment is also due to Manisha Singh and the editorial staff of Glyph International for their dedicated editing and production of this publication.

Alan Williams
1.1 Introduction

Steel is widely used as a building material. This is because of a number of factors including its mechanical properties, availability in a variety of useful and practical shapes, economy, design simplicity, and ease and speed of construction.

Steel can be produced with a variety of properties to suit different requirements. The principle requirements are strength, ductility, weldability, and corrosion resistance. Figure 1.1 shows the stress-strain curves for ASTM A36 mild steel and a typical high-strength steel. Until recently, mild steel was the most common material for hot-rolled shapes but has now been superseded by higher strength steels for a number of shapes. ASTM A242 and A588 are corrosion resistant low-alloy steels. These are known as weathering steels and they form a tightly adhering patina on exposure to the weather. The patina consists of an oxide film that forms a protective barrier on the surface, thus preventing further corrosion. Hence, painting the steelwork is not required, resulting in a reduction in maintenance costs.

The stress-strain curve for mild steel indicates an initial elastic range, with stress proportional to strain, until the yield point is reached at a stress of 36 ksi. The slope of the stress-strain curve, up to this point, is termed the modulus of elasticity and is given by

\[ E = \frac{\text{stress}}{\text{strain}} = 29,000 \, \text{ksi} \]

Loading and unloading a mild steel specimen within the elastic range produces no permanent deformation and the specimen returns to its original length after unloading. The yield point is followed by plastic yielding with a large increase in strain occurring at a constant stress. Elongation produced after the yield point is permanent and non-recoverable. The plastic method of analysis is based on the formation of plastic hinges in a structure during the plastic range of deformation. The increase in strain during plastic yielding may be as much as 2 percent. Steel with a yield point in excess of 65 ksi does not exhibit plastic yielding and may not be used in structures designed by plastic design methods. At the end of the plastic zone, stress again increases with strain because of strain hardening. The maximum stress attained is termed the tensile strength of the steel and subsequent strain is accompanied by a decrease in stress.
The stress-strain curve for high-strength steel does not exhibit a pronounced yield point. After the elastic limit is reached, the increase in stress gradually decreases until the tensile strength is reached. For these steels a nominal yield stress is defined as the stress that produces a permanent strain of 0.2 percent.

Rolled steel sections are fabricated in a number of shapes, as shown in Fig. 1.2 and listed in Table 1.1. Dimensions, weights, and properties of these sections are given by American Institute of Steel Construction, Steel Construction Manual (AISC Manual) Part 1. The W-shape is an I-section with wide flanges having parallel surfaces. This is the most commonly used shape for beams and columns and is designated by nominal depth and weight per foot. Thus a W24 × 84 has a depth of 24.1 in and a weight of 84 lb/ft. Columns are loaded primarily in compression and it is preferable to have as large a radius of gyration about the minor axis as possible to prevent buckling. W12 and W14 sections are fabricated with the flange width approximately equal to the depth so as to achieve this. For example, a W12 × 132 has a depth of 14.7 in and a flange width of 14.7 in. The radii of gyration about

![Figure 1.1 Stress-strain curves for steel.](image1)

![Figure 1.2 Standard rolled shapes.](image2)
the major and minor axes are 6.28 in and 3.76 in, respectively. Both S-shapes and M-shapes are I-sections with tapered flanges that are narrower than comparable W-shapes and provide less resistance to lateral torsional buckling. M-shapes are available in small sizes up to a depth of 12.5 in. S-shapes are available up to a depth of 24 in and have thicker webs than comparable W-shapes making them less economical.

The HP-shape is also an I-section and is used for bearing piles. To withstand piling stresses, they are of robust dimensions with webs and flanges of equal thickness and with depth and flange width nominally equal. The HP-shape is designated by nominal depth and weight per foot. Thus an HP14 × 117 has a depth of 14.2 in and a weight of 117 lb/ft.

The C-shape is a standard channel with a slope of 2 on 12 to the inner flange surfaces. The MC-shape is a miscellaneous channel with a nonstandard slope on the inner flange surfaces. Channels are designated by exact depth and weight per foot. Thus a C12 × 30 has a depth of 12 in and a weight of 30 lb/ft.

Angles have legs of equal thickness and either equal or unequal length. They are designated by leg size and thickness with the long leg specified first and the thickness last. Thus, an L8 × 6 × 1 is an angle with one 8-in leg, one 6-in leg and with each leg 1 in thickness.

T-sections are made by cutting W-, M-, and S-shapes in half and they have half the depth and weight of the original section. Thus a WT15 × 45 has a depth of 14.8 in and a weight of 45 lb/ft and is split from a W30 × 90.

There are three types of hollow structural sections: rectangular, square, and round. Hollow structural sections are designated by outside dimensions and nominal wall thickness. Thus an HSS12 × 12 × ½ is a square hollow structural section with overall outside dimensions of 12 in by 12 in and a design wall thickness of 0.465 in. An HSS14.000 × 0.250 is a round hollow structural section with an outside diameter of 14 in and a design wall thickness 0.233 in. Hollow structural sections are particularly suited for members that require high torsional resistance.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide flanged beams</td>
<td>W</td>
</tr>
<tr>
<td>Miscellaneous beams</td>
<td>M</td>
</tr>
<tr>
<td>Standard beams</td>
<td>S</td>
</tr>
<tr>
<td>Bearing piles</td>
<td>HP</td>
</tr>
<tr>
<td>Standard channels</td>
<td>C</td>
</tr>
<tr>
<td>Miscellaneous channels</td>
<td>MC</td>
</tr>
<tr>
<td>Angles</td>
<td>L</td>
</tr>
<tr>
<td>Tees cut from W-shapes</td>
<td>WT</td>
</tr>
<tr>
<td>Tees cut from M-shapes</td>
<td>MT</td>
</tr>
<tr>
<td>Tees cut from S-shapes</td>
<td>ST</td>
</tr>
<tr>
<td>Rectangular hollow structural sections</td>
<td>HSS</td>
</tr>
<tr>
<td>Square hollow structural sections</td>
<td>HSS</td>
</tr>
<tr>
<td>Round hollow structural sections</td>
<td>HSS</td>
</tr>
<tr>
<td>Pipe</td>
<td>Pipe</td>
</tr>
</tbody>
</table>

**Table 1.1** Rolled Steel Sections
There are three classifications of pipes: standard, extra strong, and double-extra strong. Pipes are designated by nominal outside dimensions. Thus, a pipe 8 Std. is a pipe with an outside diameter of 8.63 in and a wall thickness of 0.322 in. A pipe 8 xx-Strong is a pipe with an outside diameter of 8.63 in and a wall thickness of 0.875 in.

Dimensions and properties of double angles are also provided in the AISC Manual Part 1. These are two angles that are interconnected through their back-to-back legs along the length of the member, either in contact for the full length or separated by spacers at the points of interconnection. Double angles are frequently used in the fabrication of open web joists. They are designated by specifying the size of angle used and their orientation. Thus, a 2L8 × 6 × 1 LLBB has two 8 × 6 × 1 angles with the 8 in (long) legs back-to-back. A 2L8 × 6 × 1 SLBB has two 8 × 6 × 1 angles with the 6 in (short) legs back-to-back.

Dimensions and properties of double channels are also provided in the AISC Manual Part 1. These are two channels that are interconnected through their back-to-back webs along the length of the member, either in contact for the full length or separated by spacers at the points of interconnection. Double channels are frequently used in the fabrication of open web joists. They are designated by specifying the depth and weight of the channel used. Thus, a 2C12 × 30 consists of two C12 × 30 channels each with a depth of 12 in and a weight of 30 lb/ft.

The types of steel commonly available for each structural shape are listed by Anderson and Carter and are summarized in Table 1.2.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Steel Type</th>
<th>ASTM Designation</th>
<th>$F_y$, ksi</th>
<th>$F_u$, ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide flanged beams</td>
<td>A992</td>
<td>50–65</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous beams</td>
<td>A36</td>
<td>36</td>
<td>58–80</td>
<td></td>
</tr>
<tr>
<td>Standard beams</td>
<td>A36</td>
<td>36</td>
<td>58–80</td>
<td></td>
</tr>
<tr>
<td>Bearing piles</td>
<td>A572 Gr. 50</td>
<td>50</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Standard channels</td>
<td>A36</td>
<td>36</td>
<td>58–80</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous channels</td>
<td>A36</td>
<td>36</td>
<td>58–80</td>
<td></td>
</tr>
<tr>
<td>Angles</td>
<td>A36</td>
<td>36</td>
<td>58–80</td>
<td></td>
</tr>
<tr>
<td>Ts cut from W-shapes</td>
<td>A992</td>
<td>50–65</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>Ts cut from M-shapes</td>
<td>A36</td>
<td>36</td>
<td>58–80</td>
<td></td>
</tr>
<tr>
<td>Ts cut from S-shapes</td>
<td>A36</td>
<td>36</td>
<td>58–80</td>
<td></td>
</tr>
<tr>
<td>Hollow structural sections, rectangular</td>
<td>A500 Gr. B</td>
<td>46</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Hollow structural sections, square</td>
<td>A500 Gr. B</td>
<td>46</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Hollow structural sections, round</td>
<td>A500 Gr. B</td>
<td>42</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Pipe</td>
<td>A53 Gr. B</td>
<td>35</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

Note: $F_y$ = specified minimum yield stress; $F_u$ = specified minimum tensile strength.

Table 1.2  Type of Steel Used
1.2 Types of Steel Buildings

Steel buildings are generally framed structures and range from simple one-story buildings to multistory structures. One of the simplest type of structure is constructed with a steel roof truss or open web steel joist supported by steel columns or masonry walls, as shown in Fig. 1.3.

An alternative construction technique is the single bay rigid frame structure shown in Fig. 1.4.

Framed structures consist of floor and roof diaphragms, beams, girders, and columns as shown in Fig. 1.5. The building may be one or several stories in height.
Figure 1.5 illustrates the framing arrangements at the second floor of a multistory building. The floor diaphragm spans east-west over the supporting beams and consists of concrete fill over formed steel deck as shown in Fig. 1.6. The beams span north-south and are supported on girders, as shown in Fig. 1.7. The girders frame into columns as shown in Fig. 1.8.

As well as supporting gravity loads, framed structures must also be designed to resist lateral loads caused by wind or earthquake. Several techniques are used to provide lateral
resistance including special moment-resisting frames, braced frames, and shear walls. Moment-resisting frames resist lateral loads by means of special flexural connections between the columns and beams. The flexural connections provide the necessary ductility at the joints to dissipate the energy demand with large inelastic deformations. A number of different methods are used to provide the connections and these are specified in American Institute of Steel Construction, Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications (AISC 358-10). A typical moment-resisting frame building is shown in Fig. 1.9 with a reduced beam section connection detailed.

Moment-resisting frames have the advantage of providing bays free from obstructions. However, special detailing is required for finishes and curtain walls to accommodate, without damage, the large drifts anticipated.

Concentrically braced frames, described by Cochran and Honeck, and eccentrically braced frames, described by Becker and Ishler, are illustrated in Fig. 1.10. These systems
have the advantage over moment-resisting frames of less drift and simpler connections. In addition, braced frames are generally less expensive than moment-resisting frames. Their disadvantages are restrictions on maximum building height and architectural limitations.

A building with a steel plate shear wall lateral force-resisting system is shown in Fig. 1.11 and is described by Sabelli. This system provides good drift control but lacks redundancy.

1.3 Building Codes and Design Criteria

The building code adopted by most jurisdictions throughout the United States is the International Code Council, *International Building Code* (IBC). Some states and some cities publish their own code and this is usually a modification of the IBC to conform to local customs and preferences. The IBC establishes minimum regulations for building systems using prescriptive and performance-related provisions. When adopted by a local jurisdiction it becomes a legally enforceable document.

The code provides requirements to safeguard public health, safety, and welfare through provisions for structural strength, sanitation, light, ventilation, fire, and other hazards. To maintain its relevance to changing circumstances and technical developments, the code is updated every 3 years. The code development process is an open consensus process in which any interested party may participate.


AISC 360 provides criteria for the design, fabrication, and erection of structural steel buildings and structures similar to buildings. It is specifically intended for low-seismic applications where design is based on a seismic response modification coefficient R of 3 or less. This is permissible in buildings assigned to seismic design category A, B, or C.
and ensures a nominally elastic response to the applied loads. When design is based on a seismic response modification coefficient $R$ greater than 3, the design, fabrication, and erection of structural steel buildings and structures similar to buildings must comply with the requirements of the Seismic Provisions, AISC 341. This is mandatory in buildings assigned to seismic design category D, E, or F. In situations where wind effects exceed seismic effects, the building elements must still be detailed in accordance with AISC 341 provisions. These provisions provide the design requirements for structural steel seismic force-resisting systems to sustain the large inelastic deformations necessary to dissipate the seismic induced demand. The *Seismic Manual* provides guidance on the application of the provisions to the design of structural steel seismic force-resisting systems.

### 1.4 ASD and LRFD Concepts

The traditional method of designing steel structures has been by the allowable stress design method. The objective of this method was to ensure that a structure was capable of supporting the applied working loads safely. Working loads, also referred to as nominal or service loads, are the dead loads and live loads applied to a structure. Dead load includes the self-weight of the structure and permanent fittings and equipment. Live load includes the weight of the structure’s occupants and contents and is specified in *American Society of Civil Engineers, Minimum Design Loads for Buildings and Other Structures* (ASCE 7-10) Table 4-1. The allowable stress design method specified that stresses produced in a structure by the working loads must not exceed a specified allowable stress. The method was based on elastic theory to calculate the stresses produced by the working loads. The allowable stress, also known as working stress, was determined by dividing the yield stress of the material by an appropriate factor of safety. Hence:

$$
F = \frac{F_y}{\Omega} \geq f
$$

where
- $F = $ allowable stress
- $F_y = $ yield stress
- $\Omega = $ factor of safety
- $f = $ actual stress in a member, subjected to working loads, as determined by elastic theory

The advantages of the allowable stress method were its simplicity and familiarity. In 1986, American Institute of Steel Construction introduced the load and resistance factor design (LRFD) method. In this method, the working loads are factored before being applied to the structure. The load factors are given by ASCE 7 Sec. 2.3.2 and these are used in the strength design load combinations. The load factors are determined by probabilistic theory and account for:

- Variability of anticipated loads
- Errors in design methods and computations
- Lack of understanding of material behavior
The force in a member, caused by the factored load combination, may be determined by elastic, inelastic, or plastic analysis methods and this is the required strength of the member. The nominal strength of the member, also known as the ultimate capacity, is determined according to AISC 360 or AISC 341 provisions. The design strength, is determined by multiplying the nominal strength of the member by an appropriate resistance factor. The resistance factors are determined by probabilistic theory and account for:

- Variability of material strength
- Poor workmanship
- Errors in construction

Hence, in accordance with AISC 360 Eq. (B3-1)

\[ R_u \leq \varphi R_n \]

where

- \( R_u \) = required strength of a member subjected to strength design load combinations (LRFD)
- \( \varphi \) = resistance factor
- \( R_n \) = nominal strength of the member as determined by the specifications or provisions
- \( \varphi R_n \) = design strength

In 2005, American Institute of Steel Construction issued the unified specification, AISC 360. In accordance with AISC 360 Sec. B3, structural steel design must be done by either load and resistance factor design (LRFD) or by allowable strength design (ASD).

In the ASD method, the members in a structure are proportioned so that the required strength, as determined by the appropriate ASD load combination, does not exceed the designated allowable strength of the member. The ASD load combinations are given by ASCE 7 Sec. 2.4.1. The allowable strength is determined as the nominal strength of the member divided by a safety factor. The nominal strength of the member is determined according to AISC 360 or AISC 341 provisions. The nominal strength is identical for both the LRFD and ASD methods. Hence, in accordance with AISC 360 Eq. (B3-2):

\[ R_s \leq R_n / \Omega \]

where

- \( R_s \) = required strength of a member subjected to allowable stress design load combinations (ASD)
- \( \Omega \) = safety factor
- \( R_n \) = nominal strength of the member as determined by the specifications or provisions
- \( R_n / \Omega \) = allowable strength

The relationship between safety factor and resistance factor is

\[ \Omega = 1.5 / \varphi \]

**Example 1.1**  Relationship between Safety Factor and Resistance Factor

Assuming a live load to dead load ratio of \( L/D = 3 \), derive the relationship between safety factor and resistance factor.
Consider a simply supported beam of length $\ell$ supporting a uniformly distributed dead load of $D$ and a uniformly distributed live load of $L$. The required nominal flexural strength determined using both the LRFD and ASD methods is as follows:

<table>
<thead>
<tr>
<th>LRFD</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load combination from ASCE 7 Sec 2.3.2 is $w_u = 1.2D + 1.6L$</td>
<td>Load combination from ASCE 7 Sec 2.4.1 is $w_u = D + L$</td>
</tr>
<tr>
<td>Substituting $L = 3D$ gives $w_u = 6D$</td>
<td>Substituting $L = 3D$ gives $w_u = 4D$</td>
</tr>
<tr>
<td>The required flexural strength is $M_u = w_u \ell^2/8$</td>
<td>The required flexural strength is $M_u = w_u \ell^2/8$</td>
</tr>
<tr>
<td></td>
<td>$= 3D\ell^2/4$</td>
</tr>
<tr>
<td>The required nominal flexural strength is $M_n = M_u/\phi$</td>
<td>The required nominal flexural strength is $M_n = M_u/\Omega$</td>
</tr>
<tr>
<td></td>
<td>$= 3D\ell^2/4\phi$</td>
</tr>
</tbody>
</table>

Equating the nominal strength for both design methods:

$$3D\ell^2/4\phi = D\ell^2/2\Omega$$

Hence:

$$\Omega = 1.5/\phi$$

Allowable strength design is similar to allowable stress design in that both utilize the ASD load combinations. However, for strength design, the specifications are formatted in terms of force in a member rather than stress. The stress design format is readily derived from the strength design format by dividing allowable strength by the appropriate section property, such as cross-sectional area or section modulus, to give allowable stress.

**Example 1.2  Relationship between Allowable Strength Design and Allowable Stress Design**

For the limit state of tensile yielding, derive the allowable tensile stress from the allowable strength design procedure.

For tensile yielding in the gross section, the nominal tensile strength is given by AISC 360 Eq. (D2-1) as

$$P_n = F_y A_g$$

where $A_g =$ gross area of member

The safety factor for tension is given by AISC 360 Sec. D2 as

$$\Omega = 1.67$$

The allowable tensile strength is given by AISC 360 Sec. D2 as

$$P_i = P_n / \Omega = F_y A_g / 1.67 = 0.6F_y A_g$$

The allowable tensile stress for the limit state of tensile yielding is

$$F_t = P_i / A_g = 0.6F_y$$
References


Problems

1.1 Given: American Institute of Steel Construction, Steel Construction Manual

Find: Using the manual
   a. The differences between W-, M-, S-, and HP-shapes
   b. The uses of each of these shapes

1.2 Given: American Institute of Steel Construction, Steel Construction Manual

Find: Using the manual the meaning of
   a. W16 × 100
   b. WT8 × 50
   c. 2MC13 × 50
   d. HSS8.625 × 0.625
   e. 2LA × 3 × ½ LLBB
   f. Pipe 6 xx-Strong
   g. HSS6 × 4 × ½

1.3 Given: American Institute of Steel Construction, Steel Construction Manual

Find: Using the manual
   a. The meaning of “Unified Code”
   b. How the unified code developed

Find: Using the manual the distinction between
   a. Safety factor and resistance factor
   b. Nominal strength and required strength
   c. Design strength and allowable strength

1.5 Given: American Institute of Steel Construction, Steel Construction Manual

Find: Using the manual
   a. Four different types of steel that may be used for rectangular HSS-shapes
   b. The preferred type of steel for rectangular HSS-shapes

1.6 Given: A building to be designed to resist seismic loads and three different lateral force-resisting methods are to be evaluated.

Find: a. Three possible methods that may be used
   b. The advantages of each method
   c. The disadvantages of each method


Find: Describe the purpose of each document and their interrelationship.