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A PRIMER ON MATERIALS FOR A MARINE ENVIRONMENT

Main Category:	Naval Engineering
Sub Category:	-
Course #:	NAV-114
Course Content:	28 pgs
PDH/CE Hours:	2

OFFICIAL COURSE/EXAM

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NAV-114 EXAM PREVIEW

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Exam Preview:

1. Strain is the concept used to compare the elongation of a material to its original, undeformed length. Strain has no units but is often given the units of in/in or ft/ft.
    a. True
    b. False
2. If the original and final length of the cable were measured, one would find that the cable is longer under the 25,000 pound load than when it was unloaded. A steel cable originally 75 feet long would be almost ______ longer under the 25,000 pound load.
    a. 4 inches
    b. 3 inches
    c. 2 inches
    d. 1 inch
3. According to the reference material, there are four material properties that do a good job at describing the characteristics of a material. They are strength, hardness, toughness, and ductility.
    a. True
    b. False
4. Stress-Strain diagrams are used to study the behavior of a material from the point it is loaded until it breaks. Which region of the stress strain diagram matches the description: Permanently straining the material to increase the Yield Strength?
    a. Elastic Region
    b. Plastic Region
    c. Strain Hardening
    d. Necking

5. Using the Material Properties section of the reference material, which of the following material properties matches the description: is a measure of the material's ability to resist indentation, abrasion and wear?
    a. Strength
    b. Hardness
    c. Ductility
    d. Toughness
6. Another important material property is its ability to withstand fatigue. Fatigue is the repeated application of stress typically produced by an oscillating load or vibration.
    a. True
    b. False
7. Alloying is the addition of elements to the base metal for the purpose of changing the material characteristics. According to the reference material, the element tungsten is added into an alloy in order to increase what property?
    a. Ductility
    b. Brittleness
    c. Strength
    d. Hardness
8. Using the Thermal Treatment of Metals section of the refence material, which of the following processes matches the description: like annealing, is also used to relieve internal stresses, change the internal grain size, and improve manufacturability of steel?
    a. Precipitation hardening
    b. Hardening
    c. Tempering
    d. Hot working
9. Nondestructive testing (NDT) methods are inspections for material defects. The governing documents are MIL-STD-271 F and NAVSEA 5000 and 6000 series manuals.
    a. True
    b. False
10. Using the Non-Destructive Testing section of the reference material, which of the following methods is NOT and external inspection technique?
    a. Visual Testing
    b. Dye Penetrant Testing
    c. Magnetic Particle Testing
    d. Ultrasonic Testing

COURSE OBJECTIVES
CHAPTER 5

5. PROPERTIES OF NAVAL MATERIALS

1. Define a normal load, shear load, and torsional load on a material.
2. Define tension and compression.
3. Understand the concepts of stress and strain.
4. Calculate stress and strain.
5. Interpret a Stress-Strain Diagram including the following characteristics:
    a. Slope and Elastic Modulus
    b. Elastic Region
    c. Yield Strength
    d. Plastic Region
    e. Strain Hardening
    f. Tensile Strength
6. Be familiar with the following material characteristics:
    a. Ductility
    b. Brittleness
    c. Toughness
    d. Transition Temperature
    e. Endurance Limit
7. Be familiar with the following methods of non-destructive testing:
    a. Visual Test
    b. Dye Penetrant Test
    c. Magnetic Particle Test
    d. Ultrasonic Test
    e. Radiographic Test
    f. Eddy Current Test
    g. Hydrostatic Test

5.1 Classifying Loads on Materials

5.1.1 Normal Loads

One type of load which can be placed on a material is a *Normal Load*. Under a normal load, the material supporting the load is perpendicular to the load, as in Figures 5.1 and 5.2.

Normal loads may be either tensile or compressive. When a material is in tension, it is as if the ends are being pulled apart to make the material longer. Pulling on a rope places the rope in tension. Compression is the opposite of tension. When a material is in compression, it is as if the ends are being pushed in, making the material smaller. Pressing down on a book lying on a table places the book in compression.

Figure 5.1 Normal Tension

Figure 5.2 Normal Compression

5.1.2 Shear Loads

A second type of loading is called shear. When a material experiences shear, the material supporting the load is parallel to the load. Pulling apart two plates connected by a bolt, as in Figure 5.3, places the bolt in shear.

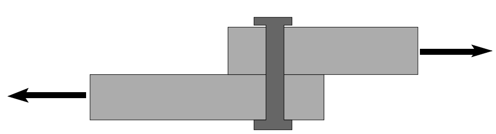


Figure 5.3 Shear

5.1.3 Torsion Loads

Another common type of loading is due to torsion. A component, such as a shaft, will “twist” or angularly distort due to an applied moment (M) or torque. This type of loading is seen on helicopter rotor shafts and ship propulsion shafting and may result in large amounts of angular deflection. Figure 5.4 illustrates torsional loading on a shaft.

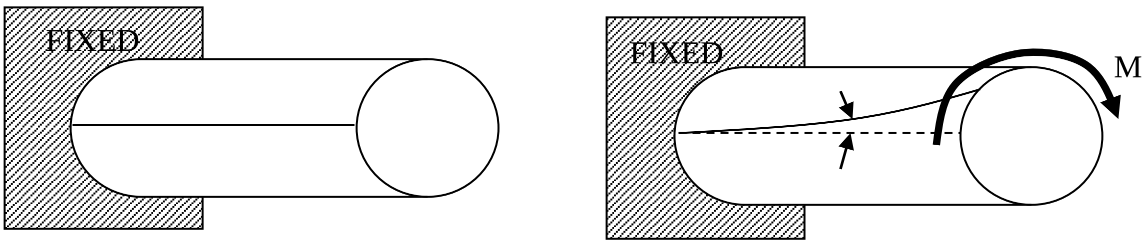


Figure 5.4 Torsion on a circular shaft

(!) Angular deflection of a shaft is a function of geometry (length and diameter), material type, and the amount of moment applied. Longer, thinner, and more ductile shafts will distort the most.

5.1.4 Thermal Loads

When a material is heated it tends to expand and conversely, when it is cooled it contracts. If the material is constrained from expanding or contracting in any direction, then the material will experience a normal load in the plane(s) that it is constrained. This is a special type of normal load that depends on the heat transfer characteristics of the material.

5.2 Stress and Strain

5.2.1 Stress

Very thick lines or wire ropes are used to moor an aircraft carrier to a pier. The forces on these mooring lines are tremendous. Obviously, thin steel piano wires cannot be used for this purpose because they would break under the load. The mooring lines and the piano wire may both be made of the same material, but because one will support the load and the other will not, the need to compare the magnitude of the load to the amount of material supporting the load is illustrated.

The concept of stress performs that comparison. Stress (σ) is the quotient of load (F) and area (A) as shown in Equation 5-1. The units of stress are normally pounds per square inch (psi).

$$\sigma = \frac{F}{A}$$

where:
- σ is the stress (psi)
- F is the force that is loading the object (lb)
- A is the cross sectional area of the object (in^2)

Example 5.1 A particular mooring line with a diameter of 1.00 inch is under a load of 25,000 lbs. Find the normal stress in the mooring line.

Solution:

$$\text{Cross Sectional Area } (A) = \pi r^2 = \pi \left(\frac{1\ in}{2}\right)^2 = 0.785\ in^2$$

$$\text{Normal Stress } (\sigma) = \frac{F}{A} = \frac{25{,}000\ lb}{0.785\ in^2} = 31{,}800\ psi$$

5.2.2 Strain

If the original and final length of the cable were measured, one would find that the cable is longer under the 25,000 pound load than when it was unloaded. A steel cable originally 75 feet long would be almost an inch longer under the 25,000 pound load. One inch is then the elongation (e) of the cable. Elongation is defined as the difference between loaded and unloaded length as shown in Equation 5-2.

$$e = L - L_o$$

where:
- e is the elongation (ft)
- L is the loaded length of the cable (ft)
- L_o is the unloaded (original) length of the cable (ft)

The elongation also depends upon original length. For instance, if the original cable length were only ½(75 ft) = 32.5 ft, then the measured elongation would be only 0.5 inch. If the cable length was instead twice 75 feet, or 150 feet, then the elongation would be 2 inches. A way of comparing elongation and length would seem useful.

Strain is the concept used to compare the elongation of a material to its original, undeformed length. Strain (ε) is the quotient of elongation (e) and original length (L_0) as shown in Equation 5-3. Strain has no units but is often given the units of in/in or ft/ft.

$$\varepsilon = \frac{e}{L_o}$$

where: ε is the strain in the cable (ft/ft)
e is the elongation (ft)
L_o is the unloaded (original) length of the cable (ft)

Example 5.2 Find the strain in a 75 foot cable experiencing an elongation of one inch.

Solution:

$$Strain(\varepsilon) = \frac{e(ft)}{L_o(ft)} = \frac{1\,in\ (1\,ft/12in)}{75\,ft} = 1.11x10^{-3}\ ft/ft$$

(!) One can easily substitute the elongations and original lengths from above and see that the numerical value of strain remains the same regardless of the original length of the cable.

Also, note that a conversion from inches to feet is necessary.

5.3 Stress-Strain Diagrams and Material Behavior

Stress and strain are calculated from easily measurable quantities (normal load, diameter, elongation, original length) and can be plotted against one another as in Figure 5.5. Such Stress-Strain diagrams are used to study the behavior of a material from the point it is loaded until it breaks. Each material produces a different stress-strain diagram.

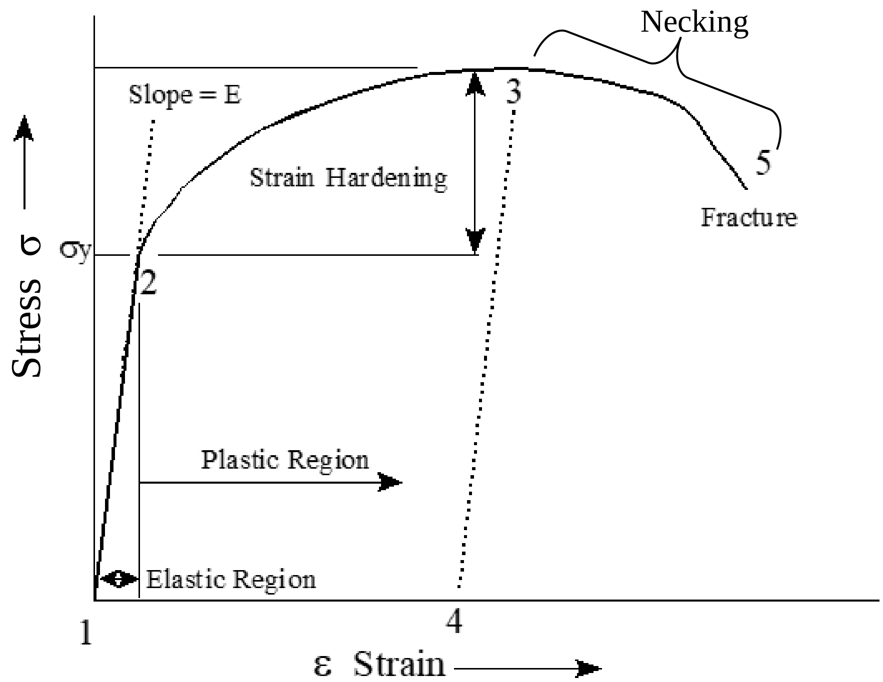


Figure 5.5 Stress/Strain Diagram

Point 1 on the diagram represents the original undeformed, unloaded condition of the material. As the material is loaded, both stress and strain increase, and the plot proceeds from Point 1 to Point 2. If the material is unloaded before Point 2 is reached, then the plot would proceed back dσ_{UTS} e same line to Point 1.

If the material is unloaded anywhere between Points 1 and 2, then it will return to its original shape, like a rubber band. This type of behavior is termed *Elastic* and the region between Points 1 and 2 is the *Elastic Region*.

The Stress-Strain curve also appears linear between Points 1 and 2. In this region stress and strain are proportional. The constant of proportionality is called the *Elastic Modulus* or *Young's Modulus (E)*. The relationship between stress and strain in this region is given by Equation 5-4.

$$E = \frac{\sigma}{\varepsilon} \qquad or \qquad \sigma = E\varepsilon$$

where:
- σ is the stress (psi)
- E is the Elastic Modulus (psi)
- ε is the strain (in/in)

(!) The Elastic Modulus is also the slope of the curve in this region, solved by taking the slope between data points (0,0) and (σ_y, ε_y).

Point 2 is called the *Yield Strength* (σ_y). If it is passed, the material will no longer return to its original length. It will have some permanent deformation. This area beyond Point 2 is the *Plastic Region.* Consider, for example, what happens if we continue along the curve from Point 2 to Point 3, the stress required to continue deformation increases with increasing strain. If the material is unloaded the curve will proceed from Point 3 to Point 4. The slope (Elastic Modulus) will be the same as the slope between Points 1 and 2. The difference between Points 1 and 4 represents the permanent strain of the material. Once in the plastic region, the material remains in the plastic region until failure.

If the material is loaded again, the curve will proceed from Point 4 to Point 3 with the same Elastic Modulus (slope). The Elastic Modulus will be unchanged, but the Yield Strength will be increased. Permanently straining the material in order to increase the Yield Strength is called *Strain Hardening.*

If the material is strained beyond Point 3, stress decreases as non-uniform deformation and necking occur. The sample will eventually reach Point 5 at which it fractures.

The largest value of stress on the diagram is called the *Tensile Strength (TS)* or *Ultimate Tensile Strength (UTS).* This is the most stress the material can support without breaking.

Example 5.3 A tensile test specimen having a diameter of 0.505 in and a gauge length of 2.000 in was tested to fracture-load and deformation data obtained during the test were as follows:

Load (lb)	Change in length (inch)
0	0.0000
2,200	0.0008
4,300	0.0016
6,400	0.0024
8,200	0.0032
8,600	0.0040
8,800	0.0048
9,200	0.0064
9,500	0.0080
9,600	0.0096
10,600	0.0200
11,800	0.0400

Load (lb)	Change in length (inch)
12,600	0.0600
13,200	0.0800
13,900	0.1200
14,300	0.1600
14,500	0.2000
14,600	0.2400
14,500	0.2800
14,400	0.3200
14,300	0.3600
13,800	0.4000
13,000	0.4125 (Fracture)

a. Make a table of stress and strain and plot the stress-strain diagram.

b. Determine the modulus of elasticity

c. Determine the ultimate strength

d. Determine the yield strength

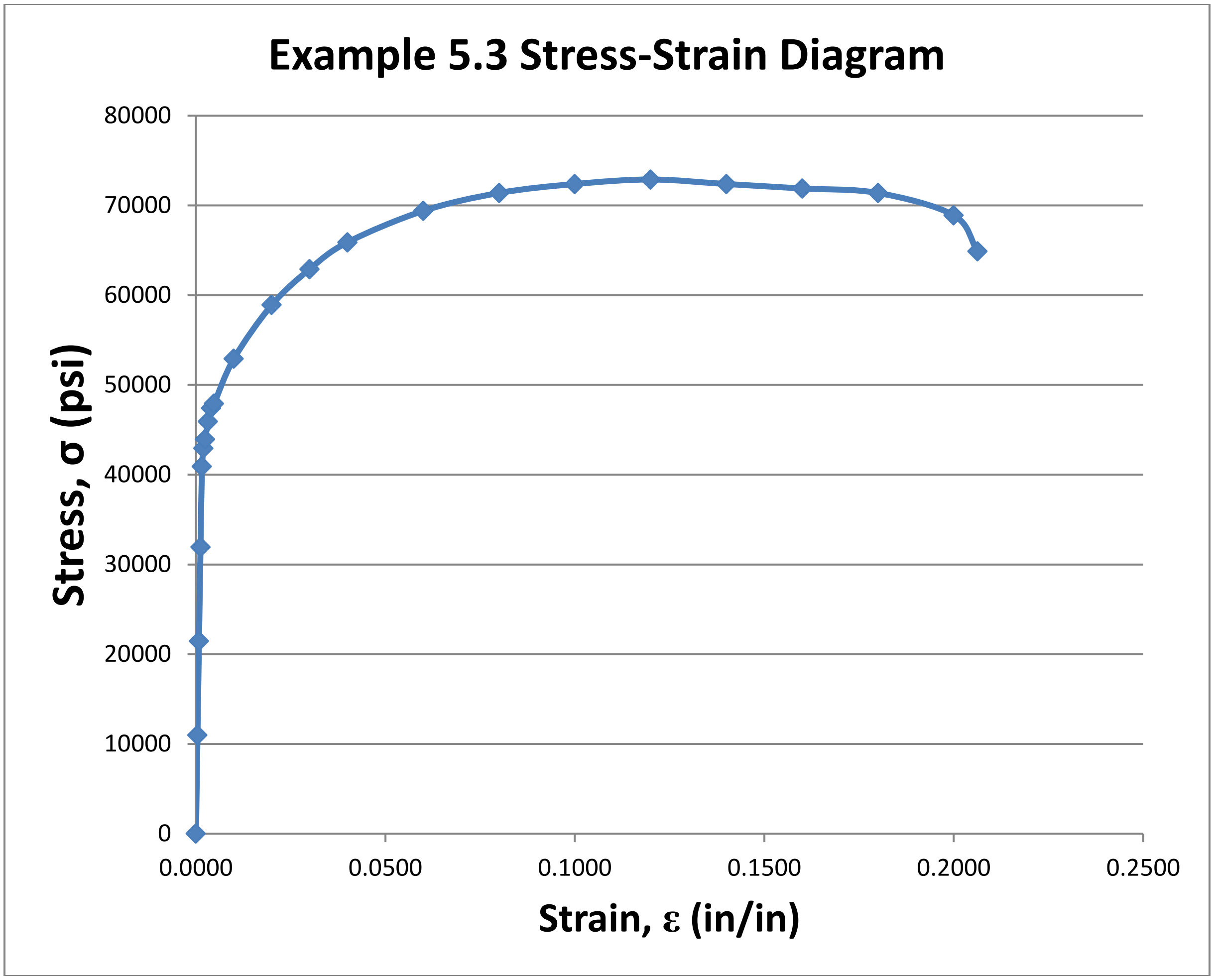
e. Determine the fracture stress

f. Determine the true fracture stress if the final diameter of the specimen at the location of the fracture was 0.425 inch.

Solution:

a. Make a table of stress and strain and plot the stress-strain diagram.

(1)	(2)	(3)	(4)
Load **P** **(lb)**	**Stress** **$\sigma = P/A$** **(psi)** **(2) = (1) / 0.2003 in^2**	**Elongation** **e** **(in)**	**Strain** **$\varepsilon = e/Lo$** **(in/in)** **(4) = (3) / 2 in**
0	0	0.0	0.0
2200	10984	0.0008	0.0004
4300	21468	0.0016	0.0008
6400	31952	0.0024	0.0012
8200	40939	0.0032	0.0016
8600	42936	0.0040	0.0020
8800	43934	0.0048	0.0024
9200	45931	0.0064	0.0032
9500	47429	0.0080	0.0040
9600	47928	0.0096	0.0048
10600	52921	0.0200	0.0100
11800	58912	0.0400	0.0200
12600	62906	0.0600	0.0300
13200	65901	0.0800	0.0400
13900	69396	0.1200	0.0600
14300	71393	0.1600	0.0800
14500	72391	0.2000	0.1000
14600	72891	0.2400	0.1200
14500	72391	0.2800	0.1400
14400	71892	0.3200	0.1600
14300	71393	0.3600	0.1800
13800	68897	0.4000	0.2000
13000	64903	0.4125 (Fract)	0.2063



b. Determine the modulus of elasticity (See plot)

$$E = \frac{32{,}000\ psi}{0.0012\ in/in} = 26.7\ \times\ 10^{6}\ psi$$

c. Determine the ultimate tensile strength (See plot)

$$UTS = \frac{14{,}600\ lb}{0.2003\ in^{2}} = 72{,}890\ psi$$

d. Determine the yield strength (See plot)

$$\sigma_Y = 32{,}000\ psi$$

e. Determine the fracture stress (See plot)

$$\sigma_F = \frac{13{,}000\ lb}{0.2003\ in^2} = 64{,}903\ psi$$

f. Determine the true fracture stress if the final diameter of the specimen at the location of the fracture was 0.425 inch.

$$\text{Cross Sectional Area at Fracture } (A_F) = \pi r_F^2 = \pi \left(\frac{0.425\ in}{2}\right)^2 = 0.142 in^2$$

$$\sigma_{true-F} = \frac{13{,}000\ lb}{0.142\ in^2} = 91{,}638\ psi$$

5.4 Material Properties

There are five material properties that do a good job at describing the characteristics of a material. They are strength, hardness, brittleness, toughness, and ductility. Most terms are used to describe materials comparatively to one another, and help to determine the type of material desired for a specific application.

5.4.1 Strength

Strength is measure of the material's ability to resist deformation and to maintain its shape. Strength can be quantified in terms of yield stress or ultimate tensile strength. Both yield stress and ultimate tensile strength can be determined from tensile test data by plotting a stress strain curve.

High carbon steels and metal alloys exhibit higher strength characteristics than pure metals. Ceramics also exhibit high strength characteristics.

(!) High strength steels used in submarine construction, designated HY-80 and HY-100 have yield stresses of 80,000 psi and 100,000 psi respectively!

5.4.2 Hardness

Hardness is a measure of the material's ability to resist indentation, abrasion and wear. Hardness is quantified by arbitrary hardness scales such as the Rockwell hardness scale or the Brinell hardness scale. These measurements are obtained by a special apparatus that uses an indenter that is loaded with standard weights. The indenter can have various shapes such as a pyramid or a sphere and is pressed into the specimen. Either the depth of penetration or the diameter of the indentation made is measured to quantify material hardness.

Hardness and strength correlate well because both properties are related to inter-molecular bonding.

5.4.3 Ductility

Ductility is a measure of the material's ability to deform before failure. Ductility can be quantified by reading the value of strain at the fracture point on the stress strain curve or by doing a percent reduction in area calculation.

Low carbon steels, pure aluminum, copper, and brass are examples of ductile materials.

5.4.3 Brittleness

Brittleness is a measure of a material's inability to deform before failure. Brittleness is the opposite of ductility. Brittleness is not quantified since it is the inability to deform. However, ductility is quantified as discussed above.

Examples of brittle materials include glass, cast iron, high carbon steels, and many ceramic materials.

Figure 5.6 shows the difference between ductile and brittle behavior on a stress-strain diagram.

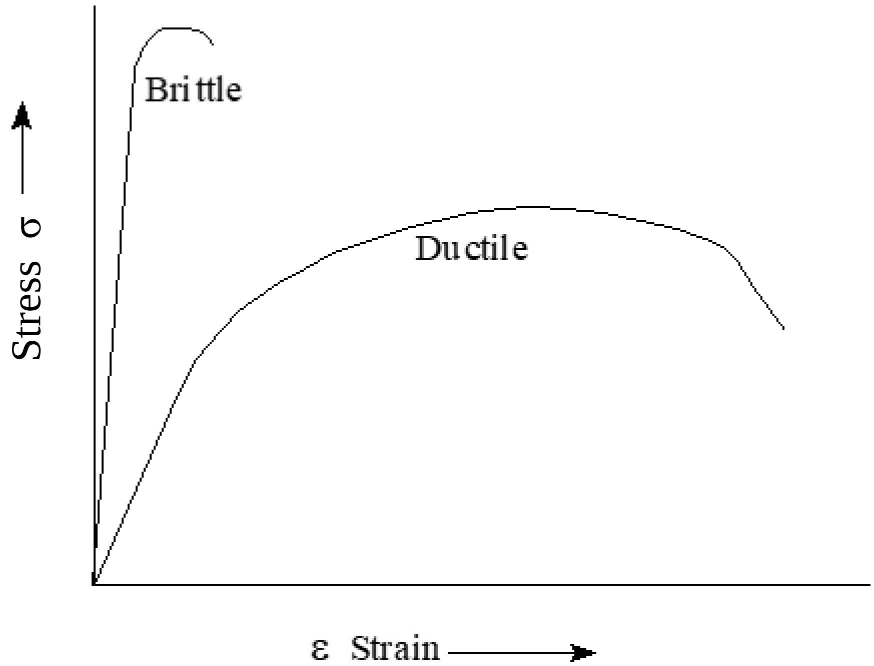


Figure 5.6 Ductile and Brittle Behavior

5.4.5 Toughness

Toughness is a measure of a materials ability to absorb energy. There are two measures of toughness.

5.4.5.1 Material Toughness can be measured by calculating the area under the stress strain curve from a tensile test. The units on this measure of toughness are in-lb/in^3. These are units of energy per volume. *Material Toughness* equates to a slow absorption of energy by the material.

5.4.5.2 Impact Toughness is measured by doing a Charpy V-notch Test. For this test, a specimen of material is broken by a pendulum as shown in Figure 5.7.

Knowing the initial and final height of the pendulum allows the engineer to calculate the initial and final potential energy of the pendulum. The difference in potential energy is the energy it takes to break the material or its *impact toughness*. *Impact toughness* is a measure of a rapid absorption of energy by the material.

The Charpy test for a single material is done with many different specimens where each specimen is held at a different temperature. The purpose of the Charpy test is to evaluate the impact toughness of a specimen as a function of temperature. Figure 5.8 shows a typical Charpy plot for a body centered cubic metal.

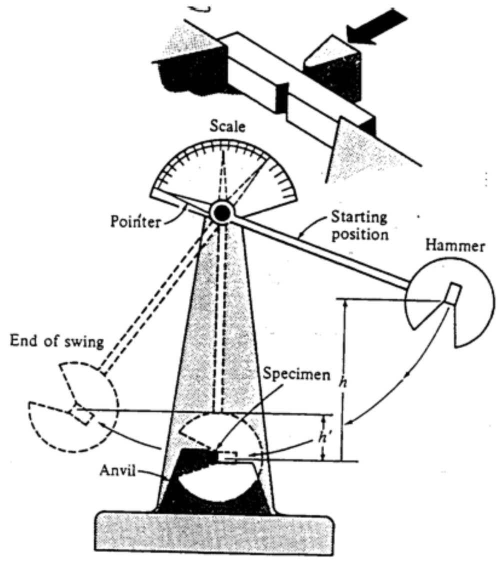


Figure 5.7 Charpy v-notch Impact Test

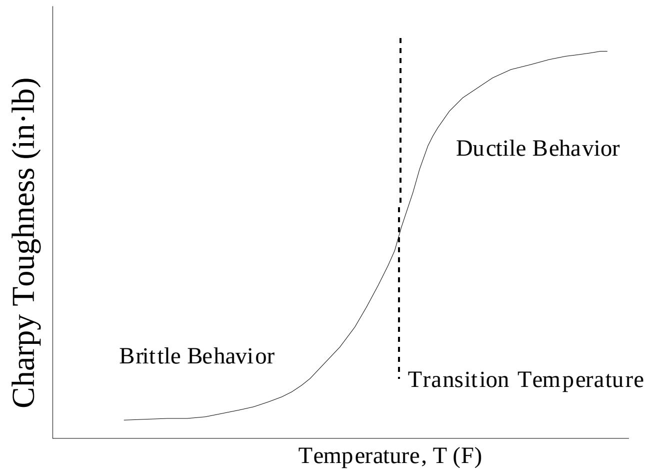


Figure 5.8 Temperature and Impact Toughness

At low temperatures, where the material is brittle and not strong, little energy is required to fracture the material. At high temperatures, where the material is more ductile and stronger, greater energy is required to fracture the material. The *Transition Temperature* is the boundary between brittle and ductile behavior. The transition temperature is an extremely important parameter in the selection of construction materials.

(!) Impact toughness can also be adversely affected by other factors such as external pressure, corrosion and radiation. It is important to take these factors into account for applications such as deep diving submersibles and reactor plant design.

5.4.7 Fatigue

Another important material property is its ability to withstand fatigue. *Fatigue* is the repeated application of stress typically produced by an oscillating load or vibration. Fatigue characteristics of a material can be found by repeatedly subjecting the material to a known level of stress. By changing the stress level and counting the repetitions of stress application until failure, a plot similar to Figure 5.9 can be created.

Figure 5.9 shows a plot of stress against number of cycles required to cause failure. It is clear that provided stresses remain below a certain threshold called the *endurance limit*, fatigue failure will not occur. The endurance limit of a material is a very important quantity when designing mechanical systems. It will be below the yield stress. As long as the level of stress in a material is kept below the endurance limit, fatigue failure will not occur.

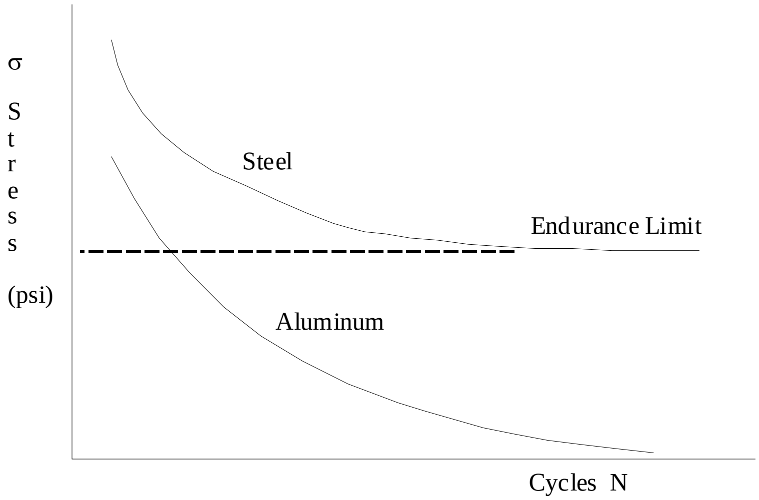


Figure 5.9 Material Fatigue Characteristics
(Note: Aluminum has no endurance limit)

Fatigue is the enemy of the pilot and the mechanics that care for his/her plane. Plane fuselages, wings, tails, and engines are constantly inspected to ensure that small cracks are found and fixed before they become big and lead to disaster.

5.4.8 Factors Effecting Material Properties

All of the material characteristics discussed so far are affected by temperature to varying degrees. In short, increasing temperature increases ductility which makes a material less brittle.

Material properties and performance are affected by a great many factors in addition to temperature. Alloying elements, heat treatments (annealing, tempering, quenching, etc), and manufacturing methods (cold rolling, hot rolling, forging, etc) also effect material properties, particularly yield strength, ultimate strength, and ductility.

5.4.8.1 Alloying

Alloying is the addition of elements to the base metal for the purpose of changing the material characteristics. Alloyed metals are generally more expensive than mild carbon steel or pure aluminum but their use is often necessary in order to achieve the desired strength, hardness, ductility, fatigue, and corrosion resistance properties in an engineering structure.

The principal alloying elements used in steels are: carbon (increases strength), chromium (increases hardness, strength, and corrosion resistance), nickel (increases toughness, hardness, and corrosion resistance), manganese (reduces brittleness), molybdenum (increases high-temperature strength and hardness), and tungsten (increases hardness). Stainless steels, for example, may contain up to 26% chromium to achieve superior corrosion resistance. Alloying, however, is a series of trade-offs and finding the “optimum” material is difficult. For example, increasing the strength of steel by adding carbon comes at the price of increased brittleness, lower toughness, and more difficult welding techniques.

The major alloying elements used with aluminum are: copper, manganese, silicon, magnesium, and zinc. Most of these alloying elements are used to improve the hardness, ductility, and strength of aluminum – aluminum, by its nature, is more corrosion resistant and alloys such as “stainless aluminum” are never seen.

5.4.8.2 Thermal Treatment of Metals

Annealing is used to relieve the internal stresses, change the internal grain size, and improve manufacturability of steel. In the annealing process, the steel is heated to slightly higher than its upper critical temperature (~723-910°C) and allowed to slowly cool in a furnace (1 to 30 hours). This process ultimately improves the hardness, strength, and ductility characteristics of the steel. Steel used in ship hulls is partially annealed.

Hardening consists of heating the steel to 100°F higher than its upper critical temperature, allowing the metal to change granularly, and then rapidly *quenching* the steel in water, oil, or brine. This process makes the steel harder. Horseshoes, armor plate, and chain mail are often quenched. Quenching too rapidly leads to thermal cracking.

Tempering, like annealing, is also used to relieve internal stresses, change the internal grain size, and improve manufacturability of steel. In the tempering process, the steel is heated to below its critical temperature and allowed to slowly cool. This process is often used after hardening to make the steel softer and tougher. Steak knives and razor blades are tempered. High quality swords are often quenched and tempered.

Hot-working is the process of mechanical forming the steel at temperatures above its critical temperature. Plastic strain develops as a result of the mechanical working. Annealing occurs due to the temperature which relieves some of the internal strain. As a result, the material remains ductile. One type of hot-working is forging, which gives the highest strength steel components. You may be familiar with this type of hot-working if you have ever watched a blacksmith work.

Cold-working a steel results in plastic deformations developing in the metal due to mechanical forming or working process being conducted at a temperature below the steel’s upper critical temperature. This process does not allow internal stresses to relieve and results in a stronger, harder, and more brittle material. If done too much, the material will become too brittle to be useful.

Precipitation Hardening is the most common heat treatment for aluminum. It consists of a series of controlled tempering and quenching, followed by a single rapid quenching and often ending with a process called *aging*, which is simply holding the material for a period of time at a set temperature.

5.4.8.3 Corrosion

Corrosion is defined as the deterioration or destruction of a material resulting from a chemical attack by its environment. Corrosion is the enemy to all marine structures and it is important to understand why it occurs and how to prevent it. This short discussion will not attempt to delve into the many mechanisms, causes, and factors affecting corrosion; rather, we will discuss how to prevent or at least, slow the effects of corrosion on your ship, tank, or aircraft.

Corrosion control can be accomplished by many means: design, coatings, and cathodic protection systems.

- Design: Design methods to control corrosion include limiting excessive stresses (stress corrosion), avoiding dissimilar metal contact (galvanic corrosion), avoiding crevices or low flow areas (crevice corrosion), and excluding air whenever possible. Good design also entails selecting the best material for a given application. The ocean environment is extremely deleterious to mild steel, yet these steels are often used in many marine structures due to their relatively low cost and high strength. After a careful economic analysis, the service life of most ships is determined by the effects of corrosion on the hull structure and the fatigue life on these thinner, degraded components. The service life may be extended by good design and effective use of other corrosion control methods explained below.

- Coating: Coatings range from simple paint to ceramic or glass enamels. These coatings separate the material from the corrosive marine environment. On a weight and cost basis, use of coatings is the most effective protection against corrosion. Navy ships make effective and frequent use of this method as you probably learned on your summer cruises! If done improperly, painting can become tiresome rework. A ship with a lot of paint can gain several LT's in displacement over its service life.

- Cathodic Protection: Cathodic protection is accomplished by impressing an electrical current on a material to slow or stop the chemical process of corrosion. Another method of cathodic protection protects the structural material by providing another dissimilar sacrificial material to preferentially corrode (often referred to as "sacrificial anodes" or "zincs"). Sacrificial anodes and cathodic protection are used in areas where it is not practical to constantly paint and re-paint components, such as heat exchangers, ballast tanks, bilges, and components fully submerged below the waterline such as the shaft and screw.

5.5 Non-Destructive Testing

Nondestructive testing (NDT) methods are inspections for material defects. In the Navy, they are often performed to insure quality control in acquisition and after installation. The governing documents are MIL-STD-271 F and NAVSEA 8000 and 9000 series manuals. Non-destructive testing methods may be grouped into two categories, external and internal inspection techniques. Additionally, we will cover two more methods, specifically hydrostatic and weight tests.

5.5.1 External (Surface) Inspection Techniques

The three most commonly used external (surface) inspection techniques currently in use are the Visual Test, Dye Penetrant Test, and Magnetic Particle Test.

- **Visual Testing (VT)** should be done during all phases of maintenance. It can usually be performed quickly and easily and at virtually no cost. Sometimes photographs are made as a permanent record. Visual inspections only allow the inspector to examine the surface of a material.

(!) You will perform VT countless times through your Navy or Marine career. Whether it is your pre-flight checks as an aviator or inspecting your Marines' rifles, you will be doing a VT, (a form of NDT).

- **Dye Penetrant Testing (PT)** uses dyes in order to make surface flaws visible to the naked eye. It can be used as a field inspection for glass, metal, castings, forgings, and welds. The technique is simple and inexpensive and is shown schematically at Figure 5.10. Only surface defects may be detected, and great care must be taken to ensure cleanliness.

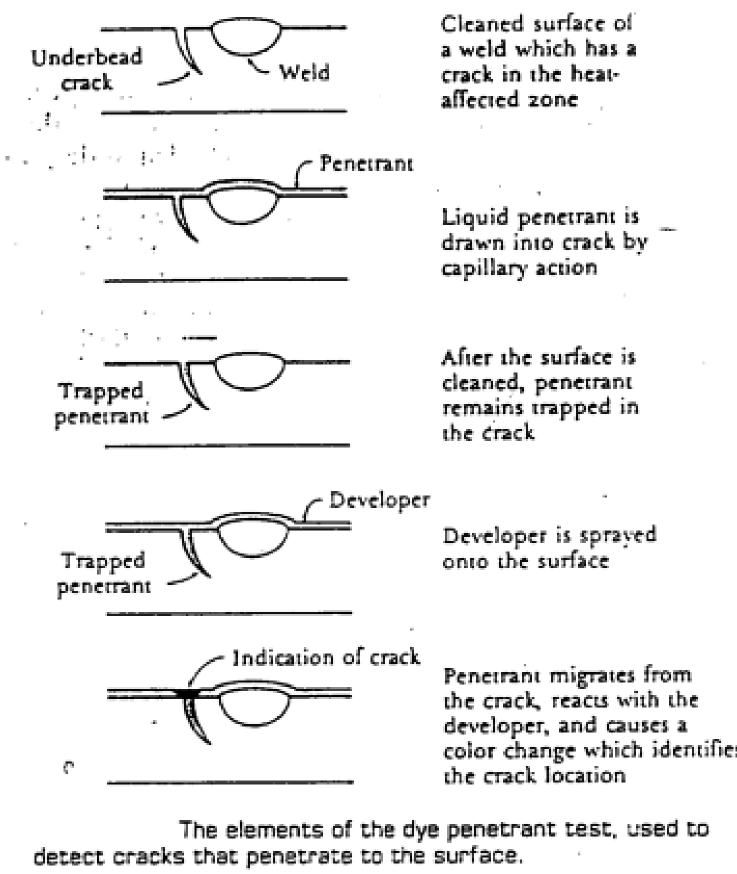
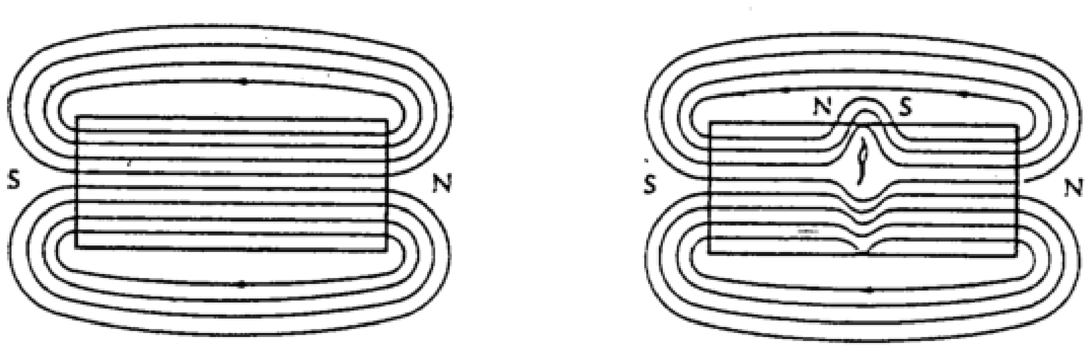


Figure 5.10 Dye Penetrant Testing

- **Magnetic Particle Testing (MT)** is only used on ferromagnetic materials. This method involves covering the test area with iron filings and using magnetic fields to align the filings with defects. Figure 5.11 shows the deformation of a magnetic field by the presence of a defect. Magnetic particle tests may detect surface and shallow subsurface flaws, and weld defects. It is simple and inexpensive to perform, however a power source is required to apply the magnetic field.



A flaw in a ferromagnetic material causes a disruption of the normal lines of magnetic flux. If the flaw is at or near the surface, lines of flux leak from the surface. Magnetic particles are attracted to the flux leakage and indicate the location of the flaw.

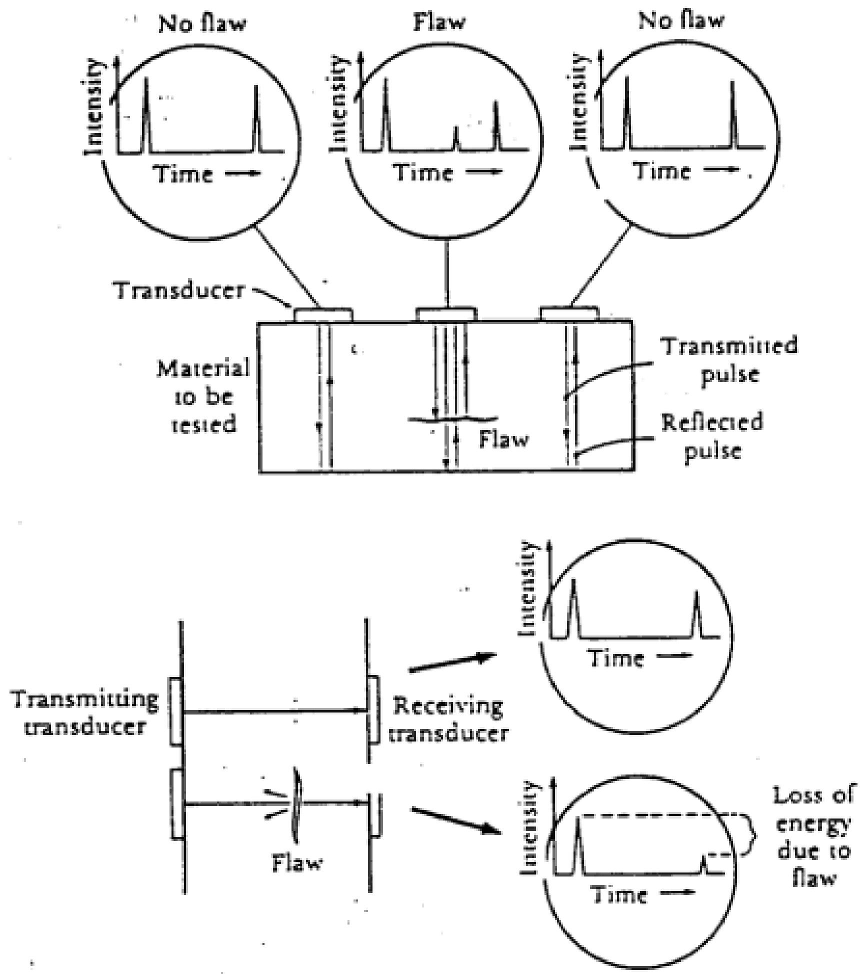
Figure 5.11 Magnetic Particle Testing

5.5.2 Internal (Sub-surface) Inspection Techniques

The three most common internal (subsurface) techniques are the Ultrasonic Testing, Radiographic Testing, and Eddy Current Testing.

- **Radiographic Testing (RT)** is accomplished by exposing photographic film to gamma or x-ray sources. This type of testing detects a wide variety if internal flaws of thin or thick sections and provides a permanent record. These methods of testing require trained technicians and present radiation hazards during testing.

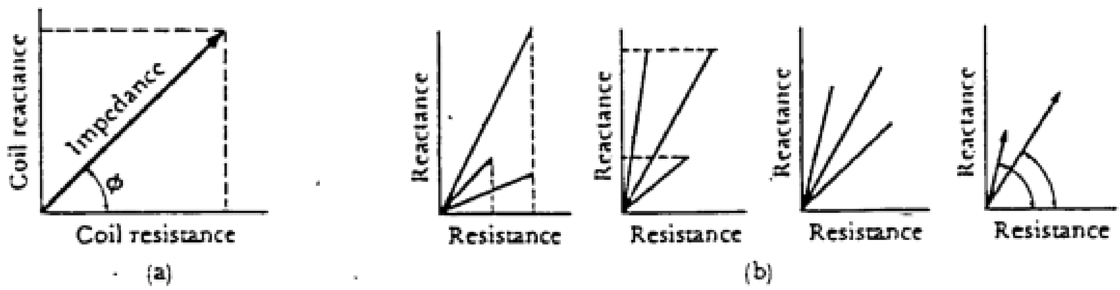
- **Ultrasonic Testing (UT)** utilizes a transducer to send sound waves through a material. It may be used on all metals and nonmetallic materials. UT is an excellent technique for detecting deep flaws in tubing, rods, brazed and adhesive-joined joints. The equipment is portable, sensitive and accurate. Interpretation of the results requires a trained technician. Figure 5.12 shows two ultrasonic transducer configurations.



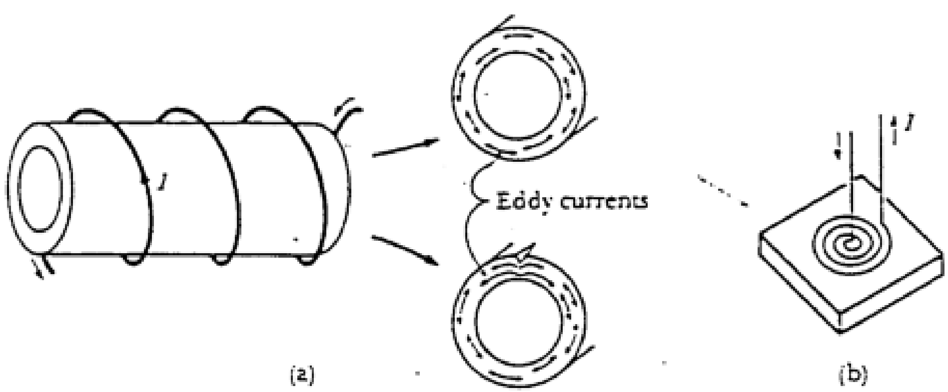
The through-transmission ultrasonic test. The presence of a discontinuity reflects a portion of the transmitted beam, thus reducing the intensity of the pulse at the receiving transducer.

Figure 5.12 Ultrasonic Testing

- **Eddy Current Testing** involves the creation of a magnetic field in a specimen and reading field variations on an oscilloscope. It is used for the measurement of wall thicknesses and the detection of longitudinal seams and cracks in tubing. Test results may be affected by a wide variety of external factors. This method can only be used on very conductive materials, and is only good for a limited penetration depth. Once very common, it is being replaced by the increasing usage of ultrasonic testing. Figure 5.13 demonstrates.



The impedance is important in the eddy current test. (a) The impedance is defined both by its magnitude and its direction, ϕ. (b) We must measure two components to define the impedance; it is possible that the impedance may be different even though the resistance, reactance, magnitude, or angle are identical.



(a) The through-coil method and (b) the probe method for eddy current inspection.

Figure 5.13 Eddy Current Testing

Two additional types of NDT common to the U.S. Navy are the hydrostatic and weight tests, used frequently in almost every form of mechanical equipment certification.

- Another type of test that you are likely to encounter is the **Hydrostatic Test**. In this test, a section of a system is isolated and pressurized by a pump to (or more commonly above) system operating pressure, as required by test specifications. Following a specified waiting period at pressure, the system is then inspected for leaks at joints, pipe welds, valve bonnets, etc. Sometimes, the ability of a valve to hold pressure is tested (seat tightness) and the pressure drop over time is noted. A hydrostatic test is a simple test *to verify system integrity*. It is typically performed following any maintenance or replacement which could impact that system's integrity.

- An equivalent type of test for gear used to lift large loads or weapons is the **Weight** or **Pull Test**. In this test, the gear or fixture is loaded to the same (or typically greater) weight than it is expected to endure in operation for a specified duration. Following release of the load, the equipment is inspected using NDT techniques (commonly VT and/or PT) for evidence of damage or permanent deformation. This test is repeated at specified periodicities or whenever maintenance or damage occurs which could impact the weight handling capacity of the gear. As an officer, you might need to verify that the weight handling gear your men are using has been tested within the required periodicities and is being used within the specified capacities for their and your own safety.

5.5.3 Non-Destructive Techniques Summary

TEST	MEASURES	USED FOR	ADVANTAGES	LIMITATIONS
Visual Test (VT)	1. Finish 2. Surface Defects	ALL	1. Cheap 2. Easy, no Equipment Required	1. Only for surface defects 2. No quantitative result.
ROCKWELL HARDNESS	1. Hardness (Strength)	1. Testing the strength of metals	1. Non-destructive	1. Not exact value of Strength
RADIOGRAPHIC (RT)	1. Internal Defects 2. Density Variations	1. Welds 2. Forgings 3. Castings	1. Gives Permanent record. 2. Great Penetration 3. Good on most geomotries 4. Portable 5. Sensitive to density variations	1. Costly 2. Radiation Hazard 3. Need highly skilled operators
DYE PENETRANT (DT)	1. Surface Defects 2. Porosities open to the surface	1. Welds 2. Forgings 3. Castings	1. Low COST 2. Portable 3. Easily interpreted	1. Surface defects only 2. Must clean surface before and after test
MAGNETIC PARTICLE (MT)	1. Surface, shallow subsurface flaws 2. Cracks and Porosities	1. Ferrous Materials 2. Forgings and Castings	1. Can locate very tight cracks which might not see with Dye 2. Low Cost 3. Fairly portable 4. Subsurface capability	1. Alignment of magnetic field is critical 2. Must demagnetize after the test 3. Must clean magnetic dust after test 4. Surface coating masks results.
EDDY CURRENT	1. Surface and shallow Subsurface defects 2. Alloy content	1. Tubes 2. Wires 3. Ball Bearings	1. High Speed 2. Automated 3. Gives Permanent Record	1. Need a Conductive material 2. Requires reference standard 3. Shallow defects only 4. Standard Geometry only
ULTRASONIC (UT)	1. Internal Defects 2. Material Thickness 3. Delaminations in Composites 4. Young's Modulus	1. Welds/Brazed Joints 2. Wrought Metals 3. Hull Thickness 4. In-Service Parts	1. Most sensitive to Cracks 2. Results known Immediately 3. Permanent record 4. Portable 5. High Penetration	1. Only on limited Geometries 2. Need Trained Operators

5.6 Other Engineering Materials

In your Navy career you will undoubtedly work with equipment that is not made of steel, aluminum or even metal. These other materials may be used for varying reasons: strength, weight, cost, corrosion resistance, manufacturability, etc. Below you will find a short description of some other common engineering materials: glass reinforced plastic (GRP), fiber reinforced plastic (FRP), ceramics, and concrete.

Glass Reinforced Plastic (GRP) – Also known as fiberglass, glass reinforced plastic is made by using glass fibers to reinforce plastic matrices (such as polyester or epoxy) in order to form structural composite and molding materials. GRP materials have high strength to weight ratios, good resistance to heat, cold, moisture and corrosion, are easy to fabricate and are relatively inexpensive. GRP materials are used in applications all around you: boats, cars, insulation, etc. The largest one-piece GRP component made is the sonar-dome of a *Trident* submarine.

Fiber Reinforced Plastic (FRP) – Carbon or aramid polymer fibers are used to reinforce plastic matrices to form structural composite and molding materials. FRP materials have high strength to weight ratios and large moduli of elasticity (E). These properties make FRP very attractive in aerospace, marine, and some automotive applications. Kevlar is an example of an aramid FRP made by DuPont. High-end FRP products include the *JSF* Wings, spars, ship propeller shafts, and golf clubs. FRP materials are generally more expensive than GRP.

Ceramics – Ceramic materials are typically hard and brittle with low toughness and ductility. Ceramics have high melting temperatures and are stable in many adverse environments. Engineering ceramics typically consist of compounds such as aluminum oxide, silicon carbide, and silicon nitride. These hard, heat resistant materials lend themselves well to applications such as engine design (e.g., gas turbine components) and circuit boards. The "skin" of the Space Shuttle is comprised of ceramic tiles.

Concrete – Concrete is the most common engineering material used in structural construction due to its low cost, durability, and ease of fabrication. Its disadvantages include low tensile strength and low ductility. Concrete is comprised of coarse material (aggregate) embedded in cement paste (binder).

(!) At this point, you should be able to prove that it is possible to build a barge (that will float) entirely out of concrete ($\rho_{concrete}$=150 lb/ft^3).

APPENDIX A

TABLE of FRESH and SALT WATER DENSITY

(reprinted from ‘Introduction to Naval Architecture’ by Gillmer and Johnson, U.S. Naval Institute, 1982)

Values of Mass Density ρ for Fresh and Salt Water

Values adopted by the ITTC meeting in London, 1963.
Salinity of salt water 3.5 percent.

Density of fresh water ρ, lb-sec²/ft⁴ (= slugs/ft³)	Temp, deg F	Density of salt water ρ_s, lb-sec²/ft⁴	Density of fresh water ρ, lb-sec²/ft⁴	Temp, deg F	Density of salt water ρ_s, lb-sec²/ft⁴
1.9399	32	1.9947	1.9384	59	1.9905
1.9399	33	1.9946	1.9383	60	1.9903
1.9400	34	1.9946	1.9381	61	1.9901
1.9400	35	1.9945	1.9379	62	1.9898
1.9401	36	1.9944	1.9377	63	1.9895
1.9401	37	1.9943	1.9375	64	1.9893
1.9401	38	1.9942	1.9373	65	1.9890
1.9401	39	1.9941	1.9371	66	1.9888
1.9401	40	1.9940	1.9369	67	1.9885
1.9401	41	1.9939	1.9367	68	1.9882
1.9401	42	1.9937	1.9365	69	1.9879
1.9401	43	1.9936	1.9362	70	1.9876
1.9400	44	1.9934	1.9360	71	1.9873
1.9400	45	1.9933	1.9358	72	1.9870
1.9399	46	1.9931	1.9355	73	1.9867
1.9398	47	1.9930	1.9352	74	1.9864
1.9398	48	1.9928	1.9350	75	1.9861
1.9397	49	1.9926	1.9347	76	1.9858
1.9396	50	1.9924	1.9344	77	1.9854
1.9395	51	1.9923	1.9342	78	1.9851
1.9394	52	1.9921	1.9339	79	1.9848
1.9393	53	1.9919	1.9336	80	1.9844
1.9392	54	1.9917	1.9333	81	1.9841
1.9390	55	1.9914	1.9330	82	1.9837
1.9389	56	1.9912	1.9327	83	1.9834
1.9387	57	1.9910	1.9324	84	1.9830
1.9386	58	1.9908	1.9321	85	1.9827
			1.9317	86	1.9823

NOTE: For other salinities, interpolate linearly.

APPENDIX B

TABLE of FRESH and SALT WATER KINEMATIC VISCOSITY

(reprinted from 'Introduction to Naval Architecture' by Gillmer and Johnson, U.S. Naval Institute, 1982)

Values of Kinematic Viscosity ν for Fresh and Salt Water

Values adopted by the ITTC meeting in London, 1963.
Salinity of salt water 3.5 percent.

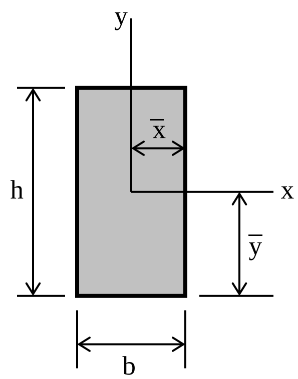
Kinematic viscosity of fresh water $\nu, \frac{ft^2}{sec} \times 10^5$	Temp, deg F	Kinematic viscosity of salt water $\nu_s, \frac{ft^2}{sec} \times 10^5$	Kinematic viscosity of fresh water $\nu, \frac{ft^2}{sec} \times 10^5$	Temp, deg F	Kinematic viscosity of salt water $\nu_s, \frac{ft^2}{sec} \times 10^5$
1.9231	32	1.9681	1.2260	59	1.2791
1.8871	33	1.9323	1.2083	60	1.2615
1.8520	34	1.8974	1.1910	61	1.2443
1.8180	35	1.8637	1.1741	62	1.2275
1.7849	36	1.8309	1.1576	63	1.2111
1.7527	37	1.7991	1.1415	64	1.1951
1.7215	38	1.7682	1.1257	65	1.1794
1.6911	39	1.7382	1.1103	66	1.1640
1.6616	40	1.7091	1.0952	67	1.1489
1.6329	41	1.6807	1.0804	68	1.1342
1.6049	42	1.6532	1.0660	69	1.1198
1.5777	43	1.6263	1.0519	70	1.1057
1.5512	44	1.6002	1.0381	71	1.0918
1.5254	45	1.5748	1.0245	72	1.0783
1.5003	46	1.5501	1.0113	73	1.0650
1.4759	47	1.5259	0.9984	74	1.0520
1.4520	48	1.5024	0.9857	75	1.0392
1.4288	49	1.4796	0.9733	76	1.0267
1.4062	50	1.4572	0.9611	77	1.0145
1.3841	51	1.4354	0.9492	78	1.0025
1.3626	52	1.4142	0.9375	79	1.9907
1.3416	53	1.3935	0.9261	80	0.9791
1.3212	54	1.3732	0.9149	81	0.9678
1.3012	55	1.3535	0.9039	82	0.9567
1.2817	56	1.3343	0.8931	83	0.9457
1.2627	57	1.3154	0.8826	84	0.9350
1.2441	58	1.2970	0.8722	85	0.9245
			0.8621	86	0.9142

NOTE: For other salinities, interpolate linearly.

APPENDIX C

PROPERTIES of COMMON GEOMETRIC SHAPES

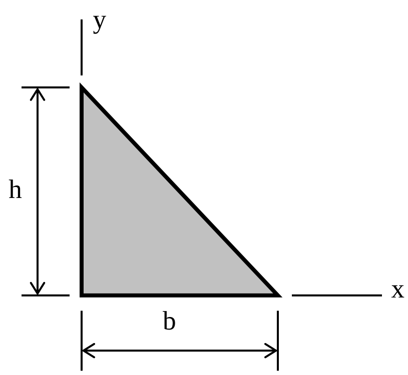
Rectangle (origin of axes at centroid)



$$A = bh \qquad \bar{x} = \frac{b}{2} \qquad \bar{y} = \frac{h}{2}$$

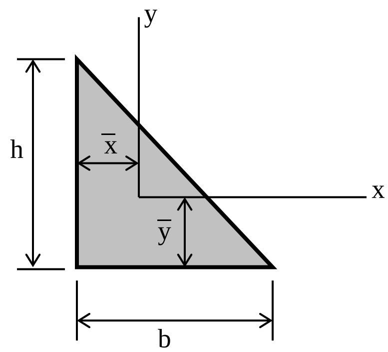
$$I_x = \frac{bh^3}{12} \qquad I_y = \frac{hb^3}{12}$$

Right Triangle (origin of axes at vertex)



$$A = \frac{bh}{2} \qquad I_x = \frac{bh^3}{12} \qquad I_y = \frac{hb^3}{12}$$

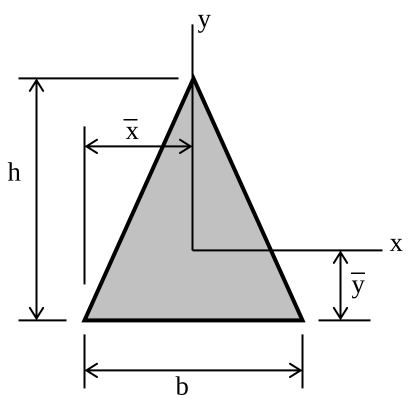
Right Triangle (origin of axes at centroid)



$$\bar{x} = \frac{b}{3} \qquad \bar{y} = \frac{h}{3}$$

$$I_x = \frac{bh^3}{36} \qquad I_y = \frac{hb^3}{36}$$

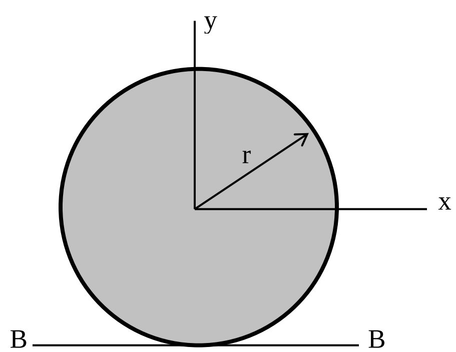
Isosceles Triangle (origin of axes at centroid)



$$A = \frac{bh}{2} \qquad \bar{x} = \frac{b}{2} \qquad \bar{y} = \frac{h}{3}$$

$$I_x = \frac{bh^3}{36} \qquad I_y = \frac{hb^3}{48}$$

Circle (origin of axes at center)

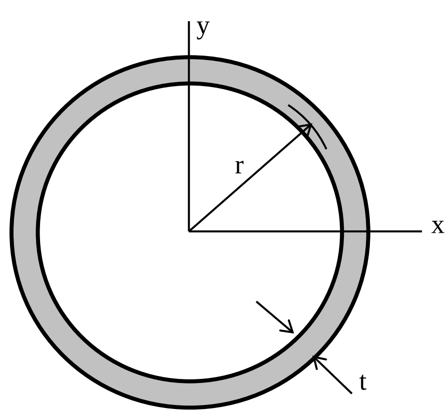


$$d = 2r \qquad A = \pi r^2 = \frac{\pi d^2}{4}$$

$$I_x = I_y = \frac{\pi r^4}{4} = \frac{\pi d^4}{64}$$

$$I_{BB} = \frac{5\pi r^4}{4} = \frac{5\pi d^4}{64}$$

Circular Ring with thickness “ *t* ” (origin of axes at center)
Approximate formulas for the case when *t* is small



$$A = 2\pi rt = \pi dt$$

$$I_x = I_y = \pi r^3 t = \frac{\pi d^3 t}{8}$$