CHAPTER 10

MECHANICS AND STRUCTURES

10-1 INTRODUCTION

April 27, 1978: In West Virginia, 51 construction workers fell 170 feet to their deaths as the scaffold and form work system peeled from the top of a cooling tower under construction. The lack of some required bolts connecting the scaffold to the tower and inadequately cured, insufficient strength concrete contributed to the accident.

May 30, 1979: A DC-10 crashed in Chicago, killing 271 people. A $^{3}/_{8}$-inch diameter bolt supporting the engine pylon failed, causing the engine to break away from the wing. As it broke away, it ripped through three redundant hydraulic flight control lines.

May 12, 1982: A report to Congress stated that more than 212,000 of the nation's 525,600 highway bridges (40.5%) were structurally deficient or functionally obsolete. A structurally deficient bridge is one that has a reduced load, is closed, or must be rehabilitated immediately. A functionally obsolete bridge can no longer safely serve its current traffic load because of lane width, load carrying capacity, clearance, or approach alignment.

June, 1979: The driver of an off-highway dump truck was crushed to death in the cab when the loaded truck's chassis collapsed. Although the exact cause is not known, some speculated that metal fatigue caused the collapse.

August, 1989: It was found that bolts that did not meet standards for strength and other properties were marketed for use in aircraft, trucks, and many other applications without the knowledge of the using companies. The bolts had been certified to meet standards, when in fact, they were manufactured and imported as inferior. Their lower production cost provided a price advantage to their marketing companies. The Federal government became heavily involved in investigating the distribution of inferior bolts throughout the United States. Some companies that imported and sold inferior bolts were criminally charged. The problem of knowing which bolts are inferior and where they are in use is virtually impossible to solve.

1995: As a worker stepped on a plastic skylight cover to gain access to an air conditioning unit on a plant roof, the plastic cover failed and the worker fell to the concrete floor 20 feet below the skylight. After being exposed to ultraviolet light for many years, the plastic skylight cover had lost much of its strength.

1998 and 1999: After six deaths and many more injuries to auto racing spectators at racing events, designers re-evaluated standards for separating speeding vehicles and crash debris from fans.

Safety and Health for Engineers, Second Edition, by Roger L. Brauer

December 26, 2004: One of the largest earthquakes on record, registering 9.0 on the Richter scale with an epicenter off the northwest coast of Samatra, created a tsunami that extended throughout the Indian Ocean as far as 1,000 miles or more from the epicenter. The tsunami changed tide patterns half way around the globe. Within a few days, the death toll in the region exceeded 170,000. The damage to buildings, vehicles, and other elements from the wall of water that was more than 25 feet in some locations and rushed inland resulted in more than two million people without homes and five million in need of assistance. The disaster created the largest international relief effort on record.

Many accidents and injuries are caused by forces that have too great a magnitude for a structure or a material. An important part of engineering is the study of forces and their actions: the field of mechanics. To make systems, devices, or products safe, engineers must account for the forces that act or might act on buildings, vehicles, toys, bottles, or other devices. In addition, engineers must account for the forces from objects that may act on the human body and its tissues. The strength of some body tissue may be the limiting factor.

In engineering mechanics, there are many specialized fields. This chapter cannot review them all. The goal is to look at some of the fundamentals and their relationships to safety.

Forces, Distribution, and Materials

The magnitude of a force acting on a body is obviously important. As a rule, large forces are more likely to cause failure or damage than small ones.

How a force acts on a body is also important. The direction of a force, its location or point of application, and the area over which it acts are also important in safety. A 50-lb force applied to the edge of a sheet of glass and parallel to it may not break it. If a hammer strikes the center of the sheet with the same force, the glass will probably break. A wood panel of the same size undergoing the same force will not break.

When evaluating the strength of a material, it is essential to evaluate the distribution or concentration of forces as they act on bodies. Figure 10-1 gives some examples of distributed and concentrated loads.

Experience tells us that different materials have different strength properties. Striking a glass panel will cause it to shatter, whereas striking a wood panel will cause a dent. The effect of a force is related to the strength of a material and its ability to deform. Important properties of materials include strength, brittleness, ductility (ability to bend or deform), thermal expansion and contraction, shape, age, exposure to environmental conditions, and exposures to chemicals. Even strength can vary, depending on whether forces are pulling, crushing, twisting, or cutting.

A key relationship between a force F and a body on which it acts is

$$F = sA, \tag{10-1}$$

where

s = force per unit area or stress (such as pounds per square inch) and

A = area (such as square inches) over which a force acts.

The stress that a material can withstand is a function of the material's strength properties and the type of loading.

If the material and the area over which the load acts are given, the designer must determine what forces the object can withstand safely. In other cases, one estimates the expected force first and then selects the material and designs for the load area.

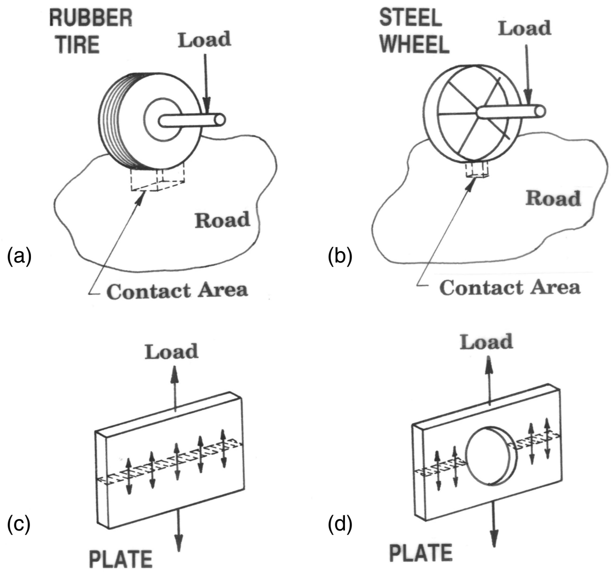


Figure 10-1. Examples of distributed and concentrated forces. In (a) tire flexion distributes the load over a larger road area than does the steel wheel in (b). The hole in the plate in (d) concentrates the load over a smaller internal area compared with the plate without a hole in (c).

A designer must envision the use environment. For example, building designers must determine the weight of building components and potential loads from building contents, wind, snow, rain, ice, and earthquakes. The designer of a wrench must consider how hard a user can pull on it. The designer of a toy must estimate how hard a child (young or old) can push or pull on it and how the toy's surfaces interface with human tissue. The toy designer should even consider the impact forces of someone falling on the toy.

The forces that an object can encounter are often different from the forces that an object should be able to withstand. For example, designers of breakaway sign posts and light poles along highways want the structure to fail at loads much lower than they could possibly encounter. The designer of a toy may want the toy to fail and fail safely rather than damaging body tissue when a child falls on it. In other cases, the designer may want a structure to withstand the greatest possible load.

Safety Factor

In applying Equation 10-1, a safety factor or factor of safety is often introduced. A factor of safety makes an allowance for many unknowns related to materials, assembly, or use. Unknowns may be inaccurate estimates of real loads or differences between actual materials and those tested in laboratories. They may be changes in area resulting from corrosion, wear, manufacturing, assembly, or use. They may be irregularities or nonhomogeneity in materials. The unknowns may include suddenly applied, dynamic loads. Technically, a safety factor (SF) refers to the ratio of a failure-producing load to the maximum safe stress a material may carry. The maximum safe stress is often called the allowable stress. Failure may not be by rupture or fracture. A failure could be a change in area or properties of the material that affect the load-carrying capacity and its safety. For structural steel, the allowable stress is derived at the yield point in a stress-strain (load per unit area-unit elongation or deformation) diagram from laboratory tests. For other materials, the allowable stress is based on the ultimate strength from similar tests. Refer to references on strength of materials for more details about test methods and stress-strain diagrams. There are many ways to determine a safety factor SF. A common way is

$$SF = \frac{\text{failure producing load}}{\text{allowable stress}}. \qquad (10\text{-}2)$$

Safety factors are often based on experience with the material in question and many of its properties and applications. Safety factors should include analysis of risk and potential consequences of failure. Different safety factors may be appropriate for different applications and use conditions for the same material. Usually, the safety factor will be higher for materials with less homogeneity. Safety factors are higher for sudden, dynamic loads. Designs that anticipate reductions in a cross-sectional area of a component through wear or some other change in properties may incorporate higher safety factors. Some safety factors are specified in regulations and standards.

In safety engineering, one must be very careful in using data from tables dealing with strength of materials. Some tables include a factor of safety, whereas others do not. Using strength data in error from a table for which a factor of safety is not included poses a significant risk. The factor of safety incorporated in a table also must be applied carefully to ensure that the assumed safety factor is suitable for the actual use conditions.

When load and strength tables are intended for field use, they should incorporate appropriate safety factors. Field personnel who have to perform computations and complex interpretations of data tables are more likely to make errors as the number of steps in using a table increases. Field tables should reflect decision tasks and situations expected.

Kinds of Forces and Stresses

If one were to slice an object that is under external load, one can describe the kind of stress acting on the object. The key is the direction in which the stress acts relative to the plane of the section. Figure 10-2 illustrates several examples. Stresses acting perpendicular to the plane are normal stresses. They can be tension or compression stresses. Stresses acting parallel to the plane are shear stresses.

Forces on an object are classified by the way they act on a body. Forces that pull an object apart are called tensile forces; those that squeeze an object are compression forces; those that cut an object are shear forces; those that twist an object are torsional forces; those that cause an object to bend are called bending or flexural loads. When one object acts on, presses against, or bears on another, the force of one on the other is a bearing force or load.

10-2 MODES OF STRUCTURAL FAILURE

Materials and structures can fail in a number of ways. The main modes of static failure are shearing, tension, compression, bearing (crushing or deforming), bending, and buckling. Names for most modes of failure come from the kinds of forces applied.

Beside static loads, dynamic loads can cause materials to fail. Impact failure and fatigue failure are dynamic failures. The ability of a material to withstand an impact load gives rise to a property called toughness. Dynamic loads, that is, continually changing loads, can change the strength, ductility, and other properties of materials. Dynamic loading itself or the changes in material properties that result can cause fatigue failures.

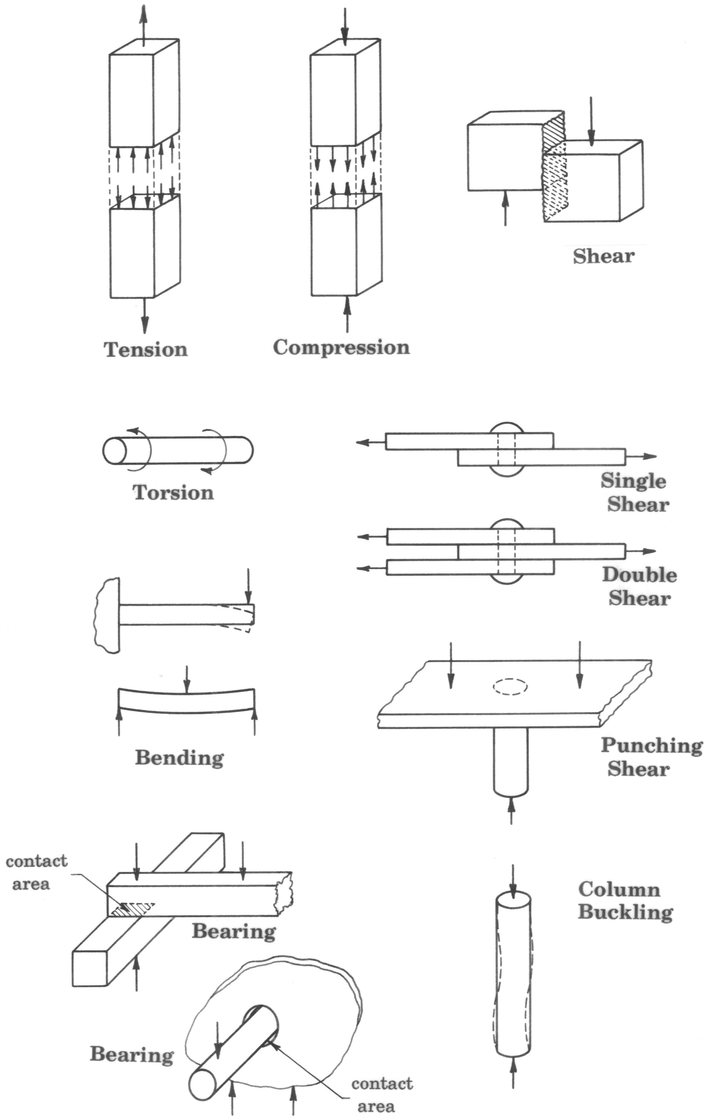


Figure 10-2. Examples of different kinds of stresses and forces.

Instability is a form of failure for an object, rather than a failure of some material it contains. Tipping over is a common instability failure. If the resultant forces on an object act outside the support area or exceed the capability of anchors, the object will fall over. Failures of structural components can shift loads so that instability results. Because their joints tend to act as hinged joints, rectangular frames are less stable than triangular ones. Rectangular bases are more stable than triangular ones, because the base extends over a larger area. Gravity, friction, inertia of some moving mass, or externally applied loads may contribute to the resultant force. To help maintain stability, football players will spread their feet apart to increase the support area or obtain support by placing their feet in line with the resultant force. If both feet are close together, the player would get knocked over easily. A crane may tip over when an excessive load is too far from the support area or a load is swinging and creating an inertial load. That occurs when the resultant force acts outside the support envelope of wheels, tracks, or outrigger pads.

There are other forms of instability worth noting. During construction of buildings, it is important to add cross bracing for rectangularly arranged structural components. Torsion and lateral loads created by wind or the materials of construction can lead to collapse, even when the load-carrying members of a building are in place and adequate. A step ladder depends on spreaders and cross bracing to keep the legs of the ladder in position relative to one another. Because of the slope of the legs, a torsional load is applied when someone climbs the ladder. The ladder has a tendency to twist and buckle without adequate bracing. It is also important that spreaders be fully down and locked. If they fold up or are not fully in place to start with, the ladder can collapse.

Another form of failure for some materials is creep. Creep is a very slow but permanent deformation of a material under load. Some plastic materials are subject to creep failures. The cross-sectional area of a part may change and weaken the part as a result of creep. Another example is electrical aluminum wire. During a shortage of copper in the late 1970s, solid aluminum was substituted for solid copper in some applications. Tight connector screws became loose later as the local load of the connector on the aluminum wire caused creep in the aluminum material, something that did not occur for copper wires. The loose connections may eventually lead to arcing and fire.

Other changes in properties of a material can lead to failures. For example, exposing some metals to caustics will make the metals more brittle. Brittleness increases the likelihood of fractures or other failures. Exposing materials to ionizing radiation may reduce strength and increase brittleness. Exposing some plastics to ultraviolet radiation, such as from sunlight, will change the strength properties. Dynamic loading of some ductile materials will make them more brittle. Freezing may make some materials more brittle; heating may reduce the strength of others. Making some materials, like cardboard or paper products, wet may significantly change their properties.

Several methods of failure are possible for an object. One must analyze what kinds of loads and what methods of failure are possible. One must analyze each method to determine what method of failure is most likely for each condition.

10-3 CAUSES OF STRUCTURAL FAILURE

There are many different causes for failures. One scheme for classifying structural failures is the following: design errors, faulty materials, physical damage, overloading, and poor workmanship and poor maintenance and inspection practices.

Design Errors

One form of design error is incorrect or poorly made assumptions. For example, one may assume some load or a maximum load as the basis for a design. The actual load may be much different in normal, adverse, or misuse conditions. In selecting a load for design, one may make tradeoffs with cost and other factors. Here are some typical issues for a designer in estimating the load on a lever:

How hard can someone push or pull on a lever?

Is the 95th percentile male strength data found in a design handbook a good choice?

Should one use a value for two people pulling on the lever?

Will using a "cheater pipe" or extension on the handle of a ratchet wrench overload it?

Another form of design error is assuming a static condition or load, even though a dynamic one is a more representative of the real conditions. The collapse of the Kemper Arena roof in Kansas City in 1979 gives us an example. The roof tended to swing a little from its suspension during windy conditions. The hanger bolts supporting the roof from an external space frame were high-strength steel. After this bolt material was selected during design, later test data on similar bolts of the same material showed a rapid reduction in strength each time a nut was tightened and induced a load. Some engineers believe that the dynamic loading of the roof bolts reduced the strength of the bolts to a point where they could no longer support the roof.[1]

Designs that are difficult to fabricate or build is another kind of design error. The error can result from lack of practical experience on the part of a designer or from improper implementation of a design in the field. For example, a welder may not have experience with special welds called for on a drawing.

Computational errors are another form of design error. Manual calculations or errors in computer programs can lead to structural failure if computations are not checked or validated.

Another form of design error can be material selection. A selection error may result from lack of knowledge or data about particular materials. Similar materials may have different properties that are critical. A selection error may result from lack of knowledge or from lack of field data or test data about a use environment. Selection of incompatible materials may induce or accelerate corrosion, fatigue, embrittlement, or other effects and reduce strength of the material.

Another form of design error is specification of materials. A designer may have selected the right material, but the specification used by others may lack precise information for purchase and application. For example, a lubricating oil may be selected for a particular flammability property to minimize the danger of fire. Similar oils, although matching other requirements, may not have that required property.

Faulty Materials

Two factors that can affect the safety of materials are lack of homogeneity and changes in properties over time. Homogeneity refers to the uniformity of a material or the similarity among several samples. Wood, for example, has knots and grain variations that affect strength across a sample. Cast and molded materials often have voids. Some materials, like glass, may have internal stresses that result from uneven temperatures during manufacturing. Composite materials may not be thoroughly mixed and have uneven distribution of components. For example, the United Airlines crash of a DC-10 in Iowa in 1989 may have been caused by a tiny flaw in the material used in the turbine wheel. The wheel flew apart and ripped out hydraulic lines that controlled flight of the aircraft.

One way to control homogeneity is through testing. Another way is grading of materials, like wood. In some cases, the cost to ensure homogeneity is too high. A proper factor of safety or accurately estimated operational loads can help compensate for nonhomogeneity.

Changes in properties of a material over time take many forms. Changes that affect strength are of great importance, but other properties, like ductility, brittleness, or toughness, are also important.

The changes may result from corrosion, dynamic loading or vibration and noise, rotting or decay, wear and exposure to sunlight or other radiation, salt air, chemicals, water, or dissimilar materials. The changes may be minimized to extend safe use by anticipating the use environment, proper selection and use, maintenance, inspection, and special treatments.

Physical Damage

Objects and structures may be damaged through use, abuse, and unplanned events so that strength and dimensions are modified. The damage to an element may not cause failure by itself. However, when a load shifts to other elements of a structure, elements may not be able to withstand the load change.

One control that may minimize physical damage is placement. A house built very close to a railroad track is likely to be hit should a train derail at that location. A mailbox placed right next to the pavement of a highway is much more likely to be struck than one set back. Someone is likely to run into or trip over objects protruding into an aisle of a storage area.

Another control is the use of barriers. Placement of wires in conduits will reduce the likelihood of damage to the wires. Bulbs in trouble lights have a protective metal cage. Islands and concrete-filled steel columns protect gas pumps in service stations so cars will not strike them. Shields in automobile engine compartments protect some components from thermal damage.

Another control is structural design that allows for some damage. A standard for warehouse storage racks, for example, requires that damage to one leg of a four-legged structure not cause collapse of a rack. The rack must stand even when one leg does not support a load.

Overloading and Inadequate Support

Conditions change in the use environment. When not foreseen by a designer or user, the changes may result in overloading or inadequate support. For example, a warehouse in Florida was converted to offices. Because there was inadequate parking for employees (not a problem for the prior use), the roof was converted to a parking deck. When the roof collapsed, it became clear that the roof was inadequate for the weight of vehicles. In another example, a flatbed truck trailer was designed to carry uniformly distributed loads of bagged material. When used to haul an earthmover with concentrated loads on the outer edges, the sides collapsed.

Inadequate support refers to an object or structure not having enough load carrying capacity. If designers or users do not foresee these problems, failure can result. There are many examples. If an operator sets supporting outriggers of cranes or backhoes in mud or disturbed soil, the soil may compress and allow the machine to tip over. The legs of tubular scaffolds are fine when they rest on concrete. When they rest on soil, they tend to sink in. A bearing plate placed under them on soils will prevent sinking. Soil with a certain moisture content provided a firm foundation for the Winchester Cathedral in England when it was built. When a nearby stream was diverted away, the soil compacted as it dried and caused a corner of the Cathedral to sink. The foundation had to be shored up to prevent the cathedral from collapsing. The vibrations from tracked earthmoving equipment can travel through the soil and cause the walls of nearby excavations to collapse. Nearly every rainy season in southern California, homes slide down hills because wet and saturated soils can no longer support the loads. Stacking cartons too high may cause the carton at the bottom to collapse and tip the stack over. Many facilities under construction are adequate when completed, but have significant weak points during construction.

Poor or Faulty Workmanship

Another cause of structural failure is improper assembly and maintenance. Some failures may result from human error; some may be the result of designs that are difficult, impractical, or impossible to implement; some may simply result from careless work and poor decisions on the part of workers and management. Sometimes these are interrelated. Lack of communication, skill, knowledge, training, procedures, and management commitment can all contribute to faulty workmanship.

One theory for the cause of the collapse of the Hartford (Connecticut) Coliseum roof in 1978 is that workers did not assemble some joints as specified in the design. The original design allowed a 160,000-lb load through the center of the connecting plate and a moment of 0 ft-lb. As actually fabricated, the joint created a 15,440-lb load and a 9,490 ft-lb moment.[2]

In 1981, a walkway collapsed in the lobby of the Hyatt Regency Hotel in Kansas City. The walkway hung from rods that protruded through box beams in the walkway. The design required supporting nuts to be threaded several feet along the rod. Because that task was difficult to complete, the design was changed on site. The change doubled the shear load at the lower supporting nut on the box beam (see Figure 10-3).[3]

Another form of faulty workmanship is a change in procedures, particularly when its consequences are not fully considered. One example is the DC-10 crash in Chicago in 1979. The manufacturer's procedure for maintenance called for removing the engine first, then the pylon that attached the engine to the wing. To save time, workers suggested changing the procedure so they could remove both engine and pylon at the same time. Some believe this practice may have placed excessive loads on the pylon–wing connection and caused cracking of components and ultimate failure.

Poor Maintenance, Use, and Inspection

Materials, products, structures, and buildings do not stay the way they are at the time of manufacture, assembly, or construction. Exposures to various conditions during their life will change them. It is important that proper maintenance be applied to prevent corrosion or damage. Improper use can affect the likelihood of structural failure. Normal use can

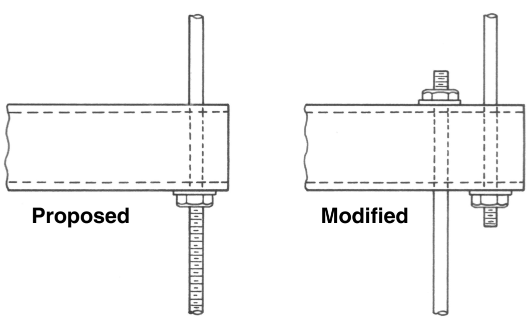


Figure 10-3. Changed load on box beams. In the original design, the load on one skywalk bears on one supporting nut below the box beam. A modification places the load of a lower skywalk on the box beam supporting the upper one. As a result, both loads bear on the nut under the upper box beam.

affect the structural integrity. Worn components need to be identified and replaced. Corroded elements may need strengthening or replacement. Inspections are an important method for identifying the change in properties. A wide range of inspection methods is possible, depending on the potential changes on the product or facility. In some cases, very specialized and sophisticated equipment may be needed to inspect the condition of structures and their components.

10-4 EARTHQUAKES

Earthquakes result from the movement of the subterranean plates forming the earth's surface. The movements between plates typically occur along fault lines. Earthquakes occur suddenly and typically are over in less than 1 minute, with smaller tremors occurring thereafter for a period of time. The Richter scale, a logarithmic scale, is a measure of earthquake intensity, or energy released during the plate movement and surface wave magnitude. An earthquake of magnitude 6 on the Richter scale is 10 times greater than one of 5, and an earthquake of magnitude 9 is 1,000 times greater than one of 6. An earthquake of 8 is an annual occurrence somewhere in the world and one of 7 is weekly. Those earthquakes originating under the sea will create ripples on the surface and the ripple may travel at rates of 300 to 400 miles per hour over great distances. A large ripple is called a tsunami.

An earthquake will cause the ground to vibrate at low frequencies. Any structure that has flexibility and can stretch to some extent or bend through connected joints has a greater chance of sustaining the vibration of the earth than a structure that has little joint strength. Mortar joints found in many structures are more brittle and are not likely to withstand the structural flexion resulting from an earthquake.

Some additional mechanics of soils can come into play during an earthquake. Because of the moisture content and the makeup of some soils, vibration from an earthquake will make them behave much like a liquid during the vibration rather than like a solid under normal conditions. This is called liquification. Some of the soils are man-made fills, while others are ancient lake bed sediments or simply soft soils. Much of Mexico City and towns and cities in the area of the New Madrid Fault in the area between Memphis, Tennessee, and southeastern Missouri are likely to exhibit the change in soil strength during an earthquake. The result is significantly greater damage to structures because foundation designs are based on normal soil properties rather than the "liquified" properties.

Another earthquake-related phenomenon affecting structures occurs when the frequency of vibration in an earthquake is at or very near the resonant frequency of the structure. The amplitude of the vibration becomes amplified and the degree of damage is significantly greater than expected from the earth's movement from the earthquake itself. A number of elevated highway structures have exhibited unexpected damage from earthquakes because of their resonant frequencies.

When an undersea earthquake occurs, it can cause a tsunami, a large wave effect. The normal water elevation changes and large amounts of water can wash into built up areas, causing severe damage from the energy produced by the moving water or from the flooding. The earthquakes cause a surge through the water that results in excessively large waves as the energy in the surge approaches the shore. In shallow areas, a tsunami can wipe out the entire built up area and most of the population located there. Usually the water's action occurs much faster than anyone can react. The force of the moving water can knock down structures and move people and vehicles uncontrollably. In recent years, a tsunami warning system has been put into place at a few locations subject to undersea earthquakes.

Many locations are defined by seismic zones that denote the likelihood and severity of potential earthquakes. It is important to know the seismic zone for any location and to follow the latest designs for buildings and structures for such zones to ensure the greatest degree of structural stability and to achieve the minimum amount of damage from an earthquake. For locations subject to structural property changes in soils or subject to potential tsunamis, other design considerations should be made.

10-5 CONTROLLING STRUCTURAL HAZARDS

There is no simple prescription for the elimination and control of structural hazards. Knowledge of the technology involved is essential. So is knowledge of materials and their behavior. One must complete calculations correctly and check them. Careful communication between designers and builders is needed. Attention to the use environment is necessary. Skill and care in assembly are needed. Designers must consider the consequences of failure. Not all structural failures cause injury, death, or major damage. In some cases, a structural failure may be desirable to control the point of failure and ensure that there are no catastrophic results. In some designs, the point of failure is controlled to minimize adverse effects.

10-6 APPLICATIONS

A safety engineer must have a good understanding of the principles of mechanics. This will help in recognizing hazards and selecting and implementing appropriate controls. A safety engineer must work with other engineers, metallurgists, architects and other structural specialists to ensure safety.

Static Mechanics

The field of static mechanics deals with forces acting on a body. Static mechanics involves bodies at rest or in equilibrium. Forces acting on them do not create motion. Common applications are bolts, rivets, welds, load-carrying components such as ropes and chains, and other structural elements. Equations 10-1 and 10-2, discussed earlier, apply to many static situations.

Example 10-1 Consider the bolt in Figure 10-4. It is loaded in tension and holds two elements together. One force acting on it is the load on the lower element (100-lb load plus 10-lb suspending elements). Another force is that caused by the tightened nut (20 lb). The total effective load on the bolt is 130 lb (100 + 10 + 20).

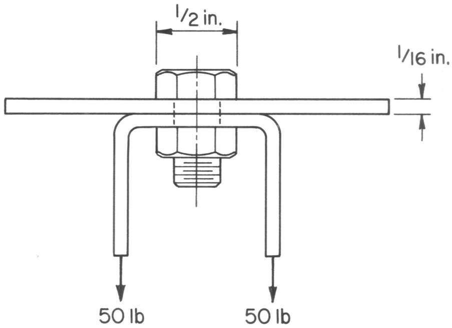


Figure 10-4. Example of tensile strength. The U-shaped member places a tensile load on the bolt.

For a mild steel bolt, one can determine its ultimate tensile strength from tables (60,000 lb/in^2). For a $^1/_4$-inch diameter bolt, the cross sectional area is 0.196 in^2. The actual stress in the bolt, using Equation 10-1, is 130 lb/0.196 in^2 = 663 lb/in^2.

Assume that for this application, a reasonable factor of safety is 3. By applying Equation 10-2, the actual factor of safety is (60,000 lb/in^2)/663 lb/in^2 = 90.5. Because 90.5 is much greater than 3, the bolt will easily carry the load.

Example 10-2 The plate in Figure 10-4 will fail in shear if the head of the bolt pulls through the plate. To determine the safe load capacity of the plate, one uses Equations 10-1 and 10-2. The bolt carries a 100-lb load. The outside diameter of its head is $^1/_2$ in. The thickness of the plate is $^1/_{16}$ in. The shear area in the plate is $\pi \times 0.5 \times 0.0625 = 0.098$ in^2. The actual shear stress is 100 lb/0.098 in^2 = 1,020 lb/in^2. If the plate is aluminum, the ultimate shear strength is approximately 35,000 lb/in^2 from tables. It is obvious that the plate will not fail in shear for the assumed load; 35,000 lb/in^2 is much greater than 1,020 lb/in^2.

Welds

Figure 10-5 shows some forms of common weld connections. The strength, P, of a butt weld is

$$P = LtS_a, \qquad (10\text{-}3)$$

where

L = the length of the weld,

t = the thickness of the thinner plate of the joint, and

S_a = the allowable stress of the weld.

The strength of a fillet weld is usually given as strength per linear inch of weld for a certain size of fillet. Because fillet welds are not often the full thickness of a plate, the size of a fillet is taken as something less than the thickness of a plate. Data on weld strength are available from the American Welding Society.

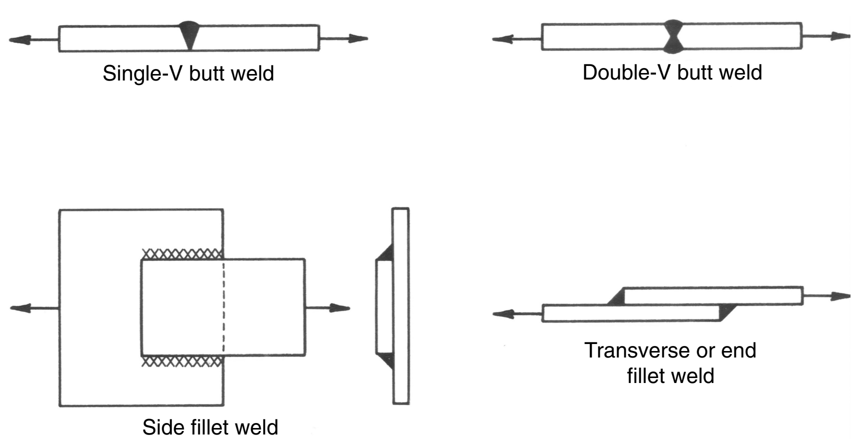


Figure 10-5. Examples of welds.

Dynamics

Dynamic mechanics deals with the forces acting on a body to cause acceleration. The motion may be linear and angular. Impulse, momentum and kinetic energy are part of the field of dynamics. Table 10-1 gives a summary of key equations for dynamics.

Many dynamic loading conditions are important for safety engineers. Some examples are deciding if rotating equipment will fly apart and whether objects striking the body will cause injury. A forklift turning a corner too sharply may cause it to tip over. The distance needed to stop a vehicle in motion is a dynamic problem. Later chapters discuss some of these in more detail.

Friction

Friction deals with one body in contact with another that is on the verge of sliding or is sliding. Friction allows us to walk, drive vehicles, and power equipment. The force tangent to the contact surface that resists motion is the friction force. When no motion occurs, the resistance is the result of static friction. If motion occurs, the resistance is due to kinetic friction. Kinetic friction values are generally lower than those for static friction. The coefficient of friction, μ, is the ratio of the frictional force F_f to the normal force N between the two bodies:

$$\mu = F_f/N. \tag{10-4}$$

Friction has limits, however. Friction will prevent motion until the coefficient of friction is exceeded. Because friction causes wear, lubricants are used to reduce friction. Some substances become lubricants. Water, snow and ice, oils, greases, soaps, and plastics may reduce friction in locations where high friction is desirable.

Example 10-3 Assume someone is about to push a large box. It may slide. It could also tip over. Which will occur, the sliding or the tipping? Assume the coefficient of friction between the box and the floor is 0.6.

Referring to Figure 10-6, one can determine what force will tip the box over by computing the moments about corner B of the box:

$$\Sigma M_B = 0, \quad F(4) - 500(^3/_2) = 0, \quad F = 188\,\text{lb}.$$

By summing forces in the horizontal direction, one can determine what force would cause the box to slide. Solving for the frictional force F_f using Equation 10-4,

$$F_f = \mu N = 0.6(500) = 300\,\text{lb},$$

$$\Sigma F_x = 0, \quad F - F_f = 0 = F - 300, \quad F = 300\,\text{lb}.$$

Because the force required to overcome friction (300 lb) is greater than the force required for tipping (188 lb), the box will tip.

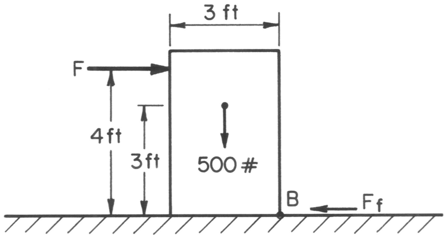


Figure 10-6. Diagram for Example 10-3.

TABLE 10-1 Summary of Mechanics Equations for Dynamics

	Linear Motion		Angular Motion	
Property	Mathematical Expressions and Formulas	Typical Units	Mathematical Expressions and Formulas	Typical Units
Displacement	s, dv, dy, dt, $s = v/2g$ $s = v_0t + 1/2\ at^2$	in, ft, m	$d\theta$ $s = r\theta$	deg, rad ft, m
Velocity	v, dx/dt, dy/dt, dz/dt $v = v_o + at$	ft/s, mi/hr, km/hr	ω, $d\theta/dt$ $\omega = \omega_0 + \alpha t$	rad/s, deg/s
Acceleration	a, dv/dt, d^2x/dt^2	ft/s^2, m/s^2	α, $d\omega/dt$, $d^2\theta/dt^2$ Tangential: $a_t = r\alpha$ Radial: $a_n = r\omega^2 = v^2/r$	rad/s^2, deg/s^2
Newton's second law of motion	$F = ma$ $m = W/g$ W = weight g = gravitational constant slugs, kg	lb_f, newtons, lbm	$T = I_\alpha$ $I = \Sigma mr^2 = mk^2$ k = radius of gyration	in-lb, ft-lb, kg-m^2, n-m
Momentum	$M = mv$	kg-m/s, slug-ft/s	$L = I\omega$	kg-m^2/s, slug-ft^2/s
Kinetic energy	$KE = 1/2\,mv^2$	ft-lb, kg-m	$KE = 1/2\ I\omega^2$	ft-lb, kg-m
Potential energy	$PE = Wh = mgh$	ft-lb, kg-m		
Work	$Work = 1/2\,m(v_2^2 - v_1^2) = \Delta KE$	ft-lb, kg-m	$Work = 1/2\,I(\omega_2^2 - \omega_1^2) = \Delta KE$	ft-lb, kg-m
Power	Rate of work, $P = Fv$	watts, hp, BTU/hr	$P = T\omega$	watts, hp, BTU/hr

Fluid Mechanics

Fluid mechanics is the study of forces on fluids. The field is sometimes called hydraulics when only liquids are involved and not gases. An understanding of fluid mechanics is necessary to predict and control the behavior of fluids. Safety engineers encounter many fluid mechanics problems and applications of fluid mechanics.

A major difference between mechanics of solids and fluids is that fluids have very little shear strength. Other important properties of fluids are density, specific weight, compressibility, viscosity, surface tension, and vapor pressure.

Pascal's law states that at any level, a fluid exerts an equal force in all directions. For a contained column of fluid, the pressure will vary with the vertical location. For incompressible fluids (such as water), the pressure p along the vertical column is given by

$$p = \gamma h, \tag{10-5}$$

where h is the vertical distance from the top surface to the point under consideration and γ is the specific weight.

Example 10-4 A tank contains oil to a depth of 25 ft (see Figure 10-7). The oil has a specific gravity of 0.9. What is the pressure at a point 8 ft from the surface? At the bottom of the tank?

Using Equation 10-5, one can solve for pressure at the two locations. The specific weight of water is assumed to be 62.4 lb/ft^3. The specific gravity of water is 1.0. The specific weight and specific gravity for a fluid have a constant ratio, the force of gravity. The specific weight of the oil can be determined: $\gamma_0 = 0.9(62.4) = 56.2$ lb/ft^3. The pressure at a depth of 8 ft is then $p = 56.2(8)/144 = 3.12$ lb/in^2. Similarly, at a depth of 25 ft, the pressure would be $56.2(25)/144 = 9.75$ lb/in^2.

Pressure increases linearly with depth in a fluid. Knowing this, one can develop a simple expression for the total pressure on a plane surface submerged in a fluid. Because the mean or average pressure p_m acting on the surface occurs at a depth located at the midpoint between the highest and lowest submerged point of the surface, the total force F is

$$F = p_m A, \tag{10-6}$$

where A is the area of the submerged plane.

Example 10-5 A 10-ft wide rectangular gate holds back water as shown in Figure 10-8. What is the force on the gate?

The midpoint of the submerged gate is $8(\sin 45°)/2 = 2.83$ ft. The mean pressure is $p_m = 62.4(2.83)/144 = 1.23$ lb/in^2. The total force on the gate acts perpendicular to it (the force of the fluid is exerted equally in all directions) and is $F = 1.23(8)(10)(144) = 14{,}170$ lb.

The volume flow of a fluid Q, or discharge, through some cross section (pipe, duct or channel) is given by

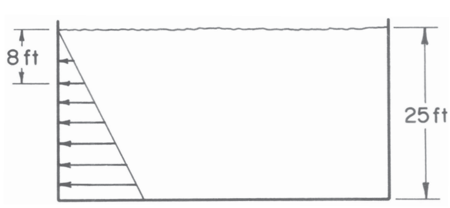


Figure 10-7. Diagram for Example 10-4.

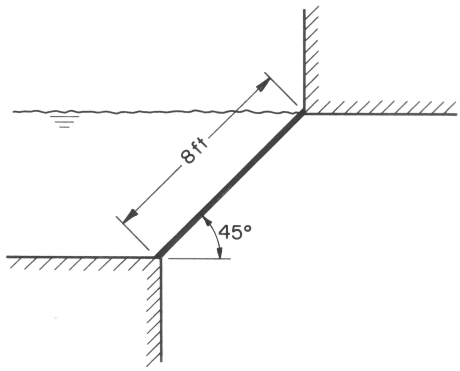


Figure 10-8. Diagram for Example 10-5.

$$Q = VA, \tag{10-7}$$

where V is the average velocity (the flow of a fluid is not uniform over its cross section) and A is the cross sectional area. Equation 10-7 is called the continuity equation. Sometimes correction factors are used with Equation 10-7 for flow through orifices of various shapes. An example for ventilation is found in Chapter 25.

In fluid dynamics, the energy of a flowing fluid remains constant (conservation of energy). The form of the energy changes. A relationship that brings these energy terms together is the Bernoulli equation, Equation 10-8. The units are the equivalent column of water or head represented. The three main components in the Bernoulli equation are pressure head (p/γ), the elevation head (z), and the velocity head ($V^2/2g$). The elevation head is measured against some vertical reference point. The sum of the elevation head and the pressure head is called the piezometric head h. The Bernoulli equation is written

$$\frac{V_1^2}{2g} + \frac{p_1}{\gamma} + z_1 = \frac{V_2^2}{2g} + \frac{p_2}{\gamma} + z_2 = C \tag{10-8}$$

where subscripts refer to locations selected for particular applications and C is a constant for a particular application.

When fluid flows through pipes, energy may change form. For example, there are "losses" resulting from surface roughness, turns, valves, and other pipe components. These are called shear losses and form losses. The velocity head is reduced as a result. The losses for each component are added and form the total loss H_L. To maintain the energy conservation in the Bernoulli equation, H_L is included in one side of the equation

$$\frac{V_1^2}{2g} + \frac{p_1}{\gamma} + z_1 = \frac{V_2^2}{2g} + \frac{p_2}{\gamma} + z_2 + H_L \tag{10-9}$$

Example 10-6 A fire truck (see Figure 10-9) pumps water to the third floor (25 ft from ground level) of a building. Water for the pump is in an open tank. The flow rate at the nozzle must be 50 gal/min. The nozzle has a 2-in diameter opening. The pressure loss resulting from friction in the hose between the pump and the nozzle is equivalent to 3 ft of water. What pressure must the pump produce? Assume that a gallon of water occupies 0.1337 ft^3.

First, one must determine the fluid velocity v at the nozzle. This is determined from the continuity equation. The cross sectional area, A, at the nozzle is $\pi d^2/4 = \pi(4)/4(144) = 0.0218\ ft^2$. The velocity is 50 gal/min (0.1337 ft^3/gal)/0.0218 ft^2 = 306.7 ft/min = 5.11 ft/s.

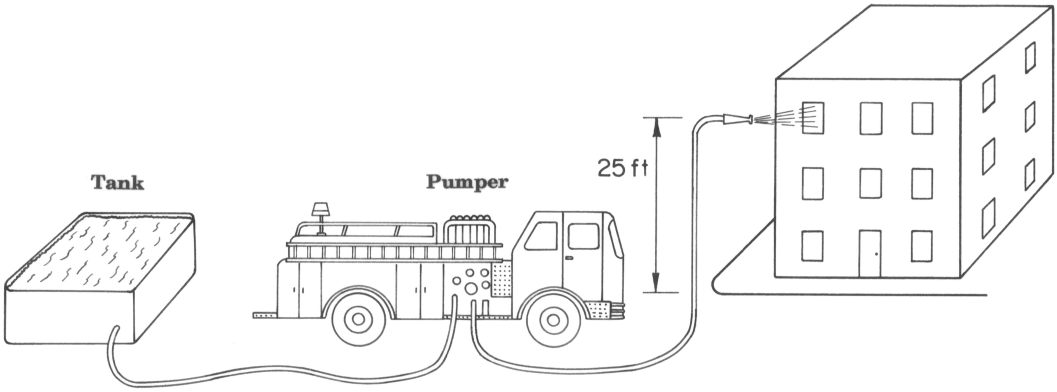


Figure 10-9. Diagram for Example 10-6.

The velocity head at the nozzle is then $v^2/2g = 5.11^2/2(32.2) = 0.406$ ft. The velocity head at the tank is zero. From the data given, the elevation head at the nozzle is 25 ft relative to the pump. The pressure head at the pump and at discharge are both zero. The friction component H_L is included in the Bernoulli equation.

Then, the resulting equation for this situation is

$$C = v^2/2g + p/\gamma + \text{h} + H_L = 0.406 \text{ ft} + 0 + 25 + 3 = 28.4 \text{ ft water} \quad \text{or}$$

$$28.4(62.4 \text{ 1b/ft}^3)(1/144 \text{ ft}^2/\text{in}^2) = 12.3 \text{ 1b/in}^2$$

Soils

The branch of engineering that deals with action of forces on soils is called soil mechanics or soil engineering. Almost all structures ultimately rest on soil. Media over which vehicles travel (roads and rails) depend on sufficient soil strength for support.

There are many kinds of soils with different properties. Sand, for example, behaves much like a fluid. Clay behaves more like a solid. Soils engineering uses many empirical equations, because soils and their properties vary considerably. A thorough knowledge of the field and much experience is needed to apply soil engineering practices skillfully.

Properties of Soils Many soils properties are documented. These properties help classify soils and apply soil engineering practices. Important properties include weight, density, modulus of elasticity, internal resistance, internal friction, cohesion, and volume changes resulting from various causes.

The weight of a given soil depends on the moisture content or the amount of water it contains. The amount of solid material for a unit volume is the dry weight. Density increases by the processes of settling and compaction and decreases by disturbing soil through excavation, tillage, and other actions. The moisture content of many soils is constantly changing from climatic conditions, natural or induced drainage, and compaction.

Internal resistance, which may vary for a soil, is a combination of frictional and cohesive forces acting on a soil. Several methods help determine this property. Results are quite dependent on the method. Internal resistance is an index of shear resistance. Internal friction is another index of shear resistance of soils and can never exceed the value of internal resistance.

The particles of some soils tend to adhere together, whereas others (sand, silt, gravel) do not. The fact that some soils tend to hold together even when well saturated results in the term cohesion. Cohesion refers to the internal tensile strength of a soil.

Volume changes in soil result from several factors. When some soils dry out, they shrink. When moisture increases, they expand. When compressed by external loads, soils will reduce in volume. The voids between particles become smaller in size from the loads. Water is squeezed out. Any process that reduces the water content of a bed of saturated soil is called consolidation.

Bearing Foundations must transfer the load of a structure to the soil. The load that a soil can support is sometimes simplified to Equation 10-1. The actual design of footings is much more complicated. Not only must the footings and soil carry the weight of the building and its contents, but the loads caused by wind and other imposed loads. Soils must carry the bearing load as well as moments that may be present. Borings help determine actual soil conditions. Building codes specify the maximum bearing loads for different soils, usually in tons per square foot. These allowable values often contain a sizeable safety factor, typically from 2 to 5.

In most foundation failures, the footings seldom fail. Failures frequently involve soil compression, unequal soil compression or movement, and changes in soil conditions (water content, volume, chemical content).

Piles Piles are slender underground columns used to support loads at their top. Loads transfer to soils by the friction and adhesion along the sides of the piles and by bearing at the bottom end. Designers establish the number, spacing, size, type, and angle of piles necessary to meet the capacities of local soil and anticipated loads.

Retaining Walls Soils exert lateral pressure on retaining walls, much like a fluid (see Example 10-5). Soils can exert one of two kinds of lateral pressure: active pressure or passive pressure. Active pressure exists when a wall resists the tendency of a soil to slide into the wall. For example, a pile of cohesionless sand will want to form a natural slope or angle of repose. A wall that restrains this action must overcome active pressure. Active pressure includes vertical force components. Active pressure varies with soil type, geometric characteristics of the wall, and the soil restrained.

The horizontal component of active and passive lateral pressure are both a function of the unit weight of soil, the square of the height of soil restrained, and the internal resistance of the soil.

Another force that can add to the pressure on a retaining wall stems from poor drainage that may cause the soil behind the wall to act like a fluid. Drainage of soils behind a wall will reduce the design load on the wall.

The design of sheeting and bracing for excavations can be complicated. Many pertinent factors must be analyzed. A qualified person must perform the design to meet acceptable engineering standards. Sheeting can be flat or corrugated and made of wood, steel, or other materials. Sheeting may be anchored or braced in a variety of ways. Sheeting itself may be embedded without braces and act as a cantilevered restraint. Poles or uprights can extend in front of the sheeting and be embedded below the sheeting. Braces can be placed in the excavation or anchors extended into the soil behind the sheeting.

Shoring for trenches is often constructed from tables like Table 10-2. Major components are illustrated in Figure 10-10. Depending on the source of the law or regulations, shoring is required in trenches more than 4 or 5 ft in depth. For trenches that are not open very long and not of great depth, a sliding trench shield (see Figure 10-11) or portable

TABLE 10-2 Minimum OSHA Requirements for Trench Shoring[a,b]

		Size and Spacing of Members										
		Uprights		Stringers		Cross Braces; Width of Trench					Maximum Spacing	
Depth of Trench (ft)	Kind or Condition of Earth	Minimum Dimension (in)	Maximum Spacing (ft)	Minimum Dimension (in)	Maximum Spacing (ft)	Up to 3 ft (in)	3–6 ft (in)	6–9 ft (in)	9–12 ft (in)	12–15 ft (in)	Vertical (ft)	Horizontal (ft)
5–10	Hard, compact	3 × 4 or 2 × 6	6			2 × 6	4 × 4	4 × 6	6 × 6	6 × 8	4	6
	Likely to crack	3 × 4 or 2 × 6	3	4 × 6	4	2 × 6	4 × 4	4 × 6	6 × 6	6 × 8	4	6
	Soft, sandy, or filled	3 × 4 or 2 × 6	Close sheeting	4 × 6	4	4 × 4	4 × 6	6 × 6	6 × 8	8 × 8	4	6
	Hydrostatic pressure	3 × 4 or 2 × 6	Close sheeting	6 × 8	4	4 × 4	4 × 6	6 × 6	6 × 8	8 × 8	4	6
10–15	Hard	3 × 4 or 2 × 6	4	4 × 6	4	4 × 4	4 × 6	6 × 6	6 × 8	8 × 8	4	6
	Likely to crack	3 × 4 or 2 × 6	2	4 × 6	4	4 × 4	4 × 6	6 × 6	6 × 8	8 × 8	—	6
	Soft, sandy or filled	3 × 4 or 2 × 6	Close sheeting	4 × 6	4	4 × 6	6 × 6	6 × 8	8 × 8	8 × 10	4	6
	Hydrostatic pressure	3 × 6	Close sheeting	8 × 10	4	4 × 6	6 × 6	6 × 8	8 × 8	8 × 10	4	6
15–20	All kinds or conditions	3 × 6	Close sheeting	4 × 12	4	4 × 12	6 × 8	8 × 8	8 × 10	10 × 10	4	6
Over 20	All kinds or conditions	3 × 6	Close sheeting	6 × 8	4	4 × 12	8 × 8	8 × 10	10 × 10	10 × 12	4	6

[a] 29 CFR 1926.652 (OSHA Table P-2).

[b] Braces and diagonal shores in a wood shoring system shall not be subjected to compressive stress in excess of values given by the formula $S = 13 - (20\ L/D)$, where L = length, unsupported, in inches; D = least side of the timber, in inches; S = allowable stress in pounds per square inch of cross section; and the maximum ratio of $L/D = 50$.

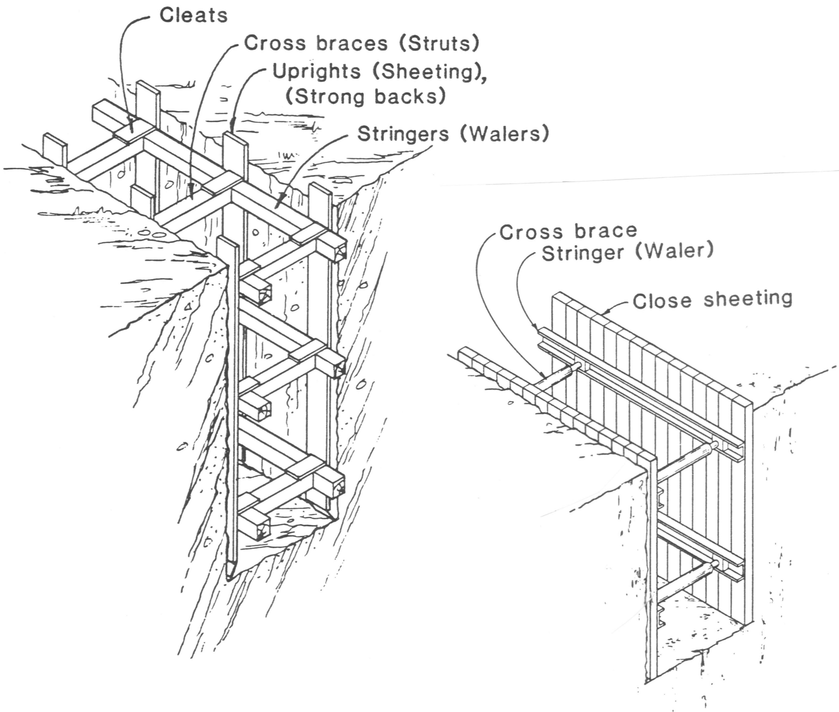


Figure 10-10. Examples of trench shoring and the components involved.

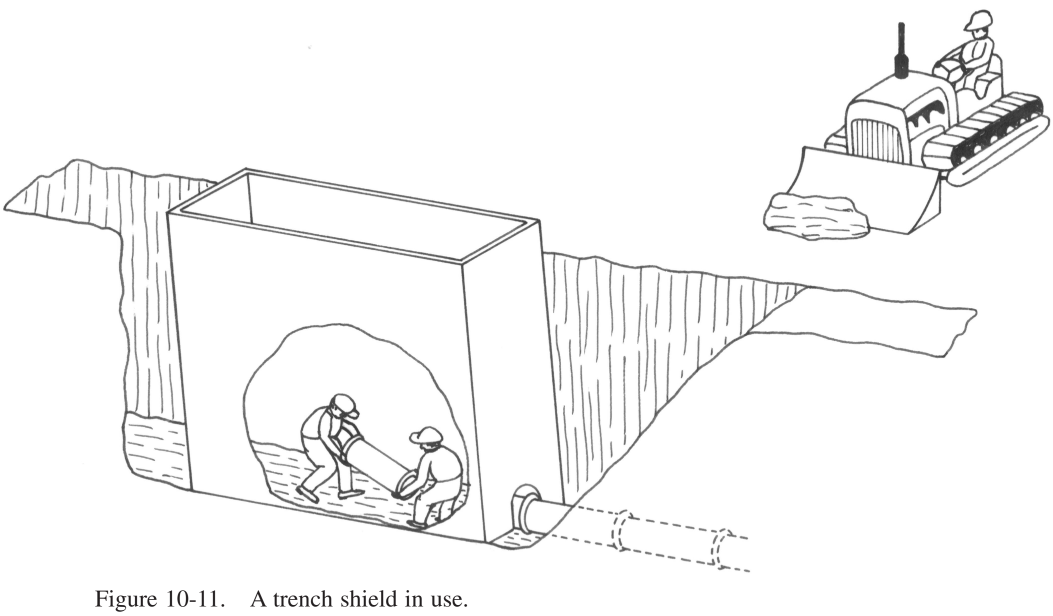


Figure 10-11. A trench shield in use.

trench box can be used. It is towed along as the trench is dug and provides a safe area for workers. In addition to shoring, there are many other requirements for safe trenching and excavation work.

Angle of Repose When soil is excavated, unrestrained walls will tend to collapse at some point in time. When that will occur is not always predictable. The remaining soil will form some angle relative to horizontal, called the angle of repose. The angle formed varies with type of soil, moisture content, presence of loose materials, and other factors. The same is true of soil or other bulk material that is piled up. The sides slide out and form some angle. In excavations, the walls can be cut back or stepped back to an angle less than the angle of repose to reduce the danger from cave-in. Figure 10-12 illustrates typical angles of repose for some soils.

Dewatering Changing the moisture content of soils can have significant effects. One effect is the change in load-bearing properties of the soil. Another is the change in volume of the soil. Pumping water from soils for construction of one facility may cause dewatering in adjacent areas and may induce damage on existing foundations and buildings.

Beams

Loading of beams is another important aspect of structural safety. A load on a beam induces stresses in its material. The strength of the beam material and the kind of loading determine the size of load that it can carry. Bending or deflection can create hazards even before total failure occurs. For example, a flat roof that deflects can cause water to accumulate or pond. The more water that accumulates, the more the roof deflects. This cycle could lead to collapse. A water buildup can be started by buildup of ice, leaves, or debris around a roof drain inlet.

As a beam bends, part of its cross section is in compression, part in tension. Figure 10-13 is a diagram of the stress distribution. The neutral axis is defined at the point where the stress is zero.

Properties of the beam cross section are important in determining the load that can be carried. One property is the moment of inertia, I. The moment of inertia is the sum of differential areas multiplied by the square of the distance from a reference plane (often the neutral axis) to each differential area. Because the distance is squared, the strength of a beam increases rapidly as its cross section is moved farther from the neutral axis. A rectangular beam will be much stronger when it is loaded along its thin dimension than along its flat dimension.

Another property used in beam load computations is the section modulus, Z. It is the moment of inertia divided by the distance from the neutral axis to the outside of the beam cross section.

The maximum bending stress s_b in a beam under a bending or flexural load is

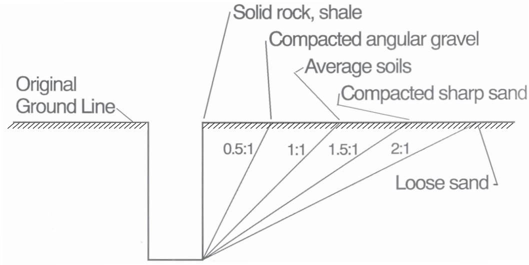


Figure 10-12. Slopes of sides of excavations recommended by OSHA.

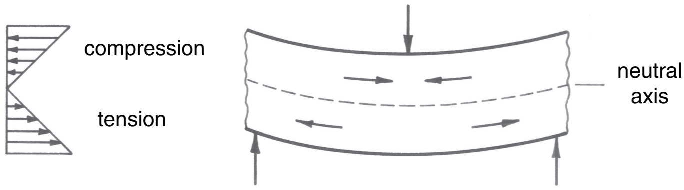


Figure 10-13. Distribution of stress in a beam cross section during bending.

$$s_b = Mc/I = M/Z, \quad (10\text{-}10)$$

where

M is the maximum moment created on the beam by the load and

c is the distance from the neutral axis to the remotest element of the beam.

A problem faced by a designer is to minimize the size and cost of a beam while providing a safe load capacity. Similar to the procedures for evaluating other stresses, computed loads are compared with allowable loads. Allowable loads differ from maximum loads that produce failure by some appropriate factor of safety. Beams are usually selected from standard types, materials, and shapes. Section properties and other data about beams can be found in engineering tables.

The deflection exhibited by a beam under load is a function of material, section properties, length, means of support or attachment, and loading. Formulas for maximum deflections and slopes created are found in engineering tables.

Floors

Determining the safe load on a floor is a commonly encountered structural issue. Loads placed on the floor are transferred to joists. The joists transfer loads to a wall or to beams. Figure 10-14 illustrates a typical assembly for a floor in a building.

Designers find floor load values in handbooks or building codes. The task is to provide an economical, attractive, and functional floor system that will safely carry expected loads. There are usually two load components. Dead loads include the weight of the building and its components. Live loads are the loads that are placed on the floor. One would expect different live loads for a warehouse, an office, and a parking garage. In an office, file cabinets may be distributed among work areas or concentrated in one location. The designer must consider such use conditions in a floor design. Some building codes require that floor loads that were used in a design be posted, at least in certain kinds of buildings.

Example 10-7 A floor has a uniformly distributed load of 150 lb/ft^2. Floor joists are 18 ft long and spaced 2 ft on center. What is the load on one joist? Ignore dead loads. If the joists are simply supported at each end by a beam, what load is transferred to each beam by each joist?

The floor area acting on each joist is 2 ft × 18 ft = 36 ft^2. The total load on one joist is 36 × 150 = 5,400 lb, evenly distributed over its length. The load transferred to each beam is 5,400/2 = 2,700 lb.

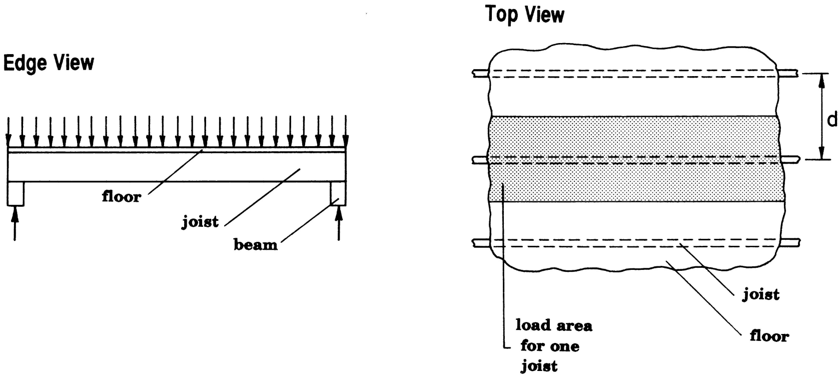


Figure 10-14. Typical structural components and load distribution for a floor.

Columns

Columns are structural members loaded in compression that have an unsupported length 10 times greater than the smallest lateral dimension. There are long and intermediate columns. Long columns fail by buckling or excessive lateral bending. Intermediate columns fail by a combination of crushing and buckling.

For a long column, the critical load is defined as the maximum possible axial load while still remaining straight. At the point of critical loading, the column is unstable and would bow easily if a slight lateral load were imposed. At greater axial loads, the column will buckle. The equation for computing the critical load P is

$$P = NEI\pi^2/L^2, \qquad (10\text{-}11)$$

where

N is an adjustment factor for end conditions,

E is the modulus of elasticity for the material, and

L is the length of the column.

For fixed ends, $N = 4$. For one end fixed and the other hinged, $N = 2$. When both ends are hinged, $N = 1$. When one end is fixed and the other is free, $N = {}^1/_4$. I is the smallest moment of inertia for the column cross section. Equation 10-11 is called Euler's formula for long columns.

Multiple Modes of Failure

For each assembly of structural components, there are several ways it can fail. A designer must analyze the assembly and identify all modes of failure. To determine which mode of failure is most likely to occur, each must be analyzed. Even very simple structures are complex.

Consider anchoring a shelf to a wall by means of a bracket and screws, one near the top of each bracket and one near the bottom (see Figure 10-15). The shelf must support some books. It may also have to support a child hanging from it, if other foreseeable conditions are considered. Several modes of failure are possible. In one mode, the screws could fail in shear at the wall–bracket interface. In a second mode, the screw at the top of a bracket could fail in tension. The moments on the bracket will be pulling the top screw away from the wall. The top screw could pull out of the wall. The head of the top screw could shear through the bracket material. The bracket could shear the head off the top

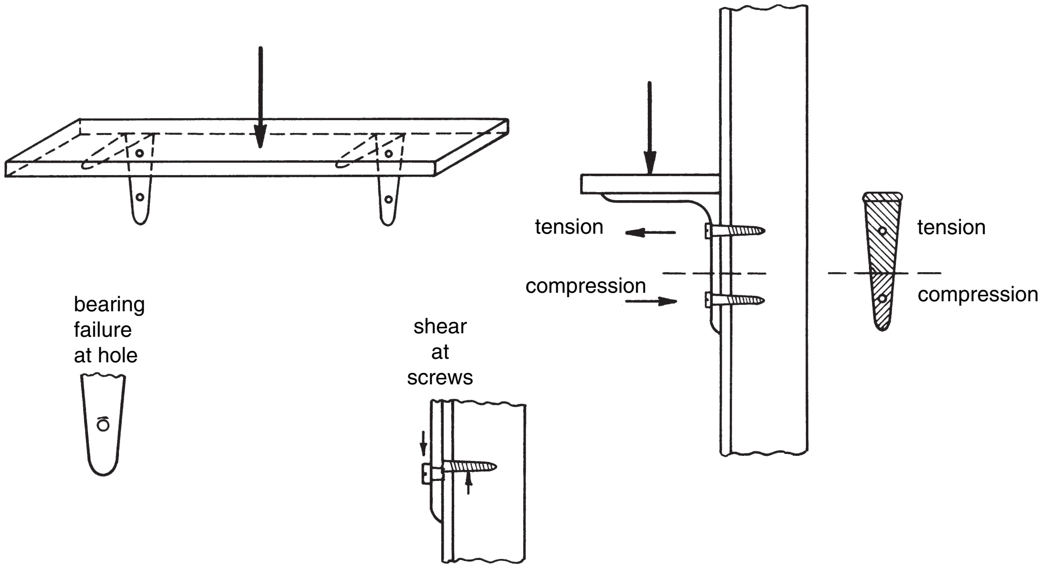


Figure 10-15. A shelf supported by brackets attached to a wall, the load distribution on the brackets, and some modes of failure.

screw. The lower end of the bracket, which is in compression, could crush the wall material. The bracket could bend, because the top leg is, in essence, a cantilevered beam. The wall material could fail in bearing where the screws bear down at the holes in the wall. The threads on the screws could cause shear failure in the wall material. Any of these modes of failure could occur. In a comprehensive evaluation, all would have to be analyzed to determine which is most likely to occur.

EXERCISES

1. In using a water slide, a number of youth piled up in one section to form as long a human chain as possible. In doing so, they overloaded the joint between sections, causing the joint to fail. The 12 young people fell about 40 ft to the ground.

There are two possible designs for the connection between sections of the slide. In each case, the joint has three bolts connecting the two sections (upper and lower) together. Assume the three bolts carry the entire load at the joint.

In the first design, a shear load is on the connecting bolts, whereas in the second design a tension load is on the bolts when the lower section carries a load.

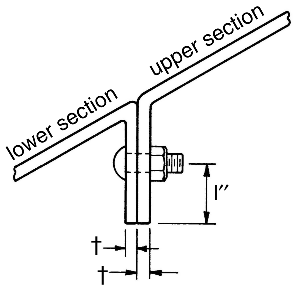
What force, *F*, acting on one side of the joint (assume the other side or section if rigidly supported) is required to cause failure when the design data at the end of the exercise are used and the mode of failure is

(a) bolt shear (for first design)

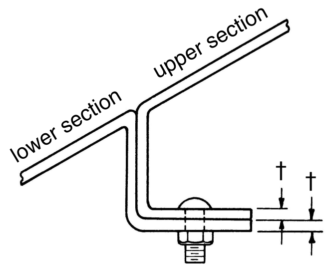
(b) plate shear in the upper section when the slide users placed a load on the lower section (for first design)

(c) bolt tension failure (for second design)

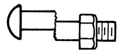
Data: factor of safety = 3, bolts are 1/2 in diameter, breaking tensile stress = 45,000 lb/in^2, breaking shear stress = 62,000 lb/in^2, holes are 1/2 in diameter, plates are 1/10 in thick, breaking shear stress = 40,000 lb/in^2.



Design (1) for Exercise 1.



Design (2) for Exercise 1.



Bolt shear diagram (a) for Exercise 1.

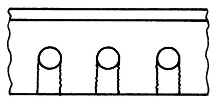


Plate shear diagram (b) for Exercise 1.

2. A floor is supported by joists that transfer their load to beams at each end of the joist. Joists are 2 ft on center (O.C.) and 30 ft long.

(a) If *w*, the load on the floor, is uniformly distributed and is 30 lb/ft^2, what is the load on one joist?

(b) If the maximum flexural stress *S* in a joist is given by $S = M/Z$, where *M* is the maximum bending moment (pound-foot) and *Z* is the section modulus (cubic inches), and the maximum bending moment for a simply loaded joist is given by $M = wL^2/8$, what is the stress in a joist that has a section modulus of 50 in^3 and is 30 ft long?

(c) If the joists are made of pine, which has an allowable bending stress of 9,300 lb/in^2, will it carry the load?

3. In an office it was decided to centralize files. All file cabinets in one department are to be placed in a row. The depth of the row is centered over a joist. Each file cabinet is 18 in wide by 30 in deep and weighs 300 lb. Determine

(a) the total load on the one joist (neglect the weight of the floor itself)

(b) the load transferred to the beam located at each end of the joist (assume the cabinets are also centered on the joist length)

(c) the maximum bending moment in the joist

(d) the maximum flexural stress in the joist

4. A 5-ft wide trench will be dug 12 ft deep in sandy soil. In considering shoring, determine the following: (a) upright dimensions and spacing, (b) size and spacing of stringers, and (c) size of cross braces and their maximum horizontal and vertical spacing.

5. A home swimming pool recirculates the water in the pool through a filter system. A pump moves the water from the drain(s) in the bottom or sides of the pool through the filters and returns it to the pool. It is known from experience that children have sat on the single drain port in some designs after the drain cover was removed and not replaced and had their intestines sucked into the recirculation system, causing serious medical problems for the children.

Consider design options for reducing or eliminating the hazard of injury to body parts caused by the suction at the drain port(s) for pool recirculation systems. What is the likelihood of occurrence and the severity of potential injury for each option? What legal cases have resulted from various recirculation designs for pools?

6. Select a product. Analyze one or more structural components and identify modes of failure for each component.

REVIEW QUESTIONS

1. List three characteristics of forces related to failure or damage.

2. Explain the concept of a structural safety factor.

3. Why is a safety factor used in structural analysis?

4. Why should a table of material strength or load capacity have a factor of safety incorporated into it?

5. Why should a field table have a factor of safety incorporated into it?

6. Define the following:
- **(a)** tensile force
- **(b)** compression force
- **(c)** shear force
- **(d)** torsional force
- **(e)** bending force
- **(f)** bearing force

7. Name eight possible methods of failure for structures.

8. Name five causes for structural failure and give an example of each.

9. Give an example of an application for safety of each of the following areas of mechanics:
- **(a)** static mechanics
- **(b)** dynamics
- **(c)** friction
- **(d)** fluids or hydraulics
- **(e)** soils
- **(f)** strength of beams
- **(g)** strength of columns

10. Locate an article on a significant earthquake event and identify the causes of failure for structures that resulted. Identify what changes in designs resulted from a study of the effects or could have been made to reduce the degree of damage in one or more of the damaged structures.

NOTES

1 "Rocking That Fatigued Bolts Felled Arena Roof," *Engineering News Record*, August 16, 1979, pp. 10–12.

2 "Design Flaws Collapsed Steel Space Frame Roof," *Engineering News Record*, April 6, 1978, pp. 10–12.

3 "Altered Design Probed in Hyatt Collapse," *Building Design and Construction*, September: 17–18 (1981).

BIBLIOGRAPHY

American National Standards Institute, New York:
ANSI/ASCE 7, *Minimum Design Loads for Buildings and Other Structures*,
ANSI A10.21, *Safety Requirements for Excavations*.

Forging Safety Manual, National Safety Council, Itasca, IL, 1991.

Levy, Matthys, and Salvadori, Mario, *Why Buildings Fall Down—How Structures Fail,* W. W. Norton & Company, New York, 1987.

Merritt, F. S., ed., *Standard Handbook for Civil Engineers*, 3rd ed., McGraw-Hill, New York, 1983.