A SunCam online continuing education course

An Introduction to the Analysis and Design of Bolted Connections

by

James Doane, PhD, PE

Contents

1.0 Course Overview and Introduction

Bolted connections are very common in both mechanical and structural applications. Fundamental knowledge of how to design bolted connections is critical for engineers. Failure of a single bolt in a connection can lead to catastrophic failure of the entire connection. This course provides a thorough, but easy to understand, approach that explains the essential details required for the analysis and design of bolted connections.

Threaded fasteners are removable fasteners that exert and maintain large axial forces (clamping force) through the use of an inclined plane. They are used to clamp members together and transmit force from one member to another. Threaded fasteners are standardized and come in many variations, both in configuration and strength. Standardization reduces cost and simplifies inventory. It is critical as an engineer to understand the terminology and types of bolts available as standard parts. Threaded fasteners are also available in many different materials and strength grades. This course will discuss the common materials and grades used for threaded fasteners. Proper understanding of the materials and grades is crucial for the design of bolted connections.

2.0 Screw Threads

2.1 Basic Terminology

There is a lot of general terminology associated with threaded fasteners. We will begin with the terminology associated with screw threads. Figure 1 illustrates the basic terminology associated with screw thread dimensions. The **pitch** is the distance, measured along the long axis of the fastener, between a similar point on two sequential threads. The **major diameter** is the diameter over the top of the threads, which corresponds to the largest diameter in the thread region. The **minor diameter** is the diameter at the root of the thread, which is the minimal diameter in the threads. The **thread angle** is the angle between two adjacent threads. The **pitch diameter**, which is also called the effective diameter, is an imaginary diameter located at the mid-point of the tooth height.

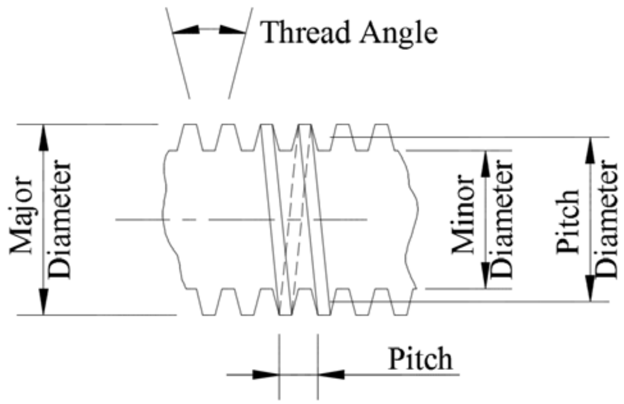


Figure 1 Basic screw thread dimension terminology

2.2 Screw Thread Systems

Many screw thread systems exist, but the most common are the systems with symmetric sides. Some of the early thread systems are shown in Figure 2. Early threads had a V-shaped thread with a sharp point, as shown in Figure 2 (a). The thread shape was easy to manufacture but the sharp point can cause fatigue failure. Figure 2 (b) shows the American National Thread, which is an improvement over the sharp V-thread because the sharp point is removed. The British standard, the Whitworth thread, is shown in Figure 2 (c) and has rounded edges.

The remaining thread systems shown in Figure 2 are more special purpose threads. For example, the square and ACME threads are used to transmit motion or generate power (such as power screws). The thread surface perpendicular to the long axis of the thread allows for maximum force transfer. Knuckle threads, as shown in in Figure 2 (g), are typically rolled and are used on products like light bulbs.

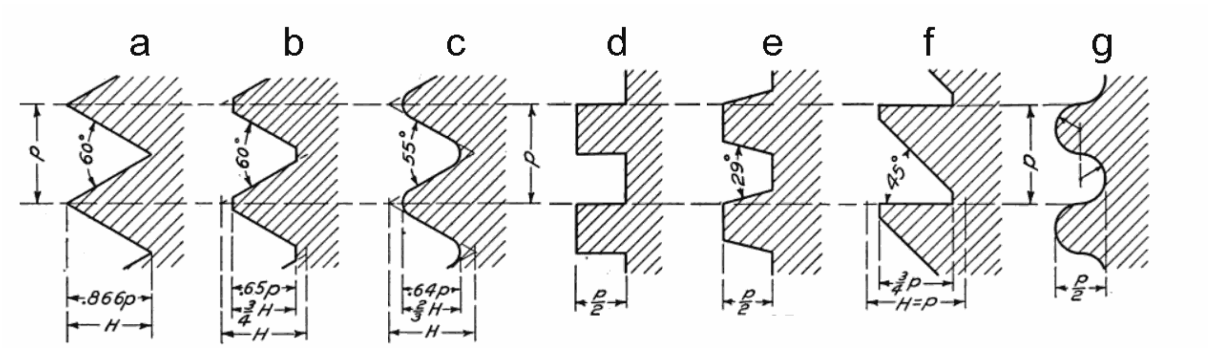


Figure 2 Early Thread Systems (a) V-thread (b) American National Thread (c) Whitworth thread (d) Square thread (e) ACME thread (f) Buttress thread (g) Knuckle thread

The Unified Standard Thread, shown in Figure 3. was adopted in 1948 and is the current standard for bolts, nuts, and other threaded fasteners used in the US, United Kingdom, and Canada. Though the Unified Standard Thread is very similar to the American National Thread, improvements in tolerances and allowances provides greater interchangeability.

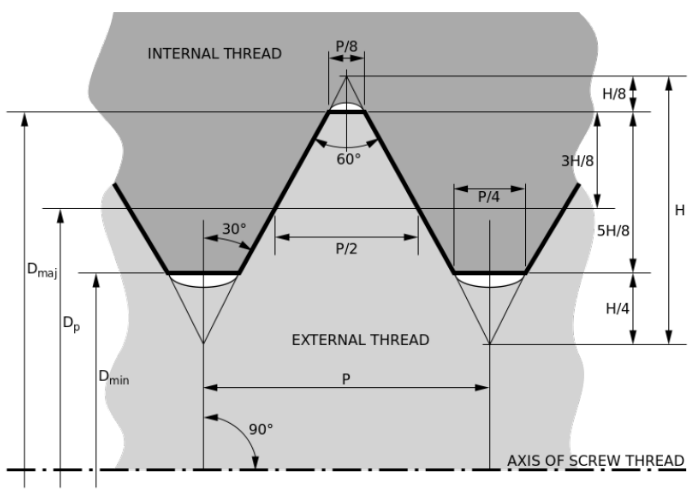


Figure 3 Unified Standard Thread

2.2.1 Thread Standardization

The current system for thread standardization, known as the Unified thread series, was established by the United States, Great Britain, and Canada. Unified screw threads are designated in the number of threads per inch. The Unified National system has a standardized tolerance system consisting of a coarse thread series and a fine thread series: The **Unified National Coarse** (UNC) and the **Unified National Fine** (UNF). The standardized tolerance allows for greater interchangeability. The UNC is most common and should be used in general applications. The UNF is used if fine adjustment is required. An additional series, **Unified National Extra Fine** (UNEF), is available and mostly used when the internal threaded member has a thin wall. Each one of the thread series is available in three different tolerance classes, which will be discussed in Section 2.2.2.

Metric fasteners are also standardized, and metric thread specification uses ISO standards. ISO metric threads are defined by nominal size and the thread pitch, with both expressed in millimeters.

2.2.2 Tolerance Classes

The Unified Standard Thread is available in different tolerance classes, as shown in Table 1. External threads are designated in the three classes 1A, 2A, and 3A. Internal thread classes are 1B, 2B, and 3B. The three classes for both external and internal threads differ in the amount of tolerance provided.

Table 1 Tolerance classes for Unified Standard Thread

Class of Fit	External Thread	Internal Thread
Loose	1A	1B
Standard	2A	2B
Close	3A	3B

Loose fit (Class 1A and 1B) have a larger amount of 'play' and are used when easy assembly and disassembly is desired. Standard fit (Class 2A and 2B) are for typical use in machine screws and fasteners. Close fit (3A and 3B) are used when a snug fit is required for precision tools and machines.

2.3 Designating Thread Type on Drawings

On engineering drawings, it is most common to show threaded fasteners in either a simplified format or a schematic, both are shown in Figure 4 (a). Either form is much easier to draw than the true thread shape. Even in modern solid modeling software, the drawings typically show fasteners in one of the two forms shown.

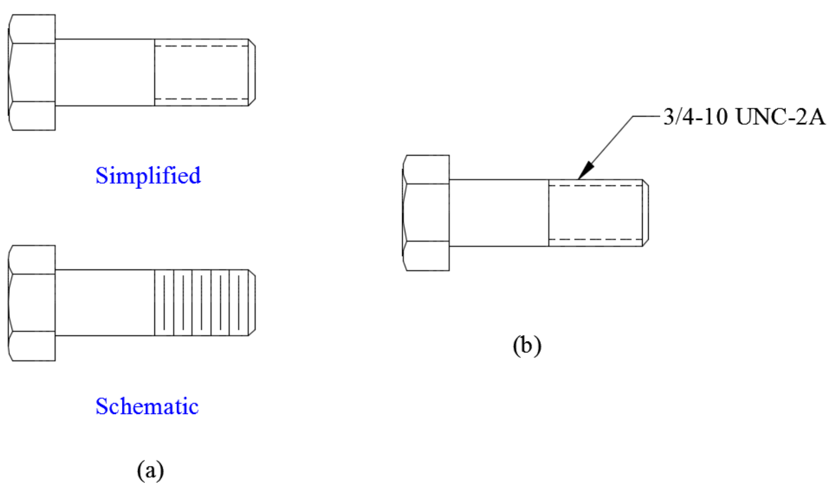


Figure 4 (a) Bolt representation (b) Example thread callout for drawings

Thread callout on drawings follows a standard notation format. The callout is in the order of *nominal diameter – number of threads per inch and thread series – class of fit*. An example of the thread callout is shown in Figure 4 (b). For the example, the bolt has a nominal diameter of ¾ inches, 10 threads per inch, unified national course thread, and standard external thread.

Metric fasteners follow a different callout designation. Metric fasteners are designated by *M diameter in millimeters x pitch in millimeters*. For example, a M5 x 0.8 fastener callout would describe a metric fastener with a diameter of 5 mm and a pitch of 0.8 mm.

3.0 Material for Bolts

3.1 General Material Information

Threaded fasteners are available in many materials, but carbon steel and steel alloys are the most common. Carbon steel bolts are good for general use. Stainless steel is a common allow that has improved corrosion resistance and is good for use in outdoor applications. Stainless steel bolts have an advantage over the coatings that will be discussed in Section 3.3; Stainless steel bolts will not lose the corrosive resistance properties if scratched because the base material is corrosion resistant.

Bolts are also commonly available in other materials such as nickel, titanium, aluminum, brass, bronze and plastic. These other materials may have specific advantages over common steel bolts. Titanium, for example, has excellent corrosion resistance to seawater.

3.2 Bolt Grade

3.2.1 SAE Grades

Materials for bolts are further rated by grades. The Society of Automotive Engineers (SAE) has developed standard specifications for fasteners used in automotive and other mechanical applications. The SAE designation uses markings (equally spaced radial lines) on the bolt head as shown in Table 2. A bolt head with no marking indicates a Grade 2 bolt, 3 markings indicates a Grade 5 bolt, and 6 markings indicates a Grade 8 bolt (the simple shortcut is to take the number of radial lines and add 2 to get the grade number). Grade 2 is a low to medium carbon steel, Grade 5 is a quenched and tempered medium carbon steel, and Grade 8 is a quenched and tempered medium carbon alloy steel.

Table 2 Bolt head markings for SAE grade designation

		
Grade 2	Grade 5	Grade 8

The strength increases with each grade, as shown in Table 3. At this point the information in Table 3 is shown as a general comparison between material grades; More details about the meaning of the different mechanical properties will be discussed in Section 5.2.

Table 3 Mechanical properties of SAE grades

	Size Range (inches)	Proof Load (psi)	Min. Tensile Strength (psi)	Min. Yield Strength (psi)
Grade 2	1/4 through 3/4	55,000	74,000	57,000
	Over 3/4 to 1 1/2	33,000	60,000	36,000
Grade 5	1/4 through 1	85,000	120,000	92,000
	Over 1 to 1 1/2	74,000	105,000	81,000
Grade 8	1/4 through 1 1/2	120,000	150,000	130,000

3.2.2 Structural Grades

Bolts used in structural applications have a different system for specifying grade. Structural bolt classifications are defined by the American Society for Testing and Materials (ASTM). A low strength bolt, sometimes called a common bolt, is classified as A307. A307 bolts are carbon steel and have strength characteristics similar to A36 steel. High strength structural bolts are available as A325 and A490. A325 is a medium carbon heat treated steel, and A490 is a heat treated alloy steel. Structural bolts have the grade stamped in the bolt head, as shown in the example bolt in Figure 5.

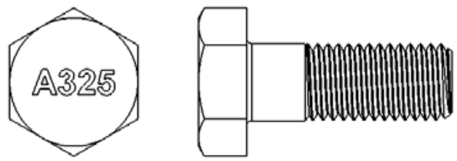


Figure 5 Example of an A325 structural bolt

The strength properties of structural bolts are similar to SAE grades. For example, the properties of a Grade 5 SAE bolt are nearly identical to that of the A325 ASTM bolt. However, the overall geometry of the two are different and they are not interchangeable. Structural bolts have different thread lengths compared to SAE bolts and structural bolts have a heavy hex head. The available diameter sizes will be different from SAE bolts and structural bolts and dimensional tolerances will be different. Grade 8 bolts are also similar to A490, though the differences are similar to those discussed for the comparison of Grade 5 and A325.

3.2.3 Metric Property Classes

Metric fasteners use property classes, which are specified by a two or three-digit number on the bolt head. Table 4 shows three examples of the grade specification, though many others exist. The numbers give approximate values of the minimum tensile strength and the minimum yield strength of the bolt. The number before the decimal place gives the approximate minimum tensile strength in 100's of MPa. For example, the 5.8 marking on the first bolt would have an approximate minimum tensile strength of 500 MPa. The number after the decimal place is a multiplier to give the approximate minimal yield strength. Again for the 5.8 example, the approximate minimum yield strength would be the 500 MPa tensile strength times 0.8 to give 400 MPa as the approximate minimum yield strength.

Table 4 Examples of bolt head markings for Metric grade designation

3.3 Coatings

Plain steel bolts are commonly oil washed to help against corrosion. However, coatings are also used to improve resistance to corrosion. Coatings do not change strength properties of a bolt, but they are only used for corrosion resistance. The coating is available in different forms discussed below.

3.3.1 Zinc Plating

Low carbon steel bolts are available with a zinc plating. Pure zinc has a very low corrosion rate (0.0001 inches per year) in normal atmospheres, where steel will rust at a rate of 30 times that value. Therefore, zinc is commonly used as a corrosion resistant. A thin coating, as low as 0.003 inches, can protect the steel for as long as 30 years in noncoastal environments. Zinc, however, does not have great chemical resistance. Zinc plated bolts offer a low cost solution for solutions with minimal exposure to the elements, and they can be a less expensive alternative to stainless steel bolts.

3.3.2 Hot Dip Galvanizing

Hot dip galvanizing is a simple process of immersing steel into a bath of molten zinc. Hot dip galvanizing provides a thicker zinc coating, as shown in Figure 6, to improve corrosion resistance. The coating has a rougher finish compared to zinc plated bolts.

Figure 6 Hot dip galvanized bolts

3.3.3 Chrome

Chrome plating offers moderate resistance to corrosion. The corrosion resistance is similar to zinc plating but at a higher cost. Bolts with chrome plating will have a very smooth and shiny appearance. Therefore, one major reason for selecting chrome plated bolts over other available coatings is for the overall look.

3.4 Galvanic Corrosion

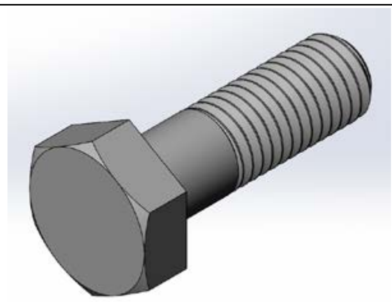
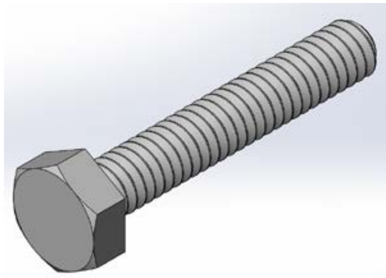
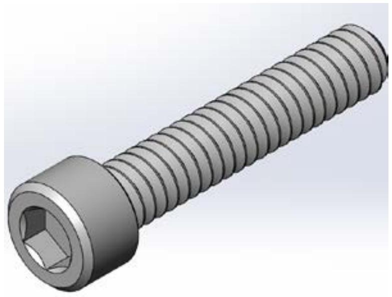
Galvanic corrosion is a very important consideration when choosing bolt material. Galvanic corrosion is an electrochemical process that occurs due to the contact between dissimilar metals. All metals will have electrical potential, and when different metals are in contact in the presence of moisture an electric current will flow. Full detail of the principle of galvanic corrosion is beyond the scope of this course. However, if you plan to use bolts of a material dissimilar to the structure of the connection you should check for potential galvanic corrosion conditions. One possible preventative measure would be to separate the dissimilar materials with a dielectric material such as paint.

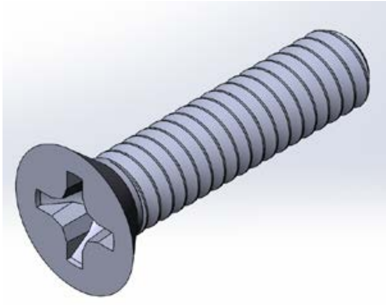
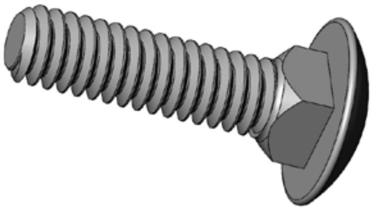
4.0 Types of Threaded Fasteners

4.1 Bolt and Screw Types

Bolts and screws are available in many different types. Table 5 lists the common types used in mechanical applications with a brief description of each type.

Table 5 Common types of threaded fasteners

Hex (Hexagon) Head Bolts	Heavy duty and usually use a nut for tightening Most common for engineering applications	
Hex Head Cap Screw	Has a thinner head and usually used in threaded hole (not a nut)	
Socket Head Cap Screw	Typically used for more precision applications Has hex socket drive	

Machine Screw	Smaller size with slot or Philips head Available with different head configurations (pan, flat, round, etc.)	
Carriage Bolts	Neck shape keeps the bolt from turning when tightened Smooth round head	

4.2 Nuts and Locking Devices

As mentioned in Table 5, some fasteners are commonly used with a nut and some are used in a threaded hole. Figure 7 (a) shows an application for a hex head bolt and nut while Figure 7 (b) shows an application for a cap screw in a tapped hole. For applications similar to Figure 7 (a) that require the use of a nut, there are different types of nuts available.

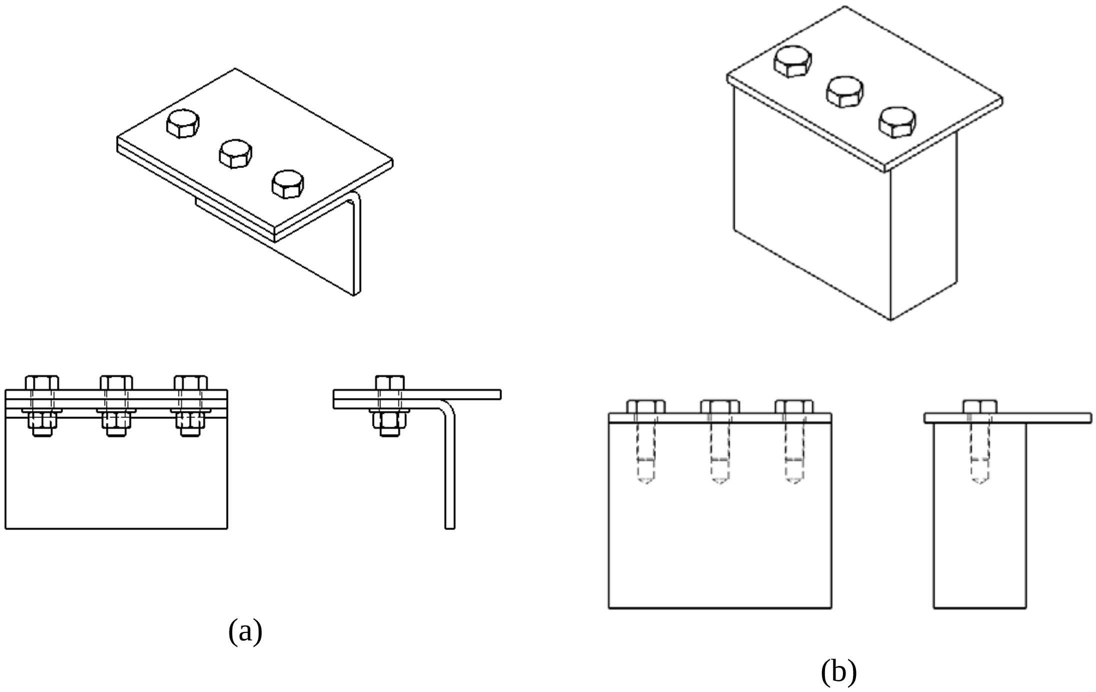
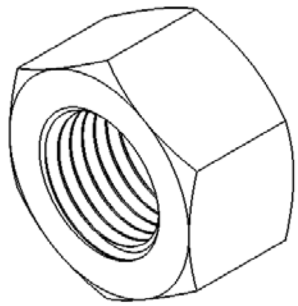
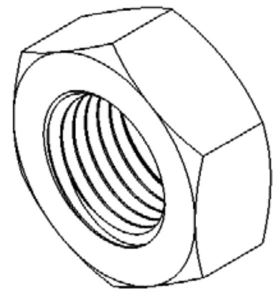


Figure 7 (a) Application for bolt with nut (b) Application for cap screw with threaded hole

The most common type of nut is the standard hex nut shown in Figure 8 (a), which will be used for many applications. The thinner version shown in Figure 8 (b) can be used in low clearance applications. The thinner version can also be used as a 'jam nut', where it is jammed against another standard hex nut to hold it in place.



(a)



(b)

Figure 8 (a) Standard hex nut (b) Thin hex nut (jam nut)

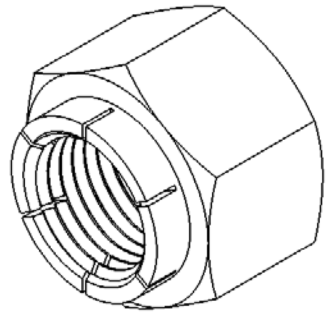
Like bolts, nuts have indicator markings to designate grade. Table 6 shows examples for SAE grade designation.

Table 6 Nut markings for SAE grade designation

Grade 2	Grade 5	Grade 8

Threaded fasteners are theoretically self-locking. However, in situations with vibration it may be desired to use a special class of nuts known as lock nuts. Lock nuts come in different varieties, but Figure 9 shows two common examples. Figure 9 (a) shows and example of a nylon insert lock nut and Figure 9 (b) shows an example of a flex top lock nut. The nylon insert grips the bolt to resist loosening and does not damage threads. Threads on the flex top lock nuts expand to grip the bolt on all sides and will provide a stronger hold.

(a)



(b)

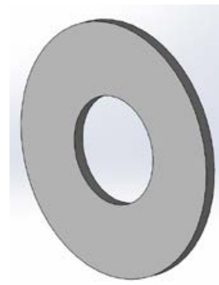
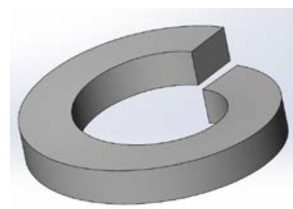
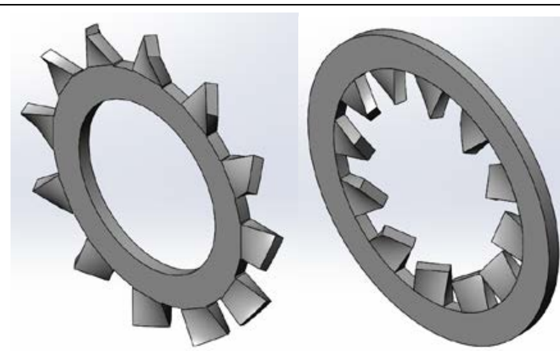
Figure 9 (a) Nylon insert locknut (b) Flex top lock nut

4.3 Washers

Washers are commonly added to a threaded fastener system and can serve many purposes. One major function of a washer is to span an oversize clearance hole. Washers also distribute the axial load from the bolt over a larger area. Washers will protect the surface of the plates from being damaged as the bolt is tightened. Also, washers are hardened so they provide a hardened surface for the bolt to contact which minimizes local deformation at the contact point between the bolt and the plate.

Lock washers are a special type of washer used to a threaded faster system to keep it tight. Table 7 gives examples of common types of washer with a brief description of each.

Table 7 Common types of washers

Flat Washer	Used to displace the load Can be used to cover the hole or act as a spacer	
Split Lock Washer	Lock washers resist loosening from vibration Split lock washers have low resistance to loosening	
Tooth Lock Washer	Better resistance to loosening compared to a split lock washer Available in external tooth and internal tooth	

5.0 Introduction to the Design of Bolted Connections

5.1 Types of Joints

5.1.1 Lap Joints

In a lap joint, the two plates are simply lapped over each other and connected with bolts. A simple example is shown in Figure 10 using a single row of two bolts.

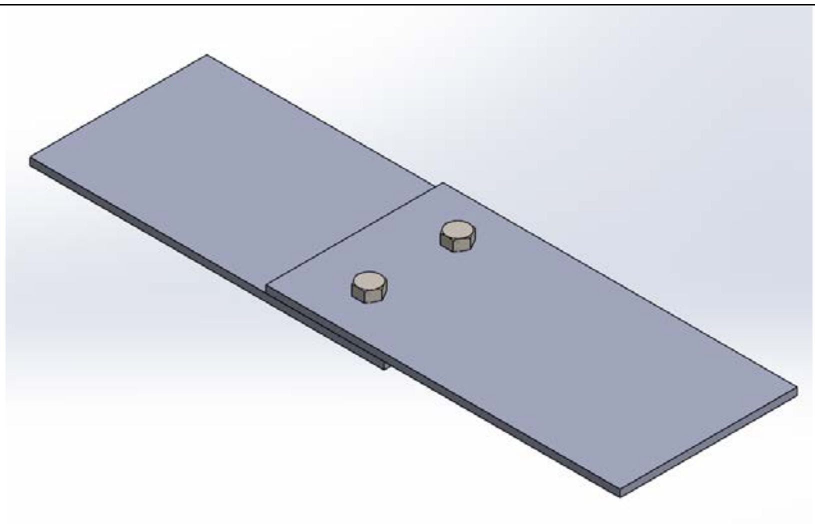


Figure 10 Bolted lap joint

Loads applied to the two plates in a lap joint are not aligned, which results in an eccentricity of the loads. Due to this eccentricity, the plates will tend to bend to attempt to align the loads as shown in Figure 11. Because of the induced bending, lap joints should only be used for minor connections.

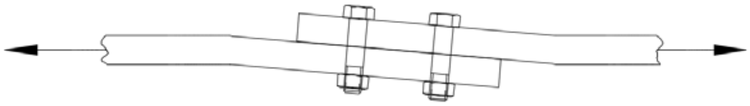


Figure 11 Plate bending in a lap joint

5.1.2 Butt Joints

Figure 12 shows an example of a bolted butt joint. In a butt joint, the two plates being connected are aligned end-to-end and cover plates are used to make the connection. In the example shown two cover plates are used, though it could be a single cover plate. Axial forces applied to the two plates in a butt joint will be aligned, which prevents bending of the plate materials.

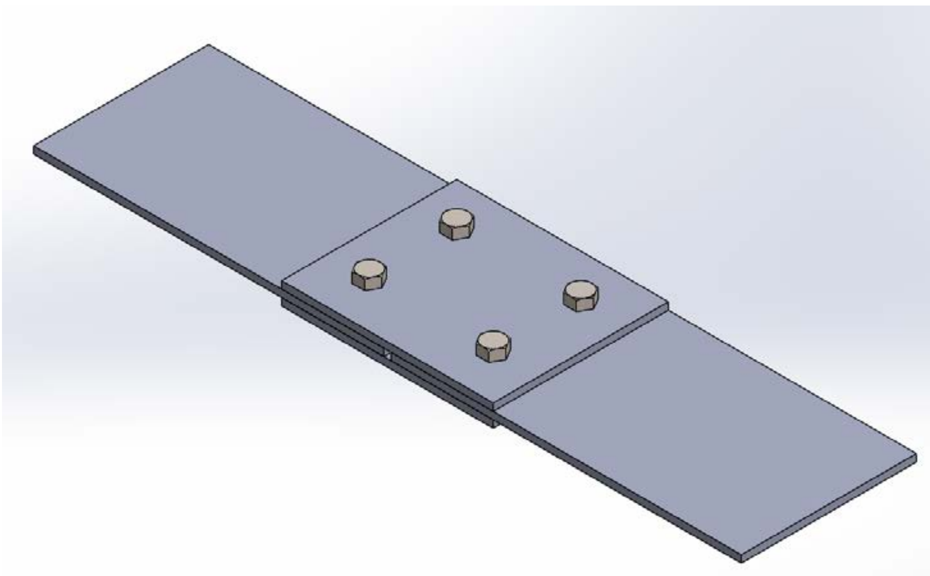


Figure 12 Bolted butt joint

5.2 Bolt Strength Properties

Some basic ideas of the mechanical properties of bolts were introduced in Table 3 for SAE grades of bolts. We will now explore the meanings of the different properties. Tables exists for all the different materials and grades of bolts. Most tables will give properties such as tensile strength, proof load, and yield strength. It is important to understand the meaning of each term. **Tensile strength** will be the maximum tension loading that can be applied to the bolt before fracture. **Yield strength** is the load limit for the end of the elastic limit. In other words, loading beyond the yield strength will cause permanent deformation of the bolt. The **proof load** is approximately 85 – 95% of the yield strength, and it represents the safe usable tensile load for the bolt.

5.3 Shear Strength of Threaded Fasteners

5.3.1 Single Shear vs. Double Shear

Shearing stress is caused by forces acting parallel to the area resisting the force. The general equation for shear stress is given in Equation 1, where V is the shearing force and A is the cross-sectional area being sheared.

Basic Shear Stress $$\tau = \frac{V}{A}$$ Equation 1

More details of this equation and the specific applications to bolted connections will be explained in sections to follow. The shear strength of a connection will depend on the number of available shear planes. The bolt shown in Figure 13 (a) will only resist shear across one shear plane (one cross-section of the bolt) and is considered **single shear**. The bolt in Figure 13 (b) must fail along two cross-sections of the bolt and is considered **double shear**.

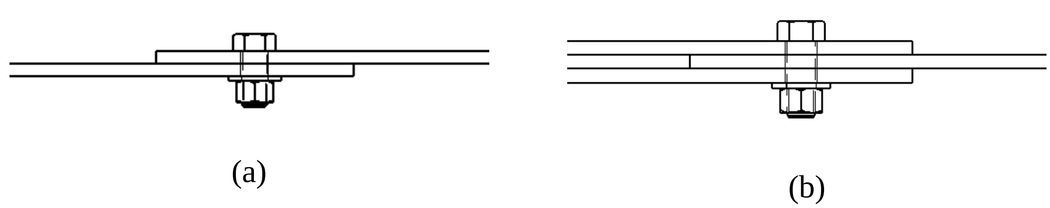


Figure 13 (a) Single shear (b) Double shear

5.3.2 Allowable Shear Stress

Tables of mechanical properties are provided for each type of threaded fastener, and the properties provided in the table were discussed in Section 5.2. Shear properties, however, are generally not provided in mechanical property tables. If shear strength is provided for the specific bolt in use that value should be used for design. In the absence of tabulated shear strength values, approximate shear strength values can be developed.

Based on a tension-type shear test, allowable shear stress will be approximately 62% of the tensile strength of the bolt material (Kulak, Fisher, & Struik, 2001).

$$\tau_u = 0.62\sigma_u \qquad \text{Equation 2}$$

When determining the shear strength, it is critical to determine the appropriate shear area. You may also have multiple shear planes (single shear versus double shear as described in Figure 13). Defining m as the total number of shear planes, the shear resistance S_u of a bolt with cross-sectional area equal to A_b is equal to

Shear Resistance out of Thread Plane

$$S_u = m(A_b)(0.62)\sigma_u \qquad \text{Equation 3}$$

The shear plane may be in the thread region, as shown in Figure 14. In this case the effective cross-sectional area of the bolt will be reduced to the root area of the bolt. The reduced area will equal approximately 70 to 75% of the nominal bolt area (Kulak, Fisher, & Struik, 2001). Using the lower bound gives a reduced shear resistance if shearing occurs in the thread plane.

Shear Resistance in Thread Plane

$$S_u = (0.7)m(A_b)(0.62)\sigma_u = (0.43)m(A_b)\sigma_u \qquad \text{Equation 4}$$

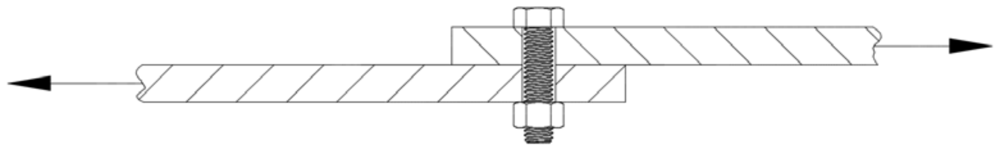


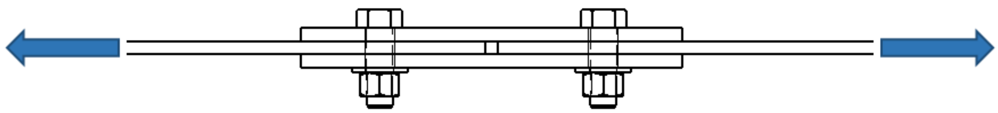
Figure 14 Shear through the thread plane

The shear resistance values calculated from Equation 3 or Equation 4 will be for a single bolt in the connection. To obtain the total shear capacity you must multiply the value by the number of bolts in the connection. Details will be explained along with example problems in Section 7.0.

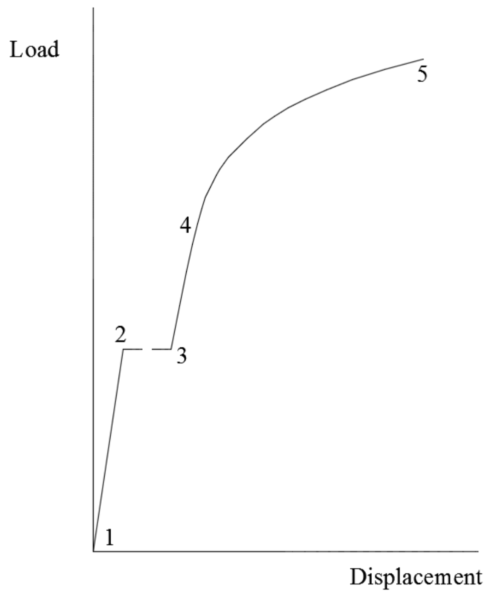
5.4 Slip-Critical Joints

5.4.1 Slip Resistance

Consider the butt joint shown in Figure 15 (a). We can construct a plot comparing the deformation versus the applied load, which is shown in Figure 15 (b). The deformation plot will have four distinct phases. The bolts will apply a clamping load on the plates, which causes friction. During phase 1 of the deformation plot (located between points 1 and 2 on the plot), the friction is holding the applied load. In this phase the joint is considered as a **slip-resistant joint** because the friction prevents slipping. As the applied load increases, it will reach a point where it will overcome the friction and the plates will slip. The slip shown on the deformation plot is phase 2 of the loading (located between points 2 and 3 on the plot). Deformation will continue until the slip causes a bearing contact between the bolt and the plates (slip causes the plate to bear against the side of the bolt). Once the joint has slipped into bearing, the deformation plot enters phase 3 (points 3 to 4 on the plot). Phase 3 is a linear relationship between load and deformation as the plates and bolts elastically deform. Phase 4 (between points 4 and 5 on the plot) begins once the plates, bolts, or both exceed the yield limit. The joint will then fail in one of several possible modes, and each will be discussed further in Section 7.0.



(a)



(b)

Figure 15 (a) Butt joint with axial loading (b) Displacement curve

5.4.2 Slip Critical Joints

Based on the discussion in Section 5.4.1, two methods exist for load transfer in a direct loaded shear connection (such as the butt joint in axial loading with the load acting through the centroid of the bolt pattern). These two methods are either load transfer by friction or by shear and bearing. If the full applied load is to be carried by friction only, the joint is considered to be slip critical. In **slip critical joints**, the bolts are not subjected to shear and no bearing stress occurs on the plates.

5.4.3 Snug Tight vs. Fully Tensioned

In bolted connections, it is possible to control the amount of clamping force in the bolts. The ability to control the clamping force allows the control over the friction developed in the joint. Therefore, bolted connections can be designed specifically to be slip resistant joints by controlling the amount of clamping force developed. The clamping force is controlled by how much the nut is tightened on the bolt. Bolts are tightened to develop one of two conditions, **snug tight** or **fully tensioned**. Snug tight conditions will only generate a small clamping force on the bolt and will result in slipping.

Different methods exist for developing a fully tensioned joint. The first is the **turn-of-the-nut method**. For this method, the bolt is first brought to a snug tight position with an impact wrench. From the snug tight position, the bolt is given an additional half to full turn depending on bolt length. The second method for developing a fully tensioned joint is the **calibrated wrench method**, which utilizes an impact wrench adjusted to stall at a certain torque. The third method for developing a fully tensioned joint is by using **direct tension indicators**, such as the tension indicating washer shown in Figure 16. The tension indicating washer has arches protruding from the surface which collapse under loading.

Figure 16 Tension indicating washer

Bolts need to be tightened to at least 70% of the specified minimum tensile strength to be considered fully tensioned. Table 8 gives some examples of tensions required for structural bolts up to 1 inch in diameter. These values are approximate based on 70% of tensile strength. Specific values should be obtained for actual bolts used.

Table 8 Approximate tension required for fully tensioned structural bolts

Bolt Diameter (inches)	Tension Required for Fully Tensioned (kips)		
	A307	A325	A490
½	6.2	12.4	15.5
5/8	9.7	19.3	24.3
¾	13.9	27.8	34.9
7/8	18.9	37.9	47.6
1	24.7	49.5	62.1

5.4.4 Summary of Slip Critical Joints

We have defined a slip critical joint as a joint designed with sufficient bolt clamping force to carry the applied load by friction forces alone. In other words, the joint will not slip and will stay in the first phase of the deformation curve shown in Figure 15 (b). Joints where slip has occurred are called **bearing type connections** because the plate and bolt surfaces will be in bearing contact.

It should be noted that bolt coatings, such as hot dip galvanized bolts, may cause complications in methods such as the turn-of-the-nut method. The complications are due to the fact that the coating may cause the nut to seize as the bolt is tightened making it difficult to determine the snug tight condition.

The process of fully tensioning bolts can be expensive. Therefore, snug tight bolts should be used in most situations.

6.0 LRFD Design

The bolted connection design procedures presented here will be based on the Load and Resistance Factor Design (LRFD) method. A full description of the method is beyond the scope of this course, but below is a list of some important requirements for bolted connections.

6.1 Resistance Factor

In the sections to follow, the design strength of bolted connections will be determined using the Load and Resistant Factor Design (LRFD) method. **Resistance factors** are used in the LRFD method to account for uncertainties in material strength. Theoretical ultimate strength values are reduced by multiplying the ultimate strength and a resistance factor ϕ. The value of the resistance factor will vary depending on the degree of uncertainties. Specific values of the resistance factor will be presented throughout the rest of this course when applicable.

6.2 Spacing, Edge Distance, and Hole Size

6.2.1 Bolt Spacing

Limitations on the spacing between bolts are provided by LRFD codes. Sufficient spacing must exist for installation purposes and for bearing stress considerations. The preferred minimal spacing between bolts will equal 3 times the bolt diameter. Code allows minimal spacing of 2.75 times bolt spacing if required.

6.2.2 Edge Distance

LRFD specifications give limitations of the distance from a bolt to the edge of the plate. The required distance is smaller for rolled edges of plates compared to sheared edges of plates. You can look up specific requirements of distances if required, but a general rule of 1.5 times bolt diameter for rolled edges and 1.8 times sheared edges can be used to give minimum edge distances.

6.2.3 Hole Size

Standard sized bolt holes will have a diameter 1/16 inch larger than the bolt diameter. Larger holes are often desired for ease of assembly. Oversize holes will have a diameter 1/8 inch larger than the bolt diameter for smaller diameter bolts (approximately 1/2 inch or below), 3/16 inch larger for mid-sized bolts (up to 1 inch), and 5/16 inch large for bolts larger than approximately 1 inch in diameter. Hardened washers are required for oversize holes. Slotted holes can also be used to allow for greater adjustment in one direction.

7.0 Design for Direct Loading Applications

7.1 Lap Joint Bearing Type Connection

We will first consider a lap joint that is a bearing type connection (not a slip critical joint). Because slipping has occurred, the plate and bolt are in bearing contact. Direct loading indicates that the applied load passes through the centroid of the bolt group. The possible modes of failure for such a joint are discussed below.

7.1.1 Shear Failure

We will begin by examining the bolted joint failure mode of bolt shear failure, which is illustrated in Figure 17. If the applied loading causes the shear stress in the bolts to exceed the allowable stress limit the bolts will fail in shear.

In the LRFD method, the design strength of a bolt in single shear is equal to the resistance factor ϕ times the bolt's cross-sectional area (in square inches) times the nominal shear strength of the bolt (in psi or ksi). For bolt shear, the resistance factor is equal to 0.75. It is best to determine the nominal shear strength from tables based on the bolt type in use. If nominal shear strength is not provided, the equations discussed in Section 5.3.2 can be used to give approximate values. It is up to the designer to determine if the threads will be in the shear plane, which will reduce the cross-sectional area.

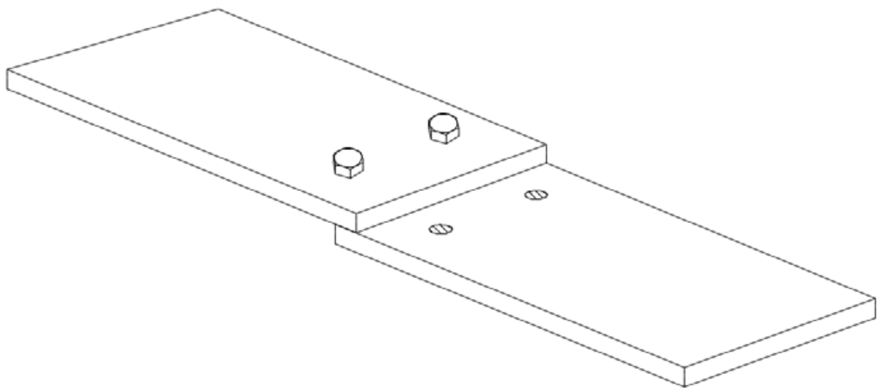


Figure 17 Bolt shear failure for a lap joint

LRFD gives the allowable design load P for a single bolt in single shear in Equation 5 where A_b is the bolt area in square inches, τ_b is the nominal shear strength of the bolt in ksi, and ϕ is the resistance factor (which has a value of 0.75 for bolt shear).

Design Load for Bolt Shear per Shear Plane $$P = \phi A_b \tau_b$$ Equation 5

For a case with multiple bolts, the value obtained in Equation 5 is multiplied by the total number of bolts in the connection. The simplifying assumption is made that all bolts in the connection will equally carry the load. The assumption is only valid if the load passes through the centroid of the bolt group, otherwise it is an eccentrically loaded connection (see Section 8.0 for details on eccentrically loaded connections). For a bolt in double shear, the value in Equation 5 is doubled to account for both planes of shear.

7.1.2 Plate Failure

The next failure mode we will consider is shear failure of the plate through the bolt line. The cross-sectional area of the plate is reduced in the line of the bolts due to the holes in the plate. The failure region is illustrated in Figure 18.

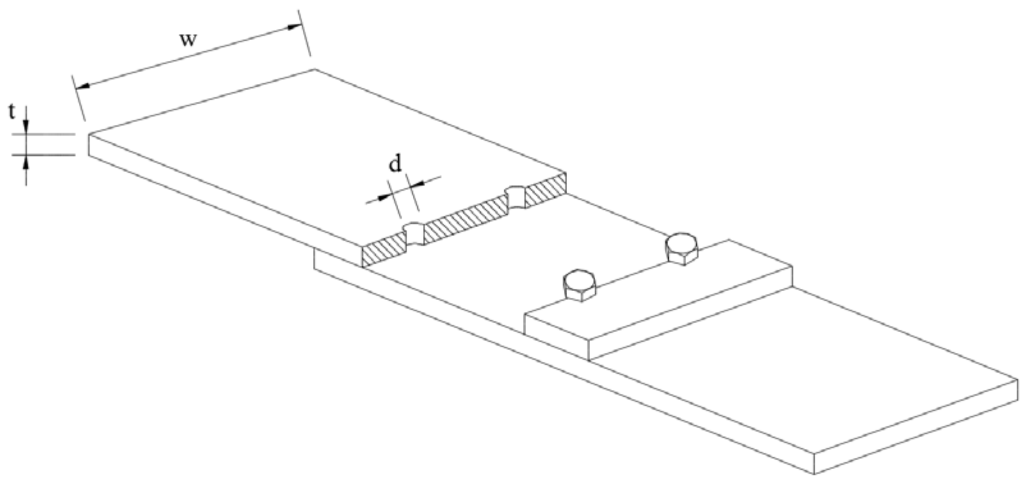


Figure 18 Plate tear failure (through bolt line) for lap joints

Consider a case similar to that illustrated in Figure 18. For n holes of a diameter of d, the effective width of the plate will be $w - nd$. Using a plate thickness of t and an applied load of P, the plate tearing stress through the bolt centers will be

Basic Plate Tearing Stress

$$\sigma_t = \frac{P}{(w - nd)t} \qquad \text{Equation 6}$$

The LRFD method determines a design load both outside the region of the bolts and in the bolt line, and the minimum value is used for the final design strength of the connection. Equation 7 determines the design load for plate tear located outside the bolt area. Because it is located out of the bolt area, the gross plate area A_g is used. The design strength is based on the yield strength F_y of the plate. The resistance factor used in Equation 7 is 0.9.

Design Load for Plate Tear Located out of Bolt Line	$P = \phi F_y A_g$	Equation 7
Design Load for Plate Tear Located in Bolt Line	$P = \phi F_u A_n$	Equation 8

Equation 8 determines the design load for plate tear through the region in a bolt line. The area of the plate is reduced to the net area A_n, which is the area used in Equation 6. The plate ultimate strength F_u is used, and the resistance factor is 0.75.

7.1.2.1 Effect of Staggered Holes

The cross-sectional area represented in the denominator of Equation 6 is known as the critical area, which is a straight forward calculation when the bolts are in a straight line. When the bolts are in line, like the situation in Figure 19 (a), the net area of the plate is calculated along line 1-1. A case where the bolts are staggered, such as that shown in Figure 19 (b), the minimum net area must be determined. The net area on line 2-2 and 3-3 must be calculated to determine which case results in a lower net area.

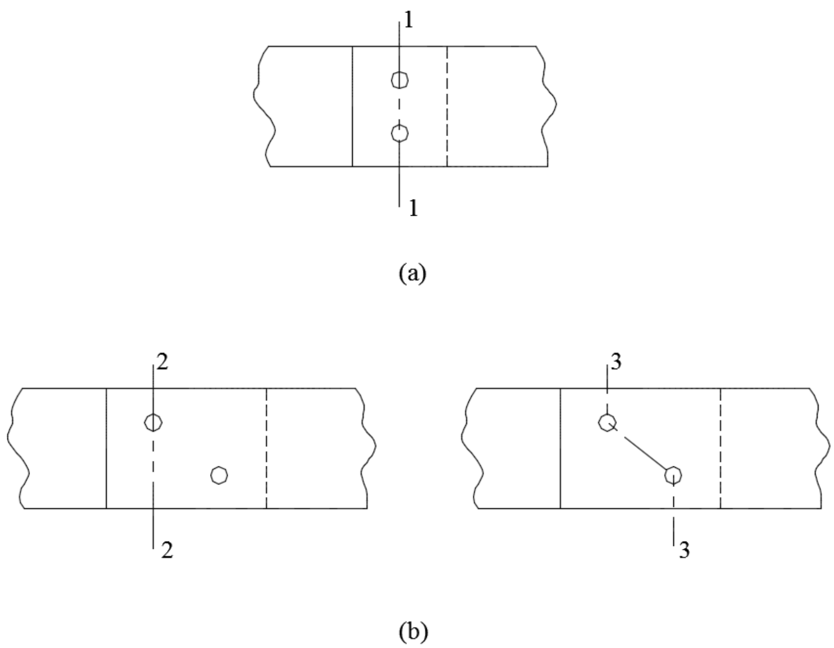


Figure 19 Plate tear failure (a) with in line bolts (b) with staggered holes

7.1.3 Plate Bearing

The final failure mode to consider is plate bearing. Bearing stress is a contact pressure between bodies. Consider the connection represented in Figure 20. As load is applied to the plates, the bolt surfaces will make contact with the inside surfaces of the holes in the plate (assuming slip has occurred). That contact will cause bearing stress. The true magnitude of bearing stress is difficult to determine and not constant throughout the bearing surfaces. Common practice is to make the assumption that the bearing stress is uniform over the projected area shown in the hatched regions of Figure 20.

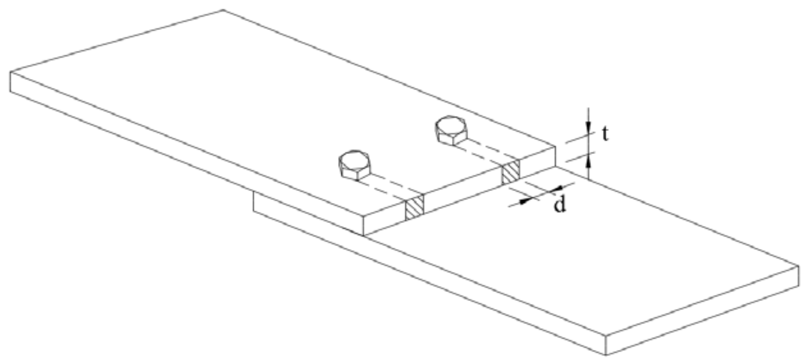


Figure 20 Bearing failure for a lap joint

The projected area for a single bolt would equal the bolt diameter d times the plate thickness t. For an applied load P, the bearing stress on the plate from a single bolt would be

Basic Bearing Stress for a Single Bolt

$$\sigma_b = \frac{P}{td} \qquad \text{Equation 9}$$

LRFD specifications state that Equation 10 be used when deformation around the bolt hole is a design consideration (Manual of Steel Construction, 2001). The resistance factor ϕ in Equation 10 is equal to 0.75, d is the bolt diameter in inches, t is the plate thickness in inches, F_u is the ultimate strength of the plate in ksi, and n is the number of bolts.

Design Load for Plate Bearing Stress

$$P = 2.4\phi(d)(t)(F_u)(n) \qquad \text{Equation 10}$$

For bolts spaced with clear distance between holes less than 3 times the diameter and for bolts with clear end distances less than 2 times the diameter, the design load for plate bearing stress is determined from Equation 11, where L_c is the clear distance between holes or between the hole and the edge of the member measured in the direction of the applied bearing force.

Design Load for Plate Bearing Stress	$P = 1.2\phi(L_c)(t)(F_u)(n)$	Equation 11

7.1.4 Procedure Summary for Lap Joint Bearing Type Connections

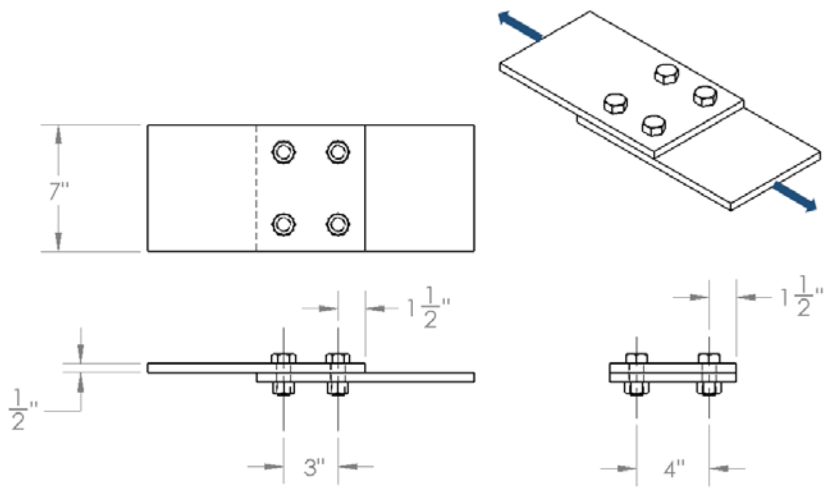
Several different failure modes must be considered when determining the design strength of a bearing type lap joint connection. The equations for each failure mode is summarized in Table 9 along with the required resistance factor ϕ for each equation.

Table 9 Summary of equations for bearing type lap joint connection

	Design Strength (kips)	**Value of ϕ**
Shear of a single bolt in single shear	$P = \phi A_b \tau_b$	0.75
Plate tear in region out of bolt line (gross area of plate)	$P = \phi F_y A_g$	0.90
Plate tear in region in bolt line (net area of plate)	$P = \phi F_u A_n$	0.75
Plate bearing	$P = 2.4\phi(d)(t)(F_u)(n)$	0.75

Example 1

The lap joint shown consists of four ¾" A325 bolts with threads excluded from the shear plane (nominal shear strength of 60ksi). The steel plates have a yield strength of 50 ksi and an ultimate strength of 65 ksi. All edge distances are 1 ½" and the holes are standard size. What is the design strength of the bearing type connection?



First we can determine the shear strength of the bolts (see Section 7.1.10). First we need the cross-sectional area for a single bolt.

$$A_b = \frac{\pi d^2}{4} = \frac{\pi (0.75in)^2}{4} = 0.442in^2$$

The connection has four bolts in single shear, so there is a total of 4 shear planes. The total strength for bolt shear is determined from Equation 5.

$$P = \phi A_b \tau_b n = 0.75(0.442in^2)(60ksi)(4) = 79.52kips$$

The gross area of the plate

$$A_g = \left(\frac{1}{2}in\right)(7in) = 3.5in^2$$

The design strength of the plate over the gross area

$$P = \phi F_y A_g = 0.9(50ksi)(3.5in^2) = 157.50kips$$

A standard hole for a ¾" bolt is 13/16". The net area of the plate through the bolt line

$$A_n = \left[7in - 2\left(\frac{13}{16}in\right)\right]\left(\frac{1}{2}in\right) = 2.69in^2$$

The design strength of the plate over the net area

$$P = \phi F_u A_n = 0.75(65ksi)(2.69in^2) = 131.02kips$$

Last we consider bearing stress of the plate.

$$P = 2.4\phi(d)(t)(F_u)(n) = 2.4(0.75)\left(\frac{3}{4}in\right)\left(\frac{1}{2}in\right)(65ksi)(4) = 175.5kips$$

The design strength is determined as the minimum of all those calculated, which is the bolt shear for this example. Therefore, the design capacity for the bolted connection is 79.52 kips.

7.2 Butt Joints

Overall, the concept for analyzing butt joints will be the same as for lap joints. However, butt joints tend to be a little more complex when considering the different possible failure modes. As an example, consider the butt joint shown in Figure 21. Instead of two plates end-to-end with cover plates, this connection has a top and bottom plate that carry the full load of the single middle plate. The resultant load of the two plates will be in line with the load of the single plate, but the magnitude will be half of the loading. Because the loading in the plates are not all equal, stresses must be considered for each plate.

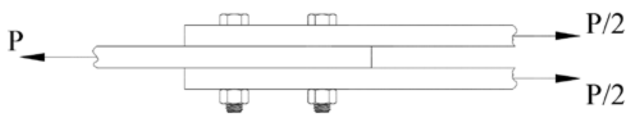


Figure 21 Butt joint

Cover plates are often thinner than the load carrying plates, and bolt patterns may include rows with different numbers of bolts. Both cases are represented in Figure 22. Full analysis of butt joints requires detailed analysis of each plate to ensure that the location of maximum stress is located.

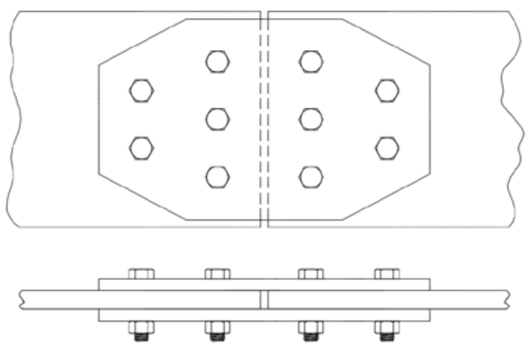


Figure 22 Butt joint with cover plates

8.0 Design for Eccentrically Loaded Applications

8.1 Introduction

It is common to have bolted connections where the applied load does not pass through the centroid of the bolt group. Connections where the load does not pass through the centroid of the bolt group are called eccentric connections. Two categories of eccentrically loaded bolted connections exist: connections where the bolts are subjected to eccentric shear and connections where the bolts are subjected to shear and tension. This course will focus on the first case resulting in bolts subjected to eccentric shear.

8.2 Connection with Bolts Subjected to Eccentric Shear

An example of a case when the bolts are subjected to eccentric shear is shown in Figure 23. The bolts will only have shear loading, but the load will not be carried equally by each bolt due to the moment caused by the eccentricity of the applied load.

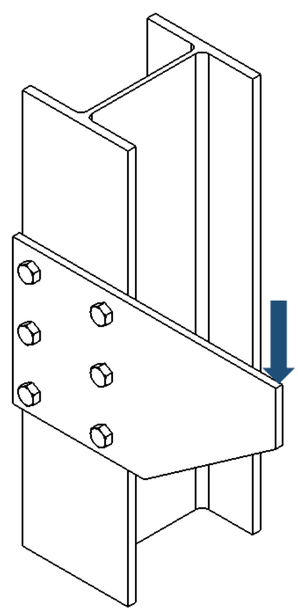


Figure 23 Eccentric connection with bolts subjected to eccentric shear

The example connection shown in Figure 23 is shown again in Figure 24 (a) to explain the procedure for determining the total shear on any single bolt in a connection. The applied load *P* will cause a moment on the connection due to the fact that it does not pass through the centroid of the bolt group. The load can be replaced with a load passing through the centroid of the bolt group and an effective applied moment *M* (equal to the applied load times the eccentricity distance) as shown in Figure 24 (b).

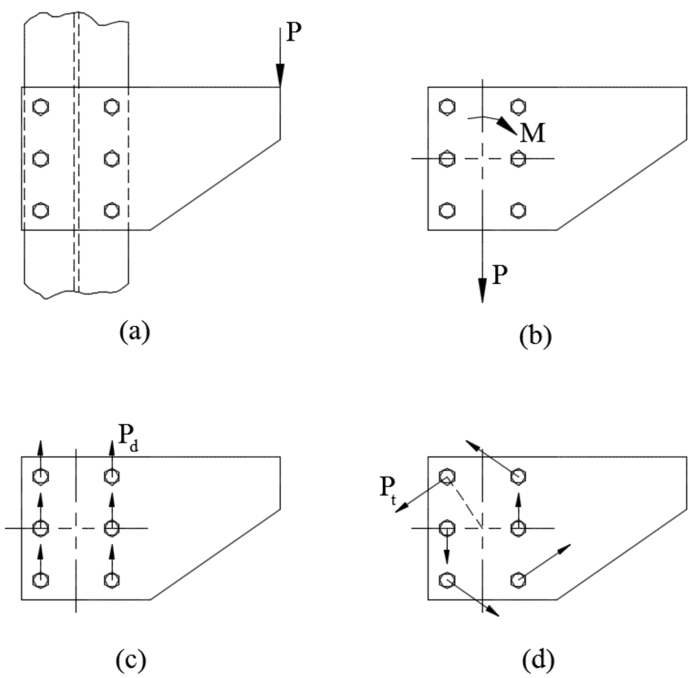


Figure 24 (a) Eccentric connection (b) Load through the centroid of the bolt group and applied moment (c) Direct loading on each bolt (d) Torsional loading on each bolt

The loading on each bolt in the group can be broken down into **direct loading** and **torsional loading**, both will cause shearing of the bolts. The direct loading, as shown in Figure 24 (c), will result from the applied load passing through the bolt centroid. Therefore, the direct load on any bolt is the magnitude of the applied load divided by the number of bolts. Again, it is assumed that the bolts equally carry the direct load.

The torsional loading on the bolts, as illustrated in Figure 24 (d), will resist the effective applied moment. The magnitude of the torsional loading will depend on the bolt's distance from the centroid, and the direction will depend on the bolt's location relative to the centroid.

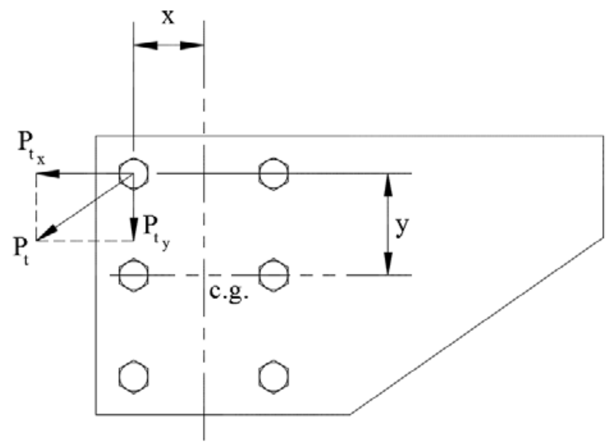


Figure 25 Development of torsional loading per bolt

Figure 25, which is an enlarged view of Figure 24 (d), will help illustrate the process of determining the torsional loading carried by each bolt. The direction of the resultant torsional load P_t on any single bolt will be perpendicular to the radial line from that bolt to the center of gravity of the bolt group. The vector representing the torsional load can be broken into *x* and *y* components of the force. The magnitude of the force components will depend on their distance to the center of gravity of the bolt group. The *x* and *y* components of the torsional loading for a single bolt will be

Torsional Loading Equation 12

$$P_{t_x} = \frac{My}{\sum x^2 + \sum y^2}$$

$$P_{t_y} = \frac{Mx}{\sum x^2 + \sum y^2}$$

In Equation 12, M is the moment caused by the force and the eccentricity and the x and y terms in the numerator are the distances from the bolt in question to the centroid. The summations in the denominator come from the equation for polar moment of inertia for the bolt group. The summations will include the x and y distances for every bolt within the group. Once the direct load and torsional load is determined for a bolt, the total resulting force on that bolt is determined using Equation 13.

Resultant Force $$P_r = \sqrt{\left(P_{d_x} + P_{t_x}\right)^2 + \left(P_{d_y} + P_{t_y}\right)^2}$$ Equation 13

8.2.1 Locating the Centroid of the Bolt Group

Solving problems of eccentrically loaded connections requires locating the centroid of the bolt group. It is common to have symmetric bolt groups, making the process easier. However, the centroid of the bolt group can easily be found by finding the averages of x and y locations. Consider the example connection shown in Figure 26 (a). To find the centroid of the bolt group you need to define the point location with the x and y coordinates of (0,0) as shown in Figure 26 (b).

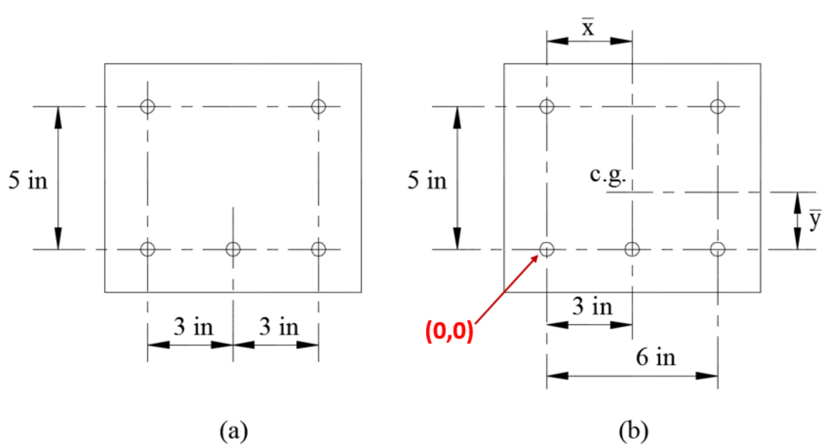


Figure 26 Location of centroid for a bolt group

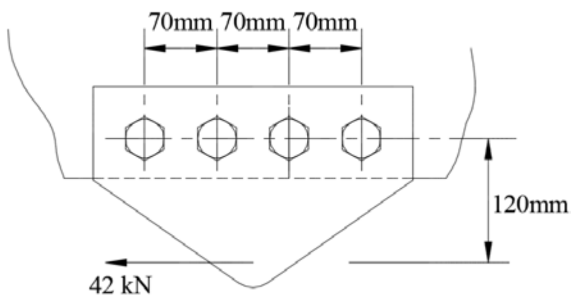
The *x* and *y* coordinates of all bolts in the group are then tabulated to find an average, which are shown in Table 10. The location of the centroid, based on the calculated averages, will be $\bar{x} = 3$ and $\bar{y} = 2$.

Table 10 Coordinates of bolts for Figure 26

Bolt	**x**	**y**
a	0	5
b	0	0
c	3	0
d	6	0
e	6	5
Average	3	2

Example 2

The connection shown has four 25 mm diameter bolts. Determine the maximum resultant shear stress for a single bolt.



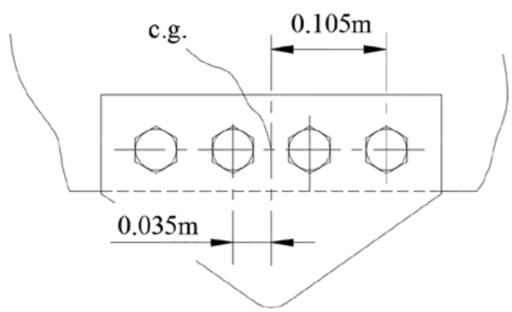
The direct loading for each bolt will be

$$P_d = \frac{42kN}{4} = 10.5kN$$

The effective moment is equal to the applied load times the eccentricity.

$$M = 42kN(0.12m) = 5040N \cdot m$$

The center of gravity of the bolt group is shown. All *y* distances to the bolts will be zero. The *x* distance to the two inside bolts will be 0.035 meters and the *x* distance to the two outside bolts will be 0.105 meters.



The summation terms for the distances equal

$$\sum x^2 = 2(0.105^2) + 2(0.035^2) = 0.0245m^2$$

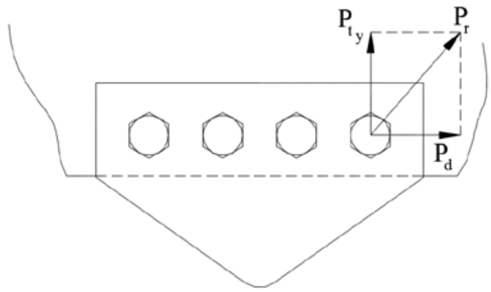
$$\sum y^2 = 0m^2$$

The maximum bolt stress will occur on the two outside bolts because they are farther away from the bolt group center of gravity. The *x* and *y* coordinates of the torsional loading on one outside bolt will be

$$P_{t_x} = \frac{My}{\sum x^2 + \sum y^2} = 0$$

$$P_{t_y} = \frac{Mx}{\sum x^2 + \sum y^2} = \frac{5040N \cdot m(0.105m)}{0.0245m^2} = 21.6kN$$

The components are shown in the figure below for the far right side bolt.



The resultant force on that bolt is

$$P_r = \sqrt{\left(P_{d_x} + P_{t_x}\right)^2 + \left(P_{d_y} + P_{t_y}\right)^2} = \sqrt{(10.5kN)^2 + (21.6kN)^2} = 24kN$$

The stress is determined using the bolt area.

$$A_b = \frac{\pi d^2}{4} = \frac{\pi(0.025m)^2}{4} = 0.00049m^2$$

$$\tau = \frac{24kN}{0.00049m^2} = 48.9MPa$$

The previous example was a basic example to illustrate the process for eccentrically loaded connections. Once the resultant force is determined, the design process would again include checking other failure modes such as plate bearing. Optimizing a design of an eccentrically loaded connection will be an iterative trial-and-error process because any small change to the bolt group will change the polar moment of inertia of the bolt group.

9.0 Design for Tension Loading Applications

Bolted connections can also be loaded in pure tension, such as the application shown in Figure 27.

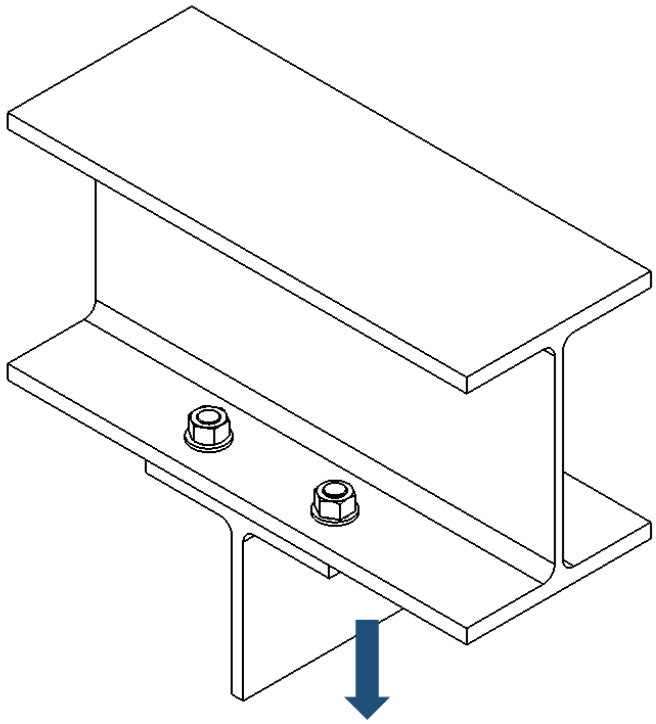


Figure 27 Application for tension loaded bolted connection

Applications with direct tension loading will have a design strength per bolt determined from Equation 14, where A_b is the bolt area and F_u is the ultimate tensile strength of the bolt. The resistance factor is 0.75.

Design Strength for a Bolt in Tension Loading

$$P = \phi A_b F_u \qquad \text{Equation 14}$$

Example 3

The connection shown in Figure 27 has four ¾ inch A325 bolts (tensile strength of 90 ksi). What is the design capacity of the connection?

$$A_b = \frac{\pi d^2}{4} = \frac{\pi\left(\frac{3}{4}in\right)^2}{4} = 0.44in^2$$

$$P = \phi A_b F_u = 0.75\left(0.44in^2\right)\left(90ksi\right)\left(4bolts\right) = 119k$$

9.1 Prying Action

The example from Section 9.0 was a basic example and was based on the assumption that the T-shaped member was stiff and did not deform. Deformation of the T-shaped member would result in a condition shown in Figure 28. Stresses will then exist in the T-shaped member from bending. Also, if the deformation is large enough it will cause a prying action on the bolts increasing the tension stress in the bolts.

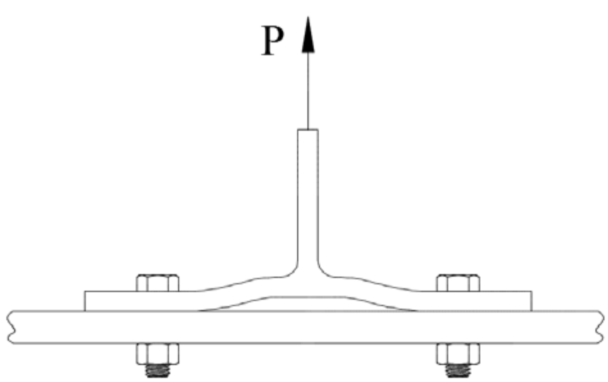


Figure 28 Prying action

Stresses involved with the prying action shown can be rather complex. Full coverage of prying action is beyond the scope of this course. Engineers designing connections similar to that shown in Figure 28 should be aware of the phenomenon.

10.0 Works Cited

Kulak, G. L., Fisher, J. W., & Struik, J. H. (2001). *Guide to Design Criteria for Bolted and Riveted Joints.* Chicago: AISC.

Manual of Steel Construction. (2001). Chicago: AISC.

