

AWS Resources for Engineers

welding know-how for engineers

Design for Welding



American Welding Society

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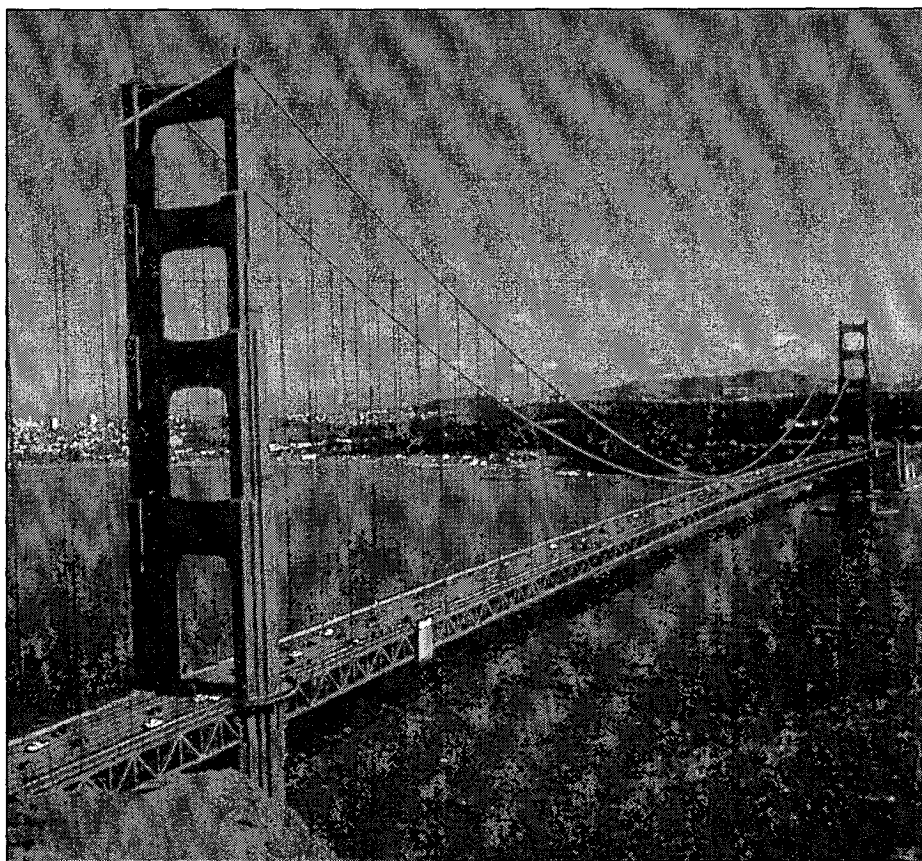
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DESIGN FOR WELDING



Photograph courtesy of Edison Welding Institute

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DESIGN FOR WELDING

INTRODUCTION

A weldment is an assembly of component parts joined by welding. It may be a bridge, a building frame, an automobile, a truck body, a trailer hitch, a piece of machinery, or an offshore oil drilling structure. In the field of weldment design,¹ the primary objectives are to produce an assembly that (1) performs its intended functions, (2) has the required reliability and safety, and (3) can be fabricated, inspected, transported, and placed in service at a minimum total cost. The total cost includes the cost of design, materials, fabrication, erection, inspection, operation, repair, and product maintenance.

The designers of weldments must have an understanding of basic design principles and concepts. They must have some knowledge of and experience in cutting and shaping metals; assembling components; preparing and fabricating welded joints; evaluating welds in compliance with established acceptance criteria; and performing nondestructive examination and mechanical testing.² Designers routinely apply knowledge of the following areas when evaluating the effects these may have on the design of weldments:³

1. Mechanical and physical properties of metals and weldments;

1. Of necessity, the topics discussed in this chapter have not been developed exhaustively. For more information, the reader should refer to available textbooks, manuals, and handbooks, several of which are listed in the Bibliography and the Supplementary Reading List at the end of this chapter.

2. A great deal of similarity exists between the designs of weldments and brazements, with the exception of joint designs and the joining processes. Consequently, much of the information presented in this chapter can also be applied to brazement design. For more information, refer to O'Brien, R. L., ed., *Welding Processes*, 1991, Vol. 2 of *Welding Handbook*, 8th ed., Miami: American Welding Society.

3. The topics listed here are covered in Vol. 1 of *Welding Handbook*, 9th ed., Miami: American Welding Society; O'Brien, R. L., ed., *Welding Processes*, 1991, Vol. 2 of *Welding Handbook*, 8th ed., Miami: American Welding Society; Oates, W. R., ed., 1996, *Materials and Applications—Part 1*, Vol. 3 of *Welding Handbook*, Miami: American Welding Society; and Oates, W. R., and A. M. Saitta, eds., 1998, *Materials and Applications—Part 2*, Vol. 4 of the *Welding Handbook*, 8th edition: Miami: American Welding Society.

2. Weldability of metals;
3. Welding processes, costs, and variations in welding procedures;
4. Filler metals and properties of weld metals;
5. Thermal effects of welding;
6. Effects of restraint and stress concentrations;
7. Control of distortion;
8. Efficient use of steel, aluminum, and other metals in weldments;
9. Design for appropriate stiffness or flexibility in welded beams and other structural members;
10. Design for torsional resistance;
11. Effects of thermal strains induced by welding in the presence of restraints;
12. Effects of stress induced by welding in combination with design stresses;
13. Practical considerations of welding and the selection of proper joint designs for the application.
14. Communication of weldment design to the shop, including the use of welding symbols; and
15. Applicable welding codes and safety standards.

As several of these topics involve highly specialized areas of science and technology, designers should refrain from relying entirely upon their own knowledge and experience, which may be generalized. They are encouraged to consult with welding experts whenever appropriate.

PROPERTIES OF METALS

The properties of metals can be divided into five general groups: (1) mechanical, (2) physical, (3) corrosion, (4) optical, and (5) nuclear. The typical characteristics of each group are presented in Table 1. These are further categorized as structure-insensitive or structure-sensitive, as this distinction is made in most textbooks

Table 1
Properties of Metals

General Groups of Properties	Structure-Insensitive Properties	Structure-Sensitive Properties
Mechanical	Elastic moduli	Ultimate strength
		Yield strength
		Fatigue strength
		Hardness
		Ductility
		Elastic limit
		Damping capacity
		Creep strength
		Rupture strength
		Toughness
Physical	Thermal expansion	Thermal stresses
	Thermal conductivity	
	Melting point	
	Specific heat	
	Emissivity	
	Thermal evaporation rate	
	Density	
	Vapor pressure	
	Electrical conductivity	
	Thermoelectric properties	
	Magnetic properties	
Corrosion	Thermionic emission	Ferromagnetic properties
	Electrochemical potential	
Optical	Color	Oxidation resistance
	Reflectivity	
Nuclear		Radiation absorptivity
		Nuclear cross section
	Wavelength of characteristic X-rays	

Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Table 3.1.

on metals to highlight the considerations that should be given to the reported values of the properties.⁴ Only those properties related to weldment design will be discussed in this chapter. These include the mechanical, physical, and corrosion properties.

4. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, p. 133.

The structure-insensitive properties of metals do not vary from one piece of a metal to another of the same composition, regardless of differences in microstructure. This has been verified by data obtained from standard engineering tests and is true for most engineering purposes. These properties can often be calculated or rationalized by examining the chemical composition.⁵ The structure-insensitive properties are commonly considered constants for metals.⁶

The structure-sensitive properties are dependent not only upon the chemical composition and crystallographic structure but also upon microstructural details that may be affected in subtle ways by the manufacturing and processing history of the metal. Even the size of the sample can influence the test results obtained for a structure-sensitive property.⁷ Structure-sensitive properties are likely to vary somewhat if differences exist in the treatment and preparation of the samples.

In the field of weldment design, the most important mechanical properties of metals, with the exception of the moduli of elasticity (see the section "Modulus of Elasticity" below), are those that are structure-sensitive. Consequently, the published single values of these properties should be considered with reservation. It is common for the mechanical properties of metal plates or bars that are unusual in size or treatment condition to deviate significantly from the values published for the particular metals. In addition, as determined by standard quality acceptance tests in an American Society for Testing and Materials (ASTM) specification, the mechanical properties of a metal do not guarantee identical properties throughout the material represented by the test sample.^{8,9} For example, the direction in which wrought metal is tested (longitudinal, transverse, or through-thickness) may result in significantly different values for strength and ductility.

The physical and corrosion properties of metals are considered structure-insensitive for the most part. Some of the values established for these properties apply only to common polycrystalline metals, however.

5. General metallurgy and welding metallurgy are covered in Chapter 4, Vol. 1 of the *Welding Handbook*, 9th ed., Miami: American Welding Society.

6. See Reference 4.

7. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society.

8. At the time of the preparation of this chapter, the referenced codes and other standards were valid. If a code or other standard is cited without a date of publication, it is understood that the latest edition of the document referred to applies. If a code or other standard is cited with the date of publication, the citation refers to that edition only, and it is understood that any future revisions or amendments to the code or standard are not included; however, as codes and standards undergo frequent revision, the reader is encouraged to consult the most recent edition.

9. American Society for Testing and Materials (ASTM), 1997, *Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, ASTM A370-97a, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

MECHANICAL PROPERTIES

As metals are generally strong, tough, and ductile, they are advantageous construction materials. This combination of properties is rarely found in nonmetallic materials, so most nonmetallic construction materials depend upon composite action with metals for their usefulness. The strength, toughness, and ductility of metals can be modified by means of alloy or heat treatment. Metals offer not only many useful individual mechanical properties and characteristics but also a large number of combinations of these properties. This versatility allows designers to select the best combination of properties to ensure the intended performance level.

Among the factors that affect the mechanical properties of metals are applied heat, the cooling rate, the addition of filler metal, and the metallurgical structure of the joint.¹⁰ The joining of metals by welding or brazing also affects their mechanical properties.

Another factor that must be considered during the materials selection process is ease of fabrication. Base metals and welding consumables should be selected to facilitate fabrication. When making a decision regarding the selection of materials, it is necessary to examine the governing properties of the metals and consider their combined effect upon the design and service behavior of the weldment.

Modulus of Elasticity

A convenient way to assess a metal's ability to resist stretching (strain) under stress in the elastic range is Young's Modulus, also known as the *modulus of elasticity*. This is the ratio between the applied strain and the resulting stress. In the elastic range, the modulus of elasticity, a constant, is expressed by the following equation:

$$E = \frac{\sigma}{\epsilon} \quad (1)$$

where

E = Modulus of elasticity;

σ = Stress, pounds per square inch, psi (megapascal [MPa]), and

ϵ = Strain, inch per inch (in./in.) (millimeter per millimeter [mm/mm]).

Young's Modulus, shown in Figure 1, can be calculated from the measured strain and calculated stress generated during a standard tension test. As the modulus of elasticity is a structure-insensitive property, it is not influenced by grain size, cleanliness, or heat treat-

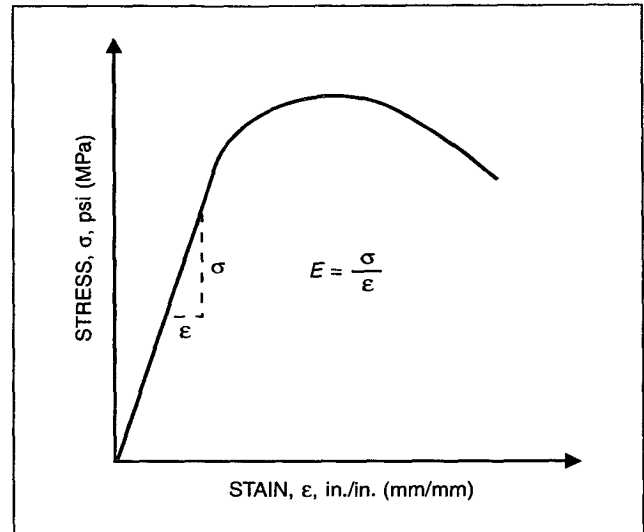


Figure 1—Young's Modulus (Modulus of Elasticity), E

ment; in fact, the modulus of elasticity often remains unchanged even after considerable alloy additions have been made.¹¹

Table 2 presents the modulus of elasticity for a number of metals.

For practical purposes, the modulus of elasticity can be used to determine the level of stress created in a piece of metal when it is forced to stretch elastically a specified amount. The stress can be determined by multiplying the strain by the modulus of elasticity. It is important to point out that the modulus of elasticity decreases with increasing temperature and that these temperature-influenced changes vary with different metals.

Elastic Limit

The elastic behavior of a metal reaches a limit at a level of stress termed the *elastic limit*. This is the highest stress a member can bear and still return to its original dimensions when the load is released. When the elastic limit is exceeded, the member permanently deforms. The elastic limit of a metal is structure-sensitive and dependent on the strain rate.

The design of many components is limited by the elastic limit. Therefore, several properties related to this limit have been defined. These properties can be deter-

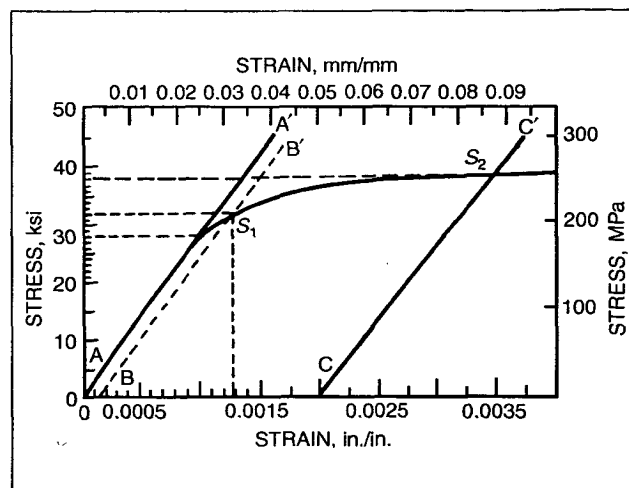
10. The testing and evaluation of welded joints are discussed in Chapter 6, Vol. 1 of the *Welding Handbook*, 9th ed., Miami: American Welding Society.

11. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, p. 139.

Table 2
Modulus of Elasticity of Metals

Metal	Modulus of Elasticity	
	psi (10^6)	MPa (10^3)
Aluminum	9.0	62.0
Beryllium	42.0	289.4
Niobium (columbium)	15.0	103.4
Copper	16.0	110.2
Iron	28.5	196.4
Lead	2.0	13.8
Molybdenum	46.0	316.9
Nickel	30.0	206.7
Steel, carbon, and alloy	29.0	199.8
Tantalum	27.0	186.0
Titanium	16.8	115.8
Tungsten	59.0	406.5

Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Table 3.2.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 3.2.

Figure 2—Typical Tensile Stress-Strain Diagram for a Metal Stressed Beyond the Limit of Elastic Behavior

mined from the stress-strain diagram that is commonly plotted for a tension test. A typical diagram is presented in Figure 2.

The stress-strain curve is initially a straight line, which is indicated in Figure 2 as line A-A'. The slope of this line is the metal's modulus of elasticity. As the line proceeds upward, a point is reached at which the strain exceeds the amount predicted by the earlier straight-line relationship. It is difficult to determine the exact point at which the proportionality between stress and strain ends because the clarity and interpretation of the curve may vary. The elastic limit on the stress-strain curve shown in Figure 2 is approximately 28 kips per square inch (ksi) (190 MPa). This is the maximum point at which the strain remains directly proportional to stress.

When a metal is strained below the elastic limit, it recovers upon removal of the load. On the other hand, when a metal is stressed beyond its elastic limit, the additional strain is plastic in nature and results in permanent deformation. As an example, if the tensile specimen depicted in Figure 2 were loaded to 32 ksi (220 MPa), as shown in S_1 , the specimen would elongate 0.00125 in./in. (0.00125 mm/mm). Upon removal of the load, the specimen would not return to its original length but would display a permanent stretch of approximately 0.00015 in./in. (0.00015 mm/mm), represented by line B-B'.

Yield Strength

The yield strength of a metal is the stress level at which the metal exhibits a specified deviation from the proportionality of stress and strain. A practical method utilized to determine the yield strength of a metal is illustrated in Figure 2. Line C-C' is drawn parallel to the elastic Line A-A' from a point on the abscissa, representing 0.2% (0.0020 in./in. [0.0020 mm/mm]) elongation. Line C-C' intersects the stress-strain curve at S_2 , where the stress level is approximately 38 ksi (260 MPa). This stress is the yield strength of the tested metal. While an offset yield strength of 0.2% is commonly used in engineering design, offsets of 0.1% and 0.5% are sometimes employed in the same manner for various metals.

Tensile Strength

The ratio of the maximum load sustained by a tension test specimen to the original cross-sectional area is referred to as the *ultimate tensile strength* (UTS). The UTS is the most common value calculated from the standard tension test. However, the true tensile strength of a metal, which is the ratio of the breaking load to the final cross-sectional area, may be substantially higher than the reported tensile strength.

The tensile strength values obtained for metals are influenced by many factors. Tensile strength is a structure-sensitive property. It is dependent upon chemical composition, microstructure, the direction of rolling, grain size, and strain history. The size and shape of the specimen and the rate of loading can also affect the result. For these reasons, the UTS of the heat-affected zone may be different from that of the unaffected base metal.

Fatigue Strength

Behavior under cyclic loading is an important aspect of the strength of metals and welded joints. Fatigue fractures develop because the applied forces, even at nominal tensile stresses lower than yield-point stress, cause the tip of a crack to advance a minute amount. This phenomenon is termed *stable crack growth*. The rate of crack growth increases as the area ahead of the crack decreases until the crack reaches a critical size. At this point, unstable crack growth initiates, and sudden, complete failure follows.

Crack growth does not occur when the net stress at the crack tip is compressive, however. A crack may initiate due to high residual tensile stresses, but the formation of the crack will relieve the local stress condition. Thus, if the applied load is compressive, the crack will not grow to a critical size.

The stress that a metal can endure without sustaining fracture decreases as the number of repeated stress applications increases. Fatigue strength is generally defined as the maximum stress that can be sustained for a stated number of cycles without failure. As the number of cycles is increased, the corresponding fatigue strength becomes lower. The term *fatigue life*, accordingly, refers to the number of cycles of stress that can be sustained by a metal under stipulated conditions.

For a given stress level, the fatigue strength of steel is constant beyond approximately two million cycles. Several million additional cycles are required to cause a significant reduction in fatigue strength. Thus, for practical purposes, the fatigue limit is the maximum stress or stress range that a metal can bear for an infinite number of cycles without sustaining fracture. Such a limiting stress level is often called the *endurance limit*.

The endurance limits reported for metals in engineering handbooks are usually determined using polished round specimens tested in air. These data are valid and useful for design in applications such as shafts in rotating machinery and other uniform members. However, they may have little relevance in the design of weldments, as these are characterized by abrupt changes in cross section, geometrical and metallurgical discontinuities, and residual stresses, all of which adversely affect fatigue life.

Weldments in rotating equipment are particularly prone to fatigue failure. Pressure vessels can also fail by fatigue when the pressurization is cyclic and stress above the fatigue strength is concentrated at some point. When designing welded built-up members and welded connections for structures subject to fatigue loading, the applicable standard governing the subject structure must be followed. In the absence of a specific standard, the designs of existing welded components should be used as a guide.

Localized stresses within a structure may result entirely from external loading, or they may be caused by a combination of applied and residual stresses. Residual stresses are not cyclic, but they may augment or detract from applied stresses, depending upon their respective signs. For this reason, it may be advantageous to induce, if possible, compressive residual stress in critical areas of a weldment where cyclic applied tensile stresses are expected. This can be accomplished by a welding sequence that controls the residual stresses produced during welding or by a localized treatment that acts to place the surface in compression.

Thermal stresses must be considered in the same light as applied stress. Thermal stresses result from the expansion and contraction of a material during heating and cooling. As a metal is heated, it expands. If the material is restrained and not free to expand, thermal compressive stresses are formed. Conversely, if a restrained part is cooled, the result is a tensile stress. Thermal cycling can lead to fatigue failure if the thermal gradients are steep or if the thermal stresses are concentrated by a stress raiser, such as a change in cross section or a discontinuity.

In summary, the designers of weldments require a thorough understanding of the fatigue characteristics of metals as used in weldments. For weldments subject to loading in the tension range, the most common cause of fracture is fatigue. One of the reasons for this is the frequent presence of stress raisers, which concentrate imposed cyclic stresses to levels above the fatigue limit of the metal for the existing conditions.

Ductility

The amount of plastic deformation that an unwelded or a welded specimen undergoes in a mechanical test carried to fracture is considered a measure of the ductility of the metal or the weld. Values expressing ductility in various mechanical tests are meaningful only for the relative geometry and size of the test specimen. Thus, they do not measure any fundamental characteristic, but merely provide relative values for the comparison of the ductilities of metals subjected to identical test conditions. The plasticity exhibited by a specimen is simply the deformation accomplished during the yielding process. Regardless of the method of measurement, ductil-

ity is a structure-sensitive property. It is affected by many of the testing conditions. The size and shape of the specimen, ambient temperature, strain rate, microstructure, and surface conditions all influence the amount and location of plastic deformation prior to fracture.¹²

The ductility values derived from precise or elaborate tests are not used directly in weldment design. Structures are usually designed to function at stresses below the yield strength, and any serious deformation usually disqualifies the unit or article from service. Nonetheless, ductility values are useful in providing an indication of the ability of a metal to yield and relieve localized high stresses. They also provide insight into the reserve of plasticity available to ensure against sudden fracture under unexpected overloading. However, as most structures are sensitive to both loading rate and temperature, ductility values do not necessarily indicate the amount of plastic deformation that will take place under all conditions of loading.¹³

Fracture Toughness

A metal that is judged ductile by a standard tension or slow-bend test may perform in a brittle manner in another type of test or when exposed to service conditions. Thus, the only prediction that can be made with reasonable certainty based on tension or bend test results is that a metal with very little ductility is not likely to perform in a ductile manner in any other type of mechanical test carried to fracture. However, a metal that displays good ductility in a tensile or bend test may or may not behave in a ductile manner in other types of mechanical tests. In fact, ductile (as determined by tensile and bend tests) metals have been known to fracture in service with little or no plastic deformation. This lack of deformation and other aspects of such failures usually indicate that little energy was required to produce the fracture. This general phenomenon prompts metallurgists to speak of the toughness of metal as a property distinct from ductility.¹⁴

The term *fracture toughness* is defined as the ability of a metal to resist fracture under conditions that are unfavorable to energy absorption in the presence of a notch and to accommodate loads by plastic deformation.

Four conditions markedly influence the behavior of a metal. These are the rate of loading, the nature of the load (i.e., whether the imposed stresses are uniaxial or multiaxial), the temperature of the metal, and the presence of a notch.

Many metals can absorb energy and deform plastically under the simple circumstances represented in tension or bend tests (and therefore would be judged ductile); however, a lesser number of these metals exhibit good toughness when tested under conditions of high stress concentration. The toughness displayed by a metal tends to decrease as (1) the rate of loading increases, (2) the applied stresses become multiaxial, and (3) the temperature of the metal is lowered. Weldments in service may easily be exposed to one or more of these conditions. Consequently, concern about the toughness of the weld metal and weld heat-affected zones is warranted.

When ductile metals are employed in the design of engineering structures, including welds, design strength is normally based on an analysis to ensure that the applied stresses are below the design strength. Failures that occur at load levels below the design strength are broadly classified as *brittle failures*. These failures can result from the effects of discontinuities or crack-like defects of critical size in the weld or the base metal that do not greatly alter the nominal stress distribution and are customarily neglected in the design.

When structural grade steel is tested in uniaxial tension, it typically deforms in a ductile manner prior to rupture at the ultimate load. Because the volume of metal must remain constant, any elongation in one direction must be accompanied by contraction in one or both of the other directions. The uniaxial tension test specimen is free to contract in the other direction, resulting in ductile behavior. If the necessary lateral contraction is severely constrained or prevented and the longitudinal stresses are sufficiently large, the same material that exhibits ductile behavior in a simple tension test may fail in a brittle manner.

In structures in which separate elements are joined by welding, the conditions of constraint and stress concentrations are usually very different from those produced by simple uniaxial tension. Substantial material thickness alone may provide sufficient constraint to prevent lateral contractions. Thus, structural details that have proved satisfactory in long usage and service may not necessarily have adequate ductile characteristics if material dimensions are proportionately increased to a large degree.

A complete fracture-safe analysis requires proper attention to the role of discontinuities. For many classes of structures, including ships, bridges, and pressure vessels, experience with specific designs, materials, and fabrication procedures has established a satisfactory correlation between Charpy V-notch test standards

12. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, pp. 147–148.

13. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, p. 148.

14. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, p. 155. For information on fracture toughness, see Chapter 6, "Test Methods for Evaluating Welded Joints," Vol. 1 of the *Welding Handbook*, 9th ed., Miami: American Welding Society; and Barsom, J. M., and S. T. Rolfe, eds., 1999, *Fracture and Fatigue Control in Structures: Applications of Fracture Mechanics*, 3rd ed., West Conshohocken, Pennsylvania: American Society for Testing and Materials.

for base and weld metals and acceptable service. The challenge is to ensure the soundness and integrity of a new design. Fracture mechanics analyses are employed to guard against the effects of common weld discontinuities. As it is widely recognized that welded joints usually contain some discontinuities, designers using welded joints in their plans are faced with a dilemma. Although they aim to design joints that are entirely free of discontinuities, this goal is not realistic. The practical approach is to place a reasonable limit on those discontinuities that are bound to be present. Consequently, the challenge consists of determining the types and the extent of discontinuities that are acceptable.

While conventional toughness testing procedures cannot directly address this challenge, fracture mechanics tests, where applicable, specifically define the relationship between flaw size transverse to the stress field and fracture stress for a given base metal or weld joint. Thus, these tests permit a direct estimate of acceptable flaw sizes for different geometrical configurations and operating conditions. Fracture mechanics can establish the minimum or critical crack-like flaw size that will initiate unstable crack propagation under tensile stress.

It should be noted, however, that in members subject to cyclic loading or corrosion, or both, cracks might initiate at stress raisers that are considered acceptable discontinuities. These small cracks could grow by stable crack extension with each application of tensile stress until the crack reaches the critical size. For such conditions, information relative to crack growth rate is essential to the establishment of acceptance criteria and continuing inspection frequencies.

Low-Temperature Behavior

As pressure vessels and other welded products are sometimes expected to operate at low (below 32°F [0°C]) temperatures, weldment designers must consider the properties exhibited by metals at these low temperatures. Very low temperatures are involved in cryogenic service, which entails the storage and use of liquefied industrial gases such as oxygen and nitrogen. Lowering the temperature of a metal profoundly affects its fracture characteristics, particularly if the metal possesses a body-centered-cubic crystalline structure (carbon steel, for example).¹⁵

Strength, ductility, and other properties change in all metals and alloys as the temperature decreases. The modulus of elasticity rises, for instance. As a rule, the tensile and yield strengths of all metals and alloys increase as the temperature is lowered.

Though the ductility of most metals and alloys tends to decrease as the temperature is lowered, some metals

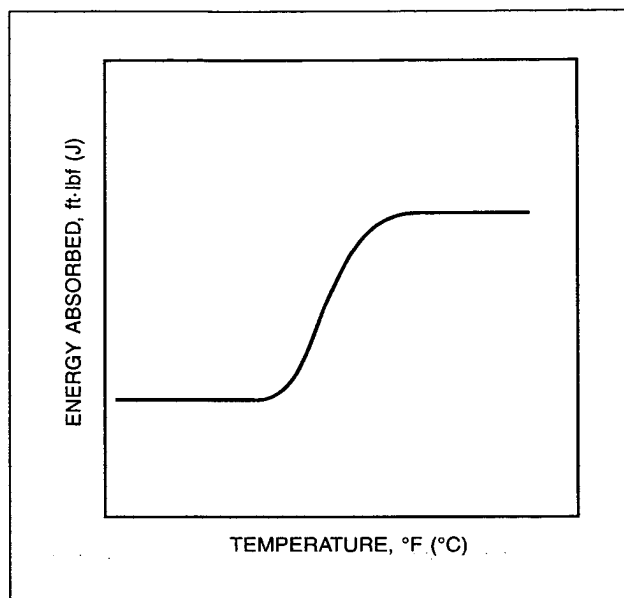


Figure 3—Typical Fracture Toughness Transition Curve

and alloys retain considerable ductility at very low temperatures. As discussed in the previous section, fracture toughness is typically a function of temperature. Figure 3 presents a transition curve that shows this relationship. At higher and lower temperatures, the fracture toughness is fairly constant. However, between these two plateaus, the fracture toughness decreases as the temperature decreases. This is known as the *ductile-to-brittle transition*. The suitability of metals for low temperature service is judged by testing.

The principal factors that determine the low-temperature behavior of a metal during mechanical testing are (1) crystal structure, (2) chemical composition, (3) the size and shape of the test specimen, (4) the conditions of manufacture and heat treatment, and (5) the rate of loading.

The most common specimen used for low-temperature testing is the Charpy V-notch impact specimen. The Charpy V-notch impact strengths for five common metals are listed in Table 3.

Iron and steel suffer a considerable reduction in impact strength at low temperatures. The addition of alloying elements to steel, especially nickel and manganese, can substantially improve fracture toughness at low temperatures, while increased carbon and phosphorus can greatly decrease low-temperature fracture toughness.

15. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, pp. 218–219.

Table 3
Typical Notch-Bar Impact Strengths of Metals Tested at Low Temperatures

Temperature, °F (°C)	Charpy V-Notch Impact Strength, ft · lb (J)									
	Aluminum*		Copper*		Nickel*		Iron†		Titanium‡	
	ft lb	J	ft lb	J	ft lb	J	ft lb	J	ft lb	J
75 (room temperature) (25)	20	27	40	54	90	122	75	102	15	20
0 (−18)	20	27	42	57	92	125	30	41	13	18
−100 (−73)	22	30	44	60	93	126	2	3	11	15
−200 (−129)	24	33	46	63	94	128	1	1	9	12
−320 (−320)	27	37	50	68	95	129	1	1	7	10

* Face-centered-cubic crystal structure.

† Body-centered-cubic crystal structure.

‡ Hexagonal close-packed crystal structure.

Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Table 3.6.

Elevated-Temperature Behavior

The performance of a metal in service at an elevated temperature (i.e., 75°F [25°C] to 500°F [260°C]) is governed by other factors in addition to strength and ductility. Time becomes a factor because at high temperatures metals undergo the phenomenon known as *creep*, defined as “deformation with time at service temperature.”¹⁶ In other words, the section under stress continues to deform even if the load is maintained constant. The rate at which a metal creeps increases rapidly with increasing temperature and increasing load. Thus, the time over which a metal under load deforms too much to be usable can vary from many years at a slightly elevated temperature to a few minutes at a temperature near the melting point.¹⁷

The creep rates of metals and alloys differ considerably. If the temperature and stress are sufficiently high, the metal will creep until rupture occurs. The term *creep rupture* is used to identify the mechanics of deformation and the failure of metals under stress at elevated temperatures.

PHYSICAL PROPERTIES

The physical properties of metals constitute an important aspect of the weldability of metals. Welding engineers must be cognizant of the fact that the success of a particular joining operation may depend on one or

more physical properties. The constants provided for metals and alloys are satisfactory for most engineering purposes.¹⁸

Only those physical properties that require consideration in the fields of weldment design and fabrication of a weldment are discussed here.¹⁹ These include thermal conductivity, melting temperature, thermal expansion and contraction, and electrical conductivity.

Thermal Conductivity

The rate at which heat is transmitted through a material by conduction is referred to as *thermal conductivity* or *thermal transmittance*. Metals are better heat conductors than nonmetals, and metals with high electrical conductivity generally have high thermal conductivity.

Metals differ considerably in their thermal conductivities. Copper and aluminum are excellent conductors, which makes these metals difficult to weld using a relatively low-temperature heat source such as an oxyacetylene flame. Conversely, the high conductivity of copper makes it a good heat sink when employed as a hold-down or backing bar.

Melting Temperature

As a rule, the higher the melting point is, the greater the amount of heat needed to effect melting. Thus, the temperature of the heat source in welding must be well

16. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, p. 242.

17. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, p. 244.

18. Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, p. 258.

19. The physical properties of metals are discussed in greater detail in Chapter 2, Vol. 1 of the *Welding Handbook*, 9th ed., Miami: American Welding Society.

above the melting point of the metal. In addition, the welding of two metals of dissimilar compositions becomes more challenging as the difference in their melting points become greater.

Thermal Expansion and Contraction

The distortion that results from welding must be considered during weldment design so that the final dimensions of the weldment are acceptable. Most metals increase in volume when heated and decrease in volume when cooled. The term *coefficient of thermal expansion* refers to the unit change in the linear dimensions of a body when its temperature is changed by one degree. Thus, this coefficient serves as an indicator of expansion and contraction in a metal subjected to increasing or decreasing temperature, respectively.

Although engineers are generally concerned with changes in length in metal components, a linear coefficient of thermal expansion is not the only design consideration. A coefficient for volume change is also important. Metals also change in volume when they are heated and cooled during welding. Thus, the greater the increase in volume and localized upsetting during heating, the more pronounced the distortion from welding.

Electrical Conductivity

Metals are relatively good conductors of electricity. However, increasing the temperature of a metal interferes with the electron flow, resulting in a decrease in electrical conductivity. Adding alloying elements to a metal and cold working also decrease conductivity. Electrical conductivity is an important variable, particularly in the resistance welding processes, inasmuch as the electrical flow is imperative to weld soundness.

CORROSION PROPERTIES

The corrosion properties of a metal determine its mode and rate of deterioration by means of a chemical or electrochemical reaction with the surrounding environment. As metals and alloys differ greatly in their corrosion resistance, this behavior merits consideration in planning and fabricating a weldment for a particular service. Designers must therefore be familiar with the behavior of welded joints under corrosive conditions.²⁰

Weld joints often display corrosion properties that differ from the remainder of the weldment. Differences may be observed between the weld metal and the base metal and sometimes between the heat-affected zone and the unaffected base metal. The surface effects pro-

duced by welding—heat tint formation and oxidation, for example—are also important factors in the corrosion behavior of the weld metal.

Welds made between dissimilar metals or with dissimilar filler metals may be subject to electrochemical corrosion. Therefore, appropriate protective coatings are required to avoid corrosion in sensitive environments.

WELDMENT DESIGN PROGRAM

A weldment design program begins with the recognition of a need. This need may be for an improvement in an existing machine or for the building of an entirely new product or structure using advanced design and fabrication techniques. In any case, many factors must be taken into account before a design is finalized. These considerations involve numerous questions and considerable research into the various areas of engineering, production, and marketing.

ANALYSIS OF EXISTING DESIGNS

When an entirely new machine or structure is to be designed, information should be obtained about similar products, including those marketed by other manufacturers or builders. If a new design is to replace an existing design, the strengths and weaknesses of the existing design should be determined. The following factors should be considered in identifying the strengths and weaknesses of existing designs:

1. Performance history of the existing products;
2. Features that should be retained, discarded, or added;
3. Any suggestions for improvements that have been made; and
4. Opinions of customers and the sales force about the existing products.

DETERMINATION OF LOAD CONDITIONS

The service conditions and requirements of a weldment that might cause the overloading of a weldment should be ascertained. As a starting point for the calculation of loads, the following guidelines may be useful:

1. Determine the torque on a shaft or revolving part from the motor horsepower and speed;

20. The types of corrosion and the corrosion testing of welds are discussed in Chapter 6, Vol. 1 of the *Welding Handbook*, 9th ed., Miami: American Welding Society.

2. Calculate the forces on members caused by the dead weight of the parts;
3. Determine the maximum load on members of a crane hoist, shovel, lift truck, or similar material handling equipment from the load required to tilt the machine;
4. Consider the force required to shear a critical pin as an indication of maximum loading on a member; and
5. Determine the desired service life and the frequency of loading (for example, designing for fatigue at lesser loads may be more critical than designing for maximum strength to resist infrequently applied maximum loads).
8. Standard rolled sections, rather than special built-up sections, should be used for economy and availability when they satisfy the need;
9. Accessibility for maintenance must be considered during the design phase; and
10. Standard, commercially available components such as index tables, way units, heads, and columns should be specified when they would serve the purpose.

In the absence of a satisfactory starting point, the designer should plan for an assumed load and adjust the design based on experience and testing.

MAJOR DESIGN FACTORS

In developing a design, designers should consider the manner in which decisions affect production operations, manufacturing costs, product performance, appearance, and customer acceptance. Many factors that are seemingly far removed from engineering considerations can become major design factors. Some of these, along with other relevant rules, are highlighted below:

1. The design should satisfy strength and stiffness requirements, but overdesigning not only constitutes a poor engineering practice but also wastes materials and labor and increases production and shipping costs;
2. Safety factors should be realistic;
3. As an attractive appearance may be necessary in areas exposed to view, the drawing or specifications should indicate those welds that must be ground or otherwise conditioned to enhance appearance;
4. Deep, symmetrical sections should be used to minimize distortion;
5. Welding the ends of beams rigidly to supports may increase strength and stiffness;
6. Rigidity may be provided by welded stiffeners, precluding the need to increase material thickness and weight;
7. Tubular sections or diagonal bracing should be used for torsion loading, as a closed tubular section is significantly more effective in resisting torsion than an open section of similar weight and proportions;

DESIGNING THE WELDMENT

Flexibility is one of the advantages of welded design, resulting in many opportunities for savings. The following are general suggestions for effective design:

1. Design for ease of material handling, inexpensive tooling, and accessibility of the joints for reliable welding;
2. Check with the shop for ideas that can contribute to cost savings;
3. Establish realistic tolerances based on end use and suitability for service, as excessively close tolerances serve no useful purpose and increase costs; and
4. Minimize the number of pieces to reduce assembly time and the amount of welding.

Workpiece Preparation

Thermal cutting, shearing, sawing, blanking, nibbling, and machining are methods used to cut blanks from stock material. The selection of the appropriate method depends on the available material and equipment and the relative costs. The quality of edges needed for good fitup and the type of edge preparation for groove welds must be kept in mind. The following points should also be considered when preparing material for welding:

1. Dimensioning of a blank may require a stock allowance for subsequent edge preparation,
2. The detail of the welded joints must be considered when laying out a blank with the intent to cut and prepare the edge for welding simultaneously,
3. Weld metal costs can be reduced for thick plate by specifying J- or U-groove preparations, and
4. Air carbon arc gouging, oxygen gouging, or chipping should be contemplated for back weld preparation.

Forming

The forming of parts can sometimes reduce the cost of a weldment by avoiding joints and machining

operations. The selection of a forming method is based on the composition of the base metal, thickness, overall dimensions, production volume, tolerances, and cost. The following suggestions may facilitate the decision-making process:

1. Corners can be created by bending or forming rather than by welding two pieces together,
2. Flanges can be bent on the plate rather than welding flanges to it,
3. A casting or forging can be used in place of a complex weldment to simplify the design and reduce manufacturing costs, and
4. A surfacing weld instead of an expensive alloy component can be used on an inexpensive component to provide wear resistance or other properties.

Cold forming reduces the ductility and increases the yield strength of metals. Heat treating the metal to restore ductility may increase or decrease the strength, depending on the alloy type. The heat produced by arc welding on a cold-formed material may also affect the mechanical properties of the base metal. The mechanical properties of the heat-affected zone of cold-formed materials may be reduced by the heat of welding. Generally, the relevant standard provides the maximum cold-forming allowances and minimum strength properties of cold-formed weldments. For instance, Section VIII of the 1998 *Boiler and Pressure Vessel Code* requires that under certain circumstances cold forming that results in extreme fiber elongation (over 5%) in carbon, low-alloy, and heat-treated steel plates must be stress relieved.²¹ It should be noted that welding in close proximity to material that has been strained 5% or more results in material with negligible notch toughness.

Weld Joint Design

Weld joint design should be selected primarily on the basis of load requirements. However, variables in design and layout can substantially affect costs. The following guidelines generally apply:

1. The joint design that requires the least amount of weld metal should generally be selected;
2. Otherwise, square-groove and partial joint penetration groove welds should be used whenever they satisfy strength and serviceability requirements;
3. Lap joint and fillet welds should be used instead of groove welds unless the lower fatigue resis-

tance of these joints is inadequate to satisfy the service requirements;

4. Double-V- or U-groove welds should be used instead of single-V- or U-groove welds on thick plates to minimize the amount of deposited weld metal and resulting distortion;
5. For corner joints in thick plates in which fillet welds are not adequate, the beveling of the members subject to through-thickness weld shrinkage strains should be considered to reduce the tendency for lamellar tearing; and
6. The assembly and joints should be designed to provide ready accessibility for welding.

Size and Amount of Weld

Overdesign is a common error, as is overwelding in production. The control of weld size begins with design, but it must be maintained during the assembly and welding operations. The following are basic guidelines regarding the control of weld size:

1. Adequate but minimum size and length should be specified for the forces to be transferred. Oversized welds may cause excessive distortion and higher residual stress without improving suitability for service; they also contribute to increased costs. The size of a fillet weld is especially important because as the fillet weld size increases, the weld metal cross-sectional area increases in proportion relative to the weld size squared;
2. For equivalent strength, a continuous fillet weld of a given size is usually less costly than a larger-sized intermittent fillet weld. Continuous fillet welds also have fewer weld terminations, which are potential sites of discontinuities;
3. An intermittent fillet weld can be used in place of a continuous fillet weld of minimum size when static load conditions do not require a continuous weld. However, it should be recognized that intermittent fillet welds should have a low allowable stress range when cyclic loading is a design consideration;
4. To derive maximum advantage from automatic welding, it may be better to use one continuous weld rather than intermittent welds;
5. Weld size should not be larger than that required for the strength of the thinner workpiece based on the load;
6. Welding of stiffeners or diaphragms should be limited to that required to prevent out-of-plane distortion of the supported components under maximum loads as well as during shipment and handling; and

21. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Committee, 1998, *1998 Boiler and Pressure Vessel Code*, New York: American Society of Mechanical Engineers (ASME).

7. The amount of welding should be kept to a minimum to limit distortion and internal stresses, thus minimizing the need for and the cost of stress relieving and straightening.

Subassemblies

In visualizing assembly procedures, designers should break the weldment into subassemblies to determine the arrangement that offers the greatest cost savings. Subassemblies offer the following advantages:

1. Two or more subassemblies can be worked on simultaneously;
2. Subassemblies usually provide better access for welding and may permit automatic welding;
3. Distortion in the finished weldment may be easier to control;
4. Large-sized welds may be deposited under lesser restraint in subassemblies, which aids in minimizing residual stresses in the completed weldment;
5. Machining of subassemblies to close tolerances and stress relieving of certain sections can be performed before final assembly, if necessary;
6. Chamber compartments can be tested for leaks and painted before final assembly;
7. In-process inspection and repair is facilitated; and
8. Handling costs tend to be much lower.

WELDING PROCEDURES

Although designers have little control of welding procedures, they can influence which procedures are used in production. The following guidelines can help to ensure the ultimate success of weldment design:

1. Backing bars increase the speed of welding when making the first pass in groove welds;
2. The use of low-hydrogen electrodes and welding processes may eliminate or reduce preheat requirements;
3. If the plates are not too thick, a joint design requiring welding from only one side should be considered to avoid repositioning or overhead welding;
4. A built-up or crown weld is generally unnecessary to obtain a full-strength joint;
5. Joints in thick sections should be welded under conditions of the least restraint, for example, prior to the installation of stiffeners; and
6. Sequencing of fitup, fixturing, and welding is particularly important for box members made of plates because after the completion of welding the correction of distortion is virtually impossible.

LAMINATIONS AND LAMELLAR TEARING

Weldment designers must understand the true significance of the residual stresses that result from the contraction of the cooling weld metal. These contractions result in strains that are in excess of yield level strains if sufficient restraint exists. The shrinkage strains provide the potential for lamellar tearing—the formation of cracks parallel to the direction of rolling in material stressed in the through-thickness direction. Lamellar tears generally initiate from flattened, low-melting-point constituents in steel (e.g., manganese sulfides).

Lamellar tears occur most often during fabrication shortly after the solidification of the weld metal. Because the strains associated with design stresses are so small (limited to less than yield point stress by code) in comparison to the weld shrinkage strains that are responsible for lamellar tearing, service loads do not initiate lamellar tearing. The detail geometry, material thickness, and weld size selected may lead to difficult or virtually impossible fabrication conditions.

In connections in which a member is welded to the outside surface of a main member, the capacity to transmit through-thickness tensile stresses is essential to the proper functioning of the joint. Laminations, which are pre-existing planes of weakness, and lamellar tears may impair this capacity.

Consideration of the phenomenon of lamellar tearing must include design aspects and welding procedures that are consistent with the properties of the base material. In connections in which lamellar tearing might be a concern, the design should provide for maximum component flexibility and minimum weld shrinkage strain.²²

The following precautions should help to minimize lamellar tearing in highly restrained welded connections:²³

1. On corner joints, the edge preparation should be on the through-thickness member, when feasible;
2. The size of the weld groove should be kept to a minimum, consistent with the design requirements;
3. Overwelding should be avoided because rather than providing conservative design it may cause the material to weaken;
4. Welds in corner and T-joints should be completed early in the fabrication process, if possible, to minimize restraint in such joints;
5. A predetermined welding sequence should be selected to minimize overall shrinkage in the most highly restrained elements;
6. The lowest-strength weld metal available, consistent with design requirements, should be used

22. For further information, see Section 2 of American Welding Society (AWS) Committee on Structural Welding, 2000, *Structural Welding Code—Steel*, AWS D1.1:2000, Miami: American Welding Society.

23. It is assumed that procedures producing low-hydrogen weld metal would be used.

- to promote straining in the weld metal rather than in the more sensitive through-thickness direction of the base metal;
7. Buttering with weld metal approximately 3/16 in. (5 mm) thick and extending beyond the limits of the joint prior to fitup has been shown by research testing to provide an area of material less susceptible to lamellar tearing at the location where the most severe strains occur. This technique has proven very effective in reducing the hazard of lamellar tearing; and
 8. Specification of a material with improved through-thickness ductility should be considered for critical connections.²⁴

In critical joint areas subject to through-thickness direction loading, ultrasonic examination should be conducted to avoid the use of a material containing pre-existing laminations and large nonmetallic inclusions. In addition, no sooner than 48 hours after the completion of welding, designers should specify postwelding ultrasonic inspection of those specific highly restrained connections that could be subject to lamellar tearing and are critical to the structural integrity. They must also consider whether minor weld flaws or base metal imperfections can be left unrepaired without jeopardizing structural integrity.

Gouging and repair welding add additional cycles of weld shrinkage to the connection and may result in the extension of existing flaws or the generation of new flaws by lamellar tearing.

CLEANING AND INSPECTION

Design specifications can affect cleaning and inspection costs. The safety requirements of the weldment determine the type and amount of inspection required. The timeliness of inspection is of paramount importance in order to maintain the orderly flow of work and correct deficiencies without interfering with subsequent operations. For example, as-welded joints that have uniform appearance are acceptable for many applications. Therefore, the surface of a weld need not be ground smooth or flush unless required for another reason inasmuch as the smoothing of a weld is an additional operation.

Undesirable overwelding should be noted during inspection because it can be costly and it contributes to distortion. Corrective action should be directed at work in progress rather than at completed weldments. The type of nondestructive inspection to be used on weld-

ments must be capable of detecting the types and sizes of weld discontinuities that are to be evaluated for acceptability.²⁵

WELDED DESIGN CONSIDERATIONS

The performance of any member of a structure depends on the properties of the material and the characteristics of the section. If a design is based on the efficient use of these properties, the weldment should function well and conserve materials. Engineers assigned to design welded members must possess the knowledge to select the most efficient structural section and determine the required dimensions. They must also know when to use stiffeners and how to size and place them when used.

The mathematical equations utilized to calculate forces and their effects on sections and to determine the sections needed to resist such forces appear quite forbidding to the novice. With the proper approach, however, it is possible to simplify the design analysis and the application of these equations. In fact, as is explained below, it is often possible to make correct design decisions merely by examining one or two factors in an equation, precluding tedious calculations. As a whole, the mathematics used in design for welding is no more complex than that used in other engineering fields.

APPROACH TO WELD REDESIGN

From the standpoint of performance and ultimate production economics, the redesign of the machine or structure as a whole is preferable. The designer is then unrestricted by the previous design and may be able to reduce the number of pieces, the amount of material used, and the labor for assembly. A better, lower-cost product is realized immediately. When the adjustment to changes in production procedures is complete, the company is in a position to benefit more fully from welded design technology.

However, considerations other than the engineer's wishes may prevail. Available capital and personnel considerations often limit a company's capabilities when changing to welded design. For example, when a machine is to be converted from a casting to a welded design, management may favor the redesign of one or more components over the use of weldments and the conversion of the design over a period of years to an all-

24. Improved quality steel does not eliminate weld shrinkage and does not necessarily prevent lamellar tearing in highly restrained joints. Thus, this material should not be specified in the absence of comprehensive design and fabrication considerations.

25. For further information, refer to the Chapter 14, "Inspection and Nondestructive Examination," Vol. 1 of the *Welding Handbook*, 9th ed., Miami: American Welding Society.

welded product. Gradual conversion avoids the obsolescence of facilities and skills and limits the requirement for new equipment. Supplementing these considerations is the need to maintain a smooth production flow and to test the production and market value of the conversion as it is made step by step.

REDESIGN VERSUS NEW DESIGN

A redesign of a product may be based on the previous design or solely on loading considerations. Following a previous design has the advantages of offering a “safe” starting point if the old design is known to have performed satisfactorily. This approach has disadvantages, however, in that it stifles creative thinking with respect to the development of an entirely new concept to solve the basic problem. Little demand is made on the ingenuity of the designer when the welded design is modeled on the previous product.

A design based on the loading requires designers to analyze what is needed and propose configurations and materials that best satisfy the identified needs. They must know or ascertain the type and amount of load, the values for stress allowables in a strength design, or the deflection allowables in a stiffness design.

STRUCTURAL SAFETY CONSIDERATIONS

The production of a safe welded structure depends upon a combination of proficient design practices, skilled fabrication, and sound construction methods. In design, the selection of a safety factor and the appropriate analytical procedures requires experience and sound engineering judgement. Deterioration as a result of corrosion or other service conditions during the life of the structure, variations in material properties, potential imperfections in materials and welded joints, and many other factors also need consideration.

A rational approach to structural safety is a statistical evaluation of the random nature of all the variables that determine the strength of a structure as well as the variables that may cause it to fail. From these data, the probability of failure can be evaluated and the probability of occurrence kept at a safe level for the application, taking into considering the risk of injury, death, property damage, and unsatisfactory service performance. The choice of materials and safe stress levels in members may not produce the most economical structure. However, safety must take precedence over cost savings whenever a question of which should govern arises.

When designers attempt a new design or structural concept, great skill and care as well as detailed stress analyses are required. Laboratory tests of models or sections of prototype structures should be used to verify new designs.

DESIGNING FOR STRENGTH AND STIFFNESS

A design may require strength only or strength and stiffness to support the load. All designs must have sufficient strength to prevent the members from failing by fracture or yielding when subjected to normal operating loads or reasonable overloads. Strength designs are common in road machinery, farm implements, motor brackets, and various types of structures. If a weldment design is based on calculated loading, design equations for strength are used to dimension the members. Tables of equivalent sections or nomographs can be used to determine required dimensions for strength and stiffness.

In weldments such as machine tools, stiffness as well as strength is important because excessive deflection under load results in a lack of precision in the product. A design based on stiffness also requires the use of design equations for sizing members.

Some parts of a weldment serve their design function without being subjected to loads much greater than their own weight, or dead loads. Typical examples of such members are fenders, dust shields, safety guards, cover plates for access holes, and enclosures included for aesthetic purposes. Only casual attention to strength and stiffness is required in sizing such members.

DESIGN EQUATIONS

The design equations for strength and stiffness always contain terms representing the load, the member, the stress, and the strain or deformation. If any two of the first three terms are known, the others can be calculated. All problems of design thus reduce into one of the following:

1. Determination of the internal stress or the deformation caused by an external load on a given member,
2. Determination of the external load that may be placed on a given member for any given strength or deformation, or
3. Selection of a member to carry a given load without exceeding a specified strength or deformation.

A force causes a reaction such as tension, compression, bending, torsion, or shear stress in the member. The result is a strain measured by means of the relative displacements in the member. These include elongation, contraction, deflection, or angular twist. A useful member must be designed to carry a certain type of load within an allowable stress or deformation. In designing within the allowable limits, designers should select the most efficient material section size and section shape.

The properties of the material and those of the section determine the ability of a member to carry a given load.

The common design equations that have been developed for various conditions and member types are too numerous for inclusion here. However, several of these equations are presented below to illustrate specific design problems.²⁶

The application of design equations can be illustrated by the problem of obtaining adequate stiffness in a cantilever beam. The amount of vertical deflection at the end of the beam under a concentrated load at the end, illustrated in Figure 4, can be determined using the following equation for deflection:

$$\Delta = \frac{FL^3}{3EI} \quad (2)$$

where

- Δ = Deflection, in. (mm);
- F = Concentrated load, lbf (N);
- L = Length, in. (mm);
- E = Modulus of elasticity, psi (MPa); and
- I = Moment of inertia, in.⁴ (mm⁴).

It is normally desirable to have the least amount of deflection. Therefore, the modulus of elasticity and moment of inertia values should be as large as possible. The commonly used structural metal that has the highest modulus of elasticity is steel, with a value of approximately 30×10^6 psi (200,000 MPa).

The other factor is the moment of inertia of a cross section. The moment of inertia of a member is a function of the geometry of the member. The beam must have a cross section with a moment of inertia about the horizontal axis large enough to limit the deflection to a permissible value. A section with an adequate in-plane moment of inertia will satisfy the vertical deflection requirement, whatever the shape of the section may be. However, the out-of-plane stability of the beam may also need consideration, especially if the forces are transverse to the principal axis or if torsion is involved. A decision must then be made as to which shape should be used for the best design at the lowest cost.

Types of Loading

The five basic types of loading are tension, compression, bending, shear, and torsion. When one or more

26. The properties of sections for standard structural shapes are given in American Institute of Steel Construction (AISC), 1994, *Manual of Steel Construction: Load and Resistance Factor Design*, Vols. 1 and 2, Chicago: American Institute of Steel Construction; and the Aluminum Association, 1994, *Aluminum Design Manual: Specifications and Guidelines for Aluminum Structures*, Washington, D.C.: Aluminum Association.

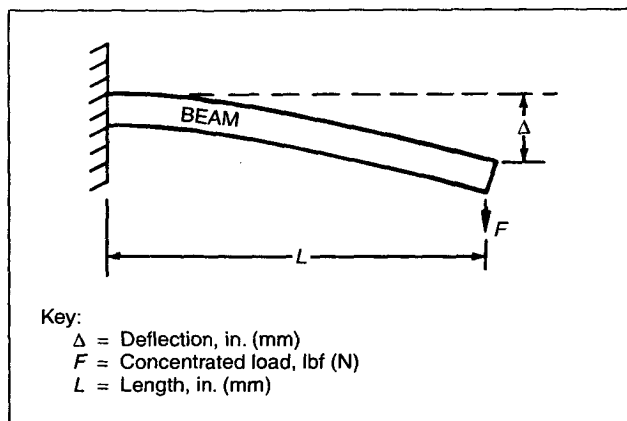


Figure 4—Deflection (Δ) of a Cantilever Beam Under a Concentrated Load, F

types of loading are applied to a member, they induce stress in addition to any residual stresses that are present.

The applied load results in stress within the member, and the magnitude of the strain is governed by the modulus of elasticity of the metal. Some deformation always takes place in a member when the load is applied because the associated stress inevitably causes strain.

Tension. Pure tensile loading is generally the simplest type of loading from a design and analysis perspective. Axial tensile loads cause axial strains and elongation. In the case of tensile loading, the principal design requirement is an adequate gross and net cross-sectional area to carry the load.

Compression. A compressive load may require appropriate design provisions to prevent buckling. Few compression members fail by crushing or by exceeding the ultimate compressive strength of the material. If a straight compression member such as the column represented in Figure 5(A) is loaded through its center of gravity, the resulting stresses are simple axial compressive stresses. If the member is a slender column, it will start to bow laterally as a result of small imperfections and accidental eccentricity of loading. This movement is shown in Figure 5(B). As a result of bowing, the central portion of the column becomes increasingly eccentric to the axis of the force and causes a bending moment on the column, as shown in Figure 5(C).

Under a steady load, the column will remain stable under the combined effect of the axial stress and the bending moment. However, with increasing load and the associated curvature, depicted in Figure 5(D), a

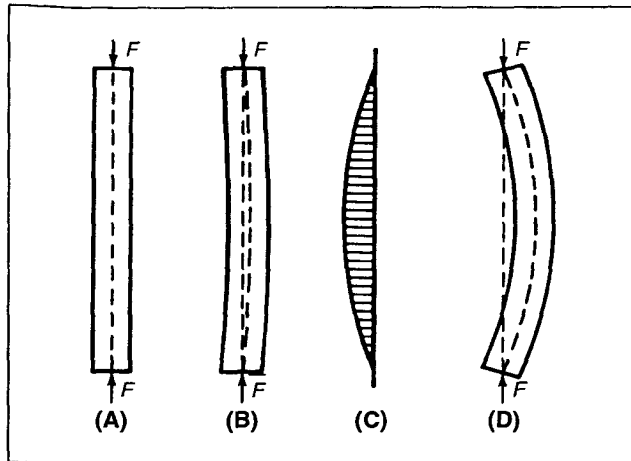


Figure 5—Schematic Representation of Compressive Load Force (F): (A) Straight Column Under Compressive Load; (B) Column Defects Laterally with Increasing Load; (C) Bending Moment Diagram; and (D) Increased Deflection with Higher Loading

critical point will be reached at which the column will buckle and fail. The presence of residual stresses developed during manufacturing may also reduce the failure load. As a column deflects under load, a bending moment can develop in restrained end connections.

Two properties of a column are important for the calculation of compressive strength—the cross-sectional area, A , and the radius of gyration, r , which is the distance from the neutral axis of the section to an imaginary line in the cross section about which the entire area of the section could be concentrated and still have the same moment of inertia about the neutral axis of the section. The area is multiplied by the critical buckling stress, σ_{cr} , to arrive at the compressive load that the column can support in the absence of buckling. The radius of gyration indicates, to a certain extent, the column's ability to resist buckling. The equation for the radius of gyration is as follows:

$$r = \sqrt{\frac{I}{A}} \quad (3)$$

where

- r = Radius of gyration, in. (mm);
- I = Moment of inertia about the neutral axis, in.⁴ (mm⁴); and
- A = Cross-sectional area of the member, in.² (mm²).

Inasmuch as the worst condition is always of concern in design work, it is necessary to use the smallest radius of gyration relative to the unbraced length. Thus, an overloaded unbraced wide-flange column section will always buckle, as shown in Figure 5(D). However, if the column is braced at the mid-length to prevent buckling, the column could buckle toward a flange. The critical slenderness ratio of a column is the larger of ratios L_x/r_x or L_y/r_y , where L_x and L_y are the distances between braced points, and r_x and r_y are the radii of gyration about the x and y axis, respectively.

The design of a long compression member is carried out by trial and error. A trial section is selected, and the cross-sectional area and the least radius of gyration are determined. A suitable column table²⁷ is used to provide the critical buckling stress, σ_{cr} , for the column slenderness ratio, KL/r . This stress is then multiplied by the cross-sectional area, A , to find the buckling strength of the column and, when a suitable safety or resistance factor is chosen, the design load the column can carry. If this value is less than the load to be applied, the design must be changed to incorporate a larger section and calculated again. Table 4 presents the AISC load and resistance factor design (LRFD) column equations.

**Table 4
Critical Axial Compressive Stress Equations**

For $\lambda_c \leq 1.5$:

$$\sigma_{cr} = \left(0.658^{\lambda_c^2} \right) \sigma_y \quad (1)$$

For $\lambda_c > 1.5$:

$$\sigma_{cr} = \left(\frac{0.877}{\lambda_c^2} \right) \sigma_y \quad (2)$$

where

λ_c = Column slenderness parameter, which equals

$$\left(\frac{1}{\pi} \sqrt{\frac{\sigma_y}{E}} \right) \frac{KL}{r};$$

- σ_{cr} = Critical compressive stress, ksi (MPa);
- K = Effective length factor (ratio of the length of an equivalent pinned ended member to the length of the actual member);
- L = Unbraced length of the member, in. (mm);
- r = Radius of gyration, in. (mm);
- E = Modulus of elasticity, ksi (MPa); and
- σ_y = Yield strength, ksi (MPa).

Source: American Institute of Steel Construction (AISC), 1993, *LRFD Specification for Structural Steel Buildings*, Chicago: American Institute of Steel Construction, Section E2.

27. See American Institute of Steel Construction (AISC), 1994, *Manual of Steel Construction: Load and Resistance Factor Design*, Vols. 1 and 2, Chicago: American Institute of Steel Construction.

Bending. Figure 6 illustrates the bending of a member under uniform loading. Loads may also be nonuniform or concentrated at specific locations on the beam. When a member is loaded in bending within the elastic range, the bending stresses total zero along the neutral axis and increase linearly to a maximum value at the outer fibers.

The bending stress at any distance from the neutral axis in the cross section of a straight beam is shown in Figure 7.

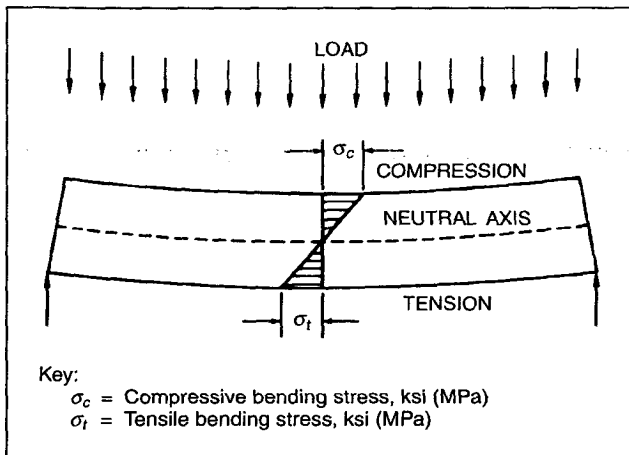


Figure 6—Bending of a Beam with Uniform Loading

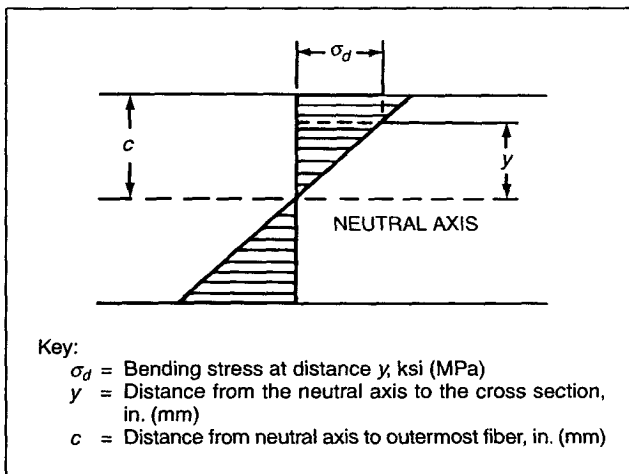


Figure 7—Bending Stress (σ_d) at Any Point (y) in the Cross Section of a Straight Beam Elastically Loaded

The bending stress can be found with the following expression:

$$\sigma = \frac{My}{I} \quad (4)$$

where

σ = Bending stress (tension or compression), ksi (MPa);

M = Bending moment at the point of interest, kip inches (kips in.) (kilonewton millimeters [kN mm]);

y = Distance from the neutral axis of bending to a specific distance, "y," in. (mm); and

I = Moment of inertia about the neutral axis of bending, in.⁴ (mm⁴).

In most cases, the maximum bending stress is of greatest interest. In this case, the equation becomes:

$$\sigma = \frac{Mc}{I} = \frac{M}{S} \quad (5)$$

where

σ = Bending stress (tension or compression), ksi (MPa);

M = Bending moment at the point of interest, kips in. (kN mm);

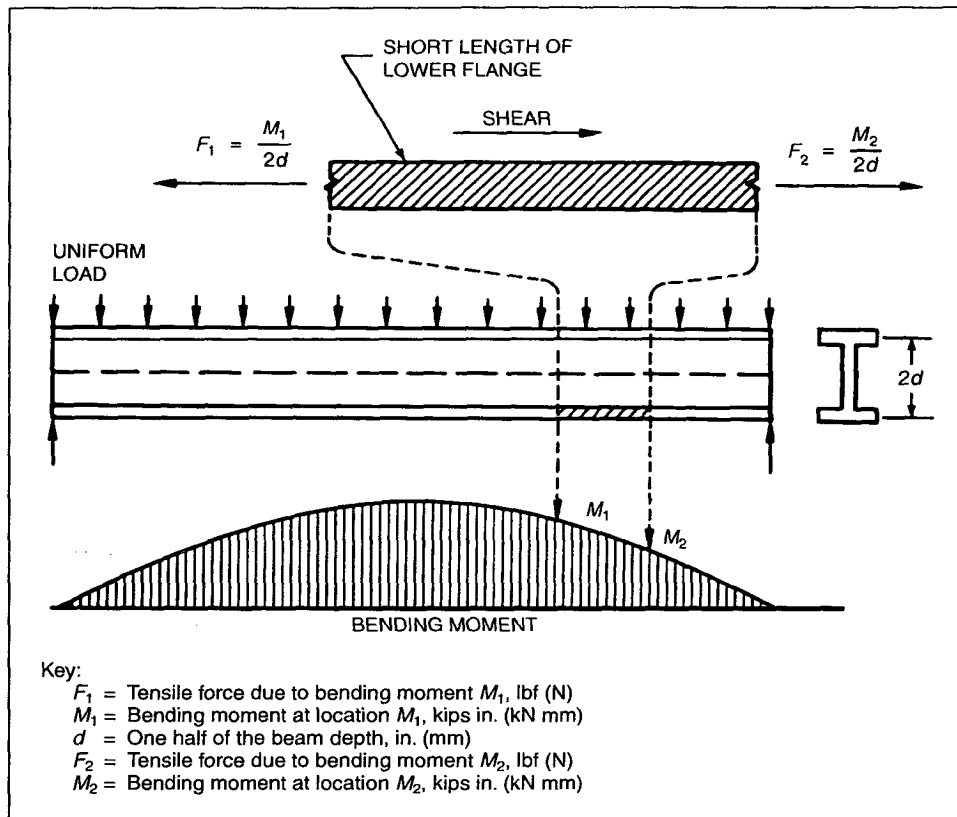
c = Distance from the neutral axis of bending to the outermost fibers, in. (mm); and

S = Section modulus (I/c), in.³ (mm³).

As the bending moment decreases along the length of a simply supported beam toward the ends, the bending stresses (tension and compression) in the beam also decrease. If a beam has the shape of an I-section, the bending stress in the flange decreases as the end of the beam is approached. If a short length of the tension flange within the beam is considered, a difference exists between tensile forces²⁸ F_1 and F_2 at the two locations in the flange, as shown in Figure 8.

The decrease in the tensile force in the flange results in a corresponding shearing force between the flange and the web. This shearing force must be transmitted by the fillet welds that join the two together. The same reaction takes place in the upper flange, which is in compression. The change in tensile force in the lower flange transfers as shear through the web to the upper flange and is equal to the change in compression in that flange.

28. The tensile force, F , is the product of the tensile stress, σ , and the flange cross-sectional area, A .



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-10.

Figure 8—Approximate Tensile Forces (F_1 and F_2) on a Section of the Lower Flange of a Loaded Beam

A common bending problem in machinery design involves the deflection of beams. The beam equations found in many engineering handbooks are useful for quick approximations of deflections of common types of beams in which the span is large compared to the beam depth. An example of a typical beam and applicable equations are presented in Figure 9.

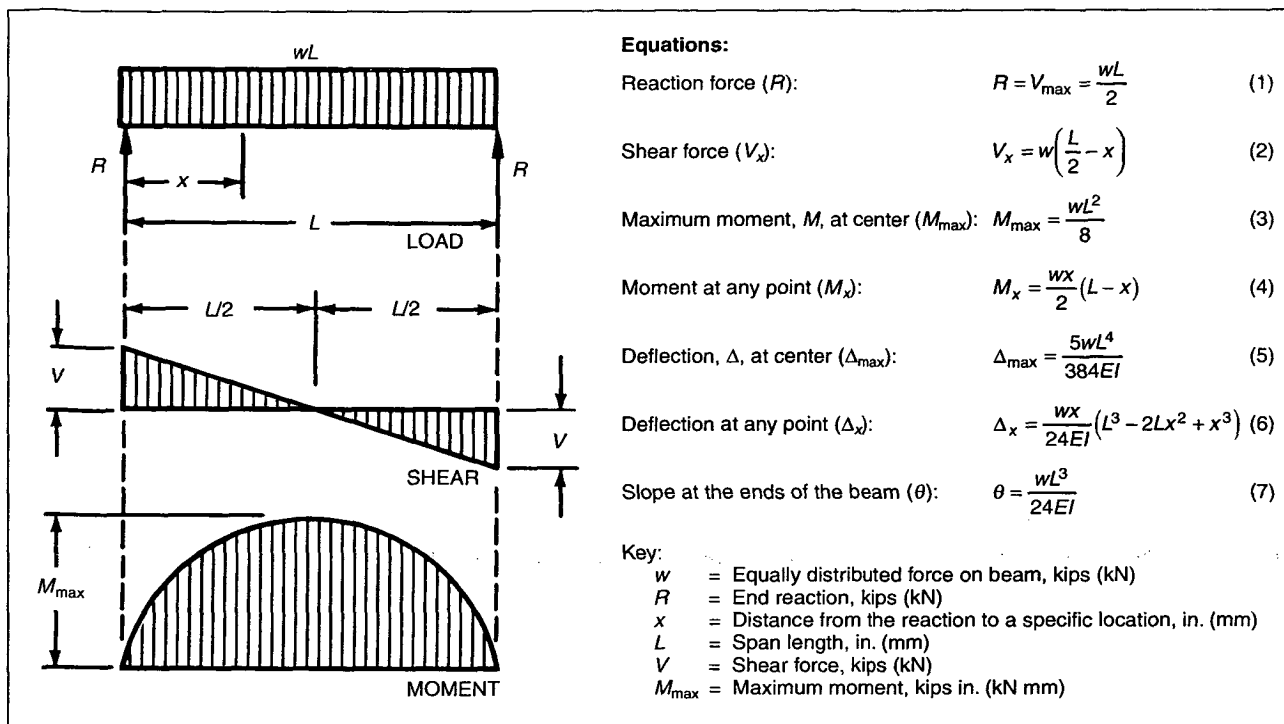
Beams that are supported or loaded in different ways have other applicable design equations. To meet stiffness requirements, the beam should have as large a moment of inertia as practical.

Information concerning the design of a compression member or column may also apply to the compression flange of a beam. The lateral buckling resistance of the compression flange must also be considered. It should have adequate width and thickness to resist local buckling. Moreover, it should be properly supported to pre-

vent twisting or lateral movement and subjected to compressive stresses within allowable limits.

Shear. Shear forces in the web of a beam under load are illustrated in Figure 10. The forces are both horizontal and vertical. They create diagonal tensile and diagonal compressive stresses.

The shear capacity of a member of either an I- or a box-beam cross section is dependent upon the slenderness proportion of the web or webs. For virtually all hot-rolled beams and welded beams of similar proportions in which the web slenderness ratio (h/t) is less than 260, the vertical shear load is resisted by pure beam shear, and lateral buckling does not occur. This is true for a level of loading well above that at which unacceptable deflections will develop. Thus, the design is configured to maintain the shear stress on the gross area of



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-15.

Figure 9—Equations for a Simply Supported Beam with a Uniformly Distributed Load on the Beam Span

the web below the nominal shear strength of $0.6 \sigma_y$ by a factor of safety or a resistance factor to prevent yielding in shear.

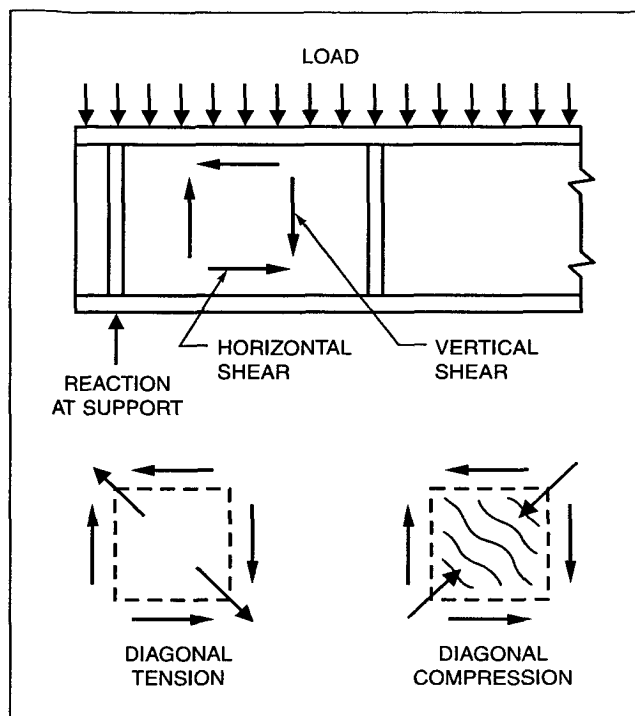
In plate girders with slender webs, shear is resisted by plane beam shear up to a level of stress that will cause shear buckling. However, webs subject to shear stress that are stiffened by transverse stiffeners have considerable postbuckling strength. Current design specifications take this strength into account. After buckling occurs, the web resists larger shear loads with a combination of beam shear and diagonal tension in the panels between stiffeners. If the length-to-depth ratio of the panel is approximately 3 or more, the direction of the diagonal tension becomes too near to the horizontal for it to be effective in providing significant postbuckling strength, and the shear strength is limited to beam shear strength.

The onset of diagonal compression buckling in a web panel has negligible structural significance. With properly proportioned transverse stiffeners, the web contin-

ues to resist higher levels of shear loading up to the point at which diagonal tension yielding occurs.²⁹

Several practical considerations independent of maximum strength may govern a design. For architectural reasons, especially in exposed fascia girders, the waviness of the web caused by controlled compression buckles may be deemed unsightly. In plate girders subject to cyclic loading to a level that would initiate web shear buckling, each application of the critical load causes an "oil canning" or "breathing" action of the web panels. This action causes out-of-plane bending stresses at the toes of web-to-flange fillet welds and the stiffener welds. These cyclic stresses eventually initiate fatigue cracking. For these cases, web stresses should be limited

29. Design criteria to achieve full maximum strength from beam shear and tension field action of the plate and box girder webs may be found in Volume I, Section 6, Chapter G of American Institute of Steel Construction (AISC), 1989, *Manual of Steel Construction: Allowable Stress Design*, Vols. 1 and 2, Chicago: American Institute of Steel Construction.



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-11.

Figure 10—Shear Forces in the Web of a Beam Under Uniform Load

to the beam shear strength values that preclude shear buckling.

In the case of a beam fabricated by welding, the shear load per unit of length on the welds joining the flanges of the beam to the web can be calculated by means of the following equation:

$$v_s = \frac{Vay}{In} \quad (6)$$

where

- v_s = Shear load per unit length of weld, kip/in. (kN/mm);
- V = External shear force on the member at this location, kip (kN);
- a = Cross-sectional area of the flange, in.² (mm²);
- y = Distance between the center of gravity of the flange and the neutral axis of bending of the whole section, in. (mm);

- I = Moment of inertia of the whole section about the neutral axis of bending, in.⁴ (mm⁴); and
- n = Number of welds used to attach the web to the flange.

The required weld size can then be determined from the value of v_s .

Torsion. Torsion creates greater design challenges for bases and frames than for other machine members. A machine with a rotating unit may subject the base to torsional loading. This is evidenced by the lifting of one corner of the base if the base is not anchored to the floor.

If torsion is a problem, closed tubular sections or diagonal bracing should be used, as shown in Figure 11. Closed tubular sections are as much as 1000 times better at resisting torsion than comparable open sections. Closed members can easily be made from channel or I-sections by intermittently welding flat plates to the toes of the rolled sections. The torsion effect on the perimeter of an existing frame may be eliminated or the frame may be stiffened for torsion by adding cross bracing. Torsion problems in structures can be avoided by the judicious arrangement of members to transmit loads by direct stresses or bending moments.

Torsional Resistance. The torsional resistance of a flat strip or open section (I-beam or channel) is very low. The torsional resistance of a solid rectangular section having a width of several times the thickness may be approximated by the following expression:³⁰

$$R = \frac{bt^3}{3} \quad (7)$$

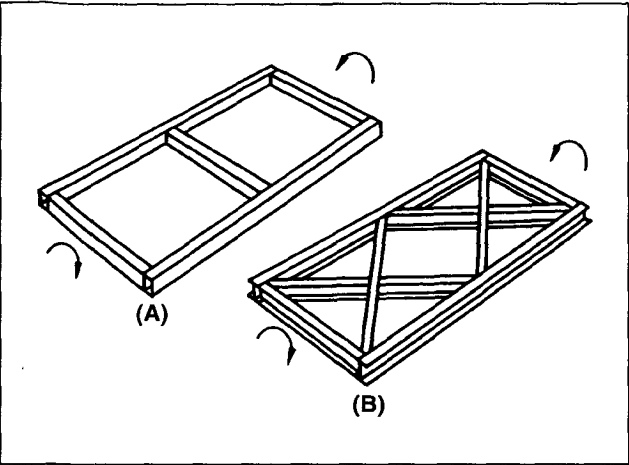
where

- R = Torsional resistance, in.⁴ (mm⁴);
- b = Width of the section, in. (mm); and
- t = Thickness of the section, in. (mm).

The unit angular twist, θ , is equal to the total angular twist divided by the length, L , of the member. The total angular twist (rotation) of a member can be estimated by the following equation:

$$\theta = \frac{TL}{GR} \quad (8)$$

30. Serberg, P. A., and C. J. Carter, 1996, *Torsional Analysis of Structural Steel Members*, Chicago: American Institute of Steel Construction.



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-13.

Figure 11—Application of (A) Closed Tubular Sections or (B) Open Structures with Diagonal Bracing to Resist Torsion

where

- θ = Angle of twist, radians;
- T = Torque, kips in. (kN mm);
- L = Length of the member, in. (mm);
- G = Modulus of elasticity in shear, ksi (MPa);
- R = Torsional resistance, in.⁴ (mm⁴).

The torsional resistance of an open structural member such as an I-beam or a channel is approximately equal to the sum of the torsional resistances of the individual flat sections into which the member can be divided. This is illustrated in Table 5, which lists the actual and calculated angle of twist of a flat strip and an I-shape made up of three of the flat strips. The applied torque is the same for both sections.

Torsional resistance increases markedly with closed cross sections, such as circular or rectangular tubing. Consequently, the angular twist is greatly reduced because it varies inversely with torsional resistance. The torsional resistance, R , of any closed box shape enclosing only one cell can be estimated by the following procedure using the equation presented in Figure 12. A dotted line is drawn through the mid-thickness around the section, as shown. The area, A , is enclosed by the dot-dash lines. The cross section of the member is divided into convenient lengths, L_n , having thicknesses t_n . The ratios of these individual lengths to their corresponding thicknesses are then determined.

Table 5
Calculated and Actual Angle of Twist

	Angle of Twist, Degrees	
	Strip*	I-Section†
Calculated using torsional resistance (R)	21.8	7.3
Actual twist	22	9.5

* 0.055 in. by 2 in. (1.4 mm by 50.8 mm).
† Made of three of the strips.

Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Table 2-3.

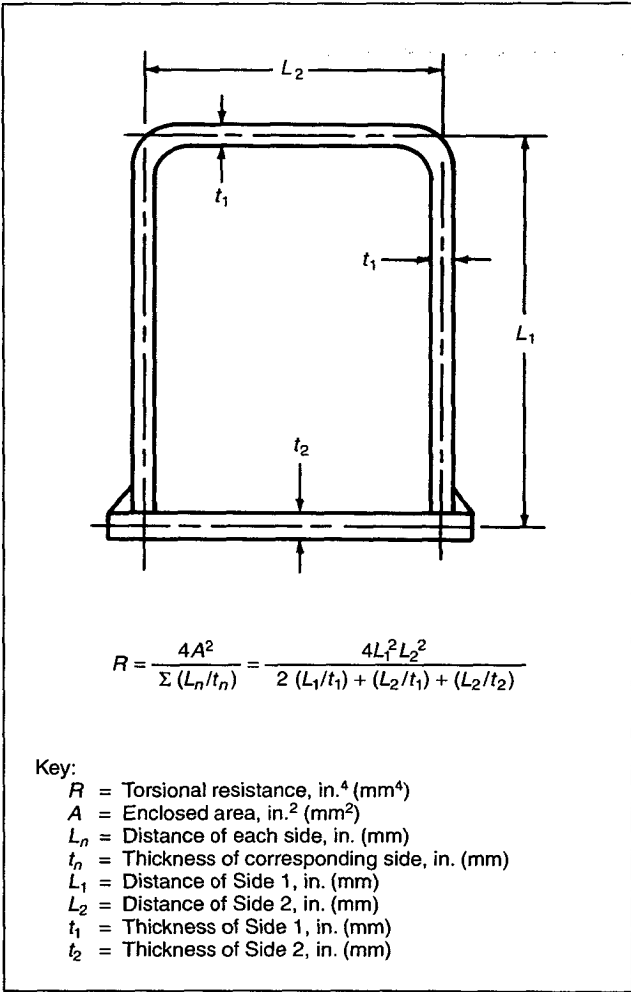


Figure 12—Torsional Resistance, R , of a Closed Box Section

The torsional resistance can then be obtained using the following equation:

$$R = \frac{4A^2}{\sum \left(\frac{L_n}{t_n} \right)} \quad (9)$$

where

- R = Torsional resistance, in.⁴ (mm⁴);
- A = Enclosed area, in.² (mm²);
- L_n = Distance of each side, in. (mm); and
- t_n = Thickness of corresponding side, in. (mm).

The maximum shear stress in a rectangular section under torsion occurs on the surface at the center of the long side. When the unit angular twist is known, the following expression is used to find the maximum shear stress at the surface of a rectangular part:

$$\tau = \theta' t G = \frac{T t}{R} \quad (10)$$

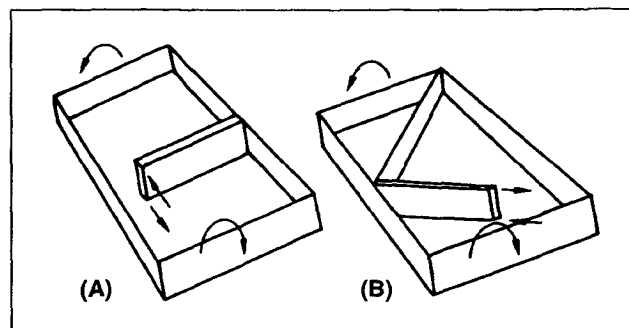
where

- τ = Maximum shear stress, ksi (MPa);
- θ' = Unit angular twist, radians/in. (radians/mm);
- G = Modulus of elasticity in shear, ksi (MPa);
- T = Applied torque, kips in. (kN mm);
- t = Thickness of the section, in. (mm); and
- R = Torsional resistance, in.⁴ (mm⁴).

This equation can be applied to a flat plate or a rectangular area of an open structural shape (channel, angle, I-beam). In the latter case, R denotes the torsional resistance of the whole structural shape.

Diagonal Bracing. Diagonal bracing is very effective in preventing the twisting of frames. A simple explanation of the effectiveness of diagonal bracing involves an understanding of the directions of the forces involved.

A flat bar of steel has little resistance to twisting, but has exceptional resistance of bending (stiffness) about its major axis. Transverse bars or open sections at 90° to the main members are not effective for increasing the torsional resistance of a frame because, as shown in Figure 13(A), they contribute only relatively low torsional resistance. However, if the bars are oriented diagonally at 45° across the frame, as in Figure 13(B), the twisting of the frame is resisted by the stiffness of the bars. To be effective, the diagonal braces must have good bending stiffness perpendicular to the plane of the frame.

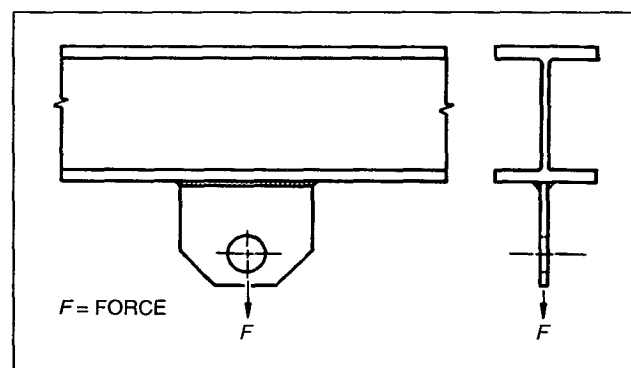


Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-24.

Figure 13—Frames Subjected to Torsion with (A) Transverse Rib Bracing and (B) Diagonal Bracing

TRANSFER OF FORCES

Loads create forces that must be transmitted through the structure to suitable places for counteraction. Designers must therefore know how to provide efficient pathways. One of the basic rules of welding design is that a force applied transversely to a member ultimately enters the portion of the section that lies parallel to the applied force. An example is a lug welded parallel to the length of a beam, as depicted in Figure 14. The portion of the beam that is parallel to the applied force, F , is the web. The force in the lug is easily transferred through the connecting welds into the web. No additional stiffeners or attaching plates are required.



Source: Adapted from The Lincoln Electric Company, 1995, *Procedure Handbook of Arc Welding*, 13th ed., Cleveland: The Lincoln Electric Company, Figure 2-27.

Figure 14—Lug Welded Parallel to the Length of a Beam; No Additional Stiffeners Are Required