NORD-LOCK GROUP

SAFE BOLTED JOINT DESIGN

AN INTRODUCTION TO WHY BOLTED JOINTS FAIL AND HOW TO MAKE THEM SAFER

CONTENTS

INTRODUCTION

We live in a time of constant change, where successful industries continuously develop their products and services while many more disappear to make way for new innovations. The manufacturing industry is becoming increasingly complex, having to integrate new high-tech materials and functionalities into products that must be lighter, stronger and more reliable than ever before.

Throughout this evolution, one fundamental piece of the manufacturing process has remained the same – the bolted connection. This technology keeps components together, be it for something as basic as a kitchen table to something as complex as a robotics control board. Although the basic characteristics, design and arrangement of the bolted connection has remained the same over the years, it has not been immune to change. It has integrated new coatings, materials and stronger bolts to answer growing application demands.

Bolt and nut assemblies offer multiple benefits such as their commodity, easy sourcing, standardized parts, and well-known tightening techniques and tools. However, their durability may be affected by factors such as loosening or corrosion, potentially leading to unexpected failure. Although the nut and screw arrangement possesses well known weaknesses, there are ways to anticipate potential failures in order to establish a safe connection.

This white paper will take on a holistic approach to examine the role bolted connections play in today's industries, the potential failures caused by design, installation and environmental factors and best practices to ensure safe bolted connections that do not fail in critical applications.

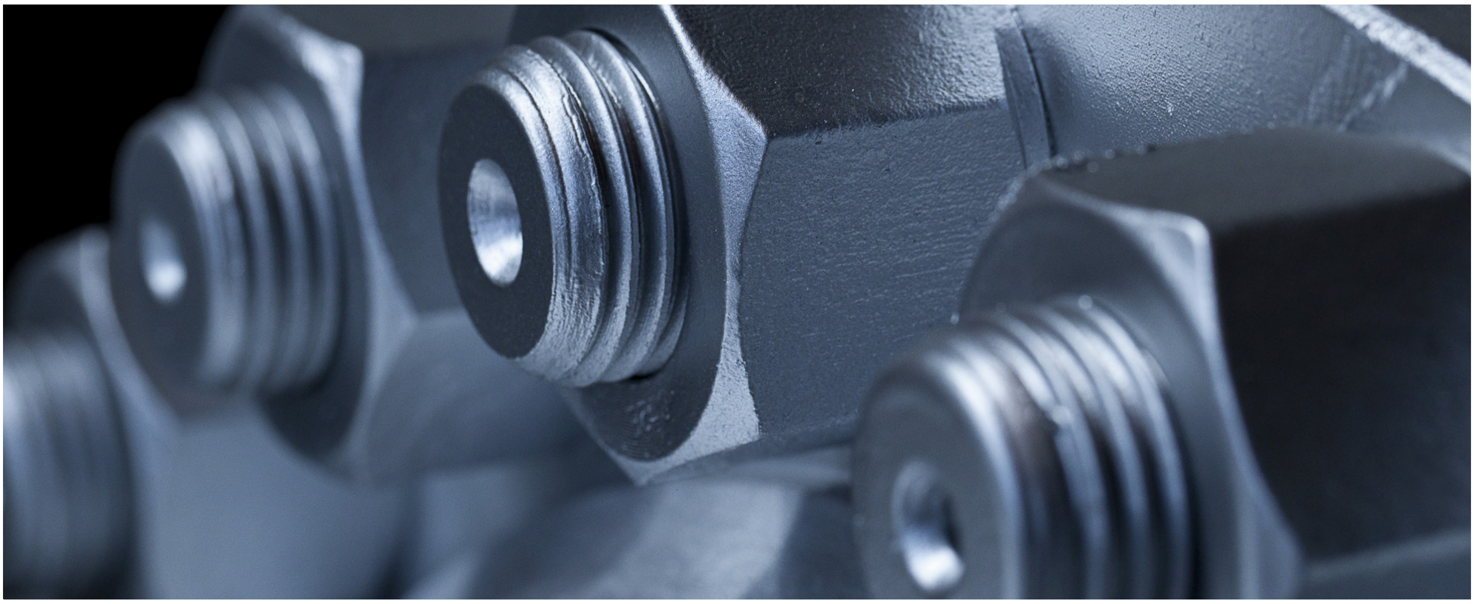
Technical terms used in the paper:

Preload
The axial force of the bolt after its installation.

Clamp load/force
The force acting on the parts by the bolt.

Torque
The force of rotation applied on a bolt to tighten it.

Stress
The amount of force shared over a surface.

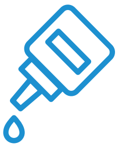


CHAPTER 1 BENEFITS OF USING BOLTED JOINTS IN THE INDUSTRIAL SECTOR

Industries now anticipate product life cycles early on in the development phase, with departments such as R&D, quality, aftermarket, operations and sales each defining their requirements. The way components are connected is of major concern as it impacts every step of how a product is used. Assembly lines are still mainly operated by humans, which makes them error prone. Therefore, easy processes are encouraged to reduce mistakes and increase product quality and safety. Multiple advantages have ensured that bolted joints are one of the most popular methods to connect components in the industrial sector today.

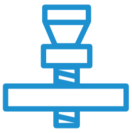
Ease of use

The bolted connection is an appealing method due to its ease of use. It combines a screw/stud with a threaded counterpart such as a nut or tapped hole and only requires a simple torque wrench to operate. This differentiates it from other technologies such as:



Bonding

Bonding relies on the operator's judgement to determine quality and correct application.



Riveting

This assembly requires press tools that makes the process more complex.

Welding

Welding requires a certified welder, advanced tooling and failure can remain undetected.

Flexibility

A bolted joint is not a permanent assembly, it can be easily removed and reused using the same tools with which it was assembled. This is very helpful for maintenance, simple checks or replacement of parts. It is also useful when the product is at the end of its life cycle as parts made of different materials can be separated, sorted and recycled effectively.

Range

Bolts are available in a range of sizes and materials depending on the demand of the application. They are commonly made of steel, which provides strong mechanical characteristics that are usually greater than the capacities of the assembled parts.

Materials

Bolts can be used to join parts made of materials that are different than the bolt itself, such as plastics and composites. No special arrangement or design is required to make this assembly compatible.

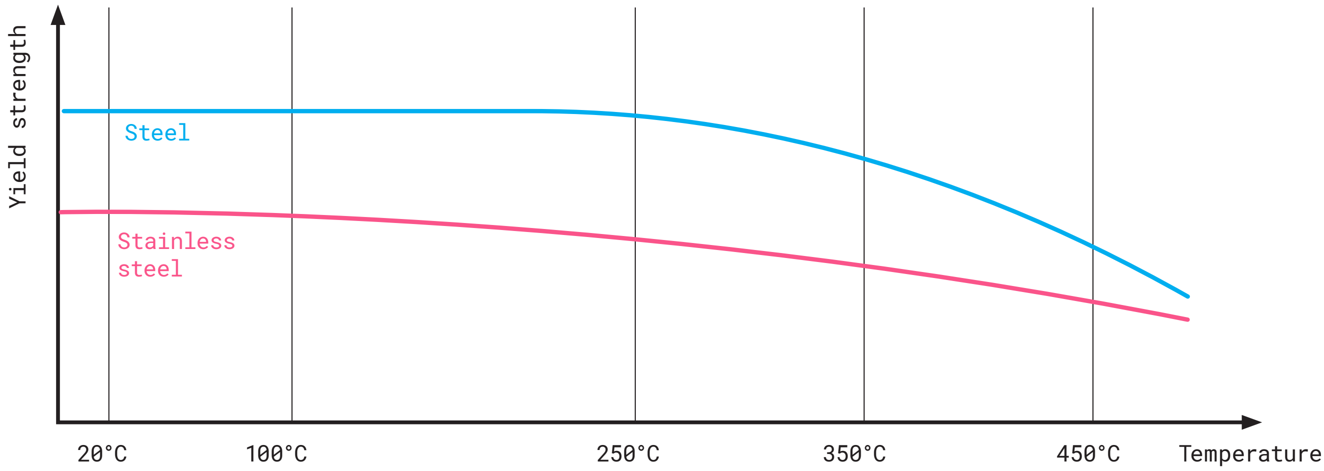
Thickness

The thickness of the assembled parts can be as large as they need to be to fit the manufacturers needs. The thickness and the hole size can be produced with large tolerances. This usually implies economical and regular well-known machining processes.

Temperature

Normalized steel bolts can sustain temperatures between -50°C and 200°C and for wider demands, stainless steel bolts can function between the ranges of -160°C and 500°C. Special designs using materials able to sustain high temperatures and alloys capable of functioning in an acidic environment can bring the connection to the right level of performance.

Loss of mechanical resistance with increase in temperature



Thanks to the above advantages, the bolted joint is widely used in the industrial sector as a practical and cost-effective solution.

> Bolt manufacturers and distributors have become well established and are able to provide affordable products that answer increasingly complex demands.

CHAPTER 2 LIMITATIONS OF USING BOLTED JOINTS

Despite their many advantages, bolted joints are also prone to limitations. These should be taken into account when considering which method to connect components on an application.

Fatigue failure

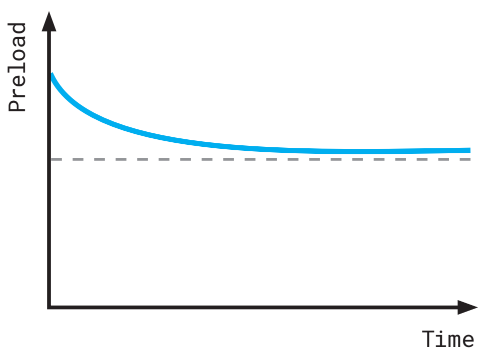
The thread of a joint can be assimilated as a notch. Due to geometry, stresses become concentrated when exposed to load. This makes the bolted joint subject to fatigue failure, accelerating the creation of cracks and the breakage of the bolt. As an example, a rounded bar is at least four times stronger against fatigue than a bolted joint.

Settlement and creep

All bolted joints lose a certain amount of tension after installation due to two basic phenomena. The most common is settlement, which is caused by surface irregularities on each of the parts. When analyzed on a microscopic level, surfaces can be seen as a field of peaks, which minimizes the contact area when two parts are pressed against each other. This results in the flattening of the peaks which increases the contact area until it is big enough to sustain the load. This deformation occurs when a bolt compresses different parts together and only takes a few minutes to stabilize. Settlement is accentuated when parts have rough surfaces and when the number of interfaces increases.

Creep is another phenomenon that reduces the preload in the bolt. When a material is stressed (compression or tension), it will deform and try to flow away from this area, which affects the reaction forces and reduces the preload. This effect is extremely slow, but it is accelerated when the temperature increases. Creep occurs even though the stress is below the yield strength. Soft materials, such as copper or aluminum, are more susceptible to this type of deformation than stronger materials such as steel.

Preload under settlement



Vibration loosening

Loosening can originate from axial relaxation (embedding, plastic deformation) or can be induced by relative movements between parts resulting from vibrations. This makes the components deform and move away from one another. The friction between the threads combined with the preload generates the friction force that has to be overcome for the parts to loosen. When those forces are exceeded, the system loosens.

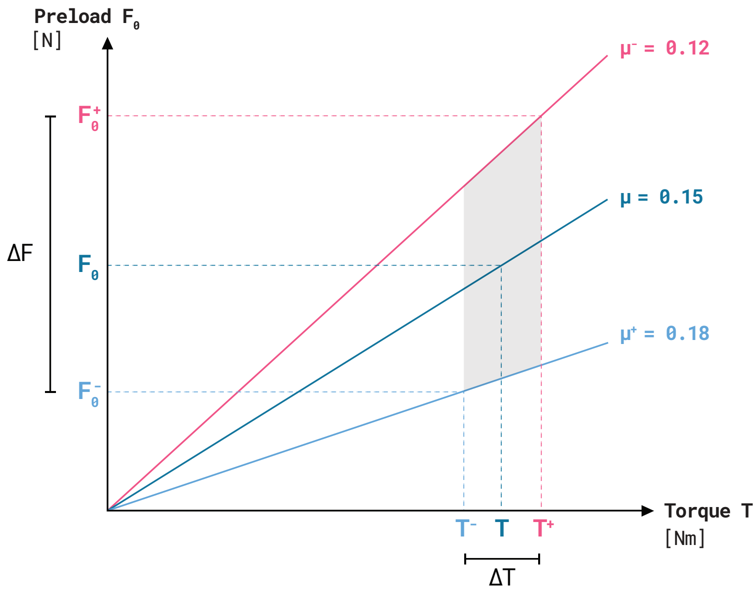
Corrosion

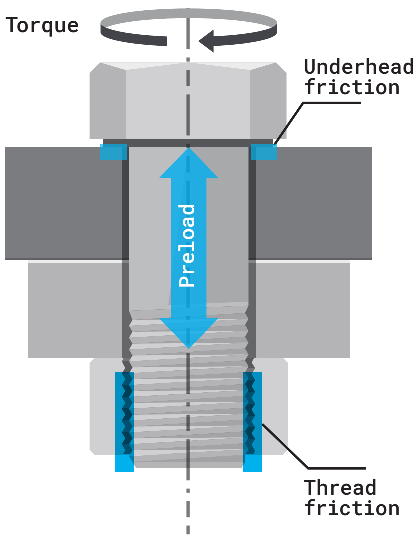
Even though bolts can be coated or made of stainless steel, exposure to external environments can lead to corrosion. This chemical reaction happens when iron (the base material of the bolt) is exposed to oxygen and results in oxidization known as corrosion.

> This transformation destroys the structure of the bolt and reduces its ability to sustain load.

Example of extreme corrosion on a flanged connection.

Torque - tension relation including tool and friction deviation.





Deviation

The most common way to create preload in a bolt is the application of torque, via the bolt head or nut. However, this method can be imprecise due to variables in installation parameters. The coefficient of friction in the thread and under the head is the most important. This is because the relation between the preload and the torque is proportional to the friction, as defined by the Kellermann and Klein formula. Friction can vary between bolts issued from the same batch of raw material and it can increase or deviate drastically due to the application of, or the lack of coatings.

CHAPTER 3 CONSEQUENCES OF BOLTED JOINT FAILURE

The limitations listed in the previous chapter can lead to two possible scenarios: bolt loosening or breakage. A bolted joint is the most sensitive part of the assembly and there are countless situations that can cause it to fail. However, some are more common than others.

When parts are assembled and the bolt is preloaded, the system can filter the outside force, spreading it between the parts and the bolt. The bolt generally experiences approximately 10% of this load, which is dependent on the stiffness of the bolt and the parts. Once the bolt loses its preload, it takes the load variation in full, which leads to fatigue failure.

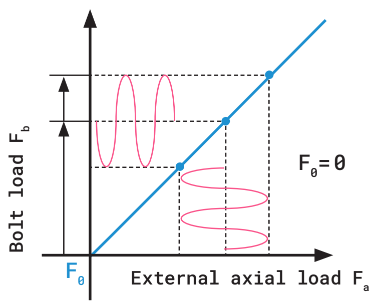
Impact of over tightening and under tightening

Over- or under-tightening can happen during first assembly. Over-tightening is when a bolt is preloaded too high in regards to the mechanical strength of one of the components. Usually it is the strength of the bolt itself, but it can be that of the clamped parts (causing risk of embedding or risk of crushing a gasket).

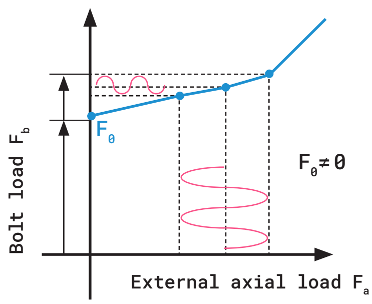
Undertightening may not be detected during the first installation as the force necessary to hold the parts together will be sufficient until the bolted joint goes into service. However, when the parts start losing contact due to the service load, this means that the stress is much higher than it is supposed to be. In this situation, the bolt will either break suddenly after a couple of cycles or break in fatigue earlier than its estimated life cycle.

Many factors can lead to wrong preload: design error, friction deviation, improper tool selection or misuse. Preventive measures should be put in place, or post-tightening controls should be carried out to ensure a correct preload, hence safe bolted joints.

Bolt not preloaded



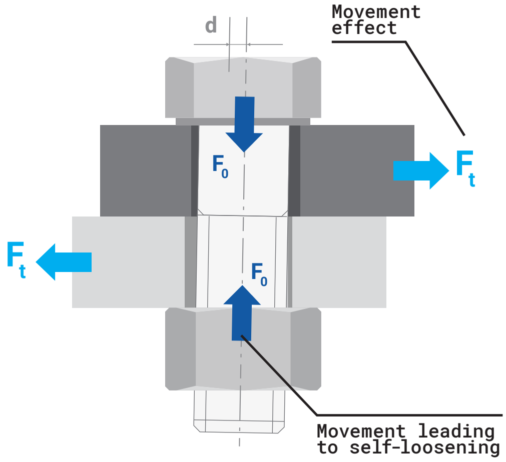
Bolt preloaded



A similar situation occurs when the preload is higher than calculated but continues to maintain the integrity of the joint. Once the bolted joint experiences service load, plastic deformation occurs, meaning that a portion of the initially installed tension is lost to permanent elongation. The bolted joint experiences a state similar to that of under tightening with the same consequences of failure.

Underestimating movement between joint parts

Self-loosening is also a possible consequence of tightening a bolted joint to the incorrect level, however, it usually occurs due to underestimating the movement between parts or deformation. When a bolted joint experiences sudden loads and vibration, this creates relative movement between the parts and the nut or bolt head. If the nut or bolt moves, it tends to release itself and causes a loss of preload. This can result in three types of failure: sudden breakage, fatigue breakage and loss of the assembly by the complete loosening of the bolted joint.

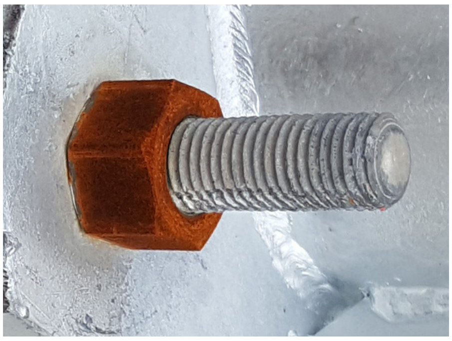


Common types of corrosion

Another common issue encountered by bolted joints is corrosion. This comes in different forms depending on the environment and manufacturing process. General corrosion, as noted in the previous chapter, acts slowly on the structure of the bolted joint material through oxidization and degrades its mechanical properties.

Galvanic corrosion produces the same result in a shorter time span. This happens when materials with different electronic potential, such as steel and stainless steel, come into contact. A current is created which corrodes the less noble material (steel will rust when it comes into contact with stainless steel).

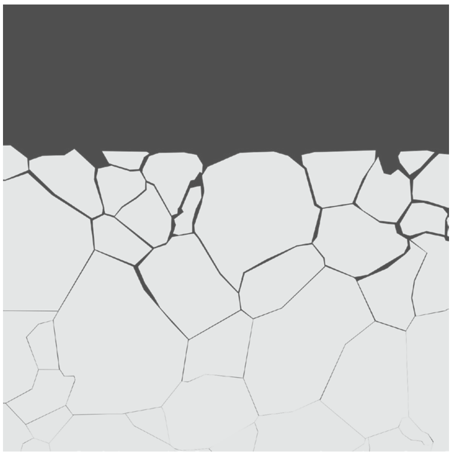
When the corrosion is localized on the threads, it may make it impossible to disassemble the assembly without compromising the integrity of the bolt. When acting across parts, but especially on the shaft, it reduces the cross section, which increases the stress until there is not enough material to sustain the load and the bolt breaks.



General corrosion.

Intergranular corrosion mainly affects stainless steel and is the result of a manufacturing issue. This type of corrosion acts on a microscopic level. When the material is heat treated at an excessive temperature for an extended period of time, the grain boundaries do not deplete which supports the appearance and progression of cracks.

High strength bolts (mainly grade 12.9) are more prone to hydrogen embrittlement in case of improper heat treatment. Just as with intergranular corrosion, the exposure to hydrogen in the air damages the cohesion of the microstructure and results in breakage. This usually happens shortly after the bolt has been installed.



Intergranular corrosion.

CHAPTER 4 BEST PRACTICES TO INCREASE BOLTED JOINT SAFETY

Knowing the potential weaknesses of bolted joints as well as the consequences of bolted joint failure has led to the development of design processes, tools and ways of working to increase their safety. However, being aware of these best practices is not enough. Instead, it is important to study the context of each specific bolted joint in order to adapt these best practices to suit each individual situation.

Application requirements and environment

Understanding the application within which the bolted joint will operate is essential to designing, manufacturing and installing a safe bolted joint. The forces and momentum that will act on the parts and their frequency provide important information on the level of force necessary to keep the parts together. From there, the dimension, amount and distribution of bolted joints can be defined. In addition, safety factors must be implicit as mechanical characteristics, dimensions, friction and external loads may deviate from expected.

> The environment in which the application will operate is crucial to consider.

It can either be neutral or aggressive. This provides information on the corrosion resistance to apply either by using an appropriate coating or manufacturing the bolted joint from a specific material. There exist norms and classifications of corrosive environments that can help to categorize the needs of the bolted joint and the measurements to take.

ISO 12944 Classification	Impact	Interior	Exterior
C1	Very low	Heated buildings with clean air, such as offices, shops, schools, hotels, etc.	None
C2	Low	Buildings not heated, where condensation may occurs, such as warehouses and sports centers.	Atmosphere with low pollution, such as the countryside.
C3	Middle	Buildings for production, with high atmospheric humidity and some degree of air pollution, such as food manufacturers, breweries, dairies and laundries.	Urban and industrial areas, moderate sulfur dioxide pollution. Coastal areas with low salt content.
C4	High	Chemical manufacturers, swimming pools and ship and boat yards located by the sea.	Industrial and coastal areas with moderate salt impact.
C5-I	Very high (Industrial)	Buildings or areas with almost permanent condensation and with high pollution.	Industrial areas with high humidity and aggressive atmosphere.
C5-M	Very high (Marine)	Buildings or areas with almost permanent condensation and with high pollution.	Coast and offshore areas with high salt content.

Installation process

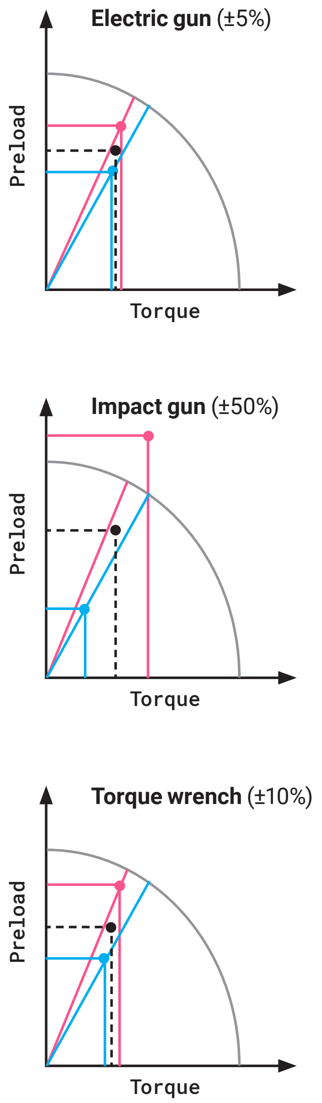
Although safety measures are applied during the design phase to anticipate deviations related to the environment, choosing an inappropriate tightening tool for a specific application can reduce the safety of the bolted joint back to zero. It is during this phase that it is important to pay attention to the precision and repeatability of the tightening process.

As mentioned in the previous chapters, torqueing is the most popular method to tighten a bolted joint, however, all tools do not have the same precision. A manual torque wrench can be extremely precise, but the operator could add deviation during the process by using the tool incorrectly. Electric and hydraulic tools with reaction arms increase precision by removing some uncertainty related to the operator. However, the precision of this tightening process is not only dependent on the tool and the operator but also on the friction of the parts.

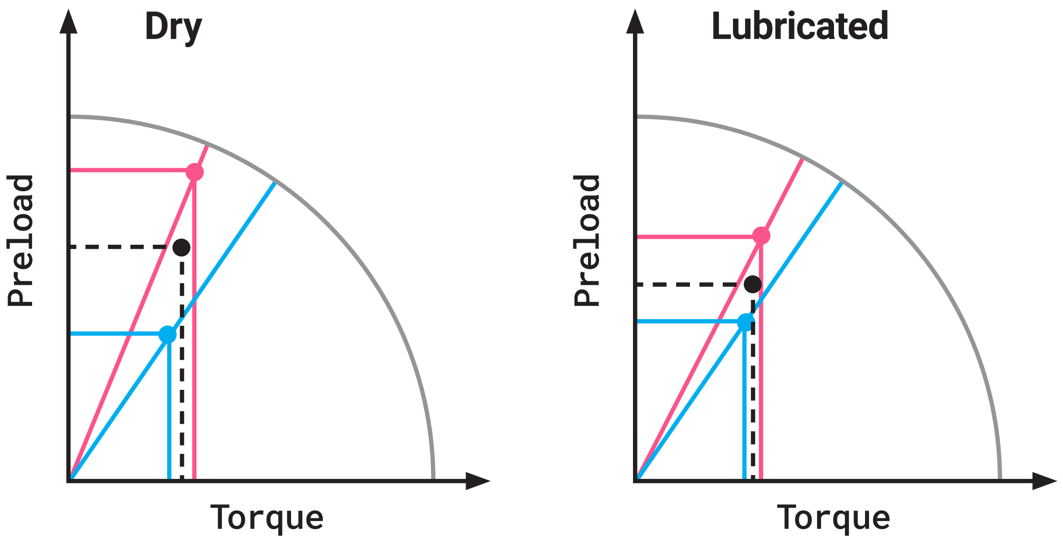
For applications such as tube connection flanges and housing closures, the safety resides in the ability to close the system homogeneously to prevent leakage. A torque tightening method is not the best candidate in this case as the build up of preload will be progressive along the sealing surface. The best method is to simultaneously preload the flange all around using a hydraulic tensioner, which can be mounted and activated on multiple joints. This tool acts directly on the elongation of the shaft, which increases accuracy as it removes the uncertainty of friction.

> The accessibility of the bolt may indicate which installation method to use.

In a very narrow space where high preload is required, a torqueing method may not be the most suitable. However, solutions such as electric guns or hydraulic tools could work effectively under these constraints.



Comparison of different tightening methods aiming for the same nominal torque.



Precision on final preload of dry and lubricated bolts when tightened with the same torque.

All tools mentioned previously must perform at their expected level in order to ensure the safety of the operation. They should be calibrated regularly to ensure their reliability and efficiency over time. Records of all actions related to critical connections allow for the traceability and detection of any eventual deviations. Correction plans and retrofitting can be deployed to avoid any failures in the field. Selecting a tightening method must be anticipated during the early phase of product development in order to ensure design and process compatibility as well as safety.

Bolt specification

Knowledge of the application and installation process must be considered with the correct bolt specification in order to create a complete picture of how to create a safe bolted connection. As discussed previously, friction can vary greatly and result in high preload deviation. Lubrication is a way to minimize friction and reduce this deviation. Reducing the friction determines the amount of torque to apply to achieve the same preload, making the process more efficient. It also reduces the stress induced by torsion and allows the use of more of the bolt capacity.

Another advantage of using lubrication is the low deviation, which improves the scatter in the preload. A lubricant can either be integrated in the coating of the bolt or can be applied externally. The use of a lubrication increases the precision and efficiency of bolted joint while lowering the risk of failure.

Further actions can be taken during the installation and use of the bolted joint to control the preload, such as incorporating tools or integrated solutions. The measurement of elongation using a controlling tool such as a micrometer provides a direct status. The design of the application and bolted joints can go ahead with this knowledge in mind. The precision of this tool depends on the particular instrument and on the amount of elongation measured. It should be kept in mind that this method is not suitable for short clamp length.

A more complex method such as ultrasonic measurement can also be precise, although this requires that the bolted joint be manufactured with the two ends of the bolt flat and parallel. As a direct measurement it is also not suitable for short clamp length.

Adding a device within the bolted joint, such as a load cell, is another solution. This solution is calibrated which means that the precision is high and not limited by design size. However, this requires extra space within the bolted joint and there is a risk that the device will be damaged by external forces when the application is in service.

The instrumentation of the bolt itself with strain gauges is another integrated solution that can be deployed. It is very accurate but requires the calibration of the bolted joint on a test bench, or must be calculated from the design phase. The bolt must be designed to fit the sensor as well as allow access to it. Small bolts can limit the feasibility of this installation.

Controlling the preload in a bolt ensures that it operates at a safe level, however, monitoring the preload over time using an integrated solution provides a real understanding of the behavior of the bolted joint. It also allows risks of failure to be identified as well as predicted.

CONCLUSION

This white paper has discussed the role of the bolted connection in today's industrial sector, common failures experienced by bolted joints and their consequences, and the best practices to consider when designing safe bolted connections. It is important to consider these various topics holistically in order to create a bolted connection that remains safe and efficient throughout its life cycle.

In this way, it should be noted that although the best practices outlined in this paper are usually solved individually, they may not be compatible with each other. For example, a thick coating may be applied to a bolt in order to achieve a high level of corrosion resistance but this could impact the friction of the bolt and degrade the efficiency and precision of the tightening process. It is rare that every parameter needed to achieve a safe bolted joint can be fully implemented, so a compromise needs to be made. This is a simple example, however, every solution discussed in this paper can influence another and choices should be made to fulfill each requirement in the best way without compromising safety.

Similarly, it is also important to take into account that the requirements necessary for a bolted joint to be considered safe can vary over its lifetime – from first assembly to maintenance and disassembly for recycling. It is not enough to ensure that it is safe during production and first service. Future activities should also be considered to ensure that the bolted joint is safe and efficient during each stage of its life cycle.

A bolted joint's external environment is also vital to consider. It is usually measured, estimated or hypothetically defined. However, unexpected situations may occur that can put the safety of the bolted connection into question. Experience and knowledge are important tools that should be used to define the correct design and approach to assembly in order to increase safety.

Products that secure bolted connections can be used to prevent unintentional loosening. They come in various forms and functionalities — some are applied to existing parts, such as locking fluids and others are added components in the assembly, such as Nord-Lock washers. In addition, many tools exist to manage the safety of a bolted joint and many more are still to come. It is important that industries are aware of these innovations in order to maintain the safety of their bolted connections. Development of industry 4.0 solutions, such as the constant monitoring of preload, are emerging. These solutions will provide industries with even more opportunities to ensure the safety and reliability of their bolted connections, however complex the application demands become.

BOLTING AND ENGINEERED SOLUTIONS

Safe Bolted Join Design is produced by Nord-Lock Group.

Nord-Lock Group specializes in bolting, design and engineering solutions. Our technologies include **Nord-Lock** wedge-locking washers that prevent bolt loosening, **Superbolt** multi-jackbolt tensioners (MJTs) that tighten large bolts safely and accurately, **Boltight** hydraulic tensioners that tighten and loosen multiple bolts simultaneously and **Expander System** pivot pins that prevent the formation of lug wear.

Along with our technologies, we provide services that focus on life cycle profitability, design and production, and training and installation support.

We hope the information provided in this white paper will help you increase the safety of your bolted connections. However, this document is only meant as a general guide. If you require more specific technical information about safe bolted joint design, please contact us at **bolting@nord-lock.com.**

Nord-Lock Group
Tel: +46 40 602 46 00
Email: info@nord-lock.com
www.nord-lock.com

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