The basics of bolted joints

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Over the last sixty years great improvements have been made by the fastener industry in improving the design and reliability of their products. However, no matter how well designed and made the fastener itself is, it cannot alone make the joint more reliable. Fastener selection, based upon an understanding of the mechanics of how a threaded fastener sustains loading and the influence that tightening procedures can play, is also needed. This article provides an introduction to the basics of bolted joints and the major factors involved in the design of such joints.

It is not widely understood how a bolted joint carries a direct load. A fully tightened bolt can survive in an application that an untightened, or loose bolt, would fail in a matter of seconds. When a load is applied to a joint containing a tightened bolt it does not sustain the full effect of the load but usually only a small part of it. This seems, at first sight, to be somewhat contrary to common sense but hopefully this article will explain why this is the case.

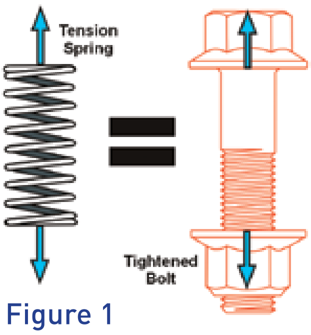

Figure 1

Bolts are made from elastic materials such as steel. When a bolt is tightened the bolt is stretched like a spring (figure 1).

The joint itself is usually made of a metallic material which is also elastic. As the bolt is tightened, the joint is compressed and acts as a compressive spring (figure 2).

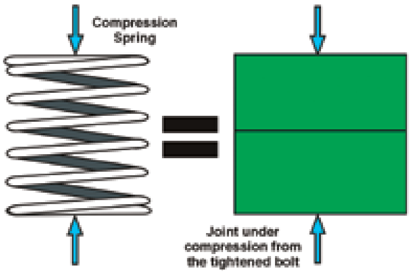

Figure 2

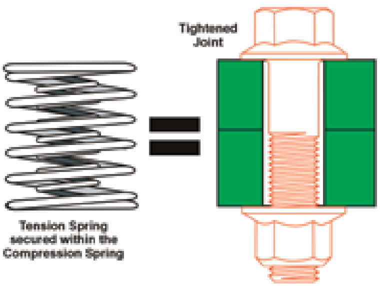

Figure 3

Put together, the bolt and the joint act as a combined spring system. In a tightened joint, the tension force in the bolt is balanced by the compressive force in the joint (figure 3). A key point to understanding how forces are transferred in a bolted joint is to realise that the only way that the bolt can be loaded is by applying a load through the joint.

Loading the joint with an axial load will change the bolt extension and the joint compression (figure 4). Because the stiffness of the joint is typically five times or more the stiffness of the bolt, the effect of the axial loading is to primarily reduce the compression in the joint rather than extending the bolt. This point can be difficult to appreciate, but this is key to understanding why bolts are tightened rather than left loose.

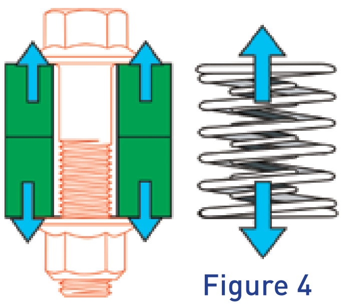

Figure 4

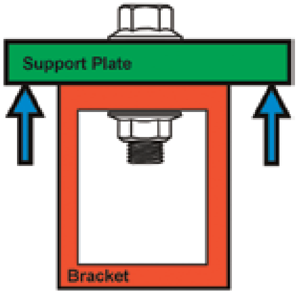

Figure 5

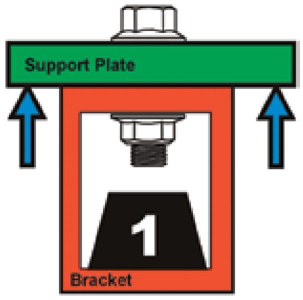

Figure 6

Figure 5 shows a bolt and nut securing a bracket to a support plate. With the nut loose on the bolt, if a weight of 1 is added to the bracket, as shown in figure 6, then the force in the bolt shank will increase by 1. However, if the nut is now tightened and the weight applied, the force in the bolt shank will not increase by 1 but usually by only a small fraction of this amount. An understanding of why the bolt does not sustain the full effect of the applied load is fundamental to the subject.

A model can often be of help in understanding why the bolt does not sustain the full effect of the applied load. Figure 7 is an attempt to illustrate the load transfer mechanism involved in a bolted joint by the use of a special fastener. In the case of this fastener no significant load increase would be sustained by the fastener until the applied load exceeded the fastener's preload (preload is the term used for a bolt's clamp force).

With the special fastener shown, the bolt is free to move within its casing, a compression spring is included within the casing so that if the bolt is pulled down the spring will compress. A scale on the side of the casing indicates the force present in the spring and hence the force present in the shank of the bolt. Figure 7 illustrates this special fastener in its untightened condition.

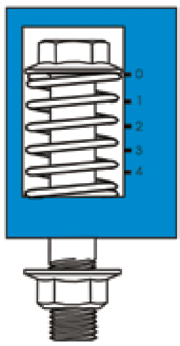

Figure 7

The bolt is now inserted through a hole in a support plate and a bracket attached to the special fastener by securing a nut to the threaded shank. If the nut is now rotated

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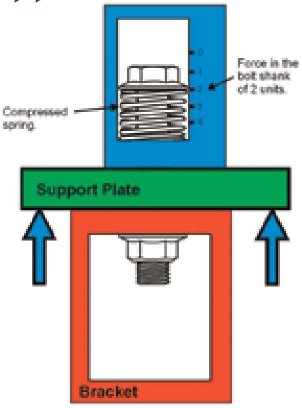

Figure 8

so that the head of the bolt is pulled down, the spring will be compressed. If the nut is rotated so that 2 force units are indicated on the casing, the compressive force acting on the spring will be 2 and the tensile force in the bolt shank will also be 2. This is illustrated in figure 8; this is like a tightened bolt without any working load applied.

If a weight is now added to the bracket (figure 9) of value 1, then the initial reaction is to think that the load in the bolt must increase, otherwise what happens to the additional force? Surprisingly it will keep at its existing value of 2 - it will not 'feel' any of the additional force. To visualise why this is so - imagine what would happen if the load in the bolt did increase. To do this it would compress the spring more and a gap would be made between the bracket and the plate. If such a gap was to form then it would mean that there would be 2 units of force acting upwards - due to the spring, and 1 unit of force acting downwards from the applied weight. Clearly this force imbalance would not occur. What does happen is that the effect of the applied load is to decrease the clamp force that exists between the plate and the bracket. With no load applied, the clamp force is 2 units and with the load applied this decreases to 1 unit of force. The bolt would not actually 'feel' any of the applied force until it exceeded the bolts clamp force.

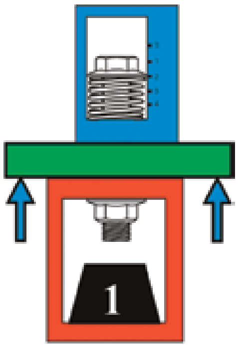

Figure 9

Figure 10 shows the condition when a load of 3 is applied. The joint will separate and the 3 units of weight acting down will be balanced by the 3 units of force in the spring. The point of joint separation, from a design perspective, is usually taken as the point at which the joint will have a finite length. Besides sustaining the full applied loading there are usually bending forces induced into the bolt because of eccentricity of the applied loading. Repeatedly applied this will rapidly lead to fatigue failure of the bolt.

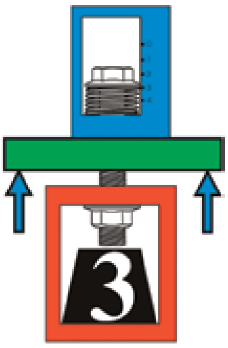

Figure 10

Older design procedures proposed calculation methods based upon the idea that the bolt will not 'feel' any of the applied load until it exceeds the bolts clamp force. That is, the bolt should be sized so that its clamp force is equal to the external load after a factor of safety has been included. Practical fasteners differ from that shown in figure 2 in that elongation of the fastener and compression of the clamped parts occurs upon tightening. This compression results in the bolt sustaining a proportion of the applied load. The actual amount of the load being sustained being dependent upon the relative stiffness of the bolt to the clamped material.

In actual practice, the bolt will sustain a proportion of the applied loading prior to the joint separating. This is due to the joint compressing, as well as the bolt extending, when tightened.

This is illustrated in figure 11. When the loading is applied, the compression of the joint is reduced. This, in turn, increases the distance between the two joint faces which, in turn, increases the loading on the bolt. The bolt and joint stiffness can be computed and, from this, the proportion of the load sustained by the bolt and the amount that the joint compression is reduced can also be computed. The key aspect of the success or otherwise of the majority of bolted joints is the residual loading that acts on the joint interface. That is, will joint separation or joint movement occur when loading is applied?

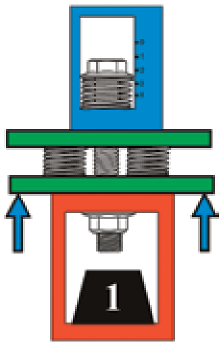

Figure 11

As the applied load acting on the joint increases, the force clamping the joint together decreases. If the clamping force decreases to zero as a result of the applied load, the bolt will have to totally sustain any subsequent increase in this load. Research has shown that bolted joints usually fail as a result of the applied forces acting on the joint decreasing the clamp force, present between the joint layers, to below a required level. Failure can include leakage from a joint (if it contains a gasket) or the bolts coming loose or failing due to fatigue. Initially it may appear that the joint failure is not due to insufficient clamp force, but a more detailed analysis often shows that this is indeed the cause rather than defective or sub-standard bolts or the bolts sustaining too much load.

Many applications require that the plates comprising the joint be clamped together tightly so that any possible movement is prevented. Effectively the plates are prevented from moving by friction increased by the bolt's clamp force. In such applications, a level of clamp force must be maintained in order that movement is prevented. If the clamp force reduces to below this level, joint movement can be caused that dramatically increases embedding (plastic deformation under the nut/bolt head) resulting in the bolt quickly losing preload and then loosening or failing by fatigue. If the joint contains a gasket, a minimum level of clamp force is usually required in order that leakage is prevented and the sealing function is maintained. Maintaining a high initial bolt preload is essential to ensuring that a bolted joint will survive.

Prior to forming his company, Bolt Science in 1992, Bill's original background was in design engineering. The company is a provider of independent technical expertise in bolted joint technology. He is a chartered engineer and has a Doctorate in Engineering on the self-loosening of threaded fasteners. Bill has delivered training courses around the world on the analysis of bolted joints and bolting technology.