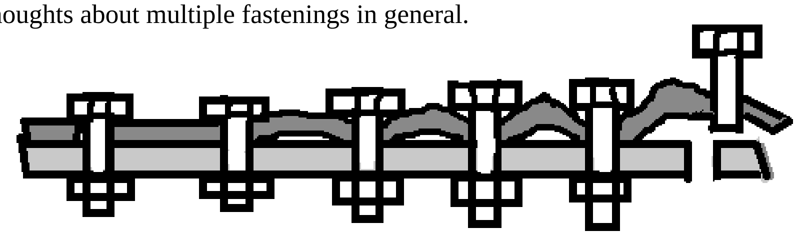
Multi-Bolt Assemblies

by Thomas Doppke

Before we get into the mathematics of multiple bolted joints, a few thoughts about multiple fastenings in general.



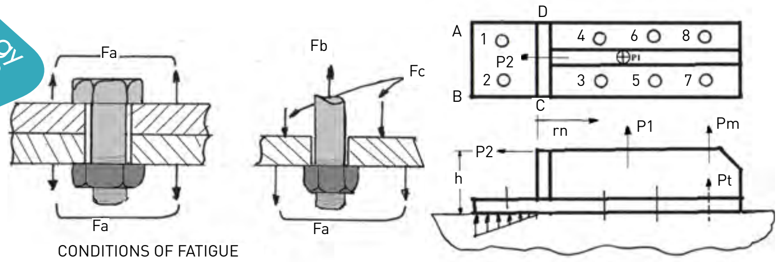
CLOTHESLINING occurs when bolts tightened sequentially added the individual tolerances of the holes. The result is buckling and probable no fit if the misfit is great enough or enough bolts are involved.

The science of fastening has had much literature written pertaining to the finer points of the art of joining. While bolted joints were studied in every aspect, every facet discussed and the loading, forces, and conditions thoroughly examined, few thoughts were ever given to the fact that most joints are not individual bolt attachments standing alone. Many assembled structures consist of multiple bolts which are, theoretically, sharing the entire fastened load. Unfortunately thinking today has become so focused that few people ever consider that most bolts are 'team players'. A famous case of narrow thinking years ago involved the replacement of bolts in a bridge. Rather than replacing one at a time the repair crew removed one, then another, etc. until the bridge fell down. OOPS! (this really happened!). This article will discuss multiple fastening and how and what loads are involved with the hope that some enlightened engineer will think before taking something entirely apart all at once. The fastening knowledge has always been a hard to obtain commodity. Few books, almost no education (most engineering classes devote as little as 3 days to fastener information), and few publications are readily available. Fastener World and its sister publications offer up the accumulated knowledge of the world's experts. I save each issue and refer to them constantly. I have added some reference notes occasionally throughout this article.

When using thinner metal, fasteners along an edge should not be tightened sequentially. An effect known as 'clotheslining' may occur. This is caused by the accumulation of the minute variations between the holes which, when added one by one, will cause a bulge in the fastened material. With a long enough series the end part may not even align with its intended mating hole. The correct way is to skip one or more bolts for the first round of tightening and then tighten the omitted ones on the second round until all are secure. Holes for multiple joints should not be too close to the edge and/or too close together to prevent fatigue cracking and to insure sufficient bearing surface beneath the fasteners for full joint strength development. Common design practice is to use a nominal edge distance of 2 fastener diameters from the fastener hole centerline. The minimum edge distance should not be less than 1.5D. The nominal distance between fasteners is generally accepted to be 4D but may be modified if the materials being joined are of a significant thickness. A wider spacing can be used as long as sealing of the surfaces is accomplished.

Let's assume that we are designing a bridge support (or truss beam or some such construction that needs several bolts to hold the joint plates together). A look at what our 'bridge plate' example needs for fasteners show some requirements depending upon the direction of loading. Real life conditions cause the joint to expand and contract, weather, wind, loading upon the structure (traffic on our bridge), joint relaxation, micro-fretting (Fretting Failures, China Fastener World June 2011) all cause cyclic action to the joint to some degree. Mostly in the shear direction but there may be times when a tensile load is involved.

If the bolt is cycled in tension, the bolt will usually break near the end of threaded part. This is the area of highest stress concentration. In order to lessen the stress concentration, often the bolt shank is machined down to approximately the root diameter of the thread. Tests have shown that bolts machined like this will survive tensile cyclic loading much longer than standard dimensioned parts.



CONDITIONS OF FATIGUE
LOADING OF BOLTS

A quick review of the forces acting on bolted joints are shown in three types of joints, above- under various loading conditions. These are a bolted flange type with an external load, left, and a free body joint with and without an external load, right, (the two examples are combined into one illustration here). Without an external load the free body example shows the tension force, Fb to be equal to force Fb and Fd combined and the force reacting against this value Fb+Fd to be Fc and Fd combined. In other words, Fb is equal to Fc. With an external load, Fb is balanced by forces Fc and Fa as shown.

The joint shown is preloaded with an initial load Fd which equals the clamp load Fc, before the external load Fa is applied. This assembly can be written as:

$$F_b = F_d + \frac{K_{sb}}{K_{sb} + K_{ss}} + F_a$$

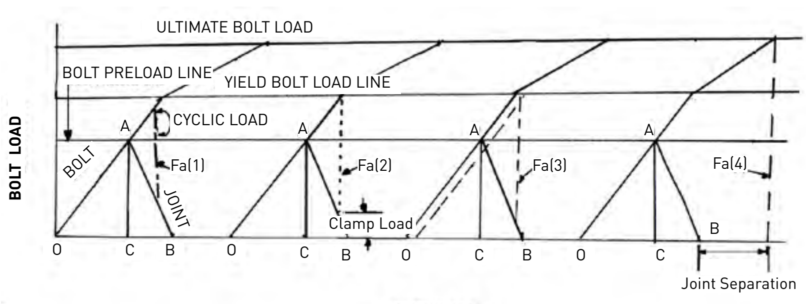
Where Fb is, as mentioned before, the total bolt loading. Ksb is a spring constant of the bolt and Kss is the spring constant of the clamped pieces. The effects of the spring constants, if we let

$R = K_{ss}/K_{sb}$, can be stated as:

$$F_b = F_d + \frac{1}{1 + R} F_a$$

Normally Kss is larger than Ksb so the bolt loading does not increase much as the initial external load is applied (R is approximately 5.0 for steel components). The point at which a significant increase in bolt load is noted is when Fa exceeds Fd.

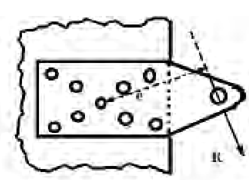
A further clarification of the effects of externally applied loads can be seen when stress triangles are drawn (See “Understanding Stress Triangles”, Fastener World. Nov/Dec 2002 for a more complete discussion of this method).



The stress triangle diagram here is a composite of the various conditions for a bolt externally loaded. The load triangle OCB is identical in each diagram. The slope OA is the bolt stiffness, the slope AB is the joint stiffness. The joint is stiffer than the bolt by the ratio of OC/CB. The first example, Fa(1), shows a joint in which the externally applied load does not load the bolt to its yield point. Fa(2) illustrates a bolt loaded to its yield point, causing a decrease in clamping load (dashed line). Fa(3) shows a bolt loaded to the point that it takes a permanent elongation. The clamping force is now less than the bolt preload line when the force Fa(3) is removed. Finally, Fa(4) shows the condition when the loading has caused a joint separation and imminent bolt failure. Of note is the observation that the flatter the slope OA is (or the larger the ratio of OC/OB) the smaller the effect of Fa has on the bolt. This translates into the fact that using more smaller diameter fasteners will give more fatigue résistance than fewer larger diameter ones.

Fatigue life is predicated by noting the cyclic load that is above that portion above the bolt preload line. This alternating load is used on stress vs load cycle diagrams of the bolt material to predict expected fatigue life of the bolts.

A second factor that impacts multi-bolt joining is thermal cyclic loading. Since most multi-bolt joints are usually found out of doors (bridges and structural construction) differential contraction can cause joints to loosen as clamp loads fall to below the specified and required value for joint tightness. Differential expansion can cause overloading of fasteners especially since most multi-bolt construction attachments utilize large diameter parts which are impact tool installed. Impact tools are famous for their lack of control of torque and are banned in many automotive plants for that reason. The use on conical washers in the assembly is often used to give additional adjustment room in the joint loading.

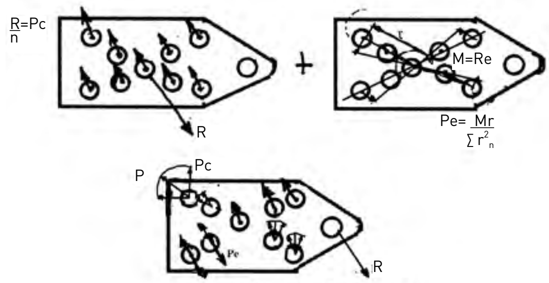


Finally, multi-bolt joints are mostly designed to operate in shear. The old rule of thumb that shear joints are only 60% of the strength value of tension joints should be considered. (Reference readings: Another Direction, Fastener World, Sept/Oct 2012 and Ninety Degree Bolting, China Fastener World, Feb 2012). The first task of a multi-bolt patterned joint is to find the centroid (center) of the group. In most cases the pattern will be symmetrical. We will use a symmetrical pattern here because it is easier (for me!).

First we divide the load, R, by the number of fasteners, n, to get the direct shear load, Pc. Next we find Σr2n where rn is the radial distance of each bolt from the centroid of the group. The moment around the center can now be calculated per the above illustration (M = Re). The shear load contributed by any particular fastener, due to the moment, can be calculated by:

$$Pe = \frac{Mr}{\Sigma r^2_n}$$

where r is the distance (in inches) from the center point (centroid) to the fastener being checked. The usual ones in question are generally the outermost ones. The two loads, shear (Pc) and moment (Pe), can be added vectorally as shown in the bottom illustration below.



Shear and Moment Loading Combined

In cases where the fastener attachment areas are not equal (symmetrical), the areas must be weighed to determine the center point of the pattern.

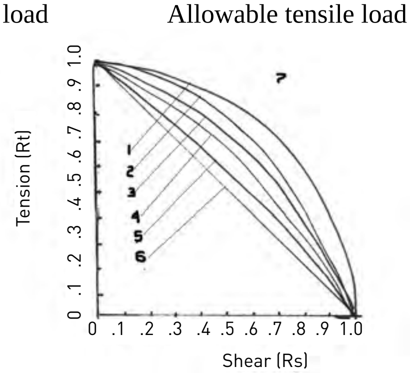
Occasionally it may be necessary to calculate the tension loads in a multi-bolt attachment although most designs, as mentioned before, are shear type joints. The procedure is similar although the center point of the fastener group may not be the geometric center. Using a symmetrical eight bolt pattern as an illustration (again easier for me), the tension load per bolt from force P1 will be P1/8. If an additional force (P2h) is encountered it will produce a tensile load on some of the fasteners. The need is to determine where the axis of force is. Fasteners to one side will show tensile loading increases and the ones to the other side will have load decreases (compression). Plates thick enough to take the increases will not bend and the neutral axis can be said to exist at edge A-B. If the thickness is such that some bending occurs (in this case I have selected line C-D as the axis) bolts 3-8 will be affected and from point C-D. Obviously bolts 7 & 8 will have the highest tensile loads. Non-mathematically speaking, it can be stated that the bolt load is proportional to its distance from the pivot axis and the moment reacted is proportional to the sum of the squares of the respective fastener distances from the pivot axis.

Comparing the total tensile loading on the joint against the preload tensile load derived from the installation torqueing should show the preload force exceeds the total applied service load. If it does not the joint will loosen.

When the joint is such that both shear and tensile loads are present, the combined loading must be compared with the total strength of the fasteners. A series of interaction curves and load ratios are usually calculated and used to make this comparison. Load ratios are derived by:

$$Rs = \frac{\text{Actual shear load}}{\text{Allowable shear load}} \quad \text{and} \quad Rt = \frac{\text{Actual tensile load}}{\text{Allowable tensile load}}$$

Plotting tension ratios against shear ratios a series of curves similar to the example below is derived:



This set is for example only and is only for illustration. Actual curves should be plotted with actual values from data. The various shown lines are:

1 – Rs3 + Rt3 = 1

2 – Rs3 + Rt2 = 1

3 – Rs2 + Rt2 = 1

4 – Rs 1.5 + Rt2 = 1

5 – Rs + Rt2 = 1

6 – Rs + Rt = 1

Other values can be derived as required.

The most conservative is line 6 and the least conservative is line 1. Review of the curves illustrates the reason why high torque should not be applied to the joint if the dominant loading is in shear. Also a material with a low yield strength will be critical for yield stress and a material with a high yield strength will usually be critical for ultimate stress.

One final caution when designing multi-bolt fastened joints. Often to save expense or because of a mistaken idea that riveted joints are better, some assemblies are manufactured with both bolted and riveted fasteners. The idea that the rivets are an additional strengthening factor and that they are better in shear and will help the bolted attachments. The two should not be used together. Bolts are installed into a clearance hole. The material substrate must yield enough under load to allow bolt attachment pattern to shift to load all of the bolts equally at their final location pattern. The looser (larger) the clearance hole the more the individual bolt must move and carry the load until all the parts have settled into place and the load is distributed overall (and equally it is hoped).

Rivets are great shear devices and are interference fitted when the parts are set. Their expansion into the hole fills the space entirely. Using both types of parts will cause the rivets to bear the entire load until there has been enough shifting to allow the bolt to take up some of the loading. Many steel structural frameworks utilize rivets only as the forces in such buildings are almost entirely in shear. Because of the complexity of using rivets (hot or cold), the force to hold the upsetting tools in place during installation, human ergonomics and operator danger and so on, has led the steel working industry to the use of bolts in many formerly designed rivet joints.

Multi-bolt attachments allow great structures to be designed and built. The great bridges and tall buildings cannot be constructed without them but used without thought, they may soon fail. Examine that office building. It is steel skeleton held together with plates bolted with multiple bolts. That bridge you drive over- it's made of plates and fastened the same way. The success of good engineering.