Strategies to Mitigate Fatigue Failure in Fasteners

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A look at the basics of fatigue in fasteners along with failure-preventative measures.

Although component failures have probably been around for as long as man has been putting things together, it wasn't until the early to mid-nineteenth century that engineers began studying the progressive failure mode that we know today as fatigue. Although highly undesirable, fatigue is a relatively common failure among fasteners and regretfully can lead to some dramatic and even life-threatening consequences. A great deal of progress in understanding fatigue has been made since the nineteenth century, and yet there is still much to be learned. Fortunately, enough is understood today that specific strategies and practices can be employed when a bolt or screw is designed in an application at risk of fatigue failure. This article will look at the basics of fatigue in fasteners and preventative measures that can be adopted to reduce the risk of failure and improve the durability or life of the fastener component.

So What is a Fatigue Failure?

The simplest description is that it is a progressive failure resulting from fluctuating forces loading and unloading a component at some localized point resulting in initiation of a crack or cracks that grow or expand until ultimately, the part fails. The loading and unloading of the part creates tensile, shear or bending loads, which cause stresses (the intensity of force being applied to the part) and strains (the amount of elongation over a unit of length) to act at vulnerable points and create minute or microscopic cracks. These cracks can grow in magnitude and ultimately result in part failure.

If you have ever bent a wire back and forth with the intent of breaking it, you understand the concept of fatigue. After maybe a dozen bends back and forth, the wire usually will break at the bend. This is what happens in a typical fatigue failure except the cyclic loading (application and release of the load) is of a much smaller magnitude than what happens in this example, and so failure occurs after many thousands or even millions of cycles.

Like other types of failure modes, a fatigue failure requires the presence of several key "ingredients". The absence of any one of these factors will prevent a fatigue crack from ever initiating, and thus fatigue failure will never occur. The three factors or ingredients that must be present are cyclic stress, tensile stress and plastic strain. Cyclic stress means that the part is getting loaded with a force and then unloaded in some regular, repeated fashion. Although overly simplistic, taking the example of the wire, it is repeatedly bending it one way and then reversing the bend to bring the wire back to the point where you started. In a laboratory setting, these loading and unloading cycles are very uniform and consistent, but in real-world service, they may vary and be somewhat irregular. The important concept to take away is that they are repeated many times in the life of the part and without such repeated loading, fatigue cannot occur.

Tensile stress is the intensity of the force tending to pull an item apart. The converse of this is a force that pushes an item together compressing it. The intensity of this force is the compressive stress. It is important to understand that a crack will only initiate under tensile stress. Therefore, as this article will later explain, methods that place the fastener surface into compressive stress are advantageous because they will prevent a crack from initiating.

Finally, plastic strain must be present. In this case, the term "plastic" is an engineering term used to refer to a permanent elongation or set in a material. Take for example the action of pulling gently on a rubber band and letting go, the band returns to its original size and shape, this is elastic behavior. In normal service conditions, metal fasteners exhibit this elastic behavior. However, if you pull on that band and stretch it out almost to breaking and then let it go, it does not go back to its original length, but is longer. This is plastic behavior. Although potentially hard to envision in a metal fastener, once it is overloaded, it is subject to such behavior. Therefore, plastic strain in a fatigue situation refers to minute (even microscopic) permanent elongation that is occurring within the part.

The combination of these three ingredients conspire, over time—usually many thousands of cycles, to initiate one or more micro-cracks in vulnerable areas. These micro-cracks propagate to form one or more macro-cracks, which grow and ultimately lead to final failure. A classic fatigue failure surface will show characteristic "beach marks", which are aptly named because they resemble the tide marks left in the sand on a beach and are the remnants of the crack front as it progresses. Eventually, the remaining undamaged material will no longer be able to withstand the applied stress and an overload failure will occur.

The good news is that with careful planning, thoughtful design and good implementation, the risk of fatigue failure can be greatly reduced, if not eliminated. With respect to a bolted joint, there are various strategies and design practices that should be considered and employed when planning for a bolted joint in a cyclic environment. They fall into four main categories:

- Bolt preload and joint stiffness.
- Processes that induce favorable compressive stresses.
- Best design practices.
- Overall surface conditions.

Bolt Preload and Joint Stiffness:

Perhaps the single most important criteria to increase fatigue life of a bolted joint is to get the preload (or bolt tension loads) right. It is critically important that the bolt be consistently and accurately tightened to achieve the desired clamp load. Getting the preload right serves three important purposes. It creates a stiffer joint, which reduces the rate of fatigue crack propagation from flexing and limits the magnitude of the applied loading on the bolt. It provides the best protection against overloading that would result in the joint separating. And it provides the best protection against the threads loosening.

The fatigue life of a bolted joint will depend on the size of the applied load, the number of times the load is applied and most importantly the amount of the load that is experienced by the bolt. If the bolt experiences loading lower than the limits where it would start to fail, it should survive forever. However, if the joint loses its preload or the preload is too low, the bolt may assume a high percentage of or the entire applied load, setting it up for potential failure.

Therefore, controlling the tightening process to maximize the preload is important. Today, there are multiple tightening technologies that provide the installer good control over this process. In general, the main principle in protecting against fatigue is to tighten to as high a level as practical, which depending on the industry is normally between the proof strength and yield point of the bolt.

To accomplish the highest possible preload, a common approach is to increase the stiffness of the joint. This can be accomplished in a variety of ways:

- Utilize a higher strength bolt (for example, a 10.9 property class rather than an 8.8 property class)
- Use smaller bolts or bolts with necked-down shanks that are higher strength.

Either of these strategies effectively changes the stiffness of the bolt allowing higher preload values, which as described above, lowers the portion of the applied load assumed by the bolt.

Guaranteeing a high clamp load in the joint is obviously important in a tension joint, but it can be equally important in a shear joint. In a shear joint, to minimize the possibility of fatigue, it is important that the joint be as solid as possible to prevent the clamped layers (or plies) from moving. The high preload effectively provides the means for friction forces to clamp the panels together as if they were one unit, which distributes the load more evenly across all the fastener members, significantly reducing the chances of fatigue.

In a normal nut and bolted joint, the highest load is carried in the first couple of threads in the nut, and often predominantly in the first thread. This effectively places a stress concentration at the bolt thread closest to the top nut face and is usually the most common failure spot in a bolted joint. Designing the nut so that it is better able to distribute the load across its threads will improve on this situation and increase the fatigue life.

Processes to Induce Favorable Compressive Stresses:

Perhaps the second most effective way of improving the fatigue life of a screw or bolt is to purposely induce favorable compressive stresses on the surface and at vulnerable locations. Remember that one of the three factors necessary for fatigue to occur is tensile stress. Therefore, if compressive residual stresses can be induced they will effectively protect the components by cancelling out the required tensile stress factor, or result in a barrier that the part has to overcome before the tensile stresses can come into play. There are various practical ways that these favorable compressive stresses can be induced into the surface of a screw or bolt.

Perhaps the most effective and commonly employed method of adding favorable compressive stresses is with controlled shot peening. It is critical that this process be tightly controlled. The condition of the shot, coverage of peening and the time in the peening chamber are all important factors that must be closely monitored and controlled. This is not a process that can be done without careful attention to detail and oversight by experienced and trained individuals. Getting it wrong can have deleterious effects, while getting it right can have dramatically positive effects.

One of the advantages of shot peening is that it can be applied selectively to key areas, and often is employed on large items such as shafts or in bulk covering all surfaces as would normally be utilized on fasteners. The parts emerge from the process with a textured appearance, which under magnification is the effect of the dimples created when the shot impinges against the surface. Controlled shot peening is commonly utilized in aerospace and automotive applications.

For bolts, two other actually more commonly employed practices are rolling the threads and fillet radius after heat treatment. Rolling the fillet radius is most commonly employed on aerospace fasteners and is an especially effective way of inducing residual compressive stresses to a critical and vulnerable area of the bolt. Today, many industries utilize rolled threads after heat treatment. It is important that this is done after heat treatment and has been experimentally shown to be very effective, particularly as the strength level of the part increases. Rolling threads hard can be difficult on tooling, and thus more expensive and challenging to the manufacturer, but is well worth the investment on parts in fatigue critical environments.

Finally, there are several thermal treatments that actually may induce favorable compressive stresses such as induction hardening, carburizing and nitriding. However, on the flip side other thermal treatments can have negative impacts by relieving the favorable residual stresses, creating unfavorable residual stresses or introducing decarburization. In particular, decarburization can dramatically impact the fatigue life unfavorably.

Best Design Practices:

The choice of material for the bolt is critical. Going up the ladder with higher grade alloy steels can have a dramatic impact on fatigue life. I recall being consulted a couple of years ago by a customer that had sampled identical parts except for the material utilized. They were identical property classes of steel, but one version was 10B21 and the other 4037. The customer had run some life testing on the application and found the 4037 version to last well past the required standard, but the 10B21 version was failing just below the minimum requirement. The customer was seeking to explain these results, which on the surface was pretty simple—all else being equal, some materials are better than others regarding fatigue life.

Reviewing parts for stress risers is important. A couple of key areas to consider are the fillet radius, thread run-out transition and thread root. Increasing the fillet radius and making it as smooth and consistent as possible without sacrificing necessary underhead bearing area can pay significant dividends. Likewise, each thread is a notch, which is the classic example of a crack initiation site. Therefore, using a more highly radiused root thread like an UNJ, MJ, or UNR thread form can have a dramatic positive impact.

The designer should review the application and guarantee that situations that could cause bending are avoided. Take for example a plate with a bearing surface that is slightly inclined. When the bolt is tensioned, the surface will act like a wedge putting the bolt in a bending mode. Therefore, special care should be taken to assure that bearing surfaces are flat, parallel and with an acceptable surface finish. Configurations that may be prone to flexing or bending by design should be strengthened to prevent this as much as possible.

Overall Surface Conditions:

The surface condition of the bolt is extremely important to the fatigue life. In the lab, test samples are highly polished with few apparent surface flaws. Commercially produced parts however, do not have this luxury and will almost always be found to have a lower life than lab specimens. This is natural because they receive nicks and damage from handling or do not receive the polish that most lab specimens can get. Additionally, the manufacturer must be very watchful for thread laps and eliminate these at set up. Every nick, scratch or sharp edge is a potential site for initiation of cracks.

Additionally, surface finishes can have an impact on fatigue life. Many components have surface finishes applied for corrosion protection. Zinc and cadmium electroplating do not seem to have any negative effects on fatigue life, however nickel and chrome finishes do. Nickel and chrome finishes create tensile stresses at the interface of the finish and base substrate. Therefore, if you are designing for fatigue life, these two finishes should probably be avoided, if possible.

In Summary

Fatigue failures in fasteners can result in exceptionally dramatic and possibly life threatening consequences. Therefore, it is important to have a basic understanding of how certain design choices can have either negative or positive effects on the fatigue life and to be able to impart this information to customers and users as well.

Although often coming at a premium, there are many options that can be employed to improve fatigue life and in the long-run may be well worth the added investment.

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