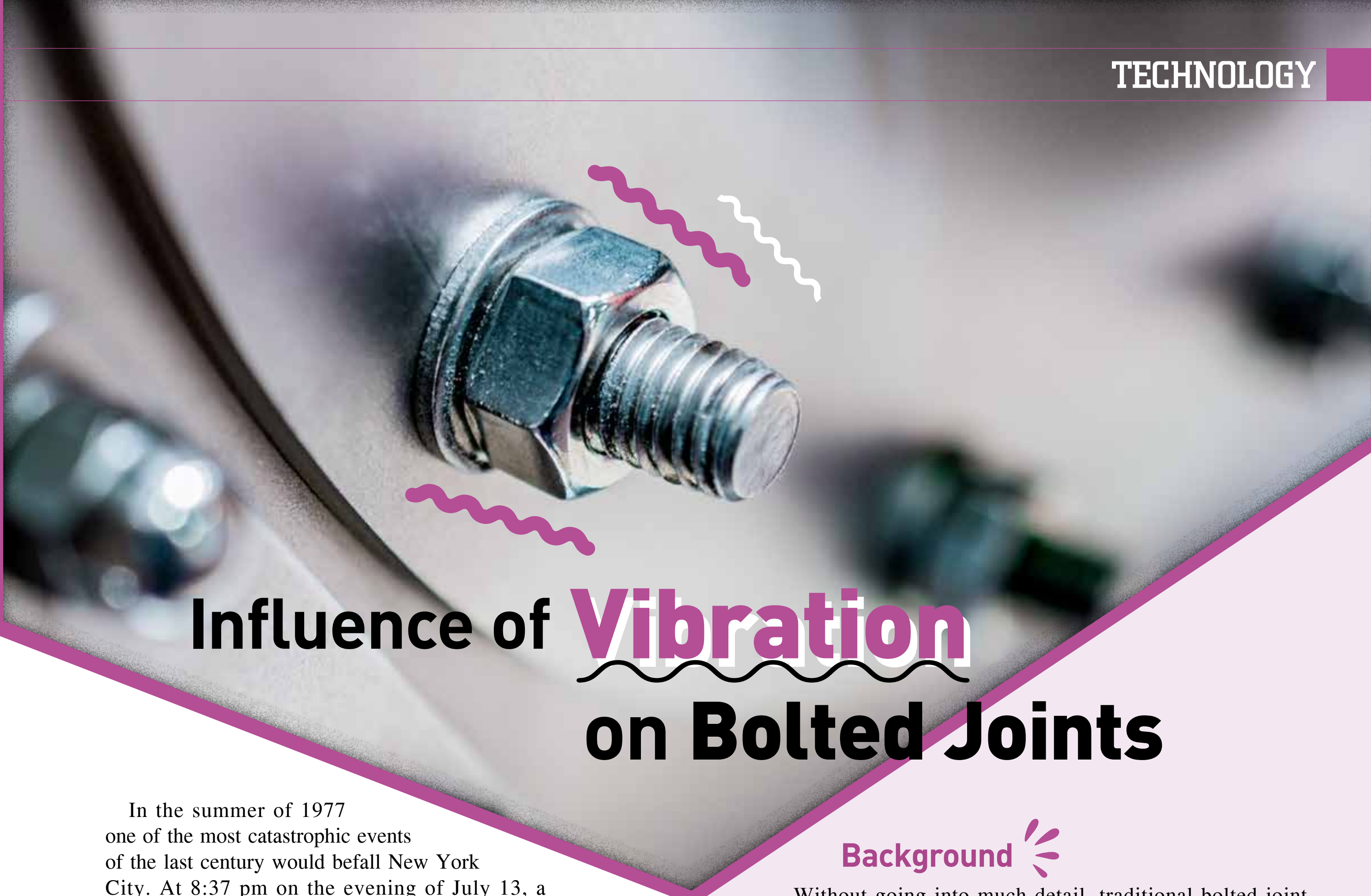


Influence of Vibration on Bolted Joints

In the summer of 1977 one of the most catastrophic events of the last century would befall New York City. At 8:37 pm on the evening of July 13, a lightning strike spawned by heavy storm activity in the Northeastern region of the United States, would take out a single power substation that swelled into a cascading series of the power grid failures knocking out power to almost all of New York City and surrounding Westchester County. It would take almost twenty-five hours for complete restoration, during which time almost 1,600 stores and residences would be looted, vandalized and burned. In fact, it was estimated that damages amounted to over US$300,000,000.

In the aftermath of this disaster, officials would track down the culprit of the initial substation failure. Amazingly, it was all due to a several cent "locknut" that had loosened causing the switchgear equipment it was part of to not perform properly. In the US Department of Energy's Federal Energy Regulatory Commission Report, " The Con Edison Power Failure of July 13 and 14, 1977 ", it stated, "Equipment malfunctions preventing the proper automatic restoration to service of three of the four lines struck, and leading directly to loss of additional transmission circuits, resulting from a loose lock nut on a control rod of a circuit breaker and a bent contact on a protective relay, both at the Millwood West Substation."

Although this is an extreme example, designers are routinely challenged with engineering joint designs and careful fastener selection to combat fastener self-loosening from vibration, flexing joint members, thermal cycling, and any other mechanism that will cause the joint to loosen. In fact, this area of fastener engineering has been the genesis of an entire category of fasteners, commonly known as "locking fasteners". Even though there are several types of cyclic loading, vibration is the most common and, theoretically speaking, the same concepts apply to all. This article will take a high altitude look at how vibrations (and these other cyclic loads) influence the bolted joints and one's choice of preferred fasteners.

Background

Without going into much detail, traditional bolted joint engineering teaches that the bolt must behave like a spring. This means that design, material, and processing choices must be carefully combined to produce a fastener that is elastic in nature. When stretched, or what is commonly referred to as "preloaded", compressive forces opposite to the preload forces are generated that result in compressive or "clamping" forces exerted between the bearing faces of the bolt head and the nut. **The more preload that we can obtain, the more clamping force that is generated.**

Of course, when we envision a spring, a bolt does not immediately pop into our minds. Bolts are, in fact, very stiff springs and to get them to do what we want when we tighten them, we introduce significant tension, torsion, and perhaps bending energy into them, which stretches, twists, and bends the bolt. When we stop tightening, this accumulated energy remains only by friction between the bearing faces of the nut, bolt head, and joint and the friction between the contacting surfaces of the internal and external threads. If these friction forces are lost for any reason, the energy that has been stored in the fastener (especially to stretch it) is released. **If enough of the preload is lost, the joint becomes vulnerable to progressive failure mechanisms like fatigue and self-loosening.** And in some cases, if the preload disappears altogether, the fastener may completely disassemble and be lost. In some cases, this scenario would just be a nuisance but in more critical applications a lost fastener can spell catastrophe.

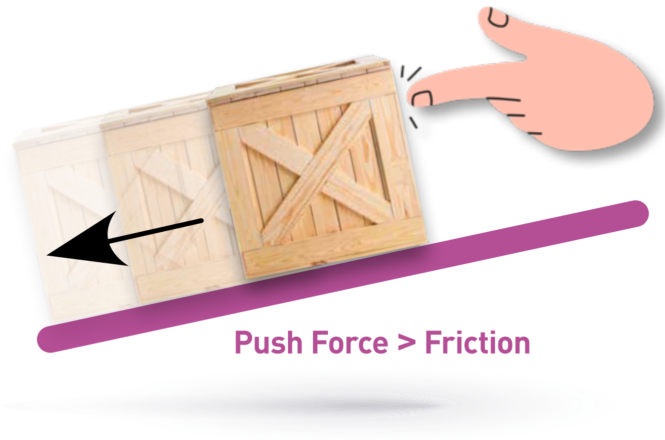
What is Self-loosening?

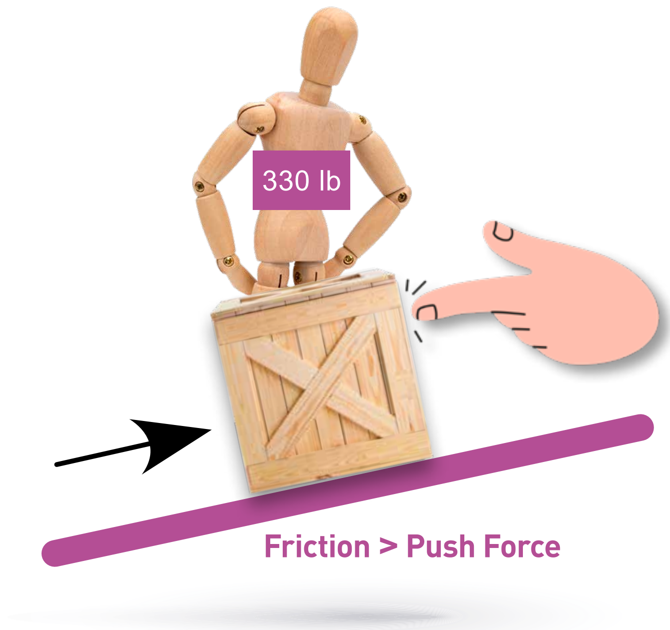
If one digs deeply into this subject, they will discover that there are multiple expert opinions and theories as to the actual mechanism of self-loosening. Although some of these theories are more compelling or better supported with empirical evidence, we don't really know that there is just one way that this works and, in the end, it's probably not that important. We all recognize that vibration (and similar loading) can cause a joint to loosen up. In Bickford's, "Introduction to the Design and Behavior of Bolted Joints- 3rd Edition", he concedes that "Everyone agrees that a threaded fastener will not loosen unless the friction forces existing between male and female threads are either reduced or eliminated by some external mechanism acting on the bolt and joint." In other words, it is only when the contacting friction between the contacting surfaces becomes low or nonexistent that self-loosening can occur.

Imagine for a moment that we have a wooden crate resting on a very gently sloped ramp. It does not move on its own because the weight of crate generates some friction between the bottom surface and the contacting surface of the ramp. However, when I give it a slight push in the downward direction, I can overcome those light frictional forces and slide the crate to the bottom of the ramp. Now imagine the same scenario, but a 150 kg (330 lb.) individual is standing on top of the crate. The added weight generates significantly more friction and, thus, what was before an easy task is now Herculean.

Now, how does vibration factor in? Let's go back to the illustration above with the crate resting on the ramp. Imagine that a force is imposed on the crate that is just high enough to break the hold of the frictional forces holding the crate in-place. What happens to the crate? With no frictional forces to resist, the crate will slide down the incline. In the same way, this illustrates what Bickford is communicating in the quoted line above. **If there are very small or no frictional forces between threads, when exposed to vibration, the thread may be free to move and, thus, begin self-loosening.**

Vibration is a more severe problem for a shear loaded joint than one in tension. In fact, it is believed that vibration acting along the axis of the bolt may only reduce the preload by 30% to 40% while **transverse vibration, where the vibration loading is perpendicular to the bolt axis, can result in 100% preload loss.** In some cases, vibrational loading may be applied in a combination of axial and transverse directions. In these cases, this loading pattern may result in loosening, tightening, or have no effect at all. Thus, transverse vibration is what designers and users must be especially wary of.





Resisting Vibration

Self-loosening is a function of two essential components being present; cyclic loading and slip between mating threads and contact surfaces. Keeping this in mind, **there are four strategies that one might employ to resist self-loosening due to vibration.**

- **Keep the friction forces between threads and contact surfaces above the vibrational forces trying to loosen them. This is accomplished by maintaining sufficient preload.**
- **Prevent slippage between the internal and external threads and contacting surfaces.**
- **Reduce the helix angle of the threads.**
- **Develop prevailing torque or create a locking action that counters the torque that is acting on the system to loosen the fastener in the joint.**

Maintaining the Right Preload

Traditionally, the most economical and simplest method of maintaining joint integrity is to **have a properly designed joint that retains sufficient preload to oppose all forces that may be acting on the joint.** For this purpose, designers may opt to take advantage of the fastener's full potential and tighten to as near yield as practical. For a number of reasons, this may not always be possible or practical and is particularly manifest with smaller screws or ones that might be considered "place keepers".

Prevailing Torque Fasteners

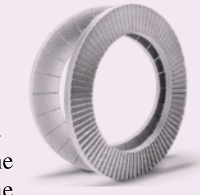
The most common form of “locking” fasteners are prevailing torque fasteners. Prevailing Torque is resistance to turning before the fastener achieves any degree of Clamp Load. This means that the prevailing torque features are not intended or, perhaps, able to create or retain any clamp load but rather simply provide additional resistance to turning. **Prevailing torque fastener performance is governed by industry standards, usually providing requirements for both first and third (or fifth) on and off torque values** which guarantee that the installation torque is not excessive and the prevailing torque is not insufficient. Common types of prevailing torque fasteners include:

- **All Metal Locking Bolts/Screws-** these have some sort of deflected thread pattern which results in, usually minimal, mating thread interference.
- **External Thread Nylon Patch-** these fasteners have Nylon applied to a discrete number of threads on one side only. When installed, the patch wedges the opposing side against the mating internal threads increasing friction and generating prevailing torque.
- **External Thread Nylon Pellet or Strip Insert-** these fasteners are modified to allow either a round plastic pellet or square strip to be installed on one side of the thread. Just like the patch described above, these inserts wedge the opposing side of the threaded fastener into the mating internal threads.
- **Side Locking Nut-** A side locking nut has a circular or square punch driven into one or more nut flats. If centered properly, these indentations develop a protrusion inside the nut, which generates interference and prevailing torque.
- **Top Locking Nut-** A top locking nut has deflections placed on two to three sides of the top of the nut. These serve to either compress the threads in those locations or turn the round thread into an oval. In either case, this causes interference with the threads of the mating external fastener and generates prevailing torque.
- **Insert Lock Nut-** An insert lock nut has an insert of Nylon or Teflon ringing the top of the nut. The externally threaded bolt or screw must bite into this ring which generates some interference and prevailing torque.

Adhesives

Another common method of retaining fasteners is gained with adhesives. These are anerobic adhesives which are activated through contact with metal and the release of chemicals encapsulated in microspheres embedded in the adhesive binder. There are different levels of adhesion, from very light duty to extremely heavy duty. Although these may provide small levels of performance on a second application, they are intended for one-time use.

Wedge Locking Fasteners



Ramp Lock Washers

Many of the methods available will help retain the fastener in-place but do not guarantee retaining the clamp load. Ramp lock washers are one of the exceptions and are an excellent method of retaining clamp load. Ramp lock washers are a two-part system. This mated pair of washers has ridged serrations on one face which bite into the bearing surface of the turned fastener element and the contact surface of the clamped element and ramped wedge features that interlock with each other on the opposite face. As the fastener is turned these ramped wedge features cam over one another until the system is locked into place. The system does not rely on friction but rather the geometry of the ramped steps and the lead angle of the externally threaded fastener. The cam angle (angle of the ramped steps)is greater than the thread lead angle, which prevents the wedges from disengaging when exposed to vibrational loading.

Wedge Locking Nuts

There are several proprietary designs where the nut thread form is specially designed so that the externally threaded component is pulled up onto wedge ramps in the root of the female thread. These are intended to eliminate any slip clearance in the mating threads. To engage this wedge feature, installation torques are higher for this style of nut compared with a traditional nut. On the positive side, however, it has been reported that these types of nuts more evenly distribute the load in the nut, significantly reducing the high load distribution found in the first three threads of a conventional nut joint.

Locking Fasteners

Although one might argue that the most important thing in the bolted joint is getting the preload right, there are cases where it is also critical that the fastener does not come loose. In these cases, to ensure that the fasteners remain in place regardless of preload status there are several common techniques used:

- **Lock Wires-** holes are drilled in the head and special safety wire is threaded through and braided to prevent the fastener head from significant rotation or the fastener coming loose or parts being lost if it should break. Although this appears to be pretty simple, the wiring techniques are specialized and require training and expertise to install properly.
- **Cotter Pin and Slotted Nut-** a hole is drilled through the threads of the externally threaded fastener. A slotted nut is driven into place, and a cotter pin is inserted through the hole and the protruding ends wrapped around the lugs of the slotted nut.
- **Tab Washers-** Special washers with tabs or anti rotation features are used to prevent the nut from turning.

Wrap-up

Vibration and self-loosening can be big challenges for the product designer. Fortunately, there are many different possible solutions to the problem. Some of the solutions provide only mild improvement while others are intended for critical applications or where a fastener must not be allowed to come loose. Understanding the advantages and limitations of these many solutions is important to ensure selection of the proper technology. ■