McGraw-Hill CONSTRUCTION

ASCE PRESS

# Structural Steel Designer's Handbook

## Fourth Edition

AISC, AASHTO, AISI, ASTM, AREMA, and ASCE-07 Design Standards

- Unified ASD and LRFD design
- AISC building design specifications
- ASCE-07 standard loadings data
- AASHTO bridge design specifications

Roger L. Brockenbrough · Frederick S. Merritt

**Cataloging-in-Publication Data is on file with the Library of Congress**



1 2 3 4 5 6 7 8 9 0 DOC/DOC 0 1 0 9 8 7 6 5

ISBN 0-07-143218-3

*The sponsoring editor for this book was Larry S. Hager, the editing supervisor was Stephen M. Smith, and the production supervisor was Richard C. Ruzycka. It was set in Times Roman by International Typesetting and Composition. The art director for the cover was Handel Low.*

*Printed and bound by RR Donnelley.*



This book is printed on acid-free paper.

# CHAPTER 1
# PROPERTIES OF STRUCTURAL STEELS AND EFFECTS OF STEELMAKING AND FABRICATION

**Roger L. Brockenbrough, P.E.**
*President*
*R. L. Brockenbrough & Associates, Inc.*
*Pittsburgh, Pennsylvania*

This chapter presents and discusses the properties of structural steels that are of importance in design and construction. Designers should be familiar with these properties so that they can select the most economical combination of suitable steels for each application and use the materials efficiently and safely.

In accordance with contemporary practice, the steels described in this chapter are given the names of the corresponding specifications of ASTM, 100 Barr Harbor Dr., West Conshohocken, PA 19428. For example, all steels covered by ASTM A588, "Specification for High-Strength Low-Alloy Structural Steel," are called A588 steel. Most of them can also be furnished to a metric designation such as A588M.

## 1.1 STRUCTURAL STEEL SHAPES AND PLATES

Steels for structural uses may be classified by chemical composition, tensile properties, and method of manufacture as carbon steels, high-strength low-alloy (HSLA) steels, heat-treated carbon steels, and heat-treated constructional alloy steels. A typical stress-strain curve for a steel in each classification is shown in Fig. 1.1 to illustrate the increasing strength levels provided by the four classifications of steel. The availability of this wide range of specified minimum strengths, as well as other material properties, enables the designer to select an economical material that will perform the required function for each application.

Some of the most widely used steels in each classification are listed in Table 1.1 with their specified strengths in shapes and plates. These steels are weldable, but the welding materials and procedures for each steel must be in accordance with approved methods. Welding information for each of the steels is available in publications of the American Welding Society.

### 1.1.1 Carbon Steels

A steel may be classified as a carbon steel if (1) the maximum content specified for alloying elements does not exceed the following: manganese—1.65%, silicon—0.60%, copper—0.60%; (2) the specified minimum for copper does not exceed 0.40%; and (3) no minimum content is specified for other elements added to obtain a desired alloying effect.

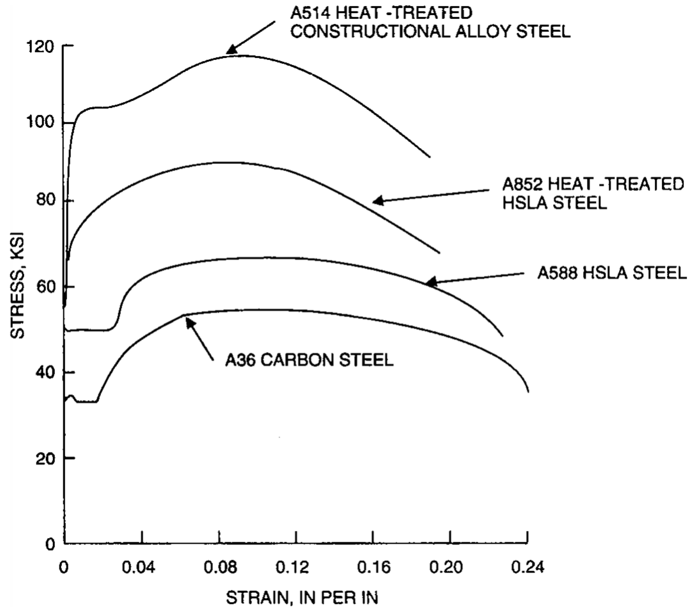


**FIGURE 1.1** Typical stress-strain curves for structural steels. (Curves have been modified to reflect minimum specified properties.)

**A36 steel** has been the principal carbon steel for bridges, buildings, and many other structural uses. This steel provides a minimum yield point of 36 ksi in all structural shapes and in plates up to 8 in thick. In structural steel framing for building construction, A36 steel has been largely replaced by the higher-strength A992 steel (Art. 1.1.2).

**A529** is a carbon-manganese steel for general structural purposes, available in shapes and plates of a limited size range. It can be furnished with a specified minimum yield point of either 50 ksi (Grade 50) or 55 ksi (Grade 55).

**A573,** another carbon steel listed in Table 1.1, is available in three strength grades for plate applications in which improved notch toughness is important.

## 1.1.2 High-Strength Low-Alloy Steels

Those steels which have specified minimum yield points greater than 40 ksi and achieve that strength in the hot-rolled condition, rather than by heat treatment, are known as HSLA steels. Because these steels offer increased strength at moderate increases in price over carbon steels, they are economical for a variety of applications.

**A242 steel** is a **weathering steel,** used where resistance to atmospheric corrosion is of primary importance. Steels meeting this specification usually provide a resistance to atmospheric corrosion at least four times that of structural carbon steel. However, when required, steels can be selected to provide a resistance to atmospheric corrosion of five to eight times that of structural carbon steels. A specified minimum yield point of 50 ksi can be furnished in plates up to ¾ in thick and the lighter structural shapes. It is available with a lower yield point in thicker sections, as indicated in Table 1.1.

**A588** is the primary weathering steel for structural work. It provides a 50-ksi yield point in plates up to 4 in thick and in all structural sections; it is available with a lower yield point in thicker plates. Several grades are included in the specification to permit use of various compositions developed by

**TABLE 1.1** Specified Minimum Properties for Structural Steel Shapes and Plates*

| ASTM designation | Plate thickness range, in | Structural shape flange or leg thickness range, in | Yield stress, ksi† | Tensile strength, ksi† | Elongation, % In 2 in‡ | Elongation, % In 8 in |
|---|---|---|---|---|---|---|
| **A36** | 8 maximum | All | 36 | 58–80 | 23–21 | 20 |
| | Over 8 | All | 32 | 58–80 | 23 | 20 |
| **A529** | | | | | | |
| Grade 50 | 1 maximum | 1½ max | 50 | 70–100 | 21 | 18 |
| Grade 55 | 1 maximum | 1½ max | 55 | 70–100 | 20 | 17 |
| **A573** | | | | | | |
| Grade 58 | 1½ maximum | ¶ | 32 | 58–71 | 24 | 21 |
| Grade 65 | 1½ maximum | ¶ | 35 | 65–77 | 23 | 20 |
| Grade 70 | 1½ maximum | ¶ | 42 | 70–90 | 21 | 18 |
| | | High-strength low-alloy steels | | | | |
| **A242** | ¾ maximum | 1½ max | 50 | 70 | 21 | 18 |
| | Over ¾ to 1½ max | Over 1½ to 2 | 46 | 67 | 21 | 18 |
| | Over 1½ to 4 max | Over 2 | 42 | 63 | 21 | 18 |
| **A588** | 4 maximum | All | 50 | 70 | 21 | 18 |
| | Over 4 to 5 max | All | 46 | 67 | 21 | — |
| | Over 5 to 8 max | All | 42 | 63 | 21 | — |
| **A572** | | | | | | |
| Grade 42 | 6 maximum | All | 42 | 60 | 24 | 20 |
| Grade 50 | 4 maximum | All | 50 | 65 | 21 | 18 |
| Grade 55 | 2 maximum | All | 55 | 70 | 20 | 17 |
| Grade 60 | 1¼ maximum | 2 max | 60 | 75 | 18 | 16 |
| Grade 65 | 1¼ maximum | 2 max | 65 | 80 | 17 | 15 |
| **A992** | ¶ | All | 50–65 | 65 | 21 | 18 |
| | | Heat-treated carbon and HSLA steels | | | | |
| **A633** | | | | | | |
| Grade A | 4 maximum | ¶ | 42 | 63–83 | 23 | 18 |
| Grade C, D | 2½ maximum | ¶ | 50 | 70–90 | 23 | 18 |
| | Over 2½ to 4 max | ¶ | 46 | 65–85 | 23 | 18 |
| Grade E | 4 maximum | ¶ | 60 | 80–100 | 23 | 18 |
| | Over 4 to 6 max | ¶ | 55 | 75–95 | 23 | 18 |
| **A678** | | | | | | |
| Grade A | 1½ maximum | ¶ | 50 | 70–90 | 22 | — |
| Grade B | 2½ maximum | ¶ | 60 | 80–100 | 22 | — |
| Grade C | ¾ maximum | ¶ | 75 | 95–115 | 19 | — |
| | Over ¾ to 1½ max | ¶ | 70 | 90–110 | 19 | — |
| | Over 1½ to 2 max | ¶ | 65 | 85–105 | 19 | — |
| Grade D | 3 maximum | ¶ | 75 | 90–110 | 18 | — |
| **A852** | 4 maximum | ¶ | 70 | 90–110 | 19 | — |
| **A913** | ¶ | All | 50 | 65 | 21 | 18 |
| | ¶ | All | 60 | 75 | 18 | 16 |
| | ¶ | All | 65 | 80 | 17 | 15 |
| | ¶ | All | 70 | 90 | 16 | 14 |

(*Continued*)

**TABLE 1.1** Specified Minimum Properties for Structural Steel Shapes and Plates* (*Continued*)

| ASTM designation | Plate thickness range, in | Structural shape flange or leg thickness range, in | Yield stress, ksi† | Tensile strength, ksi† | Elongation, % In 2 in‡ | Elongation, % In 8 in |
|---|---|---|---|---|---|---|
| Heat-treated constructional alloy steels | | | | | | |
| **A514** | $2^1/_2$ maximum | ¶ | 100 | 110–130 | 18 | — |
| | Over $2^1/_2$ to 6 max | ¶ | 90 | 100–130 | 16 | — |

*The following are approximate values for all the steels:
Modulus of elasticity—$29 \times 10^3$ ksi.
Shear modulus—$11 \times 10^3$ ksi.
Poisson's ratio—0.30.
Yield stress in shear—0.57 times yield stress in tension.
Ultimate strength in shear—$^2/_3$ to $^3/_4$ times tensile strength.
Coefficient of thermal expansion—$6.5 \times 10^{-6}$ in per in per °F for temperature range −50 to +150°F.
Density—490 lb/ft$^3$.
†Where two values are shown for yield stress or tensile strength, the first is minimum and the second is maximum.
‡The minimum elongation values are modified for some thicknesses in accordance with the specification for the steel. Where two values are shown for the elongation in 2 in, the first is for plates and the second for shapes.
¶ Not applicable.

steel producers to obtain the specified properties. This steel provides about four times the resistance to atmospheric corrosion of structural carbon steels.

These relative corrosion ratings are determined from the slopes of corrosion-time curves and are based on carbon steels not containing copper. (The resistance of carbon steel to atmospheric corrosion can be doubled by specifying a minimum copper content of 0.20%.) Typical corrosion curves for several steels exposed to industrial atmosphere are shown in Fig. 1.2.

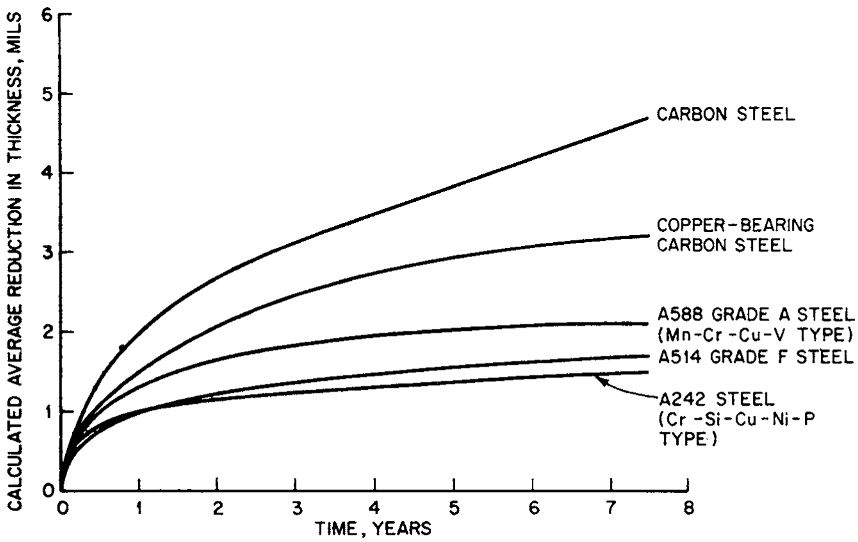


**FIGURE 1.2** Corrosion curves for structural steels in an industrial atmosphere. (*From R. L. Brockenbrough and B. G. Johnston,* USS Steel Design Manual, *R. L. Brockenbrough & Associates, Inc., Pittsburgh, Pa., with permission.*)

For methods of estimating the atmospheric corrosion resistance of low-alloy steels based on their chemical composition, see ASTM Guide G101. The A588 specification requires that the resistance index calculated according to Guide 101 shall be 6.0 or higher.

A588 and A242 steels are called **weathering steels** because, when subjected to alternate wetting and drying in most bold atmospheric exposures, they develop a tight oxide layer that substantially inhibits further corrosion. They are often used bare (unpainted) where the oxide finish that develops is desired for aesthetic reasons or for economy in maintenance. Bridges and exposed building framing are typical examples of such applications. Designers should investigate potential applications thoroughly, however, to determine whether a weathering steel will be suitable. Information on bare-steel applications is available from steel producers.

**A572** specifies columbium-vanadium HSLA steels in five grades with minimum yield points of 42 to 65 ksi. Grade 42 in thicknesses up to 6 in and Grade 50 in thicknesses up to 4 in are used for welded bridges. All grades may be used for bolted construction and for welded construction in most applications other than bridges.

**A992 steel,** introduced in 1998, is now the main specification for rolled wide flange shapes for building framing. All other hot-rolled shapes, such as channels and angles, can be furnished to A992. It provides a minimum yield point of 50 ksi, a maximum yield point of 65 ksi, and a maximum yield to tensile ratio of 0.85. These maximum limits are considered desirable attributes, particularly for seismic design. To enhance weldability, a maximum carbon equivalent is also included, equal to 0.47% or 0.45%, depending on thickness. A supplemental requirement can be specified for an average Charpy V-notch toughness of 40 ft · lb at 70°F.

### 1.1.3 Heat-Treated Carbon and HSLA Steels

Both carbon and HSLA steels can be heat treated to provide yield points in the range of 50 to 75 ksi. This provides an intermediate strength level between the as-rolled HSLA steels and the heat-treated constructional alloy steels.

**A633** is a normalized HSLA plate steel for applications where improved notch toughness is desired. Available in four grades with different chemical compositions, the minimum yield point ranges from 42 to 60 ksi depending on grade and thickness.

**A678** includes quenched-and-tempered plate steels (both carbon and HSLA compositions) with excellent notch toughness. It is also available in four grades with different chemical compositions; the minimum yield point ranges from 50 to 75 ksi, depending on grade and thickness.

**A852** is a quenched-and-tempered HSLA plate steel of the weathering type. It is intended for welded bridges and buildings and similar applications where weight savings, durability, and good notch toughness are important. It provides a minimum yield point of 70 ksi in thickness up to 4 in. The resistance to atmospheric corrosion is typically four times that of carbon steel.

**A913** is a high-strength low-allow steel for structural shapes, produced by the quenching and self-tempering (QST) process. It is intended for the construction of buildings, bridges, and other structures. Four grades provide a minimum yield point of 50 to 70 ksi. Maximum carbon equivalents to enhance weldability are included as follows: Grade 50, 0.38%; Grade 60, 0.40%; Grade 65, 0.43%; and Grade 70, 0.45%. Also, the steel must provide an average Charpy V-notch toughness of 40 ft · lb at 70°F.

### 1.1.4 Heat-Treated Constructional Alloy Steels

Steels that contain alloying elements in excess of the limits for carbon steel and are heat treated to obtain a combination of high strength and toughness are termed **constructional alloy steels.** Having a yield strength of 100 ksi, these are the strongest steels in general structural use.

**A514** includes several grades of quenched and tempered steels, to permit use of various compositions developed by producers to obtain the specified strengths. Maximum thickness ranges from 1¼ to 6 in depending on the grade. Minimum yield strength for plate thicknesses over 2½ in is 90 ksi.

Steels furnished to this specification can provide a resistance to atmospheric corrosion up to four times that of structural carbon steel depending on the grade.

Constructional alloy steels are also frequently selected because of their ability to resist abrasion. For many types of abrasion, this resistance is related to hardness or tensile strength. Therefore, constructional alloy steels may have nearly twice the resistance to abrasion provided by carbon steel. Also available are numerous grades that have been heat treated to increase the hardness even more.

**TABLE 1.2** Charpy V-Notch Toughness for A709 Bridge Steels[a]

| Grade | Maximum thickness, in, inclusive | Joining/ fastening method | Minimum average energy, ft · lb | Test temperature, °F Zone 1 | Zone 2 | Zone 3 |
|---|---|---|---|---|---|---|
| Non-fracture-critical members | | | | | | |
| 36T | 4 | Mech./weld. | 15 | 70 | 40 | 10 |
| 50T,[b] | 2 | Mech./weld. | 15 | | | |
| 50WT[b], 50ST | | | | | | |
| | 2 to 4 | Mechanical | 15 | 70 | 40 | 10 |
| | 2 to 4 | Welded | 20 | | | |
| 70WT[c] | $2\frac{1}{2}$ | Mech./weld. | 20 | | | |
| | $2\frac{1}{2}$ to 4 | Mechanical | 20 | 50 | 20 | −10 |
| | $2\frac{1}{2}$ to 4 | Welded | 25 | | | |
| 100T, 100WT | $2\frac{1}{2}$ | Mech./weld. | 25 | | | |
| | $2\frac{1}{2}$ to 4 | Mechanical | 25 | 30 | 0 | −30 |
| | $2\frac{1}{2}$ to 4 | Welded | 35 | | | |
| HPS50WT | 4 | Mech./weld. | 20 | 10 | 10 | 10 |
| HPS50WT | 4 | Mech./weld. | 25 | −10 | −10 | −10 |
| Fracture-critical members | | | | | | |
| 36F | 4 | Mech./weld.[d] | 25 | 70 | 40 | 10 |
| 50F,[b] 50WF[b] | 2 | Mech./weld.[d] | 25 | 70 | 40 | 10 |
| | 2 to 4 | Mechanical[d] | 25 | 70 | 40 | 10 |
| | 2 to 4 | Welded[e] | 30 | 70 | 40 | 10 |
| 70WF[c] | $2\frac{1}{2}$ | Mech./weld.[e] | 30 | 50 | 20 | −10 |
| | $2\frac{1}{2}$ to 4 | Mechanical[e] | 30 | 50 | 20 | −10 |
| | $2\frac{1}{2}$ to 4 | Welded[f] | 35 | 50 | 20 | −10 |
| 100F, 100WF | $2\frac{1}{2}$ | Mech./weld.[f] | 35 | 30 | 0 | −30 |
| | $2\frac{1}{2}$ to 4 | Mechanical[f] | 35 | 30 | 0 | −30 |
| | $2\frac{1}{2}$ to 4 | Welded[g] | 45 | 30 | 0 | NA |
| HPS50WF | 4 | Mech./weld. | 30 | 10 | 10 | 10 |
| HPS50WF | 4 | Mech./weld. | 35 | −10 | −10 | −10 |

[a]Minimum **service** temperatures:
Zone 1, 0°F; Zone 2, below 0 to −30°F; Zone 3, below −30 to −60°F.
[b]If yield strength exceeds 65 ksi, reduce test temperature by 15°F for each 10 ksi above 65 ksi.
[c]If yield strength exceeds 85 ksi, reduce test temperature by 15°F for each 10 ksi above 85 ksi.
[d]Minimum test value energy is 20 ft-lb.
[e]Minimum test value energy is 24 ft-lb.
[f]Minimum test value energy is 28 ft-lb.
[g]Minimum test value energy is 36 ft-lb.

### 1.1.5 Bridge Steels

Steels for application in bridges are covered by A709, which includes steel in several of the categories mentioned above. Under this specification, grades 36, 50, 70, and 100 are steels with yield strengths of 36, 50, 70, and 100 ksi, respectively. Similar AASHTO grades are designated M270.

The grade designation is followed by the letter W, indicating whether ordinary or high atmospheric corrosion resistance is required. An additional letter, T or F, indicates that Charpy V-notch impact tests must be conducted on the steel. The T designation indicates that the material is to be used in a non-fracture-critical application as defined by AASHTO; the F indicates use in a fracture-critical application. There is also a Grade 50S, where the S indicates the steel must be killed.

A trailing numeral, 1, 2, or 3, indicates the testing zone, which relates to the lowest ambient temperature expected at the bridge site. (See Table 1.2.) As indicated by the first footnote in the table, the service temperature for each zone is considerably less than the Charpy V-notch impact-test temperature. This accounts for the fact that the dynamic loading rate in the impact test is more severe than that to which the structure is subjected. The toughness requirements depend on fracture criticality, grade, thickness, and method of connection.

High-performance steels (HPS) are the newest additions to the family of bridge steels. They are being used increasingly to improve reliability and reduce cost, with approximately 200 bridges in service in 2005. The initial grade, HPS70W, with a specified minimum yield stress of stress of 70 ksi, has been used most. HPS50W, with a specified minimum yield stress of 50 ksi, has also become popular. HPS100W, with a specified minimum yield stress of stress of 100 ksi, is available to reduce thickness where members are highly loaded.

## 1.2 STEEL-QUALITY DESIGNATIONS

Steel plates, shapes, sheetpiling, and bars for structural uses—such as the load-carrying members in buildings, bridges, ships, and other structures—are usually ordered to the requirements of ASTM A6 and are referred to as **structural-quality steels.** (A6 does not indicate a specific steel.) This specification contains general requirements for delivery related to chemical analysis, permissible variations in dimensions and weight, permissible imperfections, conditioning, marking and tension and bend tests of a large group of structural steels. (Specific requirements for the chemical composition and tensile properties of these steels are included in the specifications discussed in Art. 1.1.) All the steels included in Table 1.1 are structural-quality steels.

Steel plates for pressure vessels are usually furnished to the general requirements of ASTM A20 and are referred to as **pressure-vessel-quality steels.** Generally, a greater number of mechanical-property tests and additional processing are required for pressure-vessel-quality steel.

## 1.3 STEEL SHEET AND STRIP FOR STRUCTURAL APPLICATIONS

Steel sheet and strip are used for many structural applications, particularly for cold-formed structural members for residential and light commercial building construction (Chap. 9). The facade of many high-rise structures is supported by cold-formed sheet steel systems and interior partitions are often built with steel C-sections. The stressed skin of transportation equipment is another application of such material. Tensile properties of several sheet steels are presented in Table 1.3. Many of them are available in several strength levels, with a specified minimum yield point from 25 to 80 ksi. Some grades may not be suitable for all applications, depending on the ratio of tensile strength to yield point and other considerations (Chap. 9).

**ASTM A606** covers high-strength low-alloy, hot- and cold-rolled steel sheet and strip with enhanced corrosion resistance. This material, available in cut lengths or coils, is intended for structural and other uses where savings in weight and improved durability are important. It may be ordered as Type 2 or Type 4, with atmospheric corrosion resistance approximately two or four times,

**TABLE 1.3** Specified Minimum Mechanical Properties for Steel Sheet and Strip for Structural Applications

| ASTM designation | Type of product | Grade | Yield point, ksi | Tensile strength, ksi | Elongation in 2 in, %[a] | $F_u/F_y$ |
|---|---|---|---|---|---|---|
| A606 | Hot rolled (as rolled) | — | 50 | 70 | 22 | 1.40 |
| | Hot rolled (annealed or normalized) | — | 45 | 65 | 22 | 1.44 |
| | Cold rolled | — | 45 | 65 | 22 | 1.44 |
| A653[b] | Galvanized or galvannealed | SS 33 | 33 | 45 | 20 | 1.36 |
| | | SS 37 | 37 | 52 | 18 | 1.41 |
| | | SS 40 | 40 | 55 | 16 | 1.38 |
| | | SS 50, Cl 1 | 50 | 65 | 12 | 1.30 |
| | | SS 50, Cl 3 | 50 | 70 | 12 | 1.40 |
| | | SS 80 | 80 | 82 | — | 1.03 |
| | | HSLAS 40 | 40 | 50 | 22–24 | 1.25 |
| | | HSLAS 50 | 50 | 60 | 20–22 | 1.20 |
| | | HSLAS 60 | 60 | 70 | 16–18 | 1.17 |
| | | HSLAS 70 | 70 | 80 | 12–14 | 1.14 |
| | | HSLAS 80 | 80 | 90 | 10–12 | 1.12 |
| A792 | 55% aluminum-zinc alloy coated | SS 33 | 33 | 45 | 20 | 1.36 |
| | | SS 37 | 37 | 52 | 18 | 1.41 |
| | | SS 40 | 40 | 55 | 16 | 1.38 |
| | | SS 50, Cl 1 | 50 | 65 | 12 | 1.30 |
| | | SS 50, Cl 4 | 50 | 60 | 12 | 1.20 |
| | | SS 80 | 80 | 82 | — | 1.03 |
| A1003 | Sheet for framing members | ST33H | 33 | — | 10 | 1.08[c] |
| | | ST37H | 37 | — | 10 | 1.08[c] |
| | | ST40H | 40 | — | 10 | 1.08[c] |
| | | ST50H | 50 | — | 10 | 1.08[c] |
| | | ST33L | 33 | — | 3 | — |
| | | ST37L | 37 | — | 3 | — |
| | | ST40L | 40 | — | 3 | — |
| | | ST50L | 50 | — | 3 | — |
| A1008 | Cold rolled | SS 25 | 25 | 42 | 26 | 1.68 |
| | | SS 30 | 30 | 45 | 24 | 1.50 |
| | | SS 33, Type 1 | 33 | 48 | 22 | 1.45 |
| | | SS 33, Type 2 | 33 | 48 | 22 | 1.45 |
| | | SS 40, Type 1 | 40 | 52 | 20 | 1.30 |
| | | SS 40, Type 2 | 40 | 52 | 20 | 1.30 |
| | | SS 80 | 80 | 82 | — | 1.03 |
| | | HSLAS 45, Cl 1 | 45 | 60 | 22 | 1.33 |
| | | HSLAS 50, Cl 1 | 50 | 65 | 20 | 1.30 |
| | | HSLAS 55, Cl 1 | 55 | 70 | 18 | 1.27 |
| | | HSLAS 60, Cl 1 | 60 | 75 | 16 | 1.25 |
| | | HSLAS 65, Cl 1 | 65 | 80 | 15 | 1.23 |
| | | HSLAS 70, Cl 1 | 70 | 85 | 14 | 1.21 |
| | | HSLAS 45, Cl 2 | 45 | 55 | 22 | 1.22 |
| | | HSLAS 50, Cl 2 | 50 | 60 | 20 | 1.20 |
| | | HSLAS 55, Cl 2 | 55 | 65 | 18 | 1.18 |
| | | HSLAS 60, Cl 2 | 60 | 70 | 16 | 1.17 |
| | | HSLAS 65, Cl 2 | 65 | 75 | 15 | 1.15 |
| | | HSLAS 70, Cl 2 | 70 | 80 | 14 | 1.14 |
| | | HSLAS-F 50 | 50 | 60 | 22 | 1.20 |

(*Continued*)

**TABLE 1.3** Specified Minimum Mechanical Properties for Steel Sheet and Strip for Structural Applications (*Continued*)

| ASTM designation | Type of product | Grade | Yield point, ksi | Tensile strength, ksi | Elongation in 2 in, %[a] | $F_u/F_y$ |
|---|---|---|---|---|---|---|
| A1008 (*cont.*) | Cold rolled | HSLAS-F 60 | 60 | 70 | 18 | 1.17 |
| | | HSLAS-F 70 | 70 | 80 | 16 | 1.14 |
| | | HSLAS-F 80 | 80 | 90 | 14 | 1.12 |
| A1011 | Sheet | SS 30 | 30 | 49 | 25–21 | 1.63 |
| | | SS 33 | 33 | 52 | 23–18 | 1.62 |
| | | SS 36, Type 1 | 36 | 53 | 22–17 | 1.47 |
| | | SS 36, Type 2 | 36 | 58/80 | 21–16 | 1.61 |
| | | SS 40 | 40 | 55 | 21–15 | 1.38 |
| | | SS 45 | 45 | 60 | 19–13 | 1.33 |
| | | SS 50 | 50 | 65 | 17–11 | 1.30 |
| | | SS 55 | 55 | 70 | 15–9 | 1.27 |
| | | SS 60 | 60 | 75 | 14–13 | 1.25 |
| | | SS 70 | 70 | 85 | 13–12 | 1.21 |
| | | SS 80 | 80 | 95 | 12–11 | 1.19 |
| | | HSLAS 45, Cl 1 | 45 | 60 | 25–23 | 1.33 |
| | | HSLAS 50, Cl 1 | 50 | 65 | 22–20 | 1.30 |
| | | HSLAS 55, Cl 1 | 55 | 70 | 20–18 | 1.27 |
| | | HSLAS 60, Cl 1 | 60 | 75 | 18–16 | 1.25 |
| | | HSLAS 65, Cl 1 | 65 | 80 | 16–14 | 1.23 |
| | | HSLAS 70, Cl 1 | 70 | 85 | 14–12 | 1.21 |
| | | HSLAS 45, Cl 2 | 45 | 55 | 25–23 | 1.22 |
| | | HSLAS 50, Cl 2 | 50 | 60 | 22–20 | 1.20 |
| | | HSLAS 55, Cl 2 | 55 | 65 | 20–18 | 1.18 |
| | | HSLAS 60, Cl 2 | 60 | 70 | 18–16 | 1.17 |
| | | HSLAS 65, Cl 2 | 65 | 75 | 16–14 | 1.15 |
| | | HSLAS 70, Cl 2 | 70 | 80 | 14–12 | 1.14 |
| | | HSLAS-F 50 | 50 | 60 | 24–22 | 1.20 |
| | | HSLAS-F 60 | 60 | 70 | 22–20 | 1.17 |
| | | HSLAS-F 70 | 70 | 80 | 20–18 | 1.14 |
| | | HSLAS-F 80 | 80 | 90 | 18–16 | 1.12 |

[a]Modified for some thicknesses in accordance with the specification. For A653, where two values are given, the first is for Type A and the second for Type B. For A1011, specified value varies with thickness range.
[b]Also available as A875 with zinc-5% aluminum alloy coating.
[c]For ASTM A1003, this is a specified minimum ratio.

respectively, that of plain carbon steel. Where properly exposed to the atmosphere, Type 4 can be used in the bare (unpainted) condition for many applications.

**A653** covers steel sheet, zinc coated (galvanized) or zinc-iron alloy coated (galvannealed) by the hot-dip process, in coils and cut lengths. Included are several grades based on yield strength in both structural steel (SS) and high strength low alloy (HSLA). HSLA sheets are available as Type A, where improved formability is required, and Type B, where even better formability is required.

**A792** covers 55% aluminum-zinc alloy coated steel sheet in coils and cut lengths, coated by the hot-dip process. The aluminum-zinc alloy composition is nominally 55% aluminum, 1.6% silicon, and the balance zinc. The product is intended for applications requiring corrosion resistance or heat resistance. Aluminum-zinc alloy coated sheet is available in various designations, including commercial steel, forming steel, drawing steel, and high-temperature steel, as well as structural steel (SS).

**A875** covers steel sheet, in coils and cut lengths, metallic coated by the hot-dip process, with zinc-5% aluminum alloy coating. The Zn-5Al alloy coating also contains small amounts of elements other than zinc and aluminum, which are intended to improve processing and other characteristics. The material is intended for applications requiring corrosion resistance, formability, and paintability. It is produced in a number of designations, types, grades, and classes for differing application requirements. The coating is produced as two types—zinc-5% aluminum-mischmetal alloy (Type I) and zinc-5% aluminum-0.1% magnesium alloy (Type II)—in two coating structures (classes), and in several coating weight designations. Mechanical properties are generally similar to those of A653.

**A1003** covers coated steel sheet used in the manufacture of cold-formed framing members, such as, but not limited to, studs, joists, purlins, girts, and track. The sheet steel used for cold-formed framing members includes metallic coated, painted metallic coated, and painted nonmetallic coated. The grade designations use the following suffix indicators: *H*, high ductility; *L*, low ductility; and *NS*, nonstructural. H and L are associated with structural or load-bearing applications, and NS with nonstructural or non-load-bearing applications.

**A1008** covers cold-rolled structural steel (SS), high-strength low-alloy steel (HSLAS), and high-strength low-alloy steel with improved formability (HSLAS-F), in coils and cut lengths. The steel is fully deoxidized, made to fine-grain practice, and includes microalloying elements such as columbium, vanadium, and zirconium. The steel may be treated to achieve inclusion control. Cold-rolled steel sheet is supplied for either exposed or unexposed applications.

**A1011** covers hot-rolled sheet and strip, in coils and cut lengths. The product is produced in a number of designations, including SS, HSLAS, and HSLAS-F. The steel is fully deoxidized, made to fine-grain practice, and includes microalloying elements such as columbium, vanadium, and zirconium. The steel may be treated to achieve inclusion control.

## 1.4 TUBING FOR STRUCTURAL APPLICATIONS

Structural tubing is being used more frequently in modern construction. Commonly referred to as hollow structural sections (HSS), it is often preferred to other steel members when resistance to torsion is required and when a smooth, closed section is aesthetically desirable. In addition, structural tubing may be the economical choice for compression members subjected to moderate to light loads. Square and rectangular tubing is manufactured either by cold or hot forming welded or seamless round tubing in a continuous process. A500 cold-formed carbon-steel tubing (Table 1.4) is produced in four strength grades in each of two product forms, shaped (square or rectangular) or round. A minimum

**TABLE 1.4** Specified Minimum Mechanical Properties of Structural Tubing

| ASTM designation | Product form | Yield point, ksi | Tensile strength, ksi | Elongation in 2 in, % |
|---|---|---|---|---|
| **A500** | Shaped | | | |
| Grade A | | 39 | 45 | 25 |
| Grade B | | 46 | 58 | 23 |
| Grade C | | 50 | 62 | 21 |
| Grade D | | 36 | 58 | 23 |
| **A500** | Round | | | |
| Grade A | | 33 | 45 | 25 |
| Grade B | | 42 | 58 | 23 |
| Grade C | | 46 | 62 | 21 |
| Grade D | | 36 | 58 | 23 |
| **A501** | Round or shaped | 36 | 58 | 23 |
| **A618** | Round or shaped | | | |
| Grades Ia, lb, II | | | | |
| Walls ≤ $^3/_4$ in | | 50 | 70 | 22 |
| Walls > $^3/_4$ to $1^1/_2$ in | | 46 | 67 | 22 |
| Grade III | | 50 | 65 | 20 |
| **A847** | Round or shaped | 50 | 70 | 19 |

yield point of up to 50 ksi is available for shaped tubes and up to 46 ksi for round tubes. A500 Grade B and Grade C are commonly specified for building construction applications and are available from producers and steel service centers. A500 tubing may not be suitable for dynamically loaded elements in welded structures where low-temperature notch-toughness properties are important.

A 501 tubing is a hot-formed carbon-steel product available as hot rolled or hot dip galvanized. It provides a yield point equal to that of A36 steel in tubing having a wall thickness of 1 in or less.

A618 tubing is a hot-formed HSLA product that provides a minimum yield point of up to 50 ksi. The three grades all have enhanced resistance to atmospheric corrosion. Grades Ia and Ib can be used in the bare condition for many applications when properly exposed to the atmosphere.

A847 tubing covers cold-formed HSLA tubing and provides a minimum yield point of 50 ksi. It also offers enhanced resistance to atmospheric corrosion and, when properly exposed, can be used in the bare condition for many applications.

## 1.5 STEEL CABLE FOR STRUCTURAL APPLICATIONS

Steel cables have been used for many years in bridge construction and are occasionally used in building construction for the support of roofs and floors. The types of cables used for these applications are referred to as **bridge strand** or **bridge rope.** In this use, **bridge** is a generic term that denotes a specific type of high-quality strand or rope.

A **strand** is an arrangement of wires laid helically about a center wire to produce a symmetrical section. A **rope** is a group of strands laid helically around a core composed of either a strand or another wire rope. The term **cable** is often used indiscriminately in referring to wires, strands, or ropes. Strand may be specified under ASTM A586, wire rope, under A603.

During manufacture, the individual wires in bridge strand and rope are generally galvanized to provide resistance to corrosion. Also, the finished cable is prestretched. In this process, the strand or rope is subjected to a predetermined load of not more than 55% of the breaking strength for a sufficient length of time to remove the "structural stretch" caused primarily by radial and axial adjustment of the wires or strands to the load. Thus, under normal design loadings, the elongation that occurs is essentially elastic and may be calculated from the elastic-modulus values given in Table 1.5.

Strands and ropes are manufactured from cold-drawn wire and do not have a definite yield point. Therefore, a working load or design load is determined by dividing the specified minimum breaking strength for a specific size by a suitable safety factor. The breaking strengths for selected sizes of bridge strand and rope are listed in Table 1.5.

**TABLE 1.5** Mechanical Properties of Steel Cables

| Minimum breaking strength, kips,* of selected cable sizes | | | Minimum modulus of elasticity, ksi,* for indicated diameter range | |
|---|---|---|---|---|
| Nominal diameter, in | Zinc-coated strand | Zinc-coated rope | Nominal diameter range, in | Minimum modulus, ksi |
| $\frac{1}{2}$ | 30 | 23 | Prestretched zinc-coated strand | |
| $\frac{3}{4}$ | 68 | 52 | | |
| 1 | 122 | 91.4 | $\frac{1}{2}$ to $2\frac{9}{16}$ | 24,000 |
| $1\frac{1}{2}$ | 276 | 208 | $2\frac{5}{8}$ and over | 23,000 |
| 2 | 490 | 372 | Prestretched zinc-coated rope | |
| 3 | 1076 | 824 | | |
| 4 | 1850 | 1460 | $\frac{3}{8}$ to 4 | 20,000 |

*Values are for cables with Class A zinc coating on all wires. Class B or C can be specified where additional corrosion protection is required.

## 1.6 TENSILE PROPERTIES

The tensile properties of steel are generally determined from tension tests on small specimens or coupons in accordance with standard ASTM procedures. The behavior of steels in these tests is closely related to the behavior of structural-steel members under static loads. Because, for structural steels, the yield points and moduli of elasticity determined in tension and compression are nearly the same, compression tests are seldom necessary.

Typical tensile stress-strain curves for structural steels are shown in Fig. 1.1. The initial portion of these curves is shown at a magnified scale in Fig. 1.3. Both sets of curves may be referred to for the following discussion.

***Strain Ranges.*** When a steel specimen is subjected to load, an initial **elastic range** is observed in which there is no permanent deformation. Thus, if the load is removed, the specimen returns to its original dimensions. The ratio of stress to strain within the elastic range is the **modulus of elasticity,** or **Young's modulus** $E$. Since this modulus is consistently about $29 \times 10^3$ ksi for all the structural steels, its value is not usually determined in tension tests, except in special instances.

The strains beyond the elastic range in the tension test are termed the **inelastic range.** For as-rolled and high-strength low-alloy (HSLA) steels, this range has two parts. First observed is a **plastic range,** in which strain increases with no appreciable increase in stress. This is followed by a **strain-hardening range,** in which strain increase is accompanied by a significant increase in stress. The curves for heat-treated steels, however, do not generally exhibit a distinct plastic range or a large amount of strain hardening.

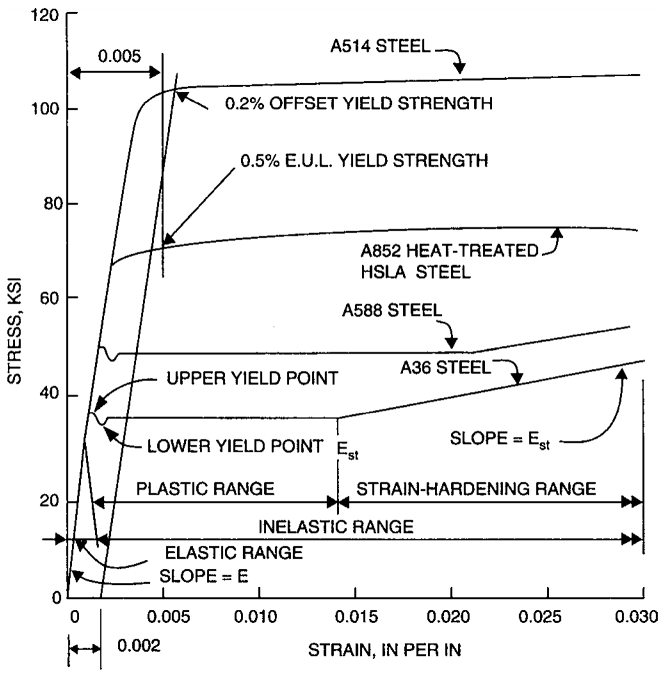


**FIGURE 1.3** Partial stress-strain curves for structural steels strained through the plastic region into the strain-hardening range. (*From R. L. Brockenbrough and B. G. Johnston*, USS Steel Design Manual, *R. L. Brockenbrough & Associates, Inc., Pittsburgh, Pa., with permission.*)

The strain at which strain hardening begins ($\epsilon_{st}$) and the rate at which stress increases with strain in the strain-hardening range (the strain-hardening modulus $E_{st}$) have been determined for carbon and HSLA steels. The average value of $E_{st}$ is 600 ksi, and the length of the yield plateau is 5 to 15 times the yield strain. (T. V. Galambos, "Properties of Steel for Use in LRFD," *Journal of the Structural Division, American Society of Civil Engineers*, Vol. 104, No. ST9, 1978.)

***Yield Point, Yield Strength, and Tensile Strength.*** As illustrated in Fig. 1.3, carbon and HSLA steels usually show an upper and lower yield point. The upper yield point is the value usually recorded in tension tests and thus is simply termed the **yield point.**

The heat-treated steels in Fig. 1.3, however, do not show a definite yield point in a tension test. For these steels it is necessary to define a **yield strength,** the stress corresponding to a specified deviation from perfectly elastic behavior. As illustrated in the figure, yield strength is usually specified in either of two ways: For steels with a specified value not exceeding 80 ksi, yield strength is considered as the stress at which the test specimen reaches a 0.5% extension under load (0.5% EUL) and may still be referred to as the yield point. For higher-strength steels, the yield strength is the stress at which the specimen reaches a strain 0.2% greater than that for perfectly elastic behavior.

Since the amount of inelastic strain that occurs before the yield strength is reached is quite small, yield strength has essentially the same significance in design as yield point. These two terms are sometimes referred to collectively as **yield stress.**

The maximum stress reached in a tension test is the tensile strength of the steel. After this stress is reached, increasing strains are accompanied by decreasing stresses. Fracture eventually occurs.

***Proportional Limit.*** The proportional limit is the stress corresponding to the first visible departure from linear-elastic behavior. This value is determined graphically from the stress-strain curve. Since the departure from elastic action is gradual, the proportional limit depends greatly on individual judgment and on the accuracy and sensitivity of the strain-measuring devices used. The proportional limit has little practical significance and is not usually recorded in a tension test.

***Ductility.*** Ductility is an important property of structural steels. It allows redistribution of stresses in continuous members and at points of high local stresses, such as those at holes or other discontinuities.

In a tension test, ductility is measured by percent elongation over a given gage length or percent reduction of cross-sectional area. The percent elongation is determined by fitting the specimen together after fracture, noting the change in gage length and dividing the increase by the original gage length. Similarly, the percent reduction of area is determined from cross-sectional measurements made on the specimen before and after testing.

Both types of ductility measurements are an index of the ability of a material to deform in the inelastic range. There is, however, no generally accepted criterion of minimum ductility for various structures.

***Poisson's Ratio.*** The ratio of transverse to longitudinal strain under load is known as **Poisson's ratio** $\nu$. This ratio is about the same for all structural steels—0.30 in the elastic range and 0.50 in the plastic range.

***True-Stress–True-Strain Curves.*** In the stress-strain curves shown previously, stress values were based on original cross-sectional area, and the strains were based on the original gage length. Such curves are sometimes referred to as **engineering-type stress-strain curves.** However, since the original dimensions change significantly after the initiation of yielding, curves based on instantaneous values of area and gage length are often thought to be of more fundamental significance. Such curves are known as **true-stress–true-strain curves.** A typical curve of this type is shown in Fig. 1.4.

The curve shows that when the decreased area is considered, the true stress actually increases with increase in strain until fracture occurs instead of decreasing after the tensile strength is reached, as in the engineering stress-strain curve. Also, the value of true strain at fracture is much greater than the engineering strain at fracture (though until yielding begins, true strain is less than engineering strain).