

## Chapter 1

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# History, Uses, and Physical Characteristics of Steel Pipe

## HISTORY

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Steel pipe has been used for water lines in the United States since the early 1850s (Elliot 1922). The pipe was first manufactured by rolling steel sheets or plates into shape and riveting the seams. This method of fabrication continued with improvements into the 1930s. Pipe wall thicknesses could be readily varied to fit the different pressure heads of a pipeline profile.

Because of the relatively low tensile strength of the early steels and the low efficiency of cold-riveted seams and riveted or drive stovepipe joints, engineers initially set a safe design stress at 10,000 psi (68.95 MPa). As riveted-pipe fabrication methods improved and higher strength steels were developed, design stresses progressed with a 4-to-1 safety factor of tensile strength, increasing from 10,000 (68.95) to 12,500 (86.18), to 13,750 (94.8), and finally to 15,000 psi (103.42). Design stresses were adjusted as necessary to account for the efficiency of the riveted seam. The pipe was produced in diameters ranging from 4 in. (100 mm) through 144 in. (3,600 mm) and in thickness from 16 gauge to 1.5 in. (38 mm). Fabrication methods consisted of single-, double-, triple-, and quadruple-riveted seams, varying in efficiency from 45 percent to 90 percent, depending on the design.

Lock-Bar pipe, introduced in 1905, had nearly supplanted riveted pipe by 1930. Fabrication involved planing 30-ft (9.1-m) long plates to a width approximately equal to half the intended circumference, upsetting the longitudinal edges, and rolling the plates into 30-ft (9.1-m) long half-circle troughs. H-shaped bars of special configuration were applied to the mating edges of two 30-ft (9.1-m) troughs and clamped into position to form a full-circle pipe section.

According to the general procedure of the times, a 55,000-psi (379.2 MPa) tensile-strength steel was used. With a 4-to-1 safety factor, this resulted in a 13,750-psi (94.8 MPa) design stress. Lock-Bar pipe had notable advantages over riveted pipe: it had only one or two straight seams and no round seams. The straight seams were considered 100-percent efficient as compared to the 45-percent to 70-percent efficiency for riveted seams. Manufactured in sizes from 20 in. (500 mm) through 74 in. (1,850 mm), from plate ranging in thickness from  $\frac{3}{16}$  in. (4.8 mm) to  $\frac{1}{2}$  in. (12.7 mm), Lock-Bar played an increasingly greater role in the market until the advent of automatic electric welding in the mid 1920s.

By the early 1930s, both the riveting and Lock-Bar methods gradually were replaced by welding. Pipe produced using automatic electric-fusion welding was advantageous because fewer pieces were used, fewer operations were performed, and because of faster production, smaller seam protrusion, and 100-percent welded-seam efficiency. The fabricators of fusion-welded pipe followed similar initial production sequences as for Lock-Bar. Through the 1930s and into the 1940s, 30-ft (9.1-m) plates were used. By the 1950s, some firms had obtained 40-ft (12.2-m) rolls, and a few formed 40-ft (12.2-m) lengths in presses.

In the 1930s, a new approach was used to design stresses. Prior to that time, it had been common practice to work with a safety factor of 4-to-1 based on the tensile strength. As welded pipe became predominant, using 50 percent of the material yield stress became widely accepted.

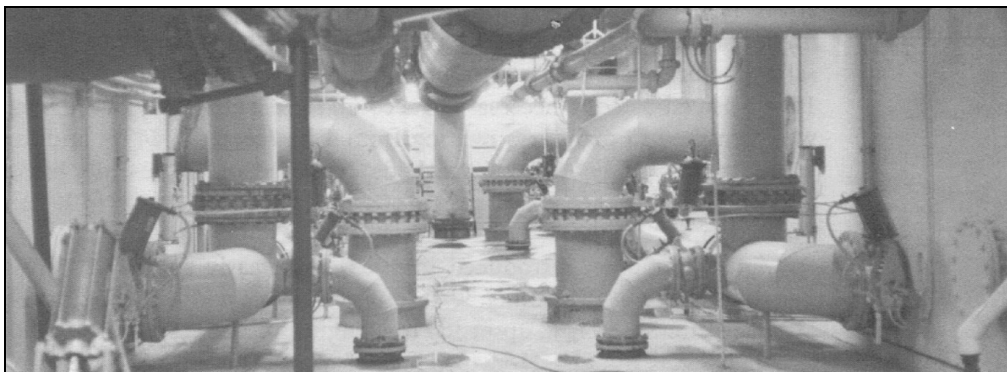
Helically formed and welded pipe was developed in the early 1930s and was used extensively in diameters from 4 in. (100 mm) through 36 in. (875 mm). Welding was performed using the electric fusion method. After World War II, German machines were imported, and subsequently, domestic ones were developed that could spirally form and weld through diameters of 144 in. (3,600 mm).

## USES

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Steel water pipe meeting the requirements of appropriate AWWA standards has been found satisfactory for many applications, some of which follow:

Aqueducts	Treatment-plant piping (Figure 1-1)
Supply lines	Self-supporting spans
Transmission mains	Force mains
Distribution mains	Circulating-water lines
Penstocks	Underwater crossings, intakes, and outfalls



The installation of pipe in this plant was simplified using the specially designed fittings and lightweight pipe.

Figure 1-1 Steel pipe in filtration plant gallery

General data on some of the notable steel pipelines have been published (Cates 1971, Hinds 1954). Data on numerous others have appeared in the *Journal AWWA* and other periodicals, as well as in many textbooks and engineering handbooks.

## CHEMISTRY, CASTING, AND HEAT TREATMENT

### General

The properties of steels are governed by their chemical composition, by the processes used to transform the base metal into the shape, and by their heat treatment. The effects of these parameters on the properties of steels are discussed in the following sections.

### Chemical Composition

Constructional steels are a mixture of iron and carbon with varying amounts of other elements—primarily manganese, phosphorus, sulfur, and silicon. These and other elements are unavoidably present or intentionally added in various combinations to achieve specific characteristics and properties of the finished steel products. 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. The effects of carbon, manganese, sulfur, silicon, and aluminum will be discussed.

Carbon is the principal hardening element in steel because each additional increment increases the hardness and tensile strength of the steel. Carbon has a moderate tendency to segregate, and increased amounts of carbon cause a decrease in durability, 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.

Table 1-1 Effects of alloying elements

Aluminum (Al)	Nickel (Ni)
<ul style="list-style-type: none"> <li>Used to deoxidize or “kill” molten steel</li> </ul>	<ul style="list-style-type: none"> <li>Increases strength and toughness</li> </ul>
Boron (B)	Nitrogen (N)
<ul style="list-style-type: none"> <li>Small amounts (0.0005 %) increases hardenability in quenched and tempered steels</li> <li>Used only in aluminum killed steels</li> <li>Most effective at low carbon levels</li> </ul>	<ul style="list-style-type: none"> <li>Increases strength and hardness</li> </ul>
Carbon (C)	Phosphorus (P)
<ul style="list-style-type: none"> <li>Principal hardening element in steel</li> <li>Increases strength and hardness</li> <li>Decreases ductility, toughness, and weldability</li> <li>Moderate tendency to segregate</li> </ul>	<ul style="list-style-type: none"> <li>Increases strength and hardness</li> <li>Decreases ductility and toughness</li> <li>Considered an impurity, but sometimes added for atmospheric corrosion resistance</li> </ul>
Chromium (Cr)	Silicon (Si)
<ul style="list-style-type: none"> <li>Increases strength</li> <li>Increases atmospheric corrosion resistance</li> </ul>	<ul style="list-style-type: none"> <li>Used to deoxidize or “kill” molten steel</li> <li>Decreases durability and toughness</li> </ul>
Copper (Cu)	Sulfur (S)
<ul style="list-style-type: none"> <li>Primary contributor to atmospheric corrosion resistance</li> </ul>	<ul style="list-style-type: none"> <li>Considered undesirable except for machinability</li> <li>Decreases ductility, toughness, and weldability</li> <li>Adversely affects surface quality</li> <li>Strong tendency to segregate</li> </ul>
Manganese (Mn)	Vanadium (V) and Columbium (Nb)
<ul style="list-style-type: none"> <li>Increases strength</li> <li>Controls harmful effects of sulfur</li> </ul>	<ul style="list-style-type: none"> <li>Small additions increase strength</li> </ul>

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.

## Casting

The traditional steel-making process is performed by pouring (teeming) molten steel into a series of molds to form castings known as ingots. The ingots are removed from the molds, reheated, then rolled into products with square or rectangular cross sections. This hot-rolling operation elongates the ingots and produces semifinished products known as blooms, slabs, or billets. All ingots exhibit some degree of nonuniformity of chemical composition known as segregation. This is an inherent characteristic of the cooling and solidification of the molten steel in the mold.

The initial liquid steel contacting the relatively cold walls and bottom of the mold solidifies very rapidly, having the same chemical composition as the liquid steel entering the mold. However, as the rate of solidification decreases away from the mold sides, crystals of relatively pure iron solidify first. The first crystals to form contain less carbon, manganese, phosphorus, sulfur, and other elements than the liquid steel from which they were formed. The remaining liquid is enriched by these elements that are continually being rejected by the advancing crystals. Consequently, the last liquid to solidify, which is located around the axis in the top half of the ingot, contains high levels of rejected elements and has a lower melting point than the poured liquid steel. This segregation of the chemical elements is frequently expressed as a local departure from the average chemical composition. In general, the content of an element that has a tendency to segregate is greater than average at the center of the top half of an ingot and less than average at the bottom half of an ingot.

Certain elements tend to segregate more than others. Sulfur segregates to the greatest extent. The following elements also segregate, but to a lesser degree, and in descending order are phosphorus, carbon, silicon, and manganese. The degree of segregation is influenced by the composition of the liquid steel, the liquid temperature, and the ingot size. The most severely segregated areas of the ingot are removed by cropping, which is the process of cutting and discarding sufficient material during rolling.

Continuous casting is the direct casting of steel from the ladle into slabs. This steel-making process bypasses the operations between molten steel and the semifinished product that are inherent in making steel products from ingots. During continuous casting, molten steel is poured at a regular rate into the top of an oscillating water-cooled mold with a cross-sectional size corresponding to the desired slab. As the molten metal begins to solidify along the mold walls, it forms a shell that permits the gradual withdrawal of the strand product from the bottom of the mold into a water-spray chamber where solidification is completed. The solidified strand is cut to length and then reheated and rolled into finished projects, 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 for steel products 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 strongly deoxidized do not evolve any gases and are called killed steels because they lie quietly in the mold. Increasing gas evolution results in semikilled, capped, or rimmed steels.

In general, killed steels are less segregated and contain negligible porosity when compared to semikilled steels. Consequently, killed-steel products usually exhibit a higher degree of uniformity in composition and properties than semikilled steel products.

## Heat Treatment for Steels

Steels respond to a variety of heat treatments that produce desirable characteristics. These heat treatments can be divided into slow cooling treatments and rapid cooling treatments. Slow cooling treatments, such as annealing, normalizing, and stress relieving, decrease hardness and promote uniformity of structure. Rapid cooling treatments, such as quenching and tempering, increase strength, hardness, and toughness. Heat treatments of base metal are generally mill options or ASTM requirements.

**Annealing.** Annealing consists of heating the steel to a given temperature followed by slow cooling. The temperature, the rate of heating and cooling, and the amount of time the metal is held at temperature depends 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 and toughness, produce a given microstructure, increase uniformity of microstructure, improve machinability, or to facilitate cold forming.

**Normalizing.** Normalizing consists of heating the steel to between 1,650°F and 1,700°F (899°C and 927°C) 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 the steel to between 1,000°F to 1,200°F (538°C to 649°C) 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 consists of heating and holding the steel at the appropriate austenizing temperature (about 1,650°F [899°C]) 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 (427°C and 649°C), holding for a specified time at that temperature, and cooling under suitable conditions to obtain the desired properties. Quenching and tempering increases the strength and improves 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; (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 (1,038° C) 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 (816° C and 982° C). Because rolling deformation at these low temperatures increases the mill loads significantly, controlled rolling is usually restricted to less than 2-in. (51-mm) 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. (64-mm) thick. The finishing temperatures in this practice (about 1,600° F [871° C]) are higher than 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.

## PHYSICAL CHARACTERISTICS

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Steel is widely used because of the following properties: great strength; ability to yield or deflect under a load while resisting it; ability to bend without breaking; and resistance to shock. The design engineer should understand these properties, how they are measured, what they will do, and how reliable they are.

## DUCTILITY AND YIELD STRENGTH

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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 final breakage. With a brittle material, the plastic deformation is not well defined, and the ultimate elongation before breakage is small. Steels, as listed in Table 4-1, are typical of the ductile materials used for steel water pipe.

It is ductility that allows comparatively thin-walled steel pipe, even though decreased in vertical diameter two to five percent by earth pressures, to perform satisfactorily when buried in deep trenches or under high fills, provided the true required strength has been incorporated in the design. Because of ductility, steel pipe with theoretically high, localized stresses at flanges, saddles, supports, and joint-harness lug connections has performed satisfactorily for many years.

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. Many eminently safe structures and parts of structures contain calculated stresses above this level. A full understanding of the performance of such structures requires that the designer empirically examine the actual behavior of steel as it is loaded from zero to the breaking point.

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 American Society for Testing and Materials (ASTM) offset yield stress, where a yield point does not exist. For steel typically used in water pipe, the yield strength is determined by the specification as the stress caused by a load creating a 0.5-percent extension of the gauge length. The point is shown in Figure 1-2. The yield strength of steel is considered the same for either tension or compression loads.

Ductility of steel is measured as an elongation, or stretch, under a tension load in a 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.

## STRESS AND STRAIN

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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.

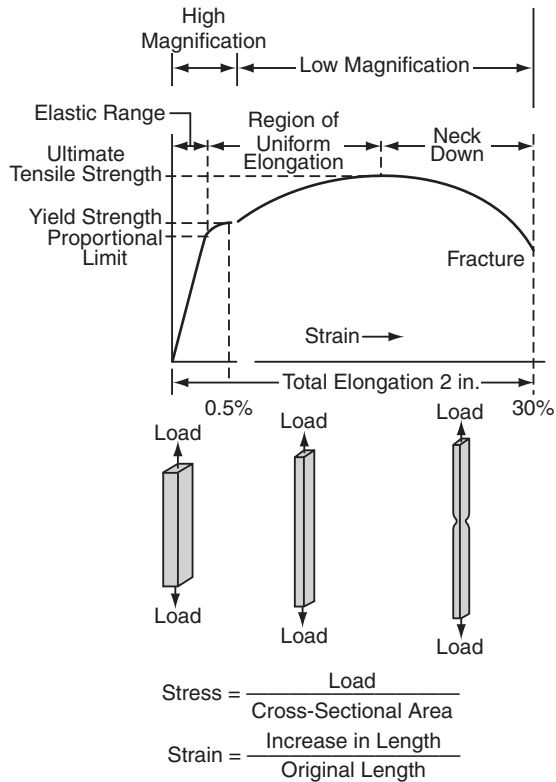
A stress–strain diagram for any given material is a graph showing the strain that occurs when the material is under a given load or stress. For example, a bar of steel is pulled in a testing machine with suitable instrumentation for measuring the load and indicating the dimensional changes. While the 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 (min) per inch, where 1 min = 0.000,001 in. (25.4 nm). 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 water utility 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.

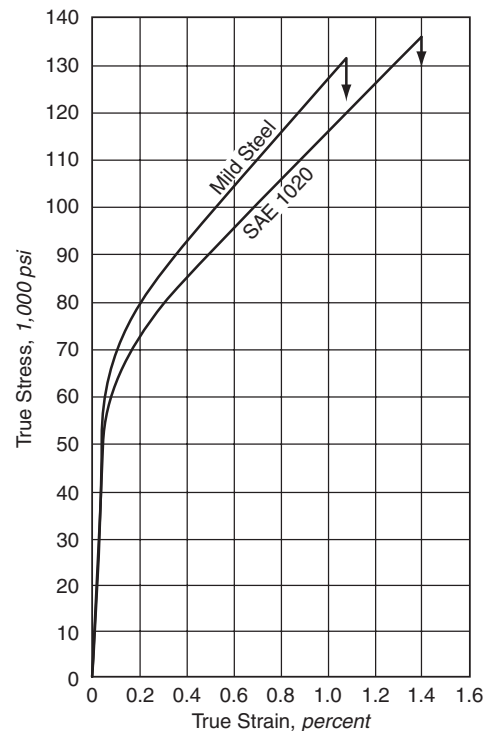
Many types of steel used in construction have stress–strain diagrams of the general form shown in Figure 1-2, whereas many other types used structurally and for machine parts have a much higher yield and ultimate strengths, with reduced ductility. Still other useful engineering steels are quite brittle. 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 at some higher stress level. Most engineering formulas involving



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

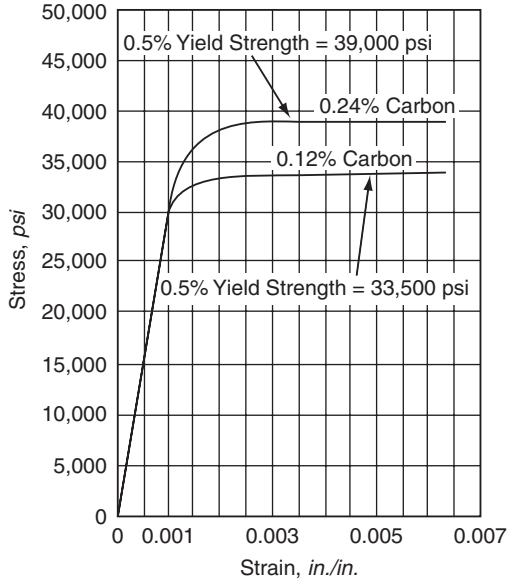
stress calculation presuppose a loading such that working stresses will be below the proportional limit.

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 precisely to their original length when the load is removed. Exceptions may occur with certain kinds and conditions of loading not usually encountered in water utility installations. Within this range, stress increases in direct proportion to strain.

The modulus of elasticity 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 (762 TPa), which means that for each increment of load that creates a strain or stretch of 1 min per inch (1 mm/m) of length, a stress of 30 psi (762 kPa) is imposed on the steel cross section ( $30,000,000 \times 0.000,001 = 30$ ).

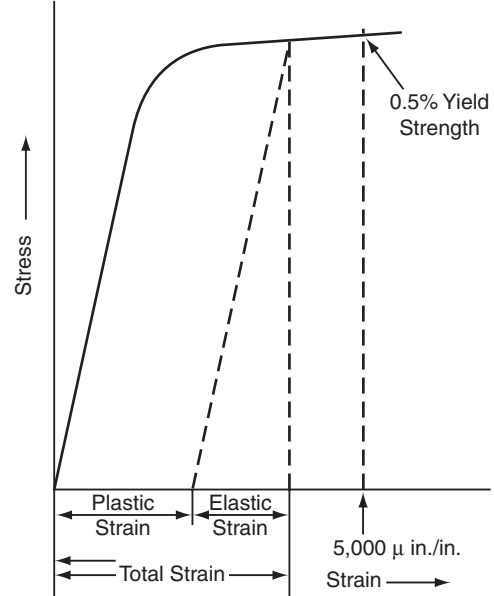
Immediately above the proportional limit, between it and the 0.5-percent extension-under-load yield strength of the material (Figure 1-2) lies a portion of the stress-strain diagram that is termed the elastic-plastic range of the material. Typical stress-strain curves with this portion magnified are shown in Figure 1-4 for two grades of carbon steel used for water pipe. Electric-resistance strain gauges provide a means of studying the elastic-plastic segment 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 for a steel stressed to a given level.

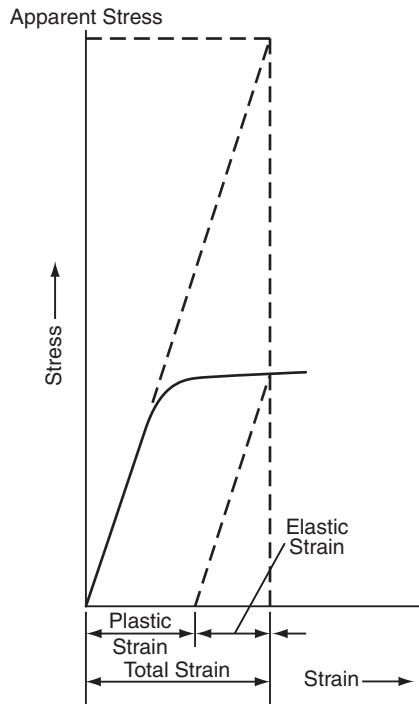
Figure 1-5 Plastic and elastic strains

The elastic-plastic range is becoming increasingly 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 elastic-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 earth load in trenches or under high fills. It is not safe to rely on performance within this 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 1-5 shows the elastic and plastic portions of a stress-strain curve for a steel stressed to a given level. 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 is determined using only the elastic strain with the modulus of elasticity, but there is at present no way to separate theoretically the elastic and plastic strains in a structure. The only alternative is to take the total measured strain as indicated by strain gauges and then determine the actual stress from the stress-strain curve, as shown in Figure 1-7.

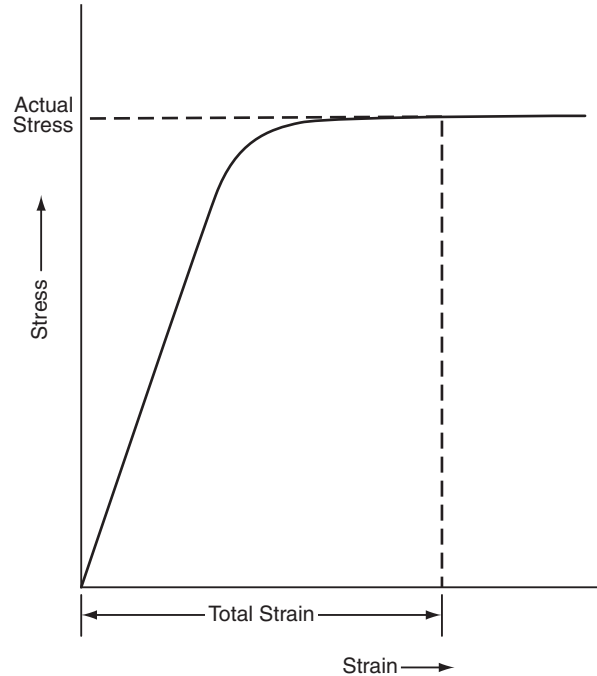
## STRAIN IN DESIGN

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.



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

By definition, the yield-strength load of a steel specimen is that load which causes a 0.5 percent extension of the gauge length. In the elastic range, a stress of 30 psi (762 kPa) is imposed on the cross-sectional area for each microinch-per-inch increase in length under load. Because an extension of 0.5 percent corresponds to 5,000 min/in. (5 nm/m), the calculated yield-strength stress is  $5,000 \times 30 = 150,000$  psi (1,034 MPa). The measured yield-strength stress, however, is approximately 30,000–35,000 psi (207–241 MPa) or about one fourth of 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 of its ultimate strength. There is a great difference in strain between the yield strength of low- or medium-carbon steel at 0.5-percent extension under load 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 5,000 min/in. (5 nm/m). To pass the specification requirement of 30 percent elongation, the strain at ultimate strength must be not less than 0.3 in./in. or 300,000 min/in. (300 nm/m). The ratio of strain at ultimate strength to strain at yield strength, therefore, is 300,000:5,000 or 60:1. On a stress basis, from the stress-strain diagram, the ratio of ultimate strength to yield strength is 50,000:30,000 or only 1.67:1.

Steels, such as those used in waterworks pipe, show nearly linear stress-strain diagrams up to the yield level, 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

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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 earth load 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.

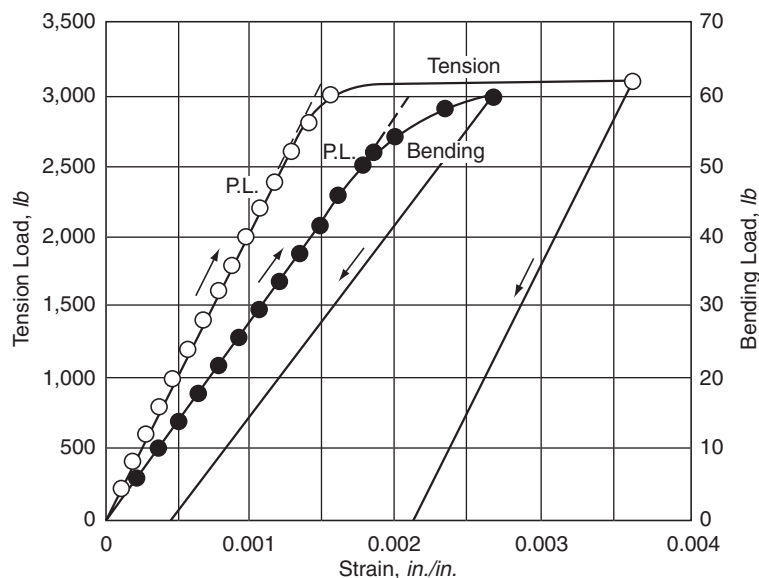
In the third phase, the fiber strains are predominantly greater than the elastic limit of the material in a uniaxial stress field. Under these conditions, the structure as a whole no longer acts in an elastic manner. The theory and formulas applicable in this phase are being developed but have not yet reached a stage where they can be generally used.

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 AWWA C200, Standard for Steel Water Pipe 6 Inches and Larger (latest edition). 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 min/in., which corresponds to a calculated stress of 52,500 psi (361.98 MPa) ( $1,750 \times 30 = 52,500$ ) using the modulus of elasticity. The specimens were taken from material having an actual yield of 39,000 psi (268.9 MPa). Therefore, this steel could be loaded in bending to produce strains up to 1,750 min/in. (1.75 nm/m) 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. The flanges ranged from 4 in. through 96 in. (100 mm through 2,400 mm) in diameter. Calculations were made to determine the strain that would occur in the pipe wall adjacent to the flanges. Table 1-2 shows the results.

Note that from the table, in practice, the limiting strain was always below the commonly recognized yield-strength strain of 5,000 min/in. (5.0 nm/m) 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.

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.



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

Standard Flange	Operating Pressure		Max. Strain	
	<i>psi</i>	<i>kPa</i>	$\mu\text{in.}/\text{in.}$	( <i>mm/m</i> )
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).

## DUCTILITY IN DESIGN

The plastic, or ductile, behavior of steel in welded assemblies may be especially important. Allowing the stress at certain points in a steel structure to go beyond the elastic range is successful current design practice. 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 yield 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 overdesigned 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. Plasticity underlies current design to an extent not usually realized and offers promise of greater economy in future construction (Symposium—Plastic Strength of Structural Members 1955, Neal 1956).

## 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 reloadings 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.

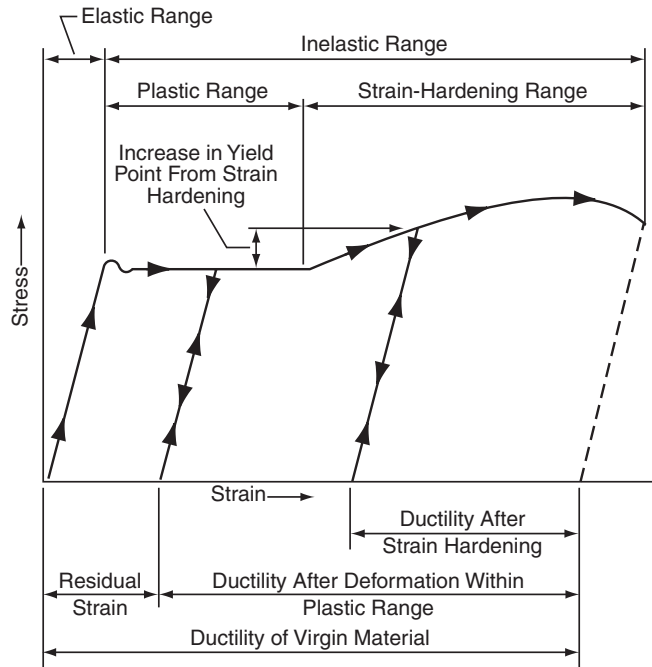
A steel specimen that has been strained into the strain-hardening range, unloaded, and allowed to age for several days at room temperature (or for a much shorter time at a moderately elevated temperature) will tend to follow the path indicated in Figure 1-10 during reloading (Dieter 1961). This phenomenon,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

## BRITTLE FRACTURE CONSIDERATIONS IN STRUCTURAL DESIGN\_\_\_\_\_

### General Considerations

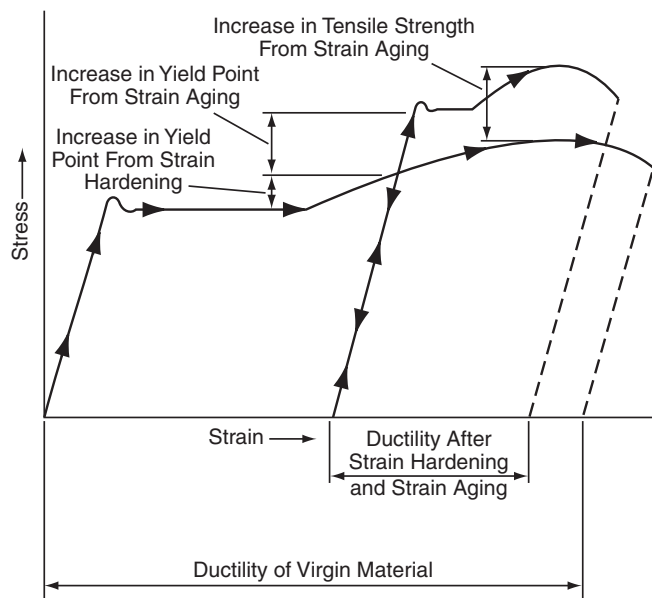
As temperature decreases, there generally is an increase in the yield stress, tensile strength, modulus of elasticity, and fatigue strength of the plate steels. In contrast, the ductility of these steels, as measured by reduction in area or by elongation under



NOTE: Diagram is schematic and not to scale.

Source: Brockenbrough, R.L. & Johnston, B.G., U.S.S. Steel Design Manual. ADUSS 27-3400-04. US Steel Corp. Pittsburgh, Pa. (Jan. 1981).

Figure 1-9 Effects of strain hardening



NOTE: Diagram is schematic and not to scale.

Source: Brockenbrough, R.L. & Johnston, B.G., U.S.S. Steel Design Manual. ADUSS 27-3400-04. US Steel Corp. Pittsburgh, Pa. (Jan. 1981).

Figure 1-10 Effects of strain aging

load, decreases with decreasing temperatures. Furthermore, there is a temperature below which a structural steel 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 a steel appropriate for the application. These factors are discussed in the following paragraphs. Parker (1957), the Welding Research Council (1957), Lightner and Vanderbeck (1956), Rolfe and Barsom (1977), and Barsom (1993) describe the subject in much more detail.

Fracture mechanics offers 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 pre-cracked 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, 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).

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\*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, discusses these mechanisms.

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 increases the likelihood of brittle fractures. This behavior is usually attributed to the 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 the edges of punched holes or at sheared edges. This effect can be essentially eliminated for holes by drilling instead of punching or by reaming after punching; for sheared edges, it can be eliminated by machining or grinding. 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.

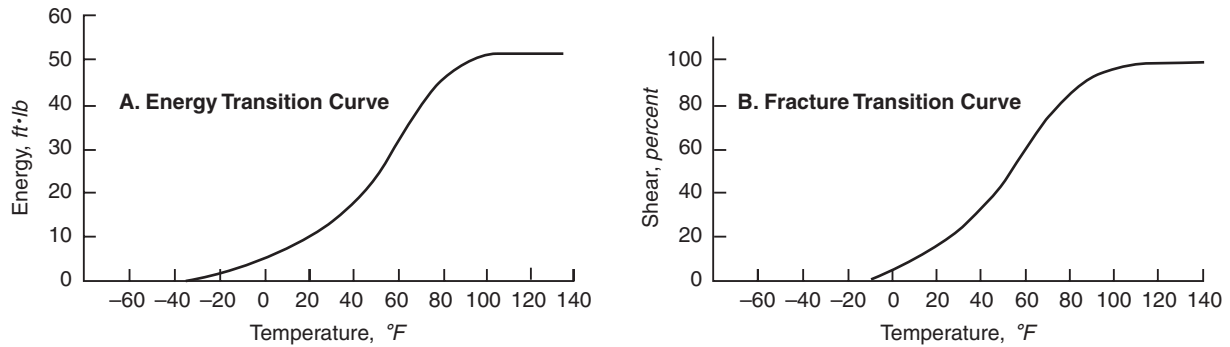
Welding may also contribute to brittle fracture by introducing notches and flaws into a structure and changing the microstructure of the base metal. Such detrimental effects can be minimized by properly designing welds, by selecting their appropriate location, and by using good welding practice. The 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. Parker (1957) and the Welding Research Council (1957) discuss in detail many other rating tests.

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 mid-length, 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.





Source: Brockenbrough, R.L. & Johnston, B.G., U.S.S. Steel Design Manual. ADUSS 27-3400-04. US Steel Corp. Pittsburgh, Pa. (Jan. 1981).

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

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

These data are used to plot curves of energy (see Figure 1-11) or percentage of shear fracture as a function of temperature. For the structural 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 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, have 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.

## GOOD PRACTICE

The ordinary water pipeline requires little stress calculation. The commonly used internal pressures for steel water pipe are given in Table 4-1 in chapter 4 and Table A-1 in appendix A. Suggested design stresses to resist other loadings are given as guides in various chapters on the different design subjects.

When designing the details of supports, wye branches, and other specials, especially for large pipe, the designer should review the data in chapter 13.

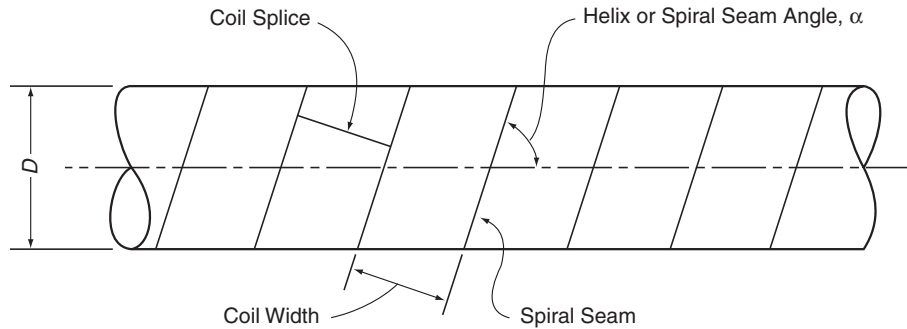


Figure 1-12 Spiral pipe weld seams

The concept of designing based on strain as well as stress will increase the knowledge of the behavior of steel and other materials in many cases where consideration of stress alone offers no reasonable explanation. The action and undesirable effects of stress raisers or stress concentrations—such as notches, threads, laps, and sudden changes in cross section—will be better understood. The steps involved in counteracting adverse effects become evident. Design using strain as well as stress will result in safer and more economical structures than if strain is ignored. Safe loads are a more important design consideration than safe stresses.

## EVALUATION OF STRESSES IN SPIRAL-WELDED PIPE

Occasionally, it is necessary to evaluate stresses of spiral-welded pipe seams. The hoop or circumferential stress,  $\sigma_2$ , is the maximum stress that occurs in a pipeline loaded under internal pressure. Therefore, the weld located perpendicular to this direction of stressing is subjected to the greatest amount of loading. The more the seam angle deviates from the direction of the pipe axis, the more the normal stress acting perpendicular to the welding seam decreases when neglecting the longitudinal stresses (Sommer 1982). The relationship is shown in the following equation:

$$\sigma_n = \sigma_1(\cos^2 \alpha) + \sigma_2(\sin^2 \alpha) \quad (1-1)$$

Where:

$\sigma_n$  = stress normal to the axis of the weld (psi)

$\sigma_1$  = longitudinal stress parallel to the longitudinal axis of the pipe (psi)

$\sigma_2$  = circumferential or hoop stress in pipe (psi)

$\alpha$  = angle of the spiral seam relative to longitudinal axis of the pipe in degrees (Figure 1-12)

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