WHY INCREASED FASTENING SYSTEM ELASTICITY LEADS TO REDUCED SELF-LOOSENING OF FASTENERS

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It is well established that bolted connections under cyclic loading are prone to self-loosening. It is also known that as preload is lost, the risk of failure in the connection is increased. In order to prevent failures due to self-loosening, it is helpful to understand the mechanism of the self-loosening phenomena.

Most bolted joints consist of at least two joint components along with the fastening system. The fastening system may be a bolt and a nut, a bolt or screw and a threaded or tapped joint component, the bolt and nut with a variety of washers designs, etc. In the most basic form, a joint consisting of two plates along with a nut and bolt is shown in Figure 1. The bolts are loaded to a preload (F_b). The amount of stretch in the bolt is proportional to the stiffness of the bolt and the active length (L).

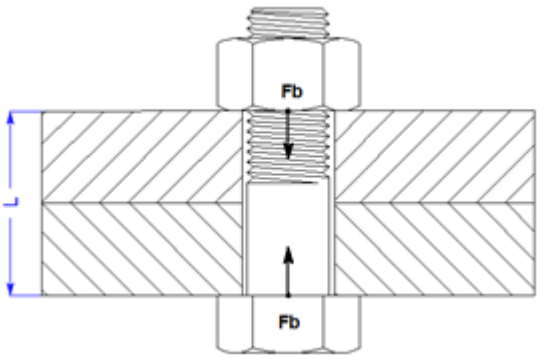


Figure 1

Now, the equation for bolt stretch is:

$$dL = \frac{F_b L}{AE}$$

For more detail on this equation refer to the article, *Why Bolts Work (and why some don't)*. The precise equation is not critical for this discussion. However, it is important to note that the stretch is proportional to the preload and bolt length. If bolt length is fixed and the load is constant (and hence, the stretch), then this is considered to be a static application.

In 1969, German engineer, Gerhard Junker, indicated that transverse loading (perpendicular to the bolt's axis) is most likely to result in self-loosening. Since that time, there have been a great many studies confirming that cyclic transverse loadings result in a very similar pattern of events that lead to the unloading of a prestressed bolt. Figure 2 shows relative slip (a) between the joint members during each cycle of vibration.

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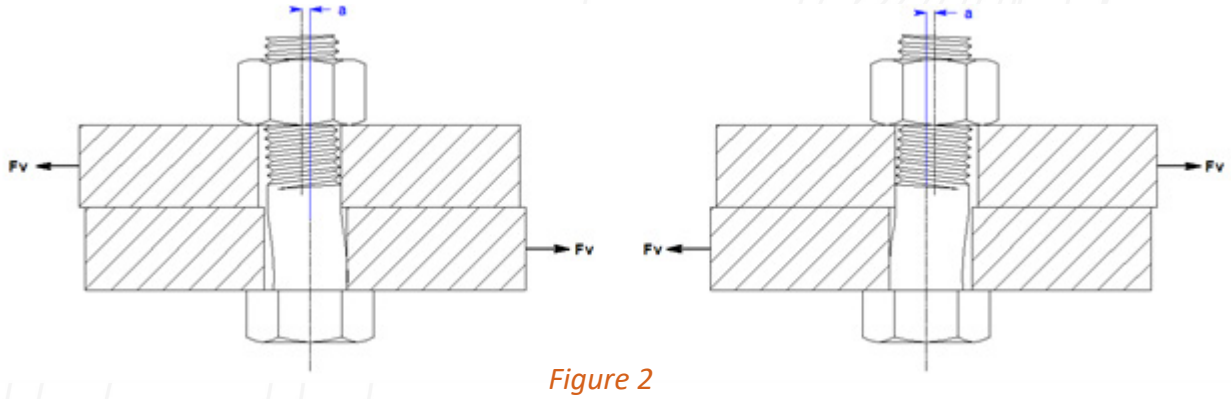


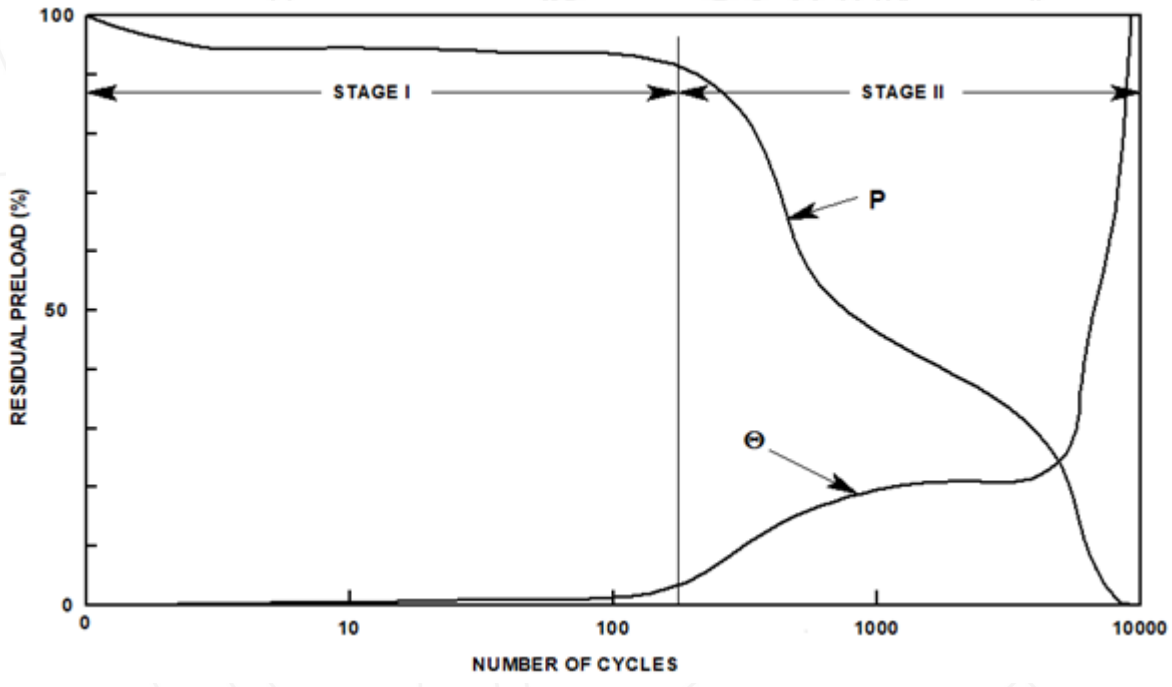
Figure 2

As this slip occurs, it is plain to see that the load on the bolt will also change. This is revealed in Junkers test data that there is an oscillation in load during each vibration. This variation in preload will be proportional to the amount of relative transverse displacement and also the stiffness of the bolt. If the bolt preload changes during each cycle (dF'b), then the bolt stretch must also change by a proportional amount (dL'). The equation for the change in force during each cycle can be solved as:

$$dF'_b = \frac{dL'AE}{L}$$

Taking this to extremes, if the value for 'a', or bolt stiffness is large, then the change in force would be greater. Conversely, as these values approach zero, then there would be no expected change in preload. In addition, if the bolt length was longer, then the change in force would be smaller for each cycle. This is because longer bolts add more elasticity to the fastening system. To an even greater extreme, if the bolt was infinitely long, then there would be no change in load during each cycle. This would become a static application.

In general, the loss of preload due to vibration follows a similar general pattern and occurs in two observed stages. In the graph below, Stage I shows a very gradual relaxation from the initial preload. Once the load drops below some critical value, Stage II begins and there is a very rapid loosening.



There is a relationship to the angular rotation of the fastener components with respect to the joint and that value is Θ shown in Figure 1. This makes sense intuitively. If the nut backs off (rotated), then one would expect the load to drop very quickly. Many of the products that aim to prevent bolt self-loosening failures aim to reduce or eliminate the losses in Stage II of the curve. These products include ways to reduce or counter the rotation of the nut or bolt head with respect to the joint. Each of these have their own relative pros and cons with respect to preventing the rotation of components. Some examples are:

i. Mechanically locked fastening systems like lock wire or pins
ii. Thread locking compounds
iii. Elastic stop nuts or bolts with nylon patch material
iv. Modified thread systems
v. Serrated washer systems
vi. Lock or toothed washers

Rather than reduce the load loss in Stage II, it clearly would be better to reduce the load lost in Stage I so that Stage II never occurs. It is clear that there is little to no angular rotation in Stage I. Most attribute the loss of preload in this stage to the embedment of plastic deformation of the stressed components during each cycle of load. Assuming that this is true, then it is also reasonable to assume that the rate of embedment diminishes over cycles. The curve agrees with this assumption given that the load lost after some very early losses flattens out to a comparably lower rate. Based on the equation for the change in preload discussed earlier, if the bolt length was very long, this would increase the elasticity of the system and the change in preload due to any embedment would be reduced proportionally.

Another way to increase the elasticity of a bolting system is to use Belleville springs. Bellevilles can increase a bolts effective length by a factor of 10X or even more.

Example: A ½ inch steel bolt with a 2.00 in active length has a preload of 6000 lbf and subjected to a vibration results in a change in preload is ±500 lbf for each cycle. Further assume that 10% of the preload is lost in Stage I. Based on these assumptions, the amount of embedment in Stage I is .00018 in. and the load would fall to 5850 lbf. Also, the initial bolt stretch is .0018 in. The total change in length for each vibration is .0003 in.

Now, consider a case where one Belleville is added to the fastening system and that the added elasticity (deflection) of the spring is .015 in. With the same assembly and vibration displacement, the change in load is reduced by a factor of 11 (since bolt stretch is not lost.) The load change during each vibration is ±91 lbf. This is virtually a static application since the change in force is so slight. This should reduce the embedment at least to some degree. Even if the same embedment occurred, the loss of load would also be 1/11th of the system with no Belleville. As a result, the load would only fall to 5940 lbf.

As an aside, it should be noted that friction should not be ignored. If friction in the bolting system approached zero, then no bolted joint would ever maintain preload. Load could be applied to the bolt using torque but as soon as the wrench was removed, the nut would immediately unload because the friction is the only thing that keeps it in place. There are many studies that confirm that vibration increases this tendency and so friction should be a consideration for the design of any bolted system. At a minimum, understand that reducing friction through lubrication, etc., may not improve retained preload in a system subject to unloading due to vibration.

“Using Bellevilles can increase a bolts effective length by a factor of 10X or more.”



In summary, increasing the elasticity on a bolted system subject to vibration should reduce the tendency of the system to unload for two reasons:

1. The change in force during each cycle of vibration is less
2. The loss of load due to embedment will be reduced

There are several methods to increase the fastening system elasticity including using longer bolts, using bolts with reduced diameter, and employing Belleville springs.

Solon Manufacturing Company offers a variety of application-specific Belleville spring washer selection tools that can assist designers in selecting the proper Belleville spring for their requirements, including:

- Electrical connections
- Flange connections
- Valve packing
- PV racking systems

For additional resources and information, visit www.solonmfg.com.

Resources

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