

# **Welding Handbook**

**Volume Five  
Seventh Edition**

# Welding Handbook

*Seventh Edition, Volume 5*

*Engineering, Costs,  
Quality, and Safety*



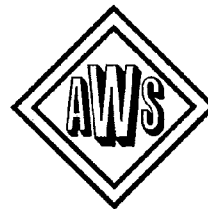
*The Five Volumes of the  
Welding Handbook, Seventh Edition*

- 1 Fundamentals of Welding
- 2 Welding Processes—  
*Arc and Gas Welding and Cutting,  
Brazing, and Soldering*
- 3 Welding Processes—  
*Resistance and Solid-State Welding  
and Other Joining Processes*
- 4 Metals and Their Weldability
- 5 Engineering, Costs,  
Quality, and Safety

# Welding Handbook

*Seventh Edition, Volume 5*

*Engineering, Costs,  
Quality, and Safety*



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## Preface

This is the fifth and final volume of the 7th Edition of the *Welding Handbook*. This volume contains revisions to several chapters that last appeared in Volume (Section) I of the 6th Edition of the Handbook. These revisions include symbols for welding, brazing, and nondestructive testing; economics and cost estimating; codes and standards; inspection; and safe practices. The volume also includes new chapters on the design for welding, fixtures and positioners, automation and control, qualification and certification, and weld quality. The information in this volume will be particularly useful to engineering as well as manufacturing and inspection personnel.

The chapter on symbols is a guide to the use of symbols, not the standard for symbols that is published separately (AWS A2.4, Symbols for Welding and Nondestructive Testing). The information on codes and standards includes currently published documents. The reader should verify the existence and latest edition of a code or standard before applying it to a product. Safe practices, the last but perhaps the most important chapter, should be referred to when planning an installation as well as during equipment installation and operation.

An index of the major subjects in all five volumes of the *Welding Handbook* precedes the volume index. It enables the reader to quickly determine the appropriate volume and chapter in which the desired information can be found.

This volume, like the others, was a voluntary effort by the Welding Handbook Committee and the Chapter Committees. The Chapter Committee Members and the Handbook Committee Member responsible for a chapter are recognized on the title page of that chapter. Other individuals also contributed in a variety of ways, particularly in chapter reviews. All participants contributed generously of their time and talent, and the American Welding Society expresses herewith its appreciation to them and to their employers for supporting the work.

The Welding Handbook Committee expresses its appreciation to Richard French, Deborah Givens, Hallock Campbell, and other AWS Staff Members for their assistance in the production of this volume.

The Welding Handbook Committee welcomes your comments on the Handbook. Please address them to the Editor, Welding Handbook, American Welding Society, 550 N.W. LeJeune Road, P.O. Box 351040, Miami, FL 33135.

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Welding Handbook Committee  
1981-1984

W.H. Kearns, *Editor*  
Welding Handbook

# 1

## Design for Welding

|                                         |    |                                             |    |
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## 1

# Design for Welding

## GENERAL CONSIDERATIONS

### OBJECTIVES

A weldment is an assembly that has the component parts joined by welding. It may be a bridge, a building frame, an automobile or truck body, a trailer hitch, a piece of machinery, or an offshore tubular structure.

The basic objectives of weldment design<sup>1</sup> are ideally to provide a weldment that

- (1) Will perform its intended functions.
- (2) Will have the required reliability and safety.
- (3) Is capable of being fabricated, inspected, transported, and placed in service at minimum total cost.

Total cost includes costs of the following:

- (1) Design
- (2) Materials
- (3) Fabrication
- (4) Erection
- (5) Inspection
- (6) Operation
- (7) Repair
- (8) Maintenance

### THE DESIGNER

Designers of weldments should have some knowledge and experience in the following processes and procedures in addition to the basic design concepts for the product or structure:

cesses and procedures in addition to the basic design concepts for the product or structure:

- (1) Cutting and shaping of metals
- (2) Assembly of components
- (3) Preparation and fabrication of welded joints

- (4) Weld acceptance criteria, inspection, mechanical testing, and evaluation

Designers also need a general knowledge of the following subjects<sup>2</sup> and their effects on the design of weldments:

- (1) Mechanical and physical properties of metals and weldments
- (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) Communication of weldment design to the shop, including the use of welding symbols
- (9) Applicable welding and safety codes and standards

Engineers who are responsible for designing welded machine parts and structures need knowl-

1. There is similarity between the design of weldments and brazements except for joint designs and joining processes. Much information presented here can be applied to brazement design. Also, see the *Welding Handbook*, Vol. 2, 7th Ed., 1978: 370-438.

2. The listed subjects are covered in this and the other four volumes of the *Welding Handbook*, 7th Edition.

edge of several areas related to weldments including the following:

- (1) Efficient use of steel, aluminum, and other metals in weldments.
- (2) Design for appropriate stiffness or flexibility in welded beams and other structural members.
- (3) Design for torsional resistance.
- (4) Effects of thermal strains induced by welding in the presence of restraints.
- (5) Effects of stresses induced by welding in combination with design stresses.
- (6) Practical considerations of welding and selection of proper joint designs for the application.

One common mistake in the design of weldments is copying the over-all shape and appearance of a casting or other form that is to be replaced by a weldment. The designer should be aware that weldments are different from castings

or forgings and can look different. There is no advantage in shaping a weldment with protrusions, separate legs, brackets, and housings that are used on castings. A weldment should have a shape appropriate for the intended function.

When a change is made from a casting to a weldment, both appearance and function may be improved because weldment design generally involves a more conservative and strategic use of materials. The motivating force for such a change is a desire to decrease production cost by fabricating the machine, part, or structure more economically. Cost, therefore, must be taken into consideration at every step in the design program. The designer must consider not only the obvious elements entering into production costs but also all incidentals from the selection of materials and methods of fabrication to the final inspection of the finished product and preparation for shipment.

## PROPERTIES OF METALS

### STRUCTURE SENSITIVITY OF PROPERTIES

The properties of metals can be divided into three general groups, (1) mechanical properties, (2) physical properties, and (3) corrosion properties. Other groups could be added, such as optical properties and nuclear properties. Table 1.1 provides a list of the properties of metals, but not all are discussed herein. It should be noted that the specific properties listed under each general heading are divided into *structure-insensitive* properties and *structure-sensitive* properties. This separation in properties is commonly made by most textbooks on metals to emphasize the consideration that should be given to reported property values.

Structure-insensitive properties are well defined properties of a metal. They do not vary from one piece of metal to another of the same kind. This is true, at least for most engineering purposes, and is verified by the data obtained

from standard engineering tests. The structure-insensitive properties often can be calculated or rationalized by consideration of the chemical composition and the crystallographic structure of the metal.<sup>3</sup> These properties (Table 1.1) commonly are listed in handbooks as constants for the particular metals. Seldom is any mention made of the size or condition of the sample upon which the determination was made.

Structure-sensitive properties, on the other hand, are dependent upon not only chemical composition and crystallographic structure, but also the microstructural details that are 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. Therefore, different

3. General and welding metallurgy of metals is covered in the *Welding Handbook*, Vol. 1, 7th Ed., 1976: 100-151.

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| Table 1.1<br>Properties of metals |                                                                                                                                                                                                                                                          |                                                                                                                                                                                |
|-----------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| General groups                    | Structure-insensitive properties                                                                                                                                                                                                                         | Structure-sensitive properties                                                                                                                                                 |
| Mechanical                        | Elastic moduli                                                                                                                                                                                                                                           | Ultimate strength<br>Yield strength<br>Fatigue strength<br>Impact strength<br>Hardness<br>Ductility<br>Elastic limit<br>Damping capacity<br>Creep strength<br>Rupture strength |
| Physical                          | Thermal expansion<br>Thermal conductivity<br>Melting point<br>Specific heat<br>Emissivity<br>Thermal evaporation rate<br>Density<br>Vapor pressure<br>Electrical conductivity<br>Thermoelectric properties<br>Magnetic properties<br>Thermionic emission | Ferromagnetic properties                                                                                                                                                       |
| Corrosion                         | Electrochemical potential<br>Oxidation resistance                                                                                                                                                                                                        |                                                                                                                                                                                |
| Optical                           | Color<br>Reflectivity                                                                                                                                                                                                                                    |                                                                                                                                                                                |
| Nuclear                           | Radiation absorbtivity<br>Nuclear cross section<br>Wavelength of characteristic x-rays                                                                                                                                                                   |                                                                                                                                                                                |

samples of the same kind of metal or alloy will have essentially identical structure-insensitive properties, but the structure-sensitive properties are likely to vary to some degree because of differences in the treatment and preparation of the samples.

All of the mechanical properties of metals, with the exception of elastic moduli, are structure-sensitive, as listed in Table 1.1. This suggests that single values, or even a narrow range of values, published in a handbook for the strength of a particular metal or alloy must be accepted with reservation. It is not uncommon to find that

plates or bars of a metal, which represent unusual sizes or conditions of treatment, may display significant deviations in mechanical properties from those published for the metal. Even the direction in which wrought metal is tested (longitudinal, transverse, or through-thickness) may give significantly different values for strength and ductility. Although the physical and corrosion properties of metals are indicated to be structure-insensitive for the most part, it is becoming more evident that some of the values established for these properties apply only to common multi-grained metals.

## MECHANICAL PROPERTIES

Metals are the most useful material for construction because they are generally strong, tough, and ductile. This combination of properties is not often found in nonmetallic materials. Furthermore, in metals, the relative degrees of strength, toughness, and ductility can be varied individually by alloy selection or by heat treatment. Joining of metals by welding or brazing also affects their mechanical properties. The applied heat, cooling rates, filler metal addition, and metallurgical structure of the joint are some of the factors that affect mechanical properties.<sup>4</sup>

Metals not only offer many useful properties and characteristics in their mechanical behavior, but they can also develop a large number of combinations of these properties. The versatility of metals with respect to mechanical properties has encouraged the selection of the best combination of properties to facilitate fabrication and to insure good service performance. Some applications require considerable thought about base and filler metal selections and treatment, particularly where fabricating properties differ from the required service properties. To solve these selection problems, or to effect a compromise, it is necessary to examine first the governing properties and then consider their combined effect upon the design and service behavior of the weldment.

### Modulus of Elasticity

A convenient way of appraising the ability of a metal to resist elastic stretching (strain) under stress is by the ratio  $E$  between the stress and the corresponding strain. This ratio is known as *Young's modulus* or the *modulus of elasticity*. It is commonly expressed by the following formula:

$$E = \frac{\sigma}{\epsilon}$$

where

$\sigma$  = the unit stress, psi

$\epsilon$  = the unit strain, in./in.

4. The testing and evaluation of welded joints are discussed in the *Welding Handbook*, Vol. 1, 7th Ed., 1976: 154-219.

This modulus is a constant characteristic of a metal as measured in polycrystalline metals during standard tensile, compression, bending, and other engineering tests in which stress and strain are correlated. The elastic modulus is a structure-insensitive property; it is virtually unaffected by grain size, cleanliness, or condition of heat treatment. In fact, the modulus of elasticity often remains unchanged for a metal even after substantial alloying additions have been made. Table 1.2 lists the modulus of elasticity for a number of metals.

**Table 1.2**  
**Modulus of elasticity of metals**

| Metal                 | Modulus of elasticity, psi |
|-----------------------|----------------------------|
| Aluminum              | $9.0 \times 10^6$          |
| Beryllium             | 42.0                       |
| Columbium             | 15.0                       |
| Copper                | 16.0                       |
| Iron                  | 28.5                       |
| Lead                  | 2.0                        |
| Molybdenum            | 46.0                       |
| Nickel                | 30.0                       |
| Steel, carbon & alloy | 29.0                       |
| Tantalum              | 27.0                       |
| Titanium              | 16.8                       |
| Tungsten              | 59.0                       |

The elastic modulus can be used practically to indicate how much a tie rod will stretch elastically when a load is placed upon it, or how much a beam will deflect elastically when under load. A frequent use of the elastic modulus in welding, however, is to determine the level of stress created in a piece of metal when it is forced to stretch elastically for a specified amount. The stress can be determined by multiplying the strain by the elastic modulus. It is important to point out that the modulus of elasticity decreases with increasing temperature, and that the change in elastic modulus with temperature varies with different metals.

### Elastic Limit

The elastic behavior of metal reaches a limit at a level of stress called the *elastic limit*. This

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term is more a definition rather than an exact stress level because the value determined for a metal is quite structure-sensitive and dependent on strain rate. The elastic limit is the upper bound of stress where the member will return to its original dimensions when the load is released. When the elastic limit is exceeded, permanent deformation will take place in the member.

Because an engineer usually is interested in knowing the capability of a metal to carry loads without plastic deformation, several properties closely related to the elastic limit have been defined for guidance. These properties can be determined easily from a stress-strain diagram, as is commonly plotted for a tensile test, Fig. 1.1. The curve on a stress-strain diagram first proceeds as a straight line, A-A'. The slope of this line conforms to the modulus of elasticity for the metal under test. As the line proceeds upward, a point is reached where the strain exceeds the amount predicted by the earlier straight line relationship. It is difficult to state exactly where the

proportionality ends between stress and strain because the clarity and interpretation of the curve may vary. The proportional limit on the stress-strain curve in Fig. 1.1 is about 28 ksi. This is the maximum stress at which the strain remained directly proportional to stress. Some additional strain may be applied beyond the proportional limit where the metal still behaves elastically. However, the upper limit of elastic behavior is the elastic limit.

Any strain in a metal below the elastic limit is recoverable upon removal of the load. When metal is stressed beyond the elastic limit, the additional strain is plastic in nature and represents permanent deformation. As an example, if the tensile specimen depicted in Fig. 1.1 were loaded to 32 ksi ( $S_2$ ), the specimen would elongate 0.00125 in./in. of length. Upon removal of the load, the specimen would not return to its original length, but would display a permanent stretch of about 0.00015 in./in., line B-B'.

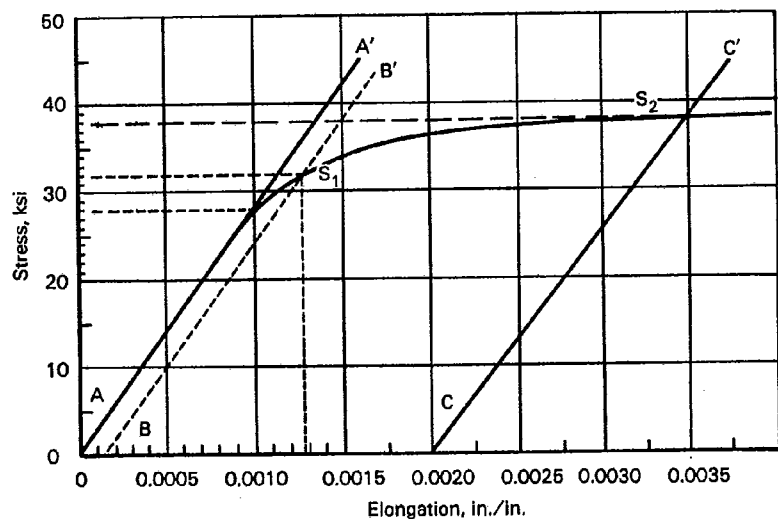


**Fig. 1.1—Typical tensile stress-strain diagram for a metal stressed beyond the limit of elastic behavior**

### Yield Strength

The *yield strength* of a metal is the stress level at which the metal exhibits a specified deviation from proportionality of stress and strain. A practicable method of determining the yield strength of a metal is illustrated in Fig. 1.1. The line C-C' is drawn parallel to the elastic line A-A' from a point on the abscissa representing 0.2 percent (0.0020 in./in.) elongation. The line C-C' will intersect the stress-strain curve at  $S_2$  where the stress level is about 38 ksi. This stress is the yield strength of the tested metal.

While a 0.2 percent offset yield strength is commonly used in engineering design, offsets of 0.1 and 0.5 percent are sometimes employed in the same manner for some metals.

Certain metals, such as low carbon steel, exhibit a *yield point* which is the stress just above the elastic limit where an increase in strain occurs without an increase in stress. The yield point is generally mentioned only for low strength steels. Offset yield strength is the more commonly used index of load-carrying ability without excessive plastic strain.

### Tensile Strength

The ratio of the maximum load sustained by a tensile test specimen to the original cross-sectional area is called the *ultimate tensile strength* (UTS), which is the value regularly listed for the strength of a metal. The ultimate tensile strength represents a convenient value calculated from a standard engineering test. The "true" tensile strength of the metal usually is substantially higher than the reported tensile strength.

After the ultimate strength of a tensile test specimen is exceeded, the loss in load-carrying ability is caused by a marked reduction in the cross section as plastic deformation increases. It is standard practice to calculate the tensile stress on the basis of the original cross section area. Therefore, the metal appears to decrease in strength as it nears the breaking point. Actually, the strength of the metal increases steadily as plastic strain takes place because of the continuing effect of cold work, and a maximum strength is reached just prior to fracture.

Tensile strength values obtained for metals are influenced by many factors. Tensile strength

is a structure-sensitive property, and is dependent upon chemistry, microstructure, orientation, grain size, strain history, and other factors. The size and shape of the specimen and the rate of loading can also affect the result. For these reasons, the ultimate tensile strengths of the weld metal and the heat-affected zone may be different from that of the unaffected base metal.

### Fatigue Strength

The effect of cyclic loading is an important aspect of the strength of metals and welded joints. Fracture can take place in a metal at a stress level well below the tensile strength when a load is applied repeatedly. Fatigue fractures develop as each application of the applied tensile stress causes the tip of a crack to advance a minute amount (stable crack growth). The rate of advance increases as the area of section ahead of the crack decreases with each application of applied load until the stress at the crack tip causes unstable crack growth. Then, sudden, complete failure occurs. Crack growth does not occur when the net stress at the crack tip is compressive; thus, while a crack may initiate as a result of tensile residual stress in combination with fluctuating compressive stress, the small crack relieves the residual welding stress and crack growth ceases.

The stress that a metal can endure without fracture decreases as the number of repeated stress applications increases. The *fatigue strength* is generally defined as the maximum stress that can be sustained for a stated number of cycles without failure. Unless otherwise stated, the stress is completely reversed within each cycle. As the desired number of stress repetitions is increased, the corresponding fatigue strength becomes smaller. For steel, the fatigue strength is usually almost constant beyond about two million cycles. Many million additional cycles are required to cause a significant reduction in fatigue strength. The *fatigue limit*, therefore, practically becomes the maximum stress or stress range which the metal will bear for an infinite number of cycles without fracture. Such a limiting stress level is often called the *endurance limit*. The *fatigue life*, accordingly, is the number of cycles of stress that can be sustained by a metal under stipulated conditions.

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The endurance limits reported for metals in engineering handbooks usually have been determined with polished round specimens tested in air. While such data are valid and useful for design of real members represented by the specimens used in the tests, such as finished shafts in rotating machinery, it may have little relevance in the design of as-welded weldments. Weldments are characterized by abrupt changes in cross section, geometrical and metallurgical discontinuities, and residual stresses.

The life (cycle life) of a welded structural member subject to repeated variation of tensile or alternately tensile and compressive stress primarily within the elastic range of the material is principally dependent on the stress range and joint geometry. *Life* is defined as the number of times a member can be subjected to a specific load prior to the initiation and growth of a fatigue crack to size where either failure of the structural component or collapse of the structure takes place.

The *stress range* is the absolute magnitude of stress variation caused by the application and removal of loads. For vehicular bridges, this load is usually a truck or train traversing the structure. Structural details and joint geometry include the type of joint, the type of weld, surface finish, and structural details that affect stress amplification caused by mechanical notches. The differences in stress concentration effects of joints and structural details are largely responsible for the variation in life obtained from details and members.

When designing welded built-up members and welded connections for structures subject to fatigue loading, the applicable code or standard governing the subject structure must be followed. In the absence of a specific code, an appropriate code or standard for similar structures should be used as a design guide.

Localized stresses within a structure may result entirely from external loading, or there may be a combination of applied and residual stresses. Residual stresses per se do not cycle, of course, 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 tension

stresses are expected. This may be accomplished by a welding sequence that controls the residual stresses from welding, or by a localized treatment that acts to place the surface in compression.

Thermal stresses also must be considered in the same light as an applied stress because thermal cycling can lead to fatigue failure if the thermal gradients are steep or if the thermal stresses are concentrated by a stress raiser.

The rate of repetition of loading is important because it determines the time required for the number of cycles that will cause a crack to initiate and propagate to a critical length. Weldments in rotating equipment are particularly prone to fatigue failure. Pressure vessels can fail by fatigue also when pressurization is cyclic and stress above the fatigue strength is concentrated at some point.

Designers of weldments need to thoroughly understand the fatigue characteristics of metals, particularly in weldments. The most common cause of fracture in weldments is fatigue. One of the reasons for this is the frequent presence of stress raisers (changes in cross section, discontinuities, etc.) that 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 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 do not measure any fundamental characteristic, but merely provide relative values for comparison of ductilities of metals subjected to the identical test conditions. The plasticity exhibited by a specimen is simply the deformation accomplished during the yielding process.

Ductility, regardless of the method of measurement, is a structure-sensitive property, and is affected by many of the conditions of testing. The size and shape of the specimen, the ambient temperature, the rate of straining, metallurgical structure, and surface conditions all influence the

amount and location of plastic deformation prior to fracture.

Ductility values obtained from precise or elaborate tests are not used directly in design. Most structures are designed to operate at stresses below the yield strength, and any significant deformation usually makes the unit or article unfit for service. Ductility values give an indication of the ability of a metal to yield and relieve high secondary stresses. These values also may give some idea of the reserve of plasticity available to insure against sudden fracture under unexpected overloading. However, ductility values do not necessarily indicate the amount of plastic deformation that will take place under all conditions of loading. Most structures are sensitive to both loading rate and ambient temperature.

### Fracture Toughness

A metal that is judged *ductile* by a standard tensile test or slow bend test may perform in a *brittle* manner when exposed to different conditions in another type of test. The only forecast that can be made with reasonable certainty from tensile or bend test results is that a metal with very little ductility is not likely to behave in a ductile fashion in any other type of mechanical test carried to fracture. A metal that displays good ductility in a tensile or bend test may or may not behave in a ductile manner in all other kinds of mechanical tests. In fact, there have been numerous cases where ductile metals (as judged by tensile and bend tests) have fractured in service with little or no plastic deformation. The lack of deformation and other aspects of such failures usually show that little energy was required to produce the fracture. This general experience prompts the metallurgist to speak of the toughness of metal as a property distinct from ductility.<sup>5</sup>

Toughness can be described as the ability of metal containing an existing small crack or other stress raiser to resist fracture while being loaded

under conditions that are unfavorable for energy absorption and plastic deformation. Three conditions markedly influence the behavior of a metal; namely, (1) the rate of straining, (2) the nature of the load, that is, whether the imposed stresses are uniaxial or multiaxial, and (3) the temperature of the metal.

While many metals can absorb energy and deform plastically under the simple circumstances represented in tensile or bend tests (and therefore would be judged ductile), a lesser number of these metals are considered to have good toughness when tested under conditions of high stress concentration. Briefly, the toughness displayed by a metal tends to decrease as (1) the rate of straining increases, (2) the stresses become multiaxial, and (3) the temperature of the metal is lowered. Weld metal in service easily may be exposed to one or more of these conditions. Consequently, there is good reason to be concerned about the toughness of weld metal.

In designing with ductile metals, the fail-safe load carrying capability of an engineering structure, including the welds, is normally based on a stress analysis to assure that the nominal stresses are below the yield strength. Failures that occur at stresses below the yield strength are broadly classified as brittle fractures. These failures can result from the effects of critical size discontinuities or crack-like defects in welds or base metal that do not greatly alter the nominal stress distribution and are customarily neglected in the stress analysis.

Conditions of high lateral restraint could cause brittle fracture in a structure because a discontinuity can greatly decrease the ductility that may have been predicted on the basis of smooth tensile specimens. Such lateral restraint may be caused by relatively large material thickness; a detail design that has been proven satisfactory in service may be unsatisfactory if the proportions are simply extrapolated upward.

It is evident that a complete fracture-safe analysis requires proper attention to the role of a discontinuity. For many classes of structures, such as ships, bridges, and pressure vessels, experience with specific designs, materials, and fabrication procedures has established a satisfactory correlation between notch test standards for base

5. For information on fracture toughness, see the *Welding Handbook*, Vol. 1, 7th Ed., 1976: 170-185; and Rolfe, S., et al, *Fracture and Fatigue Control in Structures: Applications of Fracture Mechanics*, Englewood Cliffs, NJ: Prentice-Hall, 1977.

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and weld metals and acceptable service. The problem is to insure the soundness and integrity of a new design.

One of the motivations for the application of fracture mechanics concepts and tests to welded joints is the possibility of designing safely against the effects of common weld discontinuities. It is widely recognized that welded joints almost always contain some discontinuities, and this places the designer using welded joints in a dilemma. The designer likes to think of joints that are entirely free of flaws, but this is not realistic. The practical approach is to recognize that discontinuities are present, and to place a reasonable limit on their existence. The problem is how to determine the types and extent of discontinuities that are acceptable. While conventional toughness testing procedures cannot deal directly with this problem, fracture mechanics tests, where applicable, specifically define a relationship between flaw size and fracture stress for a given base metal or weld joint. Thus, the tests permit a direct estimate of allowable flaw sizes for different geometrical configurations and operating conditions.

Where structural elements are subject to cyclical stresses or where other flaw extension mechanisms are at work, the allowable discontinuity size is further complicated. Fracture mechanics may be able to establish the safe maximum flaw size, but this size may not provide a useful life for elements subject to fatigue or corrosion, or both. For these elements, information relative to flaw growth rates is essential.

The specification of allowable flaw sizes and inspection procedures for flaw detection can be referred to a rational and logical procedure rather than one based solely on experience or opinion. As weldments of more complicated design and higher strength requirements are introduced, the designer will need to take an analytical approach to the problem of weld discontinuities.

#### Low Temperature Properties

Lowering the temperature of a metal profoundly affects fracture characteristics, particularly if the metal possesses a body-centered cubic crystalline structure (carbon steel is an example).

Strength, ductility, and other properties are changed in all metals and alloys as the temperature decreases to near absolute zero.

The properties of metals at very low temperatures are of more than casual interest. Welded pressure vessels and other pieces of equipment sometimes are expected to operate satisfactorily at temperatures far below room temperature. Very low temperatures are involved in so-called cryogenic service that entails the storage and use of liquefied industrial gases, such as oxygen and nitrogen.

As the temperature is lowered, a number of changes in properties take place in metals. The elastic modulus, for example, increases. In general, the tensile and yield strengths of all metals and alloys increase as the temperature is lowered.

The ductility of most metals and alloys tends to decrease as temperature is lowered. However, some metals and alloys have considerable ductility at very low temperatures. Because of the notch-toughness transition behavior of carbon and low alloy steels and certain other metals, the suitability of metals for low temperature service is judged by tests that evaluate propensity to brittle fracture rather than simple tensile or bend ductility. The favorite specimens for low-temperature testing are the notched tensile specimen and the notched-bar impact specimen. The principal factors that determine the low temperature behavior of a metal during mechanical testing are (1) crystal structure, (2) chemical composition, (3) size and shape of the test specimen, (4) conditions of manufacture and heat treatment, and (5) rate of loading. The notched-bar impact strengths for five common metals are listed in Table 1.3. Iron and steel suffer a marked reduction in impact strength at low temperatures. The addition of alloying elements to steel, especially nickel and manganese, can markedly improve notch toughness at low temperatures, while increased carbon and phosphorus can greatly decrease notch toughness.

#### Elevated Temperature Properties

The mechanical properties of metals at elevated temperatures are of concern for three reasons. First, many metal sections, employed in weldments are produced or formed by working

**Table 1.3**  
Notch-bar impact strengths of metals at low temperatures

| Temperature,<br>°F    | Charpy V-notch impact strength, ft · lb |                     |                     |                   |                       |
|-----------------------|-----------------------------------------|---------------------|---------------------|-------------------|-----------------------|
|                       | Aluminum <sup>a</sup>                   | Copper <sup>a</sup> | Nickel <sup>a</sup> | Iron <sup>b</sup> | Titanium <sup>c</sup> |
| 75 (room temperature) | 20                                      | 40                  | 90                  | 75                | 15                    |
| 0                     | 20                                      | 42                  | 92                  | 30                | 13                    |
| -100                  | 22                                      | 44                  | 93                  | 2                 | 11                    |
| -200                  | 24                                      | 46                  | 94                  | 1                 | 9                     |
| -320                  | 27                                      | 50                  | 95                  | 1                 | 7                     |

a. Face-centered cubic crystal structure.

b. Body-centered cubic crystal structure.

c. Hexagonal close-packed crystal structure.

Source: Linnert, G.E., *Welding Metallurgy*, Vol. 1, 3rd Ed., Miami: American Welding Society, 1965.

the metal at elevated temperatures. If the metal does not possess suitable mechanical properties for these hot working operations, flaws can be created in the section that may later interfere with the making of sound welds. Second, most welding operations involve the application of heat. Therefore, information may be needed on the changes in mechanical properties of the base metal as the temperature rises and falls to predict behavior under induced strain during welding. Even the strength and ductility of the weld metal as it cools from the solidification point to room temperature may be useful information. Finally, the properties of metals at elevated temperatures are important because many weldments are exposed to high temperatures either during heat treatments or while in service.

The strength of a metal decreases as the temperature is raised. The elastic modulus is reduced, and plastic deformation mechanisms are able to operate more freely. However, metals vary considerably in the way that their strengths and ductilities change with temperature. A metal that is strong at one temperature may be weaker than other metals at another temperature.

During welding, the temperature of the metal at the joint rises to the melting point and falls when the heat source is removed. If the parts are restrained, the hot weld metal and heat-affected zone are subjected to complex thermal strains. Whether the metal fails (cracks) or distorts badly from shrinkage stresses depends upon the various properties of the metal at the varying temperatures encountered.

Performance of a metal in service at an elevated temperature is governed by other factors in addition to strength and ductility. Time becomes a factor because at high temperatures metal will creep; that is, the section under stress will continue to deform even if the load is maintained constant. The rate at which a metal creeps under load increases rapidly with increasing temperature. Consequently, the time over which a metal under load will deform 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.

As would be expected, the creep rates of metals and alloys differ considerably. If the temperature and stress are sufficiently high, the

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metal will creep until rupture occurs. The term *creep-rupture* is used to identify the mechanics of deformation and failure of metals under stress at elevated temperatures.

**PHYSICAL PROPERTIES**

The physical properties of metals seldom receive the attention regularly given to mechanical properties in a general treatise on welding. Nevertheless, the physical properties are an important aspect of metal characteristics. Often-times, the welding engineer (and welder) may be unaware that the success of the joining operation depends heavily on a particular physical property. The physical properties of regular polycrystalline metals are not so structure-sensitive as the mechanical properties. Constant values usually are provided for metals and alloys, and they serve satisfactorily for most engineering purposes. Only the physical properties that may require some consideration in designing or fabricating a weldment are discussed here.<sup>6</sup>

**Thermal Conductivity**

The rate at which heat is transmitted through a material by conduction is called *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 accounts for the difficulty in attempting to weld these metals using a relatively low-temperature heat source, like an oxy-acetylene flame. Conversely, the good conductivity of copper makes it a good heat sink when employed as a hold down or backing bar. Steel is a relatively poor conductor; this partly accounts for the ease with which it can be welded and thermally cut.

**Melting Temperature**

The higher the melting point or range, the larger is the amount of heat needed to melt a given volume of metal. Hence, the temperature

of the heat source in welding must be well above the melting range of the metal. However, two pieces of a metal, such as iron, may be joined with a metal of lower melting point, such as bronze. The brazing filler metal wets and adheres to the steel faces to which it is applied. Welding of two metals of dissimilar composition becomes increasingly difficult as the difference in melting ranges widens.

**Coefficient of Thermal Expansion**

Most metals increase in volume when they are heated. The coefficient of thermal expansion is the unit change in linear dimensions of a body when its temperature is changed by one degree. The coefficient also serves to indicate contraction when the temperature is decreased. Engineers usually are concerned with changes in length in metal components, and most handbooks provide a linear coefficient of thermal expansion rather than a coefficient for volume change.

Metals change in volume when they are heated and cooled during welding. The greater the increase in volume and localized upsetting during heating, the more pronounced will be the distortion and shrinkage from welding. Changes in dimensions from welding must be considered during weldment design when setting part dimensions and tolerances.

**Electrical Conductivity**

Metals are relatively good conductors of electricity. Increasing the temperature of a metal interferes with electron flow; consequently, electrical conductivity decreases. Adding alloying elements to a metal or cold working also decreases conductivity. These characteristics are important variables affecting resistance welding processes.

**CORROSION PROPERTIES**

The corrosion properties of a metal determine its mode and rate of deterioration by chemical or electrochemical reaction with the surrounding environment. Metals and alloys differ greatly in their corrosion resistance. Corrosion resistance often is an important consideration in planning and fabricating a weldment for a particular service. Therefore, the designer should

6. Physical properties of metals are discussed in the *Welding Handbook*, Vol. 1, 7th Ed., 1976: 71-76.

know something about the behavior of weld joints under corrosive conditions.<sup>7</sup>

Many times, weld joints display corrosion properties that differ from the remainder of the weldment. These differences may be observed between the weld metal and the base metal, and sometimes between the heat-affected zone and the unaffected base metal. Even the surface effects produced by welding, like heat tint formation or oxidation, fluxing action of slag, and moisture absorption by slag particles can be

important factors in the corrosion behavior of the weld metal. These considerations are particularly important in the design and fabrication of weldments of unpainted weathering steels, including the selection of filler metals.

Welds made between dissimilar metals or with a dissimilar filler metal may be subject to electrochemical corrosion. Brazed joints can be particularly vulnerable. Appropriate protective coatings are required to avoid corrosion in sensitive environments.

## DESIGN PROGRAM

A weldment design program starts with a recognition of a need. The need may be for improving an existing machine or for building an entirely new product or structure using advanced design and fabrication techniques. In any event, 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 marketing, engineering, and production.

### ANALYSIS OF EXISTING DESIGN

When designing an entirely new machine or structure, an attempt should be made to obtain information on similar units including those of other manufacturers or builders. If a new design is to replace a current one, the good and bad points of the latter should be understood. The following questions can help in determining these points:

(1) What are the opinions of customers and the sales force about the current design?

- (2) What has been its history of failures?
- (3) What features should be retained, discarded, or added?
- (4) What suggestions for improvements have been made?
- (5) Is it over or under designed?

### DETERMINATION OF LOAD CONDITIONS

The service requirements of a weldment and the conditions of service that might result in overloading should be ascertained. From such information, the load on individual members can be determined. As a starting point for calculating loading, a designer may find one or more of the following methods useful:

- (1) From the motor horsepower and speed, determine the torque on a shaft or revolving part.
- (2) Calculate the forces on members caused by the dead weight of parts.
- (3) Determine the load on members of a crane hoist, shovel, lift truck, or similar material handling equipment from the load required to tilt the machine.
- (4) Use the maximum strength of critical cables on such equipment to determine the maximum loads on machine members.

7. Types of corrosion and corrosion testing of welds are discussed in the *Welding Handbook*, Vol. 1, 7th Ed., 1976: 200-207.

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(5) Consider the force required to shear a critical pin as an indication of maximum loading on a member.

If a satisfactory starting point cannot be found, design for an assumed load, and adjust from experience and tests.

**MAJOR DESIGN FACTORS**

In developing a design, the designer should consider how decisions will affect production operations, manufacturing costs, product performance, appearance, and customer acceptance. Many factors far removed from engineering considerations per se become major design factors. Some of these, along with other relevant rules, are as follows:

(1) The design should satisfy strength and stiffness requirements. Overdesigning wastes materials and increases production and shipping costs.

(2) The safety factor should not be unrealistically high.

(3) Good appearance may be necessary, but only in areas that are exposed to view. The drawing or specifications should specify those welds that are critical in respect to appearance.

(4) Deep, symmetrical sections should be used to efficiently resist bending.

(5) Welding the ends of beams rigidly to supports increases strength and stiffness.

(6) Rigidity may be provided with welded stiffeners to minimize the weight of material.

(7) Tubular sections or diagonal bracing should be used for torsion loading. A closed tubular section is significantly more effective in resisting torsion than an open section of similar weight and proportions.

(8) Standard rolled sections, plate, and bar should be used for economy and availability.

(9) Accessibility for maintenance must be considered during the design phase.

(10) Standard, commercially available components should be specified when they will serve the purpose. Examples are index tables, way units, heads, and columns.

**DESIGNING THE WELDMENT**

To a designer familiar only with castings or forgings, the design of a weldment may seem

complex because of the many possible choices. Variety in the possibilities for layout, however, is one of the advantages of welded design; opportunities for saving are presented. Certain general pointers for effective design are as follows:

(1) Design for easy handling of materials, for inexpensive tooling, and for 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. Check the tolerances with the shop. Excessively close tolerances and fits may serve no useful purpose, and may be beyond the ability of the shop to produce them economically.

(4) Plan the design to minimize the number of pieces. This will reduce assembly time and the amount of welding.

**Part Preparation**

Flame cutting, shearing, sawing, blanking, nibbling, and machining are methods for cutting blanks from stock material. Selection of the appropriate method depends on the available material and equipment and the relative costs. The quality of edge needed for good fit-up and the type of edge preparation for groove welds must also be kept in mind. The following points should be considered:

(1) Dimensioning of a blank may require stock allowance for subsequent edge preparation.

(2) The extent of welding must be considered when proposing to cut the blank and prepare the edge for welding simultaneously.

(3) Weld metal costs can be reduced for thick plate by specifying J- or U-groove preparations.

(4) Consider air carbon arc gouging, flame gouging, or chipping for back weld preparation.

**Forming**

Forming of parts can sometimes reduce the cost of a weldment by avoiding joints and machining operations. The base metal composition, part thickness, over-all dimensions, production volume, tolerances, and cost influence the choice of forming methods. The following suggestions may be helpful in making decisions in this area:

(1) Create a corner by bending or forming rather than by welding two pieces together.

(2) Bend flanges on plate rather than welding flanges to it.

(3) Use a casting or forging in place of a complex weldment to simplify design and reduce manufacturing costs.

(4) Use a surfacing weld on an inexpensive component to provide wear resistance or other properties in place of an expensive alloy component.

With some alloys, cold forming may increase the likelihood of brittle fracture in service, and heat from welding near the formed area may also contribute to the problem. The matter should be investigated before cold forming and welding of susceptible materials is specified in a design.

### Weld Joint Design

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

(1) Select the joint design that requires the least amount of weld metal.

(2) Where possible, use a square-groove joint together with a welding process capable of deep joint penetration or of welding within the groove (electrode, electrodeless, or narrow-gap welding).

(3) Use the smallest practical root opening and groove angle to minimize the amount of filler metal required.

(4) On thick plates, use double instead of single V- or U-groove welds to reduce the amount of weld metal and to control distortion.

(5) For corner joints in steel, specify a depth of preparation of the groove to intersect the full thickness of the material to minimize lamellar tearing, especially in thicknesses of 2 in. and over.

(6) For T-joints where fatigue is not a primary concern, use double fillet welds to minimize through-thickness shrinkage strains and to spread the transfer of applied forces.

(7) Use one weld in place of two welds, where possible, to joint three parts at one location.

(8) Avoid joints where it is difficult to obtain fusion at the root. For example, welds joining

two surfaces at less than 30 degrees to each other are unreliable.

(9) Design the assembly and the joints for good accessibility for welding.

### Size and Amount of Weld

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

(1) Specify welds of minimum size and length but adequate for the forces to be transferred. Oversize welds may cause increased distortion and higher residual stress without improving suitability for service. (They also contribute to increased costs.)

(2) The size of a fillet weld is especially important because the amount of weld required increases as the square of the increase in leg length (equal legs).

(3) For equivalent strength, a continuous fillet weld of a given size is usually less costly than a larger sized intermittent fillet weld. Also, there are fewer weld terminations that are potential sites of discontinuities.

(4) 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. An intermittent fillet weld should not be used under cyclic loading conditions.

(5) To derive maximum advantage of automatic welding, it may be better to use one continuous weld rather than several short welds.

(6) The weld should be placed in the section of least thickness, and the weld size should be based on the load or other requirements of that section.

(7) Welding of stiffeners or diaphragms should be limited to that required to carry the load, and should be based on expected out-of-plane distortion of the supported components under service loads as well as during shipment and handling.

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

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**Subassemblies**

In visualizing assembly procedures, the designer should break the weldment into subassemblies in several ways to determine the arrangement that offers the greatest cost savings. The following are advantages of subassemblies:

- (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 size welds may be deposited under lesser restraint in subassemblies, which, in turn, helps to minimize residual stresses in the completed weldment.
  - (5) Machining of subassemblies to close tolerances can be done before final assembly. If necessary, stress relief of certain sections can be performed before final assembly.
  - (6) Chamber compartments can be leak tested and painted before final assembly.
  - (7) In-process inspection and repair is facilitated.
  - (8) Handling costs may be much lower.
- When possible, it is desirable to construct the weldment from standard sections, so that the welding of each can be balanced about the neutral axis. Welding the more flexible sections first facilitates any straightening that might be required before final assembly.

**FIXTURES, POSITIONERS, AND ROBOTS**

Welding fixtures, positioners, and robots should be used to minimize fabrication time. In the planning of assemblies and subassemblies, the designer should decide if the fixture is to be used simply to aid in assembly and tacking or if the entire welding operation is to be done in the fixture. Welding fixtures and positioners are discussed in Chapter 4; automatic welding machines and robotic equipment are covered in Chapter 5.

**WELDING PROCEDURES**

Although designers may have little control of welding procedures, they can influence which

procedures are used in production. The following guidelines can help to effect the ultimate success of weldment design:

- (1) Backing strips increase the speed of welding when making the first pass in groove welds.
- (2) The use of low-hydrogen steel electrodes or welding processes eliminates or reduces pre-heat requirements for steel.
- (3) If plates are not too thick, consider a joint design requiring welding only from one side to avoid manipulation or overhead welding.
- (4) Excessive reinforcement of a weld is generally unnecessary to obtain a full-strength joint.
- (5) With T-joints in thick plate subject to tensile loading in the through-thickness direction, the surface of the plate should be buttered with weld metal for some distance beyond the intended weld terminations to discourage lamellar tearing in susceptible steels.
- (6) Joints in thick sections should be welded under conditions of least restraint; for example, prior to installation of stiffeners.

**RESIDUAL STRESSES AND DISTORTION**

The magnitude and extent of residual stresses and the resulting distortion during the fabrication of a weldment can cause problems with fit-up and welding operations. Such problems may offset the quality and soundness of welded joints and ultimately, the serviceability of the weldment.

Weldment design, welding procedures, and assembly methods can be beneficial in controlling residual stresses and distortion in a completed structure. Procedures for reducing residual welding stresses and for controlling distortion in a weldment are discussed in the *Welding Handbook*, Vol. 1, 7th Ed., 1972: 265-68.

**CLEANING AND INSPECTION**

Design specifications can have some effect on cleaning and inspection costs. The design factor of safety determines the type and amount of inspection required. The following shop practices also affect these costs:

- (1) As-welded joints that have uniform appearance are acceptable for many applications. Therefore, the surface of a weld need not be

machined smooth or flush unless that is required for another reason. Smoothing a weld is an expensive operation.

(2) Undesirable overwelding should be noted during inspection because it can be costly and also contributes to distortion. Corrective action

should be directed at work in progress rather than at completed weldments.

(3) The type of nondestructive inspection to be used on weldments must be capable of detecting the types and sizes of weld discontinuities that are to be evaluated for acceptability.

## DESIGN CONSIDERATIONS

The performance of any member of a structure depends on the properties of the material and the characteristics of section. If a design is based on the efficient use of these properties, the weldment should be functionally good and conservative of materials.

Engineers assigned to design welded steel members need to know (1) how to select the most efficient structural section and determine required dimensions, and (2) when to use stiffeners and how to size and place them.

The mathematical formulas for calculating forces and their effects on sections, and for determining 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 use of those formulas. In fact, as will be explained later, it is often possible to make correct design decisions merely by examining one or two factors in an equation, without using tedious calculations. On the whole, the mathematics of weld design is no more complex than in other engineering fields.

### THE DESIGN APPROACH

Considerations other than the engineer's wishes may prevail; for example, when a machine is to be converted from a cast to a welded design. Management may favor the redesign of one or more components to weldments, and conversion of the design over a period of years to an all-welded product. Gradual conversion avoids the obsolescence of facilities and skills, and limits the

requirement for new equipment. Available capital and personnel considerations often limit the ability of a company when changing to welded design. 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.

From the standpoint of performance and ultimate production economics, redesign of the machine or structure as a whole is preferable. The designer then is unrestricted by the previous design, and in many cases is 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.

### STRUCTURAL SAFETY

A safe welded structure depends upon a combination of good design practices, good workmanship during fabrication, and good construction methods. In design, the selection of a safe load factor or safety factor, whichever applies, and correct analytical procedures requires experience and sound engineering judgement. Deterioration from 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 in design.

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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 and also the variables that may cause it to fail. From these data, the risk of failure may be evaluated and the probability of occurrence kept at a safe level for the application considering the risk of injury, death, or extensive property damage.

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 when there is a question of which should govern. Great skill, care, and detailed stress analyses are needed when the designer attempts a new design or structural concept. Laboratory tests of models or sections of prototype structures should be used to verify the design.

#### SELECTING A BASIS FOR WELDED DESIGN

A redesign of a product may be based on the previous design or on loading considerations solely. Following a previous design has the advantages of offering a "safe" starting point; the old design is known to perform satisfactorily. This approach, however, has disadvantages in that it stifles creative thinking toward developing 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. Tables of equivalent sections or nomographs can be used to determine required dimensions for strength and rigidity.

A design based on the loading requires designers to analyze what is wanted and come up with configurations and materials that best satisfy the need. They must know or determine the type and amount of load, and the values for stress allowables in a strength design, or deflection allowables in a rigidity design.

#### DESIGNING FOR STRENGTH AND RIGIDITY

A design may require strength only, or strength and rigidity to support the load. All

designs must have sufficient strength so that the members will not fail by breaking 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 formulas for strength are used to dimension the members.

In certain weldments, such as machine tools, rigidity as well as strength is important, because excessive deflection under load would result in lack of precision in the product. A design based on rigidity also requires the use of design formulas for sizing members.

Some parts of a weldment serve their design function without being subjected to loadings much greater than their own weight (dead load). Typical members are fenders and dust shields, safety guards, cover plates for access holes, and enclosures for esthetic purposes. Only casual attention to strength and rigidity is required in sizing such members.

#### DESIGN FORMULAS

The design formulas for strength and rigidity 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 resolve into one of the following:

- (1) Finding the internal stress or the deformation caused by an external load on a given member.
- (2) Finding the external load that may be placed on a given member for any allowable stress, or deformation.
- (3) Selecting a member to carry a given load without exceeding a specified stress or deformation.

A load is a force that stresses a member. The result is a deformation strain measured by relative displacements in the member as 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, the designer should generally select the most efficient

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

The design formulas in use, developed for various conditions and member types, are much too numerous for inclusion here. However, some are used to illustrate specific design problems. Table 1.4 summarizes the components of design formulas.<sup>8</sup> These components are terms that describe the three basic factors: load, member, and stress or deformation. The symbols for values

and properties normally used in design formulas are also given in the table.

The use of design formulas may 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, Fig. 1.2, can be determined using the following deflection formula:

$$\Delta = (FL^3)/(3EI)$$

where

$\Delta$  = the deflection

$F$  = the applied force or load

$L$  = the length of the beam

$E$  = the modulus of elasticity of the metal

$I$  = the area moment of inertia of the beam section

8. The properties of sections for standard structural shapes are given in the *Manual of Steel Construction*, Chicago: American Institute of Steel Construction, (latest edition), and *Engineering Data for Aluminum Structures* (ED-33), Washington, D.C.: The Aluminum Association (latest edition).

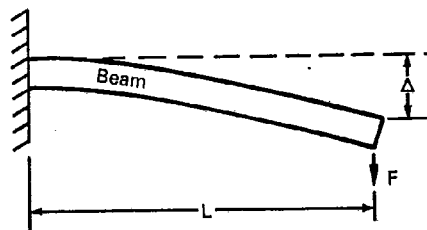
**Table 1.4**  
**Components of design formulas**

| (A) Load Components                        |                |                             |        |
|--------------------------------------------|----------------|-----------------------------|--------|
| Methods of application                     | Types of load  | Concept                     | Symbol |
| 1. Steady                                  | 1. Tension     | Force                       | F      |
| 2. Variable                                | 2. Compression |                             |        |
| 3. Cyclic                                  | 3. Shear       |                             |        |
| 4. Impact                                  | 4. Bending     | Moment                      | M      |
|                                            | 5. Torsion     | Torque                      | T      |
| (B) Member Components                      |                |                             |        |
| Property of material                       | Symbol         | Property of section         | Symbol |
| 1. Tensile strength                        | $\sigma_t$     | 1. Area                     | A      |
| 2. Compressive strength                    | $\sigma_c$     | 2. Length                   | L, l   |
| 3. Yield strength                          | $\sigma_y$     | 3. Moment of inertia        | I      |
| 4. Shear strength                          | $\tau$         | 4. Section modulus, elastic | S      |
| 5. Fatigue strength                        | FS             | 5. Torsional resistance     | R      |
| 6. Modulus of elasticity (Young's modulus) | E              | 6. Radius of gyration       | r, k   |
| 7. Modulus of rigidity in shear            | G              |                             |        |

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Table 1.4 (Continued)

| Stress         | Symbol     | Strain or deformation | Symbol     |
|----------------|------------|-----------------------|------------|
| 1. Tensile     | $\sigma_t$ | 1. Unit linear        | $\epsilon$ |
| 2. Compressive | $\sigma_c$ | 2. Total              | $\Delta$   |
| 3. Shear       | $\tau$     | 3. Angular rotation   | $\theta$   |

Fig. 1.2—Deflection,  $\Delta$ , of a cantilever beam under a concentrated load  $F$ 

It is normally desirable to have the least amount of deflection. Therefore,  $E$  and  $I$  values should be as large as possible. The common structural metal having the highest modulus of elasticity ( $E$ ) is steel, with a value of about  $30 \times 10^6$  psi. The other factor requiring a decision relative to deflection is  $I$ , the area moment of inertia. This is a *member* (geometrical) property of the cross section (Table 1.4). 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 adequate in-plane moment of inertia will satisfy the vertical deflection requirement, whatever the shape of the section. However, the out-of-plane stability of the beam may also need consideration if forces transverse to the principle axis or torsion are involved. The designer must then decide the shape to use for the best design at lowest cost.

## TYPES OF LOADING

As indicated in Table 1.4, there are five basic types of loading: tension, compression, bending, shear, and torsion. When one or more of these types of loading are applied to a member, they induce stress in addition to any residual stresses.

The stresses result in strains or movements within the member, the magnitudes of which are governed by the modulus of elasticity ( $E$ ) of the metal. Some movement always takes place in a member when the load is applied because of the stress and strain produced.

## Tension

Tension is the simplest type of load. It subjects the member to tensile stresses. A straight bar under a simple axial tension force has no tendency to bend. The axial tensile load causes axial strains and elongation of the bar. The only requirement is adequate cross-sectional area to carry the load.

## Compression

A compressive load may require designing 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 in Fig. 1.3 (A), is loaded through its center of gravity, the resulting stresses are simple axial compressive stresses. In the case of a slender column, it will start to bow laterally, as the load is increased, at a stress lower than the yield strength. This movement is shown in Fig. 1.3 (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 Fig. 1.3 (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 associated curvature, Fig. 1.3 (D), a critical point will be reached where the column will buckle and fail. As a column deflects under load, a bending moment can develop in semirigid or rigid welded end connections.

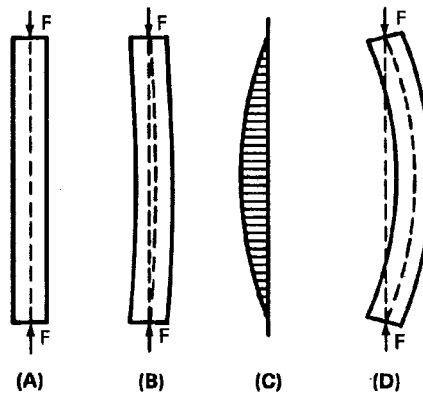


**Fig. 1.3—(A) Straight column with a compressive load; (B) column starts to deflect laterally with increasing load; (C) bending moment diagram; (D) increased deflection with higher loading**

Two properties of a column are important to compressive strength; cross-sectional area and radius of gyration. The area is multiplied by the allowable compressive stress to arrive at the compressive load that the column can support without buckling. The radius of gyration indicates, to a certain extent, the ability of the column to resist buckling. It 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 formula for the radius of gyration is as follows:

$$r = (I/A)^{1/2}$$

where

$r$  = radius of gyration

$I$  = moment of inertia about the neutral axis

$A$  = cross-sectional area of the member

The worst condition is of concern in design work and, therefore, it is necessary to use the least radius of gyration relative to the unbraced length. The smaller of the two moments of inertia about the  $x$ - $x$  and  $y$ - $y$  axes is used to obtain the least

radius of gyration. The slenderness ratio of a column is the ratio of its length,  $l$ , to its radius of gyration,  $r$ .

The design of a compression member is 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 table (*AISC Manual of Steel Construction, Appendix A*) gives the allowable compressive stress for the column length and the radius of gyration ( $l/r$  ratio). This allowable stress is then multiplied by the cross-sectional area,  $A$ , to give the allowable total compressive load that may be placed on the column. If this value is less than the load to be applied, the design must be changed to a larger section and tried again. Table 1.5 gives the AISC column formulas, and Fig. 1.4 gives allowable compressive stresses with various slenderness ratios.

**Table 1.5**  
**Allowable axial compressive stresses (AISC)**

- (1) When the effective slenderness ratio,  $Kl/r$ , is less than  $C_c$ :

$$\sigma_c = \frac{\left(1 - \frac{(Kl/r)^2}{2 C_c^2}\right) \sigma_y}{5 + \frac{3 (Kl/r)}{8 C_c} - \frac{(Kl/r)^3}{8 C_c^3}}$$

- (2) When the effective slenderness ratio,  $Kl/r$ , exceeds  $C_c$ :

$$\sigma_c = \frac{12 \pi^2 E}{23 (Kl/r)^2}$$

where:

$\sigma_c$  = allowable compressive stress, psi

$K$  = effective length factor (ratio of the length of an equivalent pinned-end member to the length of the actual member)

$l$  = unbraced length of the member, in.

$r$  = radius of gyration, in.

$C_c = (2 \pi^2 E / \sigma_y)^{1/2}$

$E$  = modulus of elasticity, psi

$\sigma_y$  = minimum yield strength, psi

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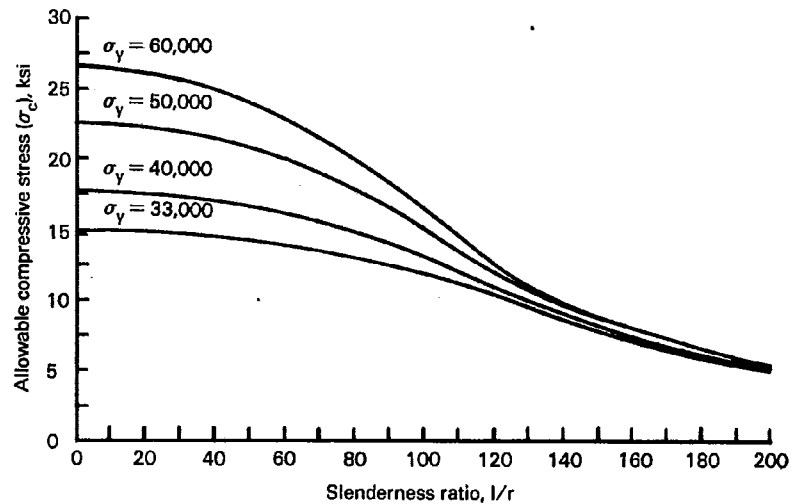


Fig. 1.4—Allowable compressive stress for steel columns of various yield strengths and slenderness ratios

### Bending

Figure 1.5 illustrates bending of a member under uniform loading. Loads may also be non-uniform or concentrated at specific locations on the beam. When a member is loaded in bending within the elastic range, the bending stresses are zero along the neutral axis and increase linearly to a maximum value at the outer fibers. The bending stress at any distance,  $d$ , from the neutral axis in the cross section of a straight beam, Fig. 1.6, may be found by the formula:

$$\sigma = \frac{Md}{I}$$

where

$\sigma$  = bending stress, tension, or compression, psi

$M$  = bending moment at the point of interest, lbf · in.

$d$  = distance from neutral axis of bending to point  $d$ , in.

$I$  = moment of inertia about the neutral axis of bending, in.<sup>4</sup>

In most cases, the maximum bending stress is of greatest interest, in which case the formula becomes:

$$\sigma_m = \frac{Mc}{I} = \frac{M}{S}$$

where

$\sigma_m$  = maximum bending stress, psi

$M$  = bending moment, lbf · in.

$c$  = distance from the neutral axis of bending to the extreme fibers, in.

$I$  = moment of inertia, in.<sup>4</sup>

$S$  = section modulus ( $I/c$ ), in.<sup>3</sup>

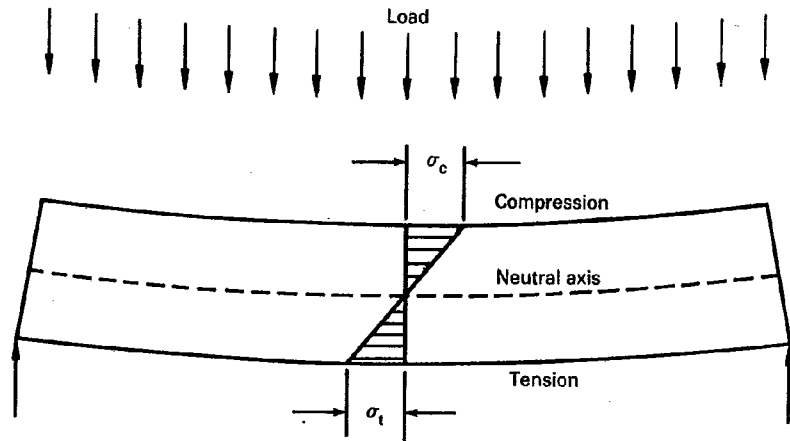


Fig. 1.5—Bending of a beam with uniform loading

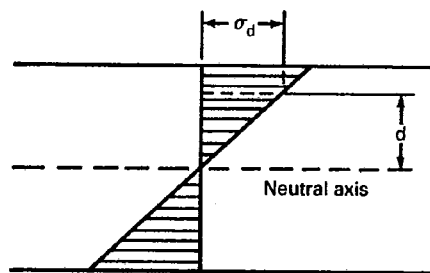


Fig. 1.6—Bending stress at any point  $d$  in the cross section of a straight beam

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 in the tensile forces  $F_1$  and  $F_2$  at the two

locations in the flange, as shown enlarged above the beam in Fig. 1.7. (The tensile force,  $F$ , is the product of the tensile stress,  $\sigma$ , and the flange cross-sectional area,  $A$ .)

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 joining 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.

A common bending problem in machinery design involves the deflection of beams. Beam formulas found in many engineering handbooks are useful for quick approximations of deflections with common types of beams where the span is large compared to the beam depth. An example of a typical beam with applicable formulas is shown in Fig. 1.8. Beams that are supported or loaded differently have other applicable design formulas. To meet stiffness requirements, beam depth should be as large as practical.

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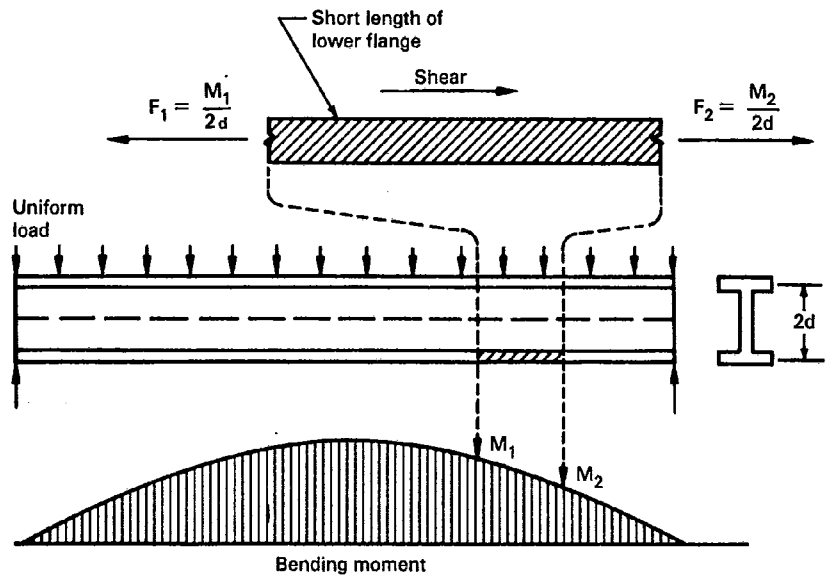


Fig. 1.7—Approximate tensile forces on a section of the lower flange of a loaded beam

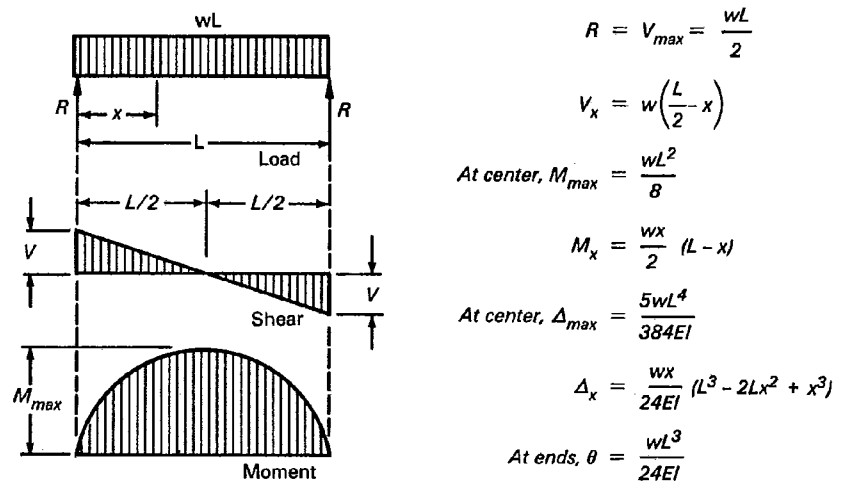


Fig. 1.8—Formulae for a simply supported beam with a uniformly distributed load on the span

Information concerning the design of a compression member or column also may 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, be properly supported to prevent twisting or lateral movement, and be subjected to compressive stresses within allowable limits.

### Shear

Figure 1.9 illustrates the shear forces in the web of a beam under load. They are both horizontal and vertical, and create diagonal tensile and diagonal compressive stresses.

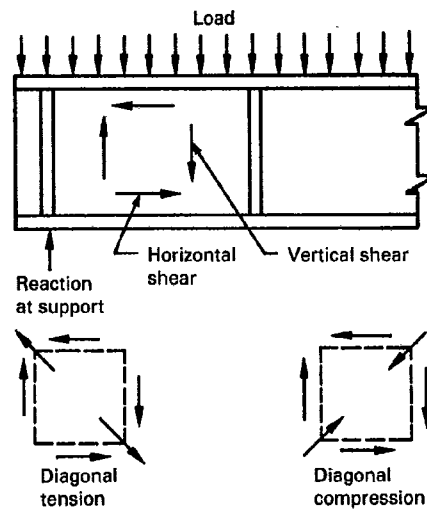


**Fig. 1.9—Shear forces in the web of a beam under load**

The shear capacity of a beam of either an I or a box cross section is dependent upon the slenderness proportions of the web or webs. For virtually all hot rolled beams and welded beams of similar proportions where the web slenderness ratio ( $h/t$ ) is less than 260, vertical shear load is resisted by pure beam shear without lateral buckling to a level of loading well above that where unacceptable deflections will develop. Thus, de-

sign is based upon keeping the shear stress on the gross area of the web below the allowable value of  $0.4 \sigma_y$  to prevent shear yielding.

In plate girders with slender webs, shear is resisted by plane beam shear up to a level of stress which will cause shear buckling. However, webs subject to shear stress have considerable post-buckling strength, and current design specifications take this strength into account. After buckling occurs, the web resists larger shear loads by a combination of beam shear and diagonal tension. If the shear span has a length-to-depth ratio greater than approximately three, the direction of the diagonal tension becomes too near to the horizontal for it to be effective, and transverse stiffeners must be provided. The stiffeners act in a manner analogous to the compression vertical members of a Pratt truss.

The onset of diagonal compression buckling in a web panel is of negligible structural significance because the magnitude of the buckle is limited by the crossing diagonal tension field. With properly proportioned transverse stiffeners, the web continues to resist higher levels of shear loading up to the point where diagonal tension yielding occurs. The true maximum shear strength would exist at this point.<sup>9</sup>

There are a few practical considerations independent of maximum strength that 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 which would initiate web shear buckling, each application of the critical load will cause 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 will eventually initiate fatigue cracking. For these cases, web stresses should be limited to the values where shear buckling is precluded.

9. Reliable criteria for the design of plate and box girder webs to achieve full maximum strength from beam shear and tension field action may be found in the *Manual of Steel Construction*, Section 5, latest edition, published by the American Institute of Steel Construction.

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In the case of a beam fabricated by welding, the unit shear load on the welds joining the flanges of the beam to the web can be calculated by the formula:

$$W_s = (Vay)/(In)$$

where

$W_s$  = load per unit length of weld.

$V$  = external shear force on the member at this location.

$a$  = cross-sectional area of the flange.

$y$  = distance between the center of gravity of the flange and the neutral axis of bending of the whole section.

$I$  = moment of inertia of the whole section about the neutral axis of bending.

$n$  = number of welds used to attach the web to the flange.

### Torsion

Torsion creates greater design problems for bases and frames than for other machine members. A machine with a rotating unit may subject the base to torsional loading. This becomes apparent 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 Fig. 1.10. Closed tubular sections are significantly better for resisting torsion than comparable open sections. Closed members can easily be made from channel or I-sections by intermittently welding flat plate to the toes of the rolled sections. The torsion effect on the perimeter of an existing frame may be eliminated or the frame stiffened for torsion by welding in cross bracing. Torsion problems in structures can be avoided by 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 formula:

$$R = \frac{bt^3}{3}$$

where

$R$  = torsional resistance, in.<sup>4</sup>

$b$  = width of the section, in.

$t$  = thickness of the section, in.

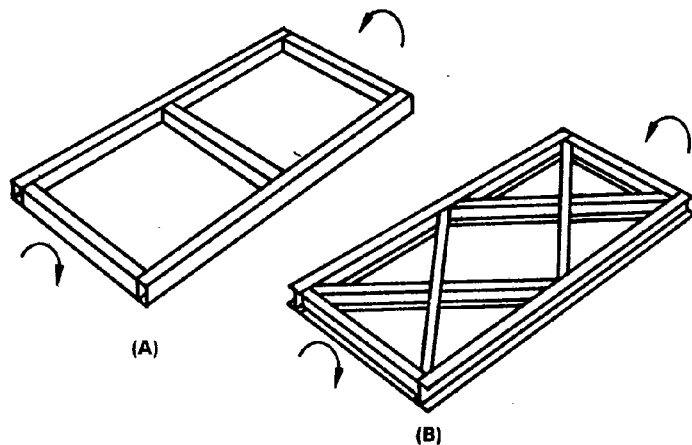


Fig. 1.10—Application of (A) closed tubular sections or (B) diagonal bracing to resist torsion

The total angular twist (rotation) of a member can be estimated by the following formula:

$$\theta = Tl/GR$$

where

$\theta$  = angle of twist, radians

$T$  = torque, lbf · in.

$l$  = length of member, in.

$G$  = modulus of elasticity in shear, psi  
( $12 \times 10^6$  for steel)

$R$  = total torsional resistance, in.<sup>4</sup>

The unit angular twist,  $\phi$ , is equal to the total angular twist,  $\theta$  divided by the length,  $l$ , of the member.

The torsional resistance of a 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 1.6, listing 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 was the same for both sections.

**Table 1.6**  
Calculated and actual angle of twist

|                                       | Angle of twist, degrees |                        |
|---------------------------------------|-------------------------|------------------------|
|                                       | Strip <sup>a</sup>      | I-section <sup>b</sup> |
| Calculated using torsional resistance | 21.8                    | 7.3                    |
| Actual twist                          | 22                      | 9.5                    |

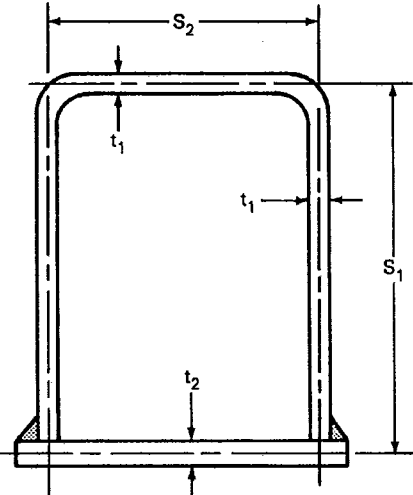
a. 0.055 in. by 2 in.

b. Made of three of the strips.

Torsional resistance increases markedly with closed cross sections, such as circular or rectangular tubing. As a result, 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. Draw a dotted line through the mid-thickness around the

section, as shown in Fig. 1.11. The area enclosed by the dotted lines is  $A$ . Divide the cross section of the member into convenient lengths,  $S_x$ , having thicknesses  $t_x$ . Determine the ratios of these individual lengths to their corresponding thicknesses and total them. Torsional resistance is then obtained from the following formula:

$$R = \frac{4A^2}{\sum (S_x/t_x)}$$



$$R = \frac{4A}{\sum (S_x/t_x)} = \frac{4S_1S_2}{2(S_1/t_1) + (S_2/t_1) + (S_2/t_2)}$$

**Fig. 1.11—Torsional resistance of a closed box section**

The maximum shear stress in a rectangular section in torsion is on the surface at the center of the long side. Knowing the unit angular twist, the following formula will give the maximum shear stress at the surface of a rectangular part.

$$\tau = \phi tG = \frac{Tt}{R}$$

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where

- $\tau$  = maximum unit shear stress, psi
- $\phi$  = unit angular twist, radians/in.
- $G$  = modulus of elasticity in shear, psi
- $T$  = applied torque, lbf · in.
- $t$  = thickness of the section, in.
- $R$  = torsional resistance, in.<sup>4</sup>

This formula can be applied to a flat plate or a rectangular area of an open structural shape (channel, angle, I-beam). In the latter case,  $R$  is 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 to bending (stiffness) parallel to the width of the bar. 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 Fig. 1.12(A), they contribute only relatively low torsional resistance. However, if the bars are oriented diagonally across the frame, as in Fig. 1.12(B), twisting of the frame is resisted by the stiffness of the bars. To be effective, the diagonal braces must have good stiffness perpendicular to the plane of the frame.

### TRANSFER OF FORCES

Loads create forces that must be transmitted through the structure to suitable places for counteraction. The designer needs to know how to provide efficient pathways.

One of the basic rules is that a force applied transversely to a member will ultimately enter that portion of the section that lies parallel to the applied force. Figure 1.13, for example, shows a lug welded parallel to the length of a beam. The portion of the beam that is parallel to the applied force 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.

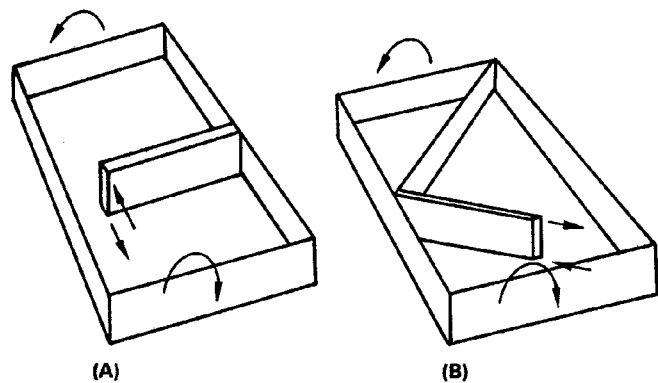


Fig. 1.12—Frames subjected to torsion with (A) transverse rib bracing and (B) diagonal bracing

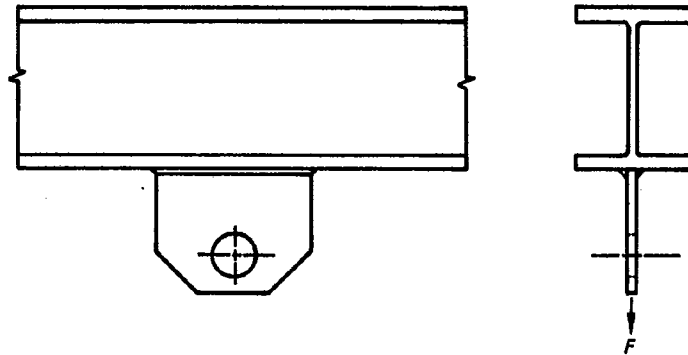


**Fig. 1.13—Lug welded parallel to the length of a beam**

Suppose, however, that the lug was welded to the beam flange at right angles to the length of the beam, Fig. 1.14(A). The outer edges of the flange tend to deflect rather than support much load. This forces a small portion of the weld in line with the web to carry a disproportionate share of the load, Fig. 1.14(B). To uniformly distribute the load on the attachment weld, two stiffeners can be aligned with the lug and then welded to the web and to the adjacent flange of the beam, as shown in Fig. 1.15. The stiffeners reinforce the bottom flange and also transmit part of the load to the web of the beam. The welds labeled *A*, *B*, and *C* in Fig. 1.15 must all be designed to carry the applied force, *F*.

If a force is to be applied parallel to the flanges, it would not be acceptable to simply weld an attachment plate to the web of the beam. The applied force on the attachment could cause excessive bending of the web, as shown in Fig. 1.16. In such a situation, the plate can be welded to the flanges of the beam, as in Fig. 1.17 for low forces, and no force is transferred to the web. For large forces, it might be necessary to place a stiffener on the opposite side of the web, Fig. 1.18. In this case, both the plate and the stiffener should be welded to the web as well as to both flanges. The stiffener is loaded only through the welds along the web. The fillet welds joining the plate to the beam flanges must not extend around the plate along the edges of the flanges. The

abrupt changes in weld direction can intensify stress concentrations.

When a force in a structure changes direction, a force component is involved. This is illustrated in Fig. 1.19, a knee of a rigid frame subjected to a bending moment. The compressive force in the interior flanges must change direction at the knee. To prevent bending of the web and

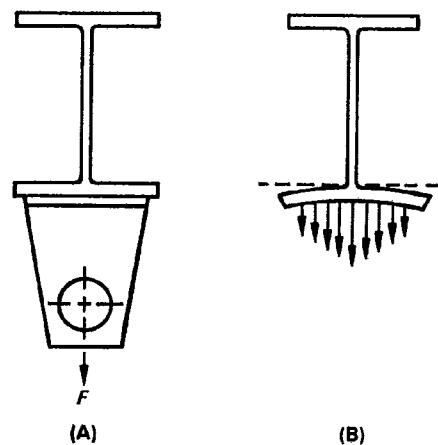


**Fig. 1.14—(A) Lug welded to a flange transverse to the beam, (B) Load distribution with unreinforced flange**

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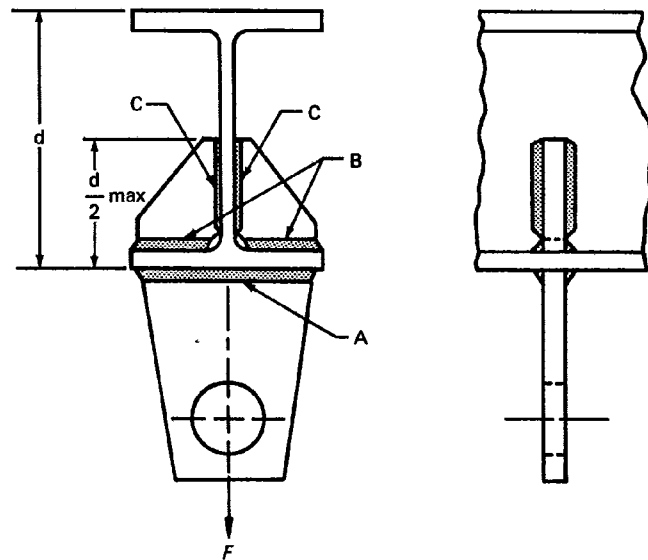


**Fig. 1.15—Stiffeners transmit a portion of the load from the flange to the web of the beam through welds A, B, and C**

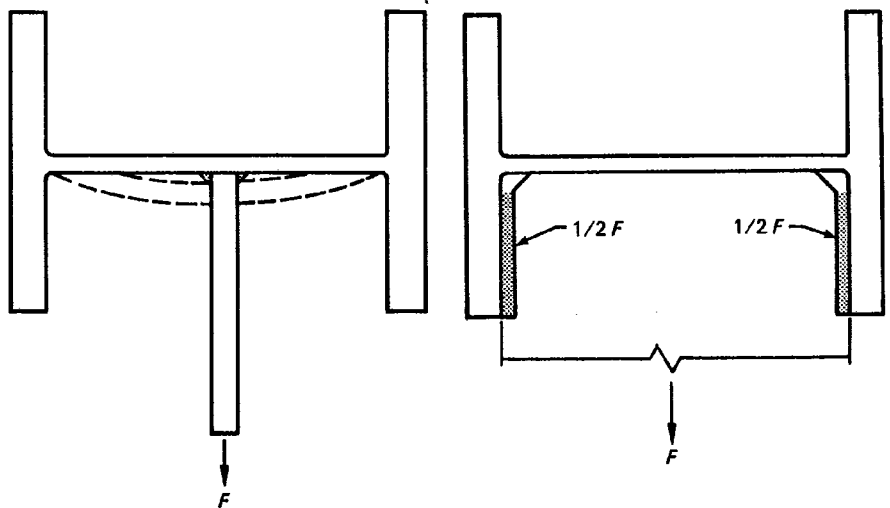


**Fig. 1.16—Deflection of beam web from loaded attachment**

**Fig. 1.17—Attachment welded to beam flanges to avoid web deflection**

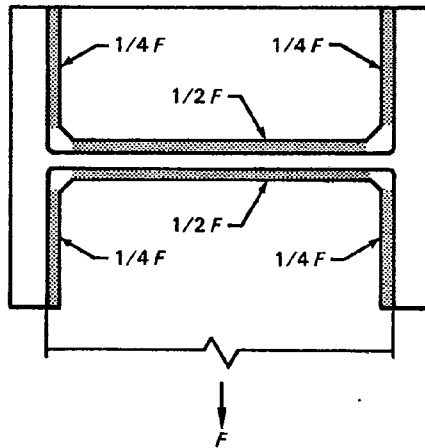


**Fig. 1.18—Stiffener on opposite side of attachment, welded as shown, for large loads**

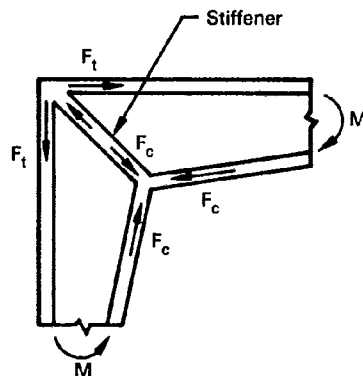


**Fig. 1.19—Knee of rigid frame**

failure of the structure, diagonal stiffeners are placed on both sides of the web at the intersections of the two flanges. The compressive force component in the web and stiffeners balances the change in direction of the tensile force in the outer flanges.

## INFLUENCE OF WELDING PROCESS

Most designs for welding are based on the use of arc welding processes where filler metal is added in multiple passes, either in a groove to obtain required penetration or in a fillet weld on one or both sides of a member.<sup>10</sup> Adding filler metal in a groove produces lateral and longitudinal shrinkage between components that can result in angular distortion about the axis of the weld and longitudinal bowing of the joints. Fillet welds primarily cause angular distortion. The amount of shrinkage and distortion depends on the size of the weld in proportion to the thickness of the components and the degree of restraint imposed on the joint during welding and cooling.

When components are restrained from shrinkage or distortion, high residual stresses remain in the assembly. Depending on the size of the weld and the level of stresses, additional distortion can occur during subsequent thermal stress relieving.

When welding quenched-and-tempered steels, the heat input must be controlled to maintain the properties of the weld and heat-affected zone of the base metal. This usually dictates the use of small weld beads using relatively low welding currents.

Most welding processes require the weld joint to be readily accessible to the welder and the welding equipment. Several high-energy welding processes sometimes used in production are unique. When applicable, they offer some added flexibility in the design that may not be available with conventional arc welding processes.

The electron beam welding (EBW) process can produce narrow, deep-penetration welds with minimal lateral shrinkage and angular distortion.<sup>11</sup> Electron beam welds made in restrained sections have lower residual stresses than welds made with most other welding processes. The heat-affected zones of electron beam welds are normally narrower than those of welds made with arc welding processes. Quenched-and-

10. Arc welding processes are discussed in the *Welding Handbook*, Vol. 2, 7th Ed., 1978.

11. Electron beam welding is covered in the *Welding Handbook*, Vol. 3, 7th Ed., 1980: 169-215.

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tempered steels can be welded with minimal degradation of properties. With some designs, welds can be made with the components in the finish-machined state. In contrast, components that are welded with conventional arc welding processes require excess stock allowance for machining the weldment in those areas that must meet close dimensional tolerances.

A high-power laser beam can produce welds with characteristics similar to those made with the nonvacuum electron beam process.<sup>12</sup> However, equipment costs with both processes must be considered when specifying these processes.

The joint design for electron beam or laser beam welding consists of a simple square groove. Fit-up for these processes is critical, and root openings must be held to a minimum (preferably metal to metal contact). To obtain the proper fit-up for welding with these processes, weld joints must be prepared by machining. Fortunately, welds made with the electron beam or laser beam normally do not require filler metal addition. However, with either process, the joint must be positioned under the welding head, and the work or head moved automatically while maintaining the beam on the joint.

The electroslag welding process is unique from a design viewpoint.<sup>13</sup> It is a high-deposition, efficient process, but it imposes certain limitations or conditions on the designer. However, the process has some definite advantages where it

can be applied.

The electroslag welding process deposits a continuous, parallel-sided weld vertically from one end of the joint to the other end. The weld has predictable lateral shrinkage, generally less than that of single or double groove welds, and essentially no angular distortion. Because of the high energy input, the weld is considered essentially self-stress relieving.

An electroslag weld is basically a continuous casting. Consequently, the weld generally has a coarse, columnar grain structure, and a wide heat-affected zone. Impact properties and fatigue strengths of welded joints in the as-welded and the stress-relieved conditions may be lower than with other welding processes. These properties can be improved with normalizing and tempering heat treatments. This process cannot be used with quenched-and-tempered steels unless the weld and heat-affected zone receive a full heat treatment after welding.

Joint preparation for electroslag welding consists of square flame-cut edges. Weld joint length is not critical, but the joint must be aligned and properly fixtured to permit continuous welding. In general, it is not practical to weld plate thicknesses less than 3/4 in. with this process. Two variations of the electroslag welding process are generally used, conventional and consumable guide. The specific variation determines joint accessibility requirements.

## DESIGN OF WELDED JOINTS

### TYPES OF JOINTS

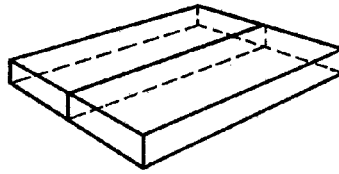
The loads in a welded structure are transferred from one member to another through welds placed in the joints. The types of joints used in welded construction and the applicable welds

are shown in Fig. 1.20. The configurations of the various welds are illustrated in Figs. 1.21, 1.22, and 1.23. Combinations of welds may be used to make a joint, depending on the strength requirements and load conditions. For example, fillet and groove welds are frequently combined in corner and T-joints.

Welded joints are designed primarily for the strength and safety required by the service conditions under which they must perform. The manner in which the stress will be applied in

12. Laser beam welding is discussed in the *Welding Handbook*, Vol. 3, 7th Ed., 1980: 218-32.

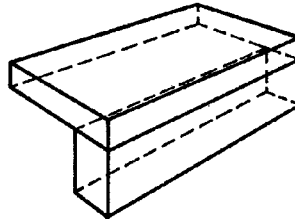
13. Electroslag welding is covered in the *Welding Handbook*, Vol. 2, 7th Ed., 1978: 225-48.



(A) Butt joint

## Applicable welds

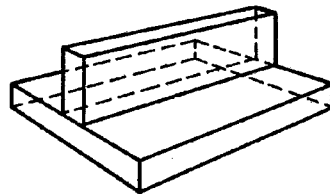
|               |                    |
|---------------|--------------------|
| Square-groove | J-groove           |
| V-groove      | Flare-V-groove     |
| Bevel-groove  | Flare-bevel-groove |
| U-groove      | Edge-flange        |
|               | Braze              |



(B) Corner joint

## Applicable welds

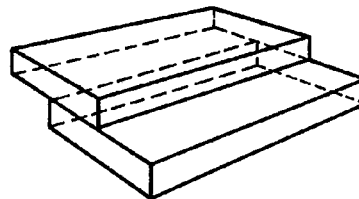
|                |                    |
|----------------|--------------------|
| Fillet         | Flare-bevel-groove |
| Square-groove  | Edge-flange        |
| V-groove       | Corner-flange      |
| Bevel-groove   | Spot               |
| U-groove       | Projection         |
| J-groove       | Seam               |
| Flare-V-groove | Braze              |



(C) T-joint

## Applicable welds

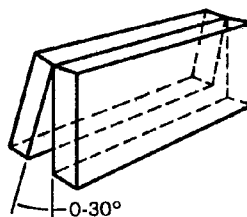
|               |                    |
|---------------|--------------------|
| Fillet        | J-groove           |
| Plug          | Flare-bevel-groove |
| Slot          | Spot               |
| Square-groove | Projection         |
| Bevel-groove  | Seam               |
|               | Braze              |



(D) Lap joint

## Applicable welds

|              |                    |
|--------------|--------------------|
| Fillet       | J-groove           |
| Plug         | Flare-bevel-groove |
| Slot         | Spot               |
| Bevel-groove | Projection         |
|              | Seam               |
|              | Braze              |



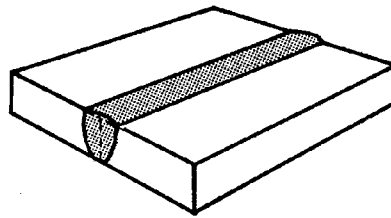
(E) Edge joint

## Applicable welds

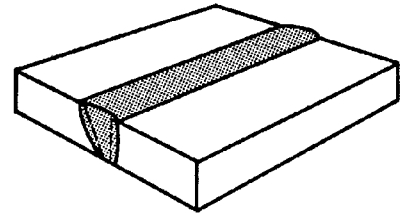
|               |               |
|---------------|---------------|
| Square-groove | Edge-flange   |
| Bevel-groove  | Corner-flange |
| V-groove      | Seam          |
| U-groove      | Edge          |
| J-groove      |               |

Fig. 1.20—Types of joints

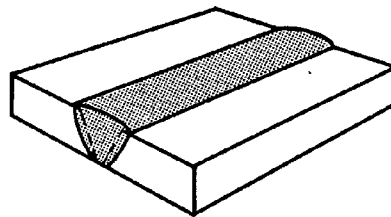
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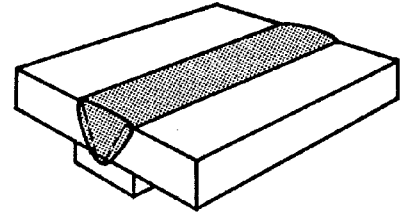
(A) Single-square-groove weld



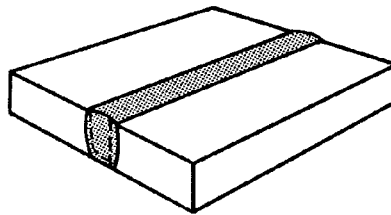
(B) Single-bevel-groove weld



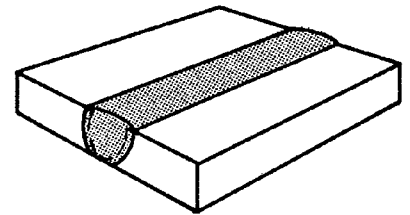
(C) Single-V-groove weld



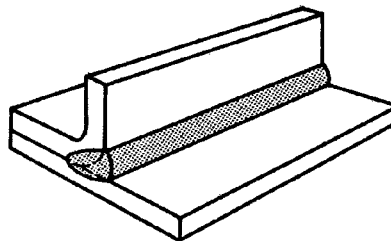
(D) Single-V-groove weld (with backing)



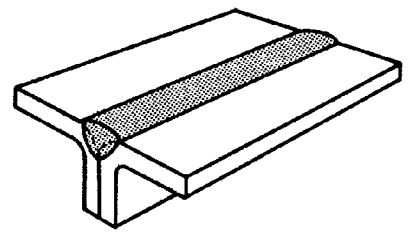
(E) Single-J-groove weld



(F) Single-U-groove weld

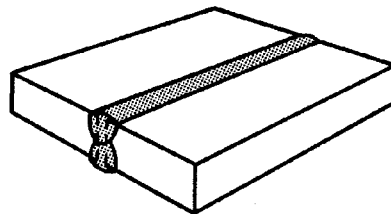


(G) Single-flare-bevel groove weld

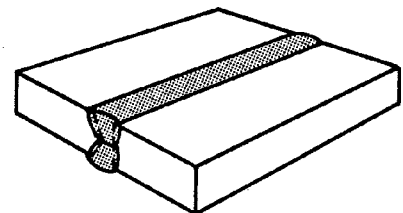


(H) Single-flare-V-groove weld

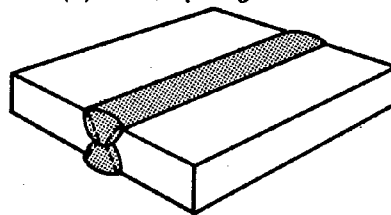
*Fig. 1.21—Single-groove welds*



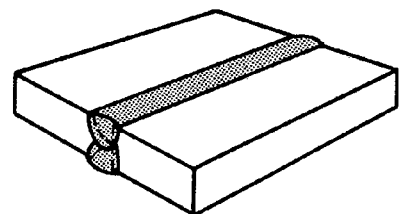
(A) Double-square-groove weld



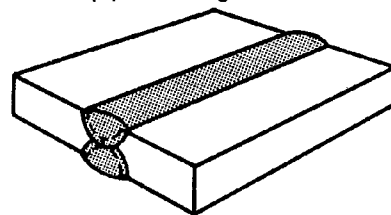
(B) Double-bevel-groove weld



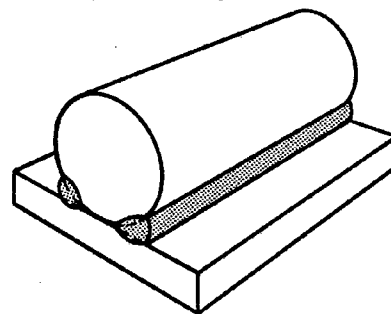
(C) Double-V-groove weld



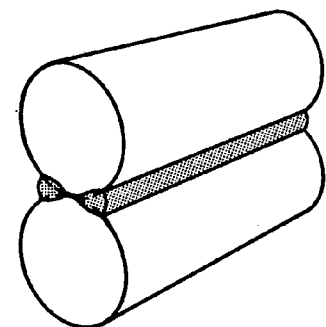
(D) Double-J-groove weld



(E) Double-U-groove weld



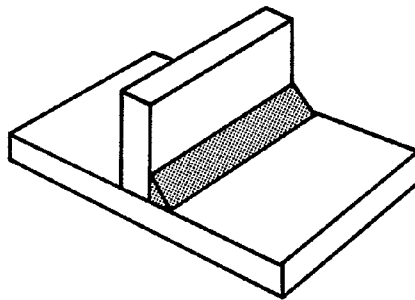
(F) Double-flare-bevel groove weld



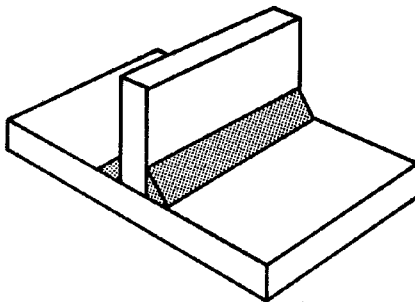
(G) Double-flare-V-groove weld

*Fig. 1.22—Double-groove welds*

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(A) Single fillet weld



(B) Double fillet weld

**Fig. 1.23—Fillet welds**

service, whether tension, shear, bending, or torsion, must be considered. Different joint designs may be required depending on whether the loading is static or dynamic where fatigue must be considered. Joints may be designed to avoid stress-raisers and to obtain an optimum pattern of residual stresses. Conditions of corrosion or erosion require joints that are free of irregularities, crevices, and other areas that make them susceptible to such forms of attack. The design must reflect consideration of joint efficiency, which is the ratio of the joint strength to the base metal strength, generally expressed as a percentage.

In addition to the above, joints are detailed for economy and accessibility during construc-

tion and inspection. Among the factors involved in construction are control of distortion and cracking, facilitation of good workmanship, and production of sound welds. Accessibility during construction not only contributes to low costs, but also provides an opportunity for better workmanship, fewer flaws, and control of distortion and residual stresses.

**GROOVE WELDS**

Groove welds of different types are used in many combinations; the selection of which is influenced by accessibility, economy, adaptation to the particular design of the structure being fabricated, expected distortion, and the type of welding process to be used.

A square-groove weld is economical to use, provided satisfactory soundness and strength can be obtained, because it only requires a square edge on each member for welding. Its use is limited by the thickness of the joint.

For thick joints, the edge of each member must be prepared to a particular geometry to provide accessibility for welding and ensure desired soundness and strength. In the interest of economy, those joint designs should be selected with root openings and groove angles that require the smallest amount of weld metal and still give sufficient accessibility for sound welds. The selection of root opening and groove angle also is greatly influenced by the metals to be joined, the location of the joint in the weldment, and the required performance.

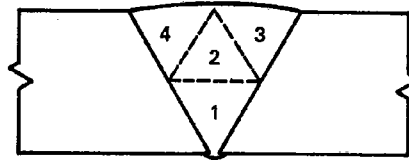
J- and U-groove welds may be used to minimize weld metal requirements when the savings are sufficient to justify the more costly machining of the edge preparation. These joints are particularly useful in the welding of thick sections. One disadvantage of J- and bevel-groove welds is that they are difficult to weld soundly when they are positioned to have a vertical side.

The most important criterion of the strength of a groove weld is the amount of joint penetration. Welded joints are usually designed so that they will be equal in strength to the base metal. To accomplish this, designs that permit penetration completely through the members being joined are most commonly used. One of the principles of welded design is the selection of joint

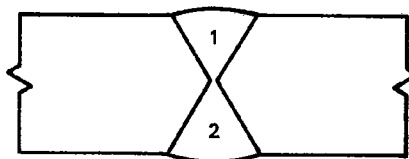
designs that provide the desired degree of joint penetration.

The details of welding grooves (groove angle, root face, root opening, etc.) depend upon the welding process and type of power to be used, and the physical properties of the base metal(s) being joined.<sup>14</sup> Some welding processes characteristically provide deeper joint penetration than others. Some metals have relatively high thermal conductivities or specific heats, or both. Those metals require greater heat input for welding than other metals with lower heat absorption. Examples are aluminum and copper.

Use of a double-welded joint in preference to a single-welded joint can reduce the amount of welding by 50 percent or more, as indicated by Fig. 1.24. This also limits distortion when equal numbers of weld passes are placed alternately on each side of the joint.



(A) Single-welded joint



(B) Double-welded joint

**Fig. 1.24—Comparison of relative volumes of filler metal for single- and double-V-groove welds of equal thickness and length**

14. Groove-weld joint preparations used with various welding processes and base metals are discussed in the *Welding Handbook*, Vols. 2, 3, and 4, 7th Ed., 1978, 1980, and 1982.

The various types of groove welds have certain advantages and limitations with respect to their applications. In the following discussion, comments on joint penetration or effective throat apply to joining of carbon steel by shielded metal arc (SMAW), gas metal arc (GMAW), flux cored arc (FCAW), and submerged arc welding (SAW). Joint penetration with other processes and base metals may be different when their physical properties vary significantly from those of carbon steel.

### Complete Joint Penetration

Groove welds with complete joint penetration are suitable for all types of loading provided they meet the acceptance criteria for the application. In many cases, a single-groove weld is not considered to have complete penetration, unless it was made using a suitable backing strip, or a back weld was applied.<sup>15</sup> In such cases, to ensure complete penetration with double-groove welds and single-groove welds without a backing strip, the root of the first weld must be back gouged to sound metal before making a weld pass on the other side.

### Partial Joint Penetration

A partial-joint-penetration groove weld has an unwelded portion at the root of the weld. This condition may also exist in joints welded from one side without backing.

The unwelded portions of groove welded joints constitute a stress raiser having significance when cyclic loads are applied transversely to the joint. This fact is reflected in applicable fatigue criteria. However, when the load is applied longitudinally, there is no appreciable reduction in fatigue strength.

Regardless of the rules governing the service application of partial-joint-penetration welds, the eccentricity of shrinkage forces in relation to

15. Welders with good technique, welding on metals that have high surface tension when molten, are able to obtain complete joint penetration without the aid of backing in single-groove welds. An appropriate joint design and welding process must be used to ensure complete root penetration and a smooth root surface.

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the center of gravity of the section can result in angular distortion on cooling after welding. This same eccentricity also tends to cause rotation of a transverse axial load across the joint. Therefore, means must be applied to restrain or preclude such rotation both during fabrication and in service.

For static loading, the allowable stresses in partial-joint-penetration groove welds depend upon the type and direction of loading and applicable code requirements. For steel, the allowable stress in tension and shear should be limited to about 30 percent of the nominal tensile strength of the weld metal. For tension or compression parallel to the weld axis, the allowable stress can be the same as that for the base metal. In no case should the actual tensile or shear stress in the base metal next to the weld exceed the allowable for the base metal.

#### Square-Groove Welds

Square-groove welds are economical in preparation and welding. Joint strength depends upon the amount of joint penetration. Adequate control of welding procedures and proper inspection are required to obtain the specified joint penetration and strength.

With most welding processes when welding from one side only, complete joint penetration can be reliably obtained only in thin sections unless a root opening and backing strip are used. With a suitable root opening and backing strip, joints up to 1/4 in. thickness can be welded by SMAW, and up to 3/8 in. thickness by GMAW, FCAW, and SAW. This type of joint should not be loaded in bending with the root of the weld in tension, nor subjected to transverse fatigue or impact loading. Also, it should not be used at low temperatures or in corrosive applications.

When welded from both sides, complete joint penetration can be obtained in sections up to 1/4-in. thickness by shielded metal arc welding, 3/8-in. thickness by gas metal arc and flux cored arc welding, and 1/2-in. thickness by submerged arc welding.

#### Single-V-Groove Welds

Single-V-groove welds are economical provided the depth of the groove does not exceed

3/4 in. Groove preparations and welding are relatively inexpensive.

The strength of the joint depends on the depth of penetration (effective throat). Joints with complete penetration are recommended for optimum mechanical properties.

Joints welded from one side only should not be used in bending with the root in tension. Also, they should not be subjected to transverse fatigue nor impact loading unless (1) complete joint penetration is obtained, (2) the backing strip, if used, is removed, and (3) the root face is machined smooth. Partially penetrated joints should not be exposed to corrosive conditions. The effective throat of such joints is never greater than the depth of joint preparation for design purposes.

#### Double-V-Groove Welds

The strength of a double-V-groove weld depends upon the total joint penetration (effective throat). For all types of loading, full strength joints can be obtained with complete joint penetration provided the root of the first weld is back gouged to sound metal before commencing welding on the other side. Partial penetration welds are recommended only for static loads transverse to the weld axis and for other types of loads parallel to the weld axis. This type of weld is economical when the depth of the grooves does not exceed 3/4 in. Double-V-groove welds with complete joint penetration may be costly when the joint thickness exceeds 1-1/2 in.; double-U-groove welds may be more economical.

#### Single-Bevel-Groove Welds

Single-bevel-groove welds have characteristics similar to single-V-groove welds with respect to properties and applications. The bevel type requires less joint preparation and weld metal; therefore, it is more economical.

One disadvantage of this type of weld is that proper welding procedures are required to obtain complete fusion with the perpendicular face of the joint. In the horizontal position, that face should be placed on the lower side of the joint to obtain good fusion.

#### Double-Bevel-Groove Welds

Double-bevel-groove welds have the same characteristics as double-V-groove welds. The

perpendicular joint faces make complete fusion more difficult. Also, back gouging the root of the first weld may be harder to accomplish.

A double-bevel joint design is economical when the depth of the groove does not exceed about 3/4 in., and the joint thickness is 1-1/2 in. or less for complete penetration.

#### Single- and Double-J-Groove Welds

J-groove welds have the same characteristics as similar bevel-groove welds. However, they may be more economical for thicker sections because less weld metal is required. Their use may be limited to the horizontal position in some applications.

#### Single- and Double-U-Groove Welds

U-groove welds and J-groove welds are used for similar applications. However, complete fusion is easier to obtain, and root gouging is more readily accomplished with U-grooves.

### FILLET WELDS

Where the design permits, fillet welds are used in preference to groove welds for reason of economy. Fillet welded joints are very simple to prepare from the standpoint of edge preparation and fit-up, although groove welded joints sometimes require less welding.

When the smallest continuous fillet weld that is practicable to make results in a joint efficiency greater than that required, intermittent fillet welding may be used to avoid overwelding unless continuous welding is required by the service conditions.

Fillet weld size is measured by the length of the legs of the largest right triangle that may be inscribed within the fillet weld cross section as shown in Fig. 1.25. The effective throat, a better indication of weld shear strength, is the shortest distance between the root of the weld and the diagrammatical weld face. With a concave weld face, the size of a fillet weld is less than the actual leg of the weld. With a convex weld face, the actual throat may be larger than the effective throat of the weld. In any case, the strength of a fillet weld is based on the effective throat and the length of the weld (effective area of the weld).

It should be noted that the actual throat may be larger than the theoretical throat by virtue of joint penetration beyond the root of the weld. When deep root penetration can be reliably assured by the use of automatic submerged arc or flux cored arc welding, some codes permit the effective throat to be taken as the size of the weld for 3/8 in. and smaller fillet welds, and as the theoretical throat plus 0.11 in. for fillet welds over 3/8 in.

#### Applications

Fillet welds are used to join corner, T-, and lap joints because they are economical. Edge preparation is not required, but surface cleaning may be needed. Fillet welds are generally applicable where stresses are low, and the required weld size is less than about 5/8 in. If the load would require a fillet weld of 5/8 in. or larger, a groove weld should be used possibly in combination with a fillet weld to provide the required effective throat. Fillet welds may be used in skewed T- or corner joints having a dihedral angle between 60 and 135 degrees. Beyond these limits, a groove weld should be used.

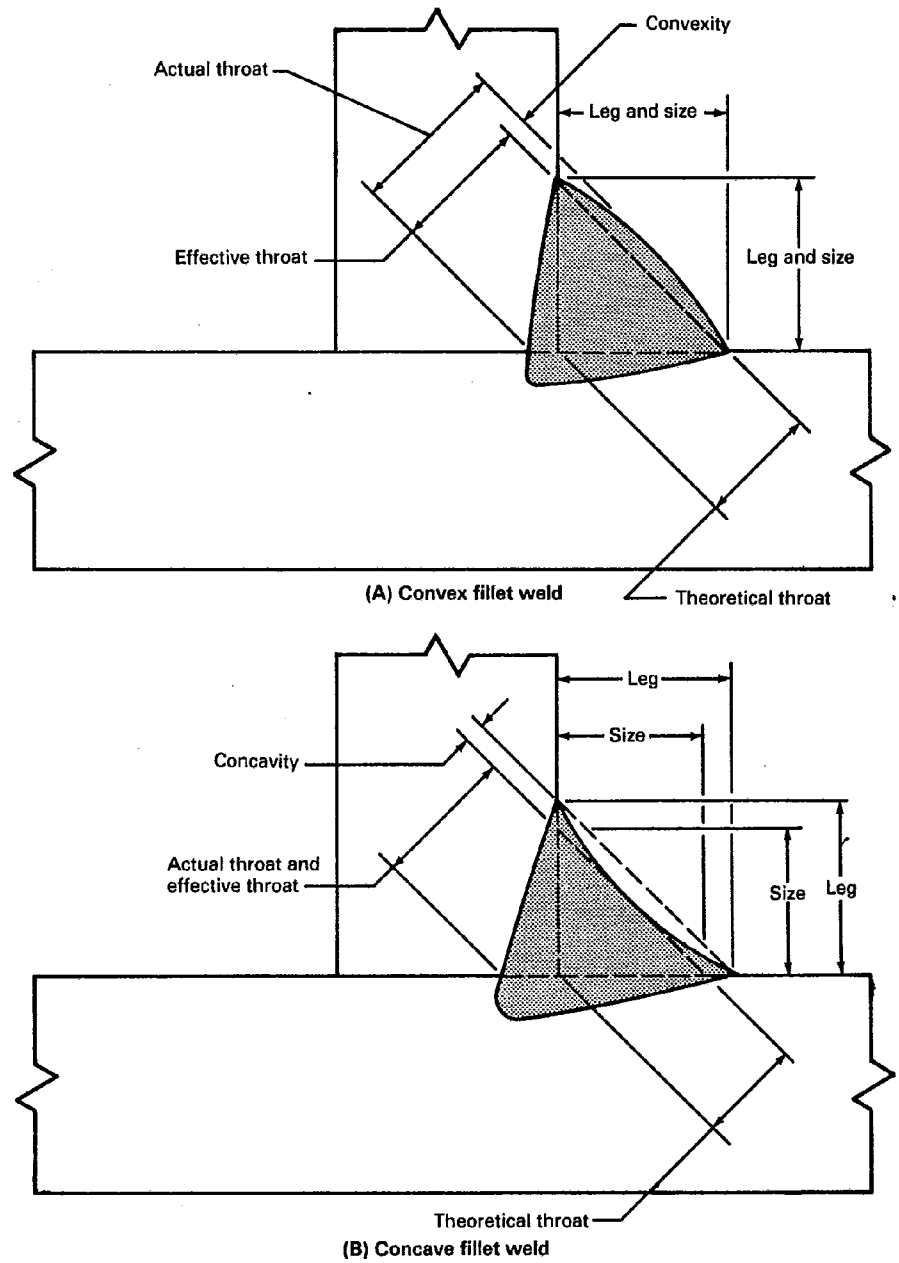
Fillet welds are always designed on the basis of shear stress on the throat. The maximum shear stress appears on the effective area of the weld. In the case of steel, the maximum shear stress is normally limited to about 30 percent of the nominal (classification) tensile strength of the weld metal.

#### Weld Size

Fillet welds must be large enough to carry the applied load and to accommodate shrinkage of the weld metal during cooling if cracking is to be avoided, particularly with highly restrained, thick sections. However, the specified fillet weld size should not be excessive to minimize distortion and welding costs. Welds in lap joints cannot exceed in size the thickness of the exposed edge, which should be visible after welding.

Fillet welds may be designed with unequal leg sizes to provide the required effective throat or the needed heat balance for complete fusion with unequal base metal thicknesses.

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**Fig. 1.25—Fillet weld size**