M11

Steel Pipe—A Guide for Design and Installation

Fifth Edition

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American Water Works Association

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Steel Pipe—A Guide for Design and Installation

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Preface

This manual provides a review of experience and theory regarding design of steel pipe used for conveying water, with appropriate references cited. The manual provides general and technical information to be used as an aid in the design and installation of steel pipe. It is a discussion of recommended practice, not an AWWA standard calling for compliance with certain specifications. Application of the principles and procedures discussed in this manual must be based on responsible judgment.

This manual was first authorized in 1943. In 1949, Committee 8310D on Steel Pipe, appointed one of its members, Russell E. Barnard, to act as editor in chief in charge of collecting and compiling the available data on steel pipe. The first draft of the report was completed by January 1957; the draft was reviewed by the committee and other authorities on steel pipe. The first edition of this manual was issued in 1964 with the title *Steel Pipe—Design and Installation*.

The second edition of this manual was approved in June 1984 and published in 1985 with the title *Steel Pipe—A Guide for Design and Installation*. The third edition of the manual was approved in June 1988 and published in 1989. The fourth edition of the manual was approved March 2003 and published in January 2004. This fifth edition was approved August 2016.

Major revisions to this fifth edition are (1) reorganization of the chapters to combine similar content in the same chapters; (2) elimination of some tables which were replaced with formulas and examples; (3) changes in aboveground design and examples to more clearly reflect conditions encountered on a water pipeline; (4) addition of a chapter on thrust design; (5) addition to the fittings chapter to include design of true wyes and crosses, design of crotch plates with higher strength steel, expanded elbow stress design in restrained areas, tangential outlet design was clarified, double outlet design was clarified, strength reduction factors for varying steel strengths of outlets was added, PDV values were clarified to 9000 for test and transient pressures, anchor ring design was added, design of ellipsoidal heads was added, and modified joint harness requirements; (6) added suggested bracing for shipping of pipe; (6) updated the flange bolt torque values and table; (7) buckling of buried pipe was clarified (8) weld details for outlets and crotch plates were added; (9) cement enhanced soil was defined and added; (10) design of welded lap joints was expanded; and (11) Appendixes were added for nomenclature, comparison of increase of E' versus increase of wall thickness, full example of harness ring design, design of harness rod placement for differential settlement, seismic considerations, and useful equations and conversions.

Chapter 1

History, Uses, and Physical Characteristics of Steel Pipe

HISTORY

Steel pipe has been used for water lines in the United States since the early 1850s. The pipe was first manufactured by rolling steel sheets or plates into shape and riveting the seams. Recognized very early in its development as a significant benefit, steel pipe offered flexibility that allowed variations in the steel sheet thickness being rolled to handle the different pressures based on the pipe's elevation and the hydraulic gradient. Roll-formed pipe with riveted seams was the dominant method of pipe fabrication until the 1930s when the electric welding process replaced the labor-intensive riveted seams.

In consideration of the relatively low tensile strength of steels produced in the second half of the nineteenth century and the inefficiencies of cold-riveted seams and riveted or drive stovepipe joints, engineers set the allowable design stress at 10,000 psi. As riveted-pipe fabrication methods improved through the early part of the twentieth century, concurrently higher strength steels were being produced. As a result, allowable design stresses progressed in this period from 10,000 psi to 12,500 psi, to 13,750 psi, and finally to 15,000 psi, in all cases maintaining a safety factor of 4 to the steel's tensile strength. Allowable design stresses were adjusted as necessary to account for the inefficiency of the riveted seam. The pipe was produced in diameters ranging from 4 in. through 144 in. and in thicknesses from 16 gauge to 1.5 in. Fabrication methods consisted of single-, double-, triple-, and quadruple-riveted seams, varying in efficiency from 45 percent to 70 percent, depending on the design.

Lockbar pipe, introduced in 1905, had nearly supplanted riveted pipe by 1930. Fabrication involved milling 30-ft-long plates to a width approximately equal to half the intended circumference, cold forming the longitudinal edges, and rolling the plates into

30-ft-long half-circle troughs. The lockbar was a specially configured H-shaped bar that was applied to the mating edges of two 30-ft troughs and clamped into position to form a full-circle pipe section. Lockbar pipe had notable advantages over riveted pipe: It had only one or two straight seams and no round seams. The straight seams were considered to be 100 percent efficient, in that the seam developed the full strength of the pipe wall, as compared to the 45 percent to 70 percent efficiency for riveted seams. Manufactured in sizes from 20 in. through 74 in., from plate ranging in thicknesses from $\frac{3}{16}$ in. to $\frac{1}{2}$ in., lockbar played an increasingly greater role in the market until the advent of automatic electric welding in the mid-1920s.

The period beginning circa 1930 saw a very abrupt reduction in the use of both riveted-seam and lockbar pipe manufacturing methods. These methods were replaced by seams that were fused together using electric-fusion welding. Pipe produced using electric-fusion welding was advantageous because the plate could be prewelded into a single flat sheet that could be fed into the three-roll forming machine to form a cylinder with only a single longitudinal seam to weld. This resulted in faster production, minimal weld-seam protrusion, and 100 percent welded-seam efficiency. The fabricators of fusion-welded seam pipe followed similar initial production sequences as for lockbar; first rolling two long half sections, then using electric-fusion welding, joining the two long pipe-halves into a single section. Also developed in the 1930s was the pipe roll forming method that is a U-ing and O-ing process producing a longitudinal weld or fused seam. Through this decade and into the 1940s, 30-ft to 40-ft-long pipe cylinders were being formed from plate.

The helical process, more commonly referred to as the *spiral-weld forming process*, for fabricating welded seam steel pipe was also developed in the early 1930s and was first used extensively to produce steel pipe in diameters from 4 in. through 36 in. This method was typically more efficient to manufacture and also offered lower weld seam stress than longitudinal welded pipe. Welding was performed using the electric-fusion method. After World War II, US manufacturers adapted German spiral weld–seam technology and developed new equipment capable of forming spiral weld seam steel pipe to diameters in excess of 144 in.

The development of the spiral-weld forming process coincided chronologically with the option developed by the steel industry to roll or coil steel sheet and plate. Steel in coil form allows modern day spiral weld forming equipment and roll-forming equipment to be very efficient in maximizing production. Present day steel mill capacities for coil allow for steel thicknesses up to 1 in. and widths up to 100 in., with mechanical properties up to 100-ksi yield strength.

The welding renaissance of the 1930s brought confidence in the design and use of steel pipe with welded seams and joints. In the prewelding era, it had been common practice to design steel pipe using a safety factor of 4 based on the tensile strength. The performance of the welded seams proved to be so significantly better than riveted joints that a change in design parameters was adopted. Pipeline designers and users no longer needed high safety factors to compensate for inefficient seams and joints. The design methodology would be changed to reflect the use of an allowable design stress of 50 percent of the material's yield strength.

USES

Steel water pipe meeting the requirements of appropriate ANSI/AWWA standards has many applications, some of which follow:

- Aqueducts
- Supply lines

Figure 1-1 Steel pipe penstock on bridge

- Transmission mains
- Distribution mains
- Penstocks
- Horizontal directional drilling
- Tunneled casing pipe
- Treatment-plant piping
- Self supporting spans
- Force mains
- Circulating-water lines
- Underwater crossings, intakes, and outfalls
- Relining and sliplining

General data and project details on some of the notable steel pipeline projects are readily available on numerous Web sites. See Figure 1-1 for an example of a steel pipe penstock on a bridge.

CHEMISTRY, CASTING, AND HEAT TREATMENT

General

The steel industry produces very high quality steels that demand accurate control of chemistry and precise control of the casting and rolling process. These steels, available in sheet, plate, and coil, meet or exceed the requirements of the ASTM standards listed in

ANSI/AWWA C200, Steel Water Pipe, 6 In. (150 mm) and Larger (latest edition), for use in steel water pipe. ASTM steel standards in ANSI/AWWA C200 allow for grades with yield strengths from 30 ksi to 100 ksi without significant changes in chemistry. ANSI/AWWA C200 utilizes grades from the ASTM standards up to about 55-ksi-minimum specified yield strength for ease of manufacturing and welding. By adding small amounts of carbon and manganese or various other metals called microalloying, the strength and other properties of these steels are modified.

Properties and chemical composition of steels listed in ANSI/AWWA C200 are governed by the applicable ASTM standards and are also a function of the processes used to transform the base metal into a shape, and, when appropriate, by controlling the heat during the steel rolling process. The effects of these parameters on the properties of steels are discussed in this section.

Chemical Composition

In general, steel is a mixture of iron and carbon with varying amounts of other elements—primarily manganese, phosphorus, sulfur, and silicon. These and other elements are present or added in various combinations to achieve specific characteristics and physical properties of the finished steel. The effects of the commonly used chemical elements on the properties of hot-rolled and heat-treated carbon and alloy steels are presented in Table 1-1. Additionally, the effects of carbon, manganese, sulfur, silicon, and aluminum will be discussed.

Carbon is the principal hardening element in steel. Incremental addition of carbon increases the hardness and tensile strength of the steel. Carbon has a moderate tendency to segregate, and an excessive amount of carbon can cause a decrease in ductility, toughness, and weldability.

Manganese increases the hardness and strength of steels but to a lesser degree than carbon. Manganese combines with sulfur to form manganese sulfides, therefore decreasing the harmful effects of sulfur.

Sulfur is generally considered an undesirable element except when machinability is an important consideration. Sulfur adversely affects surface quality, has a strong tendency to segregate, and decreases ductility, toughness, and weldability.

Silicon and aluminum are the principal deoxidizers used in the manufacture of carbon and alloy steels. Aluminum is also used to control and refine grain size. The terms used to describe the degree to which these two elements deoxidize the steel are *killed steel* or *semikilled steel*. Killed steels have a very low oxygen level, while semikilled steels have indications of slightly higher levels of oxygen.

Casting

Historically, the steel-making process involved pouring molten steel into a series of molds to form castings known as *ingots*. The ingots were removed from the molds, reheated, and then rolled into products with square or rectangular cross sections. This hot-rolling operation elongated the ingots and produced semifinished products known as *blooms*, *slabs*, or *billets*. Typically, ingots exhibited some degree of nonuniformity of chemical composition known as *segregation*. This chemical segregation was associated with yield losses and processing inefficiencies.

Most modern day steel producers use the continuous casting process to avoid the inherent detrimental characteristics that resulted from the cooling and solidification of the molten steel in the ingot mold. Continuous casting is a process where the molten steel is poured at a controlled rate directly from the ladle through a water-cooled mold to form a continuous slab. The cross section of the water-cooled mold will be dimensioned so as to correspond to that of the desired slab. This steel-making process bypasses the operations

Table 1-1 Effects of alloying elements

Alloying Element	Effects
Aluminum (Al)	Used to deoxidize or "kill" molten steel Refines grain structure
Boron (B)	Small amounts (0.005%) can be used to tie up nitrogen and soften steel Used only in aluminum-killed steels and where titanium is added to tie up nitrogen Most effective at low carbon levels, but there are a number of medium carbon steels in use today that employ boron for hardenability
Carbon (C)	Principal hardening element in steel Increases strength and hardness Decreases ductility, toughness, and weldability Moderate tendency to segregate
Chromium (Cr)	Increases strength Increases atmospheric corrosion resistance
Copper (Cu)	Primary contributor to atmospheric corrosion resistance Decreases weldability
Manganese (Mn)	Increases strength Controls harmful effects of sulfur
Nickel (Ni)	Increases strength and toughness
Nitrogen (N)	Increases strength and hardness Decreases ductility and toughness
Phosphorus (P)	Increases strength and hardness Decreases ductility and toughness Considered an impurity but sometimes added for atmospheric corrosion resistance
Silicon (Si)	Used to deoxidize or "kill" molten steel
Sulfur (S)	Considered undesirable except for machinability Decreases ductility, toughness, and weldability Adversely affects surface quality Strong tendency to segregate
Titanium (Ti)	In small amounts, it ties up nitrogen to improve toughness, and in greater amounts it can strengthen steel
Vanadium (V) and Columbium (Nb)	Small additions increase strength Often referred to as *microalloying elements*

between molten steel and the semifinished product that are inherent in making steel products from ingots. As the molten metal begins to solidify along the walls of the water-cooled mold, it forms a shell that permits the gradual withdrawal of the strand product from the bottom of the die into a water-spray chamber where solidification is completed. The solidified strand is cut to length and then reheated and rolled into finished products, as in the conventional ingot process. Continuous casting produces a smaller size and higher cooling rate for the strand, resulting in less segregation and greater uniformity in composition and properties than for ingot products.

Killed and Semikilled Steels

The primary reaction involved in most steel-making processes is the combination of carbon and oxygen to form carbon monoxide gas. The solubility of this and other gases dissolved in the steel decreases as the molten metal cools to the solidification temperature range. Excess gases are expelled from the metal and, unless controlled, continue to evolve during solidification. The oxygen available for the reaction can be eliminated and the gaseous evolution inhibited by deoxidizing the molten steel using additions of silicon or aluminum or both.

Steels that are deoxidized do not evolve any gases and are called *killed steels* because they lie quietly in the mold. Killed steels are less segregated and contain negligible porosity when compared to semikilled steels. Consequently, killed-steel products exhibit a higher degree of uniformity in composition and properties than do semikilled steel products.

Heat Treatment for Steels

Steels respond to a variety of heat treatment methods that produce desirable characteristics. These heat treatment methods can be divided into slow cooling treatment and rapid cooling treatment. Slow cooling treatment decreases hardness, can increase toughness, and promotes uniformity of structure. Slow cooling includes the processes of annealing, normalizing, and stress relieving. Rapid cooling treatment increases strength, hardness, and toughness, and includes the processes of quenching and tempering. Heat treatments of base metal are generally mill options or ASTM requirements, and are generally performed on plates rather than coils.

Annealing. Annealing consists of heating steels to a predetermined temperature followed by slow cooling. The temperature, the rates of heating and cooling, and the amount of time the metal is held at temperature depend on the composition, shape, and size of the steel product being treated and the desired properties. Usually steels are annealed to remove stresses, induce softness, increase ductility, increase toughness depending on the parameters of the process, produce a given microstructure, increase uniformity of microstructure, improve machinability, or to facilitate cold forming.

Normalizing. Normalizing consists of heating steels to between 1,650°F and 1,700°F followed by slow cooling in air. This heat treatment is commonly used to refine the grain size, improve uniformity of microstructure, and improve ductility and fracture toughness.

Stress Relieving. Stress relieving of carbon steels consists of heating steels to between 1,000°F and 1,200°F and holding for the appropriate amount of time to equalize the temperature throughout the piece followed by slow cooling. The stress-relieving temperature for quenched and tempered steels must be maintained below the tempering temperature for the product. Stress relieving is used to relieve internal stresses induced by welding, normalizing, cold working, cutting, quenching, and machining. It is not intended to alter the microstructure or the mechanical properties significantly.

Quenching and Tempering. Quenching and tempering consist of heating and holding steels at the appropriate austenizing temperature (about 1,650°F) for a significant amount of time to produce a desired change in microstructure, then quenching by immersion in a suitable medium (water for bridge steels). After quenching, the steel is tempered by reheating to an appropriate temperature, usually between 800°F and 1,200°F, holding for a specified time at that temperature, and cooling under suitable conditions to obtain the desired properties. Quenching and tempering increase the strength and improve the toughness of the steel.

Controlled Rolling. Controlled rolling is a thermomechanical treatment performed at the rolling mill. It tailors the time-temperature-deformation process by controlling the rolling parameters. The parameters of primary importance are (1) the temperature at the start of controlled rolling in the finished strand after the roughing mill reduction; (2) the percentage reduction from the start of controlled rolling to the final plate thickness; and (3) the plate finishing temperature.

Hot-rolled plates are deformed as quickly as possible at temperatures above about 1,900°F to take advantage of the workability of the steel at high temperatures. In contrast, controlled rolling incorporates a hold or delay time to allow the partially rolled slab to reach the desired temperature before the start of final rolling. Controlled rolling involves deformation at temperatures ranging between 1,500°F and 1,800°F as recrystallization ceases to occur below this temperature range. Because rolling deformation at these low temperatures increases the mill loads significantly, controlled rolling is usually restricted to less than 2-in.-thick plates. Controlled rolling increases the strength, refines the grain size, improves the toughness, and may eliminate the need for normalizing.

Controlled Finishing-Temperature Rolling. Controlled finishing-temperature rolling is a less severe practice than controlled rolling and is aimed primarily at improving notch toughness of plates up to 2½-in. thick. The finishing temperatures in this practice (about 1,600°F) are on the lower end of those required for controlled rolling. However, because heavier plates are involved than in controlled rolling, mill delays are still required to reach the desired finishing temperatures. By controlling the finishing temperature, fine grain size and improved notch toughness can be obtained.

MECHANICAL CHARACTERISTICS

The commercial success of steel as an engineered material stems from the ability to provide a wide spectrum of mechanical properties. Steel offers a balance of strength, ductility, fracture resistance, and weldability. The design engineer should understand the importance of each of these properties, how they interact, and the correct methods of incorporating them into a final design.

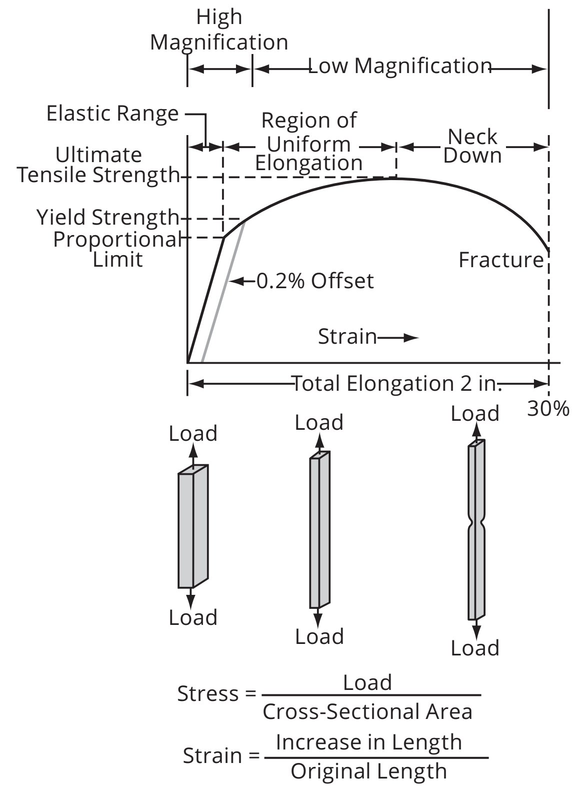
Ductility and Yield Strength

Solid materials can be divided into two classes: ductile and brittle. Engineering practice treats these two classes differently because they behave differently under load. A ductile material exhibits a marked plastic deformation or flow at a fairly definite stress level (yield point or yield strength) and shows a considerable total elongation, stretch, or plastic deformation before failure. With a brittle material, the plastic deformation is not well defined, and the ultimate elongation before failure is small. Steels, as listed in ANSI/AWWA C200, are typical of the ductile class materials used for steel water pipe.

Ductility of steel is measured as an elongation, or stretch, under a tension load in a tensile-testing machine. Elongation is a measurement of change in length under the load and is expressed as a percentage of the original gauge length of the test specimen.

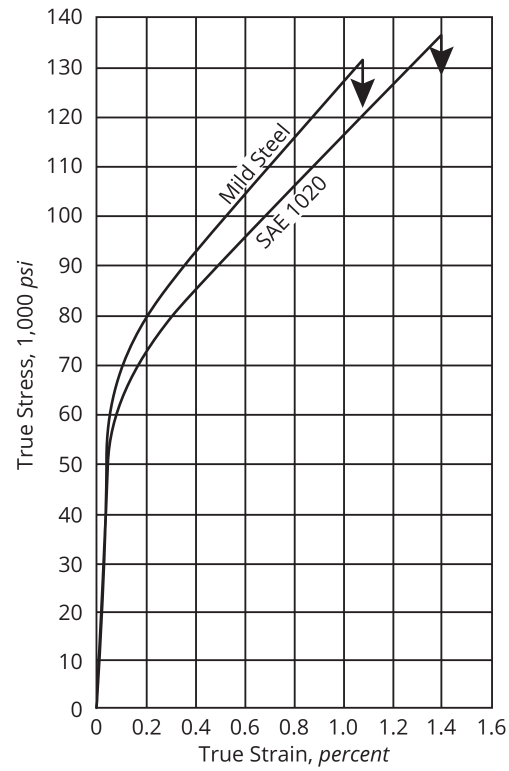
Ductility allows comparatively thin-walled steel pipe to perform satisfactorily, even when the vertical diameter is decreased 2 to 5 percent by external earth pressures, provided the true required strength has been incorporated in the design. Additionally, ductility allows steel pipe with theoretically high localized stresses at connection points of flanges, saddles, supports, and joint-harness lugs to continue to perform satisfactorily.

Designers who determine stress using formulas based on Hooke's law find that the calculated results do not reflect the integrity exhibited by the structures discussed in this manual. These discrepancies occur because the conventional formulas apply only up to a certain stress level and not beyond (stress-based design). Many otherwise safe structures and parts of structures contain calculated stresses above this level (strain-based design). A full understanding of the performance of such structures requires that the designer empirically examines the actual behavior of steel as it is loaded from zero to the fracture point.



The change in shape of the test piece of steel, which occurred during the test, is shown by the bars drawn under the curve.

Figure 1-2 Stress-strain curve for steel



Unlike conventional stress–strain curves, both true stress and true strain have been calculated for the curves shown.

Figure 1-3 True stress-strain for steel

The physical properties of steel (yield strength and ultimate tensile strength) used as the basis for design and purchase specifications are determined from tension tests made on standard specimens pulled in a tensile-testing machine. The strength of ductile materials, in terms of design, is defined by the yield strength as measured by the lower yield point, where one exists, or by the ASTM International offset yield stress, where a yield point does not exist. For steel typically used in water pipe, the yield strength is defined by the material specification as the stress determined by the 0.5 percent extension-under-load method, or the 0.2 percent offset method. The yield strength determined by the 0.2 percent offset method is most commonly used. Based on the 0.2 percent offset method, the value of the yield strength is defined as the stress represented by the intersection of the stress-strain curve and a line, beginning at the 0.002 value on the strain axis, drawn parallel to the elastic portion of the stress-strain curve. Such a line is shown in Figure 1-2. The yield strength of steel is considered the same for either tension or compression loads.

Stress and Strain

In engineering, stress is a value obtained by dividing a load by an area. Strain is a length change per unit of length. The relation between stress and strain, as shown on a stress-strain diagram, is of basic importance to the designer.

A stress-strain diagram for any given material is a graph showing the stress that occurs when the material is subjected to a given strain. For example, a bar of steel is pulled in a tensile-testing machine with suitable instrumentation for measuring the load and indicating the dimensional changes. While the bar is under load, it stretches. The change in length under load per unit of length is called *strain* or *unit strain*; it is usually expressed as percentage elongation or, in stress analysis, microinches (μin.) per inch, where 1 μin. = 0.000001 in. (For metric units, strain is defined as μmm/mm or μm/m.) The values of strain are plotted along the horizontal axis of the stress-strain diagram. For purposes of plotting, the load is converted into units of stress (pounds per square inch) by dividing the load in pounds by the original cross-sectional area of the bar in square inches. The values of stress are plotted along the vertical axis of the diagram. The result is a conventional stress-strain diagram.

Because the stress plotted on the conventional stress-strain diagram is obtained by dividing the load by the original cross-sectional area of the bar, the stress appears to reach a peak and then diminish as the load increases. However, if the stress is calculated by dividing the load by the actual cross-sectional area of the bar as it decreases in cross section under increasing load, it is found that the true stress never decreases. Figure 1-3 is a stress-strain diagram on which both true stress and true strain have been plotted. Because conventional stress-strain diagrams are used commercially, only conventional diagrams are used for the remainder of this discussion.

Figure 1-2 shows various parts of a pure-tension stress-strain curve for steel such as that used in steel water pipe. The change in shape of the test piece during the test is indicated by the bars drawn under the curve. As the bar stretches, the cross section decreases in area up to the maximum tensile strength, at which point local reduction of area (necking in) takes place.

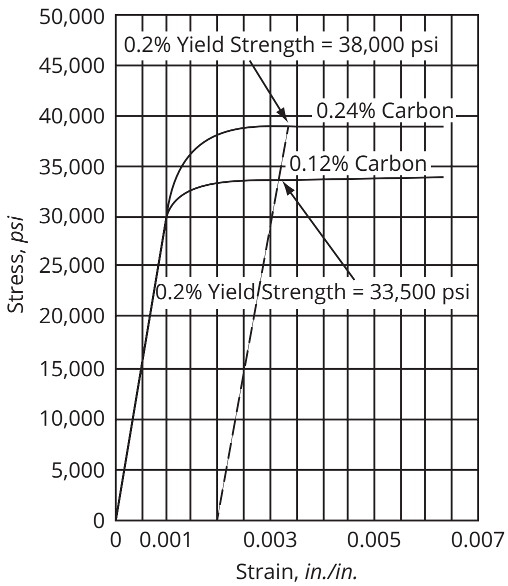
Many types of steel used in construction have stress-strain diagrams of the general form shown in Figure 1-2; whereas many other types used structurally and for machine parts have much higher yield and ultimate strengths, with reduced ductility. Still other useful engineered steels are quite brittle. In general, low-ductility steels must be used at relatively low strains, even though they may have high strength.

The ascending line on the left side of the graph in Figure 1-2 is straight or nearly straight and has a recognizable slope with respect to the vertical axis. The break in the slope of the curve is rather sudden. For this type of curve, the point where the first deviation from a straight line occurs marks the proportional limit of the steel. The yield strength is defined as a slightly higher stress level as discussed previously. Most engineering formulas involving stress calculation presuppose a loading such that working stresses will be well below the proportional limit.

Stresses and strains that fall below the proportional limit—such as those that fall on the straight portion of the ascending line—are said to be in the elastic range. Steel structures loaded to create stresses or strains within the elastic range return to their original shape when the load is removed. Exceptions may occur with certain kinds and conditions of loading not usually encountered in steel water pipe installations. Within the elastic range, stress increases in direct proportion to strain.

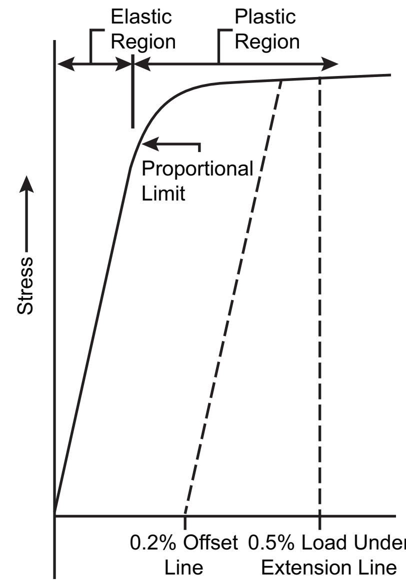
The modulus of elasticity (Young's modulus) is defined as the slope of the ascending straight portion of the stress-strain diagram. The modulus of elasticity of steel is about 30,000,000 psi, which means that for each increment of load that creates a strain or stretch of 1 μin./in. of length, a stress of 30 psi is imposed on the steel cross section (30,000,000 x 0.000001 = 30).

Immediately above the proportional limit lies a portion of the stress-strain curve that is termed the *plastic range of the material*. Typical stress-strain curves with the elastic range and the initial portion of the plastic range are shown in Figures 1-4 and 1-5 for two grades of carbon steel used for water pipe. Electric-resistance strain gauges provide a means of studying both the elastic and plastic regions of the curve. These and associated instruments allow minute examination of the shape of the curve in a manner not possible before development of these instruments.



The curves show the elastic-plastic range for two grades of carbon steel.

Figure 1-4 Stress-strain curves for carbon steel



Shown are the elastic and plastic portions of a stress–strain curve. Note: the 0.2% and 0.5% lines intersect at a specific location that may not be located on the stress–strain curve.

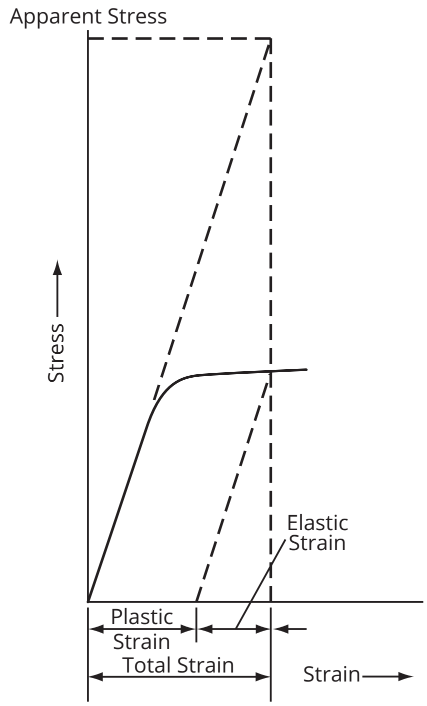
Figure 1-5 Plastic and elastic strains

The plastic range is important to the designer. Analysis of this range was necessary, for example, to determine and explain the successful performance of thin steel flanges on thin steel pipe (Barnard 1950). Designs that load steel to within the plastic range are safe only for certain types of apparatus, structures, or parts of structures. For example, designing within this range is safe for the hinge points or yield hinges in steel ring flanges on steel pipe; for hinge points in structures where local yielding or relaxation of stress must occur; and for bending in the wall of pipe under external earth pressure in trenches or under high fills. Such areas can generally involve secondary stresses, which will be discussed in the following section. It is not safe to rely on performance within this plastic range to handle principal tension stress in the walls of pipe or pressure vessels or to rely on such performance in other situations where the accompanying deformation is uncontrolled or cannot be tolerated.

Figure 1-6 shows graphically how a completely fictitious stress is determined by a formula based on Hooke's law, if the total strain is multiplied by the modulus of elasticity. The actual stress (Figure 1-7) is determined using only the elastic strain with the modulus of elasticity, but neglects what actually occurs to the steel in the plastic range.

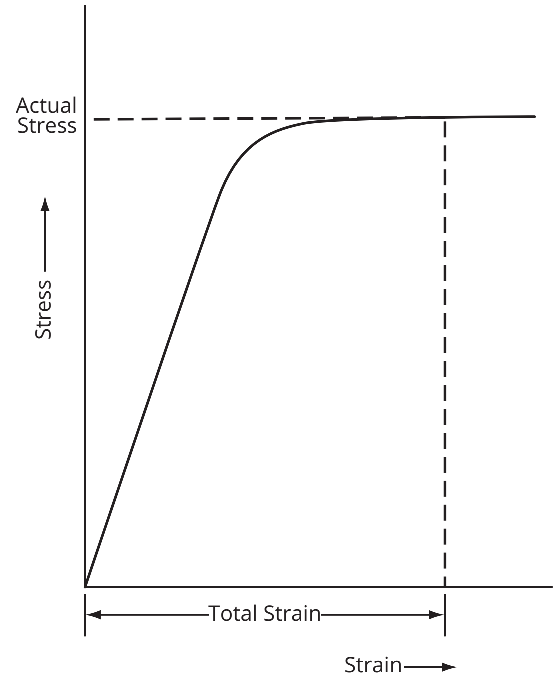
Stress in Design

Stress can be generally categorized as either principal or secondary. Although both types of stress can be present in a structure at the same time, the driving mechanism for, and a structure's response to, each differ significantly. A principal stress results from applied loads and is necessary to maintain the laws of equilibrium of a structure. If the level of a principal stress substantially exceeds the yield strength, a structure's deformation will continue toward failure. Therefore, a principal stress is not considered self-limiting. In the case of steel pipe, longitudinal and circumferential stresses resulting from internal pressure are examples of principal stresses. In contrast, secondary stress is developed when the deformation of a component due to applied loads is restrained by other components.



If the total strain is multiplied by the modulus of elasticity, the stress determined by use of a formula based on Hooke's law is fictitious.

Figure 1-6 Actual and apparent stresses



When the total measured strain is known, the actual stress can be determined by use of the stress–strain curve.

Figure 1-7 Determination of actual stress

Secondary stresses are considered self-limiting in that they are strain driven, not load driven; localized yielding absorbs the driving strain, which "relaxes" or redistributes the secondary stresses to lower levels without causing failure. Once the developed strain has been absorbed by the localized yielding, the driving mechanism for further deformation no longer exists. In the case of steel pipe, shell-bending stresses at hinge points such as flange connections, ring attachments, or other gross structural discontinuities, as well as induced thermal stress, are examples of secondary stresses.

Strain in Design

Analysis of a structure becomes more complete when considering strain as well as stress. For example, it is known that apparent stresses calculated using classic formulas based on the theory of elasticity are erroneous at hinge-point stress levels. The magnitude of this error near the yield-strength stress is demonstrated in the next paragraph, where the classically calculated result is compared with the measured performance.

By definition, the yield-strength load of a steel specimen is that load that causes a 0.5 percent extension of the gauge length or 0.2 percent offset from the linear elastic line. In the elastic range, a stress of 30 psi is imposed on the cross-sectional area for each microinch-per-inch increase in length under load. Because a load extension of 0.5 percent corresponds to 5,000 μin/in., the calculated yield-strength stress is 5,000 x 30 = 150,000 psi. The measured yield-strength stress, however, is approximately 30,000–35,000 psi or about one-fourth the calculated stress.

Similarly varied results between strain and stress analyses occur when the performance of steel, at its yield strength, is compared to the performance at its ultimate strength. There is a great difference in strain between the 0.2 percent offset yield strength of low- or medium-carbon steel and the specified ultimate strength at 30 percent elongation. This difference has a crucial bearing on design safety. The specified yield strength corresponds to a strain of about 2,000 μin/in. To pass a specification requirement of 30 percent elongation, the strain at ultimate strength must be no less than 0.3 in./in. or 300,000 μin/in.. The ratio of strain at ultimate strength to strain at yield strength, therefore, is 300,000:2,000 or 150:1. On a stress basis, assuming an ultimate tensile strength of 60,000 psi from the stress-strain diagram, the ratio of ultimate strength to yield strength is 60,000:30,000 or only 2:1.

Steels, such as those used in waterworks pipe, show nearly linear stress-strain diagrams up to the proportional limit, after which strains of 10 to 20 times the elastic-yield strain occur with no increase in actual load. Tests on bolt behavior under tension substantiate this effect (Bethlehem Steel Co. 1946). The ability of bolts to hold securely and safely when they are drawn into the region of the yield, especially under vibration conditions, is easily explained by the strain concept but not by the stress concept. The bolts act somewhat like extremely stiff springs at the yield-strength level.

ANALYSIS BASED ON STRAIN

In some structures and in many welded assemblies, conditions permit the initial adjustment of strain to working load but limit the action automatically either because of the nature of the loading or because of the mechanics of the assembly. Examples are, respectively, pipe under deep earth loads and steel flanges on steel pipe. In these instances, bending stresses may be in the region of yield, but deformation is limited.

In bending, there are three distinguishable phases that a structure passes through when being loaded from zero to failure. In the first phase, all fibers undergo strain less than the proportional limit in a uniaxial stress field. In this phase, a structure will act in a completely elastic fashion, to which the classic laws of stress and strain are applicable.

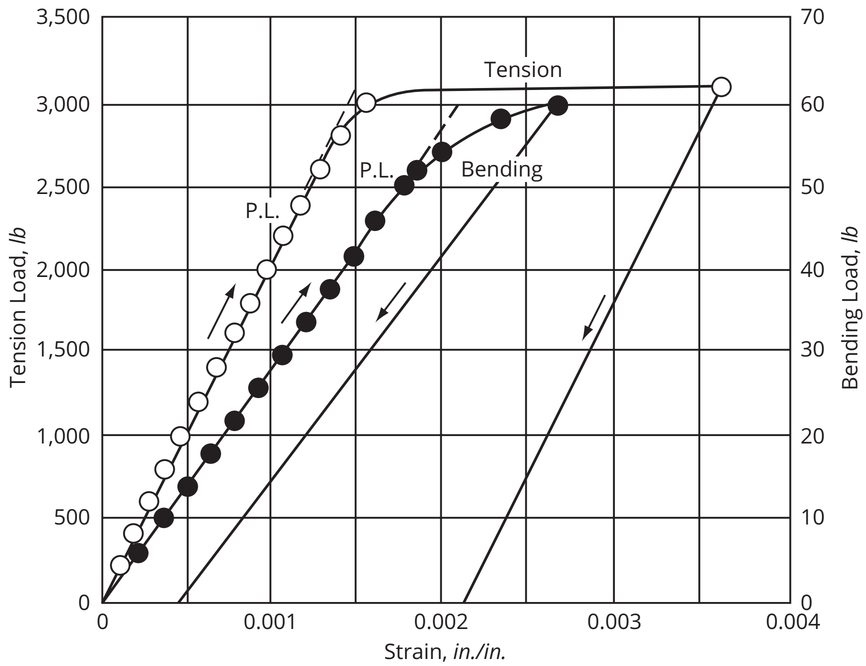
In the second phase, some of the fibers undergo strain greater than the proportional or elastic limit of the material in a uniaxial stress field; however, a more predominant portion of the fibers undergo strain less than the proportional limit, so that the structure still acts in an essentially elastic manner. The classic formulas for stress do not apply but the strains can be adequately defined in this phase.

In the third phase, the fiber strains are predominantly greater than the elastic limit of the material in a uniaxial stress field. Under these conditions, the structure as a whole no longer acts in an elastic manner.

An experimental determination of strain characteristics in bending and tension was made on medium-carbon steel (<0.25 percent carbon) similar to that required by ANSI/AWWA C200. Results are shown in Figure 1-8. Note that the proportional-limit strains in bending are 1.52 times those in tension for the same material. Moreover, the specimen in bending showed fully elastic behavior at a strain of 1,750 μin/in., which corresponds to a calculated stress of 52,500 psi (1,750 x 30 = 52,500) using the modulus of elasticity. The specimens were taken from material having an actual yield of 39,000 psi. Therefore, this steel could be loaded in bending to produce strains up to 1,750 μin/in. and still possess full elastic behavior.

Steel ring flanges made of plate and fillet welded to pipe with a comparatively thin wall have been used successfully for many years in water service. Calculations were made to determine the strain that would occur in the pipe wall adjacent to the flanges. The flanges ranged from 4 in. through 96 in. in diameter. Table 1-2 shows the results.

Note that from the table, in practice, the limiting strain was always below the 1940s' recognized yield-strength strain of 5,000 μin/in. but did approach it closely in at least one instance. All of these flanges are sufficiently satisfactory, however, to warrant their continued use by designers.



The proportional limit (P.L.) strains in bending are 1.52 times those in tension for the same material.

Figure 1-8 Experimental determination of strain characteristics

Table 1-2 Maximum strain in pipe wall developed in practice

	Operating Pressure		Maximum Strain	
Standard Flange	*psi*	*kPa*	*μin./in.*	*(mm/m)*
A	75	(517.1)	1,550–3,900	(1.55–3.90)
	150	(1,034.2)	2,200–4,650	(2.20–4.65)
B	150	(1,034.2)	1,100–3,850	(1.10–3.85)

Source: Barnard, R.E., Design of Steel Ring Flanges for Water Works Service—A Progress Report. Jour. AWWA, 42:10:931 (Oct. 1950).

Designing a structure on the basis of ultimate load capacity from test data rather than entirely on allowable stress is a return to an empirical point of view, a point of view that early engineers accepted in the absence of knowledge of the mathematics and statistics necessary to calculate stresses. The recent development of mathematical processes for stress analysis has, in some instances, overemphasized the importance of stress and underemphasized the importance of the overall strength of a structure.

DUCTILITY IN DESIGN

The plastic, or ductile, behavior of steel in welded assemblies may be especially important. Current design practice allows the stress at certain points in a steel structure to go beyond the elastic range. For many years, in buildings and in bridges, specifications have allowed the designer to use average or nominal stresses because of bending, shear, and bearing, resulting in local yielding around pins and rivets and at other points. This local yield, which redistributes both load and stress, is caused by stress concentrations that are neglected in the simple design formulas. Plastic action is and has been depended on to ensure the safety of steel structures. Experience has shown that these average or nominal maximum stresses form a satisfactory basis for design. During the manufacturing process, the steel in steel pipe has been forced beyond its yield strength many times, and the same thing may happen during installation. Similar yielding can be permitted after installation by design, provided the resulting deformation has no adverse effect on the function of the structure.

Basing design solely on approximations for real stress does not always produce safe results. The collapse of some structures has been traced to a trigger action of neglected points of high stress concentrations in materials that are not ductile at these points. Ductile materials may fail in a brittle fashion if subjected to overload in three planes at the same time. Careful attention to such conditions will result in safer design and will eliminate grossly over designed structures that waste both material and money.

Plastic deformation, especially at key points, sometimes is the real measure of structural strength. For example, a crack, once started, may be propagated by almost infinite stress, because at the bottom of the crack the material cannot yield a finite amount in virtually zero distance. In a ductile material, the crack will continue until the splitting load is resisted elsewhere.

EFFECTS OF COLD WORKING ON STRENGTH AND DUCTILITY

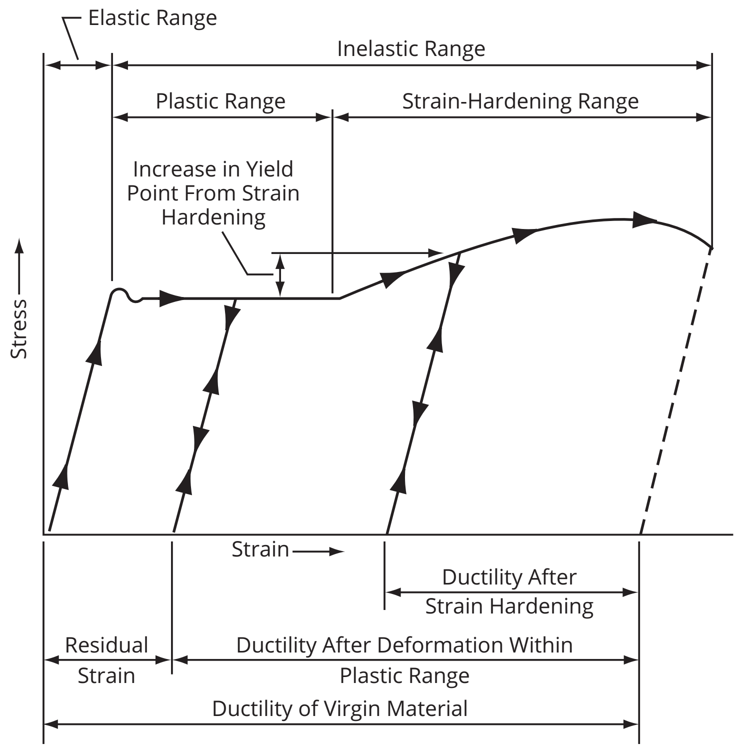
During pipe fabrication, the steel plates or sheets are often formed into the desired shape at room temperatures. Such cold-forming operations obviously cause inelastic deformation because the steel retains its formed shape. To illustrate the general effects of such deformation on strength and ductility, the elemental behavior of a carbon-steel tension specimen subjected to plastic deformation and subsequent reloading will be discussed. The behavior of actual cold-formed plates may be much more complex.

As illustrated in Figure 1-9, if a steel specimen of plate material is unloaded after being stressed into either the plastic or strain-hardening range, the unloading curve will follow a path parallel to the elastic portion of the stress-strain curve, and a residual strain or permanent set will remain after the load is removed.

If the specimen is promptly reloaded, it will follow the unloading curve to the stress-strain curve of the virgin (unstrained) material. If the amount of plastic deformation is less than that required for the onset of strain hardening, the yield strength of the plastically deformed steel will be approximately the same as that of the virgin material. However, if the amount of plastic deformation is sufficient to cause strain hardening, the yield strength of the steel will be increased. In either case, the tensile strength will remain the same, but the ductility measured from the point of reloading will be decreased. As indicated in Figure 1-9, the decrease in ductility is approximately equal to the amount of inelastic prestrain.

A steel specimen that has been strained into the strain-hardening range, unloaded, and allowed to age for several days at room temperature (or for a much shorter time at a moderately elevated temperature) will tend to follow the path indicated in Figure 1-10 during reloading (Dieter 1961). This phenomenon, known as *strain aging*, has the effect of increasing yield and tensile strength while decreasing ductility (Chajes et al. 1963).

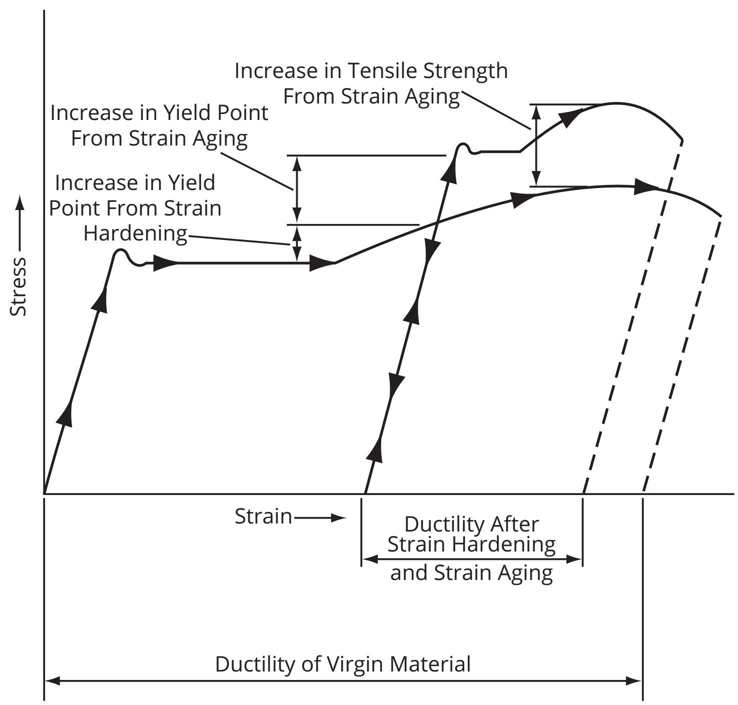
The effects of cold work on the strength and ductility of the structural steels can be eliminated largely by thermal stress relief, or annealing. Such treatment is not always possible; fortunately, it is not often necessary.



Note: Diagram is schematic and not to scale.

Source: Brockenbrough and Johnston 1981.

Figure 1-9 Effects of strain hardening



Note: Diagram is schematic and not to scale.

Source: Brockenbrough and Johnston 1981.

Figure 1-10 Effects of strain aging

BRITTLE FRACTURE CONSIDERATIONS IN STRUCTURAL DESIGN

General Considerations

As temperature decreases, there generally is an increase in the yield strength, tensile strength, modulus of elasticity, and fatigue strength of the plate steels. In contrast, the ductility of these steels, as measured by reduction in area or by elongation under load, decreases with decreasing temperatures. Furthermore, there is a temperature below which a structural steel that is subjected to tensile stresses may fracture by cleavage with little or no plastic deformation, rather than by shear, which is usually preceded by a considerable amount of plastic deformation or yielding.*

Fracture that occurs by cleavage at a nominal tensile stress below the yield stress is referred to as *brittle fracture*. Generally, a brittle fracture can occur when there is an adverse combination of tensile stress, temperature strain rate, and geometrical discontinuity (such as a notch). Other design and fabrication factors may also have an important influence. Because of the interrelation of these effects, the exact combination of stress, temperature, notch, and other conditions that cause brittle fracture in a given structure cannot be readily calculated. Preventing brittle fracture often consists mainly of avoiding conditions that tend to cause brittle fracture and selecting steel appropriate for the application. These factors are discussed in the following paragraphs. Parker (1957), Lightner and Vanderbeck (1956), Rolfe and Barsom (1977), and Barsom (1993) have described the subject in much more detail.

Fracture mechanics offer a more direct approach for prediction of crack propagation. For this analysis, it is assumed that an internal imperfection forming a crack is present in the structure. By linear-elastic stress analysis and laboratory tests on precracked specimens, the applied stress causing rapid crack propagation is related to the size of the imperfection. Fracture mechanics has become increasingly useful in developing a fracture-control plan and establishing, on a rational basis, the interrelated requirements of material selection, design stress level, fabrication, and inspection requirements (Barsom 1993).

Conditions Causing Brittle Fracture

Plastic deformation occurs only in the presence of shear stresses. Shear stresses are always present in a uniaxial or a biaxial state of stress. However, in a triaxial state of stress, the maximum shear stress approaches zero as the principal stresses approach a common value. As a result, under equal triaxial tensile stresses, failure occurs by cleavage rather than by shear. Consequently, triaxial tensile stresses tend to cause brittle fracture and should be avoided. As discussed in the following material, a triaxial state of stress can result from a uniaxial loading when notches or geometrical discontinuities are present.

If a transversely notched bar is subjected to a longitudinal tensile force, the stress concentration effect of the notch causes high longitudinal tensile stresses at the apex of the notch and lower longitudinal stresses in adjacent material. The lateral contraction in the width and thickness direction of the highly stressed material at the apex of the notch is restrained by the smaller lateral contraction of the lower stressed material. Therefore, in addition to the longitudinal tensile stresses, tensile stresses are created in the width and thickness directions, so that a triaxial state of stress is present near the apex of the notch.

The effect of a geometrical discontinuity in a structure is generally similar to, although not necessarily as severe as, the effect of the notch in the bar. Examples of geometrical discontinuities include poor design details (such as abrupt changes in cross section,

* Shear and cleavage are used in the metallurgical sense (macroscopically) to denote different fracture mechanisms. Parker (1957), as well as most elementary textbooks on metallurgy, discussed these mechanisms.

attachment welds on components in tension, and square-cornered cutouts) and fabrication flaws (such as weld cracks, undercuts, arc strikes, and scars from chipping hammers).

Increased strain rates tend to increase the possibility of brittle behavior. Therefore, structures that are loaded at fast rates are more susceptible to brittle fracture. However, a rapid strain rate or impact load is not a required condition for a brittle fracture.

Cold work and the strain aging that normally follows generally increase the likelihood of brittle fractures. This behavior is usually attributed to a reduction in ductility. The effect of cold work occurring in cold-forming operations can be minimized by selecting a generous forming radius, therefore limiting the amount of strain. The amount of strain that can be tolerated depends on both the steel and the application. A more severe but quite localized type of cold work occurs at sheared edges, but this effect can be essentially eliminated by machining or grinding the edges after shearing. Severe hammer blows may also produce enough cold work to locally reduce the toughness of the steel.

When tensile residual stresses are present, such as those resulting from welding, they increase any applied tensile stress, resulting in the actual tensile stress in the member being greater than the applied stress. Consequently, the likelihood of brittle fracture in a structure that contains high residual stresses may be minimized by a postweld heat treatment. The decision to use a postweld heat treatment should be made with assurance that the anticipated benefits are needed and will be realized, and that possible harmful effects can be tolerated. Many modern steels for welded construction are designed for use in the less costly as-welded condition when possible. The soundness and mechanical properties of welded joints in some steels may be adversely affected by a postweld heat treatment.

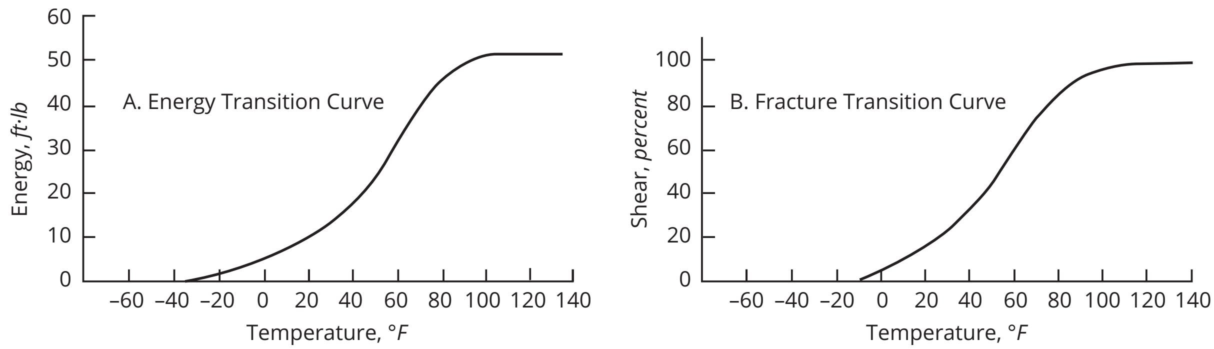
Welding may also contribute to brittle fracture by introducing notches and flaws into a structure and changing the microstructure of the base metal. Such detrimental effects can be minimized by properly designing welds, by selecting their appropriate location, and by using good welding practice. The proper electrode must be selected so that the weld metal will be as resistant to brittle fracture as the base metal.

Charpy V-Notch Impact Test

Some steels will sustain more adverse temperature, notching, and loading conditions without fracture than other steels. Numerous tests have been developed to evaluate and assign a numerical value determining the relative susceptibility of steels to brittle fracture. Each of these tests can establish with certainty only the relative susceptibility to brittle fracture under the particular conditions in the test; however, some tests provide a meaningful guide to the relative performance of steels in structures subjected to severe temperature and stress conditions. The most commonly used rating test, the Charpy V-notch impact test, is described in this section, and the interpretation of its results is discussed briefly.

The Charpy V-notch impact test specifically evaluates notch toughness—the resistance to fracture in the presence of a notch—and is widely used as a guide to the performance of steels in structures susceptible to brittle fracture. In this test, a small rectangular bar with a V-shaped notch of specified size at its midlength is supported at its ends as a beam and fractured by a blow from a swinging pendulum. The energy required to fracture the specimen (which can be calculated from the height to which the pendulum raises after breaking the specimen) or the appearance of the fracture surface is determined for a range of temperatures. The appearance of the fracture surface is usually expressed as the percentage of the surface that appears to have fractured by shear as indicated by a fibrous appearance. A shiny or crystalline appearance is associated with a cleavage fracture.

These data are used to plot curves of energy (see Figure 1-11) or percentage of shear fracture as a function of temperature. For most ferritic steels, the energy and percentage of shear fracture decrease from relatively high values to relatively low values with decreasing temperature. The temperature near the lower end of the energy-temperature curve, at which



Note: Curves are for carbon steel and are taken from the Welding Research Council (1957).

Source: Brockenbrough and Johnston 1981.

Figure 1-11 Transition curves obtained from Charpy V-notch impact tests

a selected value of energy is absorbed (often 15 ft-lb), is called the *ductility transition temperature*. The temperature at which the percentage of shear fracture decreases to 50 percent is often called the *fracture-appearance transition temperature* or *fracture transition temperature*. Both transition temperatures provide a rating of the brittle fracture resistance of various steels; the lower the transition temperature, the better the resistance to brittle fracture. The ductility transition temperature and the fracture transition temperature depend on many parameters (such as composition, thickness, and thermomechanical processing) and, therefore, can vary significantly for a given grade of steel.

Steel Selection

Requirements for notch toughness of steels used for specific applications can be determined through correlations with service performance. Fracture mechanics, when applied in conjunction with a thorough study of material properties, design, fabrication, inspection, erection, and service conditions, has been beneficial. In general, where a given steel has been used successfully for an extensive period in a given application, brittle fracture is not likely to occur in similar applications unless unusual temperature, notch, or stress conditions are present. Nevertheless, it is always desirable to avoid or minimize the previously cited adverse conditions that increase the susceptibility to brittle fracture.

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