Material Testing

STRESS-STRAIN RELATIONSHIPS

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Stress-Strain Curve

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Nomenclature

\( A \) area \( \text{in}^2 \)

\( C_v \) impact energy \( \text{ft-lbf} \)

\( E \) modulus of elasticity \( \text{lbf/in}^2 \)

\( F \) force \( \text{lbf} \)

\( L \) length \( \text{in} \)

\( N \) number of cycles

\( S \) strength \( \text{lbf/in}^2 \)

Symbols

\( \gamma \) weight density \( \text{lb/ft}^3 \)

\( \epsilon \) engineering strain \( \text{in/in} \)

\( \sigma \) engineering stress \( \text{lb/ft}^2 \)

Subscripts

\( e \) endurance

\( f \) fracture, final

\( o \) original

\( p \) particular

\( u \) ultimate

\( y \) yield

STRESS-STRAIN RELATIONSHIPS

Engineering Stress and Strain

Figure 41.1 shows a load-elongation curve of tensile test data for a ductile ferrous material (e.g., low-carbon steel or other BCC transition metal). In this test, a prepared material sample (i.e., a specimen) is axially loaded in tension and the resulting elongation, \( \Delta L \), is measured as the load, \( F \), increases.

When elongation is plotted against the applied load, the graph is applicable only to an object with the same length and area as the test specimen. To generalize the test results, the data are converted to stresses and strains by use of Eqs. 41.1 and 41.2. Engineering stress, \( \sigma \) (usually called stress), is the load per unit original area. Typical engineering stress units are \( \text{lbf/in}^2 \) and MPa. Engineering strain, \( \epsilon \) (usually called strain), is the elongation of the test specimen expressed as a percentage or decimal fraction of the original length. The units in/in and m/m are also used for strain.

\[ \sigma = \frac{F}{A_o} \]  

\[ \epsilon = \frac{\Delta L}{L_o} \]

As the stress increases during a tensile test, the length of a specimen increases and the area decreases. Therefore, the engineering stress and strain are not true stress and strain parameters, which must be calculated from instantaneous values of length and area. Figure 41.2 illustrates engineering and true stresses and strains for a ferrous alloy. Although true stress and strain are more accurate, most engineering work has traditionally been...
based on engineering stress and strain, which is justifiable for two reasons: (1) design using ductile materials is limited to the elastic region where engineering and true values differ little, and (2) the reduction in area of most parts at their service stresses is not known; only the original area is known.

**Stress-Strain Curve**

Segment OA in Fig. 41.3 is a straight line. The relationship between the stress and the strain in this linear region is given by Hooke's law, Eq. 41.3. The slope of the line segment OA is the modulus of elasticity, \( E \), also known as Young's modulus. Table 41.1 lists approximate values of the modulus of elasticity for materials at room temperature. The modulus of elasticity will be lower at higher temperatures.

\[ \sigma = E\varepsilon \quad 41.3 \]

The stress at point A in Fig. 41.3 is known as the proportionality limit (i.e., the maximum stress for which the linear relationship is valid). Strain in the proportional region is called proportional (or linear) strain.

**Figure 41.3** Typical Stress-Strain Curve for Steel

The **elastic limit**, point B in Fig. 41.3, is slightly higher than the proportionality limit. As long as the stress is kept below the elastic limit, there will be no permanent set (permanent deformation) when the stress is removed. Strain that disappears when the stress is removed is known as elastic strain, and the stress is said to be in the elastic region. When the applied stress is removed, the recovery is 100% and the material follows the original curve back to the origin.

If the applied stress exceeds the elastic limit, the recovery will be along a line parallel to the straight line portion of the curve, as shown in the line segment PO'. The strain that results (line OO') is permanent set (i.e., a permanent deformation). The terms plastic strain and inelastic strain are used to distinguish this behavior from the elastic strain.

For steel, the **yield point**, point C, is very close to the elastic limit. For all practical purposes, the **yield strength** or yield stress, \( S_y \), can be taken as the stress that accompanies the beginning of plastic strain. Yield strengths are reported in lbf/in\(^2\), kips/in\(^2\), and MPa.

Most nonferrous materials, such as aluminum, magnesium, copper, and other FCC and HCP metals, do not have well-defined yield points. In such cases, the yield point is usually taken as the stress that will cause a 0.2% parallel offset (i.e., a plastic strain of 0.002), shown in Fig. 41.4. However, the yield strength can also be defined by other offset values, or by total strain characteristics.

**Table 41.1** Approximate Modulus of Elasticity of Representative Materials at Room Temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>lbf/in(^2)</th>
<th>MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum alloys</td>
<td>(10-11 \times 10^6)</td>
<td>(7-8 \times 10^4)</td>
</tr>
<tr>
<td>brass</td>
<td>(15-16 \times 10^6)</td>
<td>(10-11 \times 10^4)</td>
</tr>
<tr>
<td>cast iron</td>
<td>(15-22 \times 10^6)</td>
<td>(10-15 \times 10^4)</td>
</tr>
<tr>
<td>cast iron, ductile</td>
<td>(22-25 \times 10^6)</td>
<td>(15-17 \times 10^4)</td>
</tr>
<tr>
<td>cast iron, malleable</td>
<td>(26-27 \times 10^6)</td>
<td>(18-19 \times 10^4)</td>
</tr>
<tr>
<td>copper alloys</td>
<td>(17-18 \times 10^6)</td>
<td>(11-12 \times 10^4)</td>
</tr>
<tr>
<td>glass</td>
<td>(7-12 \times 10^6)</td>
<td>(5-8 \times 10^4)</td>
</tr>
<tr>
<td>magnesium alloys</td>
<td>(6.5 \times 10^6)</td>
<td>(4.5 \times 10^4)</td>
</tr>
<tr>
<td>molybdenum</td>
<td>(47 \times 10^6)</td>
<td>(32 \times 10^4)</td>
</tr>
<tr>
<td>nickel alloys</td>
<td>(26-30 \times 10^6)</td>
<td>(18-21 \times 10^4)</td>
</tr>
<tr>
<td>steel, hard(^{(4)})</td>
<td>(30 \times 10^6)</td>
<td>(21 \times 10^4)</td>
</tr>
<tr>
<td>steel, soft(^{(4)})</td>
<td>(29 \times 10^6)</td>
<td>(20 \times 10^4)</td>
</tr>
<tr>
<td>steel, stainless</td>
<td>(28-30 \times 10^6)</td>
<td>(19-21 \times 10^4)</td>
</tr>
<tr>
<td>titanium</td>
<td>(15-17 \times 10^6)</td>
<td>(10-11 \times 10^4)</td>
</tr>
</tbody>
</table>

(Multiply lbf/in\(^2\) by \(6.89 \times 10^{-3}\) to obtain MPa.)

\(^{(4)}\) Common values given.

The ultimate strength or tensile strength, \( S_u \), point D in Fig. 41.3, is the maximum stress the material can support without failure. This property is seldom used in the design of ductile material, since stresses near...
the ultimate strength are accompanied by large plastic strains.

The breaking strength or fracture strength, $S_f$, is the stress at which the material actually fails (point E in Fig. 41.3). For ductile materials, the breaking strength is less than the ultimate strength, due to the necking down in cross-sectional area that accompanies high plastic strains.

**TESTING METHODS**

**Standard Tensile Test**

Many useful material properties are derived from the results of a standard tensile test. As described previously, a tensile test is performed on a prepared material sample (i.e., a specimen) that is axially loaded in tension. The resulting elongation, $\Delta L$, is measured as the load, $F$, increases.

The standard tensile test may be used to determine the modulus of elasticity, yield strength, ultimate tensile strength, and ductility of a specimen.

Ductility is the ability of a material to yield and deform prior to failure. The percent elongation, short for percent elongation at failure, is the total plastic strain at failure. (Percent elongation does not include the elastic strain, because after ultimate failure the material snaps back an amount equal to the elastic strain.)

\[
\text{percent elongation} = \frac{L_f - L_o}{L_o} \times 100\% \\
= \epsilon_f \times 100\%
\]

Highly ductile materials exhibit large percent elongations at failure. However, percent elongation is not the same as ductility. One typical definition of ductility is given by Eq. 41.5.

\[
\text{ductility} = \frac{\text{ultimate failure strain}}{\text{yielding strain}}
\]

Not all materials are ductile. Brittle materials, such as glass, cast iron, and ceramics, can support only small strains before they fail catastrophically without warning. As the stress is increased, the elongation is linear and Hooke's law can be used to predict the strain. Failure occurs within the linear region, and there is very little, if any, necking down. Since the failure occurs at a low strain, brittle materials are not ductile.

**Endurance Test**

A material can fail after repeated stress loadings even if the stress level never exceeds the ultimate strength, a condition known as fatigue failure.

The behavior of a material under repeated loadings is evaluated by an endurance test (or fatigue test). A specimen is loaded repeatedly to a specific stress amplitude, $\sigma$, and the number of applications of that stress required to cause failure, $N$, is counted. Rotating beam tests that load the specimen in bending (Fig. 41.5) are more common than alternating deflection and push-pull tests but are limited to round specimens. The mean stress is zero in rotating beam tests.

![Figure 41.5 Rotating Beam Test](image)

This procedure is repeated for different stresses using different specimens. The results of these tests are graphed on a semi-log plot, resulting in the $S-N$ curve shown in Fig. 41.6.

![Figure 41.6 Typical S-N Curve for Steel](image)

For a particular stress level, say $S_p$ in Fig. 41.6, the number of cycles required to cause failure, $N_p$, is the fatigue life. $S_p$ is the fatigue strength corresponding to $N_p$.

For steel subjected to fewer than approximately $10^3$ loadings, the fatigue strength approximately equals the ultimate strength. (Although low-cycle fatigue theory has its own peculiarities, a part experiencing a small number of cycles can usually be designed or analyzed as for static loading.) The curve is linear between $10^3$ and approximately $10^6$ cycles if a logarithmic $N$-scale is used.
used. Above $10^6$ cycles, there is no further decrease in strength.

Therefore, below a certain stress level, called the **endurance limit**, endurance stress, or fatigue limit, $S'_e$, the material will withstand an almost infinite number of loadings without experiencing failure. This is characteristic of steel and titanium. If a dynamically loaded part is to have an infinite life, the stress must be kept below the endurance limit.

The yield strength is an irrelevant factor in cyclic loading. Fatigue failures are fracture failures, not yielding failures. They start with microscopic cracks at the material surface. Some of the cracks are present initially; others form when repeated cold working reduces the ductility in strain-hardened areas. These cracks grow minutely with each loading. Since cracks start at the location of surface defects, the endurance limit is increased by proper treatment of the surface. Such treatments include polishing, surface hardening, shot peening, and filleting joints.

The endurance limit is not a true property of the material since the other significant influences, particularly surface finish, are never eliminated. However, representative values of $S'_e$ obtained from ground and polished specimens provide a baseline to which other factors can be applied to account for the effects of surface finish, temperature, stress concentration, notch sensitivity, size, environment, and desired reliability. These other influences are accounted for by reduction factors that are used to calculate a working endurance strength, $S_e$, for the material.

**Impact Test**

**Toughness** is a measure of a material’s ability to yield and absorb highly localized and rapidly applied stress. A tough material will be able to withstand occasional high stresses without fracturing. Products subjected to sudden loading, such as chains, crane hooks, railroad couplings, and so on, should be tough. One measure of a material’s toughness is the **modulus of toughness**, which is the *strain energy* or work per unit volume required to cause fracture. This is the total area under the stress-strain curve. Another measure is the **notch toughness**, which is evaluated by measuring the *impact energy* that causes a notched sample to fail.

In the **Charpy test** (Fig. 41.7), popular in the United States, a standardized beam specimen is given a 45-degree notch. The specimen is then centered on a simple supports with the notch down. A falling pendulum striker hits the center of the specimen. This test is performed several times with different heights and different specimens until a sample fractures.

The kinetic energy expended at impact, equal to the initial potential energy, is calculated from the height. It is designated $C_V$ and is expressed in either foot-pounds (ft-lbf) or joules (J). The energy required to cause failure is a measure of toughness. Note that without a notch, the specimen would experience uniaxial stress (tension and compression) at impact. The notch allows triaxial stresses to develop. Most materials become more brittle under triaxial stresses than under uniaxial stresses.

At 70°F ($21^\circ$C), the energy required to cause failure ranges from 45 ft-lbf (60 J) for carbon steels to approximately 110 ft-lbf (150 J) for chromium-manganese steels. As temperature is reduced, however, the toughness decreases. In BCC metals, such as steel, at a low enough temperature the toughness decreases sharply. The transition from high-energy ductile failures to low-energy brittle failures begins at the **fracture transition plastic (FTP) temperature**.

Since the transition occurs over a wide temperature range, the **transition temperature** (also known as the ductility transition temperature) is taken as the temperature at which an impact of 15 ft-lbf (20 J) will cause failure. This occurs at approximately 30°F ($-1^\circ$C) for low-carbon steel.

---

**Table 41.2 Approximate Ductile Transition Temperatures**

<table>
<thead>
<tr>
<th>type of steel</th>
<th>ductile transition temperature, °F</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbon steel</td>
<td>30°</td>
<td>$-1^\circ$</td>
</tr>
<tr>
<td>high-strength,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>low-alloy steel</td>
<td>0° to 30°</td>
<td>$-18^\circ$ to $-1^\circ$</td>
</tr>
<tr>
<td>heat-treated,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>high-strength carbon</td>
<td>$-25^\circ$</td>
<td>$-32^\circ$</td>
</tr>
<tr>
<td>steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>heat-treated,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>construction alloy</td>
<td>$-40^\circ$ to $-80^\circ$</td>
<td>$-40^\circ$ to $-62^\circ$</td>
</tr>
</tbody>
</table>
The appearance of the fractured surface is also used to evaluate the transition temperature. The fracture can be fibrous (from shear fracture) or granular (from cleavage fracture), or a mixture of both. The fracture planes are studied and the percentages of ductile failure are plotted against temperature. The temperature at which the failure is 50% fibrous and 50% granular is known as fracture appearance transition temperature, FATT.

Not all materials have a ductile-brittle transition. Aluminum, copper, other FCC metals, and most HCP metals do not lose their toughness abruptly. Figure 41.8 illustrates the failure energy curves for several materials.

Sample Problems

Problem 1
What is the ratio of stress to strain below the proportional limit called?
(A) the modulus of rigidity
(B) Hooke’s constant
(C) Poisson’s ratio
(D) Young’s modulus

Solution
Young’s modulus is defined by Hooke’s law.

\[ \sigma = E\epsilon \]

\( E \) is Young’s modulus, or the modulus of elasticity, equal to the stress divided by strain within the proportional region of the stress-strain curve.

Answer is D.

Problem 2
What is the value of 40 MPa in the following illustration called?

![Graph showing failure energy versus temperature]

I. fatigue limit
II. endurance limit
III. proportional limit
IV. yield stress

(A) I only
(B) I and II
(C) II and IV
(D) I, II, and IV

Solution
The diagram shows results of an endurance (or fatigue) test. The value of 40 MPa is called the endurance stress, endurance limit, or fatigue limit, and is equal to the maximum stress that can be repeated indefinitely without causing the specimen to fail.

Answer is B.

Problem 3
What does the Charpy test determine?
(A) endurance
(B) yield strength
(C) ductility
(D) toughness

Solution
The Charpy test is an impact test to measure the toughness of the material—localized and rapidly applied stress.

Answer is D.
FE-STYLE EXAM PROBLEMS

Problems 1–5 refer to the following illustration.

1. What test is represented by the diagram?
   (A) resilience test
   (B) rotating beam test
   (C) ductility test
   (D) tensile test

2. Which of the following is most likely the material that was tested to produce these results?
   (A) glass
   (B) concrete
   (C) low-carbon steel
   (D) aluminum

3. What is the modulus of elasticity?
   (A) $2 \times 10^4$ MPa
   (B) $8 \times 10^4$ MPa
   (C) $12.5 \times 10^4$ MPa
   (D) $20 \times 10^4$ MPa

4. What is the ductility?
   (A) 14
   (B) 19
   (C) 25
   (D) 215

5. What is the percent elongation at failure?
   (A) 14%
   (B) 19%
   (C) 25%
   (D) 28%

For the following problems use the NCEES Handbook as your only reference.

6. Which of the following material properties cannot be determined directly from a standard tensile test?
   (A) modulus of elasticity
   (B) yield strength
   (C) ultimate strength
   (D) hardness

7. The density of a particular metal is 2750 kg/m³. The modulus of elasticity for this metal is 210 GPa. A circular bar of this metal 3.5 m long and 160 cm² in cross-sectional area is suspended vertically from one end. What is the elongation of the bar due to its own mass?
   (A) 0.00055 mm
   (B) 0.00079 mm
   (C) 0.0016 mm
   (D) 0.0024 mm

8. Which of the following is the primary factor in determining if sheet metal can be bent and formed without experiencing stress fractures and other undesirable effects?
   (A) martensitic structure
   (B) surface hardness
   (C) modulus of elasticity
   (D) ductility

9. Which of the figures is (are) illustrative of a ductile metal after a tensile failure?
   I.
   II.
III.

(A) I only  
(B) II only  
(C) III only  
(D) I and II

10. What test is used to determine the toughness of a material under shock loading?
   (A) impact test  
   (B) hardness test  
   (C) fatigue test  
   (D) creep test

11. Which of the following cannot be used as a nondestructive testing method for steel castings and forgings?
   (A) radiography  
   (B) magnetic particle testing  
   (C) ultrasonic testing  
   (D) chemical analysis

**SOLUTIONS TO FE-STYLE EXAM PROBLEMS**

1. The diagram shows results from a tensile test. Both resilience and ductility may be calculated from the results, but the test is not known by those names. The rotating beam is a cyclic test and does not yield a monotonic stress-strain curve.

   Answer is D.

2. The diagram shows results for a material with high ductility. Glass and concrete are relatively brittle materials. Aluminum may be ductile, but it does not have a well-defined yield point. Most likely, steel is the material tested.

   Answer is C.

3. The modulus of elasticity (Young’s modulus) is the slope of the stress-strain line in the proportional region.

   \[ E = \frac{\sigma}{\epsilon} = \frac{150 \text{ MPa}}{0.00075} = 200,000 \text{ MPa} \ (20 \times 10^4 \text{ MPa}) \]

   Answer is D.

4. Ductility is the ratio of ultimate to yield strain.

   \[ \text{ductility} = \frac{\text{ultimate failure strain}}{\text{yielding strain}} = \frac{0.28}{0.0013} = 215 \]

   Answer is D.

5. percent elongation \( = \epsilon_f \times 100\% \)
   \[ = 0.25 \times 100\% = 25\% \]

   The strain at failure used in the equation is found by extending a line from the failure point to the strain axis, parallel to the linear portion of the curve. Note that the percent elongation is an indicator of the ductility of a material, but it is not the same as the ductility, which was calculated in Prob. 4.

   Answer is C.

6. The standard tensile test can determine the modulus of elasticity, yield strength, ultimate tensile strength, and ductility. Poisson’s ratio can be determined from the lateral and axial strains. Although correlations between surface hardness and ultimate strength have been developed, hardness cannot be measured directly.

   Answer is D.

7. The mass of the bar is

   \[ \text{mass} = \rho V = \rho AL = \left( 2750 \frac{\text{kg}}{\text{m}^3} \right) \left( 160 \text{ cm}^2 \right) \left( \frac{1 \text{ m}}{100 \text{ cm}} \right)^2 (3.5 \text{ m}) = 154 \text{ kg} \]

   The total gravitational force is experienced by the metal at the suspension point. Farther down the rod, however, there is less volume contributing to the force, and the stress is reduced. The average force on the metal in the bar is half of the maximum value.

   \[ F_{\text{ave}} = \frac{1}{2} F_{\text{max}} = \frac{1}{2} mg = \left( \frac{1}{2} \right) (154 \text{ kg}) \left( 9.81 \frac{\text{m}}{\text{s}^2} \right) = 755 \text{ N} \]
The elongation is
\[
\Delta L = \epsilon L_0 = \frac{\sigma}{E} L_0
\]
\[
= \frac{F}{AE} L_0
\]
\[
= \frac{755 \text{ N}(3.5 \text{ m})}{(160 \text{ cm}^2) \left( \frac{1 \text{ m}}{100 \text{ cm}} \right)^2 (210 \times 10^9 \text{ Pa})}
\]
\[
= 7.86 \times 10^{-7} \text{ m} \quad (0.00079 \text{ mm})
\]

Answer is B.

8. Ductility is a measure of a material's ability to deform without failure.

Answer is D.

9. I is a necking failure, typical of very ductile materials. II is a cup-and-cone failure, common of moderately ductile materials. III is a shear failure, common of brittle materials. There is no reduction in the area at failure.

Answer is D.

10. Toughness is defined as a measure of a material's ability to absorb highly localized, rapidly applied (shock) loads. The impact test measures toughness.

Answer is A.

11. Chemical analysis requires a sample of the material to be taken. Tests that require taking samples of the material are not nondestructive tests. All of the other methods can be used with steel castings and forgings.

Answer is D.