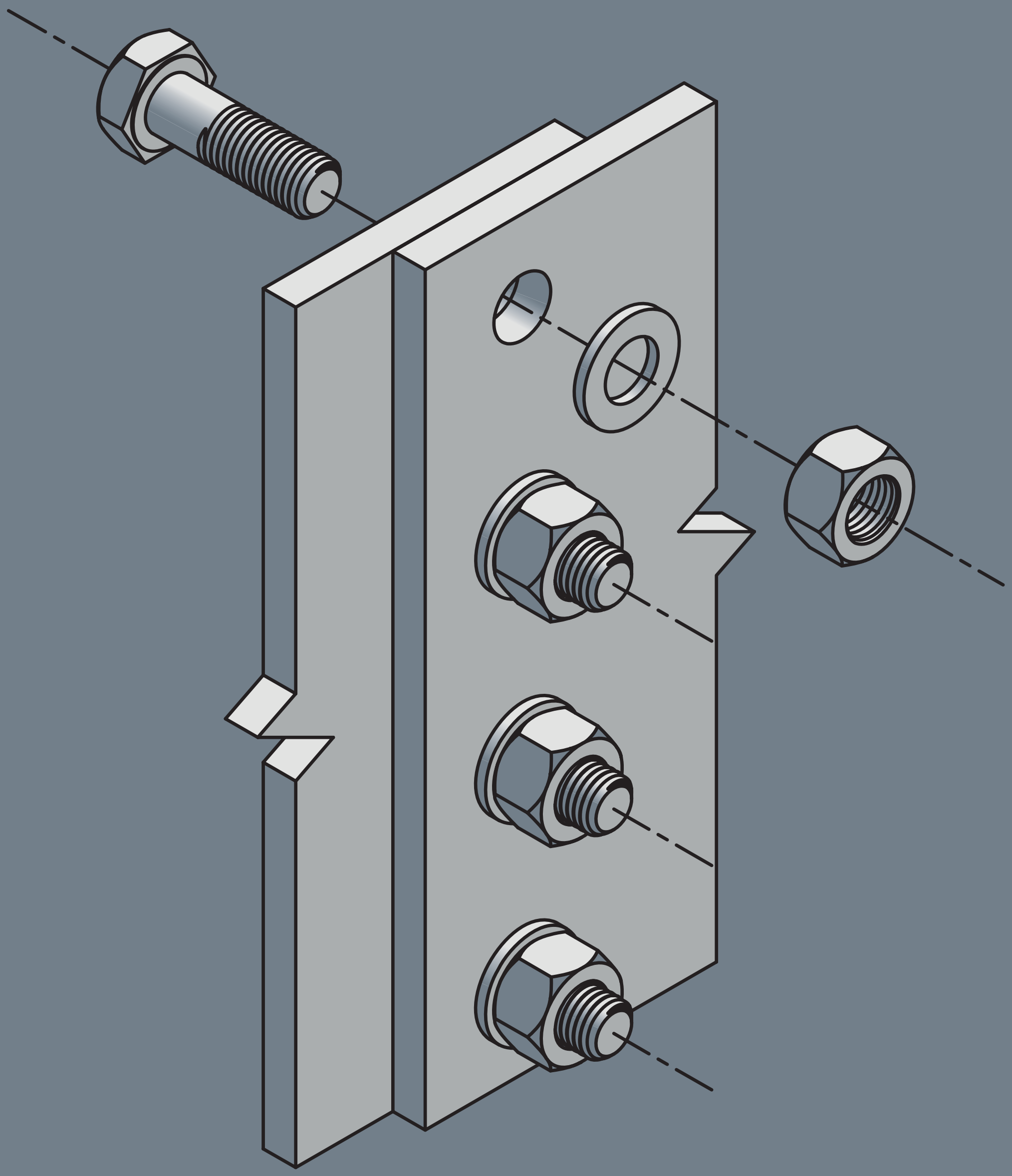


Design Guide 41

Structural Joints Using Stainless Steel Bolts

boltcouncil
RESEARCH COUNCIL ON STRUCTURAL CONNECTIONS
rcsc

AMERICAN INSTITUTE OF STEEL CONSTRUCTION
AISC
FOUNDED 1921

Smarter.
Stronger.
Steel.

Design Guide 41

Structural Joints Using Stainless Steel Bolts

Francisco Meza, PhD
Nancy Baddoo
Jason Provines, PE

American Institute of Steel Construction

Printed in the United States of America

Authors

Francisco Meza, PhD, is a Principal Engineer at the Steel Construction Institute (SCI). He obtained his PhD at the University of Sheffield in cold-formed steel built-up members and has worked on a number of projects developing design guidance and specifications for structural stainless steel, including the second-generation version of the stainless steel Eurocode, EN 1993-1-4. He has undertaken a key role in drafting ANSI/AISC 370-21, *Specification for Structural Stainless Steel Buildings,* and co-authored the second edition of AISC Design Guide 27, *Structural Stainless Steel*.

Nancy Baddoo is an Associate Director at SCI and Fellow of the Institution of Civil Engineers. She has worked on many research projects studying the structural performance of stainless steel, as well as being active in disseminating design guidance through publications and seminars. She chairs the European technical committee responsible for the stainless steel Eurocode, EN 1993-1-4, and wrote the first edition of AISC Design Guide 27, *Structural Stainless Steel*. She has played a key role in drafting ANSI/AISC 370-21, *Specification for Structural Stainless Steel Buildings,* and is an active member of the AISC Committee on Structural Stainless Steel, chairing the Connections Subcommittee. She was a co-author of the second edition of AISC Design Guide 27.

Jason Provines, PE, is a Senior Research Scientist at the Virginia Transportation Research Council (VTRC) conducting research for the Virginia Department of Transportation (VDOT), with a focus on implementing research into specifications and standard practice. While at VTRC, Jason's primary research focus has been on developing long-term durable solutions for steel bridges, including the use of stainless steel. Jason has led numerous research projects on stainless steel connections and has provided technical assistance to VDOT on multiple stainless steel bridges. He has implemented stainless steel welding specifications within VDOT and AASHTO/AWS D1.5, currently serves as the chair of the AASHTO/NSBA Task Group 18 on duplex stainless steel, and previously served as the Connections Subcommittee chair of the AISC Committee on Structural Stainless Steel.

Acknowledgments

The authors gratefully acknowledge the contribution of the following people in the preparation of this edition of the Design Guide:

Pete Ault (KTA-Tator, Inc.)
Professor Dr.-Ing. Natalie Stranghöner (Universität Duisburg-Essen, Germany)
Carmen Vertullo (Carver Fastening Applications Consulting Testing and Training Center)

The following Design Guide reviewers are also gratefully acknowledged:

Benjamin Baer
Richard Beldyk
Ted Bush
Michael Desch
Karl Frank
Andrew Gadzic
Richard Garvin
Nate Gonner
Mark Holland
Larry Kruth
Margaret Matthew
Jon McGormley
Ronnie Medlock
Michael Mulhern
Justin Ocel
Brad Porter
Chris Raebel
Gian Rassati
Tom Schlafly
Bob Shaw
Todd Ude

Preface

This AISC/RCSC Design Guide covers the design, fabrication, and installation of connections with stainless steel bolts, aligning with the main topics in the RCSC *Specification for Structural Joints Using High-Strength Bolts*. It covers commonly available austenitic and duplex stainless steel alloys. Precipitation-hardening stainless steel S17400 (17-4) is also included. The information in this Design Guide is relevant to bolted connections in building-type structures, as well as bridges, and to bolted connections between stainless steel members and dissimilar metal connections joining stainless steel to carbon steel members. It covers snug-tight, pretensioned, and slip-critical bolted connections. The guidance is based on existing design provisions and information in ANSI/AISC 370 and the Second Edition of AISC Design Guide 27, complemented by practical experience and advice from bolt manufacturers, designers, researchers, corrosion engineers, and metallurgists.

Three design examples demonstrate the application of the design guidance.

TABLE OF CONTENTS

Chapter 1
Introduction and General Requirements

1.1 INTRODUCTION

1.1.1 What Is Stainless Steel?

Stainless steel is the name given to a family of corrosion- and heat-resistant steels containing a minimum of 10.5% chromium and a maximum of 1.20% carbon. Just as there are various structural and engineering steels meeting different strength, weldability, and toughness requirements, there is also a wide range of stainless steels with varying levels of corrosion resistance and strength. This array of stainless steel properties is the result of controlled alloying element additions, each affecting specific mechanical properties and the ability to resist different corrosive environments. To achieve the optimal economic benefit, it is important to select a stainless steel that is adequate for the application without being unnecessarily highly alloyed and costly.

With the combination of a chromium content above 10.5%, a clean surface, and exposure to air or any other oxidizing environment, a transparent and tightly adherent chromium-rich oxide film forms spontaneously on the surface of stainless steel. If scratching or cutting damages the film, it reforms immediately in the presence of oxygen. Although the film is very thin, about 0.2×10^{-6} in., it is both stable and nonporous, and—as long as the type of stainless steel is corrosion resistant enough for the service environment—it will not react further with the atmosphere. For this reason, it is called a passive film. The stability of this passive film depends on the composition of the stainless steel, its surface treatment, and the corrosiveness of its environment. Its stability increases as the chromium content increases and is further enhanced by alloying additions of nickel, molybdenum, and nitrogen.

Stainless steel alloys are identified by the unified numbering system (UNS) designation in accordance with SAE J1086 (SAE, 2012) and ASTM E527 (ASTM, 2023)—for example, S30400. However, most bolting standards give alternative designations.

Austenitic Stainless Steels

The most widely used types of austenitic stainless steel contain 17–18% chromium and 8–11% nickel additions. Austenitic stainless steels, in addition to their corrosion resistance, have high ductility, are easily cold-formed, and are readily weldable. Relative to structural carbon steels, they also have significantly better toughness over a wide range of temperatures. They can be strengthened by cold working, but not by heat treatment. Their corrosion performance can be further enhanced by higher levels of chromium and additions of molybdenum and nitrogen. They are generally considered nonmagnetic but may become mildly magnetic when work hardened.

Ferritic Stainless Steels

The chromium content of the most popular ferritic stainless steels is between 10.5% and 18%. Ferritic stainless steels contain either no or very small amounts of nickel. They are generally less ductile, less formable, and less weldable than austenitic stainless steels. They can be strengthened by cold working, but to a more limited degree than the austenitic stainless steels. They cannot be strengthened by heat treatment. Because of their relatively low strength, they are not recommended for use in structural joints. They have good resistance to stress corrosion cracking (SCC), and their corrosion performance can be further enhanced by the addition of molybdenum. They are also among the most affordable stainless steel alloys.

Duplex Stainless Steels

Duplex stainless steels have a mixed microstructure of austenite and ferrite and are sometimes called austenitic-ferritic stainless steels. They typically contain 20–26% chromium, 1–8% nickel, up to 5% molybdenum, and 0.05–0.3% nitrogen. They provide higher strength levels than austenitic stainless steels and are suitable for a broad range of corrosive environments. Although duplex stainless steels have good ductility, their higher strength results in more restricted formability compared to austenitic stainless steels. They can also be strengthened by cold working, but not by heat treatment. They have good weldability and good resistance to SCC.

Martensitic Stainless Steels

Martensitic stainless steels can be strengthened by heat treatment and are generally used in a hardened and tempered condition, which gives them high strength and provides moderate corrosion resistance. They are used for applications that take advantage of their wear and abrasion resistance and hardness, like cutlery, surgical instruments, industrial knives, wear plates, and turbine blades. They are less ductile and more notch sensitive than the ferritic, austenitic, and duplex stainless steels.

Precipitation-Hardening Stainless Steels

Precipitation-hardening stainless steels (sometimes abbreviated as PH) can be strengthened by heat treatment to very high strengths and fall into three microstructure families depending on the type: martensitic, semi-austenitic, and austenitic. These stainless steels are not normally used in welded fabrication. Their corrosion resistance is generally better than the martensitic stainless steels and similar to the 18% chromium, 8% nickel austenitic types. Although they are mostly used in the aerospace industry, they are also used for tension bars, shafts, bolts, and other applications requiring high strength and moderate corrosion resistance. A wide range of mechanical properties are achievable through heat treatment.

The main reasons for using stainless steel are listed here:

Corrosion resistance and long life
Stainless steels are highly resistant to corrosion in most aggressive environments.

Aesthetics
Stainless steels can undergo a number of different surface treatments, including mirror-polishing, abrading with different grit sizes, roll texturing, and coloring.

Low maintenance costs
As stainless steel does not need painting or a protective coating, it is an obvious choice for components that are inaccessible, or that would be expensive or difficult to maintain.

Whole life cost
Experience has shown that the benefits of a long life with minimal maintenance and repair requirements more than compensate for the higher material cost of stainless steel.

Nonmagnetic properties
Austenitic stainless steels are generally nonmagnetic but may become slightly magnetic when cold-worked. Nonmagnetic stainless steels may be desired in defense installations or medical buildings where magnetic scanners are used.

Strength and ductility
Cold and warm working develop very high strengths with good ductility and toughness even after working.

Resistance to hydrogen embrittlement
Austenitic stainless steels can be considered immune to hydrogen embrittlement, while duplex stainless steels are highly resistant.

Good high- and low-temperature properties
Austenitic stainless steel retains high strength and good resistance to corrosion and oxidation at elevated temperatures. They also display excellent ductility and resistance to impact at very low temperatures.

Ease of removal
Sometimes fasteners need to be capable of being released without damaging their surrounding components; however, rust and other corrosion products may cause seizure and prevent fasteners from unscrewing. Providing the correct alloy of stainless steel has been chosen, corrosion will not occur, and the fastener can be removed without any difficulty if effective lubricants are used.

1.1.2 Applications of Stainless Steels in the Construction Industry

Stainless steel is the material of choice in applications situated in aggressive environments—for example, structures in proximity to salt water, exposed to deicing salts, or in very heavily polluted locations. They are commonly used in industrial structures for the water treatment, pulp and paper, nuclear, biomass, chemical, pharmaceutical, and food and beverage industries. The industrial structural applications include platforms, barriers, gates, and equipment supports. Stainless steel is also used for pedestrian and vehicular bridge components exposed to aggressive environments. Seawalls, piers, parking garages, and other structures exposed to high levels of coastal or deicing salts are increasingly making use of stainless steel structural components.

In aesthetic buildings and structure exteriors, stainless steel structural components are a popular choice for supporting cladding, roofs, canopy supports, security barriers, and other applications that take advantage of the material's corrosion resistance and strength to reduce maintenance requirements and improve safety. They are widely used for hand railings and street furniture for the same reasons.

In swimming pools, stainless steels are used both for architectural and structural applications such as pool liners, handrails, ladders, structural components, fasteners, furniture, diving structures, decorative items, and water treatment and ventilation systems. Special precautions should, however, be taken for structural components in swimming pools due to the risk of SCC in areas where condensates may form—see Section 2.7.1.

The good corrosion resistance of stainless steels makes them the ideal material for fasteners, anchoring systems, and support angles for wood and masonry. This is because wood and masonry can be inherently corrosive to other metals, and they are likely to absorb moisture and corrosive chemicals over time. Additionally, these types of components are often inaccessible or difficult to replace. Excellent corrosion resistance and good strength mean stainless steels are also suitable for applications in soil or stone, such as tunnel linings, security and other fencing, and retaining walls.

Stainless steel bolts should always be used when connecting stainless steel members. Figure 1-1 shows two examples of structural joints using stainless steel bolts.

1.1.3 Material Properties

The shape of the stress-strain curve of stainless steels differs from that of structural carbon steels—while carbon steel typically exhibits linear-elastic behavior up to the yield stress and a plateau before strain hardening is encountered, stainless steel has a more rounded response with no well-defined yield stress. Austenitic and duplex stainless steels also demonstrate significant strain hardening whereby strength levels are enhanced by cold work (such as that imparted during cold-forming operations). As strength increases with cold work, there is a reduction in ductility.

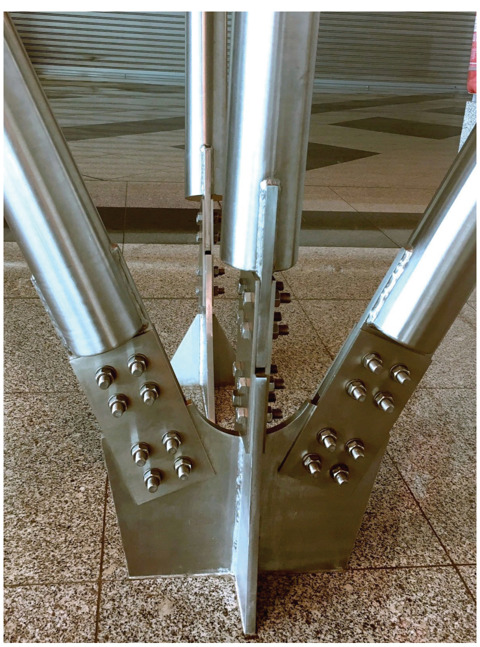
Although the yield plateau of structural carbon steel bolts is lost during manufacturing, stainless steel bolts still exhibit a more rounded stress-strain behavior than carbon steel bolts. This is illustrated in Figure 1-2, which shows typical experimental stress-strain curves for common austenitic ASTM A193/A193M Grade B8 Class 2 (ASTM, 2025a) and duplex ASTM A1082/A1082M S32205 (ASTM, 2021a) stainless steel bolts, as well as carbon steel bolts ASTM F3125/F3125M Grades A325 and A490 (ASTM, 2025c).

The thermal conductivities of stainless steels are about 30% of the thermal conductivity of carbon steel. Hence, using stainless steel bolts in lieu of carbon steel bolts at a thermal break connection will improve the effectiveness of the break.

The linear thermal expansion for austenitic stainless steels is approximately 30% higher than for carbon steels. In comparison, the thermal expansion of duplex and precipitation-hardening stainless steels is closer to that of carbon steels. Both duplex and precipitation-hardening stainless steels are magnetic. Austenitic stainless steels are essentially nonmagnetic, but heavy cold working, particularly of lean-alloyed austenitic stainless steels, can increase magnetic permeability.

1.1.4 Effect of Manufacturing Method on Bolt Properties

Stainless steel bolts can be produced by a number of techniques—for example, cold or hot deformation by drawing, extrusion, thread rolling or heading, as well as machining. Cut threading is a process that normally takes place in a lathe where steel is cut away from a round bar to form the threads. A rolled thread is produced by a forming tool that, when pressed into the surface of a blank, displaces material radially. Rolled threads are stronger than machined threads because of the strain hardening that occurs during rolling. The compressive stresses at the surface of rolled threads improve resistance to corrosion fatigue and, in some cases, SCC. Rolled threads are often smoother than cut threads. They also have greater resistance to thread galling—see



(a) Bracing for a stainless steel canopy at Porto Airport, Portugal

(b) Roof structure (photo courtesy of TriPyramid Structures, Inc.)

Fig. 1-1. Examples of structural joints using stainless steel bolts.

Section 2.4. Thread rolling is the most common method of producing bolts and screws, especially for large volume production of common sizes. For larger diameter bolts (≥1½ in.), and especially for the stronger duplex stainless steel bolts, threads are more likely to be cut.

High-strength carbon steel bolts are strengthened by hardening and tempering. They have relatively homogeneous strength and thus always fail at the least area under tension—that is, the threaded length. Methods of manufacturing stainless steel bolts can significantly increase the bolt strength and ductility, particularly at the head and in the threaded area. The final metallurgical condition of the component is therefore not as uniform as low-alloy or carbon steel bolts. The effect of the manufacturing process is illustrated in Figure 1-2, which shows that the strain-hardened austenitic (Grade B8 Class 2) stainless steel bolt has a slightly greater tensile strength but much less ductility than the duplex (S32205) stainless steel bolt, which is manufactured in the solution annealed condition. An austenitic bolt manufactured in the solution annealed condition would be expected to have a significantly lower tensile strength and greater ductility than the duplex stainless steel bolt.

1.2 SCOPE OF THIS DESIGN GUIDE

This Design Guide covers the design of bolted joints and the installation and inspection of bolting components and bolting assemblies made of austenitic, duplex, or precipitation-hardening stainless steel. Ferritic and martensitic bolting assemblies are outside the scope. The information in this Design Guide applies to bolted joints between stainless steel members and joints between stainless steel and carbon steel members.

The main topics in the Research Council on Structural Connections (RCSC) *Specification for Structural Joints Using High-Strength Bolts*, hereafter referred to as the RCSC *Specification* (RCSC, 2025), are covered with guidance on snug-tightened, pretensioned, and slip-critical bolted joints. The guidance is not applicable to anchor rods. Unlike carbon steel, corrosion resistance is a primary factor in the selection of a stainless steel bolt alloy, and guidance on this is given in Chapter 2. Availability is also a significant factor in the selection of a stainless steel bolt alloy, and Chapter 2 also gives guidance on this topic.

Only the turn-of-nut and combined methods of installation are included in this Design Guide. The calibrated wrench, twist-off tension control, and direct tension indicator (DTI) methods are outside the scope of this Design Guide. The calibrated wrench method is not included because it has been found to lead to a large variability in torque-to-tension relationship for similar bolts and conditions, which is also the reason this method has been eliminated from the 2025 edition of the RCSC *Specification*. Twist-off tension control bolts and DTIs are not currently produced in stainless steel and thus are not included.

The guidance herein is based on the following sources of information:

- ANSI/AISC 370-21, *Specification for Structural Stainless Steel Buildings* (AISC, 2021b), hereafter referred to as ANSI/AISC 370.

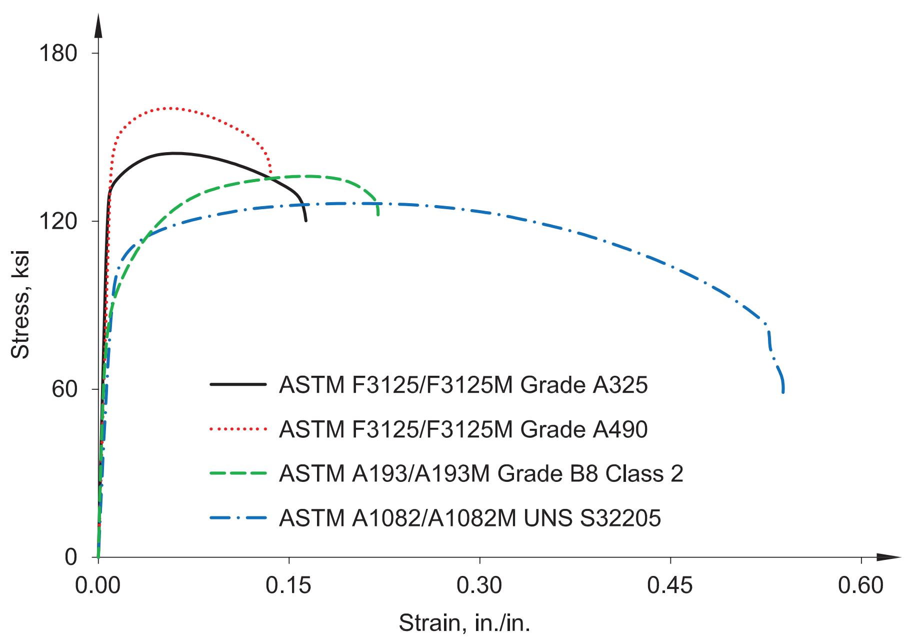


Fig. 1-2. Typical stress-strain curves for common stainless and carbon steel bolts.

- AISC 313-21, *Code of Standard Practice for Structural Stainless Steel Buildings* (AISC, 2021a).
- AISC Design Guide 27, *Structural Stainless Steel*, 2nd Ed. (Baddoo and Meza, 2022).
- *Specification for Structural Joints Using High-Strength Bolts* (RCSC, 2025).
- Practical experience from bolt manufacturers, designers, metallurgists, and corrosion engineers.

This Design Guide is written for bolted joints in primary and secondary structural components in building-type structures and in bridge structures.

1.3 DESIGN BASIS

1.3.1 Loads, Load Factors, and Load Combinations

Guidance on loads, load combinations, system limitations, and general design requirements is given in the applicable building code. In the absence of a building code, guidance is given in ASCE/SEI 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE, 2022).

The design and construction of the structure should conform to either an applicable load and resistance factor design (LRFD) specification for stainless steel structures or to an applicable allowable strength design (ASD) specification for stainless steel structures. Because factored load combinations account for the reduced probabilities of maximum loads acting concurrently, the design strengths given in this Design Guide should not be increased.

1.3.2 Design for Strength Using Load and Resistance Factor Design (LRFD)

Design according to the provisions for LRFD satisfies the requirements of this Design Guide when the design strength of each structural component or connection element equals or exceeds the required strength determined on the basis of the LRFD load combinations.

Design should be performed in accordance with Equation 1-1:

$$R_u < \phi R_n \tag{1-1}$$

where

R_n = nominal strength, kips

R_u = required strength using LRFD load combinations, kips

ϕ = resistance factor

ϕR_n = design strength, kips

1.3.3 Design for Strength Using Allowable Strength Design (ASD)

Design according to the provisions for ASD satisfies the requirements of this Design Guide when the design strength of each structural component or connection element equals or exceeds the required strength determined on the basis of the ASD load combinations.

Design should be performed in accordance with Equation 1-2:

$$R_a \leq \frac{R_n}{\Omega} \tag{1-2}$$

where

R_a = required strength using ASD load combinations, kips

Ω = safety factor

R_n/Ω = allowable strength, kips

1.4 STRUCTURAL DESIGN DOCUMENTS AND SPECIFICATIONS

The engineer of record (EOR) should specify the following information in the contract documents:

- The stainless steel alloy and condition to be used—see Chapter 2.
- The joint type—see Chapter 4.

For structural connections, the EOR should also specify the following in the contract documents:

- That all bolting assemblies meet the requirements of a structural bolting assembly as defined in Section 2.5.
- The required class of slip resistance and slip coefficient, if slip-critical joints are specified—see Chapter 4.

Additional information that the EOR may specify, may require the engineer's attention, or may require the engineer's approval is provided below:

- Bolting assembly alloy, condition, style (hex or heavy hex head), and any other considerations on special components or installation methods related to the bolting assembly—see Chapter 2.
- If threads need to be excluded from the shear plane—see Chapter 5.
- Use of faying surfaces in slip-critical joints other than grit blasted faying surfaces or faying surfaces that provide a mean slip coefficient determined in accordance with Appendix D, but differing from surface classes SSB, SSC, or SSD—see Section 3.2.
- Use of any materials other than stainless steel within the joint, if snug-tight joints for dissimilar metals are specified.

- Reuse of bolts—see Section 2.10.
- Use of oversized, short-slotted, or long-slotted holes in lieu of standard holes—see Section 3.3.
- Use of a value of D_u other than the value provided in Section 5.4.
- Restrictions on the use of hole types—see Section 3.3.
- Use of hole sizes larger than permitted in Section 3.3.

Chapter 2
Bolting Components, Assemblies, and Alloy Selection

The stainless steel bolts, nuts, and washers for use in structural joints designed with this Design Guide are given in Section 2.1. Other stainless steel or nonferrous alloys may be suitable for bolts in specific applications, but the evaluation of those alloys is the responsibility of the engineer specifying them.

Carbon steel bolts, including galvanized bolts, should not be used to connect stainless steel elements, even for short term use, because of the risk of the bolt being susceptible to galvanic corrosion. Appendix B discusses galvanic corrosion.

2.1 DESIGNATION OF STAINLESS STEEL BOLTING COMPONENTS

2.1.1 Bolts

Unlike carbon steel, stainless steel bolts are not organized into groups according to their tensile strength level. There are many different stainless steel alloys offering a wide range of corrosion resistance, and during manufacture, the material can undergo a range of treatments that modify the strength of the bolt. Therefore, a stainless steel bolt is defined according to both the alloy and condition.

There is no single ASTM standard that covers all the stainless steel bolts that may be used for structural bolted joints in typically encountered atmospheric environments. The following provides an overview of some commonly used ASTM standards that cover stainless steel bolts.

ASTM F593, Standard Specification for Stainless Steel Bolts, Hex Cap Screws, and Studs

ASTM F593 (ASTM, 2024g) covers austenitic and precipitation-hardening stainless steel bolts up to a 1½ in. diameter for applications requiring general corrosion resistance properties. ASTM F593 bolts can be produced by a number of techniques, for example, machining or cold forming—and in different conditions, for example, annealed (A, AF, or AH), cold-worked (CW), hardened (H or HT) or strain-hardened (SH). Austenitic stainless steel bolts in ASTM 593 in the cold-worked or strain-hardened condition need to be specified as a special order. For bolts in the SH condition, a strain-hardening operation is carried out prior to or during manufacturing to achieve an increase in strength and reduce the potential for galling—see Section 2.4. The inverse correlation between the strength and size of the cold-worked or strain-hardened bolts is due to the difficulty in achieving uniform work hardening through the cross section of a bolt. Heat treatment is necessary for precipitation-hardening stainless steel bolts to achieve their high strength, which is significantly higher than that of austenitic and duplex stainless steel bolts. The heat treatment condition specified for the precipitation-hardening alloy in ASTM F593 is equivalent to the H1150 heat treatment condition.

ASTM F593 classifies bolt alloys into different groups. Bolt alloys belonging to the same group are considered to be chemically equivalent for general purpose use: S30400 (304) bolts are classified as Alloy Group 1 and S31600 (316) are Alloy Group 2 bolts. Precipitation-hardening stainless alloy S17400 (630) is Group 7.

The chemical composition and mechanical properties of the austenitic stainless steel bolts specified to ASTM F593 meet similar requirements to those of the bolts specified to ASTM A193/A193M and ASTM A320/A320M (ASTM, 2024b). However, ASTM F593 bolts in the CW condition that have been hot worked have to be tested for susceptibility to intergranular corrosion, which can add to both the cost and lead time to produce the bolt. If heavy hex structural bolts in accordance with ASME B18.2.6 (ASME, 2019) are desired, they need to be explicitly specified in the purchase order, otherwise the manufacturer will provide hex cap screws.

ASTM A193/A193M, Standard Specification for Alloy-Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Applications

ASTM A193/A193M is the most common standard for specifying austenitic stainless steel bolts that are used in the oil and gas industry. It specifies bolts that can resist high temperatures or pressures, or other special-purpose applications, but it is also used to specify structural stainless steel bolts. This standard can be used for ordering stainless steel bolts in diameters larger than 1½ in.

Bolts specified to ASTM A193/A193M will, by default, be a heavy hex cap screw in accordance with ASME B18.2.1 (ASME, 2021), unless a different bolt type is specified in the purchase order. These are not the same dimensionally as heavy hex structural bolts in accordance with ASME B18.2.6 but will function the same in structural applications. ASTM A193/A193M covers a wide range of austenitic stainless steel bolts, but the most commonly available are the austenitic stainless steel bolts B8 (S30400) and B8M (S31600).

These bolts may be specified in a Class 1 or Class 2 condition. Class 1 bolts are carbide solution treated (also known as solution annealed), whereby the bolt (or bar before the threading and bolt heading operations are carried out) is heated and then water-quenched to ensure maximum corrosion resistance. For Class 2 bolts, a strain-hardening operation is carried out prior to or during manufacturing to achieve an increase in strength and reduce the potential for galling—see Section 2.4.

ASTM A320/A320M, Standard Specification for Alloy-Steel and Stainless Steel Bolting for Low Temperature Service

ASTM A320/A320M is the standard for stainless steel bolts for applications at low temperatures, but it can also be used to specify structural stainless steel bolts. This ASTM standard covers bolts made of the same austenitic stainless steel alloys as those in ASTM A193/A193M and subject to the same heat treatment conditions. The chemical composition and mechanical properties requirements in ASTM A320/A320M are also identical to those in ASTM A193/A193M. However, ASTM A320/A320M also requires the bolt to have defined impact properties at low temperatures—although for austenitic stainless steel bolts at service temperatures above −325°F (−200°C), impact tests are not required—making the requirements almost identical to those in ASTM A193/A193M. If heavy hex structural bolts in accordance with ASME B18.2.6 are desired, this should be specified in the purchase order.

ASTM A1082/1082M, Standard Specification for High Strength Precipitation Hardening and Duplex Stainless Steel Bolting for Special Purpose Applications

ASTM A1082/A1082M covers duplex and precipitation-hardening stainless steel bolts. There are no limits on the maximum diameter for the duplex stainless steel bolts covered in ASTM A1082/A1082M. However, ASTM A1082/A1082M only covers duplex stainless steel bolts in the solution-annealed condition. The most widely available duplex stainless steel bolt in ASTM A1082/A1082M is S32205 (2205). This ASTM standard also covers the super duplex alloys S32750 and S32760, which offer higher corrosion resistance.

Work is under way to develop a new ASTM standard that covers strain-hardened duplex stainless steel bolts. Until this new ASTM standard is available, strain-hardened duplex stainless steel bolts may be specified to ISO 3506-1 (ISO, 2020a). It covers duplex stainless steel bolts in three property (i.e., strength) classes, depending on the level of strain hardening: F_{ub} = 102 ksi for property class 70, F_{ub} = 116 ksi for property class 80, and F_{ub} = 145 ksi for property class 100, where F_{ub} is the specified minimum tensile strength of the bolt.

From all the precipitation-hardening stainless steel bolts covered in ASTM A1082/A1082M, this Design Guide only recommends the use of S17400 (630) bolts in the H1150 heat treatment condition. ASTM A1082/A1082M covers other heat treatment options and precipitation-hardening alloys that can offer higher strengths. However, these options are discouraged due to their known risk of hydrogen embrittlement. Bolts in the H1150 heat treatment condition have the greatest ductility and least susceptibility to hydrogen embrittlement and SCC. The maximum diameter of the precipitation-hardening bolt S17400 (630) in ASTM A1082/A1082M is 8 in. This bolt alloy can also be specified in accordance with ASTM F593, which imposes almost identical requirements in terms of the chemical composition and mechanical properties of the bolt, but a slightly different heat treatment.

This Design Guide classifies stainless steel bolts into two categories: high-strength and non-high-strength. High-strength stainless steel bolts should have a diameter from ½ to 1½ in. Table 2-1 lists some common high-strength stainless steel bolts, giving the stainless steel family, ASTM standard, condition, alloy, and yield and tensile strengths based on bolt diameter. Other austenitic and duplex stainless steel bolts in accordance with the ASTM standards and the conditions listed in Table 2-1 can also be classified as high-strength stainless steel bolts. Austenitic and duplex stainless steel bolts in accordance with ISO 3506-1 in property classes 80 and 100 can also be regarded as high-strength stainless steel bolts.

The high-strength stainless steel bolts listed in Table 2-1 are likely to be sufficient for most applications. However, there may be specific applications, such as those in particularly corrosive environments, in which other high-strength stainless steel bolt alloys may need to be considered.

Any stainless steel bolt that does not meet the requirements for a high-strength stainless steel bolt is considered a non-high-strength stainless steel bolt. Table 2-2 provides common non-high-strength stainless steel bolts, including their stainless steel family, ASTM standard, condition, alloy, and yield and tensile strengths based on bolt diameter.

Stainless steel bolts are required by ASTM standards to be distinctively marked as shown in Table 2-3. For ASTM F593 bolts in Condition SH and ASTM A193/A193M bolts in Class 2, the designation should be underlined. In addition to mandatory marks, the manufacturer may also apply additional distinguishing marks.

2.1.2 Nuts

The type of nut should match the bolt in terms of corrosion resistance, mechanical properties, and thread geometry. For corrosion resistance, this is most easily achieved by specifying the same alloy designation (i.e., UNS number) for the nut as was used for the bolt. Matching the mechanical properties can be achieved by specifying a compatible ASTM standard for the nut when compared to the bolt. Table 2-4 lists the ASTM standards, alloy, and condition for matching stainless steel bolts and nuts. Stainless steel nuts should be distinctively marked in accordance with the requirements

Table 2-1. Common High-Strength Stainless Steel Bolts

Family	ASTM	Alloy	Condition[a]	Diameter, d_b, in.	F_{yb}, ksi	F_{ub},[b] ksi
Austenitic	ASTM F593	Alloy Group 1 (S30400)[c] or Alloy Group 2 (S31600)[d]	SH1	$½ \le d_b \le ⅝$	95	120
			SH2	$¾ \le d_b \le 1$	75	110
			SH3	$1⅛ \le d_b \le 1¼$	60	100
			SH4	$1⅜ \le d_b \le 1½$	45	95
	ASTM A193/A193M and ASTM A320/A320M	B8 (S30400)[e]	Class 2	$d_b \le ¾$	100	125
				$¾ < d_b \le 1$	80	115
				$1 < d_b \le 1¼$	65	105
				$1¼ < d_b \le 1½$	50	100
		B8M (S31600)[e]	Class 2	$d_b \le ¾$	95	110
				$¾ < d_b \le 1$	80	100
				$1 < d_b \le 1¼$	65	95
				$1¼ < d_b \le 1½$	50	90
Duplex	ASTM A1082/A1082M	S32205 (2205)[e]	—	$½ \le d_b \le 1½$	65	95
Precipitation hardening	ASTM A1082/A1082M	S17400 (630)[e]	H1150	$½ \le d_b \le 1½$	105	135
	ASTM F593	Group 7 S17400 (630)[e]	AH	$½ \le d_b \le 1½$	105	135

F_{ub} = specified minimum tensile strength of the bolt, ksi
F_{yb} = specified minimum yield stress of the bolt, ksi

[a] Condition:
SH: machined from strain-hardened stock or cold-worked to develop the specific properties.
AH: age hardened
Class 2: solution treated and strain hardened. Austenitic stainless steels in the strain-hardened condition may not show uniform properties throughout the section particularly in sizes over ¾ in. diameter.
[b] Some ASTM standards provide minimum and maximum F_{ub} values. Only minimum values are shown here.
[c] Alloy Group 1 includes alloys 303, 304, 304L, 305, 384, XM1, 18-9LW, 302HQ, 304J3, and 303SE. The specific alloy must be specified on the purchase order.
[d] Alloy Group 2 includes alloys 316 and 316L. The specific alloy must be specified on the purchase order.
[e] The alloy designation used in the ASTM standard is given first, followed by the UNS designation in parentheses.
— There is no applicable condition.

of ASTM F594 (ASTM, 2024h), ASTM A194/A194M (ASTM, 2024c), or ASTM A1082/A1082M.

Matching nuts to bolts in accordance with ISO 3506-1 should be specified to ISO 3506-2 (ISO, 2020b).

2.1.3 Washers

There are currently no ASTM standards specifically for stainless steel washers. Therefore, stainless steel washers need to be specified by their alloy designation, mechanical properties, and dimensional requirements—see Section 2.2.

The chemical composition of stainless steel washers should be specified to produce equivalent corrosion resistance to the bolt and nut of the bolting assembly. This is most easily achieved by specifying that the alloy designation of the washer matches the alloy designation of the bolt. When using austenitic or duplex stainless steel bolts, the alloy designation of the washers can be specified by referencing ASTM A240/A240M (ASTM, 2025b) with the matching UNS number of the bolt. When using precipitation-hardening stainless steel bolts, the alloy designation of the washer can be specified by referencing ASTM A693 (ASTM, 2024f) with the matching UNS number of the bolt. Table 2-5 provides the ASTM standard to be referenced for specifying the alloy designation of the washer for common high-strength stainless steel bolts.

Alternatively, ISO 3506-7 (ISO, 2024) can be used to specify austenitic and duplex stainless steel washers.

Stainless steel washers should have sufficient hardness to resist deformation and galling during the installation of the bolting assembly, which is especially important for pretensioned or slip-critical joints with high-strength stainless steel bolts. This can be achieved by specifying that the stainless steel washers have greater hardness than the maximum

Table 2-2. Common Non-High-Strength Stainless Steel Bolts

Family	ASTM	Alloy	Condition[a]	Diameter, d_b, in.	F_{yb}, ksi	F_{ub},[b] ksi
Austenitic	ASTM F593	Alloy Group 1 (S30400)[c] or Alloy Group 2 (S31600)[d]	CW1	$1/4 \le d_b \le 5/8$	65	100
			CW2	$3/4 \le d_b \le 1\frac{1}{2}$	45	85
	ASTM A193/A193M and ASTM A320/A320M	B8[e] (S30400)	Class 1	all diameters	30	75
		B8M[e] (S31600)	Class 1	all diameters	30	75

F_{ub} = specified minimum tensile strength of the bolt, ksi
F_{yb} = specified minimum yield stress of the bolt, ksi

[a] Condition:
CW: headed and rolled from annealed stock thus acquiring a degree of cold work. Sizes ¾ in. and larger may be hot-worked and solution annealed.
Class 1: solution treated.
[b] Some ASTM standards provide minimum and maximum F_{ub} values. Only minimum values are shown here.
[c] Alloy Group 1 includes alloys 303, 304, 304L, 305, 384, XM1, 18-9LW, 302HQ, 304J3, and 303SE. The specific alloy must be specified on the purchase order.
[d] Alloy Group 2 includes alloys 316 and 316L. The specific alloy must be specified on the purchase order.
[e] The alloy designation used in the ASTM standard is given first, followed by the UNS designation in parentheses.

Table 2-3. Marking for Common Stainless Steel Bolts for Structural Applications

Family	ASTM	Alloy	Condition	Marking
Austenitic	ASTM F593	Alloy Group 1 (S30400)	CW1	F593C
			CW2	F593D
			SH1	F593A
			SH2	F593B
			SH3	F593C
			SH4	F593D
		Alloy Group 2 (S31600)	CW1	F593G
			CW2	F593H
			SH1	F593E
			SH2	F593F
			SH3	F593G
			SH4	F593H
	ASTM A193/A193M and ASTM A320/A320M	B8 (S30400)	Class 1	B8
			Class 2	B8SH
		B8M (S31600)	Class 1	B8M
			Class 2	B8MSH
Duplex	ASTM A1082/A1082M	S32205 (2205)	—	32205
Precipitation hardening	ASTM A1082/A1082M	S17400 (630)	AH (H1150)	174G
	ASTM F593	Alloy Group 7 S17400 (630)	AH	F593U

— There is no applicable condition.

Table 2-4. Matching Bolt and Nuts		
Family	**Component**	**Specification**
Austenitic	Bolt	ASTM F593 Group 1 S30400 Condition SH
	Nut	ASTM F594 Group 1 S30400 Condition SH[a]
	Bolt	ASTM F593 Group 2 S31600 Condition SH
	Nut	ASTM F594 Group 2 S31600 Condition SH[a]
	Bolt	ASTM A193/A193M B8 Class 2
	Nut	ASTM A194/A194M 8, Strain hardened[b]
	Bolt	ASTM A193/A193M B8M Class 2
	Nut	ASTM A194/A194M 8M, Strain hardened[b]
	Bolt	ASTM A320/A320M B8 Class 2
	Nut	ASTM A194/A194M 8, Strain hardened[b]
	Bolt	ASTM A320/A320M B8M Class 2
	Nut	ASTM A194/A194M 8M, Strain hardened[b]
Duplex	Bolt and nut	ASTM A1082/A1082M S32205
Precipitation hardening	Bolt and nut	ASTM A1082/A1082M S17400 (630) Condition H1150
	Bolt	ASTM F593 Group 7 S17400 (630) Condition AH
	Nut	ASTM F594 Group 7 S17400 (630) Condition AH

[a] Nuts are supplied in the CW condition unless the optional SH condition is specified.
[b] Supplementary Requirement 1 should be specified for strain hardened nuts.

Table 2-5. Washer Alloy Designation Standards and Recommended Hardness for Use with Common High-Strength Stainless Steel Bolts			
Family	**Bolt Specification**	**ASTM Standard to Be Referenced for Washer Alloy Designation**	**Minimum Washer Hardness, HRC**
Austenitic	ASTM F593 Group 1 S30400 Condition SH	ASTM A240/A240M S30400	40
	ASTM A193/A193M Grade B8 Class 2		
	ASTM A320/A320M Grade B8 Class 2		
	ASTM F593 Group 2 S31600 Condition SH	ASTM A240/A240M S31600	40
	ASTM A193/A193M Grade B8M Class 2		
	ASTM A320/A320M Grade B8M Class 2		
Duplex	ASTM A1082/A1082M S32205	ASTM A240/A240M S32205	30
Precipitation hardening	ASTM A1082/A1082M S17400 (630) Condition H1150	ASTM A693 S17400	40
	ASTM F593 Group 7 S17400 (630) Condition AH		40

specified hardness of the stainless steel nuts and bolts used in the assembly. Recommended washer hardness for common high-strength stainless steel bolts are provided in Table 2-5. The recommended washer hardness values in this table are at least 2 HRC (Rockwell hardness, scale C) greater than the maximum hardness specified in each respective bolt specification and have been rounded up for simplification.

It is recommended that stainless steel washers are distinctively marked with the stainless steel alloy (e.g., 304 or S30400).

An ASTM standard for hardened stainless steel flat washers is under development at the time of publication. It is

Table 2-6. Dimensional Requirements for Bolting Components	
Bolting Component	**Dimensional Standard**
Heavy hex structural bolt	ASME B18.2.6
Hex bolt, heavy hex bolt, hex cap screws and heavy hex cap screws, square bolt, heavy square bolt	ASME B18.2.1
Countersunk bolt	ASME B18.5
Heavy hex nut	ASME B18.2.6
Hex nut, heavy hex nut, square nut, heavy square nut	ASME B18.2.2
Washer	ASTM F436/436M Section 7 for hardened circular washers

anticipated that this standard will contain similar chemical composition, mechanical properties, and dimensional requirements to those contained in this Design Guide.

2.2 GEOMETRY OF BOLTING COMPONENTS AND ASSEMBLIES

Stainless steel bolting components and assemblies should meet the dimensional requirements given in the standards listed in Table 2-6.

High-strength stainless steel bolts should have a diameter from ½ to 1½ in. and meet the dimensional requirements for heavy hex structural bolts given in ASME B18.2.6 or heavy hex cap screws given in ASME B18.2.1. Non-high-strength stainless steel bolts should meet the dimensional requirements for hex bolts, heavy hex bolts, hex cap screws, square bolts, or heavy square bolts given in ASME B18.2.1, or countersunk bolts given in ASME B18.5 (ASME, 2023).

For all bolts, the length used should be such that when installed sufficient thread engagement is achieved (as defined in the Glossary).

Nuts used with high-strength stainless steel bolts should meet the dimensional requirements for heavy hex nuts given in ASME B18.2.6. Nuts used with non-high-strength stainless steel bolts should meet the dimensional requirements for hex nuts, heavy hex nuts, square nuts, or heavy square nuts given in ASME B18.2.2 (ASME, 2022). Other nut styles, such as flange nuts or lock nuts, may also be used for non-high-strength stainless steel bolting assemblies if specified by the EOR.

The dimensional requirements for heavy hex bolts in accordance with ASME B18.2.1 are very similar to those for heavy hex structural bolts in ASME B18.2.6, while for heavy hex nuts the dimensional requirements in ASME B18.2.2 are identical to those in ASME B18.2.6. However, the range of diameters covered in ASME B18.2.1 and ASME B18.2.2 exceed 1½ in., which is the largest diameter covered in ASME B18.2.6 and the maximum diameter allowed for a high-strength stainless steel bolt in this Design Guide.

ASME B18.2.1 also covers hex cap screws and heavy hex cap screws. The dimensions of the hex cap screws and heavy hex cap screws in ASME B18.2.1 are similar to those of hex bolts and heavy hex bolts. However, their dimensional tolerances are more stringent.

The threads of all stainless steel bolts and nuts should be cut or rolled in accordance with the unified coarse (UNC) or 8 thread series specified in ASME B1.1 (ASME, 2024). The thread tolerances should satisfy the Class 2A and Class 2B for the bolt and nut, respectively.

Washers used with either high-strength or non-high-strength stainless steel bolts should meet the dimensional requirements given in ASTM F436/436M (ASTM, 2024e).

2.3 LUBRICATION

Effective stainless steel bolting lubricants should minimize torque during tensioning of the bolting assembly. Minimizing torque reduces torsional stresses in the bolt shank while maximizing bolt tension. Maximizing the bolt tension during installation is critical for pretensioned or slip-critical joints to develop the necessary clamping force in the bolts. Bolting assemblies with ineffective lubricants can experience an increase in the torsional stress in the bolt, which reduces the bolt's tensile capacity and ductility. Effective lubrication is especially important for stainless steel bolting assemblies to prevent galling—see Section 2.4—and to provide consistent levels of friction between the bolt and nut threads.

For stainless steel bolting assemblies to be used in snug-tightened joints, a lubrication designed for stainless steel threaded parts should be applied in a light, uniform layer to the turning face of the stainless steel nut and to the threads of either the stainless steel bolt or nut before installation. This Design Guide recommends applying the lubrication to the turning face and the internal threads of the nut (rather than to the turning face of the nut and the threads of the bolt) because it allows all lubrication to be applied to a single component. If it is necessary to rotate the bolt head during installation, the lubrication should be applied to the bolt thread and the bottom of the bolt head.

For stainless steel bolting assemblies to be used in pretensioned or slip-critical joints, the effectiveness of lubrication in combination with the bolting assembly should be evaluated according to the rotational capacity test procedure given in Appendix C. As described in that test procedure, the lubrication is, by definition, part of the bolting assembly. Therefore, the specific type, application method, and placement location of the lubrication used during the rotational capacity testing should be adopted during pre-installation verification testing and production installation. If the nut cannot be accessed during installation and the bolting assembly has to be tightened by turning the bolt, the lubrication should be applied to the bolt thread and the bottom of the bolt head, following, as far as possible, the procedure used during rotational capacity testing.

As also stated in the rotational capacity test procedure, the choice of type, application method, and placement location of the lubrication is the decision of the supplier of the stainless steel bolting assembly or responsible party, provided the bolting assembly meets the testing requirements.

Stainless steel bolts and nuts are generally sold without pre-applied lubrication; however, some suppliers do provide them with pre-applied lubrication. Purchasers can inquire from suppliers of stainless steel bolting assemblies as to whether or not they provide pre-lubricated bolting assemblies. Lubrication applied by the supplier is preferred because it is more likely to be applied in a consistent manner that would produce successful rotational capacity tests. However, contractors can apply lubrication to stainless steel bolting assemblies in the field prior to installation if these have been purchased without lubrication. If lubrication is applied in the field, it should be applied shortly before or at the time of installation.

Not all types of lubrication are effective for all types of stainless steel bolting assemblies, even if the lubrication is marketed for use with stainless steel threaded parts. Lubricants containing molybdenum disulfide and polytetrafluoroethylene (PTFE) generally provide successful installation performance and prevention of galling. Wax or other lubricants containing silver or copper powders, mica, graphite, or talc may also provide successful installation performance and prevent galling.

Heavy hex head bolting components for snug-tightened joints that accumulate debris or dirt should not be incorporated into the work unless they are cleaned and lubricated, as necessary. Bolting components and bolting assemblies intended for pretensioned or slip-critical joints that accumulate debris or dirt should not be incorporated into the work unless they are cleaned and lubricated, as necessary, and then retested as specified in Chapter 7.

2.4 GALLING

Galling is the displacement of material between mating threads during tightening that causes interface contact points to shear, producing high friction, increased resistance to tightening, or seizing of the threads, as shown in Figure 2-1. Galling is more likely to occur in stainless steel bolting assemblies than in other steel alloy bolting assemblies due to the presence of the passive film. If galling occurs during installation of a bolting assembly, it will increase the bolt torque causing premature failure of the bolt. Severe galling, which is essentially “cold welding,” can cause the two surfaces to fuse together, which makes the joint impossible to disassemble without cutting the bolt or splitting the nut. Pretensioned bolting assemblies are especially prone to galling.

Galling should be considered in the design of all types of bolted joints, and especially if disassembly is a performance requirement.

Galling can be minimized by taking the following measures:

- Use high-strength stainless steel bolts, as defined in Section 2.1.1, with corresponding nuts and washers, as defined in Sections 2.1.2 and 2.1.3, respectively. Hardened washers are less susceptible to galling than softer washers.
- Lubricate the bolting assembly according to Section 2.3. Make sure that all threads are undamaged with no burrs.

Fig. 2-1. A bolt and nut that have suffered from galling.

- Keep the bolted interface clean and free of grit and abrasive materials.

2.5 STAINLESS STEEL BOLTING ASSEMBLIES

This Design Guide classifies stainless steel bolting assemblies into two categories: structural and nonstructural. Structural bolting assemblies are comprised of:

- A high-strength stainless steel bolt as defined in Section 2.1.1, meeting the dimensional requirements of a heavy hex structural bolt or a heavy hex cap screw in Table 2-6.
- A heavy hex stainless steel nut as defined in Section 2.1.2, meeting the dimensional requirements of a heavy hex nut in Table 2-6.
- A washer meeting the chemistry and hardness requirements of Section 2.1.3, meeting the dimensional requirements in Table 2-6.
- Test reports showing that the bolt, nut, washer, and lubrication combination have successfully passed the rotational capacity test requirements described in Appendix C. This testing should be completed and certified by the manufacturer or supplier of the bolting assembly or by another responsible party.

Nonstructural bolting assemblies are defined as those that do not meet the requirements of a structural bolting assembly.

Examples of how to specify stainless steel bolting assemblies are shown in Appendix A.

2.6 AVAILABILITY OF STAINLESS STEEL BOLTING COMPONENTS

The most commonly available stainless steel bolts from general service centers are ASTM F593 condition CW and ASTM A193/A193M and ASTM A320/A320M Class 1. Bolts and nuts in accordance with the other ASTM standards specified in Sections 2.1.1 and 2.1.2 are available from specialist manufacturers and service centers that focus on supplying the oil and gas and process industries.

With regard to alloys, austenitic stainless steel S30400 and S31600 bolts are the most common. In duplex stainless steel, the most common alloy is S32205, and for precipitation hardening, it is S17400.

The availability of bolts, washers, and nuts made from other specific alloys may be limited and should be confirmed prior to specification. Some manufacturers regularly make short runs of specialized products and higher alloyed fasteners as needed, but it may be more expedient and cost effective to use off-the-shelf higher alloyed or larger fasteners. When the manufacture of specialized higher alloyed bolting assemblies is necessary, it can often be arranged by the service center supplying the other components.

Twist-off tension control bolts and DTIs are not currently produced in stainless steel.

2.7 DESIGN FOR CORROSION CONTROL AND ALLOY SELECTION

Stainless steels are generally very corrosion resistant and achieve satisfactory performance in most environments. The limit of corrosion resistance for a given stainless steel is predominantly dependent on its alloying elements, which means that each type has a slightly different response when exposed to a corrosive environment. Care is therefore needed to select the most appropriate stainless steel for a given application. Generally, higher levels of corrosion resistance increase the cost of the material. For example, Type S31600 stainless steel costs more than Type S30400 because of the addition of molybdenum. Duplex stainless steels can potentially offer increased corrosion resistance with less of a price premium. Austenitic material in the cold-worked condition has a similar corrosion resistance to that in the annealed condition.

Even when surface staining or corrosion occur, it is unlikely that structural integrity will be compromised. However, the user may still regard unsightly rust staining on external surfaces as an aesthetic failure. In aggressive industrial and marine environments, tests have shown no indication of reduction in component strength even where a small amount of weight loss occurred. In very corrosive environments, the specific environmental conditions and loads should be considered, and the advice of a stainless steel corrosion specialist should be obtained.

In addition to careful material selection, good detailing and workmanship can significantly reduce the likelihood of staining and corrosion. Experience indicates that any serious corrosion problem is most likely to show up in the first two or three years of service. In certain aggressive environments, some stainless steels are susceptible to localized attack; these are described in Section 2.7.1.

2.7.1 Type of Corrosion Affecting Stainless Steel Bolting Components

Reference should be made to the ANSI/AISC 370 Commentary and AISC Design Guide 27 for information on the types of localized corrosion which may affect stainless steel.

Corrosion can initiate when environmental conditions are too corrosive for the particular stainless steel specified. This could include exposure to corrosive chemicals, fumes, particulates, and chlorides (e.g., chloramines, hydrochloric acid, food additives, coastal and deicing salts, or water processing) in applications like industrial plants, building exteriors, swimming pools, and infrastructure.

Joints are particularly susceptible to corrosion due to the crevices that form between the different bolting components, such as under the bolt head and between the tightly connected elements. Under these circumstances, crevice corrosion may occur as a result of the infiltration of moisture (e.g., rainwater, humidity, fog, or condensation) and corrosive substances (e.g., chloride salts) into the crevice, and the lack of the oxygen needed for the stainless steel surface to maintain its passive film. Crevice corrosion is more likely with lower-alloy stainless steels, particularly where the crevice gap is very small, such as under a fastener head.

Correct design of the joint can reduce the potential for crevice corrosion. The bolt should be sufficiently tightened to prevent moisture from infiltrating between the bolt hole and the bolt. In joints with oversize or slotted holes, a washer should be used to completely cover the hole after installation of the bolt—see Chapter 6.

The design of nonimmersed bolted connections is very different from the design for applications that have fluid ponding or immersion on a continuous or regular basis. Where possible, designers should avoid situating bolted joints in immersed conditions and bolted joints should be designed to minimize moisture exposure and retention—that is, water-shedding. This can be achieved by moving joints away from ponding locations, improving ventilation and drainage of cavities, or ensuring that the ambient temperature within the structure lies above the dew point temperature.

Bolted joints may be subjected to pitting corrosion, which occurs as a result of local breakdown of the passive film on the surface of the stainless steel—normally by chloride ions—although other halides and anions can have a similar effect. If the attack is mild, the pits may not detract from the general appearance or function. In the most severe cases, the number and depth of the pits can increase to give an extensively corroded appearance. The suitability of stainless steel for a specific environment and the structure's requirements will determine the cleaning frequency needed to avoid pitting damage. In addition to chloride content, the probability of a service environment causing pitting depends on factors such as the temperature, corrosive pollutants and particulates, acidity or alkalinity, the content of oxidizing agents, and the presence or absence of oxygen.

The pitting resistance equivalent number (PREN) has been developed for each alloy family to estimate the pitting resistance of a particular alloy based on its chemical composition. An alloy's PREN value is determined using Equation 2-1 or 2-2, where %Cr, %Mo, and %N are the percentage of chromium, molybdenum, and nitrogen, respectively.

For austenitic stainless steels:

$$\text{PREN} = \%\text{Cr} + 3.3(\%\text{Mo}) + 30(\%\text{N}) \tag{2-1}$$

For duplex and precipitation-hardening stainless steels:

$$\text{PREN} = \%\text{Cr} + 3.3(\%\text{Mo}) + 16(\%\text{N}) \tag{2-2}$$

These are relative rankings, and the values do not address factors like improper heat treatment or surface contamination. The PREN of a stainless steel is a useful guide to its corrosion resistance relative to other stainless steels but should only be used as a first rough indicator. Small differences in PREN can easily be overshadowed by other factors that also influence corrosion pitting resistance. Therefore, the PREN should not be the only factor in selection.

While their high strength draws interest, the precipitation-hardening stainless steels have the lowest pitting corrosion resistance and PREN values of the alloys in this Design Guide. If they are used for a critical fastener application in combination with any of the other stainless steels in a service environment that is too corrosive for them, they become the weak link in the design.

AISC Design Guide 27 gives more guidance on how to quantify the pitting and crevice corrosion resistance of austenitic and duplex stainless steels.

The risk of SCC should also be considered when selecting the stainless steel alloy for a bolting component. SCC requires the simultaneous presence of tensile stresses and specific environmental factors unlikely to be encountered in normal building atmospheres. Note that tensile stresses include both applied stresses and residual stresses such as those accumulated during fabrication. One common application in which SCC may be a particular concern is indoor swimming pools. For example, the high humidity in indoor swimming pools, combined with high levels of chlorine-based disinfectants and contaminants introduced by bathers, result in a very aggressive environment. The higher air temperatures in indoor swimming pools can also significantly accelerate corrosion by promoting condensation in cooler parts of the building and during the cool of the night. Repeated drying out and re-condensing of chlorine rich water vapor results in very aggressive buildup of chlorine-containing species that can produce a highly corrosive film on structural components located in areas immediately above the pool. Similarly, SCC can occur in exterior applications with aggressive environments. Such examples are bridges or tunnels, which are both commonly subjected to deicing salt to prevent ice from forming on roadways. Bridges and tunnels also undergo wetting and drying cycles, which cause chlorides to build up. In addition, tunnels can experience higher temperatures, which also increases the risk of SCC.

Stainless steel bolted joints between dissimilar metals may also be susceptible to galvanic (or bimetallic) corrosion. When two dissimilar metals are in direct electrical contact and are also bridged by an electrolyte (i.e., an electrically conducting liquid such as sea water or impure fresh water), a current flows from the anodic metal to the cathodic or more noble metal through the electrolyte. As a result, the less noble metal corrodes. When stainless steel is connected to carbon steel or galvanized steel, the stainless steel is the

Table 2-7. Recommended Alloy Selection for a Bolting Assembly		
Category	Stainless Steel for Connected Elements	Stainless Steel for Bolting Assembly[a]
1	S30400, S30403, S32100	B8 (S30400) or S17400 (630)[b]
2	S31600, S31603, S32101, S32304, S32202, S32003, S82011	B8M (S31600)
3	S32205, N08904, S82441, S31703	S32205 (2205)
4	N08926, S31254, S32750, S32760, N08367	B8MLCuN (S31254)[c], S32750, or S32760

[a] Alloys for bolting assemblies in higher categories may be used for the category indicated.
[b] Only recommended in mildly corrosive environments.
[c] This is the only bolt alloy included in the table that is recommended for indoor swimming pool environments.

more noble metal and does not suffer from additional corrosion. Further information about this type of corrosion and design measures to prevent it are given in Appendix B.

2.7.2 Alloy Selection

A careful assessment of the service environment is essential to design a bolted connection using an appropriate stainless steel alloy that has sufficient durability for the intended service life of the structure. The ANSI/AISC 370 Commentary and AISC Design Guide 27 give guidance on alloy selection.

There are many different stainless steel alloys offering a wide range of corrosion resistance.

Stainless steel bolts, washers, and nuts should all have equivalent or greater corrosion resistance than the most corrosion resistant of the metal alloys joined. This is because joints tend to be more susceptible to corrosion because the crevices in the joint may trap moisture and impurities. Table 2-7 lists the most common stainless steel alloys that are recommended for the bolting assembly based on the alloy selected for the connected members.

The austenitic alloy S30400 is suitable for use in mildly corrosive environments. It should not be used in marine environments, the oil and gas industry, or chemical processing plants because it may be susceptible to pitting and crevice corrosion. For low to moderate exposure to industrial pollution, or coastal or deicing chloride salts, austenitic alloy S31600 can be chosen, which, due to the addition of 2–3% molybdenum, has improved resistance to pitting and crevice corrosion in chloride environments. S30400 and S31600 stainless steels may be susceptible to crevice corrosion when chlorides or salts are present in the environment. Neither of these alloys are suitable for applications where SCC is a concern.

In ASTM F593, bolt alloys are divided into chemically equivalent groups for general corrosion resistance purposes, from which S30400 belong to Group 1 and S31600 belong to Group 2. All alloys belonging to a specific group will offer similar levels of corrosion resistance. For example, alloy S30300, S30430, S30500, and S38400 are variations of S30400 that were developed to meet specific manufacturing requirements. The higher sulfur content of S30300 makes it suitable for bolts that are made by machining, while alloys S30430, S30500, and S38400 were developed specifically for cold-forming operations. Because of their similar corrosion properties, these alloys may generally be used as substitutes to S30400. However, it is important to recognize that their properties are not identical. For example, the sulfur content in S30300 results in a somewhat lower corrosion resistance than S30400, especially when in direct and continuous contact with water or some chemical solutions. When in doubt of the suitability of the alloy, the designer should consult with a corrosion engineer.

ASTM A193/A193M and ASTM A320/A320M also include different variations of the common S30400 and S31600 alloys. However, the alloy variations in ASTM A193/A193M and ASTM A320/A320M have been developed to achieve specific properties for special applications, for example:

- B8N (S30451) and B8MN (S31651) were developed to achieve improved strength and hardness.
- B8R (S20910), also known as Nitronic 50 or XM-19, was developed to offer excellent seawater resistance with high strength and ductility due to the addition of manganese and nitrogen, and to remain nonmagnetic after severe cold working or exposure to low temperatures.
- B8T (S32100) was developed to retain mechanical properties at high temperature.

ASTM A193/A193M also includes the super austenitic alloy S31254 (B8MLCuN), which has around 6% molybdenum and around 18% nickel. The high molybdenum and nickel content combined with copper gives excellent resistance to pitting and crevice corrosion in environments with high levels of chlorine concentrations and sulfuric acid, including seawater and brackish water. S31254 is highly resistant to SCC. It is therefore suitable for use in highly loaded bolts subjected to chloride rich environments, such as indoor swimming pools, marine or offshore construction, or where cleaning cannot be carried out to remove chloride contamination.

The duplex stainless steel alloy S32205 (2205) specified in ASTM A1082/A1082M has improved resistance to pitting and crevice corrosion compared to S31600. It is used in offshore and marine environments, the oil and gas industry, or chemical processing plants. S32205 bolts are also suitable for applications requiring high strength such as in pretensioned or slip-critical joints, as they possess roughly twice the strength of austenitic stainless steel bolts in the solution annealed condition. They also possess increased hardness and toughness. They have better resistance to SCC than the common austenitic stainless steel bolts and are suitable for most exterior applications where SCC may be a concern. They may also be suitable for indoor pool environments in which the concentration of chloride ions in the pool water is less than or equal to 250 ppm. However, their resistance to SCC as well as their resistance to pitting and crevice corrosion is not as good as that of the super austenitic alloy S31254.

The super duplex alloys S32750 and S32760 may offer even higher strength than the standard duplex alloy S32205 and a resistance to pitting and crevice corrosion similar to that of the super austenitic alloy S32154 due to their high molybdenum and chromium content. This makes them suitable for extreme environments such as desalination plants, seawater systems, and petrochemical industries. S32750 and S32760 bolts also have superior resistance to SCC versus S32205 bolts.

All duplex and super duplex alloys are susceptible to embrittlement if exposed to temperatures above 570°F for an extended period of time.

Precipitation-hardening stainless steel S17400 (630) is the least corrosion resistant and least ductile alloy covered in this Design Guide. These bolts may be suitable for applications requiring very high strength. However, they should only be considered for mildly corrosive environments, such as in rural locations without pollutants, farm chemical, or salt exposure, and light industrial exposure. They are not suitable for coastal, deicing salt, or swimming pool building applications.

Nonferrous nickel alloy bolts may be suitable for use in very corrosive environments where there is a need for higher strength than that possible with duplex stainless steel bolting assemblies. If the surface hardness of nonferrous nickel alloy bolts is higher than that of austenitic and duplex stainless steel bolts, they may also be used as a way of avoiding galling in situations where surface hardening or lubrication is not possible. The design of these bolts is outside the scope of this Design Guide, and therefore, if these types of bolts are used, the designer is responsible for ensuring the bolting assembly performs as intended. The structural performance of these types of bolts should be determined by testing.

2.8 TEST REPORTS

Test reports documenting conformance to the applicable specifications for all bolting components and matched bolting assemblies should be available prior to assembly or erection of the structure. These are necessary to verify that the components are identifiable and meet the requirements of the applicable ASTM standard or appropriate consensus standard. Stainless steel structural bolting assemblies should also pass the rotational capacity test described in Appendix C. This testing should be completed and certified by the manufacturer or supplier of the bolting assembly or by another responsible party.

2.9 STORAGE

Once received at the installation site, all bolting components and bolting assemblies apart from temporary bolts should be kept in protected storage to ensure the as-manufactured conditions are maintained until they are incorporated into the work. Only as many bolting components and bolting assemblies as are anticipated to be installed during the work shift should be taken from protected storage. Bolting components and bolting assemblies that are not incorporated into the work should be returned to protected storage at the end of the work shift.

Preventive measures should be taken to avoid surface finish damage of the stainless steel bolting components, free iron or other material contamination due to exposure to steel cutting or grinding, and other potential sources of damage that may adversely affect the appearance or performance. Contact with chemicals and acids, including dyes, glues, adhesive tape, hydrochloric acid, chloride containing cleaning products, and undue amounts of oil and grease, should be avoided. If it is necessary to use them, their suitability and the maximum duration of exposure should be evaluated.

2.10 REUSE

If bolts are lubricated and have not been fully tensioned, then reuse may be permitted with approval by the EOR for connections other than slip-critical joints and pretensioned connections. If a bolt is to be reused, it should be re-lubricated according to Section 2.3 prior to reuse.

Stainless steel bolts used in slip-critical and pretensioned joints should not be reused after they have been tightened to their design pretension. This is because stainless steel bolts in these types of joints are expected to have yielded during pretensioning.

Chapter 3
Bolted Parts

This chapter covers the bolted parts in stainless steel bolted assemblies. Joints between dissimilar metals are covered in Appendix B.

3.1 CONNECTED PLIES

Stainless steel connected plies should generally be uncoated.

The slope of the surfaces of parts in contact with the bolt head and nut should not exceed 1:20 with respect to a plane that is normal to the bolt axis. Carbon steel structural bolting assemblies can be expected to be ductile enough to deform to a surface with a slope that is less than or equal to 1:20 with respect to a plane normal to the bolt axis when pretensioned, and similar behavior is expected for stainless steel bolting assemblies, though there is no known test data on this topic. Greater slopes are undesirable because the resultant localized bending decreases both the strength and the ductility of the bolt.

3.2 FAYING SURFACES

In all bolted joints, the faying surfaces and surfaces adjacent to the bolt head and nut should be free of dirt and other foreign material. In addition, in slip-critical joints, the faying surfaces should be (1) free of scale (except tight mill scale) in areas closer than one bolt diameter but not less than 1 in. from the edge of any hole, and in all areas within the bolt pattern, or (2) blast cleaned prior to assembly.

Although the faying surfaces of snug-tightened joints and pretensioned joints do not need to be treated, for slip-critical joints the faying surfaces should be adequately treated in order to achieve the slip coefficient assumed in design.

Tests have shown that the slip coefficient of stainless steel faying surfaces is mostly dependent on the roughness of the faying surfaces, the latter being controlled by the type of media that is used to blast the surfaces (Stranghöner et al., 2019). The roughness of grit-blasted faying surfaces is sharper than that of the shot-blasted surfaces and consequently provides better mechanical interlocking between the surfaces, which means better slip resistance behavior in the connections. For this reason, it is recommended that the faying surfaces of stainless steel slip-critical joints be grit-blasted. The slip coefficients given in Table 5-2 are only applicable to grit-blasted faying surfaces that meet the roughness values given in the table. If different faying surfaces are employed, such as with a blast media other than grit or a different surface roughness, tests can be conducted according to the testing method given in Appendix D to determine the slip coefficient of the potential faying surface. There are currently no known tests to determine the slip coefficient of stainless steel surfaces with clean mill scale.

Blasting the stainless steel surfaces can increase the possibility of corrosion due to the risk of contamination by free iron becoming embedded into the surface. To avoid contamination, hard, nonmetallic abrasive (e.g., aluminum oxide or garnet), or clean stainless steel grit or shot should be used. The use of brand-new media is advisable to minimize the risk of contamination.

3.3 BOLT HOLES

The nominal dimensions of standard, oversized, short-slotted, and long-slotted holes for stainless steel bolts are the same as those for high-strength carbon steel bolts. They should not exceed the limits given in Table 3-1.

There may be situations in which holes detailed larger than those shown in Table 3-1 may be needed. For example, slots longer than standard long slots may be necessary to accommodate construction tolerances or expansion joints, and larger oversized holes may be necessary to accommodate construction tolerances or misalignments. In these cases, the use of nonstandard holes should be specified or approved by the EOR. Guidance for calculating the reduction in strength associated with these types of holes or allowable loads are not given in this Design Guide. The EOR will most likely have to base the design of the joint on testing, or other means. At a minimum, engineering design considerations in these cases should include the effects of edge distance, net section, reduction in clamping force (in slip-critical joints), washer requirements, bearing capacity, and hole deformation.

When complete connection design is not shown in the structural design documents, the EOR should be notified of the type and dimensions of holes to be used. Oversized holes, short slots not perpendicular to the applied load, and long slots in any direction should be subject to approval by the EOR. Any restrictions on the use of hole types permitted in this section should be specified in the design documents.

Machined, drilled, or water jet cut holes are permitted. In drilling, positive cutting should be maintained to avoid strain hardening This requires sharp bits with correct angles of rake and correct cutting speeds. Thermal cutting of holes by plasma or by laser can be used as long as at least ⅛ in. of material is mechanically removed from any cut edge. Punching holes is possible, but may be more difficult than for carbon steel, especially for duplex stainless steel due to their high strength. Oxyacetylene torch cutting cannot be used

Table 3-1. Nominal Bolt Hole Dimensions				
Nominal Bolt Diameter, d_b, in.	Nominal Bolt Hole Dimensions, [a], [b] in.			
	Standard (diameter), in.	Oversized (diameter), in.	Short-Slotted (width × length), in. × in.	Long-Slotted (width × length), in. × in.
½	9⁄16	⅝	9⁄16 × 11⁄16	9⁄16 × 1¼
⅝	11⁄16	13⁄16	11⁄16 × ⅞	11⁄16 × 19⁄16
¾	13⁄16	15⁄16	13⁄16 × 1	13⁄16 × 1⅞
⅞	15⁄16	11⁄16	15⁄16 × 1⅛	15⁄16 × 23⁄16
1	1⅛	1¼	1⅛ × 115⁄16	1⅛ × 2½
≥ 1⅛	d_b + ⅛	d_b + 5⁄16	(d_b + ⅛) × (d_b + ⅜)	(d_b + ⅛) × (2.5d_b)

[a] The detailed hole dimension(s) should not exceed the nominal dimension(s). The fabricated hole dimension(s) should not exceed the nominal dimension(s) + 1⁄32 in.
Exception: In the width of slotted holes, gouges not more than 1⁄16 in. deep are permitted.
[b] The slightly conical hole that naturally results from punching operations with properly matched punches and dies is acceptable.

with stainless steel because the formation of the chromium oxide layer prevents oxidation from fully occurring.

Standard Holes

Standard holes may be used in all plies of bolted joints.

Oversized Holes

For snug-tightened or pretensioned joints subjected to shear or combined shear and tension, oversized holes should not be used. In such joints subjected to tension only, oversized holes may be used upon approval by the EOR.

For slip-critical joints, oversized holes may be used in any or all plies upon approval by the EOR.

Short-Slotted Holes

Short slots are used to account for minor adjustments in main members such as web thickness differences and member length.

For snug-tightened or pretensioned joints, short-slotted holes may be used in only one ply at any individual faying surface of any joint, provided the applied load is approximately perpendicular (between 80° and 100°) to the axis of the slot. When complete connection design is not shown in the structural design documents, the EOR should be notified when short-slotted holes are used in this manner. Upon approval by the EOR, short-slotted holes may be used in more than one or all plies, provided the applied load is approximately perpendicular (between 80° and 100°) to the axis of the slot(s).

The limitation on the use of short-slotted holes to one ply with snug-tight bolts is to avoid the use of short-slotted holes in opposing plies of a faying surface. The use of short-slotted holes with snug-tight bolts in connections with multiple plies that do not share a faying surface is still permitted. An example that would be permitted with multiple plies includes beam end connections on opposing sides of a column web.

For slip-critical joints, upon approval by the EOR, short-slotted holes may be used in any or all plies without regard for the direction of the applied load.

Long-Slotted Holes

For snug-tightened or pretensioned joints, long-slotted holes may be used in only one ply at any individual faying surface upon approval by the EOR, provided the applied load is approximately perpendicular (between 80° and 100°) to the axis of the slot.

For slip-critical joints, long-slotted holes may be used in only one ply at any individual faying surface upon approval by the EOR, without regard for the direction of the applied load.

Fully inserted finger shims between the faying surfaces of load-transmitting elements of bolted joints are not considered a long-slotted element of a joint, nor are they considered to be a ply at any individual faying surface. However, for slip-critical joints, finger shims should have the same surface preparation as the plies.

3.4 BURRS

Burrs less than or equal to 1⁄16 in. in height are permitted to remain on faying surfaces of all joints. However, burrs of larger height should be removed or reduced to 1⁄16 in. or less from the faying surfaces of all joints.

Chapter 4
Joint Type

For joints with bolts that are loaded in shear or combined shear and tension, the EOR should specify the joint type in the contract documents as snug-tightened, pretensioned, or slip-critical. For slip-critical joints, the required class of slip resistance should also be specified, see Section 5.4. For joints with bolts that are loaded in tension only, the EOR should specify the joint type in the contract documents as snug-tightened or pretensioned. Table 4-1 summarizes the applications and requirements of the three joint types.

In joints with non-pretensioned bolts, the shear load is transferred by shear in the bolts and bearing stress in the connected material. At the ultimate limit state, failure will occur by shear failure of the bolts, by bearing failure of the connected material, or by failure of the member itself. If pretensioned bolts are used in such a joint, the frictional force that develops between the connected plies will initially transfer the load. Until the frictional force is exceeded, there is no shear in the bolts and no bearing stress in the connected components. A further increase of load places the bolts into shear and against the connected material in bearing, just as was the case when non-pretensioned bolts were used. Because it is known that the pretension in bolts will have been dissipated by the time bolt shear failure takes place (Kulak et al., 1987), the ultimate limit state of a pretensioned bolted joint is the same as an otherwise identical joint that uses non-pretensioned bolts.

4.1 SNUG-TIGHTENED JOINTS

Except as indicated in Sections 4.2 and 4.3 snug-tightened joints are generally permitted. Snug-tightened joints may use either structural or nonstructural bolting assemblies.

Table 4-1. Summary of Applications and Requirements for Bolted Joints

Load Transfer	Application	Joint Type[a],[b]	Faying Surface Preparation	Install per Section	Inspect per Section	Arbitrate per Chapter 10
Shear only	Resistance to shear load by shear/bearing.	ST	No	8.1	9.1	No
	Resistance to shear load by shear/bearing. Bolt pretension is required, but for reasons other than slip resistance.	PT	No	8.2	9.2	If required to resolve dispute
	Resistance to shear load by friction on faying surfaces is required.	SC	3.2	8.2	9.3	If required to resolve dispute
Combined shear and tension	Resistance to shear load by shear/bearing. Tension load is static only.	ST	No	8.1	9.1	No
	Resistance to shear load by shear/bearing. Bolt pretension is required, but for reasons other than slip resistance.	PT	No	8.2	9.2	If required to resolve dispute
	Resistance to shear load by friction on faying surfaces is required.	SC	3.2	8.2	9.3	If required to resolve dispute
Tension only	Static loading only.	ST	No	8.1	9.1	No
	All other conditions of tension-only loading.	PT	No	8.2	9.2	If required to resolve dispute

[a] Joint Type: ST = snug-tightened, PT = pretensioned, and SC = slip-critical; as defined in this chapter.
[b] See Chapters 4 and 5 for the design requirements for each joint type.

Bolts in snug-tightened joints should be designed according to the applicable guidance of Sections 5.1, 5.2, and 5.3, installed in accordance with Section 8.1, and inspected in accordance with Section 9.1. As indicated in Table 4-1, requirements for faying surface condition do not apply to snug-tightened joints. Also, there are no specific minimum or maximum tension requirements for snug-tight bolts. Some level of pretension, which may be up to full pretensioning, may be necessary to ensure the desired full contact between the connected surfaces in the snug-tight condition. Bolts that have been pretensioned are permitted in snug-tightened joints unless specifically prohibited on design documents.

4.2 PRETENSIONED JOINTS

Pretensioned joints are necessary in the following applications:

1. Joints subjected to significant load reversal.
2. Joints subjected to fatigue load with no reversal of the loading direction.
3. Joints subjected to tensile fatigue.

Pretensioned joints should use structural bolting assemblies. Bolts in pretensioned joints subjected to shear should be designed according to the applicable guidance of Sections 5.1 and 5.3, installed in accordance with Section 8.2, and inspected in accordance with Section 9.2. Bolts in pretensioned joints subjected to tension or combined shear and tension should be designed according to the applicable guidance of Sections 5.1, 5.2, 5.3, and 5.5, installed in accordance with Section 8.2, and inspected in accordance with Section 9.2. As indicated in Table 4-1, requirements for faying surface condition do not apply to pretensioned joints.

4.3 SLIP-CRITICAL JOINTS

Slip-critical joints are necessary in the following applications involving shear or combined shear and tension:

1. Joints subjected to fatigue load with reversal of the loading direction.
2. Joints that utilize oversized holes.
3. Joints that utilize slotted holes, except those with applied load approximately normal (between 80° and 100°) to the direction of the long dimension of the slot.
4. Joints in which slip at the faying surfaces would be detrimental to the performance of the structure.

Application 4 includes cases where slip movement could theoretically exceed an amount deemed by the EOR to affect the serviceability of the structure, or where excessive distortion could cause a reduction in strength or stability, even though the resistance to fracture of the connection and yielding of the member may be adequate. It also includes cases where slip of any magnitude should be prevented, such as in joints between elements of built-up compression members in which any slip could cause a reduction of the flexural stiffness, which is needed for the stability of the built-up member.

Slip-critical joints should use structural bolting assemblies. Bolts in slip-critical joints should be designed according to the applicable guidance of Sections 5.1, 5.2, 5.3, 5.4, and 5.5; installed in accordance with Section 8.2; and inspected in accordance with Section 9.3.

Chapter 5
Limit States in Bolted Joints

The equations for calculating the strength of stainless steel bolted joints are similar to those given in the RCSC *Specification*. However, the coefficients used in these equations have been adjusted to account for the different material behavior of stainless steel.

Like the RCSC *Specification*, the information given in this Design Guide is not intended to provide comprehensive coverage of the design of stainless steel bolted connections. Other design considerations of importance to the satisfactory performance of the connected material—such as block shear rupture, shear lag, prying action, and connection stiffness and its effect on the performance of the structure—are beyond the scope of this Design Guide.

The design of bolted joints that transmit shear requires consideration of the shear strength of the bolts and the bearing strength of the connected material. If such joints are designated as slip-critical joints, the slip resistance should also be checked.

The available shear strength and available tensile strength of stainless steel bolts should be determined in accordance with Section 5.1. The interaction of combined shear and tension on stainless steel bolts should be limited in accordance with Section 5.2. The available bearing strength of the connected parts at bolt holes should be determined in accordance with Section 5.3. Each of these available strengths should be greater than or equal to the required strength. The axial load in bolts that are subjected to tension or combined shear and tension should be calculated with consideration of the effects of the externally applied tensile load and any additional tension resulting from prying action produced by deformation of the connected parts.

When slip resistance is needed at the faying surfaces subjected to shear or combined shear and tension, slip resistance should be checked at either the LRFD-load level or ASD-load level, at the option of the EOR. When slip of the joint under applied loads would affect the ability of the structure to support the loads, the available strength determined in accordance with Section 5.4 should be greater than or equal to the required strength. In addition, slip-critical joints should meet the strength requirements of shear/bearing joints. Therefore, the strength requirements of Sections 5.1, 5.2, and 5.3 should also be met.

When bolts are subjected to cyclic application of axial tension, the allowable stress range determined in accordance with Section 5.5 should be greater than or equal to the stress range due to the effect of the service loads and moments, including any additional tension resulting from prying action produced by deformation of the connected parts.

In general, bolted joints that are designed in accordance with this Design Guide will have a higher reliability than the members they connect. This occurs primarily because the resistance factors used in limit states for the design of bolted joints were chosen to provide a reliability higher than that used for member design.

5.1 NOMINAL SHEAR AND TENSILE STRENGTHS

Shear and tensile strengths should not be reduced by the installed bolt pretension. For joints, the nominal shear and tensile strengths should be taken as the sum of the strengths of the individual bolts.

The design strength in shear or tension for an austenitic, duplex, or precipitation-hardening stainless steel bolt is ϕR_n, and the allowable strength in shear or tension is R_n/Ω, where R_n, ϕ, and Ω are defined as follows.

$$R_n = F_n A_b \tag{5-1}$$

For austenitic and duplex stainless steel bolts

$$\phi = 0.75 \text{ (LRFD)} \qquad \Omega = 2.00 \text{ (ASD)}$$

For precipitation-hardening stainless steel bolts

$$\phi = 0.67 \text{ (LRFD)} \qquad \Omega = 2.25 \text{ (ASD)}$$

where

A_b = cross-sectional area based upon the nominal bolt diameter, in.^{2}

F_n = nominal strength per unit area from Table 5-1 for the appropriate applied load conditions, ksi, adjusted for the presence of fillers as given later in this section

R_n = nominal strength (shear strength per shear plane or tensile strength) of a bolt, kips

Due to the variety of stainless steel bolts on the market, produced in accordance with different specifications with varying strength, this Design Guide does not give specific nominal strength values for bolts in tension and shear, as is done in the RCSC *Specification*. Instead, the nominal strength values in Table 5-1 are given as a function of the tensile strength.

The coefficients for the shear strength of stainless steel bolts given in Table 5-1 were derived from experimental data on austenitic and duplex stainless steel bolted connections collected by Stranghöner and Abraham (2021). These data include tests conducted by Ryan (1999), Song et al. (2020a;

Table 5-1. Nominal Strengths per Unit Area of Bolts				
Applied Load Condition			**Nominal Strength per Unit Area, F_n, ksi**	
			$F_{ub} \leq 120$ ksi	**$F_{ub} > 120$ ksi**
Tension[a]	Static		$0.75F_{ub}$	$0.75F_{ub}$
	Fatigue		See Section 5.5	
Shear[a],[b]	Threads included in shear plane	$L_s \leq 38$ in.	$0.45F_{ub}$	$0.40F_{ub}$
		$L_s > 38$ in.	$0.37F_{ub}$	$0.33F_{ub}$
	Threads excluded from shear plane	$L_s \leq 38$ in.	$0.56F_{ub}$	$0.50F_{ub}$
		$L_s > 38$ in.	$0.46F_{ub}$	$0.42F_{ub}$

F_{ub} = specified minimum tensile strength of the bolt given in the relevant ASTM standard, ksi.
L_s = length between the extreme bolt hole centers in a bolt pattern parallel to the line of force on one side of the connection, in.

[a] Except as needed in Section 5.2.
[b] Reduction for values for $L_s > 38$ in. applies only when the joint is axially end loaded, such as splice plates on a beam or column flange, but it does not apply for web connections in shear.

2020b), as well as Stranghöner and Abraham (2021). A reliability analysis showed that the value of the shear coefficient is slightly affected by the strength of the bolt, and hence a lower coefficient is needed for bolts with F_{ub} greater than 120 ksi. Similar to carbon steel bolts, the shear coefficients given in Table 5-1 include a reduction factor of 0.90 for joints up to 38 in. in length to account for an increase in bolt force due to minor secondary effects resulting from simplifying assumptions made in the modeling of structures that are commonly accepted in practice (e.g., equal force distribution in all the bolts of a shear connection). Second-order effects such as those resulting from the action of the applied loads on the deformed structure should be accounted for through a second-order analysis of the structure. The average shear strength of bolts in joints longer than 38 in. is reduced by a factor of 0.75 instead of 0.90. This factor is the same as the one applied to carbon steel bolted connections and accounts for both the nonuniform force distribution between the bolts in a long joint and the minor secondary effects discussed earlier. Note that the 0.75 reduction factor does not apply in cases where the distribution of force is essentially uniform along the joint, such as a web shear connection of a beam or girder.

Also similar to carbon steel bolts is the use of a reduction factor of 0.80 to account for the reduction in shear strength for a bolt with threads included in the shear plane but calculated with the area corresponding to the nominal bolt diameter. For the case of a bolt in double shear with a non-threaded section in one shear plane and a threaded section in the other shear plane, it is recommended to conservatively assume that threads are included in all shear planes.

As for carbon steel bolts, the tensile strength area of stainless steel bolts is taken as 75% of the nominal cross-sectional area of the bolts. This is reflected by the 0.75 coefficient given in Table 5-1 for the calculation of the nominal tensile strength of the bolt. The strengths so calculated are intended to form the basis for comparison with the externally applied bolt tension plus any additional tension that results from prying action that is produced by deformation of the connected elements.

The value of the coefficients given in Table 5-1 ensures an equivalent level of safety for austenitic and duplex stainless steel bolts to that given by the shear strength provision for carbon steel bolts. Insufficient data were available to enable a reliability analysis to be carried out for bolts made from precipitation-hardening stainless steels bolts. Therefore, the appropriate resistance factors for austenitic and duplex stainless steel bolts were reduced by 10% for precipitation-hardening stainless steel bolts to give an extra margin of safety.

When a bolt that carries load passes through fillers or shims in a shear plane that are less than or equal to ¼ in. thick, F_n from Table 5-1 should be used without reduction. When a bolt that carries load passes through fillers or shims that are greater than ¼ in. thick, the connection should be designed in accordance with one of the following procedures:

1. F_n from Table 5-1 should be multiplied by the factor $[1 - 0.4(t' - 0.25)]$, which should not be taken as greater than 1.00 nor smaller than 0.85, where t' is the total thickness of fillers or shims, in.
2. The fillers or shims should be extended beyond the joint, and the filler or shim extension should be secured with enough bolts to uniformly distribute the total force in the connected element over the combined cross section of the connected element and the fillers or shims.
3. The size of the joint should be increased to accommodate a number of bolts that is equivalent to the total number needed in procedure 2.
4. The joint should be designed as a slip-critical joint.

5.2 COMBINED SHEAR AND TENSION

When combined shear and tension loads are transmitted, the design limit state interaction is:

$$\left[\frac{T_u}{(\phi R_n)_t}\right]^2 + \left[\frac{V_u}{(\phi R_n)_v}\right]^2 \le 1 \tag{5-2a}$$

where

T_u = required strength in tension, per bolt, using LRFD load combinations, kips

V_u = required strength in shear, per bolt, using LRFD load combinations, kips

$(\phi R_n)_t$ = design strength in tension determined in accordance with Section 5.1, kips

$(\phi R_n)_v$ = design strength in shear determined in accordance with Section 5.1, kips

When combined shear and tension loads are transmitted, the allowable limit state interaction is:

$$\left[\frac{T_a}{(R_n/\Omega)_t}\right]^2 + \left[\frac{V_a}{(R_n/\Omega)_v}\right]^2 \le 1 \tag{5-2b}$$

where

T_a = required strength in tension, per bolt, using ASD load combinations, kips

V_a = required strength in shear, per bolt, using ASD load combinations, kips

$(R_n/\Omega)_t$ = allowable strength in tension determined in accordance with Section 5.1, kips

$(R_n/\Omega)_v$ = allowable strength in shear determined in accordance with Section 5.1, kips

The shear and tension interaction given by Equations 5-2a and 5-2b is identical to that given in the RCSC *Specification*. This interaction can be conveniently approximated using three straight lines, as has been done in ANSI/AISC 370. The elliptical interaction given by Equations 5-2a and 5-2b in effect shows that, for design purposes, significant interaction does not occur until either force component exceeds 20% of the limiting strength for that component.

5.3 NOMINAL BEARING STRENGTH AT BOLT HOLES

For bolted joints, the nominal bearing strength should be taken as the sum of the strengths of the connected material at the individual bolt holes.

For connected austenitic or duplex stainless steel material at a standard bolt hole, oversized bolt hole, short-slotted bolt hole independent of the direction of loading, or long-slotted bolt hole with the slot parallel to the direction of the bearing load, the design bearing strength is ϕR_n, where $\phi = 0.75$ and the allowable bearing strength is R_n/Ω, where $\Omega = 2.00$.

1. When deformation of the bolt hole at service load is a design consideration,

$$R_n = 1.25\left(\frac{l_1}{2d_h}\right)d_b t F_u \le 1.25 d_b t F_u \tag{5-3}$$

2. When deformation of the bolt hole at service load is not a design consideration,

   For $l_2/d_h > 1.5$

$$R_n = 2.5\left(\frac{l_1}{3d_h}\right)d_b t F_u \le 2.5 d_b t F_u \tag{5-4a}$$

   For $l_2/d_h \le 1.5$

$$R_n = 2.5\left(\frac{l_1}{3d_h}\right)d_b t F_u \le 2.0 d_b t F_u \tag{5-4b}$$

For the connected material at a long-slotted bolt hole with the slot perpendicular to the direction of the bearing load, the design bearing strength is ϕR_n, where $\phi = 0.75$, and the allowable bearing strength is R_n/Ω, where $\Omega = 2.00$.

$$R_n = 1.04\left(\frac{l_1}{2d_h}\right)d_b t F_u \le 1.04 d_b t F_u \tag{5-5}$$

In Equations 5-3, 5-4, and 5-5,

F_u = specified minimum tensile strength per unit area of the connected material, ksi

R_n = nominal strength (bearing strength of the connected material), kips

d_b = nominal diameter of bolt, in.

d_h = nominal diameter of bolt hole, in.

l_1 = half of the distance between the center of the hole and the center of the adjacent hole or distance between the center of the hole and the edge of the material, in the direction of the force, in.

l_2 = half of the distance between the center of the hole and the center of the adjacent hole or distance between the center of the hole and the edge of the material, in the direction perpendicular to the force, in.

t = thickness of the connected material, in.

Distances l_1 and l_2 are illustrated in Figure 5-1.

For countersunk bolts in standard bolt holes made of austenitic or duplex stainless steel, the design bearing strength is ϕR_n, where $\phi = 0.75$, and the allowable bearing strength is R_n/Ω, where $\Omega = 2.00$, and R_n is calculated using Equations 5-3 and 5-4, as appropriate, but subtracting one-half the depth of the countersink from the thickness of the connected material, t.

For bolted joints in which at least one of the connected plies is made of carbon steel, the available bearing strength of the carbon steel material should be determined in accordance with the RCSC *Specification*.

In Equations 5-3 through 5-5, the bearing strength of the bolted joint is limited either by bearing of the hole or by tearout (a bolt-by-bolt block shear rupture) of the material upon which the bolt bears. Bearing of the bolt itself is not considered, as this will never be critical. The formatting of the bearing equations for stainless steel bolted joints differs slightly from the equations given in the RCSC *Specification*. The most notable difference is that while the carbon steel equations are given as a function of the clear distance to another hole or edge of the material (L_c in the RCSC *Specification*), for stainless steel bolted joints, the bearing strength is given as a function of the center-to-center distance to another hole or edge of the material (l_1 or l_2).

The bearing behavior of a bolt hole in stainless steel material differs from that of a bolt hole in carbon steel material. While for carbon steel material the bearing strength that is developed at the bolt hole as the bolt bears into the material flattens off after the initiation and spreading of yielding, for stainless steel the strength continues to rise significantly owing to strain hardening. For this reason, greater clarity in defining the bearing capacity of stainless steel bolted joints is necessary. Similar to carbon steel bolted joints, bearing strength equations are provided depending on whether serviceability deformations are or are not a design consideration. The bearing equations for stainless steel material are based on numerical studies carried out by Salih et al. (2011). For the case in which deformation of the bolt hole at service load is not a design consideration, Salih et al. considered that the bearing strength of the bolt hole was reached when the peak plastic strain of the material in front of the bolt hole, at an angle $\theta = 45°$ and 135°, which correspond to the directions of maximum strain, reaches the localized fracture strain of the material. When deformation of the bolt hole at service load is a design consideration, the bearing equation was developed targeting a deformation of 1⁄32 in. under service load.

5.4 DESIGN SLIP RESISTANCE

Slip-critical joints should be designed to prevent slip and for the limit states of bearing-type connections in accordance with Sections 5-1, 5-2, and 5-3. When bolts in slip-critical joints pass through fillers, all faying surfaces subject to slip should be prepared to achieve design slip resistance.

At LRFD load levels, the design slip resistance is ϕR_n, and at ASD load levels, the allowable slip resistance is R_n/Ω, where R_n, ϕ, and Ω are defined as follows.

Stainless steel slip-critical joints should only be used with structural bolting assemblies.

The nominal slip resistance per bolt for the limit state of slip, R_n, is determined as follows:

$$R_n = \mu D_u h_f T_m n_s k_{sc} \tag{5-6}$$

For standard size and short-slotted holes perpendicular to the direction of the load

$$\phi = 1.00 \text{ (LRFD)} \qquad \Omega = 1.50 \text{ (ASD)}$$

For oversized and short-slotted holes parallel to the direction of the load

$$\phi = 0.85 \text{ (LRFD)} \qquad \Omega = 1.76 \text{ (ASD)}$$

For long-slotted holes

$$\phi = 0.70 \text{ (LRFD)} \qquad \Omega = 2.14 \text{ (ASD)}$$

where

D_u = a multiplier that reflects the ratio of the mean installed bolt pretension to the minimum bolt pretension
= 1.00

T_m = minimum bolt pretension, kips
= $0.7F_{ub}A_s$ (5-7)

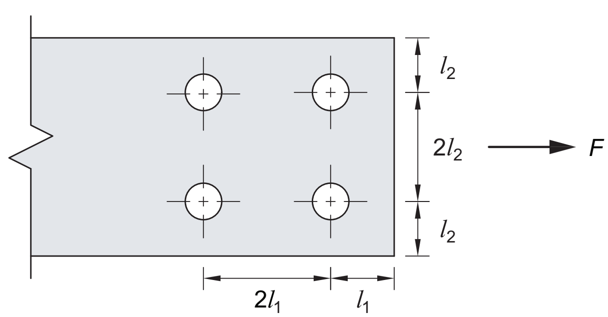


Fig. 5-1. Illustration of distances l_1 *and* l_2.

Table 5-2. Slip Coefficients, μ, for Grit-Blasted Faying Surfaces	
Class[a]	**Slip Coefficient, μ[b]**
SSB	0.20
SSC	0.40
SSD	0.50

[a] Surface classes meeting the requirements in Table 5-3.
[b] The potential loss of preloading force due to time dependent relaxation from its initial value is considered in these slip coefficient values.

Table 5-3. Definition of Surface Classes for Slip-Critical Grit-Blasted Faying Surfaces		
Surface Class	**Average R_t,[a] mils**	**Profile Height,[b] mils**
SSB	≥ 1.4	≥ 2.0
SSC	≥ 1.8	≥ 2.4
SSD	≥ 2.2	≥ 2.8

[a] Average R_t surface roughness according to ASTM D4417 Method D (ASTM, 2021b).
[b] Profile height is determined according to ASTM D4417 Method B (using the average of maximum values option) or Method C.

A_s = tensile stress area of bolt given in Table 5-4, in.^{2}

h_f = factor for fillers, determined as follows:

1. Where there are no fillers, or where bolts have been added to distribute loads in the filler

$$h_f = 1.0$$

2. Where bolts have not been added to distribute the load in the filler

i. For one filler between connected parts

$$h_f = 1.0$$

ii. For two or more fillers between connected parts

$$h_f = 0.85$$

$$k_{sc} = 1 - \frac{T_u}{D_u T_m n_b} \geq 0 \text{ (LRFD)} \tag{5-8a}$$

$$k_{sc} = 1 - \frac{1.5T_a}{D_u T_m n_b} \geq 0 \text{ (ASD)} \tag{5-8b}$$

T_a = required tensile force using ASD load combinations, kips

T_u = required tensile force using LRFD load combinations, kips

n_b = number of bolts carrying the applied tension

n_s = number of slip planes

μ = mean slip coefficient, given in Table 5-2 for grit-blasted faying surfaces, or as established by tests in accordance with the testing method given in Appendix D. For the definition of the surface classes given in Table 5-2, see Table 5-3.

Equation 5-6 is identical to the corresponding equation given in the RCSC *Specification*. The relationship between the slip coefficient and the surface profile of grit-blasted faying surfaces given in Table 5-2 and Table 5-3 is based on the results from a European research project (European Commission, 2019).

Equation 5-7 differs from the one given in ANSI/AISC 370 that limits T_m to $0.7F_{yb}A_s$. Since ANSI/AISC 370 was published in 2021, there has been further testing of a range of stainless steel bolts that has shown that, providing appropriate lubricants are used, it is possible to reliably obtain a minimum bolt pretension based on $0.7F_{ub}A_s$ (Provines, 2023). Table 5-5 provides minimum bolt pretension values for high-strength stainless steel bolts.

The value of the multiplier D_u is conservatively set to 1.0 for stainless steel slip-critical connections because there is insufficient data to justify a higher value. This contrasts with the value of 1.13 used for carbon steel slip-critical joints in building structures, for which significantly more data are available on the different bolt installation methods.

The reduction factor that is used when two or more fillers are placed between the connected parts, h_f, is the same as for carbon steel slip-critical connections. The reduction

Table 5-4. Tensile Stress Area of Bolts		
Bolt Diameter, d_b, in.	Tensile Stress Area, A_s,[a] in.^{2}	Threads per Inch, n[b]
½	0.142	13
⅝	0.226	11
¾	0.334	10
⅞	0.462	9
1	0.606	8
1⅛	0.763	7
1¼	0.969	7
1⅜	1.16	6
1½	1.41	6

[a] Tensile stress area, $A_s = (\pi/4)(d_b - 0.9743/n)^2$.
[b] For diameters listed, thread series is UNC (coarse).

Table 5-5. Minimum Bolt Pretension for Common Stainless Steel Structural Bolting Assemblies					
Nominal Bolt Diameter, d_b, in.	Minimum Bolt Pretension, $T_m = 0.7F_{ub}A_s$, kips				
	ASTM F593 Group 1 or Group 2 Condition SH	ASTM A193/A193M Grade B8 Class 2 or ASTM A320/A320M Grade B8 Class 2	ASTM A193/A193M Grade B8M Class 2 or ASTM A320/A320M Grade B8M Class 2	ASTM A1082/A1082M S32205	ASTM A1082/A1082M S17400 (630) Condition H1150 or ASTM F593 Group 7 S17400 (630) Condition AH
½	12	12	11	9	13
⅝	19	20	17	15	21
¾	26	29	26	22	32
⅞	36	37	32	31	44
1	47	49	42	40	57
1⅛	53	56	51	51	72
1¼	68	71	64	64	92
1⅜	77	81	73	77	109
1½	93	98	89	93	133

factor k_{sc} given by Equation 5-8, that is used to account for the reduction in the clamping force between the faying surfaces that results when a tensile force is applied, is also the same as that used in the RCSC *Specification*.

5.5 TENSILE FATIGUE

For austenitic and duplex stainless steel bolts, the range of tensile stress on the tensile stress area of the bolt from applied cyclic axial load and moment plus load due to prying action should not exceed the allowable stress range, F_{SR}, given by Equation 5-9. Precipitation-hardening stainless steel bolts should not be used when the bolt is subjected to cyclic axial load or moment.

$$F_{SR} = 1{,}000\left(\frac{0.39}{n_{SR}}\right)^{0.333} \geq 7\text{ ksi} \quad (5\text{-}9)$$

where

n_{SR} = number of stress range fluctuations during the design life

For joints in which the material within the grip is not limited to steel, or joints other than pretensioned joints in accordance with Section 4.2 or slip-critical joints in accordance with Section 4.3, all axial load and moment applied to the joint plus the effects of any prying action should be assumed to be carried exclusively by the bolts.

For pretensioned joints in accordance with Section 4.2 or slip-critical joints in accordance with Section 4.3, in which the material within the grip is limited to steel, an analysis of the relative stiffness of the connected parts and bolts may be used to determine the tensile stress range in the pretensioned bolts due to the total applied cyclic load and moment, plus the effects of any prying action. Alternatively, the stress range in the bolts may be assumed to be equal to the stress on the tensile stress area due to 20% of the absolute value of the applied cyclic axial load and moment from dead, live, and other loads.

In pretensioned joints subjected to cyclic shear, the fatigue resistance of the bolt will never govern, and instead, the fatigue resistance of the joint will be governed by fatigue cracking of the connected material.

Equation 5-9 is the same equation used to verify the fatigue resistance of carbon steel bolts. This equation is recommended for austenitic and duplex stainless steel bolts because tests have shown austenitic and duplex stainless steel details have very similar fatigue strength to carbon steel details. There is limited fatigue testing data on precipitation-hardening stainless steels, and therefore, it is conservatively recommended that bolts made from this alloy family not be used when fatigue is a design consideration.

Chapter 6
Use of Washers

The primary function of washers is to provide a hardened, nongalling surface under the turned element. Stainless steel washers are typically softer than carbon steel washers specified by ASTM F436/F436M, which can lead to galling (Provines et al., 2021).

Circular flat washers that meet the dimensional requirements of ASTM F436/F436M provide an increase in bearing area that is approximately 50% larger than that provided by a heavy hex bolt head or nut.

It is important that fabrication documents and connection details clearly reflect the number and disposition of washers when they are needed, especially the thick, hardened washers or plate washers that are needed for some oversized and slotted hole applications.

6.1 SNUG-TIGHTENED JOINTS

Washers are not necessary in snug-tightened joints, except when the outer face of the joint has a slope that is greater than 1:20 with respect to a plane that is normal to the bolt axis, in which case a beveled washer should be used to compensate for the lack of parallelism, or when a slotted hole occurs in an outer ply, in which case a washer with dimensions as specified in ASTM F436/F436M or a 5/16-in.-thick common plate washer is needed to completely cover the hole.

However, the use of beveled washers is less common in stainless steel structures than in carbon steel structures. Carbon steel beveled washers are often used when bolting the flanges of hot rolled structural shapes for which the sloped flanges exceed the 1:20 limit, such as American standard beams (S-shapes) and channels. These types of hot-rolled shapes are only available in stainless steel in small sizes, and in many cases equivalent welded sections (fabricated from plates) are used instead.

In joints with slotted holes, the reason for the washer having to completely cover the hole is to prevent "dishing" of the washer, which becomes more critical when an edge is unsupported, and to prevent moisture from entering the connection, which could result in corrosion issues.

6.2 PRETENSIONED JOINTS AND SLIP-CRITICAL JOINTS

Stainless steel washers should generally be used under the nut in pretensioned joints and slip-critical joints. However, when the connected material has a specified minimum yield strength of less than 40 ksi, a washer is also necessary under the bolt head. Washers should be selected in accordance with Section 2.1.3. The use of washers is to prevent the bolt from deforming the soft surface of the connected plate. Depending on the yield strength of the clamped steel material, plastification of the surface can occur. For this reason, washers are more important for steel plates of lower strength.

When an oversized or slotted hole occurs in an outer ply, the washer requirements given in Table 6-1 should be followed. The washer used should be of sufficient size to completely cover the hole.

Table 6-1. Washer Requirements for Pretensioned and Slip-Critical Bolted Joints with Oversized and Slotted Holes in the Outer Ply

Family	Nominal Bolt Diameter, d_b, in.	Hole Type in Outer Ply		
		Oversized	Short-Slotted	Long-Slotted
Austenitic and duplex	½–1½	Dimensions should match ASTM F436/F436M[a]		5/16-in.-thick plate washer or continuous bar[b],[c]
Precipitation hardening	≤ 1			
	> 1	Dimensions should match ASTM F436/F436M extra thick[a],[b],[d]		ASTM F436/F436M washer with either a 3/8-in.-thick plate washer or continuous bar[b],[c]

[a] For alloy designation and hardness, see Section 2.1.3.
[b] See ASTM F436/F436M, Section 1.2. Multiple washers with a combined thickness of 5/16 in. or larger do not satisfy this requirement.
[c] The plate washer or bar should be of structural stainless steel material but need not be hardened. For alloy designation, see Section 2.1.3.
[d] Alternatively, a 3/8-in.-thick plate washer and an ordinary thickness ASTM F436/F436M washer may be used. The plate washer need not be hardened.

Chapter 7
Pre-Installation Verification

Pre-installation verification should be carried out for pretensioned and slip-critical bolting assemblies as described in Section 8.2.

7.1 REQUIRED TESTING

Pre-installation verification testing is essential for:

- Evaluating the suitability of the bolting assembly, including the specific type, application method, and location placement of the lubrication that is applied to the bolting assembly, to develop the specified minimum pretension
- Verifying the adequacy and proper use of the specified pretensioning method to be used
- Verifying the initial torque applied achieves at least the required initial tension when using the combined method of pretensioning
- Demonstrating the suitability of the bolt tightening equipment to be used during installation
- Verifying that the pretensioning method does not cause galling

Pre-installation verification testing provides a practical means for ensuring that nonconforming bolting assemblies are not incorporated into the work. Experience on many projects with carbon steel has shown that bolts, nuts, and/or bolting assemblies not meeting the requirements of the applicable ASTM standards would have been identified prior to installation if they had been tested as an assembly in a bolt tension measurement device, and the expense of replacing bolts installed in the structure when the nonconforming bolts were discovered at a later date would have been avoided.

Additionally, pre-installation verification testing clarifies for the bolting crew and the inspector the proper implementation of the selected pretensioning method and the adequacy of the installation equipment. It will also identify potential sources of problems, such as the effectiveness of the lubrication to prevent failure of bolts by combined high torque with tension, significant galling, or other failures to meet strength or geometric requirements of applicable ASTM standards.

Pre-installation verification testing is only required for structural bolting assemblies and should be performed in compliance with all of the following:

1. At the site of installation
2. Prior to the placement of bolting assemblies of verified lots in the work
3. On a sample of not fewer than three complete bolting assemblies of each combination of diameter, length, alloy, and lot to be used in the work
4. Using bolting assemblies that are representative of the condition of those that will be pretensioned in the work
5. Using stainless steel washers positioned in accordance with Section 6.2
6. In accordance with the test procedure in Section 7.2

For pretensioned installation in accordance with Section 8.2.2 (combined method), this testing should be performed at least annually to verify that each installation tool continues to have the capability to produce the required initial torque for the bolting assemblies that are being installed. Alternatively, if there is a means to measure the torque output of the tool while in use, this testing can be performed during installation.

7.2 TEST PROCEDURE

The bolting assembly should be tested in a bolt tension measurement device to verify that the pretensioning method to be used in the work develops a pretension that is greater than or equal to that specified in Equation 7-1.

$$T_p = 1.05T_m \tag{7-1}$$

where

T_m = minimum bolt pretension, kips (from Section 5.4)

T_p = pre-installation verification bolt pretension, kips

Hydraulic bolt tension measurement devices undergo a slight deformation during bolt pretensioning. Hence, when bolts are pretensioned the nut rotation corresponding to a given pretension reading may be somewhat larger than it would be if the same bolt were pretensioned in a solid steel assembly. Stated differently, the reading of a hydraulic bolt tension measurement device tends to underestimate the pretension that a given rotation of the turned element would induce in a bolt in a pretensioned joint.

The test procedure is also used to determine the installation parameters, such as the nut rotation for the turn-of-nut method and the initial torque and nut rotation for the combined method of installation. This is done because sufficient test data does not exist to produce tabulated installation parameters for stainless steel bolting assemblies to ensure the bolt force reaches the minimum specified pretension.

Table 7-1. Minimum Bolt Pretension for Pre-Installation Verification for Common Stainless Steel Structural Bolting Assemblies					
Nominal Bolt Diameter, d_b, in.	Minimum Bolt Pretension for Pre-Installation Verification, $T_p = 1.05T_m$, kips				
	ASTM F593 Group 1 or Group 2, Condition SH	ASTM A193/A193M Grade B8 Class 2 or ASTM A320/A320M Grade B8 Class 2	ASTM A193/A193M Grade B8M Class 2 or ASTM A320/A320M Grade B8M Class 2	ASTM A1082/ A1082M S32205	ASTM A1082/A1082M S17400 (630) Condition H1150 or ASTM F593 Group 7 S17400 (630) Condition AH
½	13	13	11	10	14
⅝	20	21	18	16	22
¾	27	31	27	23	33
⅞	37	39	34	32	46
1	49	51	45	42	60
1⅛	56	59	53	53	76
1¼	71	75	68	68	96
1⅜	81	85	76	81	115
1½	98	103	93	98	139

The accuracy of the bolt tension measurement device should be confirmed through calibration at least annually.

It is recognized in this Design Guide that a natural scatter is found in the results of the pre-installation verification testing. Furthermore, the pretensions developed in tests of a representative sample of the bolting assemblies that will be installed in the work need to be slightly higher to provide confidence that the majority of bolting assemblies will achieve the minimum required pretension as given in Equation 5-7. Accordingly, the minimum pretension to be used in pre-installation verification is 1.05 times that required for installation and inspection. This is the same process used for pre-installation verification testing of high-strength carbon steel bolting assemblies.

Table 7-1 provides the minimum bolt pretension for pre-installation verification of common stainless steel structural bolting assemblies.

The tools used to tension the structural bolting assemblies should be the same as those that will be used during production installation of all assemblies at the jobsite. Impact wrenches, if used, should be of adequate capacity and, if pneumatic, supplied with sufficient air to perform the required pretensioning of each bolt within approximately 10 seconds for bolts up to and including 1¼ in. diameter, and within approximately 15 seconds for larger bolts.

For the turn-of-nut method of installation in accordance with Section 8.2.1, pre-installation verification testing should be in accordance with Section 7.2.1.

For the combined method of installation in accordance with Section 8.2.2, pre-installation verification testing should be in accordance with Section 7.2.2.

7.2.1 Turn-of-Nut Method Pretensioning

Step 1: Snug-Tightening

Apply lubricant in accordance with Section 2.3. The type of lubricant used should also match the rotational capacity test report. The structural bolting assembly should be installed with sufficient thread engagement to the snug-tight condition in the bolt tension measurement device using the tools, bolting components, assembly configuration, and installation methods to be used in the work.

Step 2: Matchmarking

If matchmarking is to be used in the work, the bolting assembly should be match-marked.

Step 3: Pretensioning

Turn the nut of the structural bolting assembly to tighten it until the bolt reaches the tension value specified in Equation 7-1. Round the nut rotation value up to the nearest multiple of 60°. Record the rounded nut rotation value and the tension value.

Step 4: Final Verification

Continue tightening the structural bolting assembly up to the rounded nut rotation value from the previous step. Verify that the bolt tension is still greater than the minimum bolt tension specified in Equation 7-1. If the bolt tension is not greater, the cause(s) should be determined and resolved before the structural bolting assemblies are used in the work. Cleaning, re-application of lubrication, and retesting of these structural bolting assemblies is permitted provided that all assemblies are treated in the same manner.

Step 5: Determination of Required Nut Rotation

The maximum rounded nut rotation values determined in Step 3 from three tests will be the required nut rotation for the turn-of-nut method of installation to be used in the work.

7.2.2 Combined Method Pretensioning

Step 1: Initial Tensioning and Determination of Initial Torque Range

Apply lubricant in accordance with Section 2.3. The type of lubricant used should also match the rotational capacity test report. The structural bolting assembly should be installed with sufficient thread engagement in the bolt tension measurement device using the tools, bolting components, assembly configuration, and installation methods to be used in the work.

Tension the structural bolting assembly until the bolt reaches the tension value of $0.20T_m$. Record the tension and torque values for three tests. Tools used should demonstrate or have certified output that does not vary by more than ±10% during use. For carbon steel bolting assemblies, the RCSC *Specification* specifies a pre-installation verification tension of 45% of the specified minimum pretension for the combined method. For stainless steel bolting assemblies, the pre-installation verification tension is only 20% of the specified minimum pretension for the combined method. This difference is because torque values at greater bolt forces are more variable for stainless steel bolting assemblies.

Take the average torque value for the three tests and round it up to the nearest 10 ft-lbs to determine the minimum torque that is used to define the initial torque range required for the combined method installation to be used in the work.

Calculate the maximum torque that is used to define the initial torque range for the combined method of installation using Equation 7-2:

$$Q_{max} = 0.04\left(\frac{1,000}{12}\right)T_m d_b \tag{7-2}$$

where

Q_{max} = maximum torque of the initial torque range used for the combined method of installation, ft-lbs (rounded up to the nearest 10 ft-lbs)

T_m = minimum bolt pretension, kips (from Section 5.4)

d_b = nominal diameter of bolt, in.

This equation includes two 0.20 factors, of which their product is 0.04. The first 0.20 factor represents that the bolt tension used in this step is equal to $0.20T_m$. Rationale for this value is provided previously in this section. The second 0.20 factor represents the maximum torque coefficient for stainless steel structural bolting assemblies. For carbon steel bolting assemblies, the maximum torque coefficient value is 0.25, as indicated in ASTM F3125/F3125M, Annex A.2. The maximum torque coefficient for stainless steel bolting assemblies is smaller to prevent galling. The (1000) factor in this equation represents unit conversions to convert the tensile force from kips to pounds and the length from inches to feet.

Step 2: Matchmarking

If matchmarking is to be used in the work, the structural bolting assembly should be match-marked.

Step 3: Pretensioning

Turn the nut of the structural bolting assembly to tighten it until the bolt reaches the tension value specified in Equation 7-1. Round the nut rotation value up to the nearest multiple of 60°. Record the rounded nut rotation value and the tension value.

Step 4: Final Verification

Continue tightening the structural bolting assembly up to the rounded nut rotation value from the previous step. Verify that the bolt tension is still greater than the minimum bolt tension specified in Equation 7-1. If the bolt tension is not greater than the minimum bolt tension specified in Equation 7-1, the cause(s) should be determined and resolved before the assemblies are used in the work. Cleaning, re-application of lubrication, and retesting of these structural bolting assemblies is permitted provided that all assemblies are treated in the same manner.

Step 5: Determination of Required Nut Rotation

The maximum rounded nut rotation values determined in Step 3 from the three tests will be the required nut rotation for the combined method of installation to be used in the work.

Chapter 8
Installation

The storage and lubrication of bolting assemblies and bolting components should comply with the guidance in Sections 2.9 and 2.3, respectively. For joints that are designated in the contract documents as snug-tightened joints, the bolting assemblies should be installed in accordance with Section 8.1. For joints that are designated in the contract documents as pretensioned joints or slip-critical joints, the bolting assemblies should be installed in accordance with Section 8.2.

Additional information on installation is given in AISC 313, *Code of Standard Practice for Structural Stainless Steel Buildings* (AISC, 2021a).

8.1 SNUG-TIGHTENED JOINTS

Snug-tightened joints should comply with all of the following:

1. All bolt holes should be aligned to permit insertion of the bolts without undue damage to the threads.
2. Bolts should be placed in all holes with washers positioned in accordance with Section 6.1 and nuts threaded onto the bolt with sufficient thread engagement to complete the assembly.
3. Compacting the joint should progress systematically from the most rigid part of the joint.
4. A lubrication designed for stainless steel threaded parts should be applied in accordance with Section 2.3.
5. The joint should be installed to the snug-tight condition with sufficient thread engagement.

The snug-tightened condition is typically achieved with a few impacts of an impact wrench or the full effort of a worker using an ordinary spud wrench. More than one cycle through the bolt pattern may be needed to achieve the snug-tightened condition.

The actual tensions that result in individual bolts in snug-tightened joints will vary from joint to joint depending upon the thickness, flatness, and degree of parallelism of the connected plies, as well as the effort applied. In most joints, plies of joints involving material of ordinary thickness and flatness can be drawn into firm contact at relatively low levels of bolt tension. However, in some joints in thick material or in material with large burrs, it may not be possible to achieve faying surface contact at all bolt hole locations as is commonly achieved in joints of thinner plates. This is generally not detrimental to the performance of the joint.

8.2 PRETENSIONED JOINTS AND SLIP-CRITICAL JOINTS

The pre-installation verification procedures specified in Chapter 7 should be performed using bolting assemblies that are representative of the condition of those that will be pretensioned in the work. Pretensioned joints and slip-critical joints should comply with the following.

1. One of the following installation methods should be used to pretension the bolting assemblies in the joint:
   - For bolting assemblies listed in Section 2.1, either the method in Section 8.2.1 (turn-of-nut method) or the method in Section 8.2.2 (combined method) may be used.
2. For pretensioned installation using the turn-of-nut method in accordance with Section 8.2.1:
   - All bolting assemblies should be installed to the snug-tight condition in accordance with Section 8.1, lubrication should be in accordance with Section 2.3, and washers should be positioned in accordance with Section 6.2.
   - Subsequently, the installation method verified for the bolting assemblies should be used as specified in Section 8.2.1.
3. For pretensioned installation using the combined method in accordance with Section 8.2.2:
   - All bolting assemblies should first be installed in accordance with Section 8.1, list items 1, 2, and 3; lubrication applied in accordance with Section 2.3; and washers positioned in accordance with Section 6.2. Each bolting assembly should be tightened by application of the initial torque as determined in the pre-installation verification testing, and the plies should be brought into firm contact with sufficient thread engagement. The initial torque should be applied only by turning the nut.
   - Subsequently, the bolting assemblies should be installed as specified in Section 8.2.2.

For all methods, the part not turned by the wrench should be prevented from rotating during pretensioning. When it is impractical to turn the nut, pretensioning by turning the bolt head is permitted while rotation of the nut is prevented, provided that the washer requirements in Section 6.2 are met. Upon completion of pretensioning, it is not permitted to turn the nut or the bolt head in the loosening direction except for the purpose of complete removal of the individual bolting assembly. Removed bolting assemblies should not be reused except as permitted in Section 2.10.

With all installation methods, it is important to first install bolts in all holes of the joint and to compact the joint until the connected plies are in firm contact. Only after completion of this operation can the joint be reliably pretensioned. Both the initial phase of compacting the joint and the subsequent phase of pretensioning should begin at the most rigidly fixed or stiffest point.

In some joints in thick material, it may not be possible to reach continuous contact throughout the faying surface area, as is commonly achieved in joints of thinner plates. This is not detrimental to the performance of the joint. If the specified pretension is present in all bolting assemblies of the completed joint, the clamping force, which is equal to the total of the pretensions in all bolting assemblies, will be transferred at the locations that are in contact, and the joint will be fully effective in resisting slip through friction.

If individual bolting assemblies are pretensioned in a single continuous operation in a joint that has not first been properly compacted or fitted up, the pretension in the bolting assemblies that are pretensioned first may be relaxed or removed by the pretensioning of adjacent bolting assemblies. The resulting reduction in total clamping force will reduce the slip resistance.

8.2.1 Turn-of-Nut Method Pretensioning

After the snug-tightening operation has been performed, the nut or head rotation—as determined in Section 7.2.1, Step 3, during pre-installation verification—should be applied to all bolting assemblies in the joint, progressing systematically from the most rigid part of the joint in a manner that will minimize relaxation of the previously pretensioned bolting assemblies.

Similar to carbon steel bolting assemblies, proper implementation of the turn-of-nut method is dependent upon ensuring that the joint is properly compacted prior to application of the required partial turn and that the bolt head (or nut) remains stationary when the nut (or bolt head) is being turned.

Match-marking of the nut and protruding end of the bolt after snug-tightening can be helpful in the subsequent installation process and is certainly an aid to inspection.

8.2.2 Combined Method Pretensioning

After application of the initial torque—as determined in Section 7.2.2, Step 1, during pre-installation verification—and after the plies have been brought into firm contact, the nut rotation—as determined in Section 7.2.2, Step 3, during pre-installation verification—should be applied to all bolting assemblies in the joint, progressing systematically from the most rigid part of the joint in a manner that will minimize relaxation of previously pretensioned bolting assemblies.

The combined method relies on an established relationship between fastener torque and tension to achieve or surpass the prescribed initial tension. Next, the nut (or bolt) is rotated by a designated additional amount relative to the bolt (or nut) to reliably achieve the minimum specified pretension. This final pretensioning step is similar to the turn-of-nut method, but the angle of rotation is different and likely to be smaller because it is relative to the initial tension condition of the combined method, which is usually greater than the minimum snug condition required for the turn-of-nut method. Matchmarking of the nut and protruding end of the bolt after initial tensioning can be helpful in subsequent installation and as an aid to inspection.

Bolting assemblies used for the combined method should be treated as matched bolting assemblies.

Chapter 9
Inspection

Inspection tasks prior to and during bolting should be performed in accordance with the invoking specification or standard as stated in this chapter.

ANSI/AISC 370, Chapter N, contains the requirements for inspection of stainless steel bolting assemblies.

Generally, torque measurements do not provide consistent results for inspection, as they are greatly dependent on the friction between the bolting components, which is influenced by the effectiveness of the lubrication. Routine observation of installation methods is always preferred.

9.1 SNUG-TIGHTENED JOINTS

Prior to the start of work, it should be verified that all bolting components to be used in the work meet the requirements in Chapter 2. This includes verifying that a lubrication designed for stainless steel threaded parts has been applied in accordance with Section 2.3 prior to bolting assembly installation. Subsequently, it should be verified that all connected plies meet the requirements of Section 3.1 and all bolt holes meet the requirements in Sections 3.3 and 3.4. After the connections have been assembled to the requirements of Section 8.1, it should be visually verified that the plies of the connected elements have been brought into firm contact, that sufficient thread engagement exists for all bolts and that washers have been used in accordance with Chapter 6. No further evidence of conformity is necessary for snug-tightened joints.

Inspection requirements for snug-tightened joints consist of verification that the proper bolting components were used, the connected elements were fabricated properly, the bolted joint was drawn into firm contact, and the bolting assemblies appear to be in the snug-tightened condition. Because pretension is not necessary for the proper performance of a snug-tightened joint, the installed bolts should not be inspected to determine the actual installed pretension.

9.2 PRETENSIONED JOINTS

For pretensioned joints, the following inspection should be performed in addition to that in Section 9.1:

1. For all pretensioned joints, the specific type, application method, and placement location of the lubrication should be verified to be in accordance with Section 2.3 prior to bolting assembly installation.
2. When the turn-of-nut method is used for pretensioning, the inspection should be in accordance with Section 9.2.1.
3. When the combined method is used for pretensioning, the inspection should be in accordance with Section 9.2.2.

When joints are designated as pretensioned, they are not subject to the same faying surface inspection requirements that are specified for slip-critical joints in Section 9.3.

9.2.1 Turn-of-Nut Method Pretensioning

The inspector should:

1. Observe the pre-installation verification testing in Chapter 7.
2. Verify by routine observation that the snug-tight condition has been achieved in accordance with Section 8.1.
3. Verify by routine observation that the bolting crew subsequently rotates the turned element relative to the unturned element by the amount as determined in Section 7.2.1, Step 3, during pre-installation verification. Alternatively, when bolting assemblies are match-marked after snug-tightening of the joint but prior to pretensioning, visual inspection after pretensioning is permitted in lieu of routine observation. No further evidence of conformity is necessary.

A pretension that is greater than the value as determined in Section 5.4 should not be the cause for rejection. A rotation that exceeds the required values as determined in Section 7.2.1, Step 3, should not be cause for rejection.

Matchmarking of the assembly during installation improves the ability to inspect bolts that have been pretensioned with the turn-of-nut method. Impact tools should not be used because they increase the propensity for galling.

Proper inspection of the bolting assemblies includes observing the required pre-installation verification testing of the bolting assemblies and the method to be used, monitoring the work in progress to verify that the method is routinely and properly applied, or visually inspecting match-marked assemblies.

9.2.2 Combined Method Pretensioning

The inspector should:

1. Observe the pre-installation verification testing in Chapter 7.
2. Verify by routine observation that the bolting crew applies the initial torque to the turned element, as determined in Section 7.2.2, Step 1, during pre-installation verification, that the plies have been brought into firm

contact, and that the requirements of Section 8.1 have been met.

3. Verify by routine observation that the bolting crew properly rotates the turned element relative to the unturned element by the amount as determined in Section 7.2.2, Step 3, during pre-installation verification. Alternatively, when bolting assemblies are match-marked after the initial application of the torque, but prior to pretensioning, visual inspection after pretensioning is permitted in lieu of routine observation. No further evidence of conformity is required.

A pretension that is greater than the value specified in Section 5.4 should not be the cause for rejection. A rotation that exceeds the required values, including tolerance, as determined in Section 7.2.2, Step 3, should not be cause for rejection.

Matchmarking of the assembly during installation improves the ability to inspect bolts that have been pretensioned with the combined method.

Proper inspection of the bolting assemblies includes observing that the required initial torque is applied to the bolting assemblies in the joint and that the plies have been brought into firm contact before the prescribed rotation is applied to the turned element. Subsequently, the inspector should observe that the prescribed rotation was applied.

9.3 SLIP-CRITICAL JOINTS

Prior to assembly, it should be visually verified that the faying surfaces of slip-critical joints meet the requirements in Section 3.2. Subsequently, the inspection in Section 9.2 should be performed.

When joints are specified as slip-critical joints, it is necessary to verify that the faying surface condition meets the requirements as specified in the contract documents prior to assembly of the joint and that the bolts are properly pretensioned after they have been installed.

9.4 JOINTS BETWEEN DISSIMILAR METALS

In addition to carrying out inspection in accordance with Sections 9.1, 9.2, or 9.3, as applicable, the following additional inspection tasks are required for joints between dissimilar metals.

Prior to assembly, it should be visually verified that the isolation system has been installed as specified. If an insulation system has been used, it should be verified that (1) the material of the insulation system matches what was specified, (2) an insulating washer has been installed between the stainless steel bolting assemblies and the carbon steel plates, (3) an insulating gasket has been installed between the stainless steel plates and the carbon steel plates, and (4) an insulating bushing has been installed into the bolt hole and is located in between the stainless steel bolting assembly and the carbon steel plate. The insulating washer should have an outer diameter greater than or equal to the stainless steel washer of the bolting assembly. The insulating bushing should be slightly shorter than the combined thickness of the connected plates. The entire insulation system should be inspected for damage prior to installation. If damage is found, the insulation system should be discarded and replaced with an undamaged one.

If a coating system has been used, it should be verified that the coating system matches what was specified. It should be visually verified that the coating system covers both sides of the carbon steel plate for at least the length of the faying surface. The coating system should be inspected for damage prior to installation. If damage is found, the coating system should be re-coated prior to continuing installation.

Chapter 10
Arbitration

When it is suspected after inspection that bolts in pretensioned or slip-critical joints do not have the proper pretension in accordance with Sections 9.2 or 9.3, the following arbitration procedure is recommended.

1. A representative sample of five bolting assemblies of each combination of diameter, length, alloy, lot, and lubrication in question should be installed in a bolt tension measurement device. The specific type, application method, and location of lubrication should be in accordance with Section 2.3. The material under the turned element should be the same as in the actual installation—that is, the steel plate or a hardened washer. The bolt should be partially tightened to approximately 15% of the pretension specified in Section 5.4. Subsequently, the bolt should be pretensioned to the minimum value indicated in Section 5.4.
2. A torque wrench that indicates torque by means of a readout, or one that may be adjusted to give an indication that a defined torque has been reached, should be applied to the pretensioned bolt. The torque that is necessary to rotate the nut or bolt head 5° (approximately 1 in. at 12 in. radius) relative to its mating component in the tightening direction should be determined.
3. The arbitration torque should be determined by rejecting the high and low values and averaging the remaining three.
4. Bolts represented by the preceding sample should be tested by applying the arbitration torque in the tightening direction to 10% of the bolting assemblies, but no fewer than two bolting assemblies, selected at random in each joint in dispute. If no nut or bolt head is turned relative to its mating component by the application of the arbitration torque, the joint should be accepted as properly pretensioned.

If verification of bolt pretension is needed after the passage of a period of time and exposure of the completed joints, an alternative arbitration procedure that is appropriate to the specific situation should be used.

If any nut or bolt is turned relative to its mating component by an attempted application of the arbitration torque, all bolts in the joint should be tested. Those bolts whose nut or head is turned relative to its mating component by the application of the arbitration torque should be removed, replaced, and pretensioned by the fabricator or erector and reinspected. Alternatively, the fabricator or erector, at their option, may remove, replace, and pretension all of the bolts in the joint and subsequently resubmit the joint for inspection.

Other arbitration methods as agreed upon by the parties and approved by the EOR are acceptable.

Appendix A
Examples of How to Specify Stainless Steel Bolted Assemblies

Austenitic stainless steel 302HQ (30430) condition CW2 nonstructural bolting assembly from ASTM F593:

- Quantity: 50 pieces. Hex bolt in accordance with ASTM F593 S30433 Group 1 302HQ. ⅝ in. diameter × 3 in. long. Dimensions in accordance with ASME B18.2.1 for hex bolt.
- Quantity: 50 pieces. Hex nut in accordance with ASTM F594 S30433. For ⅝-in.-diameter bolt. Dimensions in accordance with ASME B18.2.2 for hex nut.
- Quantity: 50 pieces. Flat washer. For ⅝-in.-diameter bolt. Chemistry meeting the requirements of ASTM F594 S30433. Minimum hardness of 40 HRC, tested according to Sections 9 and 10 of ASTM F436/F436M. Dimensions in accordance with Section 7 of ASTM F436/F436M for hardened circular washer.

Austenitic stainless steel 316 (S31600) Class 1 nonstructural bolting assembly from ASTM A320/A320M:

- Quantity: 500 pieces. Hex bolt in accordance with ASTM A320/A320M S31600 Grade B8M Class 1. ½ in. diameter × 2 in. long. Dimensions in accordance with ASME B18.2.1 for hex bolt.
- Quantity: 500 pieces. Hex nut in accordance with ASTM A194/194M 8M. For ½-in.-diameter bolt. Dimensions in accordance with ASME B18.2.2 for hex nut.
- Quantity: 500 pieces. Flat washer. For ½-in.-diameter bolt. Chemistry meeting the requirements of ASTM A320/A320M S31600. Minimum hardness of 40 HRC, tested according to Sections 9 and 10 of ASTM F436/F436M. Dimensions in accordance with Section 7 of ASTM F436/F436M for hardened circular washer.

Austenitic stainless steel 304 (S30400) Class 2 structural bolting assembly from ASTM A193/A193M:

- Quantity: 5,000 pieces. Heavy hex bolt in accordance with ASTM A193/A193M S30400 Grade B8 Class 2. ¾ in. diameter × 3.5 in. long. Dimensions in accordance with ASME B18.2.6 for heavy hex structural bolt.
- Quantity: 5,000 pieces. Heavy hex nut in accordance with ASTM A194/A194M Grade 8. For ¾-in.-diameter bolt. Dimensions in accordance with ASME B18.2.6 for heavy hex nut.
- Quantity: 5,000 pieces. Flat washer. For ¾-in.-diameter bolt. Chemistry meeting the requirements of ASTM A240/A240M S30400. Minimum hardness of 40 HRC, tested according to Sections 9 and 10 of ASTM F436/F436M. Dimensions in accordance with Section 7 of ASTM F436/F436M for hardened circular washer.
- Bolting assemblies should meet the rotational capacity requirements in Appendix C.

Duplex stainless steel 2205 (S32205) structural bolting assembly:

- Quantity: 10,000 pieces. Heavy hex bolt in accordance with ASTM A1082/A1082M S32205. ⅞ in. diameter × 4 in. long. Dimensions in accordance with ASME B18.2.6 for heavy hex structural bolt.
- Quantity: 10,000 pieces. Heavy hex nut in accordance with Section 9 of ASTM A1082/A1082M S32205. For ⅞-in.-diameter bolt. Dimensions in accordance with ASME B18.2.6 for heavy hex nut.
- Quantity: 10,000 pieces. Flat washer for ⅞-in.-diameter bolt. Chemistry meeting the requirements of ASTM A240/A240M UNS S32205. Minimum hardness of 30 HRC, tested according to Sections 9 and 10 of ASTM F436/F436M. Dimensions in accordance with Section 7 of ASTM F436/F436M for hardened circular washer.
- Bolting assemblies should meet the rotational capacity requirements in Appendix C.

Precipitation-hardening stainless steel 17-4 PH (S17400) Condition H1150 structural bolting assembly from ASTM F593:

- Quantity: 200 pieces. Heavy hex bolt in accordance with ASTM F593 Group 7 S17400. 1 in. diameter × 5 in. long. Dimensions in accordance with ASME B18.2.6 for heavy hex structural bolt.
- Quantity: 200 pieces. Heavy hex nut in accordance with ASTM F594 Group 7 S17400. For 1-in.-diameter bolt. Dimensions in accordance with ASME B18.2.6 for heavy hex nut.
- Quantity: 200 pieces. Flat washer. For 1-in.-diameter bolt. Chemistry meeting the requirements of ASTM A240/A240M S17400. Minimum hardness of 40 HRC, tested

according to Sections 9 and 10 of ASTM F436/F436M. Dimensions in accordance with Section 7 of ASTM F436/F436M for hardened circular washer.

- Bolting assemblies should meet the rotational capacity requirements in Appendix C.

Appendix B
Joints between Dissimilar Metals

This appendix gives guidance on how to design joints between dissimilar metals to avoid issues associated with galvanic corrosion.

When designing a joint, due consideration should be given to all types of corrosion that might affect the bolting components and connected elements. In all cases, the bolting components should be made of a stainless steel alloy that has equivalent or greater corrosion resistance than the connected elements.

Section 2.7 gives guidance on the different types of corrosion that may affect stainless steel and the selection of the appropriate alloy for different environments, with further guidance also available in the ANSI/AISC 370 Commentary (AISC, 2021b) and AISC Design Guide 27 (Baddoo and Meza, 2022).

B.1 GALVANIC CORROSION

Galvanic corrosion can occur when two dissimilar metals are in direct electrical contact with each other and are also bridged by an electrolyte solution. It is also known as bimetallic corrosion, or dissimilar metal corrosion. The electrolyte solution may consist of any electrically conducting liquid such as seawater, impure fresh water, rainwater, dew, fog, high humidity, condensation, etc., or it can be a wet solid material such as a poultice or another hygroscopic material. Under these circumstances, an electrical current flows from the anodic metal—that is, the less noble metal—to the cathodic—or more noble—metal through the electrolyte solution, leading to the less noble metal corroding at higher rates than would be expected for the service environment. The more noble metal does not corrode due to the galvanic contact, and in fact, it is protected against corrosion by the less noble metal.

The prediction of the rate at which the less noble metal corrodes is determined by a number of complex issues, including the conductivity of the electrolyte solution, the type of metals being connected (i.e., their relative galvanic potentials), the relative surface area of the metals in contact, and the time of wetness.

Because of this, galvanic corrosion will be more severe in joints that are exposed to seawater than to most fresh waters, which are likely to have lower conductivity. Although rainwater in clean rural environments can be expected to have low conductivity, fuel combustion products may dissolve in rainwater in more polluted environments, or sea salts in coastal environments, resulting in water of moderately high conductivity. In a similar way, moisture from the air can dissolve contaminants, such as deicing salts on bridges, creating the conditions for galvanic corrosion. Galvanic corrosion is likely to be more severe under immersed conditions than in atmospheric conditions, with the level of severity being dependent on the time the galvanic contact remains wet and increased by the presence of crevices in the joint. It is therefore recommended that immersed joints between dissimilar metals should be avoided; bimetallic interfaces in atmospheric environments are far less likely to lead to problems.

Interior applications, such as schools, offices, warehouses, or residences with typical temperature and humidity for human occupancy are generally not susceptible to galvanic corrosion.

If the surface area of the more noble metal that is in contact with the electrolyte is large compared to that of the less noble metal, the electrical current produced by the noble metal will be larger and will concentrate in the small area of the less noble metal, accelerating its rate of corrosion. This effect increases with larger differences in surface area, which is one of the reasons stainless steel bolting components should always be used in joints connecting stainless steel elements to dissimilar metals. In atmospheric conditions, bimetallic corrosion is usually localized in the vicinity of the line of contact.

As mentioned previously, the severity of the galvanic corrosion is dependent on the relative galvanic potentials of the connected metals. Table B-1 gives an indication of the susceptibility to galvanic corrosion of common metals in contact with stainless steel in five different environments, three atmospheric and two immersed. The information in the table was extracted from PD 6484, "Commentary on Corrosion at Bimetallic Contacts and its Alleviation" (BSI, 1979). In all these cases, stainless steel will constitute the more noble metal and will, therefore, not corrode due to the galvanic contact. The table only considers galvanic corrosion, and therefore, the ratings should not be taken to imply that the metals in contact need no protection under any conditions of exposure. The ratings given in the table assume the metals in contact have the same wetted area. They may not consider all the different factors that can affect galvanic corrosion and should, therefore, only be regarded as an approximate indication of the response of the less noble metal to galvanic corrosion, which may be useful for an initial assessment. Galvanic corrosion between different stainless steel alloys is hardly ever a concern and then only under fully immersed conditions.

Table B-1. Susceptibility to Galvanic Corrosion of Some Common Metals in Contact with Stainless Steel					
Metal In Contact with Stainless Steel	Environment				
	Atmospheric			Immersed	
	Rural	Industrial/ Urban	Marine	Fresh Water	Seawater
Aluminum and aluminum alloys	0	1	2	2	3
Carbon and low alloy steels	1	—	2 to 3	2	2 to 3
Zinc and galvanized steels	0 to 1	0 to 1	0 to 1	0 to 2	1 to 2

Ratings:
0 The metal will suffer either no additional corrosion or, at the most, only very slight additional corrosion, usually tolerable in service.
1 The metal will suffer slight or moderate corrosion that may be tolerable in some circumstances.
2 The metal may suffer fairly severe additional corrosion, and protective measures will usually be necessary.
3 The metal may suffer severe additional corrosion, and the contact should be avoided.
— No general guidance is given due to lack of evidence.

Table B-1 shows that in a dissimilar joint between stainless steel and galvanized steel, the galvanized steel element may be susceptible to galvanic corrosion even under atmospheric conditions. If the relative wetted surface area of the galvanized steel is smaller than that of the stainless steel, the behavior can be expected to be significantly worse than shown in the table. Therefore, if galvanized carbon steel bolts were used to connect stainless steel elements, first the zinc coating would start to corrode, and after it has dissolved and exposed the underlying carbon steel, the bolt would corrode at an even faster rate. A stainless steel bolt connecting two less noble metals will not have an accelerated corrosion rate in the presence of an electrolyte.

Areas of the metal that are coated with an inert coating like paint—for example, coated carbon steel—should not be considered when assessing surface area, but the potential loss of paint due to abrasion or deterioration should be considered.

It is usually helpful to draw on previous experience in similar sites because dissimilar metals can often be safely coupled under conditions of occasional condensation or dampness with no adverse effects, especially when the conductivity of the electrolyte is low.

The main strategies to prevent the galvanic corrosion of the metal in contact with stainless steel, assuming that it cannot be replaced with stainless steel, consist of:

1. Insulating the dissimilar metals from each other (i.e., breaking the metallic path).
2. Preventing the formation of a continuous bridge of electrolyte solution between the two metals (i.e., breaking the electrolytic path).

The method of isolation should be appropriate for the type of exposure and should not permit moisture infiltration into the joint, particularly in immersed or otherwise regularly wet applications.

The following section discusses different design alternatives that may be used to insulate the dissimilar metals in bolted joints situated in nonimmersed environments while ensuring that the structural performance of the joint is maintained.

B.2 DESIGN OF JOINTS BETWEEN DISSIMILAR METALS

This section describes two options for breaking the bimetallic contact in bolted joints between dissimilar metals that are situated in water-shedding (nonimmersed) environments. Other solutions may also be successful at preventing galvanic corrosion in bolted joints, and this Design Guide does not discourage their use. However, due consideration should be taken of the structural performance of the joint and how it may be affected by any of the measures adopted to prevent galvanic corrosion.

For structures exposed to immersed environments, it is recommended that any bolted joint between dissimilar metals is moved away from the immersed zone.

If a slip-critical joint between dissimilar metals is likely to be exposed to high temperatures, the greater thermal expansion of the stainless steel bolt (in particular an austenitic stainless steel bolt) compared to carbon steel plate material should be taken into consideration as it could lead to a decrease in the bolt pretension. In these situations, the use of austenitic stainless steel bolts is not recommended. Note that this does not apply to joints designed for accidental situations such as fire, for which slip at the joint is usually acceptable.

B.2.1 Insulating Bushing, Washer, and Gasket

With this option, the separation between the dissimilar metal and the stainless steel bolt and connecting plate is achieved by using an insulating bushing, washer, and gasket, as shown in Figure B-1. The galvanic separation shown in the figure is suitable for snug-tightened joints in water-shedding atmospheric applications. It would not be an appropriate design for a regularly or continuously immersed condition or where crevice corrosion of the stainless steel was a concern. As an alternative, an insulating washer may be included between the stainless steel plate and the stainless steel washer to limit moisture infiltration into the joint. In most cases, the insulating bushing and washer on the non-stainless steel side consists of one single piece, while the insulating washer on the stainless steel side comes as a separate piece. This ensures better insulation of the non-stainless steel plate from the stainless steel bolting components. The bushing should be slightly shorter than the combined thickness of the connected plates to avoid compressing it—and therefore causing damage—when snug-tightening the bolt.

Insulating components are commonly made of thermoset plastics like neoprene, nylon, mylar, G10/G11 glass epoxy, PTFE (Teflon), or phenolic resin, among others, because of their resistance to degradation. The designer should ensure that the bushing is able to resist the bearing pressure at the bolt holes that the joint is designed to resist. Many bushings are dimensioned to fit into standard size bolt holes. To prevent damage of the bushing due to punching of the bolt threads when the bolt bears onto the bolt hole, it is recommended that the joint is designed with the bolt threads excluded from the shear plane. An insulating washer can be very thin but should be sufficient to prevent burrs or other imperfections from perforating it.

The use of insulating washers and gaskets is not recommended for pretensioned or slip-critical bolted connections because they may exacerbate the loss of pretension in the bolt, especially when the pretension value is high. The use of insulating gaskets between the faying surfaces will also affect the slip resistance of the joint. There is no known published test data or research on the effect that insulating washers and gaskets have on pretensioned or slip-critical bolted connections.

B.2.2 Coating the Less Noble Metal

Another way of separating the dissimilar metals is to protect the less noble metal with a waterproof coating such as an epoxy coating or metal primer and paint system, as shown in Figure B-2. This type of solution is suitable for pretensioned and slip-critical joints because it does not require the introduction of insulating materials within the joint. However, the effect the coating and condition of the faying surfaces have on the slip coefficient should be established by tests. At the time of publication, there are no known published slip coefficient test results between coated carbon steel and stainless steel faying surfaces.

The coating used on the less noble metal should meet all the requirements imposed on the coating used in slip-critical joints made of carbon steel. When coating galvanized steel, additional consideration should be given to potential loss of pretension. If the stainless steel connected element is painted to provide additional protection against galvanic corrosion, the passive film should be abrasively or chemically removed

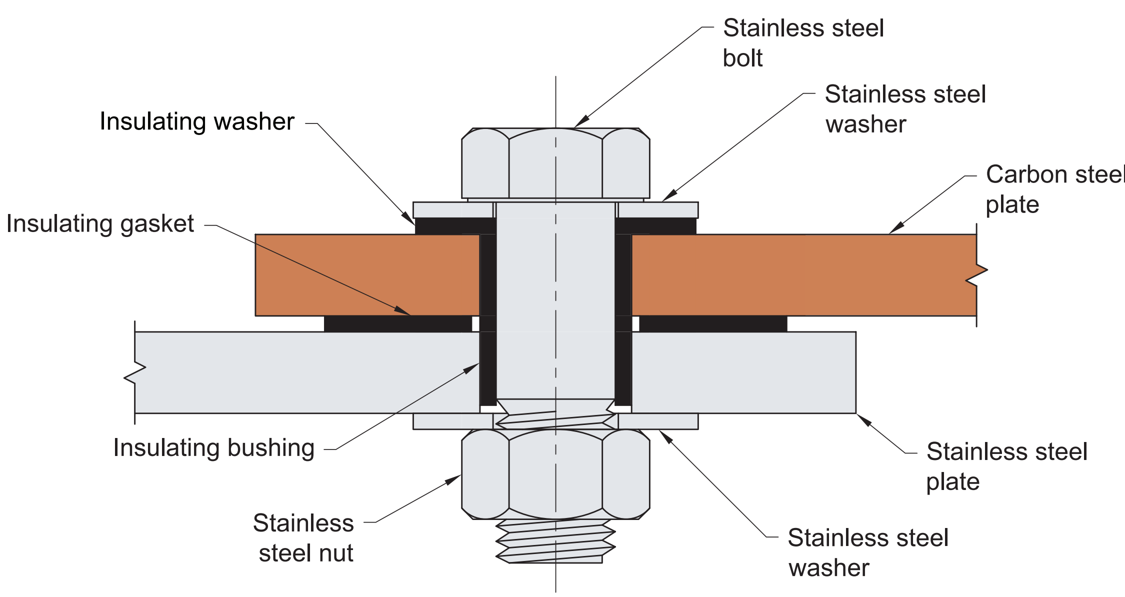


Fig. B-1. Galvanic separation for a snug-tightened joint using an insulating bushing, washer, and gasket in a water-shedding service environment.

immediately before application of the metal primer, or a suitable etchant primer should be used.

As an additional means of protection, an insulating bushing may be installed to separate the stainless steel bolt from the less noble metal. This option may be considered because it is not always easy to ensure that the inside of the bolt hole is coated. However, the inside of the bolt hole is somewhat protected from ingress of an electrolyte solution by the bolting components, and even if galvanic corrosion takes place, this will most likely be limited to the edge of the bolt hole.

To enhance galvanic separation, stainless steel bolts can also be coated with zinc and aluminum flake coatings.

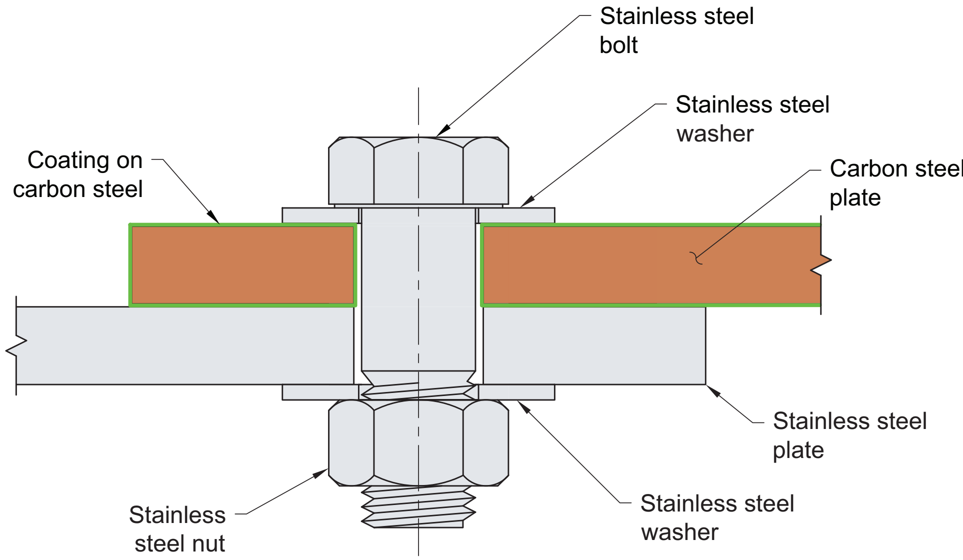


Fig. B-2. Galvanic separation for bolted joints using waterproof coatings in a water-shedding service environment.

Appendix C
Procedure for a Rotational-Capacity Test for Stainless Steel Bolting Assemblies

C.1 SCOPE

This test procedure details the rotational capacity test for stainless steel structural bolting assemblies intended to evaluate the effectiveness of the lubricant and the compatibility of bolting components. The test serves as a further quality control measure against material with insufficient ductility and generally assures the assembly of elements (bolt, nut, washer, and lubricant) will function together as a unit to achieve required pretension values. When tested to meet the requirements of this appendix, assemblies should be purchased and installed as matched sets consisting of a heavy hex structural bolt or heavy hex cap screw, heavy hex nut, at least one hardened washer, and lubricant.

Note that the lubrication is included in the bolting assembly for stainless steel. This is different from carbon steel bolting assemblies, which only include the bolt, nut, and washer. Stainless steel threads are susceptible to galling, as explained in Section 2.4. Not all lubricants designed for stainless steel threaded parts will provide similar performance. Lubricants containing molybdenum disulfide or PTFE have good performance history of use with pretensioned stainless steel bolts. The manufacturer, or another responsible party, is responsible for selection of the lubricant used during testing.

Not all structural bolting assembly combinations will be able to develop the minimum testing requirements in this test procedure. If a structural bolting assembly fails to meet the minimum requirements, one or more of the elements may be substituted and the new assembly tested. The performance of stainless steel structural bolting assemblies can be improved with better lubrication.

The test method in this appendix follows the general Rotational Capacity Test requirements as specified in ASTM F3125/F3125M, Annex A2, but has been modified for stainless steel structural bolting assemblies. The test is intended primarily for stainless steel structural bolting assemblies as defined in Section 2.5 to be used in fully tensioned structural applications.

When specified in contract documents, this test may also be used for field testing. It is the intent of this test that the bolts, nuts, and washers of the assembly lot be packaged together in the same shipping container when practical to maintain lot integrity. Research has not been done on all types, heat treatments, strengths, diameters, lengths, lubricants, etc., of stainless steel bolting assemblies available; therefore, some of the requirements in this test are extrapolated from existing requirements. The purchaser and supplier should consider any additional investigation necessary to establish appropriate testing guidelines.

C.2 TESTING

C.2.1 Requirement

Assemblies should be tested in an assembled joint or tension-measuring device in accordance with Test Method 1 or Test Method 2, as given in Sections C.3 and C.5, and should meet the acceptance criteria given in Sections C.4 or C.6, respectively.

C.2.2 Testing Responsibility

Each lot of bolting assemblies should be tested by the manufacturer or responsible party prior to shipment, but after lubrication or any secondary processing of components.

When the bolts are furnished by a source other than the manufacturer, the responsible party should ensure all tests have been performed and the bolts comply with the requirements of this test method.

Sampling should be made to ASTM F1470 (ASTM, 2024a), except that a minimum of three bolting assemblies should be tested regardless of lot quantity. Alternate sampling may be agreed upon between the supplier and purchaser.

C.3 METHOD 1—LONG BOLT TEST PROCEDURE

C.3.1 Equipment Required

The following equipment is needed to perform Test Method 1:

- Calibrated bolt tension-measuring device appropriate for the bolts to be used
- Calibrated torque wrench and spud wrenches
- Appropriate bushings and spacers

C.3.2 Procedure—Bolts That Fit in a Tension Measuring Device

The test procedure for bolts that fit in a tension measuring device is as follows:

- Step 1: Install the bolt and any required spacers in the tension measuring device so that the bolt stick-out is flush

Table C-1. Initial Tension Requirements for Common Stainless Steel Structural Bolting Assemblies						
Nominal Bolt Diameter, d_b, in.	Tensile Stress Area, A_s, in.^{2}	Initial Tension Requirement, $T_i = 0.10T_m$, kips				
		ASTM F593 Group 1 or Group 2, Condition SH	ASTM A193/A193M Grade B8 Class 2 or ASTM A320/A320M Grade B8 Class 2	ASTM A193/A193M Grade B8M Class 2 or ASTM A320/A320M Grade B8M Class 2	ASTM A1082/A1082M S32205	ASTM A1082/A1082M S17400 (630) Condition H1150 or ASTM F593 Group 7 S17400 (630) Condition AH
½	0.142	1	1	1	1	1
⅝	0.226	2	2	2	2	2
¾	0.334	3	3	3	2	3
⅞	0.462	4	4	3	3	4
1	0.606	5	5	4	4	6
1⅛	0.763	5	6	5	5	7
1¼	0.969	7	7	6	6	9
1⅜	1.16	8	8	7	8	11
1½	1.41	9	10	9	9	13

with the nut to a maximum of three threads stick-out. This will typically provide three to five threads within the grip.

- Step 2: Apply the proper lubrication in a light, uniform layer to the threads and the turning face of the nut.
- Step 3: Tighten the bolting assembly to the initial tension calculated using Equation C-1 with a tolerance of −0/+2 kips.

$$T_i = 0.10T_m \tag{C-1}$$

where

T_i = initial tension requirement for rotational capacity testing of stainless steel bolting assemblies, kips

T_m = minimum bolt pretension, kips
$= 0.70F_{ub}A_s$

A_s = tensile stress area of bolt, in.^{2}

F_{ub} = specified minimum tensile strength of the bolt given in the relevant ASTM standard, ksi

In Equation C-1, the 0.10 factor represents that 10% of the minimum bolt pretension is used as the initial tension in rotational capacity testing of stainless steel bolting assemblies. This is the same value as is used in the rotational capacity testing in ASTM F3125/F3125M, Annex A2. The 0.70 factor in the minimum bolt pretension equation is the same as what is used for carbon steel bolting assemblies in the RCSC *Specification*.

Table C-1 provides the initial tension requirements for high-strength stainless steel bolting assemblies. The table also includes the tensile stress areas for the given bolt diameters.

- Step 4: Match-mark the bolt, nut, and faceplate of the calibrator.
- Step 5: Tighten the bolting assembly to a tension value of at least T_m, and record the tension and torque. Round up the nut rotation to the nearest 30° and record the rounded value. The torque should be read with the nut in motion and should not exceed $0.19PD$, where P is the tension in pounds and D is the bolt diameter in feet ($D = d_b/12$). The coefficient of 0.19 is the torque coefficient for stainless steel bolting assemblies.
- Step 6: Further tighten the nut to twice the rounded rotation recorded in Step 5. The rotation is measured from the initial marking in Step 4. Assemblies that strip or fracture prior to this rotation fail the test.
- Step 7: Record the tension at the completion of the nut rotation in Step 6. The tension should equal or exceed 1.15 × the minimum bolt pretension. The 1.15 coefficient is a safety factor that ensures the bolt can develop sufficient tension above T_m. The minimum required tension at full rotation for high-strength stainless steel bolting assemblies are listed in Table C-2.
- Step 8: Loosen and remove the nut. There should be no signs of galling, thread shear failure, stripping, or torsional failure. The nut should turn by hand on the bolt threads to the position it was in during the test. The nut does not need to run the full length of the threads. Inability to turn the nut by hand is considered thread failure. Broken bolts fail the test.

Table C-2. Minimum Required Tension at Full Rotation for Common Stainless Steel Structural Bolting Assemblies					
Nominal Bolt Diameter, d_b, in.	Minimum Required Tension at Full Rotation = 1.15T_m, kips				
	ASTM F593 Group 1 or Group 2 Condition SH	ASTM A193/A193M Grade B8 Class 2 or ASTM A320/A320M Grade B8 Class 2	ASTM A193/A193M Grade B8M Class 2 or ASTM A320/A320M Grade B8M Class 2	ASTM A1082/ A1082M S32205	ASTM A1082/A1082M S17400 (630) Condition H1150 or ASTM F593 Group 7 S17400 (630) Condition AH
½	14	14	13	11	15
⅝	22	23	20	17	25
¾	30	34	30	26	36
⅞	41	43	37	35	50
1	54	56	49	46	66
1⅛	61	65	58	58	83
1¼	78	82	74	74	105
1⅜	88	93	84	88	126
1½	107	113	102	107	153

C.4 LONG BOLT ACCEPTANCE CRITERIA

The stainless steel bolting assembly lot, including lubrication type, passes this test if all samples meet the requirements of Steps 5, 7, and 8 of Section C.3.2. In addition, the lot should be considered nonconforming if the assembly experiences any of the following failures:

- Inability of the assembly to reach the rotation required in Step 6 of Section C.3.2.
- Inability to remove the nut after installing to the rotation specified in Step 6 of Section C.3.2.
- Shear failure of the threads as determined by visual examination of bolt and nut threads following removal.
- Torsional or torsional/tension failure of the bolt. Note: Elongation of the bolt, in the threads between the nut and bolt head, is to be expected and is not to be classified as a failure.

C.5 METHOD 2—SHORT BOLT TEST PROCEDURE

C.5.1 Equipment Required

The following equipment is needed to perform Test Method 2:

- Steel plate
- Calibrated torque wrench and spud wrenches
- Appropriate bushings and spacers

C.5.2 Procedure—Bolts Too Short to Fit into a Tension Measuring Device

The test procedure for bolts that are too short to fit into a tension measuring device is as follows:

- Step 1: Select three longer "surrogate" bolts that fit into the tension measuring device using no more than ½ in. of combined spacer thickness. The surrogate bolts should match the specification and diameter of the bolts which are too short to be tested in the tension measuring device.

  Unlike carbon steel bolting assemblies tested to ASTM F3125/F3125M, Annex A2, stainless steel bolts do not have tabulated installation parameters, such as the nut rotation required to reach the minimum specified pretension using the turn-of-nut installation method. For this reason, longer surrogate bolts should be tested first to determine the required nut rotation to be used for testing short bolts. The maximum thickness of hardened spacers used during the test is to prevent much longer bolts from being used as surrogates. Much longer bolts require larger nut rotations to reach the minimum specified pretension.

- Step 2: Complete the test procedure for Test Method 1 given in Section C.3 using the longer surrogate bolts combined with nuts, washers, and the lubricant in the bolting assembly to be tested. These three tests should pass the acceptance criteria given in Section C.4. If any of the tests fail, a different lot of these longer surrogate bolts may be used for testing.

- Step 3: Take the maximum recorded rounded nut rotation from Step 5 of Section C.3.2 for the three tests. This is the required nut rotation for tensioning to be used in Step 7.
- Step 4: Sample the required number of short bolt assemblies. Apply the proper lubrication in a light, uniform layer to the threads and turning face of the nut. Install the short bolt and any required spacers in the steel plate so that the bolt stick-out is flush with the nut or up to a maximum of three threads stick-out. This will typically provide three to five threads within the grip.
- Step 5: Snug the assembly in the steel plate. The torque used should not exceed $0.20 \times 1.15 \times 0.19 T_m D$, where T_m is the minimum bolt pretension from Section C.3.2 in pounds and D is the bolt diameter in feet ($D = d_b/12$).

  The maximum torque limit in this step includes three coefficients. The first coefficient of 0.20 represents the torque limit in this step, which is 20% of the maximum torque limit in Step 7. The other two coefficients are discussed in Section C.3.2.
- Step 6: Match-mark the nut, bolt, and plate.
- Step 7: Tension the bolt by rotating the nut to the required nut rotation for tensioning as determined using the longer surrogate bolts in Step 3. Prevent the bolt head from rotating. Take a torque reading at the required rotation with the nut in motion. The torque obtained should not exceed $1.15 \times 0.19 \times T_m D$, where T_m is the minimum bolt pretension from Section C.3.2 in pounds and D is the bolt diameter in feet ($D = d_b/12$). Assemblies that exceed the maximum torque limit in this step fail the test.
- Step 8: Further tighten the bolt to twice the nut rotation used in Step 7. Assemblies that strip or fracture prior to this rotation fail the test.
- Step 9: Loosen and remove the nut. There should be no signs of galling, thread shear failure, stripping, or torsional failure. The nut should turn by hand on the bolt threads to the position it was in during the test. The nut does not need to run the full length of the threads. Inability to turn the nut by hand is considered thread failure. Broken bolts fail the test.

C.6 SHORT BOLT ACCEPTANCE CRITERIA

The stainless steel bolting assembly lot, including lubrication type, passes this test if all samples meet the requirements of Steps 2, 5, 7, and 9. In addition, the lot should be considered nonconforming if the assembly experiences any of the following failures:

- Failure of the longer surrogate bolt assembly tests to meet the acceptance criteria given in Section C.4.
- Failure to achieve the required nut rotation as specified in Step 8 of Section C.5.2.
- Inability to remove the nut after installing to the rotation specified in Step 8 of Section C.5.2.
- Shear failure of the threads as determined by visual examination of bolt and nut threads following removal.
- Torsional or torsional/tension failure of the bolt. Note: Elongation of the bolt, in the threads between the nut and bolt head, is to be expected and is not to be classified as a failure.

C.7 TEST REPORTS

When specified on the purchase order, the manufacturer or supplier—whichever is the responsible party—should furnish the purchaser a test report that includes the following:

- Results of the rotational capacity tests; this includes the test method used (solid plate or tension measuring device).
- Assembly and component lot numbers.
- Specific type of lubricant used during testing.
- Application method and placement location of lubricant during testing.
- Mailing address of responsible party.
- Title and signature of the individual assigned test report responsibility.

Appendix D
Testing Method to Determine the Slip Coefficient in Stainless Steel Bolted Joints

The testing method in this appendix is based on the method in Appendix B of AISC Design Guide 27 (Baddoo and Meza, 2022). It has been extended to cover faying surface combinations that are in accordance with Section B.2.2, consisting of stainless steel with coated or uncoated carbon steel.

D.1 GENERAL PROVISIONS

D.1.1 Purpose and Scope

The purpose of this testing procedure is to determine the mean slip coefficient for use in the design of slip-critical joints made with stainless steel structural bolting assemblies. The mean slip coefficient is determined upon successful completion of both short-term compression tests and long-term tension creep tests.

The testing procedure described in this appendix largely follows the testing procedure given in Appendix A of the RCSC *Specification* for determining the mean slip coefficient of faying surfaces with applied coatings, with the exceptions necessary for assessing the slip resistance of an uncoated stainless steel joint.

This appendix provides designers with a method to qualify uncoated stainless steel faying surfaces not covered in Tables 5-2 and 5-3. For instance, when proving a certain surface roughness can achieve a higher slip resistance than that reported in Table 5-2; when using a blast media other than grit; or when using a different stainless steel alloy for each faying surface, though subjecting it to the same blast process that could yield different surface roughness on each faying surface. This testing procedure can also be used to qualify faying surface combinations that are in accordance with Section B.2.2 that consist of stainless steel with coated or uncoated carbon steel.

D.1.2 Definition of Essential Variables

Essential variables are those that, if changed, will require retesting to determine the mean slip coefficient. The slip coefficient testing should be repeated if there is any change in these essential variables.

The surface roughness is an essential variable. This should be determined using Method B, C, or D of ASTM D4417 and reported on the certification. The surface roughness is enhanced through blast cleaning. Grit-blasted faying surfaces are specified for stainless steel faying surfaces in Table 5-2 because they have a more angular profile, leading to better mechanical interlocking between the faying surfaces and, consequently, to a higher mean slip coefficient (Stranghöner et al., 2017, 2019). The blast process variables should be reported on the slip certificate.

For faying surface combinations that are in accordance with Section B.2.2, the following are essential variables:

- *Degree of cure:* Cure should be performed according to published coating manufacturer's recommendations. The degree of cure of the coating should be evaluated using one or more of the following: (1) sclerometer hardness, (2) pencil hardness, (3) MEK double rub test, or (4) by other means as recommended by the coating manufacturer. Each evaluation method recommended by the coating manufacturer should be performed at the time of test and recorded on the certification.
- *Coating thickness:* The maximum average coating thickness, as per SSPC PA2 (AMPP, 2022), allowed on the faying surfaces is 2 mils less than the average thickness, rounded to the nearest whole mil, of the coating that is used on the test specimens.
- *Coating composition and method of manufacture.*

D.1.3 Retesting

A surface condition that fails to meet the creep requirements in Section D.4 may be retested in accordance with the methods in Section D.4 at a lower slip coefficient without repeating the static short-term tests specified in Section D.3. Essential variables should remain unchanged in the retest. Retests should use new bolts because preloading stainless steel bolting assemblies causes irreversible viscoplastic deformation in the bolts (Afzali et al., 2019), and reuse of stainless steel bolting assemblies results in smaller viscoplastic deformations, which improves the relaxation behavior of the bolted joint.

D.1.4 Duration of Coating Slip Certificate

Any coating slip certificate issued using the method presented in this appendix is valid for a term of 84 months after the certificate has been issued. After 84 months, the coating should be fully retested according to this appendix and reissued a new certificate.

D.2 TEST PLATES FOR THE SPECIMENS

D.2.1 Test Plates

The test specimen plates for the short-term static tests are shown in Figure D-1. The plates should be 4 in. × 4 in. × ⅝ in. thick, with a 1-in.-diameter hole drilled 1½ in. ± 1⁄16 in. from one edge. The test specimen plates for the creep tests are shown in Figure D-2. The plates should be 4 in. × 7 in. × ⅝ in. thick with two 1-in.-diameter holes drilled 1½ in. ± 1⁄16 in. from each end. The use of 1-in.-diameter bolt holes in the specimens is to ensure that adequate clearance is available for slip. Fabrication tolerances and assembly tolerances tend to reduce the apparent clearances.

The edges of the plates may be milled, as-rolled, or saw-cut; thermally cut edges should not be used. The plates should be flat enough to ensure that they will be in reasonably full contact over the faying surface. All burrs, lips, or rough edges should be removed. The plates should be fabricated from the same stainless steel alloy to be used in the structural application.

If specimens with more than one bolt are required, the contact surface per bolt should be 4 in. × 3 in., as shown for the single-bolt specimen in Figure D-1.

D.2.2 Specimen Blasting

Clean stainless steel grit media should be used when blasting the faying surfaces to avoid iron contamination on the surface, which may lead to corrosion. In all the specimens, the surface roughness of each contact surface should be measured in accordance with Method B, C, or D of ASTM D4417. The average surface roughness should be calculated for each of the contact surfaces of each specimen and reported.

D.2.3 Specimen Coating

For faying surface combinations that are in accordance with Section B.2.2, coatings are to be applied to the specimens in a manner that is consistent with that to be used in the actual intended structural application. The method of applying the coating and the surface preparation should be given in the test report. The specimens are to be coated to an average thickness that is 2 mils greater than the maximum thickness to be used in the structure on both of the plate surfaces (the faying and outer surfaces). The thickness of the total coating and the primer, if used, should be measured on the contact surface of the specimens. The thickness should be measured in accordance with SSPC-PA2. Two spot readings (six gage readings) should be made for each contact surface. The overall average thickness from the three plates comprising a specimen is the average thickness for the specimen. This value should be reported for each specimen. The average coating thickness of the creep specimens should be calculated and reported.

The time between application of the coating and specimen assembly should be the same for all specimens within ±4 hours. The average time should be calculated and reported.

D.3 SLIP TESTS

The methods and procedures described herein are used to experimentally determine the mean slip coefficient under short-term static loading for stainless steel structural bolting assemblies. The mean slip coefficient should be determined by testing one set of five specimens and then verified for long-term tension creep loading as described in Section D.4.

The initial testing of the short-term compression specimens provides a measure of the scatter of the slip coefficient. The slip coefficient under short-term static loading has been

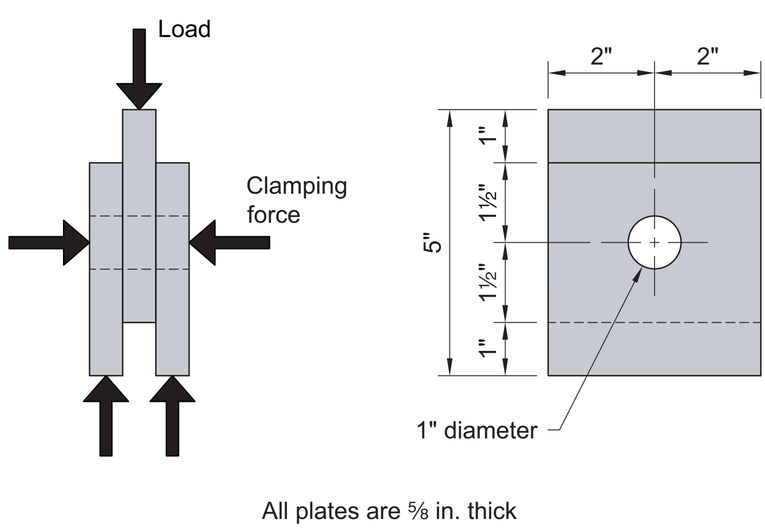


Fig. D-1. Compression slip test specimen.

found to be independent of the magnitude of the clamping force and bolt hole diameter.

D.3.1 Compression Test Setup

The test setup shown in Figure D-3 has two major loading components—one to apply a clamping force to the specimen plates and the other one to apply a compressive load to the specimen so that the load is transferred across the faying surfaces by friction. The clamping force system simulates the clamping action of a pretensioned high-strength bolt in a controlled and directly measurable way.

Clamping Force System

The clamping force system should consist of a ⅞-in.-diameter threaded rod that passes through the specimen and a centerhole compression ram. The loading rod should be made of steel with a tensile strength greater than or equal to 150 ksi. Understrength rods may fracture under loading, causing flying debris that could injure test operators, and it is recommended to proof test the rod to 55 kips before use in testing. Testing agencies should consider regular replacement of the loading rod.

An ASTM A563/A563M grade DH nut (ASTM, 2024d) should be used at both ends of the rod, and a hardened washer should be used at each side of the test specimen. Between the ram and the specimen is a specially modified ⅞-in.-diameter ASTM A563/A563M grade DH nut in which the threads have been drilled out so that it will slide with little resistance along the rod. When oil is pumped into the centerhole ram, the piston rod extends, thus forcing the special nut against one of the outside plates of the specimen. This action puts tension in the threaded rod and applies a clamping force to the specimen, thereby simulating the effect of a pretensioned bolt. If the diameter of the centerhole ram is greater than 1 in., additional plate washers will be necessary at the ends of the ram. The clamping force system should have a capability to apply a load of at least 49 kips (or the clamping force intended to be used in structural application) and should maintain this load during the test with an accuracy of ±0.5 kip.

Compressive Load System

A compressive load should be applied to the specimen until slip occurs. This compressive load should be applied with a compression test machine or a reaction frame using a hydraulic loading device. The loading device and the necessary supporting elements should be able to support a force of 120 kips.

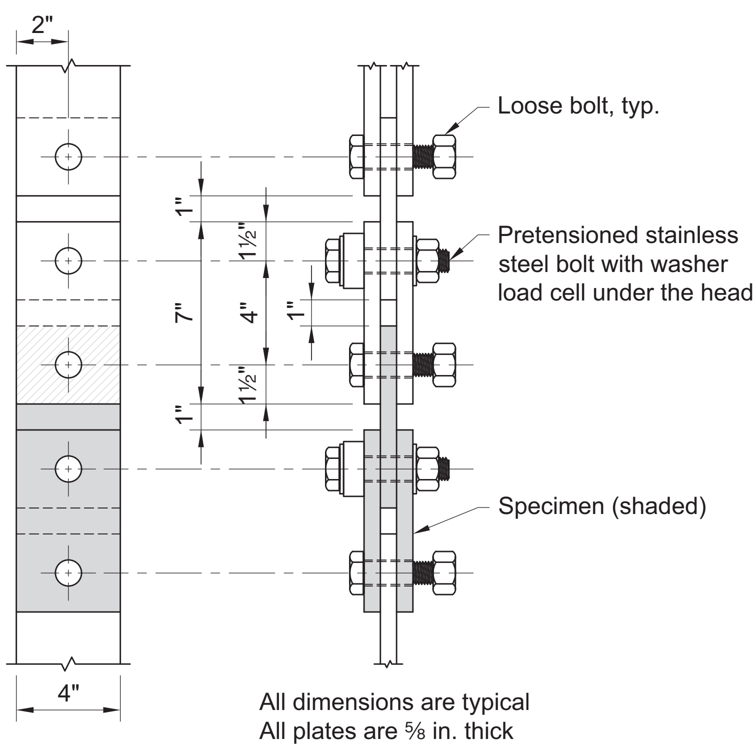


Fig. D-2. Creep test specimen assembly.

Load Train Alignment

The testing agency should ensure that the loading system is constructed such that the lines of action from the spherical head and the centerhole ram intersect at the theoretical center of the three test plates. A tolerance of ±⅛ in. is considered allowable in any direction. This alignment should be checked every time a new specimen is installed.

D.3.2 Instrumentation

Clamping Force

The clamping force may be measured from pressure readings in the ram or by placing a load cell in series with the ram. The device measuring clamping load should be calibrated annually and be accurate within ±0.5 kip.

Compression Load

The compression load should be measured during the test by direct reading from a compression testing machine, a load cell in series with the specimen and the compression loading device, or pressure readings on a calibrated compression ram. The device measuring compression load should be calibrated annually and be accurate within ±1.0 kip.

Slip Deformation

The displacement of the center plate relative to the two outside plates should be measured. This displacement, called "slip" for simplicity, should be the average of the displacement gauges on each side of the specimen. Deflections should be measured by dial gauges or any other calibrated device that has a resolution of at least 0.001 in. The devices measuring deflection should be calibrated annually.

The preferred method of measuring the relative displacement is by referencing the displacement measurement between the plates directly, and not between the loading platens. Referencing the displacement between the loading platens may result in a load versus slip displacement response with a low initial stiffness due to seating of the specimen into the loading platens, more so than can be overcome by the 5 kip offset described in Section D.3.3. The low stiffness may erroneously affect determination of the slip load described in Section D.3.4. More details about the initial displacement response and means to mount displacement gauges can be found in Ocel et al. (2014).

D.3.3 Test Procedure

The specimen should be installed in the test setup as shown in Figure D-3. Before the hydraulic clamping force is applied, the individual plates should be positioned so that they are in, or close to, full bearing contact with the ⅞ in. threaded rod in a direction that is opposite to the planned compressive loading to allow a clear slip deformation. It is recommended to use a temporary support beneath the center plate before application of the clamping load to maximize the amount of slip before the plates go into bearing on the loading rod once clamped.

Care should be taken when positioning the specimen so that the specimen is perpendicular to the base and the two

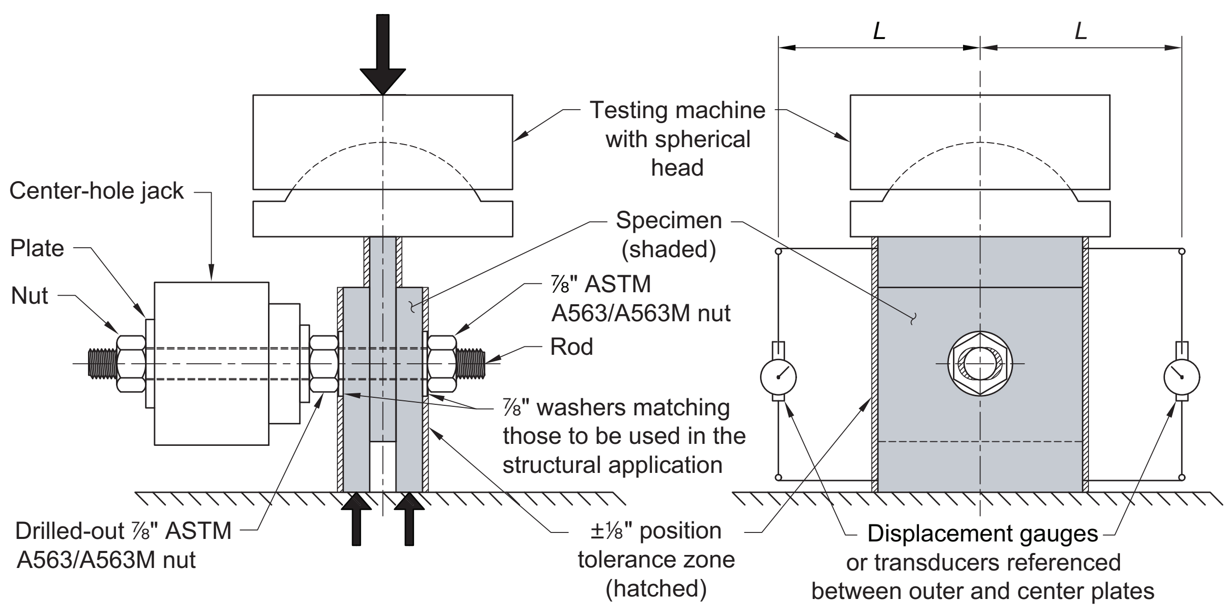


Fig. D-3. Compression slip test setup.

plates on the outside are in contact with the base. After the plates are positioned, the centerhole ram should be engaged to produce a clamping force of 49 kips (or the clamping force intended to be used in the structural application). The applied clamping force should be maintained within ±0.5 kip during the test until slip occurs.

The spherical head of the compression loading machine should be brought into contact with the inner plate of the specimen after the clamping force is applied. The spherical head or other appropriate device ensures concentric loading. In order to eliminate seating displacement of the specimens, the displacement gauges should be engaged, attached, or zeroed at a compressive load of 5.0 kips.

When the slip gauges are in place, the compression load should be applied at a rate that does not exceed 25 kips/min or 0.003 in. of slip displacement per minute until the slip load is reached. The test should be terminated when a slip of 0.04 in. or greater is recorded. The load-slip relationship should be continuously recorded in a manner sufficient to evaluate the slip load defined in Section D.3.4.

D.3.4 Slip Load

Typical load-slip responses are shown in Figure D-4. Three types of curves are usually observed and the slip load associated with each type is defined as follows:

- Curve (a): The slip load is taken as the maximum load, provided this maximum occurs before a slip of 0.02 in. is recorded.
- Curve (b): The slip load is taken as the load at which the slip rate increases suddenly.
- Curve (c): The slip load is taken as the load corresponding to a deformation of 0.02 in. This definition applies when the load versus slip curve shows a gradual change in response.

D.3.5 Slip Coefficient

The slip coefficient for an individual specimen k_s is calculated as follows:

$$k_s = \frac{\text{Slip load}}{2 \times \text{Clamping force}} \tag{D-1}$$

The mean slip coefficient, μ, for one set of five specimens is calculated as the average of the five samples. Alternatively, in case the result of one of the samples is substantially lower than the average of the other four, the mean slip coefficient may be calculated as the average of four samples provided the lowest attained value satisfies the following criteria:

$$\frac{\mu - k_{s,min}}{\sigma} \geq 1.71 \tag{D-2}$$

where

$k_{s,min}$ = lowest k_s value in five samples

μ = the average of the five k_s values attained

σ = the standard deviation of the five k_s values attained

The criterion for the outlier analysis can only detect a single outlier based on the work of Grubbs (1950). The threshold value of 1.71 is based on a sample size of five

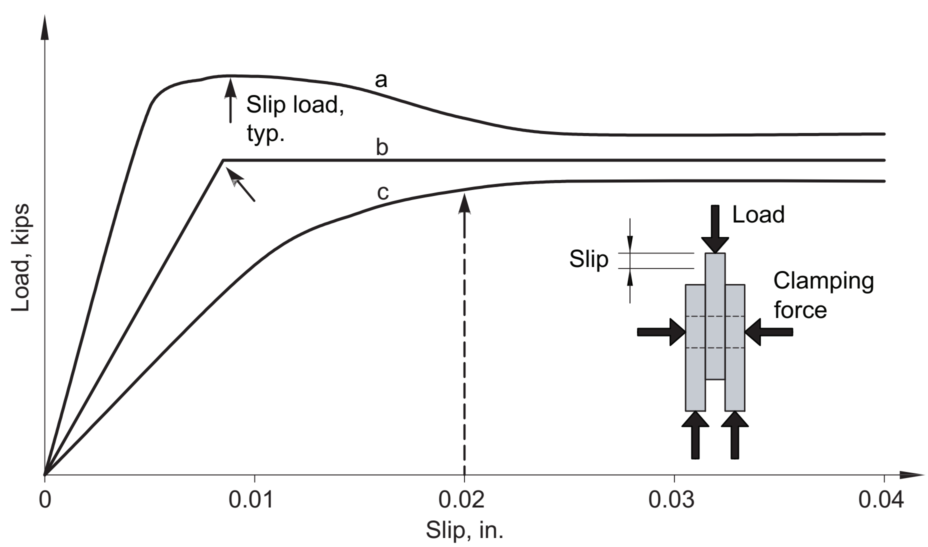


Fig. D-4. Definition of slip load.

with a critical value of 5% based on a two-tailed student *t*-distribution. This effectively means the outlier passing the criterion in Equation D-2 falls outside the 95% confidence limits of an assumed normal distribution. Grubbs' test is only valid for the removal of one outlier. The rejection of more than one outlier is not used because the compression test method only relies on five replicates to begin with. If the testing agent feels there may be two or more outliers, it is recommended to run a new series of five tests. It is important to consider that in sample populations with small scatter (i.e., coefficient of variation < 1%), the outlier criterion may identify good data as an outlier, and some discretion should therefore be used on whether it is appropriate to screen for an outlier.

To demonstrate the outlier analysis, consider the slip curves shown in Figure D-5 that were obtained by testing five replicates of a liquid applied coating. Test 2 may be a suspected outlier. Equation D-2 determines that $(0.44 - 0.34)/0.058 = 1.72$ is greater than 1.71; therefore, test 2 may be disregarded as an outlier. Therefore, the reported mean slip coefficient would be the average of the remaining four results, or 0.46.

The testing agent should also be aware of the information that can be obtained from load versus slip plots. In the plot shown in Figure D-5, test 2 has a double plateau response that is characteristic of a specimen that is not seated correctly; that is, only one of the two outer plates was initially in contact with the platen. Additionally, it is possible to distinguish if slip is occurring, or if the plates are bearing on the loading rod. Figure D-6 shows the response of a slip test where the load continuously increases as the slip occurs. Such a response is typical when bearing has interfered with free slip. If such a response is unique among the five tested specimens, the test should be eliminated when determining the mean slip coefficient.

D.3.6 Alternative Test Methods

Alternative test methods to determine the slip may be used, provided the accuracy of the load measurement, specimen geometry, and clamping force satisfy the conditions presented in the previous sections. For example, the slip load may be determined from a tension-type test setup rather than the compression-type test setup described in Section D.3.1, as long as the contact surface area per bolt of the test specimen is the same as that shown in Figure D-1. The clamping force of at least 49 kips (or the clamping force intended to be used in the structural application) may be applied by any means, provided the force can be established within ±0.5 kip. Strain-gaged bolts can usually provide the desired accuracy. However, bolts that are pretensioned by the turn-of-nut method usually show too much variation to meet the ±0.5 kip accuracy of the slip test.

D.4 TENSION CREEP TEST

The tension creep test is intended to ensure that the stainless steel bolted joint will not undergo significant creep and relaxation deformation under sustained service loading. The

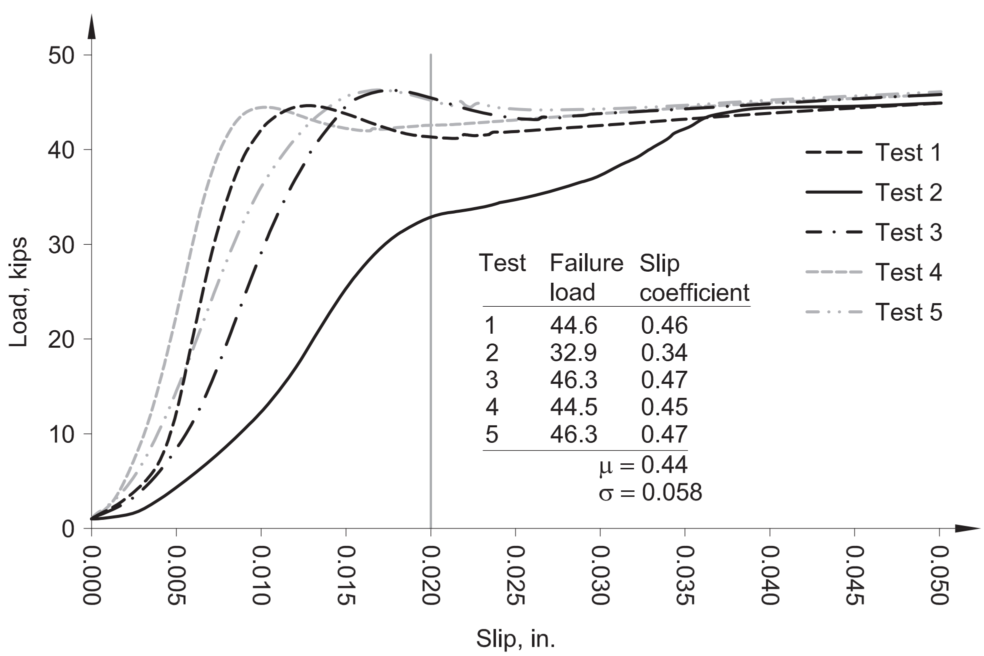


Fig. D-5. Example load versus slip plots.

test also indicates the loss in clamping force from the initial embedment effects on the faying surfaces and creep and relaxation deformation of the stainless steel bolting assemblies. Three replicate specimens are to be tested. Adherence to this testing method ensures that the creep deformation of the stainless steel faying surface due to both the clamping force of the bolt and the service-shear load applied to the joint is such that the stainless steel faying surface will provide satisfactory performance under sustained loading.

D.4.1 Test Setup

Tension-type specimens, as shown in Figure D-2, are to be used. The replicate specimens are to be linked together in a single chain-like arrangement, using loose pin bolts, so the same load is applied to all specimens. The specimens should be assembled so the specimen plates are bearing against the bolt in a direction opposite to the applied tension loading. Care should be taken in the assembly of the specimens to ensure the centerline of the holes used to accept the pin bolts is in line with the bolts used to assemble the joint. The load level, specified in Section D.4.2, should be maintained constant within ±1% by springs, load maintainers, servo controllers, dead weight, or other suitable equipment. The stainless steel bolt assemblies used to clamp the specimens together should be ⅞ in. diameter and should match those intended for use in the structural application. All bolts should come from the same lot.

The clamping force in the bolts should be at least 49 kips, or the minimum clamping force intended to be used in the structural application. The clamping force in each bolt should be directly measured using calibrated strain gauges, calibrated load-indicating washers, or calibrated load cells. Alternatively, a tightening method, such as the turn-of-nut, or combined methods may be used to attain the desired clamping load, though the clamping load will be the average of three bolt calibrations performed in a bolt tension measurement device using the desired installation method. The method for measuring the bolt force should ensure the clamping force is within ±2 kips of the desired value.

The relative slip between the outer plates and the inner plates should be measured to an accuracy of 0.001 in. These slips are to be measured on both sides of each specimen.

D.4.2 Test Procedure

The load to be placed on the creep specimen is as follows:

$$R_s = \frac{2\mu_t T_t}{1.5} \tag{D-3}$$

where

R_s = load to be placed on creep specimens, kips

T_t = average clamping force from the three bolt calibrations, kips

μ_t = mean slip coefficient for the particular slip coefficient category under consideration or the average of the short-term slip tests

The load should be applied to the specimen and held for 1,000 hours. The creep deformation of a specimen is calculated using the average reading of the two displacements

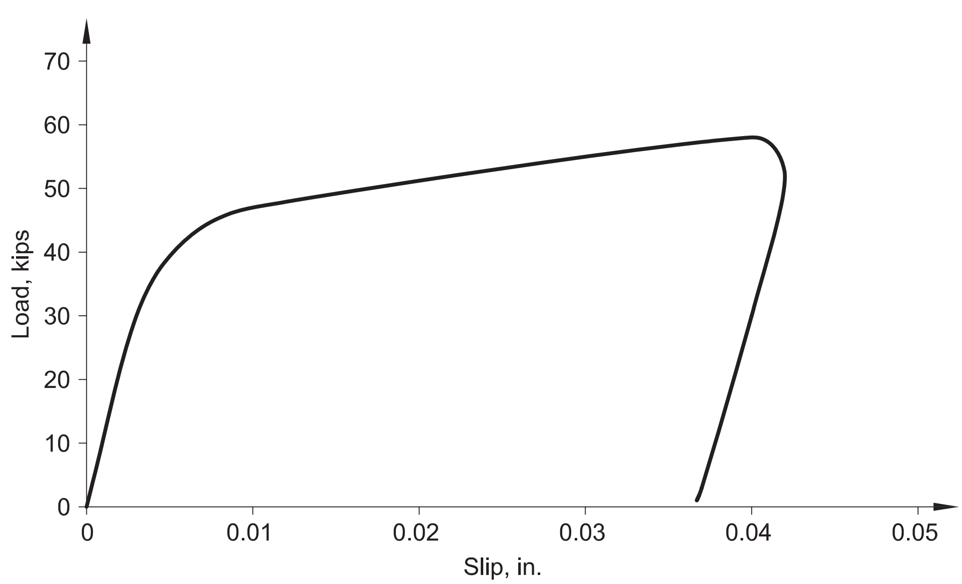


Fig. D-6. Example load versus slip curve bearing on loading rod.

on each side of the specimen. The difference between the average after 1,000 hours and the initial average reading taken within ½ hour after loading the specimens is defined as the creep deformation of the specimen. This value should be reported for each specimen. If the creep deformation of any specimen exceeds 0.005 in., the faying surface has failed the test for the slip coefficient used. The faying surface may be retested using new specimens in accordance with this section at a load corresponding to a lower value of the slip coefficient.

The rate of creep deformation increases as the applied load approaches the slip load. Extensive testing has shown that the rate of creep is not constant with time but rather decreases. After about 1,000 hours of loading, the additional creep deformation is negligible.

Appendix E
Design Examples

This section includes three design examples that illustrate the application of the design provisions presented in this Design Guide. The examples are as follows:

- **Design Example 1—**Bolt Subjected to Combined Tension and Shear
- **Design Example 2—**Combined Tension and Shear in a Slip-Critical Connection
- **Design Example 3—**Shear End-Plate Connection for a Beam-to-Girder Web

Design Example 1—Bolt Subjected to Combined Tension and Shear

Given:

A ⅞-in.-diameter, ASTM A193/A193M Class 2 B8M (S31600) stainless steel bolt with threads not excluded from the shear plane (thread condition N) is subjected to a tensile force of 4.34 kips due to dead load and 14.9 kips due to live load, and a shear force of 1.65 kips due to dead load and 4.96 kips due to live load. This bolt is shown in Figure E-1. Verify that the available strength of the bolt is adequate for the combined forces.

Solution:

From ASCE/SEI 7, Chapter 2, the required tensile and shear strengths are:

LRFD	ASD
Tension: $$\begin{aligned} T_u &= 1.2(4.34 \text{ kips}) + 1.6(14.9 \text{ kips}) \\ &= 29.0 \text{ kips} \end{aligned}$$ Shear: $$\begin{aligned} V_u &= 1.2(1.65 \text{ kips}) + 1.6(4.96 \text{ kips}) \\ &= 9.92 \text{ kips} \end{aligned}$$	Tension: $$\begin{aligned} T_a &= 4.34 \text{ kips} + 14.9 \text{ kips} \\ &= 19.2 \text{ kips} \end{aligned}$$ Shear: $$\begin{aligned} V_a &= 1.65 \text{ kips} + 4.96 \text{ kips} \\ &= 6.61 \text{ kips} \end{aligned}$$

From Table 2-1, the bolt material properties are as follows:

⅞-in.-diameter bolt
ASTM A193/A193M Class 2 BM8 (S31600)
F_{ub} = 100 ksi

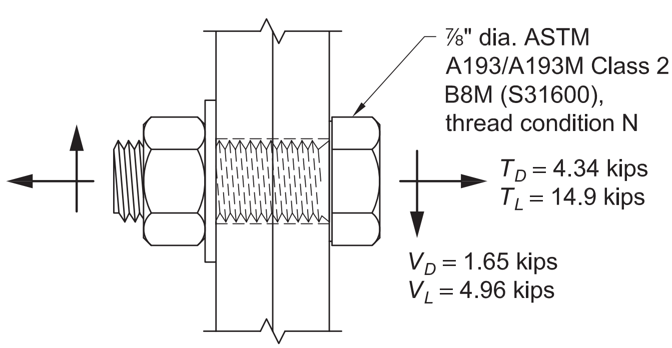


Fig. E-1. Bolt subjected to combined tension and shear forces for Design Example 1.

Available Shear Strength

From Section 5.1, the nominal shear rupture strength of the bolt is determined as follows:

From Table 5-1, for a stainless steel bolt with $F_{ub} \le 120$ ksi:

$$\begin{aligned} F_{nv} &= 0.45F_u \\ &= 0.45(100 \text{ ksi}) \\ &= 45.0 \text{ ksi} \end{aligned}$$

$$\begin{aligned} A_b &= \frac{\pi(\tfrac{7}{8}\text{ in.})^2}{4} \\ &= 0.601 \text{ in.}^2 \end{aligned}$$

From Section 5.1, the available shear strength is determined from Equation 5-1 as follows and should be greater than or equal to the required shear force.

LRFD	ASD
$\phi = 0.75$ $(\phi R_n)_v = \phi F_{nv} A_b$ $= 0.75(45.0 \text{ ksi})(0.601 \text{ in.}^2)$ $= 20.3 \text{ kips} > 9.92 \text{ kips}$ **o.k.**	$\Omega = 2.00$ $\left(\dfrac{R_n}{\Omega}\right)_v = \dfrac{F_{nv} A_b}{\Omega}$ $= \dfrac{(45.0 \text{ ksi})(0.601 \text{ in.}^2)}{2.00}$ $= 13.5 \text{ kips} > 6.61 \text{ kips}$ **o.k.**

Available Tensile Strength

From Section 5.1, the nominal tensile strength of the bolt is determined as follows:

From Table 5-1, for a stainless steel bolt with $F_{ub} \le 120$ ksi:

$$\begin{aligned} F_{nt} &= 0.75F_u \\ &= 0.75(100 \text{ ksi}) \\ &= 75.0 \text{ ksi} \end{aligned}$$

The available tensile strength of the bolt is determined from Equation 5-1 as follows and should be greater than or equal to the required tensile force.

LRFD	ASD
$\phi = 0.75$ $(\phi R_n)_t = \phi F_{nt} A_b$ $= 0.75(75.0 \text{ ksi})(0.601 \text{ in.}^2)$ $= 33.8 \text{ kips} > 29.0 \text{ kips}$ **o.k.**	$\Omega = 2.00$ $\left(\dfrac{R_n}{\Omega}\right)_t = \dfrac{F_{nt} A_b}{\Omega}$ $= \dfrac{(75.0 \text{ ksi})(0.601 \text{ in.}^2)}{2.00}$ $= 22.5 \text{ kips} > 19.2 \text{ kips}$ **o.k.**

Available Strength for Combined Shear and Tension

From Section 5.2, the available strength of a bolt subjected to combined tension and shear is determined using Equations 5-2a and 5-2b as follows:

LRFD	ASD
$\left[\frac{T_u}{(\phi R_n)_t}\right]^2 + \left[\frac{V_u}{(\phi R_n)_v}\right]^2 \le 1$ $\left[\frac{29.0\text{ kips}}{33.8\text{ kips}}\right]^2 + \left[\frac{9.92\text{ kips}}{20.3\text{ kips}}\right]^2 \le 1$ $0.975 < 1$ **o.k.**	$\left[\frac{T_a}{(R_n/\Omega)_t}\right]^2 + \left[\frac{V_a}{(R_n/\Omega)_v}\right]^2 \le 1$ $\left[\frac{19.2\text{ kips}}{22.5\text{ kips}}\right]^2 + \left[\frac{6.61\text{ kips}}{13.5\text{ kips}}\right]^2 \le 1$ $0.968 < 1$ **o.k.**

The available strength of the bolt is adequate for the combined forces.

Design Example 2—Combined Tension and Shear in a Slip-Critical Connection

Given:

The slip critical bolt group shown in Figure E-2 is subjected to tension and shear. This example shows the design for bolt slip resistance only and assumes that the beam and tee stub are adequate to transmit the loads. Determine if the bolts are adequate. The bolts are ⅞-in.-diameter, ASTM A1082/A1082M S32205 stainless steel heavy hex structural bolts, in standard holes.

Solution:

From ASCE/SEI 7, Chapter 2, the required tensile and shear strengths are:

LRFD	ASD
$P_u = 1.2(15\text{ kips}) + 1.6(45\text{ kips})$ $= 90.0\text{ kips}$ By geometry: $T_u = \frac{4}{5}(90.0\text{ kips})$ $= 72.0\text{ kips}$ $V_u = \frac{3}{5}(90.0\text{ kips})$ $= 54.0\text{ kips}$	$P_a = 15\text{ kips} + 45\text{ kips}$ $= 60.0\text{ kips}$ By geometry: $T_a = \frac{4}{5}(60.0\text{ kips})$ $= 48.0\text{ kips}$ $V_a = \frac{3}{5}(60.0\text{ kips})$ $= 36.0\text{ kips}$

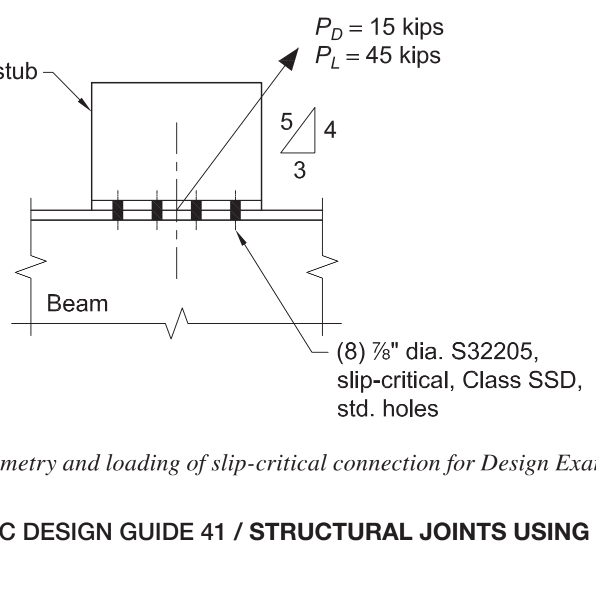


Fig. E-2. Geometry and loading of slip-critical connection for Design Example 2.

From Table 2-1, the bolt material properties are as follows:

⅞-in.-diameter bolts
ASTM A1082/A1082M S32205
$F_{ub} = 95$ ksi

Available Bolt Tensile Strength

From Section 5.1, the nominal shear rupture strength of the bolt is determined as follows:

From Table 5-1, the nominal tensile stress is:

$$\begin{aligned} F_{nt} &= 0.75F_u \\ &= 0.75(95 \text{ ksi}) \\ &= 71.3 \text{ ksi} \end{aligned}$$

$$\begin{aligned} A_b &= \frac{\pi(\tfrac{7}{8} \text{ in.})^2}{4} \\ &= 0.601 \text{ in.}^2 \end{aligned}$$

The nominal tensile strength for a single bolt is:

$$\begin{aligned} R_n &= F_{nt}A_b \\ &= (71.3 \text{ kips})(0.601 \text{ in.}^2) \\ &= 42.9 \text{ kips} \end{aligned}$$ (from Eq. 5-1)

The available tensile strength is:

LRFD	ASD
$\phi = 0.75$ $\phi R_n = 0.75(42.9 \text{ kips/bolt})(8 \text{ bolts})$ $= 257 \text{ kips} > 72.0 \text{ kips}$ **o.k.**	$\Omega = 2.00$ $\dfrac{R_n}{\Omega} = \dfrac{(42.9 \text{ kips/bolt})(8 \text{ bolts})}{2.00}$ $= 172 \text{ kips} > 48.0 \text{ kips}$ **o.k.**

Available Slip Resistance of the Connection

The available slip resistance for bolts in standard size holes is determined using Section 5.4.

From Section 5.4, assuming no more than one filler, the ratio of the mean installed bolt pretension to the minimum bolt pretension multiplier, D_u, and the factor for fillers, h_f, are as follows:

$D_u = 1.00$

$h_f = 1.0$

From Table 5-2, for Class SSD grit blasted faying surfaces, the slip coefficient is:

$\mu = 0.50$

From Table 5-4, for ⅞-in.-diambeter bolts, the tensile stress area is:

$A_s = 0.462 \text{ in.}^2$

Therefore, the minimum bolt pretension for a single bolt is:

$$
\begin{aligned}
T_m &= 0.7F_{ub}A_s &\text{(5-7)}\\
&= 0.7(95\text{ kips})(0.462\text{ in.}^2)\\
&= 30.7\text{ kips}
\end{aligned}
$$

In this connection, the number of slip planes, $n_s = 1$, and the number of bolts, $n_b = 8$.

Because the slip-critical connection is subjected to combined tension and shear, the available slip resistance is multiplied by the reduction factor, k_{sc}, which is calculated using Equations 5-8a and 5-8b.

LRFD	ASD
$k_{sc} = 1 - \dfrac{T_u}{D_u T_m n_b} \geq 0$ $= 1 - \dfrac{72.0\text{ kips}}{1.00(30.7\text{ kips/bolt})(8\text{ bolts})} \geq 0$ $= 0.707$	$k_{sc} = 1 - \dfrac{1.5T_a}{D_u T_m n_b} \geq 0$ $= 1 - \dfrac{1.5(48.0\text{ kips})}{1.00(30.7\text{ kips/bolt})(8\text{ bolts})} \geq 0$ $= 0.707$

The available strength is calculated from Equation 5-6 as follows.

LRFD	ASD
$\phi = 1.00$ $\phi R_n = \phi \mu D_u h_f T_m n_s k_{sc} n_b$ $= 1.00(0.50)(1.00)(1.0)(30.7\text{ kips/bolt})(1)$ $\times(0.707)(8\text{ bolts})$ $= 86.8\text{ kips} > 54.0\text{ kips}$ **o.k.**	$\Omega = 1.50$ $\dfrac{R_n}{\Omega} = \dfrac{\mu D_u h_f T_m n_s k_{sc} n_b}{\Omega}$ $= \dfrac{0.50(1.00)(1.0)(30.7\text{ kips/bolt})(1)(0.707)(8\text{ bolts})}{1.50}$ $= 57.9\text{ kips} > 36.0\text{ kips}$ **o.k.**

The available strength of the bolt group is adequate for the applied load.

Note: The bolt group should still be checked for all applicable strength limit states for a bearing-type connection.

Design Example 3—Shear End-Plate Connection for Beam-to-Girder Web

Given:

Verify that the number of bolts used in the end-plate connection shown in Figure E-3 is adequate to preclude failure due to bearing at the bolt holes and shearing of the bolts. The dimensions of the beam and end plate are shown in Figure E-3. The beams and the end plates are made of S30400 stainless steel material. The bolts are ¾-in.-diameter, ASTM A320/A320M S30400, Class 1 stainless steel, thread condition N, in standard holes. The girder supports the following end reactions from each of the beams:

$R_D = 14.2$ kips

$R_L = 42.5$ kips

Solution:

From AISC Design Guide 27, Table 2-2, the girder and end-plate material properties are as follows:

Girder and end plates
S30400 stainless steel
$F_u = 75$ ksi

From Table 2-2 of this Design Guide, the bolt material properties are as follows:

¾-in.-diameter bolts
ASTM A320/A320M S30400, Class 1
$F_{ub} = 75$ ksi

From Table 4-1 of AISC Design Guide 27, the pertinent geometric properties are as follows:

W24×104 Girder
$t_w = 0.500$ in.

From Table 3-1 of this Design Guide, the hole diameter for a ¾-in.-diameter bolt in a standard bolt hole is:

$d_h = 13/16$ in.

From ASCE/SEI 7, Chapter 2, the required strength of each end plate is:

LRFD	ASD
$R_u = 1.2(14.2 \text{ kips}) + 1.6(42.5 \text{ kips})$ $= 85.0$ kips	$R_a = 14.2 \text{ kips} + 42.5 \text{ kips}$ $= 56.7$ kips

The required strength of the bolt group and the girder web will be twice that of each end plate. Therefore:

LRFD	ASD
$R_u = 2(85.0 \text{ kips})$ $= 170$ kips	$R_a = 2(56.7 \text{ kips})$ $= 113$ kips

Available bearing and tearout strengths of the girder web at the bolt holes

Assuming that deformation at the service load is a design consideration. The available bearing or tearout strength of the girder web is determined in accordance with Section 5.3.

The nominal bearing strength on the girder web of a single bolt is:

$$R_n = 1.25 d_b t F_u \quad \text{(from Eq. 5-3)}$$

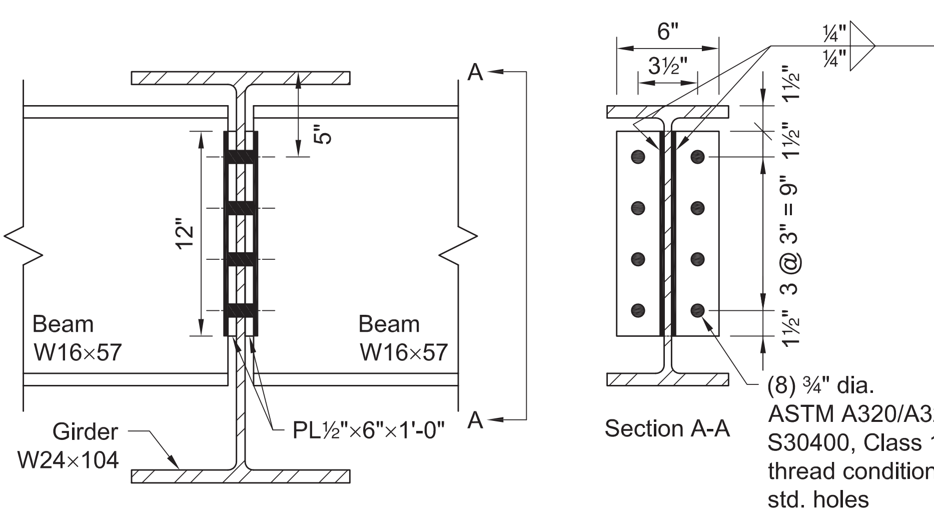


Fig. E-3. Shear end-plate connection geometry for Design Example 3.

where t is taken as the thickness of the girder web, $t_w = 0.500$ in.

$$R_n = 1.25(\text{¾ in.})(0.500\text{ in.})(75\text{ ksi})$$
$$= 35.2\text{ kips/bolt}$$

For the two bolt holes in the bottom row:

Bearing is the only possible type of failure at the bolt hole. Therefore, for these bolt holes the nominal bearing strength on the girder web is:

$$nR_n = (2\text{ bolts})(35.2\text{ kips/bolt})$$
$$= 70.4\text{ kips}$$

For the inner bolt holes:

Figure E-3 shows that half of the distance between the center of the hole in the direction of the force, l_1, is:

$$l_1 = \frac{3.00\text{ in.}}{2}$$
$$= 1.50\text{ in.}$$

The nominal tearout strength on the girder web of a single bolt is:

$$R_n = 1.25\left(\frac{l_1}{2d_h}\right)d_b t F_u \qquad \text{(from Eq. 5-3)}$$
$$= 1.25\left[\frac{1.50\text{ in.}}{2(\text{13⁄16 in.})}\right](\text{¾ in.})(0.500\text{ in.})(75\text{ ksi})$$
$$= 32.5\text{ kips/bolt} < 35.2\text{ kips/bolt}$$

Because 32.5 kips/bolt < 35.2 kips/bolt, inner bolt hole failure is governed by tearout of the web.

For the six inner bolt holes, the nominal tearout strength of the girder web is:

$$nR_n = (6\text{ bolts})(32.5\text{ kips/bolt})$$
$$= 195\text{ kips}$$

The total nominal bearing/tearout strength for the entire bolt group is:

$$R_{n,total} = 70.4\text{ kips} + 195\text{ kips}$$
$$= 265\text{ kips}$$

From Section 5.3, the available bolt bearing strength on the girder web is:

LRFD	ASD
$\phi = 0.75$ $\phi R_{n,total} = 0.75(265\text{ kips})$ $= 199\text{ kips} > 170\text{ kips}$ **o.k.**	$\Omega = 2.00$ $\dfrac{R_{n,total}}{\Omega} = \dfrac{265\text{ kips}}{2.00}$ $= 133\text{ kips} > 113\text{ kips}$ **o.k.**

Available bearing and tearout strength of the end plate at bolt holes

Assume deformation at the service load level is a design consideration. The available strength of the end plate at the bolt hole for the limit state of bearing and tearout is determined in accordance with Section 5.3.

The nominal bearing strength on the end plate of a single bolt is:

$$R_n = 1.25 d_b t F_u \qquad \text{(from Eq. 5-3)}$$

where t is the thickness of the plate, t = ½ in.

$$\begin{aligned} R_n &= 1.25(\tfrac{3}{4}\text{ in.})(\tfrac{1}{2}\text{ in.})(75\text{ ksi}) \\ &= 35.2\text{ kips/bolt} \end{aligned}$$

The nominal tearout strength on the end plate of a single bolt is:

$$R_n = 1.25\left(\frac{l_1}{2d_h}\right) d_b t F_u \qquad \text{(from Eq. 5-3)}$$

For the bolt holes in the top row:

Figure E-3 shows that the distance between the center of the hole and the edge of the material in the direction of the force, l_1, is 1½ in. Therefore:

$$\begin{aligned} R_n &= 1.25\left[\frac{1\tfrac{1}{2}\text{ in.}}{2(\tfrac{13}{16}\text{ in.})}\right](\tfrac{3}{4}\text{ in.})(\tfrac{1}{2}\text{ in.})(75\text{ ksi}) \\ &= 32.5\text{ kips/bolt} < 35.2\text{ kips/bolt} \end{aligned}$$

Because 32.5 kips/bolt < 35.2 kips/bolt, the bolt hole failure is governed by tearout of the plate.

For the two bolt holes in the top row, the nominal tearout strength of the end plate is:

$$\begin{aligned} nR_n &= (2\text{ bolts})(32.5\text{ kips}) \\ &= 65.0\text{ kips/bolt} \end{aligned}$$

For the inner bolt holes:

Figure E-3 shows that half of the distance between the center of the hole in the direction of the force, l_1, is:

$$\begin{aligned} l_1 &= \frac{3.00\text{ in.}}{2} \\ &= 1.50\text{ in.} \end{aligned}$$

Therefore:

$$\begin{aligned} R_n &= 1.25\left[\frac{1.50\text{ in.}}{2(\tfrac{13}{16}\text{ in.})}\right](\tfrac{3}{4}\text{ in.})(\tfrac{1}{2}\text{ in.})(75\text{ ksi}) \\ &= 32.5\text{ kips/bolt} < 35.2\text{ kips/bolt} \end{aligned}$$

Because 32.5 kips/bolt < 35.2 kips/bolt, inner bolt hole failure is governed by tearout of the plate.

For the six inner bolt holes, the nominal tearout strength of the end plate is:

$$nR_n = (6 \text{ bolts})(32.5 \text{ kips/bolt})$$
$$= 195 \text{ kips}$$

The total nominal bearing/tearout strength for the entire bolt group is:

$$R_{n,total} = 65.0 \text{ kips} + 195 \text{ kips}$$
$$= 260 \text{ kips}$$

From Section 5.3, the available strength of the end plate at the bolt hole for the entire bolt group is:

LRFD	ASD
$\phi = 0.75$ $\phi R_{n,total} = 0.75(260 \text{ kips})$ $= 195 \text{ kips} > 85.0 \text{ kips}$ **o.k.**	$\Omega = 2.00$ $\dfrac{R_{n,total}}{\Omega} = \dfrac{260 \text{ kips}}{2.00}$ $= 130 \text{ kips} > 56.7 \text{ kips}$ **o.k.**

Available bolt shear strength

From Section 5.1, the nominal shear rupture strength of the bolts is determined as follows:

$$R_n = F_n A_b \tag{5-1}$$

From Table 5-1, for a stainless steel bolt with threads included in the shear plane and $F_{ub} \leq 120$ ksi:

$$F_{nv} = 0.45F_{ub}$$
$$= 0.45(75 \text{ ksi})$$
$$= 33.8 \text{ ksi}$$

$$A_b = \frac{\pi(\text{¾ in.})^2}{4}$$
$$= 0.442 \text{ in.}^2$$

Therefore:

$$R_n = (33.8 \text{ ksi})(0.442 \text{ in.}^2)$$
$$= 14.9 \text{ kips/bolt}$$

From Section 5.1, the available bolt shear strength for eight bolts in double shear is:

LRFD	ASD
$\phi = 0.75$ $2n(\phi R_n) = 2(8 \text{ bolts})(0.75)(14.9 \text{ kips/bolt})$ $= 179 \text{ kips} > 170 \text{ kips}$ **o.k.**	$\Omega = 2.00$ $2n\left(\dfrac{R_n}{\Omega}\right) = 2(8 \text{ bolts})\left(\dfrac{14.9 \text{ kips/bolt}}{2.00}\right)$ $= 119 \text{ kips} > 113 \text{ kips}$ **o.k.**

The number of bolts is adequate to preclude failure of the connection due to bearing at the bolt holes and shearing of the bolts.

Note: A complete design of the end-plate connection will also require verification of the weld strength between the end plates and the beams; shear yield strength and shear rupture of the beam web; and shear yield strength, shear rupture, and block shear strength of the end plates. These verifications are not included in this design example.

Symbols

Some definitions in the list below have been simplified in the interest of brevity. Symbols without text definitions, used only in one location and defined at that location, are omitted in some cases.

A_b Cross-sectional area based upon the nominal diameter of bolt, in.^{2}

A_s Tensile stress area of bolt, in.^{2}

D Bolt diameter used in rotational capacity test, ft

D_u Multiplier that reflects the ratio of the mean installed bolt pretension to the minimum bolt pretension, T_m

F_{SR} Allowable stress range, ksi

F_n Nominal strength per unit area, ksi

F_{nt} Nominal tensile stress, ksi

F_{nv} Nominal shear stress, ksi

F_u Specified minimum tensile strength per unit area of the connected material, ksi

F_{ub} Specified minimum tensile strength of bolt, ksi

F_{yb} Specified minimum yield stress of bolt, ksi

L_s Length between the bolt hole centers parallel to the line of force on one side of the connection for longitudinally loaded connections, in.

P Measured tensile force used in rotational capacity test, lb

Q_{max} Maximum torque range, ft-lb

R_a Required strength using ASD load combinations, kips

R_n Nominal strength, kips

R_n/Ω Allowable strength, kips

$(R_n/\Omega)_t$ Allowable strength in tension, kips

$(R_n/\Omega)_v$ Allowable strength in shear, kips

R_s Load to be placed on creep specimens, kips

R_t Surface roughness (see ASTM D4417 Method D for average R_t), mils

R_u Required strength using LRFD load combinations, kips

T_a Required strength in tension per bolt using ASD load combinations, kips

T_i Initial tension requirement for rotational capacity testing, kips

T_m Minimum bolt pretension for pretensioned joints, kips

T_p Pre-installation verification bolt pretension, kips

T_t Average clamping force used in coating creep tests, kips

T_u Required strength in tension per bolt using LRFD load combinations, kips

V_a Required strength in shear per bolt using ASD load combinations, kips

V_u Required strength in shear per bolt using LRFD load combinations, kips

d_b Nominal diameter of bolt, in.

d_h Nominal diameter of bolt hole, in.

h_f Factor for fillers

k_s Slip coefficient for an individual short-term slip load tests specimen

k_{sc} Factor accounting for the presence of an applied tensile force that reduces the net clamping force

$k_{s,min}$ Lowest slip coefficient from short-term slip load tests

l_1 Half of the distance between the center of the hole and the center of the adjacent hole or distance between the center of the hole and the edge of the material, in the direction of the force, in.

l_2 Half of the distance between the center of the hole and the center of the adjacent hole or distance between the center of the hole and the edge of the material, in the direction perpendicular to the force, in.

n Number of threads per inch

n_{SR} Number of stress range fluctuations during the design life

n_b Number of bolts in the joint

n_s Number of slip planes

t Thickness of the connected material, in.

t' Total thickness of fillers or shims, in.

Ω Factor of safety

ϕ Resistance factor

ϕR_n Design strength, kips

$(\phi R_n)_t$ Design strength in tension, kips

$(\phi R_n)_v$ Design strength in shear, kips

μ Mean slip coefficient

μ Average slip coefficient from short-term slip load tests

μ_t Mean slip coefficient for a long-term creep test

σ Standard deviation of the slip coefficient from short-term slip load tests

Glossary

The following terms are used in this Design Guide.

Allowable strength. The resistance to be used in ASD design; the nominal strength, R_n, divided by the safety factor, Ω.

Arbitration torque. The torque used for the process of arbitration of disputes of pretensioned bolts. See Chapter 10.

Available strength. Design strength or allowable strength, as appropriate.

ASD load. Load due to a load combination in the applicable building code intended for allowable strength design (allowable stress design).

Bolt tension measurement device. A calibrated device that is used to verify that the bolting assembly, the pretensioning method, and the tools used are capable of achieving the required tensions when a pretensioned joint or slip-critical joint is specified.

Bolting assembly. An assembly of bolting components that is installed as a unit.

Bolting component. Bolt, nut, washer, or other element used as a part of a bolting assembly.

Combined method. Pretensioning technique that relies upon application of an installation wrench that has been calibrated to provide the initial torque to attain the required initial tension, followed by the application of the determined relative rotation between a bolt and nut. See Section 8.2.2.

Connection. An assembly of one or more joints that is used to transmit forces between two or more members.

Contractor. Any company, or that individual representing a company, responsible for the bolting operations.

Construction documents. Written, graphic, and pictorial documents prepared or assembled for describing the design (including the structural system), location, and physical characteristics of the elements of a building necessary to obtain a building permit and construct a building.

Contract documents. The documents that define the responsibilities of the parties that are involved in bidding, fabricating, and erecting structural steel. Contract documents include the design documents, the specifications, and the contract.

Design documents. Design drawings, design model, or a combination of drawings and models.

Design strength. The resistance to be used in LRFD design; the product of the nominal strength, R_n, and the resistance factor, ϕ.

Direct tension indicator (DTI). A washer-shaped device incorporating small arch-like protrusions on the bearing surface that are designed to deform in a controlled manner when subjected to a compressive load.

Engineer of Record (EOR). The party responsible for the design of the structure and for the required approvals. See Section 1.4.

Faying surface. In a connection the contact surface between two connected elements.

Firm contact. The condition that exists on a faying surface when the plies are solidly seated against each other, but not necessarily in continuous contact.

Grip. The total thickness of material a bolt passes through, exclusive of washers or direct-tension indicators.

High-strength bolt. A bolt with a diameter from ½ to 1½ in. that meets the requirements given in Section 2.1.1.

Initial tension. Minimum bolt tension attained before application of the required rotation when using the combined method to pretension bolting assemblies.

Initial torque. Amount of torque necessary to reach the initial tension in a bolting assembly pretensioned with the combined method.

Inspector. The party responsible for verifying that the contractor has satisfied the provisions of the specification applicable to the work.

Joint. The area of a connection in which one group of welds or one group of bolting assemblies joins two or more members or connection elements.

Lot. A quantity of uniquely identified bolting components or assemblies or matched bolting assemblies of the same nominal size and length produced consecutively at the initial operation from a single mill heat of material and processed at one time, by the same process, in the same manner, so that statistical sampling is valid.

LRFD load. Load due to a load combination in the applicable building code intended for strength design (load and resistance factor design).

Manufacturer. The party that produces one or more bolting components.

Matched bolting assembly. Bolting assembly made of components that are supplied and tested by the manufacturer or supplier in controlled lots as an assembly.

Mean slip coefficient. μ, the ratio of the frictional shear load at the faying surface to the total normal force when slip occurs.

Nominal strength. The capacity of a structure or component to resist the effects of loads, as determined by computations using the specified material strengths and dimensions and equations derived from accepted principles of structural mechanics or by field tests or laboratory tests of scaled models, allowing for modeling effects and differences between laboratory and field conditions.

Non-high-strength bolt. Any bolt that does not meet the requirements for a high-strength bolt as outlined in Section 2.1.1.

Nonstructural bolt assembly. Any bolting assembly which does not meet all the requirements of a structural bolting assembly in Section 2.5.

Pretension (noun). A level of tensile force achieved in a bolting assembly through its installation, as required for pretensioned and slip-critical joints.

Pretension (verb). The act of tightening a bolting assembly to a level required for pretensioned and slip-critical joints.

Pretensioned joint. A joint that transmits shear and/or tensile loads in which the bolts have been installed in accordance with Section 8.2 to provide a minimum specified pretension in the installed bolt.

Protected storage. Storage of bolting components or bolting assemblies that provides protection from environmental conditions and contamination that are detrimental to the installation of components and assemblies.

Prying action. Lever action that exists in connections in which the line of application of the applied load is eccentric to the axis of the bolt, causing deformation of the fitting and an amplification of the axial tension in the bolt.

Required strength. The load effect acting on an element or connection determined by structural analysis from the factored loads using the most appropriate critical load combination.

Reuse. Pretensioning of a bolting assembly that has been previously pretensioned and subsequently loosened.

Routine observation. Periodic monitoring of the work in progress.

Shear/bearing joint. A snug-tightened joint or pretensioned joint with bolts that transmit shear loads and for which the design criteria are based upon the shear strength of the bolts and the bearing strength of the connected materials.

Slip-critical joint. A joint that transmits shear loads or shear loads in combination with tensile loads in which the bolting assemblies have been installed in accordance with Section 8.2 to provide a pretension in the installed bolt (clamping force on the faying surfaces), and with faying surfaces that have been prepared to provide a calculable resistance against slip.

Snug-tight condition. The joint condition in which the plies have been brought into firm contact and each bolting assembly has at least the tightness attained with either a few impacts of an impact wrench, resistance to a suitable nonimpacting wrench, or the full effort of an ironworker using an ordinary spud wrench.

Snug-tightened joint. A joint in which the bolting assemblies have been installed to the snug-tight condition.

Specifications. The portion of the construction documents and the contract documents that consist of the written requirements for materials, standards, and workmanship.

Structural bolt assembly. A bolting assembly that meets all the requirements of Section 2.5.

Start of work. Any time prior to the installation of bolts in structural connections.

Stress corrosion cracking (SCC). A form of environmental cracking in a metal where a tensile stress, which may be residual from manufacturing or applied, interacts with a specific corrosive medium, leading to crack initiation and propagation.

Style. The physical configuration of a bolt or bolting assembly (heavy hex head or hex head).

Sufficient thread engagement. Having the end of the bolt or the available bolt threads extending beyond or at least flush with the outer face of the nut; a condition that develops the strength of the bolt.

Supplier. The party that sells the bolting components or matched bolting assemblies.

Temporary bolts. Bolting components or bolting assemblies that are temporarily used in a joint for purposes such as alignment, fit-up, or shipping.

Torque coefficient. A dimensionless factor that accounts for friction losses that occur during bolt tightening that relates the applied torque to the resulting bolt tension.

Turn-of-nut method. Pretensioning technique that relies upon application of a designated amount of relative rotation between bolt and nut. See Section 8.2.1.

Uncoated faying surface. A faying surface that has neither been primed, painted, nor hot-dip galvanized.

Abbreviations

The following abbreviations appear in this Design Guide. The abbreviations are written out where they first appear within a section.

AISC (American Institute of Steel Construction)
AMPP (Association of Materials Protection and Performance)
ANSI (American National Standards Institute)
ASCE (American Society of Civil Engineers)
ASME (American Society of Mechanical Engineers)
ASD (allowable strength design)
ASTM (American Society for Testing and Materials)
EOR (engineer of record)
DTI (direct tension indicator)
HRC (Rockwell hardness scale C)
ISO (International Organization for Standardization)
LRFD (load and resistance factor design)
PH (precipitation hardening)
PREN (pitting resistance equivalent number)
PTFE (polytetrafluoroethylene)
RCSC (Research Council on Structural Connections)
SAE (Society of Automotive Engineers)
SCC (stress corrosion cracking)
SCI (Steel Construction Institute)
SEI (Structural Engineering Institute)
UNC (unified coarse series)
UNS (unified numbering system)

References

Afzali, N., Stranghöner, N., Pilhagen, J., Manninen, T., and Schedin, E. (2019), "Viscoplastic Deformation Behaviour of Preloaded Stainless Steel Connections," *Journal of Constructional Steel Research*, Elsevier, Vol. 152, pp. 225–234.

AISC (2021a), *Code of Standard Practice for Structural Stainless Steel Buildings*, AISC 313-21, American Institute of Steel Construction, Chicago, Ill.

AISC (2021b), *Specification for Structural Stainless Steel Buildings,* ANSI/AISC 370-21, American Institute of Steel Construction, Chicago, Ill.

AMPP (2022), *Procedure for Determining Conformance to Dry Coating Thickness Requirements*, SSPC-PA 2-2022, Association of Materials Protection and Performance, Houston, Tex.

ASCE (2022), *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE/SEI 7-22, American Society of Civil Engineers, Reston, Va.

ASME (2019), *Fasteners for Use in Structural Applications*, B18.2.6-2019, American Society of Mechanical Engineers, New York, N.Y.

ASME (2021), *Square, Hex, Heavy Hex, and Askew Head Bolts and Hex, Heavy Hex, Hex Flange, Lobed Head, and Lag Screws (Inch Series)*, B18.2.1-2012(R2021), American Society of Mechanical Engineers, New York, N.Y.

ASME (2022), *Nuts for General Applications: Machine Screw Nuts; and Hex, Square, Hex Flange, and Coupling Nuts (Inch Series)*, B18.2.2-2022, American Society of Mechanical Engineers, New York, N.Y.

ASME (2023), *Round Head Bolts (Inch Series)*, B18.5-2012(R2023), American Society of Mechanical Engineers, New York, N.Y.

ASME (2024), *Unified Inch Screw Threads (UN, UNR, and UNJ Thread Forms)*, B1.1-2024, American Society of Mechanical Engineers, New York, N.Y.

ASTM (2021a), *Standard Specification for High Strength Precipitation Hardening and Duplex Stainless Steel Bolting for Special Purpose Applications*, ASTM A1082/A1082M-16(2021), ASTM International, West Conshohocken, Pa.

ASTM (2021b), *Standard Test Methods for Field Measurement of Surface Profile of Blast Cleaned Steel*, ASTM D4417-21, ASTM International, West Conshohocken, Pa.

ASTM (2023), *Standard Practice for Numbering Metals and Alloys in the Unified Numbering System (UNS)*, ASTM E527-23, ASTM International, West Conshohocken, Pa.

ASTM (2024a), *Standard Practice for Fastener Sampling for Specified Mechanical Properties and Performance Inspection*, ASTM F1470-24, ASTM International, West Conshohocken, Pa.

ASTM (2024b), *Standard Specification for Alloy Steel and Stainless Steel Bolting for Low Temperature Service*, ASTM A320/A320M-24a, ASTM International, West Conshohocken, Pa.

ASTM (2024c), *Standard Specification for Carbon, Alloy Steel, and Stainless Steel Nuts for Bolts for High Pressure or High Temperature Service, or Both*, ASTM A194/A194M-24, ASTM International, West Conshohocken, Pa.

ASTM (2024d), *Standard Specification for Carbon and Alloy Steel Nuts (Inch and Metric)*, ASTM A563/A563M-24, ASTM International, West Conshohocken, Pa.

ASTM (2024e), *Standard Specification for Hardened Steel Washers Inch and Metric Dimensions*, ASTM F436/F436M-24, ASTM International, West Conshohocken, Pa.

ASTM (2024f), *Standard Specification for Precipitation-Hardening Stainless and Heat-Resisting Steel Plate, Sheet, and Strip*, ASTM A693-24, ASTM International, West Conshohocken, Pa.

ASTM (2024g), *Standard Specification for Stainless Steel Bolts, Hex Cap Screws, and Studs*, ASTM F593-24, ASTM International, West Conshohocken, Pa.

ASTM (2024h), *Standard Specification for Stainless Steel Nuts*, ASTM F594-24, ASTM International, West Conshohocken, Pa.

ASTM (2025a), *Standard Specification for Alloy Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Applications*, ASTM A193/A193M-25, ASTM International, West Conshohocken, Pa.

ASTM (2025b), *Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications*, ASTM A240/A240M-25a, ASTM International, West Conshohocken, Pa.

ASTM (2025c), *Standard Specification for High Strength Structural Bolts and Assemblies, Steel and Alloy Steel, Heat Treated, Inch Dimensions 120 ksi, 144 ksi, and 150 ksi Minimum Tensile Strength, and Metric Dimensions 830 MPa and 1040 MPa Minimum Tensile Strength*, ASTM F3125/F3125M-25, ASTM International, West Conshohocken, Pa.

Baddoo, N. and Meza, F. (2022), *Structural Stainless Steel*, Design Guide 27, 2nd Ed., AISC, Chicago, Ill.

BSI (1979), "Commentary on Corrosion at Bimetallic Contacts and Its Alleviation," PD 6484:1979, British Standards Institution, London, U.K.

European Commission (2019), "Execution and Reliability of Slip-Resistant Connections for Steel Structures Using Carbon Steel and Stainless Steel (SIROCO)," Final Report, Directorate-General for Research and Innovation, Brussels, Belgium.

Grubbs, F.E. (1950), "Sample Criteria for Testing Outlying Observations," *The Annals of Mathematical Statistics*, Vol. 21, No. 1, pp. 27–58.

ISO (2020a), *Fasteners—Mechanical Properties of Corrosion-Resistant Stainless Steel Fasteners—Part 1: Bolts, Screws, and Studs with Specified Grades and Property Classes*, ISO 3506-1:2020, International Organization for Standardization, Geneva, Switzerland.

ISO (2020b), *Fasteners—Mechanical Properties of Corrosion-Resistant Stainless Steel Fasteners—Part 2: Nuts with Specified Grades and Property Classes*, ISO 3506-2:2020, International Organization for Standardization, Geneva, Switzerland.

ISO (2024), *Fasteners—Mechanical Properties of Corrosion-Resistant Stainless Steel Fasteners—Part 7: Flat Washers with Specified Grades and Property Classes*, ISO 3506-7:2024, International Organization for Standardization, Geneva, Switzerland.

Kulak, G.L., Fisher, J.W., and Struik, J.H. (1987), *Guide to Design Criteria for Bolted and Riveted Joints*, 2nd Ed., John Wiley & Sons, New York, N.Y.

Ocel, J., Kogler, R., and Ali, M. (2014), "Interlaboratory Variability of Slip Coefficient Testing for Bridge Coatings," FHWA-HRT-14-093, Federal Highway Administration, McLean, Va.

Provines, J.T. (2023), "Specified Pretension Values and Installation Parameters for 2205 and 17-4 PH Condition H1150 Stainless Steel Fastener Assemblies," *Journal of Constructional Steel Research*, Elsevier, Vol. 210, p. 108052.

Provines, J.T., Audrey, K.M., and Stephen, R.S. (2021), "Corrosion-Resistant Steel Fastener Assemblies for ASTM A709 Grade 50CR Steel Bridges," FHWA/VTRC 21-R13, Virginia Transportation Research Council, Charlottesville, Va.

RCSC (2025), *Specification for Structural Joints Using High-Strength Bolts*, Research Council on Structural Connections, AISC, Chicago, Ill.

Ryan, I. (1999), "Development of the Use of Stainless Steel in Construction—Bolted Connections (WP4.2), Part 1: Cover Plate Connections," ECSC Project No. 7210-SA/327, Steel Construction Institute, Ascot, U.K.

SAE (2012), *Numbering Metals and Alloys*, J1086-201210, SAE International, Warrendale, Pa.

Salih, E.L., Gardner, L., and Nethercot, D.A. (2011), "Bearing Failure in Stainless Steel Bolted Connections," *Engineering Structures*, Elsevier, Vol. 33, No. 2, pp. 549–562.

Song, Y., Wang, J., Uy, B., and Li, D. (2020a), "Experimental Behaviour and Fracture Prediction of Austenitic Stainless Steel Bolts under Combined Tension and Shear," *Journal of Constructional Steel Research*, Elsevier, Vol. 166, p. 105916.

Song, Y., Wang, J., Uy, B., and Li, D. (2020b), "Stainless Steel Bolts Subjected to Combined Tension and Shear: Behaviour and Design," *Journal of Constructional Steel Research*, Elsevier, Vol. 170, p. 106122.

Stranghöner, N. and Abraham, C. (2021), "Shear Resistance of Austenitic and Duplex Stainless Steel Bolts," *Journal of Constructional Steel Research*, Elsevier, Vol. 184, p. 106807.

Stranghöner, N., Afzali, N., de Vries, P., Schedin, E., and Pilhagen, J. (2017), "Slip-Resistant Bolted Connections of Stainless Steel," *Steel Construction*, Wiley, Vol. 10, No. 4, pp. 333–343.

Stranghöner, N., Afzali, N., de Vries, P., Schedin, E., and Pilhagen, J. (2019), "Slip Factors for Slip-Resistant Connections Made of Stainless Steel," *Journal of Constructional Steel Research*, Elsevier, Vol. 152, pp. 235–245.

Further Resources

International Molybdenum Association
www.imoa.info

For queries concerning material selection, corrosion, and end uses of molybdenum-containing stainless steels.

Nickel Institute
www.nickelinstitute.org

For queries concerning material selection, corrosion, and end uses.

World Stainless
www.worldstainless.org

For queries concerning technical information, statistics, and training resources on the use of stainless steel.

Produced in association with:

boltcouncil
RESEARCH COUNCIL ON STRUCTURAL CONNECTIONS
rcsc

AMERICAN INSTITUTE OF STEEL CONSTRUCTION
AISC
FOUNDED 1921

Smarter. Stronger. Steel.

American Institute of Steel Construction
312.670.2400 | www.aisc.org

D841-25