Three Ways Increasing the L/D Ratio Improves Reliability of Dynamically Loaded Bolt Joints

Jon Ness, Principal Engineer
Matrix Engineering Consultants
12986 Valley View Road
Eden Prairie, MN 55344 USA
www.matrixengrg.com

and

Barbara Donohue
Freelance Technical Writer
Donohue Communications
www.the-engineer-who-writes.com

Design engineers are often told to design bolted joints with larger length/diameter ratios. Here's why.

During design reviews, experienced engineers may point out that a larger ratio of clamped length to bolt diameter (L/D) improves the reliability of dynamically loaded bolted joints, but they may not give a satisfactory explanation for this advice. This article explains three benefits of designing dynamically loaded bolted joints (**Figure 1**) with a sufficiently large L/D ratio:

- Reduced preload relaxation due to embedment
- Resistance to self-loosening
- Reduced risk of fatigue failure

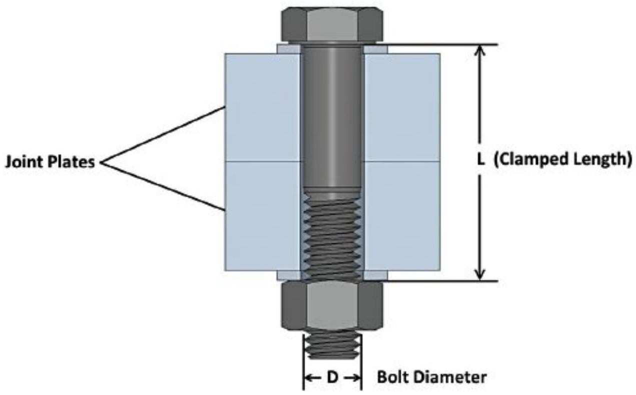

Fig. 1 — A bolted joint (image courtesy of Matrix Engineering Consultants).

The Function of Dynamically Loaded Bolted Joints

It is widely accepted that the design criteria for bolted joints exposed to dynamic loads are significantly more rigorous than the criteria for statically loaded joints. Dynamically loaded joints must be designed and assembled such that the in-service bolt preload is high enough to prevent:

- Joint opening due to axial loading
- Joint slippage due to shear loading

If the preload is not sufficient to prevent these joint movements, the bolted joint has a high probability of failing in the application.

In addition to the requirement to provide the necessary preload, an often-cited design parameter for dynamically loaded bolted joints is the ratio of clamped length to bolt diameter. Increasing this L/D ratio improves the performance of dynamically loaded bolted joints when these bolted joints are placed into service.

This article examines three aspects of bolted joint design that benefit from a large enough clamped length to bolt diameter (L/D) ratio.

Embedment

The surfaces of fastener threads, joint plates and washers may appear to be smooth, but on a microscopic level, they are jagged and rough, covered in mountains and valleys (**Figure 2**). When two of these surfaces are forced into contact in the bolted joint, localized stresses are very high, causing plastic flattening of the microscopic features in the surfaces. This phenomenon is called embedment. It happens between each pair of surfaces—bolt head and washer, washer and joint plate, between joint plates, etc. The amount of embedment depends on such factors as materials, surface finish and clamping pressure. Note that the amount of embedment is not affected by bolt length.

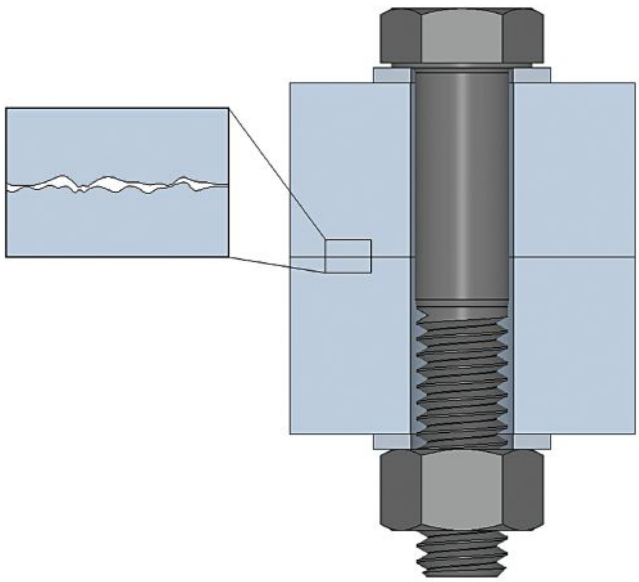

Fig. 2 — A bolted joint showing asperities on the surfaces of the joint plates (image courtesy of Matrix Engineering Consultants).

As it is tightened, a bolt stretches a slight amount. For example, in a small, short bolt made from stainless steel, the length change may be 0.001" (0.025 mm) or less. Even small amounts of embedment can cause significant loss of stretch in this small, short bolt and a corresponding relaxation (loss) of preload.

The greatest amount of embedment occurs during tightening of the fastener. The tightening process itself generally compensates for this. Embedment continues slowly after tightening is complete until a number of hours later, it approaches a steady value (**Figure 3**). Additional embedment happens when the joint is put into service and experiences dynamic loading. This causes an additional permanent loss of preload, which can be as much as 40% or more in extreme cases.

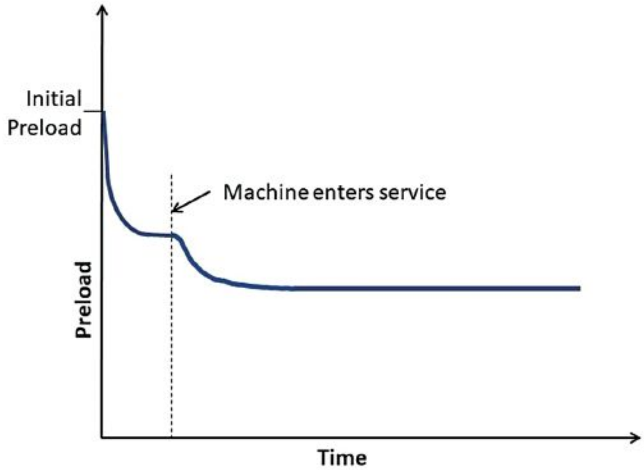

Fig. 3 — Preload relaxation due to embedment vs. time (image courtesy of Matrix Engineering Consultants).

How does a larger L/D ratio reduce preload relaxation due to embedment? Since the amount of embedment is the same for a given combination of embedding surfaces (bolt head, washer, joint plates, etc.), this amount of embedment would reduce the bolt stretch in a longer bolt by a smaller proportion than it does in a shorter bolt.

For example, for a bolt with an L/D ratio of 5, embedment might result in a loss of preload of 7%. The same bolted joint, but with thinner joint plates and an L/D ratio of 1, would experience a loss of preload of 35%.

Larger L/D ratios can reduce another kind of relaxation—not covered in this article—which happens when the joint includes a gasket. After tightening and over time, the gasket material continues to deform under the clamping load. The gasket thickness decreases, which reduces the stretch of the bolt and reduces the preload.

Self-Loosening

External and internal threads unwinding on their own is called self-loosening. This often occurs when the joint plates repeatedly slip relative to each other.

When the joint plates slip a short distance, the bolt, nut and their washers maintain a friction grip with each other and the joint plates, but the bolt can bend slightly (**Figure 4**). As long as the bolt, nut and washers maintain their friction grip, self-loosening does not occur.

At larger slip values, the lateral forces increase until they overcome the friction grip and the bolt, nut or washer slips slightly. At that instant, an incrementally small amount of loosening rotation occurs. With repeated joint slip, the fasteners incrementally loosen. Each bit of loosening reduces the preload, which makes further loosening more likely. Eventually, the fasteners can loosen completely.

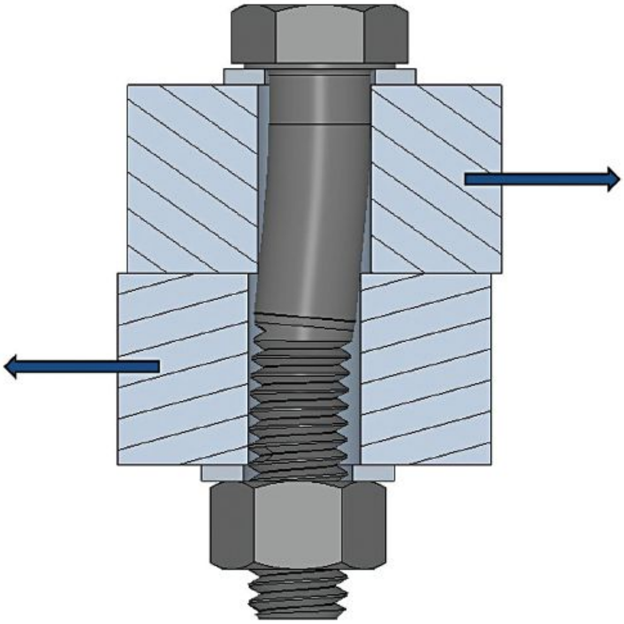

Fig. 4 — Bolt bending when joint plates slip (image courtesy of Matrix Engineering Consultants).

How does a larger L/D ratio provide resistance to self-loosening? A larger L/D reduces the bending stiffness of the bolt. As a result, if the joint plates slip, the bolt can bend more readily and the lateral forces are insufficient to make the bolt head, nut or washers lose their friction grip. Since the friction grip is maintained, self-loosening is not triggered. It has been shown that joints having L/D ratios of 5 or greater are generally resistant to self-loosening assuming "Normal" Fit Class clearance hole sizes (according to standards *ASME B18.2.8* or *ISO 273*).

Additional strategies can help reduce the likelihood of self-loosening. It is also possible, by reducing the clearance hole size, to design a joint inherently resistant to self-loosening by limiting the distance a joint can slip. Other proven techniques are available to reduce the risk of self-loosening, such as thread adhesive and wedge-lock washers.

However, keep in mind that joint slip can cause other problems. Joint slip subjects the bolt to reverse bending stress. And if the joint slips repeatedly, the repetitive bending can cause fatigue in the bolt. Additionally, repeated joint slip can cause wear on the joint and the bolt, which results in the loss of preload.

Fatigue

Often fatigue failures in bolted joints occur due to the fact that the preload provided by the bolt is insufficient to resist the applied loading. And this results in transverse joint movement under shear loading or joint separation under axial loading.

A fatigue crack initiates and propagates because of varying stress that exceeds the bolt material's capability. The crack extends slightly with each load cycle (**Figure 5**) and propagates across the section of the bolt. When the cross section is reduced so much that the remaining material cannot carry the load, the bolt fractures. The higher the stress, the fewer cycles before failure occurs. Lower stress in the bolt results in longer fatigue life.

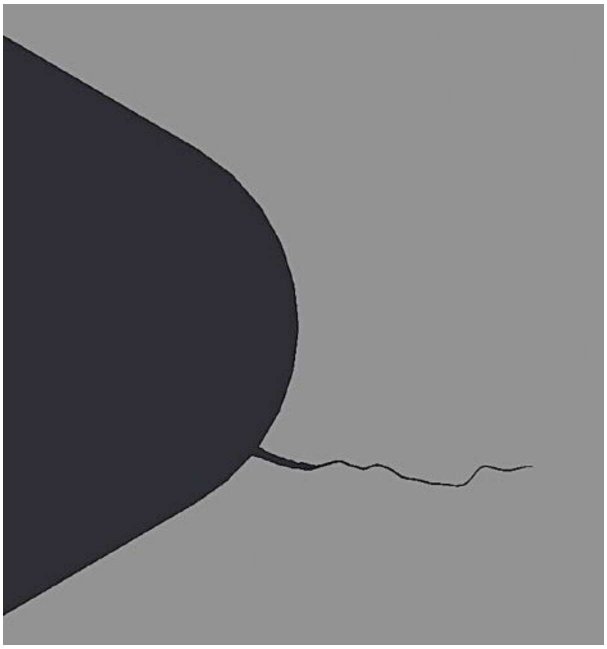

Fig. 5 — Fatigue crack initiated near the thread root in a bolt (image courtesy of Matrix Engineering Consultants).

How does a larger L/D ratio reduce the risk of fatigue failure? A longer bolt is less stiff than a shorter bolt. This reduces the maximum bending stresses in the bolt for a given amount of slip between the joint plates. Reducing the amplitude of the stresses in the bolt reduces the risk of fatigue. Similarly, for axial loading, the longer, less stiff bolt is subject to lower axial stresses if the joint separates.

The fatigue failure of a bolt is not necessarily due to the fastener having inadequate fatigue strength. More often, the fatigue failure is a consequence of inadequate bolt preload that results in joint slippage or separation. This loads the bolt in a way that was not intended.

Conclusion

Designing dynamically loaded bolted joints with larger L/D ratios improves the performance of the joints in three ways.

- A larger L/D ratio reduces the preload relaxation due to embedment.
- An L/D ratio of 5 or greater can make the joint resistant to self-loosening.
- Increases in the L/D ratio incrementally reduce the risk of fatigue failure.

Engineers with extensive experience designing bolted joints know about these advantages. However, in design reviews they may simply say to use larger L/D ratios, but not explain why. Such design choices can help produce equipment and products that perform to specification over a long life. References, training and consulting services are available to aid in the effective design of bolted joints. To learn more, visit the website of Matrix Engineering Consultants. *www.matrixengrg.com* FTI

Author Profiles:

Jon Ness *is a principal engineer with Matrix Engineering Consultants, a firm that focuses on product development and machine design. Jon has over 32 years of engineering and design experience related to the development of on- and off-road vehicles and equipment. His technical expertise includes design and validation of dynamically loaded bolted joints. Jon has consulted in the investigation of bolted joint failures, including fastener testing, and participated in research projects related to preload relaxation in bolted joints. He has taught numerous classes related to Failure Modes and Effects Analysis and Bolted Joint Design. A licensed engineer in the state of Minnesota, Jon is a current member of the UL2703 Standards Technical Panel and a Certified Fastener Specialist through the Fastener Training Institute.*
www.matrixengrg.com

Barbara Donohue*, a freelance technical writer/editor and technical journalist for 20 years, started out in mechanical engineering and worked in design, manufacturing, and heat transfer. She specializes in writing about industrial equipment and processes for companies and publications, occasionally covering other areas such as business. She was formerly a contributing writer for Today's Machining World and web editor at VALVE Magazine.* ***www.the-engineer-who-writes.com***

Company Profile:

Matrix Engineering Consultants *offers product development and engineering design consulting to many industries, including on- and off-road motor vehicles, agricultural equipment, mining, construction, forestry, rail, utilities, defense, and consumer products. From generating product ideas through product development and validation, verification, and testing of the final design, Matrix is a proven partner.*
One Matrix specialty with broad application is bolted joint design and failure analysis. Matrix provides state-of-the-art solutions to fastener and bolting problems based on extensive experience and research. Bolted joint consulting services include advanced bolted joint analysis and design, finite element analysis, torque-tension testing, and resolution of product service and field problems caused by bolted joints, including self-loosening and fatigue. In addition, on-site training courses led by Matrix experts help scale up in-house engineering skills in this important area.
Other consulting services include field validation and data acquisition, risk assessment, and reverse engineering. ***www.matrixengrg.com***