STEEL STRUCTURES DESIGN

ASD/LRFD

Alan Williams

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About the Author

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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.

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Preface

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. B3, 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.

In this book the theoretical background and fundamental basis of steel design are introduced and the detailed design of members and their connections is covered. The book provides detailed interpretations of the AISC *Specification for Structural Steel Buildings*, 2010 edition, the ASCE *Minimum Design Loads for Buildings and Other Structures*, 2010 edition, and the ICC *International Building Code,* 2012 edition. The code requirements are illustrated with 170 design examples with concise step-by-step solutions. Each example focuses on a specific issue and provides a clear and concise solution to the problem.

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

CHAPTER 1

Steel Buildings and Design Criteria

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 superceded 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

$$\begin{aligned} E &= \text{stress}/\text{strain} \\ &= 29{,}000 \text{ ksi} \end{aligned}$$

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.

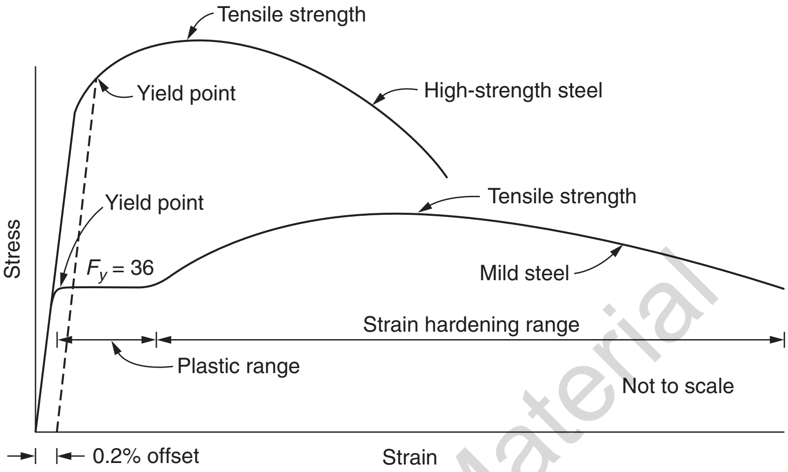

Figure 1.1 Stress-strain curves for steel.

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)[1] 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

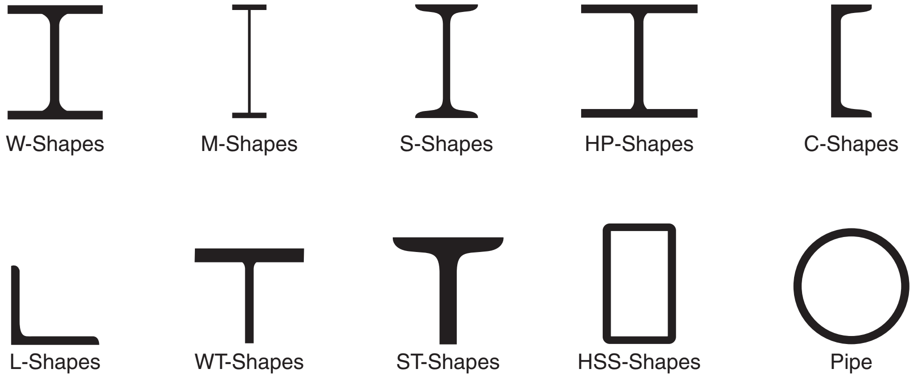

Figure 1.2 Standard rolled shapes.

Shape	Designation
Wide flanged beams	W
Miscellaneous beams	M
Standard beams	S
Bearing piles	HP
Standard channels	C
Miscellaneous channels	MC
Angles	L
Tees cut from W-shapes	WT
Tees cut from M-shapes	MT
Tees cut from S-shapes	ST
Rectangular hollow structural sections	HSS
Square hollow structural sections	HSS
Round hollow structural sections	HSS
Pipe	Pipe

Table 1.1 Rolled Steel Sections

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 out side 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 dimension of 14 in and a design wall thickness 0.233 in. Hollow structural sections are particularly suited for members that require high torsional resistance.

There are three classifications of pipes: standard, extra strong, and double-extra strong. Pipes are designated by nominal out side 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[2] and are summarized in Table 1.2.

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

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.

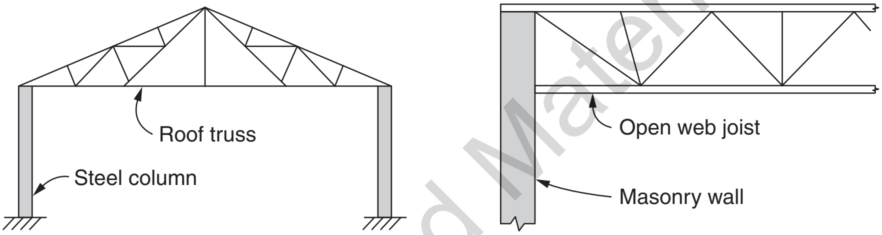

Figure 1.3 Steel roof construction.

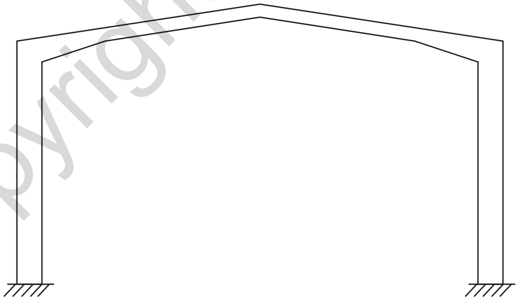

Figure 1.4 Single bay rigid frame.

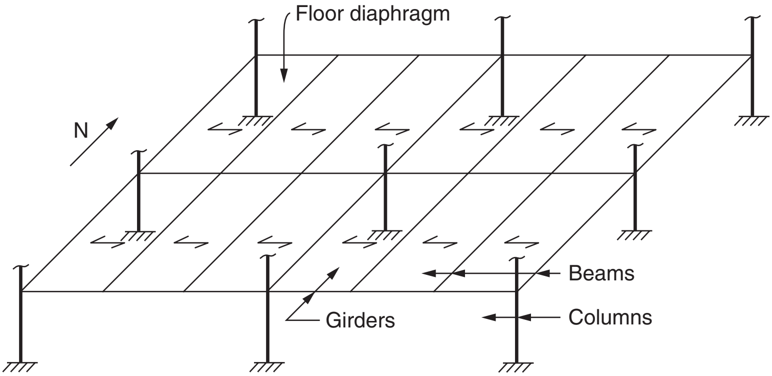

Figure 1.5 Framed building.

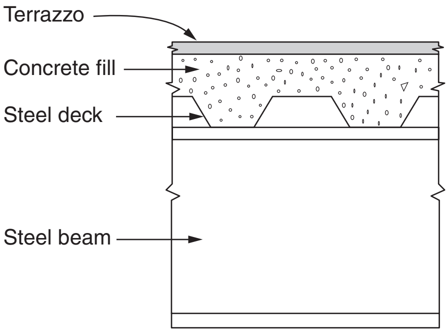

Figure 1.6 Beam detail.

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

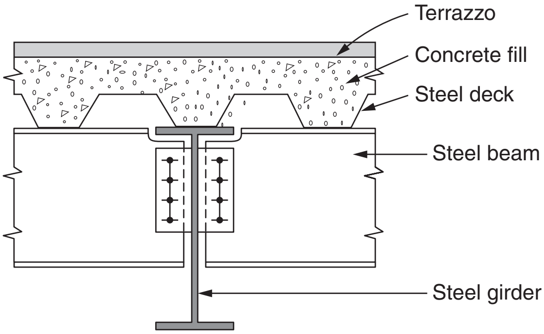

Figure 1.7 Girder detail.

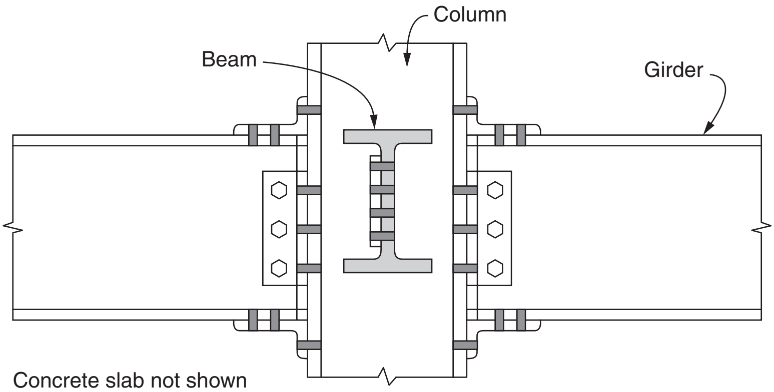

Figure 1.8 Column detail.

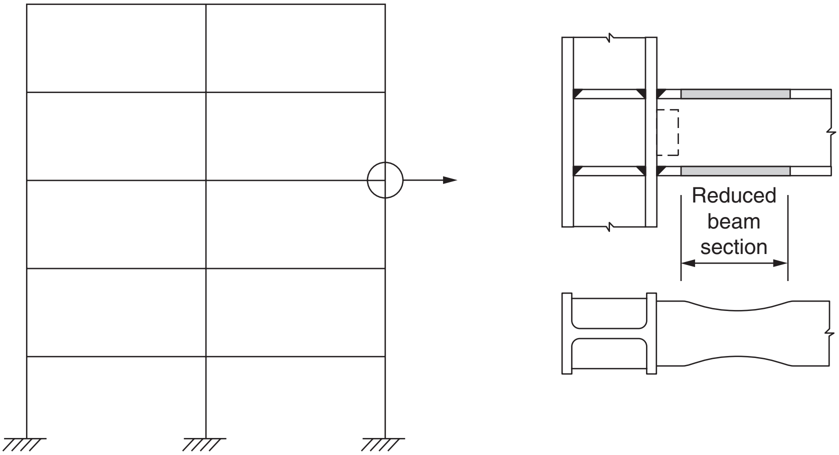

Figure 1.9 Moment-resisting frame.

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).[3] 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,[4] and eccentrically braced frames, described by Becker and Ishler,[5] are illustrated in Fig. 1.10. These systems

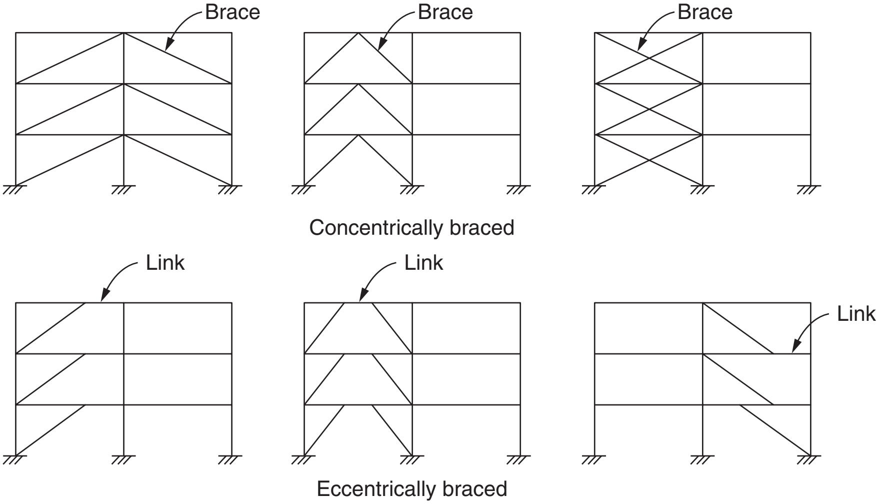

Figure 1.10 Braced frames.

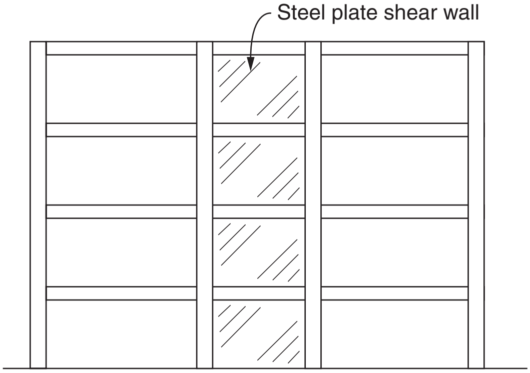

Figure 1.11 Steel plate shear wall building.

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.[6] 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).[7] 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.

The requirements for structural steelwork are covered in IBC Chap. 22. In IBC Sec. 2205, two specifications of the American Institute of Steel Construction are adopted by reference. These are, *Specification for Structural Steel Buildings* (AISC 360)[8] and *Seismic Provisions for Structural Steel Buildings* (AISC 341).[9] The *Specification for Structural Steel Buildings* is included in AISC Manual Part 16. The *Seismic Provisions for Structural Steel Buildings* is included in AISC *Seismic Design Manual* (AISCSDM)[10] Part 6. The Specification and the Provisions provide complete information for the design of buildings. Both include a Commentary that provides background information on the derivation and application of the specifications and provisions.

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)[11] 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:

$$\begin{aligned} F &= F_y/\Omega \\ &\geq f \end{aligned}$$

where F = allowable stress
F_y = yield stress
Ω = 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)
φ = resistance factor
R_n = nominal strength of the member as determined by the specifications or provisions
φR_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):

$$R_a \leq R_n/\Omega$$

where R_a = required strength of a member subjected to allowable stress design load combinations (ASD)
Ω = safety factor
R_n = nominal strength of the member as determined by the specifications or provisions
R_n/Ω = 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 ℓ 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:

LRFD	ASD
Load combination from ASCE 7 Sec 2.3.2 is	Load combination from ASCE 7 Sec 2.4.1 is
$w_u = 1.2D + 1.6L$	$w_a = D + L$
Substituting $L = 3D$ gives	Substituting $L = 3D$ gives
$w_u = 6D$	$w_a = 4D$
The required flexural strength is	The required flexural strength is
$M_u = w_u\ell^2/8$	$M_a = w_a\ell^2/8$
$= 3D\ell^2/4$	$= D\ell^2/2$
The required nominal flexural strength is	The required nominal flexural strength is
$M_n = M_u/\varphi$	$M_n = M_a\Omega$
$= 3D\ell^2/4\varphi$	$= D\ell^2\Omega/2$

Equating the nominal strength for both design methods

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

Hence:

$$\Omega = 1.5/\varphi$$

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

$$\boxed{P_n = F_y A_g}$$

where A_g = gross area of member

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

$$\boxed{\Omega_t = 1.67}$$

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

$$\begin{aligned} P_c &= P_n/\Omega_t \\ &= F_y A_g/1.67 \\ &= 0.6F_y A_g \end{aligned}$$

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

$$\begin{aligned} F_t &= P_c/A_g \\ &= 0.6F_y \end{aligned}$$

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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.* 2L4 × 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

1.4 *Given:* American Institute of Steel Construction, *Steel Construction Manual*

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

1.7 *Given:* American Institute of Steel Construction, *Steel Construction Manual* and International Code Council, *International Building Code*

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