# Properties of Materials

## 1. IMPORTANCE OF PROPERTIES

All materials have certain properties which must be known in order to promote their proper use. These properties are essential to selection of the best material for a given member.*

In the design of structural members, the properties of materials which are of primary concern are those that indicate material behavior under certain types of load. Some property of material is called for in each of the basic design formulas.

Properties commonly found in engineering handbooks and suppliers catalogs are these:

1. ultimate tensile strength
2. yield strength in tension
3. elongation
4. modulus of elasticity
5. compressive strength
6. shear strength
7. fatigue strength

Other properties such as modulus of resilience and ultimate energy resistance, may also be given.

Tables 1 and 2 present physical properties and chemical composition of various steels. These are proprietary steels that are not provided for by the ASTM specifications for basic steels used in the structural field. The specification steels are covered in Section 7.1 on the Selection of Structural Steel.

* Also see "Metals and How to Weld Them" by T. B. Jefferson and G. Woods; James F. Lincoln Arc Welding Foundation.

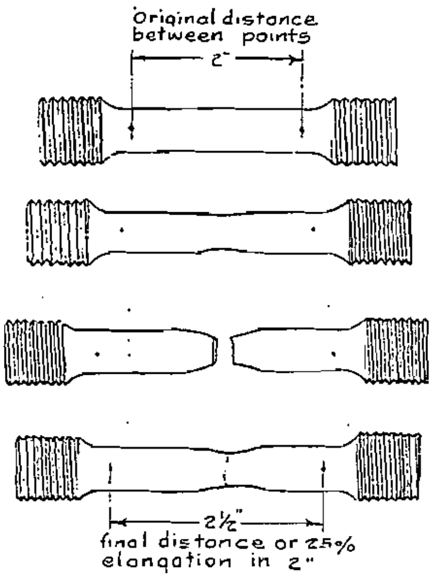


FIG. 1 Tensile test specimen before and after testing to failure, showing maximum elongation.

**TABLE 1—Properties and Composition of Constructional Alloy Steels**

| Producer | Alloy | Yield Point, psi | Ult. Strength, psi | Elong., % | C | Mn | Si | Cu | Mo | Cr | Ni | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Nominal Composition, % | | | | | | | |
| Great Lakes Steel | N-A-Xtra 80 | 80,000 | 95,000 | 18 | 0.15 | 0.80 | 0.70 | | 0.20 | 0.65 | | 0.09 Zr |
| | 90 | 90,000 | 105,000 | 18 | 0.15 | 0.80 | 0.70 | | 0.20 | 0.65 | | 0.09 Zr |
| | 100 | 100,000 | 115,000 | 18 | 0.15 | 0.80 | 0.70 | | 0.20 | 0.65 | | 0.09 Zr |
| | 110 | 110,000 | 125,000 | 18 | 0.15 | 0.80 | 0.70 | | 0.20 | 0.65 | | 0.09 Zr |
| Jones & Laughlin | Jalloy-S-90 | 90,000 | 105,000 | 18 | 0.15 | 1.25 | 0.25 | | 0.25 | | | |
| | Jalloy-S-100 | 100,000 | 115,000 | 18 | 0.15 | 1.25 | 0.25 | | 0.25 | | | Cb |
| | Jalloy-S-110 | 110,000 | 125,000 | 18 | 0.15 | 1.25 | 0.25 | | 0.25 | | | Cb |
| Lukens Steel | T-1 | 100,000 | 115,000 | 18 | 0.15 | 0.80 | 0.25 | 0.35 | 0.55 | 0.60 | 0.85 | V, B |
| Republic Steel | Republic 65 | 65,000 | 85,000 | 20 | 0.15 | 1.00 | 0.15 | 1.15 | 0.25 | | 1.25 | |
| | 70 | 70,000 | 90,000 | 18 | 0.20 | 1.00 | 0.15 | 1.25 | 0.25 | | 1.50 | |
| US Steel | T-1 | 100,000 | 115,000 | 18 | 0.15 | 0.80 | 0.25 | 0.35 | 0.55 | 0.60 | 0.85 | V, B |
| Youngstown Sheet & Tube | Yoloy S | 65,000 | 95,000 | 20 | 0.12 | 0.60 | 0.30 | 1.00 | | | 1.80 | |

— Table courtesy PRODUCT ENGINEERING Magazine

## TABLE 2—Properties and Composition of High-Strength Low Alloy Steels

| Producer | Alloy | Yield Point, psi | Ult. Strength, psi | Elong., % | Nominal Composition, % C | Mn | Si | Cu | Mo | Cr | Ni | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alan Wood Steel | Dynalloy I | 50,000 | 70,000 | 22 | 0.15 | 0.80 | 0.30 | 0.45 | 0.10 | | 0.55 | |
| | Dynalloy II | 45,000 | 62,000 | 25 | 0.15 | 0.80 | 0.30 | 0.45 | 0.10 | | 0.55 | |
| Armco Steel | High Strength No. 1 | 50,000 | 70,000 | 22 | 0.15 | 0.70 | 0.15 | 0.60 | | | 0.75 | |
| | 2 | 45,000 | 64,000 | | 0.15 | 0.70 | 0.15 | 0.60 | | | 0.75 | |
| | 3 | 40,000 | 60,000 | 35 | 0.10 | 0.60 | 0.10 | 0.20 | | | | 0.02 V |
| | 4 | 50,000 | 70,000 | 22 | 0.25 | 1.35 | 0.25 | 0.20 | | | | |
| | 5 | 45,000 | 60,000 | 25 | 0.22 | 1.25 | 0.30 | 0.20 | | | | 0.02 V |
| Bethlehem Steel | Mayari R | 50,000 | 70,000 | 22 | 0.12 | 0.75 | 0.55 | 0.50 | | 0.70 | 1.0 | 0.10 Zr |
| | Medium Manganese | 50,000 | 75,000 | 20 | 0.25 | 1.35 | 0.30 | 0.30 | | | | |
| | Manganese Vanadium | 50,000 | 70,000 | 22 | 0.22 | 1.25 | 0.30 | 0.20 | | | | 0.02 V |
| Crucible Steel of America | Maxeloy | 50,000 | 70,000 | 22 | 0.15 | 1.20 | 0.50 | 0.20 | | | 0.50 | |
| Colorado Fuel & Iron | Clay-Loy | 50,000 | 70,000 | | 0.22 | 1.25 | 0.35 | 0.50 | | | | 0.2 V |
| Inland Steel | Hi-Steel | 50,000 | 70,000 | 22 | 0.12 | 0.75 | 0.15 | 0.95 | 0.18 | | 0.55 | |
| | Hi-Man | 50,000 | 75,000 | 20 | 0.25 | 1.35 | 0.30 | 0.20 | | | | |
| | Hi-Man 440 (A440) | 50,000 | 70,000 | | 0.28 | 1.35 | 0.30 | 0.20 | | | | |
| | Tri-Steel | 50,000 | 70,000 | 22 | 0.22 | 1.25 | 0.30 | 0.20 | | | | 0.02 V |
| Jones & Laughlin | Jalten No. 1 | 50,000 | 70,000 | 22 | 0.15 | 1.30 | 0.10 | 0.30 | | | | 0.05 V |
| | 2 | 50,000 | 70,000 | 22 | 0.15 | 1.40 | 0.10 | 0.30 | | | | |
| | 3 | 50,000 | 70,000 | 22 | 0.25 | 1.50 | 0.25 | 0.20 | | | | |
| | JLX-45-W | 45,000 | 65,000 | 22 | 0.15 | 0.75 | 0.10 | | | | | 0.03 Cb |
| | -50-W | 50,000 | 70,000 | 22 | 0.15 | 0.75 | 0.10 | | | | | 0.03 Cb |
| | -55-W | 55,000 | 75,000 | 22 | 0.15 | 0.75 | 0.10 | | | | | 0.03 Cb |
| | -60-W | 60,000 | 80,000 | 22 | 0.15 | 0.75 | 0.10 | | | | | 0.03 Cb |
| Kaiser Steel | Kaisaloy No. 1 | 50,000 | 70,000 | 23 | 0.20 | 1.25 | 0.60 | 0.35 | 0.15 | 0.25 | 0.60 | V, Ti |
| | 2 | 45,000 | 60,000 | 25 | 0.12 | 0.60 | 0.50 | 0.30 | 0.10 | 0.25 | 0.60 | V, Ti |
| | 3 | 58,000 | 83,000 | 15 | 0.30 | 1.50 | 0.35 | 0.35 | 0.10 | 0.25 | 0.40 | V, Ti |
| | *Structural High Strength* | *50,000* | *75,000* | *18* | *0.27* | *1.60* | *0.30* | *0.20* | | | | |
| Lukens Steel | Cor-Ten | 50,000 | 70,000 | 22 | 0.12 | 0.35 | 0.50 | 0.40 | | 0.80 | 0.65 | |
| National Steel (Great Lakes Steel and Weirton Steel) | GLX-45-W | 45,000 | 65,000 | 22 | 0.15 | 0.75 | 0.10 | | | | | 0.03 Cb |
| | GLX-50-W | 50,000 | 70,000 | 22 | 0.15 | 0.75 | 0.10 | | | | | 0.03 Cb |
| | GLX-55-W | 55,000 | 75,000 | 22 | 0.15 | 0.75 | 0.10 | | | | | 0.03 Cb |
| | GLX-60-W | 60,000 | 80,000 | 22 | 0.15 | 0.75 | 0.10 | | | | | 0.03 Cb |
| | N-A-X High Tensile | 50,000 | 70,000 | 22 | 0.15 | 0.75 | 0.75 | 0.25 | 0.20 | 0.55 | | 0.10 Zr |
| | N-A-X High Manganese | 50,000 | 70,000 | 22 | 0.25 | 1.35 | 0.30 | 0.20 | | | | |
| Pittsburgh Steel | Pitt-Ten No. 1 | 50,000 | 70,000 | 22 | 0.12 | 0.75 | 0.20 | 0.85 | | | 0.70 | |
| Republic Steel | Republic 50 | 50,000 | 70,000 | 22 | 0.15 | 0.75 | | 0.65 | 0.10 | 0.30 | 0.75 | |
| | Republic M | 50,000 | 75,000 | 20 | 0.25 | 1.35 | 0.30 | 0.20 | | | | |
| US Steel | Cor-Ten | 50,000 | 70,000 | 22 | 0.12 | 0.35 | 0.50 | 0.40 | | 0.80 | 0.65 | |
| | Ex-Ten-45 | 45,000 | | | 0.20 | 0.75 | 0.10 | | | | | 0.01 Cb |
| | Ex-Ten-50 | 50,000 | | | 0.25 | 0.75 | 0.10 | | | | | 0.01 Cb |
| | Man-Ten | 50,000 | 75,000 | 20 | 0.25 | 1.35 | 0.30 | 0.20 | | | | |
| | Man-Ten (A440) | 50,000 | 70,000 | | 0.28 | 1.35 | 0.30 | 0.20 | | | | |
| | Par-Ten | 45,000 | 62,000 | 28 | 0.12 | 0.75 | 0.10 | | | | | 0.04 V |
| | Tri-Ten | 50,000 | 70,000 | 22 | 0.22 | 1.25 | 0.30 | 0.20 | | | | 0.02 V |
| Youngstown Sheet & Tube | Yoloy | 50,000 | 70,000 | 22 | 0.15 | 0.75 | 0.30 | 1.00 | | | 1.70 | |
| | Yoloy A242 | 50,000 | 70,000 | 22 | 0.22 | 1.25 | 0.30 | 0.20 | | | | 0.02 V |
| | Yoloy E HSX | 45,000 | 80,000 | 25 | 0.18 | 1.00 | 0.30 | 0.35 | | 0.40 | 0.70 | |
| | Yoloy EHS | 50,000 | 70,000 | 22 | 0.18 | 1.00 | 0.30 | 0.35 | 0.40 | 0 40 | 0.70 | |
| | Yoloy M-A | 50,000 | 70,000 | 20 | 0.25 | 1.60 | 0.30 | 0.35 | | | | |
| | Yoloy M-B | 45,000 | 70,000 | 22 | 0.23 | 1.40 | 0.25 | 0.20 | | | | |
| | Yoloy 45W | 45,000 | 65,000 | 30 | 0.15 | 0.65 | | | | | | Cb |
| | Yoloy 50W | 50,000 | 70,000 | 28 | 0.15 | 0.65 | | | | | | Cb |

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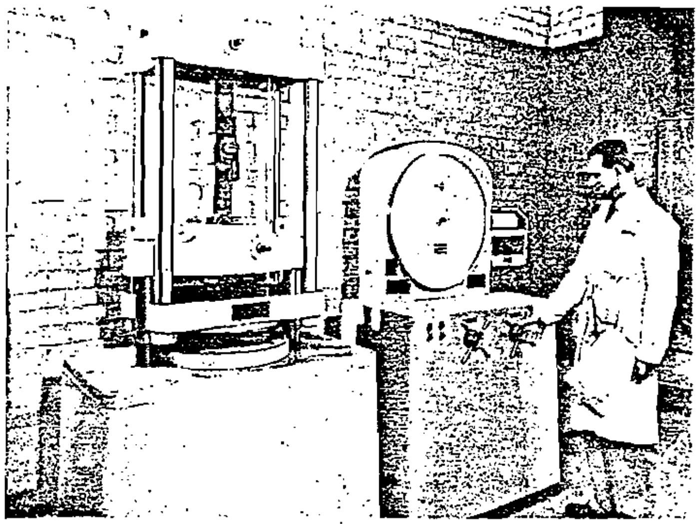

FIG. 2 A tensile testing machine applies a pulling force on the test piece. The maximum load applied before failure of the piece, divided by the original cross-section, equals the material's ultimate tensile strength.

The various properties are best defined by a description of what happens when a specimen of the material is subjected to load during laboratory tests.

## 2. TENSILE PROPERTIES

In a tensile test, the machined and ground specimen of the material is marked with a centerpunch at two points 2″ apart, as shown in Figure 1. The specimen is placed in a tensile testing machine, and an axial load is applied to it by pulling the jaws holding the ends of the specimen in opposing directions at a slow and constant rate of speed, Figure 2.

As the pulling progresses, the specimen elongates at a uniform rate which is proportionate to the rate at which the load or pulling force increases. The load divided by the cross-sectional area of the specimen within the gage marks represents the unit stress or resistance of the material to the pulling or tensile force. This *stress* ($\sigma$) is expressed in pounds per square inch, psi. The elongation of the specimen represents the *strain* ($\epsilon$) induced in the material and is expressed in inches per inch of length, in./in. Stress and strain are plotted in a diagram, shown in simplified form in Figure 3.

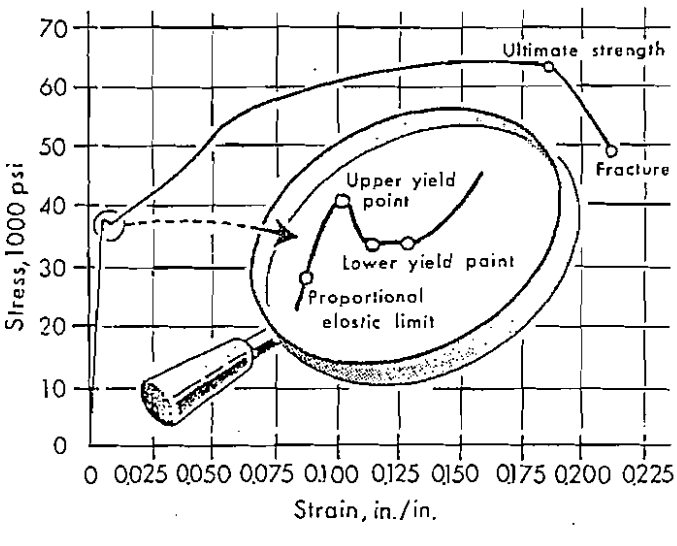


FIG. 3 A stress-strain diagram for mild steel, showing ultimate tensile strength and other properties. Here, the most critical portion of the curve is magnified.

The proportional relationship of load to elongation, or of stress to strain, continues until a point is reached where the elongation begins to increase at a faster rate. This point, beyond which the elongation of the specimen no longer is proportional to the loading, is the *proportional elastic limit* of the material. When the load is removed, the specimen returns to its original dimensions.

Beyond the elastic limit, further movement of the test machine jaws in opposing directions causes a permanent elongation or deformation of the specimen material. In the case of a low- or medium-carbon steel, a point is reached beyond which the metal stretches briefly without an increase in load. This is the yield point.

For low- and medium-carbon steels, the unit stress at the yield point is considered to be the material's *tensile yield strength* ($\sigma_y$).* For other metals, the yield strength is the stress required to strain the specimen by a specified small amount beyond the elastic limit. For ordinary commercial purposes, the elastic limit is assumed to coincide with the yield strength.

Beyond the material's elastic limit, continued pulling causes the specimen to neck down across its diameter or width. This action is accompanied by a

* The symbols commonly used for yield strength, ultimate strength, and axial strain do not indicate the type of load.

further acceleration of the axial elongation, which is now largely confined within the relatively short necked-down section.

The pulling force eventually reaches a maximum value and then falls off rapidly, with little additional elongation of the specimen before failure occurs. In failing, the specimen breaks in two within the necked-down portion. The maximum pulling load, expressed as a stress in psi of the original cross-sectional area of the specimen, is the material's ultimate tensile strength ($\sigma_u$).

### *Ductility and Elasticity*

The two halves of the specimen are then put together, and the distance between the two punch marks is measured (Fig. 1). The increase in length gives the *elongation* of the specimen in 2″, and is usually expressed as a percentage. The cross-section at point of failure is also measured to give the *reduction in area*, which is usually expressed as a percentage. Both elongation percentage and reduction of area percentage indicate the material's *ductility*.

In the design of most members, it is essential to keep the stresses resulting from loading within the elastic range. If the elastic limit (very close to the material's yield strength) is exceeded, permanent deformation takes place due to plastic flow or slippage along molecular slip planes. When this happens, the material is strain-hardened and thereafter has a higher effective elastic limit and higher yield strength.

Under the same amount of stress, some materials stretch less than others. The *modulus of elasticity* (E) of a material simplifies the comparison of its stiffness

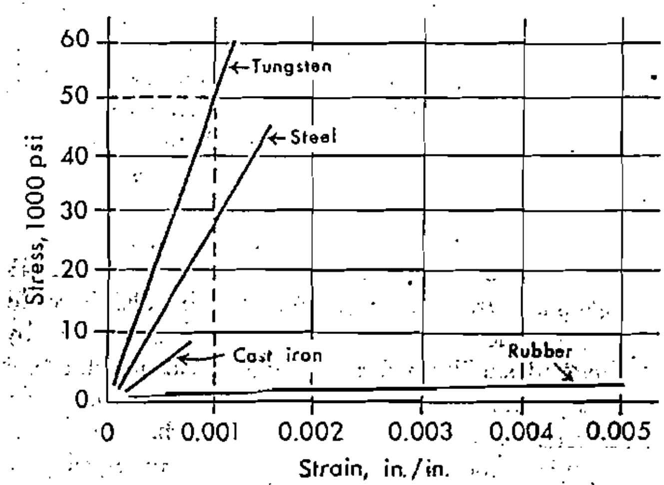


FIG. 4 Stress-strain curves for several materials show their relative elasticity. Only that portion of curve displaying a proportional relationship between stress and strain is diagrammed.

with that of another material. This property is the ratio of the stress to the strain within the elastic range:

$$\frac{\text{Stress } \sigma}{\text{Strain } \epsilon} = \text{Modulus of elasticity E}$$

On a stress-strain diagram, the modulus of elasticity is represented visually by the straight portion of the curve where the stress is directly proportional to the strain. The steeper the curve, the higher the modulus of elasticity and the stiffer the material (Fig. 4).

Any steel has a modulus of elasticity in tension of approximately 30,000,000 psi. AISC in their specifications still use a more conservative value of 29,000,000 psi for the modulus of elasticity of steel. The modulus of elasticity will vary for other metals. Steel, however, has the highest value of any commercially available metal used in the structural field.

## 3. COMPRESSIVE STRENGTH

The general design practice is to assume that the compressive strength of a steel is equal to its tensile strength. This practice is also adhered to in some rigidity design calculations, where the modulus of elasticity of the material in tension is used even though the loading is compressive.

The actual *ultimate compressive strength* of steels may be somewhat greater than the ultimate tensile strength. The variation in compressive values is at least partially dependent on the condition of the steel: the compressive strength of an annealed steel is closer to its tensile strength than would be the case with a cold-worked steel. (There is less of a relationship between the compressive strength and the tensile strength of cast iron and non-ferrous metals.)

A compressive test is conducted similar to that for tensile properties, but a short specimen is subjected to a compressive load. That is, force is applied on the specimen from two directions in axial opposition. The ultimate compressive strength is reached when the specimen fails by crushing.

A stress-strain diagram is developed during the test, and values are obtained for *compressive yield strength* and other properties. However, instead of the Young's modulus of elasticity conventionally used, the *tangential modulus of elasticity* ($E_t$) is usually obtained. This will be discussed in Section 3.1 on Compression.

Compression of long columns is more complex, since failure develops under the influence of a bending moment that increases as the deflection increases. Geometry of the member has much to do with its capacity to withstand compressive loads, and this will

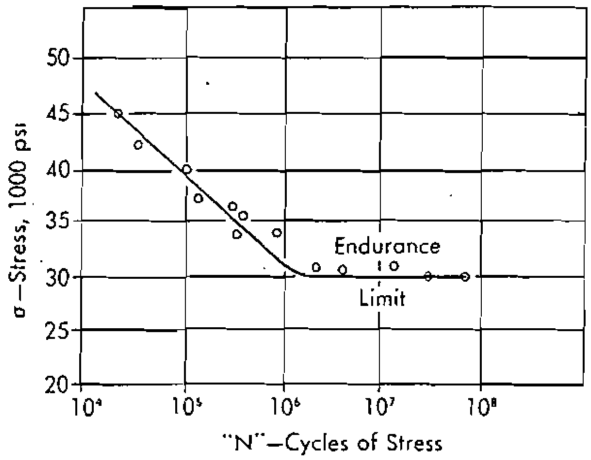


FIG. 5 Fatigue test results are plotted on σ–N diagram; stress vs. number of cycles before failure.

be discussed more completely under Section 3.1.

With long columns, the effect of eccentric loading is more severe in the case of compression than tension.

## 4. SHEAR STRENGTH

There is no recognized standard method of testing for shear strength of a material. Fortunately, pure shear loads are seldom encountered in structural members but shear stresses frequently develop as a by-product of principal stresses or the application of transverse forces.

The ultimate shear strength is often obtained from an actual shearing of the metal, usually in a punch-and-die setup using a ram moving slowly at a constant rate of speed. The maximum load required to punch through the metal is observed, and ultimate shear strength is calculated from this.

Where it is not practical to physically determine it, the *ultimate shear strength* ($\tau$) is generally assumed to be ¾ the material's ultimate tensile strength for most structural steels.

## 5. FATIGUE STRENGTH

When the load on a member is constantly varying in value, is repeated at relatively high frequency, or constitutes a complete reversal of stresses with each operating cycle, the material's fatigue strength must be substituted for the ultimate strength where called for by the design formulas.

Under high load values, the variable or fatigue mode of loading reduces the material's effective ultimate strength as the number of cycles increases. At a given high stress value, the material has a definite service life, expressed as "N" cycles of operation.

A series of identical specimens are tested, each under a specific load value expressible as a unit stress. The unit stress is plotted for each specimen against the number of cycles before failure. The result is a $\sigma$–N diagram (Fig. 5).

The *endurance limit* (usually $\sigma_r$) is the maximum stress to which the material can be subjected for an indefinite service life. Although the standards vary for various types of members and different industries, it is a common practice to accept the assumption that carrying a certain load for several million cycles of stress reversals indicates that load can be carried for an indefinite time.

Theoretically the load on the test specimens should be of the same nature as the load on the proposed member, i.e. tensile, torsional, etc. (Fig. 6).

Since the geometry of the member, the presence of local areas of high stress concentration, and the condition of the material have considerable influence on the real fatigue strength, prototypes of the member or its section would give the most reliable information as test specimens. This is not always practical however. Lacking any test data or handbook values on endurance limit, see Section 2.9 on Fatigue.

## 6. IMPACT PROPERTIES

*Impact strength* is the ability of a metal to absorb the energy of a load rapidly delivered onto the member. A metal may have good tensile strength and good ductility under static loading, and yet break if subjected to a high-velocity blow.

The two most important properties that indicate the material's resistance to impact loading are obtained from the stress-strain diagram (Fig. 7). The first of these is the *modulus of resilience* (u) which is a measure of how well the material absorbs energy providing it is not stressed above the elastic limit or yield

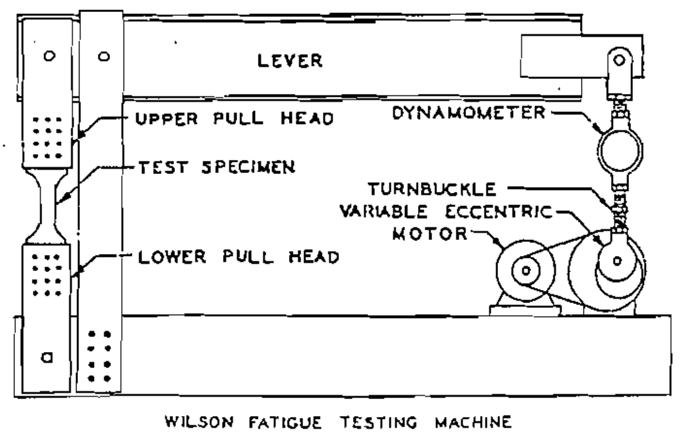


FIG. 6 Typical setup for fatigue testing under pulsating axial stresses.

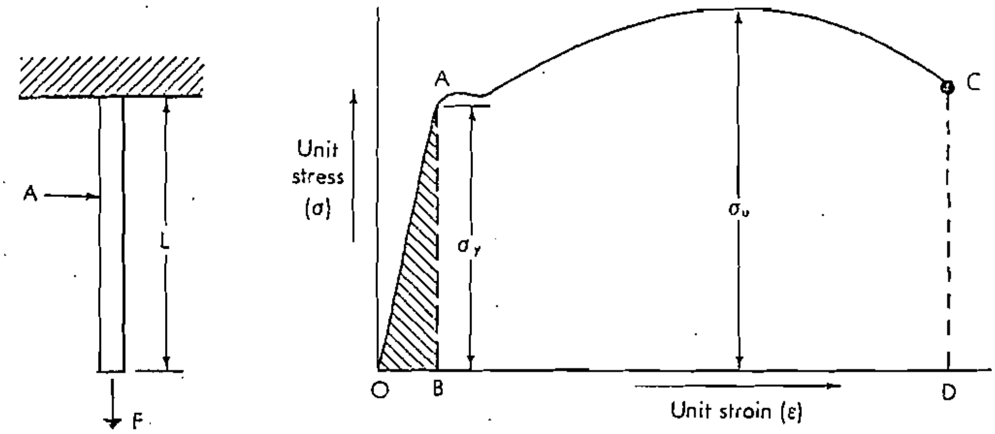


FIG. 7 In the stress-strain diagram for impact, the elongation at moment of ultimate stress is a factor in determining the toughness of the material in terms of ultimate energy resistance.

point. It indicates the material's resistance to deformation from impact loading. (See Section 2.8 on Impact.)

The modulus of resilience (u) is the triangular area OAB under the stress-strain curve having its apex at the elastic limit. For practicality let the yield strength ($\sigma_y$) be the altitude of the right triangle and the resultant strain ($\epsilon_y$) be the base. Thus,

$$u = \frac{\sigma^2}{2E}$$

where E = modulus of elasticity.

Since the absorption of energy is actually a volumetric property, the u in psi = u in in.-lbs/cu. in.

When impact loading exceeds the elastic limit (or yield strength) of the material, it calls for toughness in the material rather than resilience. Toughness, the ability of the metal to resist fracture under impact loading, is indicated by its *ultimate energy resistance* ($u_u$). This is a measure of how well the material absorbs energy without fracture.

The ultimate energy resistance ($u_u$) is the total area OACD under the stress-strain curve. For practicality the following formula can be used:

$$u_u = \frac{\sigma_y + \sigma_u}{2} \epsilon_u$$

where:

$\sigma_y$ = material's shear strength
$\sigma_u$ = material's ultimate strength
$\epsilon_u$ = strain of the material at point of ultimate stress

Since the absorption of energy is actually a volumetric property, the $u_u$ in psi = $u_u$ in in.-lbs/cu. in.

Tests developed for determining the impact strength of materials are often misleading in their results. Nearly all testing is done with notched specimens, in which case it is more accurately the testing for notch toughness.

The two standard tests are the Izod and Charpy. The two types of specimens used in these tests and the method of applying the load are shown in Figure 8. Both tests can be made in a universal impact testing machine. The minimum amount of energy in a falling pendulum required to fracture the specimen is considered to be a measure of the material's impact strength. In actuality, test conditions are seldom duplicated in the working member and application of these test data is unrealistic.

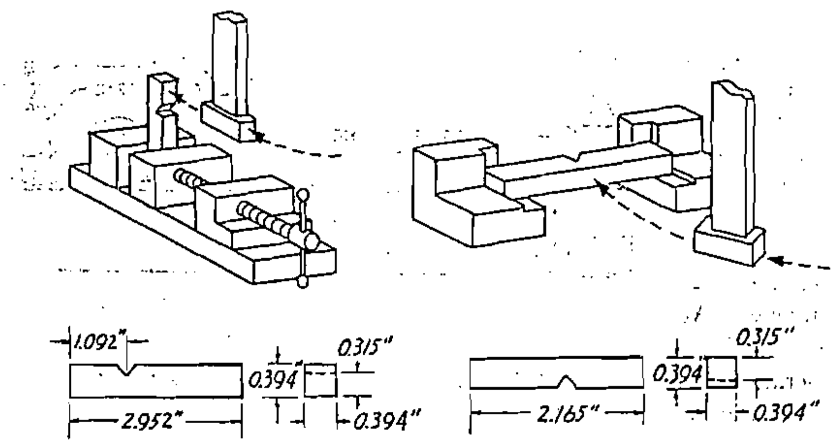


FIG. 8 Typical Izod (left) and Charpy (right) impact test specimens, methods of holding and of applying the test load. The V-notch specimens shown have an included angle of 45° and a bottom radius of 0.010" in the notch.