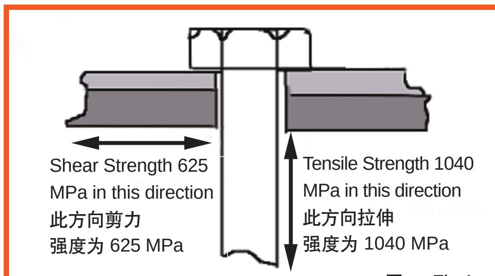
Ninety Degree Bolting

by Thomas Doppke

Attaching things by the use of a bolt and nut has become so basic in the practice of fastening technology that few ever consider just what forces are involved and how they affect how the joint actually works. The bolt is inserted through the various components of the joint, sometimes backed up with a washer at one or both ends, and tightened with a nut. The most common mistake made, even by long time users of bolts, is to think that the strength of the joint is equal in all directions, up, down and sideways. Tables list the minimum tensile strength of the bolt so that is what force the joint can withstand. Correct?

No! Wrong! Bolts and bolted joints are **tension** fasteners. That is, they generate force in a tensile mode (in the direction of their longitudinal axis) by stretching the bolt and compressively clamping the intermediate parts tightly. Unthinkingly, it is never considered how much weaker they are in other directions. Shear forces in joints may be in any direction other than the longitudinal (on a tangent or vector forces); however, for purposes of discussion we shall use those which are in the direction of a right angle to the longitudinal axis of the fastener. Joints in shear are considered to show an approximate strength value of 60% of the listed tensile strength. This will be discussed later.

A typical shear joint consists of two (or more) plates that are held tightly together by a fastener which passes through them and is tightly stretched to prevent any movement between the plates (the typical tensile joint so far) **(Fig.1)**. But in addition, there are forces that are causing movement in a transverse direction. To prevent this the fastener site should be designed to prevent any transverse movement. The usual fastener for a joint in shear is a rivet. Soft and deformable, it fills the hole entirely, preventing slippage. However, being soft the joint will require larger and/or more fasteners to adequately preload the joint together. When faced with this problem the designer unconsciously turns to using a bolted joint. The problem with use of a bolt in a shear loaded joint is not so much the strength of the fastener as is with the motion in the joint and



图一 Fig.1

螺栓接合学问大

在紧固件科技中，使用螺丝及螺帽来固定东西是很基本的动作，因此究竟其中牵涉的应力类型，以及应力如何影响接合处等问题鲜少被考虑。螺栓穿过接合处上许多不同的组件，有时一端或两端会加上垫圈，接着以螺帽锁紧。即使是熟练的老手也可能犯的错误是，认为接合处每一方向（上方、下方及侧面）的力都是平均的。依照安装指示，表格中列出的螺栓最小抗拉强度，也就是接合处所能抵挡的应力。这样正确吗？

错了！螺栓和螺栓接合件是**拉力紧固件**（tension fasteners）。它们在拉力模式下（由它们的纵向轴方向），藉著螺栓的拉伸并压缩钳紧中间部分的零件而产生应力。然而，很少有人想过它们在其他方向的应力有多脆弱。除了纵轴方向，接合处的剪力可能出现在任何方向（切线力和向量力）。在这篇文章中，我们著重讨论紧固件从90度直角到纵轴方向的应力。受剪力中的接合处应会显示60%的抗拉强度，这将於稍後讨论。

一个典型的剪力接合处包含两片（或多片）金属板件，透过紧固件彼此紧合，并且拉紧固定以防止板件与板件之间有任何移动（此为典型的拉力接合，**图一**）。但另外在横向部分存有应力，会引起移动。紧固件的设计应防止这样横向的移动。通常，受剪力的接合处适用的紧固件是铆钉，铆钉柔软可变形，且能够与洞完全密合，防止滑动。然而这种柔软的接合将需要更大且/或更多的紧固件以将接合处预压（preload）在一起。当遇到这种状况时，设计者会下意识地转而使用螺丝接合件，而在受剪力接合处使用螺栓接合的问题不在於紧固件的强度，而是在於接合处的移动和接合介面的摩擦力。大部分在剪力方向的应用手法显示循环负载（cyclic loading）。典型的车辆、引擎等许多机件的转向轴接合、悬吊接合的载荷都由高至低再由低至高循环。

friction in the joint interfaces. Most applications which are loaded in a shear direction show cyclic loading. Typical joints are those found in the steering, suspension joints of vehicles, engine parts, and various machinery which "pulses" through cycles of high to low loads and back again.

Shear joints are different than tensile joints in that they rely upon a high coefficient of friction to prevent sideways movement. Movement in the parts that make up the joint will cause wear, loosening the preload which will result in an eventual failure via one of several means, to be discussed later. Whereupon joints loaded in tension have the entire preload force to resist the forces that are trying to loosen the joint, shear joints must divide their preload force between resisting these outside loosening forces, called service loads, and resisting movement, via friction, between the various components of the joint. The screw thread on the bolt has one fault that is not present in other shear fasteners: it is reversible. Under conditions that exceed the preloaded state, it begins to unwind, loosen. Cyclic loading is famous for causing loosening. Even load cycles which do not exceed the preload force can cause the threaded fastener to back out (fretting is one typical occurrence). While the tensile loaded bolt has its entire preload force to resist this, the shear loaded part utilizes only about 60% of the tensile loaded force in clamping the parts together, the other 40% being lost in trying to resist frictional sliding between the shear planes.

剪力接合与拉力接合不同之处在於它依赖非常高的摩擦系数以防止侧滑。接合若有局部的移动将会导致磨损及预压的松弛，最终致使失败。失败的方式有许多种，稍後讨论。拉力接合具有完整的预压受力以抵抗造成接合松脱的应力，而剪力接合则将预压力分作两部分，一部分对抗外在的松脱力，称为操作负载，另一部分透过摩擦力来对抗接合内不同零件的移动。螺栓上的螺纹有一个缺点，它是可反转的。在超过预压的状况下，螺纹开始松脱，而剪力紧固件则没有这缺点，循环负载就是造成松脱的主要原因。即便是没有超过预压的负载循环，一样会造成螺纹紧固件脱落（磨损就是一个典型的情况）。当拉力加载的螺栓拥有完整的预压来抵抗这个状况时，剪力加载部分只使用了60%的拉力预压应力以钳紧零组件，其馀的40%则用以抵抗剪切面间的侧滑情形。

Four Steps in Shear Joint Failure

There are four steps to a shear failure with a threaded fastener **(Fig.2)**. Static friction resists movement between the shear planes of the joint **(Step 1)**. At high point of the cyclic loading "pulse" the clamping load, the load that pulls the joint together, is exceeded. Remember, this is only 60% approximately of the full strength that could be developed if joint was in full tension. The more planes in the joint (number of components) the worse the situation will be.

When the plates slide **(Step 2)**, they come to rest against the side of the fastener. In some cases of alternating cyclic loads, the plates may slide back and forth. Adding interface wear to the problem. The shear load is now being held by and against the body of the bolt. How strong this is depends somewhat upon where the plates rest; the shank area being much stronger due to its physically larger diameter than thread areas. In **Step 3**, the bolt and possibly the plates deform elastically as the cyclic load pulses and, at the same time, the bolt begins to elongate under load, becoming thinner as it stretches. The more it stretches the less load it is capable of sustaining until **Step 4** occurs. At this point the joint fails; usually by bolt breakage but plates may also yield or both may fail. Any clamp load, preload, that was present has long since departed during step 3.

剪力接合破坏四步骤

螺纹紧固件的剪力破坏有四个步骤（**图二**）。接合处内各剪切面以静摩擦力抵抗移动（**步骤一**）。在循环负载的高点，使接合处拉紧的夹紧力将超出。这大约是所有拉力的60%，接合处的剪切面（组件数量）越多，状况越糟。

当板型组件开始滑动（**步骤二**），便开始由紧固件的侧面来支撑。在某些例子里，交替循环负载可能使板型组件向前或向後滑动使介面磨损。剪力负载此时由螺栓体承受，其承受力有多强大则端看板型组件倚靠的位置；螺杆部位的直径较螺纹部位为大，所以较为稳固。在**步骤三**，螺栓会因循环负载开始弹性变形，同时螺栓因承受负载而延长，并越来越

We have used the figure of 60% as the amount of strength that a bolted joint retains when placed in a shear condition. Where does this come from? Actual testing shows that the strength of a bolt in shear is slightly more than 60% but the 60% figure is used as a Rule of Thumb. The differences between a bolt tested in tensile shear and a compression shear test show a variation of about 6%. Since both types of applications exist in the real world, the 60% number covers all eventualities **(Chart 1)**.

Another danger with shear joints in failure is that when the plates have slid to one side they begin to deform. The hole side begins to act as a knife edge, pressing against the bolt shank. The bending and deformation of the bolt increases the pressure on the shear edge pressing against the bolt shank. When the strength of the bolt has been exceeded (remember it is only 60% of its rated tensile strength) the edge acts as a knife, cutting the bolt transversely **(Fig.3)**.

To summarize what happens when a shear joint is loaded to beyond its capacity: When the loading exceeds the frictional forces that keep the planes from sliding past each other, they move until they come in contact the shank of the bolt. During heavy

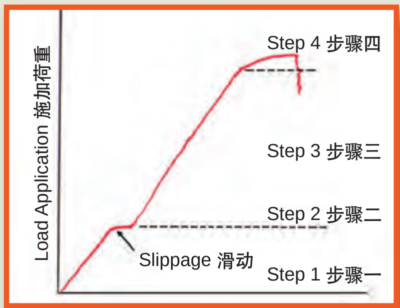
Size 尺寸	Grade 8.8 Tensile Strength 级数 8.8 拉伸强度	Grade 8.8 Shear Strength 级数 8.8 剪力强度	Grade 10.9 Tensile Strength 级数10.9 拉伸强度	Grade10.9 Shear Strength 级数10.9 剪力强度
M 5 x 0.8	---	---	14.8 kN Min.	8.8 kN
M 6 x 1	16.7 kN Min.	10.0 kN	20.9	12.5
M 8 x 1.25	30.4	18.2	38.1	22.8
M10 x 1.5	48	28.8	60.3	36.2
M12 x 1.75	70	42	87.7	52.6
M14 x 2.0	95	57	120	72
M16 x 2.0	130	78	163	97.8
M20 x 2.5	203	121.8	255	153
M22 x 2.5	251	150.6	315	189

Chart 1. Minimum Tensile Strength and Approximate Shear Strength of Common Bolt Grades
表一　一般螺栓等级的最小值拉伸强度与估计剪力强度

细，伸展的越长，能承受的力越少，直到**步骤四**，接合处故障，通常是因为螺栓断裂，任何夹紧力、预压早在步骤三就开始崩解。

在剪力状况下，我们计算螺栓接合保有60%的应力，这是怎麽来的？实际测试发现螺栓的拉力些微超过60%，在拉剪测试中与静态剪压测试中，两者的差异大约有6%，既然真实世界中两种状况都存在，就以60%为通则（**表一**）。

剪力接合另一个失败的可能在於，板型组件向一侧滑动开始变形。因滑落而形成的洞孔像刀刃边缘，开始向螺杆推挤。螺栓的弯曲和变形增加剪切面对螺杆的压力。当螺栓的强度被超越（那只是拉力强度的60%），边缘就像刀刃一样对螺栓横向切割（**图三**）。



图二 剪力接合破坏四步骤

Fig.2 Four Steps in Shear Joint Failures

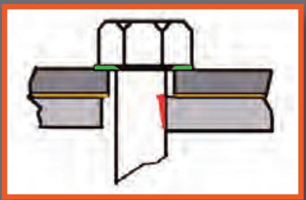


Fig.3 Forces in Slipped Joint
图三 滑动接合处的受力程度

- Green-Moderate- Induced by clamp preload
  绿色-中度，由夹紧预压力造成。
- Yellow-Low now. Reduced by plate slipping to one side of hole. Will continue reducing under cyclic loading.
  黄色-目前受力低。由于板型组件滑动到孔动一旁，将因循环负载持续减弱。
- Red-High stress area. Plate edge acts like knife edge. Transverse fracture of bolt will occur here.
  红色-高受力区。板型组件如刀刃边缘，螺栓横向断裂将于此发生。

cyclic loading, the sliding may be back and forth, which increases the wear between the plates, under the head of the bolt and any other contact surfaces that may become involved. This wear, along with any yielding of the bolt material or the plate, reduces the amount of stretch of the bolt (preload). Since it is this stretch that maintains the integrity of the joint, the reduction and eventual loss of the tensile induced preload causes the bolt to become little more than a loose fitting shaft of metal in the holes of the components. The edges of the plate are forced against the shaft, and acting like a knife blade, cutting through the bolt shank or in cases of great reciprocal movement, acting as an origin point for a fatigue failure. Shear failures are characterized by having a transverse fracture face and a noticeable origin point. When does this happen? With higher loading, violent vibration, and cyclic loading, failure comes sooner than joints subject to lower impacts and more static conditions. Some joints in shear may last years if subjected to only occasional impacts.

现在总结当剪力接合的负载超过其承载能力时会发生甚麼状况。当负载超过防止切面互相侧滑的摩擦力时，切面将开始移动直到接触到螺杆的部位。负载周期在高峰时，可能发生向前或向後的滑动，增加螺栓头部下切面和任何可能接触面的磨损。此磨损及零件变形情况会降低螺栓的延展（预压）。因为此延展维持整个接合的完整性，所以拉伸力的减少及消失，将使螺栓变成安装在组件洞孔里的松脱杆件。板型组件的边缘作用如一把刀刃，切过螺杆，或是来回的移动形成一个疲劳断裂的原始作用点。剪切破坏的特色是有一个横向的切割面及一个该注意的疲劳断裂作用原始点。这何时会发生？当负载过高，剧烈震动，负载周期存在时，接合很快就崩解。在冲击只是偶尔发生的情形下，一般剪力接合可以维持数年。

Design for Shear Joints

Designing for shear can be accomplished with a variety of solutions. First, obviously, do not use a bolt if possible. To prevent slippage, which is transverse movement of planes to the limit of the difference of the hole outside diameter and the retaining shaft (bolt shank) outside diameter, the best solution is no clearance. This is accomplished with the use of a solid rivet or interference fit plug. While filling the hole, the disadvantages are that they are not removable / repairable. They have low strength generally and require costly tooling to install and increased labor. Often backside clearance for installation tooling is required and not available. Being of lower strength material, the joint will require larger fasteners or more of them. Since many joints are subjected to both shear and tension forces, the rivet fails again. It is a poor tension fastener and has little or no generated clamping force. The advantage is that they are not affected by frictional properties of the joint. Often a failure can be attributed to the fact that one or more of the parts was oiled, greased or had a low friction coating that was not accounted for in design.

A second solution is that if a bolt is needed, usually for one of the reasons noted above, it should be of as high a strength level as possible. This will generate more preloading which also increases the amount of force of frictional resistance to slippage. The limitation to clamping load has to be the yield point of the weakest material; usually this is one of the

剪力接合设计

设计一个剪力接合有许多种方法。首先，尽可能不要使用螺栓。滑动是由於因孔洞外径与螺栓外径落差而造成的横切性移动，因此最好的方法就是不要产生空隙。可使用铆钉或是插塞（interference fit plug），其缺点是一旦孔洞被填满，铆钉和插塞就无法移动或是修理。它们是低强度的紧固件，需要昂贵的工具安装，增加劳力支出，另外也需要有间隙位置来使用安装工具，但通常不会有多馀空间。既然是低强度的材质，接合就需要更大或更多的紧固件。既然接合本来就要承受剪力与拉力，因此使用铆钉也不可行。铆钉拉力太低，其夹紧力低或甚至没有夹紧力，但好处是它不会被接合的摩擦性质影响。通常设计时上油润滑，或无足够摩擦涂层等动作未加以说明时，也会导致失败。

第二个解决之道在於，如果一定要使用螺栓，其强度应越高越好，因为可产生足够预压，并增加对抗滑动的摩擦力。夹紧力的极限应等於最脆弱材料的屈服点。当扭矩越高时，螺栓会嵌入板型组件，接著随时间丧失其预

plates. The bolt, tightened to the higher torque will embed in the plate material and, over time, cause much of the preload (bolt stretch) to be lost. Tests have shown that a joint can be loosened with as little as one half a revolution from full tight to zero tension. For an M6 bolt this is 0.5mm. **For maximum strength, no portion of the threads should be within any shear plane. This is good practice with every joint and is emphasized here especially.** The threaded area is smaller in diameter than the shank and the thread grooves offer fatigue origin points (stress risers). Also, the first threads of every bolt bear the greatest stress should avoid joints where the planes cross the area of the first threads.

Three, since slippage between the planes is the problem, increasing the friction may alleviate the problem. Insuring at no “down-the-line” operation adds lubes, greases or oils. Often oil is sprayed on steel parts to prevent rusting between operations, especially if the parts must travel from one location to another over any great distance. Platings and corrosion prevention have evolved tremendously over the past few years and many are highly lubricous. Choosing the right one and accounting for its effects during design are important. For example, using galvanizing in place of zinc electrocuting increases surface roughness and friction by more than 100%. Finally, increasing the surface roughness to retard movement is an added step but maybe essential in the case of a problem joint. Rough machining of the surface parts is a first step if possible. The addition of “rasp” like gouges to the contact surfaces is expensive but effective. However the “zest grater” will cause some wear and will not be an improvement to corrosion resistance.

Four, a reduction in hole clearance reduces the amount of travel that the joint can slip. Oversized holes are almost always a demand by the assembly function. That and the request that a slot is added to ease assembly concerns cause shear problems later on. Be careful that a slot is not added in one or another of the parts for adjustability. Mixed holes and mixed diameters are often found in many application packages where some adjustability is needed. Many times these are added later in design without much thought.

Finally, a comparison on review of the strength of the various components of the joint should be done. The softest material is the weakest link in the design. A high strength bolt into a soft plate will elongate the hole over time, increasing slippage further and further. Also locating the hole too near the edge of the plate may cause that section to breakout. Too hard a plate and too soft a bolt will act as a knife into butter and precipitate a bolt failure.

压。试验显示接合松脱，由锁紧到拉力为零只需半圈转紧距离。以M6螺丝为例，距离只有0.5mm。**为达到最大强度，螺栓中的螺纹处不应接触到任何剪切面。这是对每一种接合来说都有利的做法，特别于此强调。**具有螺纹的部位直径较螺杆来得小，且螺纹间的沟槽提供疲劳原始点（应力集中源），且每个螺丝的第一个螺纹都承受最大的应力，应避免该区有任何剪切面。

第三，滑动既然是个问题，增加摩擦力应可减缓这个问题。确保生产线上的作业没有添加任何润滑油。通常润滑油会喷洒在钢材部分上以防止锈蚀，特别是当零件需要一段很长的运送距离。电镀和其他防锈的措施近年来已大幅演进。在设计的过程中选择正确方法是很重要的。举例来说，在锌导电的区域镀锌，可增加表面的粗糙程度及摩擦力，程度超过100%。最後，增加接合处的摩擦力虽是一个额外动作，但对於解决有问题的接合处却是必要。如有可能，表面粗糙加工应为第一步。在接触面增加凿刻虽然昂贵但效用明显，然而这有可能引起磨损并无法改善耐磨性。

第四，减小孔洞空隙可缩短接合滑动的距离。因为组装的需求，孔洞通常都会先钻过大，虽然便於组装，但随後会引起剪力的问题。要确认调整部位中没有空隙，许多时候不同直径和不同孔洞混用情形在调整应用时常常发生，这些状况通常在设计的後期没有被仔细考虑。

最後，审视接合各组件的强度是非常重要的。在设计中，最柔软的材料就是最脆弱的所在。当高强度的螺栓插入柔软的板型组件，孔洞会随时间逐渐延展，最终引起滑动。当孔洞过於靠近板型组件边缘，会造成该部位断裂。另板型组件过硬或过软都会导致失败。

A Real World Example

实例分享

The exact location cannot be revealed but a major company wanted to place their name and logo in the front of their new office building. Consisting of large steel letters, each weighing more than 2000 pounds (900+kg). Each letter was to be fastened to the building façade with a bracket which was fastened with a 1/2” (12mm) bolt, SAE Grade 5 (120,000PSI/825MPa). The problem was that the wall was not very even over the 100 foot (30m) distance. This was solved by adding 1/2” thick plastic shims where needed, in the amount needed. In some cases the shim packages were as thick as 1-3/8” (35mm).

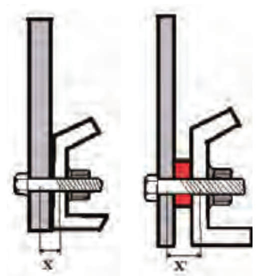


Fig.4 Bolts in Shear
图四 受剪力螺栓

Further, each bolt that held a letter was to carry about 900 pounds (409 kg). After the name sign was partially erected it was found that some of the bolts were bending and gouges were seen on the shanks of several. It was determined that the loading induced an increase in force in the shear direction to 103 ft-lb on the fasteners with thick shim packages. The yield strength of this grade of bolt is 97 ft-lb. This yielding, plus plastic shim cold flow under pressure, lost all the tension in the joint, bending the bolts **(Fig.4)**. The edges of the holes in the mounting plate acted as knife edges against the bolt shanks and the bolts would have sheared off at some future time. The heavy steel letters may have fallen upon visitors entering the building, causing death or serious injury. At the very least, the company would be greatly embarrassed if their sign fell off their building. This is a case of poor design of a joint in shear, the additional problem of a bending moment and a poor choice of materials. The solution was to use hardened metal shims and increase the bolt to a stronger grade. The best solution would have been to increase the number of attachment points and use a larger sized fastener but the building was already in place.

有间大公司想在其新办公大楼放上公司名称及商标，但这些钢制字母每个重量超过2,000磅（900公斤以上）。每个字母都要锁紧在大楼正面的托架上，托架是以1/2”（12mm），SAE规格5号（120,000PSI/825MPa）的螺栓锁紧在大楼正面。问题是墙面并没有超过100尺（30m），解决的方法是在需要的地方增加1/2”厚的塑胶垫片，有些甚至厚度达1又3/8”（35mm）。

每个锁紧字母的螺栓承重约900磅（409公斤），当公司名称字母大致竖立好後，该公司发现有些螺栓已经弯曲且螺杆已有凿孔。据判断，荷重使加上厚重垫片的紧固件产生了103 ft-lb的剪力，此等级的螺栓降伏强度是97 ft-lb。此降伏强度加上塑胶垫片的冷流，使接合处的拉力消失，引起螺栓的弯曲（**图四**）。安装的板型组件孔洞边缘就像一把刀对螺杆位置施压，假以时日螺栓可能会被切断，钢制字母可能掉落而砸伤进入大楼的访客。即使以上的状况都没发生，起码这间公司也会因为商标掉落而颜面尽失。这个例子显示，在设计时没有考虑剪力的问题，也未预料到螺丝会变形，且选择了错误的材质。解决之道须使用较硬的金属垫片，并增加螺栓的强度等级。最佳的解决方法为，增加连接点并使用较大尺寸的紧固件，但是该建筑物早已盖好，无法改变了。