REPRINTED COURTESY OF

GWY

ABSOLUTE ACCURACY®

Specification for

Structural Joints Using High-Strength Bolts

June 5, 2025
Supersedes the June 11, 2020
Specification for Structural Joints Using High-Strength Bolts

Prepared by RCSC Committee A.1—Specifications and approved by the Research Council on Structural Connections

boltcouncil
RESEARCH COUNCIL ON STRUCTURAL CONNECTIONS
rcsc

GWY

ABSOLUTE ACCURACY®

SALES • RENTALS • TRAINING • SERVICE

Contact your bolting specialist today!

1 (888) 838-6500 - sales@gwyinc.com - gwyinc.com

217 Forest Road, Greenfield, NH 03047

Specification for Structural Joints Using High-Strength Bolts

June 5, 2025
Supersedes the June 11, 2020
Specification for Structural Joints Using High-Strength Bolts

Prepared by RCSC Committee A.1—Specifications and approved by the Research Council on Structural Connections

boltcouncil
RESEARCH COUNCIL ON STRUCTURAL CONNECTIONS
rcsc

Printed in the United States of America

PREFACE

The purpose of the Research Council on Structural Connections (RCSC) is:

(1) To stimulate and support such investigation as may be deemed necessary and valuable to determine the suitability, strength, and behavior of various types of structural connections;
(2) To promote the knowledge of economical and efficient practices relating to such structural connections; and
(3) To prepare and publish related specifications and such other documents as necessary to achieve its purpose.

The Council membership consists of qualified structural engineers from academic and research institutions, practicing design engineers, representatives of *suppliers* and *manufacturers* of *bolting components*, steel fabricators, steel erectors, *contractors*, associations, and code-writing bodies.

The first Specification approved by the Council, called the *Specification for Assembly of Structural Joints Using High Tensile Steel Bolts*, was published in January 1951. Since that time the Council has published 18 successive editions. Each was developed through the deliberations and approval of the full Council membership and based upon past successful usage, advances in the state of knowledge, and changes in engineering design practice. This edition of the Council's *Specification for Structural Joints Using High-Strength Bolts* continues the tradition of earlier editions. The most significant changes are listed below.

Section 1.6—Section on *Contract Documents* expanded to include what shall be specified, what may be specified, and what requires approval by the *Engineer of Record*
Section 1.7—Section on *Contractor's* Responsibilities added
Section 1.8—Section on *Bolting Personnel* Qualifications added
Table 2.1—F3125 Grade 144 Heavy Hex and Grade 144 twist-off tension control bolts, including plain and coated matched assemblies, added
Section 2.3.2—ASTM A194 Grade DH nuts permitted as substitute for ASTM A563 Grades C, D, and DH
Section 2.5—ASTM F3394 hardened backup and reaction washers added
Section 2.8.1—ASTM F3125 Group 144 bolts, except for spline-end matched bolting assemblies, are permitted to be galvanized
Section 2.8.2—ASTM F3393 standard replaces ASTM F1136, F2833, and F3019 standards
Section 2.10.4—Permission to relubricate select matched bolting assemblies and bolting components is extended to personnel under the direction of the *Manufacturer*
Section 2.11.1—Plain finish ASTM F3125 Group 144 bolts are permitted to be reused
Section 3.3—Surface roughness limits for thermal-cut bolt holes moved from Commentary to the Specification
Section 6.2.5—Plate washer and continuous bar requirements regarding strength and corrosion resistance clarified
Sections 7.2, 8.2, and 9.2—Calibrated wrench method withdrawn

Sections 7.2.3, 8.2.3, and 9.2.3—Direct tension indicator feeler gauge entry provisions revised
Table 7.4—Minimum torque requirements for the *combined method* revised
Section 7.3—Procedures for nonconforming pre-installation verification tests added
Table 8.1 Note C—For turn-of-nut method, requirement to increase rotation when using F3394 backup/reaction washers added
Section 10—Requirement for calibration of torque wrench used for arbitration added

In addition, many editorial changes to the 2020 edition of this Specification are reflected in this latest edition.

By the Research Council on Structural Connections,

Officers

Robert E. Shaw, Jr. Chair	Gian A. Rassati Vice Chair	Sahil Prabhudesai Secretary/Treasurer

Directors

Toby Anderson	Carly McGee	Salim Brahimi
Jason Chadee	Ronnie Medlock	Dan Wrobleski

Task Groups

1 General Requirements	Gian A. Rassati
2 Products and Parts	Toby Anderson
3 Design	James A. Swanson
4 Installation	Chad M. Larson
5 Inspection	Thomas J. Schlafly

Committees

A1	Specification	Larry F. Kruth
A2/A4	Research, Education, and Projects	Todd C. Ude
A3	Membership and Funding	Jason Chadee
A5	Organizational Liaison	Salim V. Brahimi
B	Editorial	Thomas J. Schlafly
	Staff Support	Martin Downs

Members

Jones Barton
Peter C. Birkemoe
David Bogaty
David Bornstein
Carolyn Carbonneau
Chad T. Case
Derrick Castle
David Cohen
Bastiaan Cornelissen
Chris Curven
John Davis
James DiPasquale
Brady Dobbin
John W. Fisher
James Foreman
Alana Fossa
Karl H. Frank
Michael C. Friel
Christopher Garrell
Michael Gase
Albert Gelles
Bill Germuga
Rodney D. Gibble
Ted Goldstein
Jeff Greene
Philip A. Goldsby
Quentin Greiner
Matthew Haaksma
Jerome F. Hajjar
Robert A. Hay III
Mark V. Holland
Larry Kloiber
Alyssa Kumfer
Debra Laefer
Chad M. Larson
Bill R. Lindley II
John Martinez
John Marvin
John McGormley
Helen McKay
Jinesh K. Mehta
Heath E. Mitchell
Thomas M. Murray (dec.)
James Neeley
Justin Ocel
Travis Pechacek
Anna Petroski
Lee Pielaet
Brad Porter
Joseph Poulin
David Rank
Clint Rex
Mathew Reynolds
Joseph T. Ridgway
Thomas E. Ringelstetter
Andy Rios
Sougata Roy
Vince Sagan
Michael Samuels
Tom Schlafly
Rachel Shanley
David F. Sharp
Daniel Ethan Smith
Eric Smith
Nicholas Sovell
Mritunjaya Srivastava
Carlos Suarez Gallardo
James A. Swanson
Donny Dean Thompson
Willam A. Thornton
Chris Tribble
Todd C. Ude
Carmen Vertullo
Nathan Wilkinson
Ryan Wilson
Doug Yates
Joseph A. Yura

Additional Contributors

The Council gratefully acknowledges the contributions of these individuals to this edition of the Specification:

Ashik M. Ali
Rodney L. Baxter
Rich Brown
Bruce M. Butler
Garret O. Byrne
Helen Chen
Robert J. Connor
Nick E. Deal
Noah Dorsey
Peter Dusicka
Douglas B. Ferrell
Mike Gase
Philip A. Goldsby
Brian Goldsmith
Allen J. Harrold
Todd Helwig
Charles J. Kanapicki
Peter F. Kasper
Daniel J. Kaufman
Thomas J. Langill
Mike Marian
Curtis Mayes
Neil L. McMillan
Eugene R. Mitchell
Tate Nickerson
Christian Noveral
Sarah Olthof
Randy Reagan
Jordan Richardson
Jeremy Ruggio
Michael Samuels
Gerald E. Schroeder
Ben Seinola
Victor Shneur
Lee Shoemaker
Thomas S. Tarpy Jr.
Raymond H.R. Tide
Floyd J. Vissat
John Westphal

TABLE OF CONTENTS

SYMBOLS

The following symbols are used in this Specification.

A_b	Cross-sectional area based upon the nominal diameter of bolt, in.^{2}
C_f	Constant-amplitude fatigue constant, ksi^3
D_u	Multiplier that reflects the ratio of the mean installed bolt *pretension* to the specified minimum bolt *pretension*, T_m, (see Section 5.4)
F_n	*Nominal strength* (per unit area), ksi
F_{sr}	Allowable stress range, ksi
F_{TH}	Constant-amplitude fatigue threshold stress range for infinite life, ksi
F_u	Specified minimum tensile strength (per unit area), ksi
F_y	Yield strength of material, ksi
H_1	Thickness of head for a heavy hex bolt, in.
H_2	Thickness of nut for a heavy hex nut, in.
I	Moment of inertia of the built-up member about the axis of buckling (see Commentary to Section 5.4), in.^{4}
L	Total length of the built-up member (see Commentary to Section 5.4), in.
L_c	Clear distance, in the direction of load, between the edge of the hole and the edge of the adjacent hole or the edge of the material, in.
L_e	Distance from the end of the connected part to the center of the nearest hole, in.
L_s	For longitudinally loaded connections, length between outermost bolt hole centers parallel to the line of force (see Figure C-5.1), in.
P_u	*Required strength* in compression, kips; axial compressive force in the built-up member (see Commentary to Section 5.4), kips
Q	First moment of area of one component about the axis of buckling of the built-up member (see Commentary to Section 5.4), in.^{3}
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 determined in accordance with Section 5.1, kips
$(R_n/\Omega)_v$	*Allowable strength* in shear determined in accordance with Section 5.1, kips
R_s	Load to be placed on creep specimens
R_u	*Required strength* using LRFD load combinations, kips

T Applied service load in tension, kips

T_a *Required strength* in tension (service tensile load) per bolt, kips

T_m Specified minimum bolt *pretension* (for *pretensioned* joints as specified in Table 5.2), kips

T_t Average clamping force used in coating creep tests (see Appendix A), kips

T_u *Required strength* in tension (factored tensile load), kips

V_a *Required strength* in shear (service shear load) per bolt, kips

V_u *Required strength* in shear (factored shear load), kips

d_b Nominal diameter of bolt, in.

d_h Nominal diameter of bolt hole, in.

h_f Factor for fillers (see Section 5.4)

k_s Slip coefficient for an individual specimen determined in accordance with Appendix A

k_{sc} Factor accounting for the presence of an applied tensile force that reduces the net clamping force (see Section 5.4)

n_b Number of bolts in the *joint*

n_s Number of slip planes

n_{sr} Number of stress range cycles in the design life

s Bolt spacing in the direction of applied force, in.

t Thickness of the connected material, in.

t' Total thickness of fillers or shims (see Section 5.1), in.

Ω Safety factor

ϕ Resistance factor

ϕR_n *Design strength*, 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

μ *Mean slip coefficient*

μ_t *Mean slip coefficient* for a long-term creep tests

GLOSSARY

The following terms are used in this Specification. Where used, they are italicized to alert the user that the term is defined in this Glossary.

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 regarding *pretensioned* bolts. (Section 10)

Available Strength. Design strength or a*llowable strength*, as appropriate.

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

Backup Washer. Circular washer having a knurled surface on both sides (Source: ASTM F3394-23).

Bolt Tension Measurement Device (BTMD). A calibrated device used to verify that the *bolting assembly*, the *pretensioning method*, and the tools used are capable to achieve the required tensions when a *pretensioned joint* or *slip-critical joint* is specified.

Bolting Assembly. An assembly of *bolting components* installed as a unit.

Bolting Component. Bolt, nut, washer, *direct tension indicator*, or other element used as a part of a *bolting assembly*.

Bolting Material. Rod, flat plate, bar, sheet, or forging subsequently manufactured into a *bolting component*.

Bolting Personnel. Contractor's personnel performing supervision, installation, or inspection tasks.

Bolting Procedure. A document providing the detailed methods and practices involved in the installation, snug-tightening, and pretensioning (when required) of a high-strength bolt.

Calibrated Gap. For verification testing, the average gap, measured to the nearest 0.001 in., between a *direct tension indicator* and the hardened surface on which the protrusion is bearing when a *pretension* equal to that in Table 7.1 is applied.

Coated Faying Surface. A *faying surface* that has been primed, primed and painted, or protected against corrosion, except by hot-dip galvanizing.

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

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 structure. (Adapted from: AISC 360-22 and AISC 303-22)

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. See Section 1.6. (Sources: AISC 360-22 and AISC 303-22)

Contractor. Any company, or that individual representing a company, responsible for the bolting operations in conformance with the provisions of this Specification.

Contractor's Inspection. Also referred to as a Quality Control Inspection in AISC. Inspection and testing performed as necessary prior to assembly, during assembly, during bolting, and after bolting to ensure that materials and workmanship meet the requirements of the *contract documents* and this Specification. (See AISC 360-22 Chapter N)

Cure (noun). A condition of an applied coating in which physical properties such as hardness and slip resistance are achieved.

Cure (verb). The action of changing a coating from the physical properties it had when it was applied to the physical properties it is expected to have in service.

Degree of Cure. Quantitative measurement or qualitative rating of a physical property, such as hardness, to determine the development of acceptable intended in-service properties of an applied coating.

Design Documents. Design drawings, design model, or a combination of drawings and models. (Adapted from: AISC 360-22 and AISC 303-22)

Design Drawings. Graphic and pictorial portions of the *contract documents* showing the design, location, and dimensions of the work. These documents generally include, but are not necessarily limited to, plans, elevations, sections, details, schedules, diagrams, and notes. (Sources: AISC 360-22 and AISC 303-22)

Design Model. Three-dimensional digital model of the structure that conveys the structural steel requirements. (Sources: AISC 360-22 and AISC 303-22)

Design Strength. ϕR_n 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 approvals that are required in this Specification. (See Section 1.6 and the corresponding Commentary)

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

Feeler Gauge. A measurement tool provided by a *direct tension indicator (DTI)* manufacturer of precisely controlled uniform thickness that is inserted in the spaces between *DTI* protrusions during preinstallation verification, installation, and inspection.

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.

Galvanized Faying Surface. A *faying surface* that has been hot-dip galvanized.

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

Guide. The *Guide to Design Criteria for Bolted and Riveted Joints*, 2nd Edition (Kulak et al., 1987).

High-Strength Bolt. An ASTM F3125 or ASTM F3148 bolt, or an alternative design bolt that meets the requirements of Section 2.12.

Initial Tension. When using the *combined method* to *pretension bolting assemblies, the* minimum bolt tension attained before application of the required rotation.

Initial Torque. When using the *combined method* to *pretension bolting assemblies*, the torque necessary to reach the *initial tension.*

Inspector. The party responsible for verifying that the *Contractor* has satisfied the provisions of this Specification in the work.

Joint. The area of a *connection* in which one weld 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 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.

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.

Pretensioning Methods:

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. (Section 8.2.4)

Direct Tension Indicator Method. Pretensioning technique that relies upon deformation of the protrusions of a *direct tension indicator*. (Section 8.2.3)

Turn-of-Nut Method. Pretensioning technique that relies upon application of a designated amount of relative rotation between bolt and nut. (Section 8.2.1)

Twist-Off Tension Control Bolt Method. Pretensioning technique that relies upon the application of torque to the nut that causes the removal of the spline by the installation wrench. (Section 8.2.2)

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.

Reaction Washer. Circular washer with a knurled surface on one side and a contoured outside diameter designed to couple with an installation tool (Source: ASTM F3394-23)

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* previously *pretensioned* and subsequently loosened.

Rotational Capacity Test. A test to evaluate the presence and efficacy of lubricant and the compatibility of *bolting assemblies.*

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 where 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* where the *bolting assemblies* have been installed to the *snug-tight condition*.

Specifications. The portion of the *construction documents* and the *contract documents* that consists of the written requirements for materials, standards, and workmanship. (Sources: AISC 360-22 and AISC 303-22)

Spline End Matched Bolting Assemblies:

Fixed. A *matched bolting assembly* with a spline end that is to remain attached to the bolt once the installation is complete.

Twist-Off. A *matched bolting assembly* with a spline end that is to be sheared off by the installation wrench when using the *twist-off tension control bolt method* for installation.

Start of Work. Any time prior to the installation of *high-strength bolts* in structural *connections*.

Style. The physical configuration of a *high-strength bolt* or *bolting assembly* (heavy hex, spline end twist-off, spline end fixed).

Sufficient Thread Engagement. Having the end of the bolt, not including the spline of a spline-end 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* temporarily used in a *joint* for purposes such as alignment, fit-up, or shipping.

Third-Party Inspection. Inspection and testing performed as necessary prior to assembly, during assembly, during bolting, and after bolting by an *Inspector* independent from the *Contractor* when required by the authority having jurisdiction, the applicable building code, the purchaser, the owner, or the *Engineer of Record,* to ensure that materials and workmanship meet the requirements of the *contract documents* and this Specification. (See AISC 360-22 Section N1.)

Touching up. Retightening of a bolt loosened by the tightening of adjacent bolts.

Uncoated Faying Surface. A *faying surface* that is not primed, painted, or hot-dip galvanized.

SPECIFICATION FOR STRUCTURAL JOINTS USING HIGH-STRENGTH BOLTS

SECTION 1. GENERAL REQUIREMENTS

This section addresses the scope of the Specification; basic requirements for loading criteria and design methods; the standards referenced in the Specification; and the items that the Engineer of Record shall address, may address, or are subject to the approval of the Engineer of Record.

The section is organized as follows:

1.1. Scope

This Specification covers the design of bolted *joints* and the installation and inspection of *bolting components* and *bolting assemblies* listed in Section 1.5. This Specification also considers the use of alternative-design *bolting components, assemblies*, or installation methods as permitted in Section 2.12. This Specification relates only to those aspects of the connected materials that bear upon the performance of bolted *joints*.

The Symbols, Glossary, and Appendix are a part of this Specification. The Commentary to this Specification that is interspersed throughout is not part of this Specification.

This Specification is based on research and empirical evidence developed within the U.S. Customary Unit system, thus the values stated in U.S. Customary Units are to be regarded as standard. Direct conversion to SI units is strongly discouraged, as some prescribed quantities, formulas, and methods have been developed and verified explicitly for inch-series *bolting components* and design considerations. SI equivalents have not been validated. Use of metric *bolting components* and *assemblies* may result in nonconformance with this Specification.

This Specification shall not be interpreted in a way that prevents the use of alternatively designed fasteners and installation methods that comply with Section 2.12.

Commentary:

This Specification covers the design of bolted *joints* with collateral materials in the *grip* that are made of steel. These provisions do not apply when materials other than steel are included in the *grip.* These provisions are not applicable to anchor rods.

Recently, other types of *joints* that contain low-modulus materials in the *grip*, and most notably thermal break joints, have made an entrance into the market, and there are questions on their use. These materials are chiefly for components, such as cladding, awnings, and roof posts, that are not part of a primary load-resisting system. Thermal break joints are not intended for primary load-resisting systems. Several research projects have been conducted (Peterman et al., 2017; Peterman et al., 2020; Hamel and White, 2016) investigating the structural properties of thermal break joints showing that the presence of compressible gaskets, insulation, or other materials or coatings within the *grip* will preclude the development and/or retention of the installation *pretension* in the bolts.

Peterman et al. (2017) show that low-modulus materials are permissible in snug-tightened *joints* with bolts subject to shear when long-term loads are limited to 30% of the low-modulus materials' ultimate load. Low-modulus materials that showed acceptable behavior in that study had a through-thickness modulus of elasticity between 400 ksi and 800 ksi and a through-thickness compressive strength between 25 ksi and 65 ksi.

Additionally, with the presence of compressible materials in the *grip*, the snug-tightening operation will not generate a sufficient force in the bolt to deform the shank so that the head and/or the nut adapt to the slope of the surfaces under them. Therefore, only surfaces that are near-perpendicular to the bolt axis should be used in thermal break joints.

Based on the results in the literature, the *Engineer of Record* should consider, as a minimum, the following aspects of a thermal break joint:

- The stiffness and strength of the inserted layers and their influence on the intended performance of the joint;
- The maximum bolt tension that the layers in the *grip* can withstand without losing integrity or performance;
- The installation instructions to prevent overtightening of bolts;
- The effects of the thickness of the added plies on the stiffness and strength of the *bolting assembly* and of the *connection* as a whole;
- The resistance to exposure of the added plies, when applicable;
- The type of forces that the joint is intended to transfer (e.g., shear, shear and tension, compression, tension without fatigue);
- The long-term behavior of the inserted layers; and
- The electro-chemical interactions of the inserted layers with coatings on steel, if applicable.

1.2. Loads, Load Factors, and Load Combinations

The design and construction of the structure shall conform to either an applicable load and resistance factor design specification for steel structures or to an applicable allowable strength design specification for steel structures. Because factored load combinations account for the reduced probabilities of maximum loads acting concurrently, the *design strengths* given in this Specification shall not be increased.

1.3. Design for Strength Using Load and Resistance Factor Design (LRFD)

Design according to the provisions for load and resistance factor design (LRFD) satisfies the requirements of this Specification 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 shall be performed in accordance with Equation 1.1:

$$R_u \leq \phi R_n \tag{1.1}$$

where

R_u = *required strength* using *LRFD load* combinations
R_n = *nominal strength*
ϕ = *resistance factor*
ϕR_n = *design strength*

1.4. Design for Strength Using Allowable Strength Design (ASD)

Design according to the provisions for allowable strength design (ASD) satisfies the requirements of this Specification 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 shall be performed in accordance with Equation 1.2:

$$R_a \leq R_n/\Omega \tag{1.2}$$

where

R_a = *required strength* using *ASD load* combinations
R_n = *nominal strength*
Ω = *safety factor*
R_n/Ω = *allowable strength*

Commentary:

This Specification is written in a dual format covering both load and resistance factor design (LRFD) and allowable strength design (ASD). Both approaches provide a method of proportioning structural components such that no applicable limit state is exceeded when the structure is subject to all appropriate load combinations. When a structure or structural component ceases to fulfill the intended purpose in some way, it is said to have exceeded a limit state. Strength limit states concern maximum load-carrying capability and are related to safety. Serviceability limit states are usually related to performance under normal service conditions and usually are not related to strength or safety. The term "resistance" includes both strength limit states and serviceability limit states.

Although loads, load factors, and load combinations are not explicitly specified in this Specification, the safety and resistance factors herein are based upon the loads, load factors, and load combinations specified in ASCE/SEI 7. When the design is governed by other load criteria, the safety and resistance factors specified herein should be adjusted as appropriate.

1.5. Referenced Standards and Specifications

The following standards and specifications are referenced herein:

AISC: American Institute of Steel Construction

ANSI/AISC 303-22, *Code of Standard Practice for Steel Buildings and Bridges*
ANSI/AISC 360-22, *Specification for Structural Steel Buildings*

ASME: American Society of Mechanical Engineers

ANSI/ASME B18.2.6-19, *Fasteners for Use in Structural Applications*

ASTM: ASTM International

ASTM A123/A123M-24, *Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products*

ASTM A194/A194M-22, *Standard Specification for Carbon Steel, Alloy Steel, and Stainless Steel Nuts for Bolts for High Pressure or High Temperature Service, or Both*

ASTM A563/A563M-24, *Standard Specification for Carbon and Alloy Steel Nuts (Inch and Metric)*

ASTM A1059/A1059M-24, *Standard Specification for Zinc Alloy Thermo-Diffusion Coatings (TDC) on Steel Fasteners, Hardware, and Other Products*

ASTM B695-21, *Standard Specification for Coatings of Zinc Mechanically Deposited on Iron and Steel*

ASTM D3363-22, *Standard Test Method for Film Hardness by Pencil Test*

ASTM D4752-20(2024), *Standard Practice for Measuring MEK Resistance of Ethyl Silicate (Inorganic) Zinc-Rich Primers by Solvent Rub*

ASTM F436/F436M-24, *Standard Specification for Hardened Steel Washers, Inch and Metric Dimensions*

ASTM F959/F959M-17a(2023), *Standard Specification for Compressible-Washer-Type Direct Tension Indicators for Use with Structural Fasteners, Inch and Metric Series*

ASTM F1136/F1136M-11(2019), *Standard Specification for Zinc/Aluminum Corrosion Protective Coatings for Fasteners* (withdrawn 2025, see ASTM F3393)

ASTM F2329/F2329M-15(2023), *Standard Specification for Zinc Coating, Hot-Dip, Requirements for Application to Carbon and Alloy Steel Bolts, Screws, Washers, Nuts, and Special Threaded Fasteners*

ASTM F2833-11(2017), *Specification for Corrosion Protective Fastener Coatings with Zinc Rich Base Coat and Aluminum Organic/Inorganic Type* (withdrawn 2025, see ASTM F3393)

ASTM F3019/F3019M-19, *Standard Specification for Chromium Free Zinc-Flake Composite, with or without Integral Lubricant, Corrosion Protective Coatings for Fasteners* (withdrawn 2025, see ASTM F3393)

ASTM F3125/F3125M-25, *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 F3148-17a(2024), *Standard Specification for High Strength Structural Bolt Assemblies, Steel and Alloy Steel, Heat Treated, 144ksi Minimum Tensile Strength, Inch Dimensions*

ASTM F3393-24, *Standard Specification for Zinc-Flake Coating Systems for Fasteners*

ASTM F3394/F3394M-23, *Standard Specification for Hardened Steel Backup and Reaction Washers Inch and Metric Dimensions*

ASCE: American Society of Civil Engineers

ASCE/SEI 7-22, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*

IFI: Industrial Fastener Institute

IFI 144-2000(R2013), *Test Evaluation Procedures for Coating Qualification Intended for Use on High-Strength Structural Bolts*

ISO: International Standards Organization

ISO 4586-2:2018, High Pressure Decorative Laminates (HPL, HPDL)—Sheets Based on Thermosetting Resins (usually called laminates)

AMPP: The Association for Materials Protection and Performance

SSPC-PA 2 (2022), *Procedure for Determining Conformance to Dry Coating Thickness Requirements*

Commentary:
Within this specification, dual designation standards are cited only by the U.S. Customary standard name.

1.6. Contract Documents

This section consolidates information that the *Engineer of Record* is required to provide (Section 1.6.1) or has the option to specify (Section 1.6.2), or where the approval of the *Engineer of Record* is required (Section 1.6.3).

1.6.1. The *Engineer of Record* shall specify the following information:

(1) *Joint* type, if other than *snug tight* (i.e., *pretensioned* or *slip-critical*) (Section 4)
(2) Connection steel type and grade (Commentary to Section 2)
(3) Class of slip resistance, for *slip-critical joints* (Sections 4 and 5)
(4) Group designation of bolt or *bolting assembly* (120, 144, or 150) (Section 2)
(5) Type of *bolting assembly* (Type 1 or Type 3) (Section 2)
(6) Corrosion protection of *bolting assembly* if required (e.g., hot-dip galvanized, mechanically galvanized, zinc-flake coating) (Section 2)
(7) Where bolt threads shall be excluded from the shear plane, if applicable (Section 5)
(8) Material, if other than steel, if required within the *joint* (Section 1.1 and Commentary to 1.1)

1.6.2. The *Engineer of Record* may specify the following information:

(1) Grade of *bolting assembly* (Section 2)
(2) Style of *bolting assembly* (heavy hex, fixed spline end, or twist-off spline end) (Section 2)
(3) Use of special components (Section 2)

(4) *Pretensioning* method (Section 8)
(5) If re-pretensioning of galvanized *bolting assemblies* is required (Commentary to Section 8.2)
(6) Restrictions on the use of hole types (OVS, SSL, LSL restrictions) (Section 3.3)

1.6.3. The *Engineer of Record's* written approval is required for:

(1) Use of *faying surface* coatings in *slip-critical joints* that provide a mean slip coefficient determined in accordance with Appendix A, but differing from Class A or Class B coatings [Section 3.2.2(2)]
(2) Use of alternative-design *bolting components*, *assemblies*, or installation methods, including the corresponding installation and inspection requirements that are provided by the manufacturer (Section 2.12)
(3) Reuse of bolts, except for plain finish Group 120 heavy hex bolts in *snug-tightened joints,* which do not require approval (Section 2.11)
(4) Use of thermal cutting of bolt holes produced freehand (Section 3.3)
(5) For cyclically loaded *pretensioned joints*, use of thermal cutting for bolt holes (Section 3.3)
(6) Use of oversized, long-slotted holes, or short-slotted holes parallel to the direction of loading, in lieu of standard holes (Sections 3.3.2 through 3.3.4)
(7) Use of a value of D_u other than that provided in Section 5.4 (Section 5.4)
(8) Use of hole sizes larger than those permitted in Section 3.3 (Section 3.3)
(9) Limitations on pretensioning force for special purpose *joints* (e.g., thermal break joints) (Commentary to Section 1.1)

1.7. Contractor's Responsibilities

1.7.1. **Bolting Personnel Qualification:** The *Contractor* shall permit bolting to be performed only by *bolting personnel* who are qualified in conformance with the requirements of 1.8.

1.7.2. **Specific Bolting Requirements:** When a *joint* or a group of *joints* require a specific assembly order, bolting sequence, or bolting method, it shall be clearly indicated in the shop or erection documents.

1.7.3. Test Reports and Records

1.7.3.1. Test Reports: See Section 2.9.

1.7.3.2. Test Records: Records of pre-installation verification test results shall be kept by the *Contractor* and shall be made available to those required to examine them. When applicable, records of *rotational-capacity test* results shall be kept by the *Contractor* and shall be made available to those required to examine them.

1.7.4. **Preparation of Bolting Procedures:** For *pretensioned joints* and *slip-critical joints*, the *Contractor* shall prepare and provide to the *bolting personnel* a written *bolting procedure* that specifies all the required steps for installation, snug-tightening, and pretensioning, including the bolt orientation when required to ensure that the threads are excluded from the shear plane.

1.7.5. **Materials and Equipment:** The *Contractor* shall ensure that only materials and equipment conforming to the requirements of this Specification are used.

1.7.6. **Bolting Procedures in Production:** The *Contractor* shall ensure that all bolting operations are performed in conformance with *bolting procedures* that meet the requirements of this Specification and the *contract documents*.

1.7.7. **Contractor's Inspection:** The *Contractor* shall perform inspection of the work in accordance with Section 9.

1.7.8. **Correction of Deficiencies:** The *Contractor* shall perform necessary correction of all deficiencies in materials and workmanship in conformance with the requirements of this Specification and the *contract documents*.

1.7.9. **Approvals:** The *Contractor* shall request and receive in writing the approval of the *Engineer of Record* for items listed in 1.6.3.

1.7.10. **Notifications:** The *Engineer of Record* shall be notified by the party responsible for connection design, fabrication, or erection, as applicable:

(1) Type and dimensions of holes to be used when complete connection design is not shown in the design documents (see 3.3);
(2) When short-slotted holes are used as permitted in 3.3.3.1;
(3) For *bolting assemblies* designed to resist shear with the threads excluded from the shear plane (see 5.1), when additional washers are added under the bolt head; and
(4) When field rework or repair of *joints* results in conditions different from the *contract documents*.

1.8. Bolting Personnel Qualifications

1.8.1. **Installation Personnel:** The *Contractor* shall ensure that the personnel installing *bolting assemblies* have the knowledge and skills required to:

(1) Snug-tighten *joints* in accordance with 8.1; and
(2) If applicable, *pretension* joints applying the method(s) to be used in the work in accordance with 8.2.

1.8.2. **Supervision and Inspection Personnel:** The *Contractor* shall ensure that personnel responsible for supervision and inspection have the knowledge and skills required to supervise and inspect:

(1) Preinstallation verification testing in accordance with 7.1 and 7.2, for the *pretensioning method* to be used in the work;
(2) *Rotational capacity* testing in accordance with ASTM F3125 or F3148, if required; and

(3) Installation of *bolting assemblies* in accordance with 8.1 and, if applicable, *pretensioning* method(s) to be used in the work in accordance with 8.2.

1.8.3. **Bolting Personnel:** All *bolting personnel* shall have knowledge of:

(1) Bolt, nut, and washer types and markings, including any special type of *bolting component* to be used, as described in 2.1;
(2) Storage and lubrication in accordance with 2.10;
(3) Bolt hole types, dimensions, and quality, in accordance with 3.3 and 3.4;
(4) Washer requirements in accordance with Section 6;
(5) Bolt dimensions and bolt orientation when bolt threads are to be excluded from the shear plane, if designated in accordance with 1.6.1(7); and
(6) Proper use of installation tools.

1.8.4. **Assessment and Documentation**

1.8.4.1. Qualification assessments shall be conducted annually, or when the applicable *pretensioning method* has not been used by the installer for a period exceeding 6 months.

1.8.4.2. The *Contractor* shall have documented evidence of the training, knowledge, and skills of all *bolting personnel*.

1.8.5. **Installation Personnel Traceability:** Markings or other methods to identify the person responsible for installing bolting assemblies are not required.

SECTION 2. BOLTING COMPONENTS AND ASSEMBLIES

This section addresses the groups, types, identification, and requirements of bolting components and assemblies included in the Specification. It also includes requirements for alternative-design bolting components, assemblies, and methods.

The section is organized as follows:

2.1. Group Designations
2.2. Heavy Hex Structural Bolts
2.3. Heavy Hex Nuts
2.4. Spline End Matched Bolting Assemblies
2.5. Washers
2.6. Washer-Type Indicating Devices
2.7. Geometry of Bolting Components and Assemblies
2.8. Coated Bolting Components and Assemblies
2.9. Test Reports
2.10. Storage and Lubrication
2.11. Reuse
2.12. Alternative-Design Bolting Components, Assemblies, and Methods

2.1. Group Designations

This Specification addresses three tensile strength levels of bolts and categorizes the *bolting component* or *bolting assembly* by Group, as shown in Table 2.1.

Commentary:

This Specification deals principally with *high-strength bolts* in three tensile strengths—120, 144, and 150 ksi; their design, installation, inspection, and performance in structural steel *joints*; and those few aspects of the connected material that affect performance. Many other aspects of *connection* design and fabrication are of equal importance and must not be overlooked. For more general information on design and issues related to *high-strength bolting* and the connected material, refer to current steel design textbooks and the *Guide to Design Criteria for Bolted and Riveted Joints*, 2nd Edition (Kulak et al., 1987).

For convenience, this specification identifies these tensile strength levels as Groups and categorizes the bolt or *bolting assembly* as shown in Table 2.1.

ASTM structural bolt standards currently provide for two types of *high-strength bolts,* according to metallurgical classification. Type 1 bolts may be manufactured from medium carbon steel, carbon boron steel, alloy steel, or alloy steel with added boron. Type 3 bolts have improved atmospheric corrosion resistance and weathering characteristics. When the bolt type is not specified, either Type 1 or Type 3 may be supplied at the *Manufacturer's* option.

Structural bolts addressed in this Specification are supplied in diameters from ½ in. through 1½ in. Not all styles are available in all diameters.

Table 2.1
Group Designations for Bolts and Matched Bolting Assemblies

Group	Tensile Strength	Bolts	Matched Bolting Assemblies
Group 120	**120 ksi**	ASTM F3125 Grade A325	ASTM F3125 Grade F1852
			ASTM F3125 Grade A325 Coated
Group 144	**144 ksi**	ASTM F3125 Grade 144	ASTM F3125 Grade 144TC
			ASTM F3125 Grade 144 Coated
			ASTM F3148
Group 150	**150 ksi**	ASTM F3125 Grade A490	ASTM F3125 Grade F2280
			ASTM F3125 Grade A490 Coated

Structural bolts, nuts, and washers are required by ASTM standards to be distinctly marked. In addition to mandatory marks, the *manufacturer* may apply additional distinguishing marks. The mandatory marks are illustrated in Figure C-2.1.

2.2. Heavy Hex Structural Bolts

Group 120, 144, and 150 heavy hex structural bolts shall meet the requirements of ASTM F3125 Grades A325, 144, and A490, respectively.

2.3. Heavy Hex Nuts

2.3.1. Heavy hex nuts shall meet the requirements of ASTM A563, except as noted in 2.3.2. The grade of such nuts shall be as given in Table 2.2.

2.3.2. ASTM A194 Grade 2H nuts are permitted as substitutes for ASTM A563 Grades C, D, and DH nuts.

Commentary:
Nuts for use with plain Grade 150 bolts are often specified with lubricant to reduce the effort required to tighten the bolting assembly and to increase their elongation during installation.

2.4. Spline End Matched Bolting Assemblies

2.4.1. Group 120, 144 and 150 *spline end twist-off matched bolting assemblies* shall meet the requirements of ASTM F3125 Grade F1852, 144TC, and F2280, respectively. See Section 2.8 for requirements for coated *assemblies.*

Commentary:
ASTM F3125 Grades F1852, 144TC, and F2280 *spline end twist-off matched bolting assemblies* may be manufactured with a round head or a heavy hex head.

2.4.2. Group 144 *spline end fixed matched bolting assemblies* shall meet the requirements of ASTM F3148 Grade 144. See Section 2.8 for requirements for coated *assemblies*.

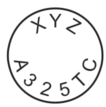
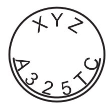
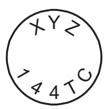
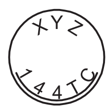
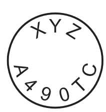
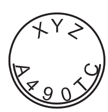
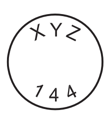
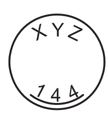
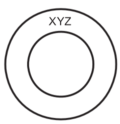
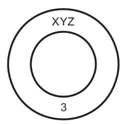
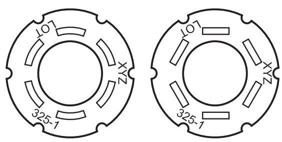
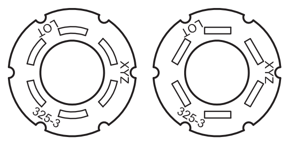
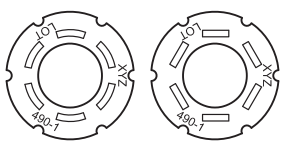
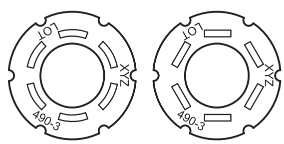
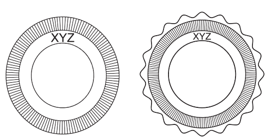
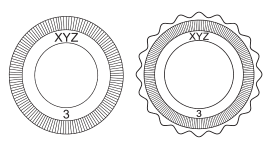
Bolting Component	Type 1	Type 3
ASTM F3125 Grade A325 bolt		
ASTM F3125 Grade F1852 bolt		
ASTM F3125 Grade 144 bolt		
ASTM F3125 Grade 144 TC bolt		
ASTM F3125 Grade A490 bolt		
ASTM F3125 Grade F2280 bolt		
ASTM F3148 Grade 144 bolt		

Fig. C-2.1. Required marks for bolting components.

Bolting Component	Type 1	Type 3
ASTM A563 nut	 Arcs indicate Grade C	 Arcs with “3” indicate Grade C3
	 Grade D	
	 Grade DH	 Grade DH3
ASTM A194 nut		
ASTM F436 washers		
ASTM F959 Direct Tension Indicators for Group 120		
ASTM F959 Direct Tension Indicators for Groups 144 and 150		
ASTM F3394 Backup and Reaction Washers		

1. XYZ represents the manufacturer’s identification mark.
2. Spline end matched bolting assemblies made to ASTM F3125 Grades F1852 and F2280 may be produced with heavy hex heads and have similar marks.

Fig. C-2.1. Required marks for bolting components (cont’d).

Table 2.2
Permitted Nut Grades

Group Designation	Bolt Type	Coating	ASTM A563 Nut Grade (See 2.3.2)
Group 120	1	Plain	C, C3, D, DH, and DH3
		Coated in compliance with 2.8	DH
	3	Plain	C3 and DH3
Groups 144 and 150	1	Plain	DH and DH3
		Coated in compliance with 2.8	DH
	3	Plain	DH3

2.5. Washers

2.5.1. Flat circular washers and beveled washers shall meet the requirements of ASTM F436, except as provided in Table C-6.1. Hardened backup and reaction washers shall meet the requirements of ASTM F3394.

2.5.2. The type (Type 1 or Type 3) of washers shall be the same as the bolt.

2.6. Washer-Type Indicating Devices

Compressible-washer-type *direct tension indicators* shall meet the requirements of ASTM F959. The type of *direct tension indicators* shall be as given in Table 2.3.

Commentary:
ASTM F959 requires that coatings other than mechanically galvanized zinc and thermally diffused zinc are to be used only when approved by the *Manufacturer*.

Because of common installation tension requirements, Group 150 *direct tension indicators* are appropriate for installation with Group 144 *bolting components*.

2.7. Geometry of Bolting Components and Assemblies

Bolting components and *assemblies* shall meet the dimensional requirements shown in Table 2.4. The bolt length used shall be such that, when installed, *sufficient thread engagement* is achieved.

Commentary:
Structural bolts are manufactured to the dimensions specified in ASME B18.2.6. The basic dimensions are listed in Table C-2.1 and illustrated in Figure C-2.2.

The principal geometric features of heavy hex structural bolts that distinguish them from bolts for general applications are the head size, unthreaded body length, and diameter tolerance. Heavy hex structural bolt heads have the same width-across-flat dimensions as heavy hex nuts so that an ironworker may use the same wrench or socket on either the bolt head or the nut.

Table 2.3
Permitted Types of Direct Tension Indicators

Group Designation	Bolt Type	DTI Type
Group 120	1	ASTM F959, Type 325-1
	3	ASTM F959, Type 325-3
Group 144 Group 150	1	ASTM F959, Type 490-1
	3	ASTM F959, Type 490-3

Table 2.4
Dimensional Requirements for Bolting Components and Assemblies

Bolting Component or Assembly	Dimensional Standard
Group 120, 144, and 150 heavy hex bolt	ASME B18.2.6
Group 120, 144, and 150 *spline end twist-off matched bolting assembly*	ASME B18.2.6
Group 144 *spline end fixed matched bolting assembly*	ASME B18.2.6, except for spline dimensions
ASTM A563 heavy hex nut ASTM A194 heavy hex nut	ASME B18.2.6 ASME B18.2.2
ASTM F436 washer	ASTM F436
ASTM F959 *direct tension indicator*	ASME B18.2.6
ASTM F3394 backup and reaction washers	ASTM F3394

With the specific exception of fully threaded bolts and the other permitted variances discussed below, heavy hex structural bolts have shorter threaded lengths than bolts for general applications. By making the body length of the bolt the control dimension, it is possible to exclude the bolt threads from all shear planes when desirable (except in cases of thin plies adjacent to the nut).

The shorter threaded lengths provided with heavy hex structural bolts tend to minimize the threaded portion of the bolt within the *grip*. Accordingly, care must be exercised to provide adequate threaded length between the nut and the bolt head to enable appropriate installation without jamming the nut on the thread run-out.

Depending upon the length increments of supplied bolts, for a *bolting assembly* without washers, the full thread of a bolt may extend into the *grip* as far as ⅜ in. for ½-, ⅝-, ¾-, ⅞-, 1¼- and 1½-in.-diameter bolts, and as far as ½ in. for 1-, 1⅛-, and 1⅜-in.-diameter bolts. When the thickness of the ply closest to the nut is less than these dimensions, it may still be possible to exclude the threads from the shear plane, when required, depending upon the specific combination of bolt length, *grip*, and number of washers used under the nut (Carter, 1996). If necessary, the next increment of bolt length can be specified along with ASTM F436 washers in sufficient quantity to both exclude the threads from the shear plane and ensure that the *bolting assembly* can be properly installed with adequate threads included in the *grip*.

At maximum accumulation of tolerances from all components in the *bolting assembly*, the thread run-out may cross the shear plane for the critical combination of bolt length and *grip* used to select the foregoing rules of thumb for ply thickness required to exclude the threads. Previous editions of this Specification treated shear planes in the thread transition length (see dimension *Y* in Figure C-2.2) as if the threads were excluded. Recent evaluation of this transition area and the variations permitted by ASME B18.2.6 (Swanson et al., 2020a,b) have caused the more conservative approach taken in this edition. See Section 5.1.

There are exceptions to the standard thread length requirements for F3125 Grades A325, 144, and A490 bolts; Grades F1852 and 2280 *matched bolting assemblies*; and F3148 Grade 144 *matched bolting assemblies*. First, ASME B18.2.6 requires that bolts shorter than certain lengths be fully threaded. (Table 2.5 lists such bolt lengths, which vary by diameter.) However, due to different *Manufacturers'* production methods the threads on such short bolts may not reach completely to the head and thus may leave the appearance of a usable shank or full-diameter body. Since any such appearance may differ and its presence cannot be predicted reliably, for certain *joints* with thin plies where such short, fully threaded bolts are used, the *Engineer of Record* should assume that no usable shank or full-body diameter exists and should assume that in such *joints* any shear planes will cross the bolt threads. Additional information on this approach can be found in Swanson et al. (2020a,b).

Secondly, optional supplementary requirements for ASTM F3125 Grade A325, 144, and F3148 bolts permit the purchaser to specify bolts that are threaded for the full length of the shank if the nominal length of the bolt is equal to or less than four times its nominal diameter. This option is provided to increase economy through simplified ordering and inventory control in the fabrication and erection of structures. It is particularly useful in those structures in which the strength of the *connection* is dependent upon the bearing strength of relatively thin connected material rather than the shear strength of the bolt, whether with threads in the shear plane or not. ASTM F3125 and ASTM F3148 require that bolts ordered to such supplementary requirements be marked with the symbol "T".

Lastly, optional supplementary requirements in ASTM F3125 permit the purchaser to specify threads of any length when necessary. ASTM F3125 requires that such bolts be marked with an "S". Such special thread lengths are produced only when specifically ordered.

Table 2.5
Bolt Lengths Required to Be Fully Threaded in Accordance with ASME B18.2.6

Nominal Bolt Diameter, d_b, in.	Bolt Length, L, in.
½	11⁄16
⅝	⅞
¾	1
⅞	1⅛
1	1¼
1⅛	1½
1¼	1⅝
1⅜	1¾
1½	1⅞

To determine the required bolt length, the value shown in Table C-2.2 should be added to the *grip* (i.e., the total thickness of all connected material, exclusive of washers). For each ASTM F436 washer that is used, add 5⁄32 in.; for each F436 extra thick washer, add 11⁄32 in.; for each F959 *direct tension indicator*, add 3⁄16 in.; for each F3394 reaction or backup washer, add 7⁄32 in.; for each beveled washer, add 5⁄16 in. The tabulated values provide for manufacturing tolerances and *sufficient thread engagement* with a heavy hex nut. The length determined by the use of Table C-2.2 should be adjusted to the nearest ¼-in. increment (or ½-in. increment for lengths exceeding 6 in.). A more extensive table for bolt length selection based upon these rules is available (Carter, 1996; Swanson et al., 2020a).

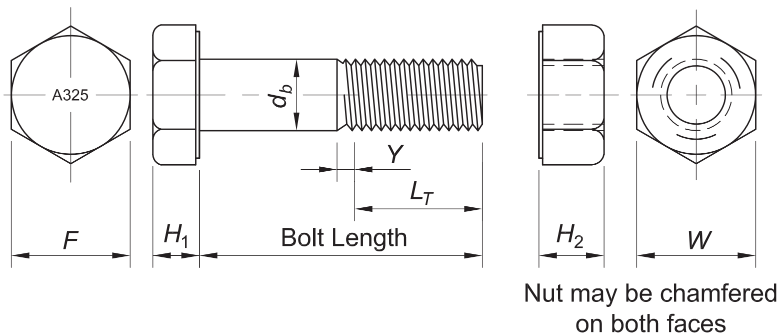


Fig. C-2.2. Heavy hex structural bolt and heavy hex nut.

Table C-2.1
Heavy Hex Bolt and Nut Nominal Dimensions

Nominal Bolt Diameter, d_b	Heavy Hex Bolt Dimensions, in.[a]				Heavy Hex Nut Dimensions, in.[b]	
	Width across Flats, F	Height, H_1	Thread Length L_T[c]	Transition Thread Length, Y	Width across Flats, W	Height, H_2
½	⅞	5⁄16	1	3⁄16	⅞	31⁄64
⅝	1 1⁄16	25⁄64	1¼	7⁄32	1 1⁄16	39⁄64
¾	1¼	15⁄32	1⅜	¼	1¼	47⁄64
⅞	1 7⁄16	35⁄64	1½	9⁄32	1 7⁄16	55⁄64
1	1⅝	39⁄64	1¾	5⁄16	1⅝	63⁄64
1⅛	1 13⁄16	11⁄16	2	11⁄32	1 13⁄16	1 7⁄64
1¼	2	25⁄32	2	⅜	2	1 7⁄32
1⅜	2 3⁄16	27⁄32	2¼	7⁄16	2 3⁄16	1 11⁄32
1½	2⅜	1 5⁄16	2¼	7⁄16	2⅜	1 15⁄32

[a]See ASME B18.2.6 Table 2.1-1 for additional dimensional information.
[b]See ASME B18.2.6 Table 3.1-1 for additional dimensional information.
[c]See Commentary to Section 2.7 for other thread length configurations.

Table C-2.2
Bolt Length Selection

Nominal Bolt Diameter, d_b, in.	As applicable, to Determine the Required Bolt Length, add to *Grip* + *Washer* + *Direct tension indicator*, + Reaction Washer + Backup Washer, in.
½	11⁄16
⅝	⅞
¾	1
⅞	1⅛
1	1¼
1⅛	1½
1¼	1⅝
1⅜	1¾
1½	1⅞

2.8. Coated Bolting Components and Assemblies

2.8.1. **Galvanized Bolting Components and Assemblies:** Except as noted in 2.8.1.2 and 2.8.1.5, *bolting components* are permitted to be hot-dip or mechanically galvanized. All threaded components of a *bolting assembly* shall be galvanized by the same process.

2.8.1.1. Hot-dip galvanized *bolting components* shall meet the requirements of ASTM F2329. Hot-dip galvanized nuts shall be overtapped in accordance with ASTM A563.

2.8.1.2. Hot-dip galvanizing is not permitted for Group 150 heavy hex bolts, *spline-end matched bolting assemblies* of any Group, or *direct tension indicators*.

2.8.1.3. Mechanically galvanized *bolting components* shall meet the Class 55 requirements of ASTM B695. Mechanically galvanized nuts shall be overtapped in accordance with the requirements of ASTM A563.

2.8.1.4. Mechanical galvanizing of *spline-end twist-off* and *fixed matched bolting assemblies* shall be performed only under the direction of the *manufacturer* and as permitted by the *assemblies*' respective standards.

2.8.1.5. Mechanical galvanizing is not permitted for Group 150 bolts or *assemblies.*

Commentary:
ASTM Specifications permit the galvanizing of ASTM F3125 Grade A325, and Grade 144 bolts. Applying zinc to Grade A490 bolts by galvanizing, metallizing, or mechanical coating is not permitted because its effects on embrittlement and delayed cracking have not been fully investigated to date. Research is in progress into whether this prohibition can be repealed.

Coating *bolting components* affects the stripping strength of the *bolting assembly*. To accommodate the variation in coating thickness on bolt threads, it is usual practice when coating structural nuts to tap the nut oversize (or "overtap"). This results in a reduction of thread engagement with a consequent reduction of the stripping strength. It is important that the specified proof load of the nut be higher than the tensile strength of the bolt. Only the hardened nut grades have adequate strength after overtapping to meet ASTM structural bolt strength requirements. Therefore, only ASTM A563 Grades DH and DH3 and ASTM A194 Grade 2H nuts are suitable for use as overtapped coated nuts.

Galvanized *high-strength bolts* and nuts must be furnished as a *matched bolting assembly*, and three principal factors must be considered so that the provisions of this Specification are understood and properly applied. These are:

(1) The effect of the galvanizing process on the mechanical properties of high-strength *bolting materials*;
(2) The effect of overtapping galvanized nuts on the nut's stripping strength; and

(3) The effect of galvanizing and lubrication on the torque required for *pretensioning*.

Birkemoe and Herrschaft (1970) showed that, in the as-galvanized condition, galvanizing increases the friction between the bolt and nut threads as well as the variability of the torque-induced *pretension*. A lower required torque and more consistent results are obtained if the nuts are lubricated. Thus, ASTM F3125 requires that a galvanized bolt and a galvanized and lubricated nut be assembled in a steel *joint* with a galvanized washer and tested by the *Supplier* prior to shipment. This testing, called rotational capacity (or "rocap") testing, must show that the galvanized nut with the lubricant provided can be rotated from the *snug-tight condition* well in excess of the rotation required for *pretensioned* installation without stripping. This requirement applies to hot-dip galvanized and mechanically galvanized *bolting assemblies*. The above requirements clearly indicate that:

(1) Galvanized *high-strength bolts* and nuts must be treated as a *matched bolting assembly*; and
(2) The *Supplier* must supply nuts that have been lubricated and tested with the supplied bolts.

The purchase of galvanized *high-strength bolts* and nuts from separate *Suppliers* is not in accordance with the intent of ASTM F3125 because the *Supplier* responsibility for the performance of the *bolting assembly* clearly could not have been provided as required. Should such bolts and nuts be purchased from separate *Suppliers*, the purchaser would become responsible for conducting any assembly tests and certifying the assemblies.

Because some of the lubricants used to meet the requirements of ASTM standards are water soluble, it is advisable that galvanized *high-strength bolts* and nuts be shipped and stored in sealed metal or plastic containers. Containers of *bolting components* with wax-type lubricants should not be subjected to heat that would cause depletion or change in the properties of the lubricant.

ASTM F3125 allows for both hot-dip galvanizing (ASTM F2329) and mechanical galvanizing (ASTM B695). The effects of the two coating processes on the performance characteristics and installation requirements are different. In accordance with ASTM F3125, all threaded components of the *bolting assembly* must be galvanized by the same process. (The *Supplier's* option is limited to one process per item with no mixed processes in a *lot*.) Mixing *high-strength bolts* that are galvanized by one process with nuts that are galvanized by the other may result in an unworkable *bolting assembly*.

Bolts with tensile strength above 180 ksi (i.e., with hardnesses above 39 HRC) are subject to embrittlement if hydrogen is present and the bolts are subjected to high tensile stress. Therefore, care must be taken with such bolts to avoid stress concentrations and exposure to environments that may induce hydrogen embrittlement.

The minimum tensile strength of ASTM F3125 Grades A325 and F1852 bolts is 120 ksi, while the minimum for ASTM F3148 bolts is 144 ksi. Maximum hardness limits result in production tensile strengths well below the critical range. The minimum tensile strength for ASTM F3125 Grades A490 and F2280 bolts is 150 ksi, and in addition, a maximum tensile strength limit of 173 ksi is specified to provide a margin below 180 ksi. The hardness maximum of 38 HRC for ASTM F3125 Grade A490 bolts provides a safeguard against hydrogen embrittlement. However, because *Manufacturers* must target their production slightly higher than the required minimum, Grades A490 and F2280 bolts close to the critical range of tensile strength must be anticipated. For plain finish *high-strength bolts*, this is not a cause for concern. However, if the bolt is hot-dip galvanized, delayed brittle fracture in service is a concern because of the possibility of the introduction of hydrogen during the pickling operation of the hot-dip galvanizing process and the subsequent "sealing-in" of the hydrogen by the zinc coating. There also exists the possibility of cathodic hydrogen absorption arising from the corrosion process in certain aggressive environments.

Research (Swanson and Rassati, 2025) into the installation of ASTM F3394 backup and reaction washers on galvanized connection material found satisfactory performance. However, these washers may be sensitive to use with thicker (>60 mil) coatings or paint systems. When thicker coatings or paints are to be used, testing is recommended.

2.8.2. **Zinc-Flake Coated Bolting Components and Assemblies:** Zinc-flake coating complying with ASTM F3393, Corrosion D, Appearance 1, Coefficient of Friction R, is permitted to be applied prior to installation under the limitations listed in this section. All threaded components of a *bolting assembly* shall be coated by the same process.

2.8.2.1. Zinc-flake coating of *spline-end twist-off* and *fixed bolting assemblies* shall be performed only under the direction of the *manufacturer* and as permitted by the respective product standards.

2.8.2.2. Zinc-flake coated nuts shall be overtapped in accordance with ASTM A563.

2.8.2.3. Zinc-flake coating is only permitted for *direct tension indicators* with the approval of the *manufacturer* of the *direct tension indicator*.

Commentary:
ASTM F3393, *Zinc-Flake Coating Systems for Fasteners*, replaced the three coating standards cited in prior editions of this Specification (i.e., ASTM F1136, ASTM F2833, and ASTM F3019). See ASTM F3393 Appendix X.1 for additional information.

While zinc-flake coatings are thin, overtapping the nuts is necessary. Similar to mechanical galvanizing, such a process results in a comparatively uniform and evenly distributed coating.

Coated *high-strength bolts* and nuts must be considered as a *matched bolting assembly*, and three principal factors must be considered so that the provisions of this Specification are understood and properly applied:

(1) The effect of the coating process on the mechanical properties of *bolting materials*;
(2) The effect of overtapping coated nuts on the nut's stripping strength; and
(3) The effect of coating and lubrication on the torque required for *pretensioning*.

ASTM F3393 coatings have been tested to indicate they will not degrade the performance of Group 150 bolts. Inclusion in that table does not imply any specific corrosion protection performance.

Investigations in accordance with IFI-144 were completed and presented to the ASTM F16 Committee on Fasteners (Brahimi, 2006, 2011, 2014, 2017). These investigations demonstrated that a zinc-flake coatings applied in accordance with ASTM F3393 to ASTM F3125 Grade A490 bolts does not cause delayed cracking by internal hydrogen embrittlement, nor does it accelerate environmental hydrogen embrittlement by hydrogen absorption.

Although these bolts are typically not used in this manner, the *Engineer of Record* should address the embedding of bolts in concrete if the bolts have coatings containing aluminum. The alkalinity of wet and freshly hardened concrete (less than 7 days old) reacts with free aluminum leading to evolution of hydrogen gas that consumes the aluminum and can lead to "wormholes" in the concrete. No research has been performed to date to determine if the aluminum bound within the coatings is susceptible to this reaction.

2.8.3. Under the alternative-design provisions of Section 2.12, the *Engineer of Record* may permit other coatings that have been approved by ASTM for use on *bolting components* or *matched bolting assemblies* between published editions of this Specification.

2.8.4. **Coated Direct Tension Indicators:** *Direct tension indicators* are permitted to be mechanically galvanized in accordance with ASTM B695 Class 55 or thermo-diffusion coated in accordance with ASTM A1059. In accordance with ASTM F959, other coatings (e.g., zinc-flake) compatible with threaded components used in the work are permitted with the approval of the direct tension indicator *Manufacturer*.

2.9. Test Reports

Test reports documenting conformance to the applicable specifications for all *bolting components* and *matched bolting assemblies* shall be available to the *Engineer of Record* and *Inspector* prior to assembly or erection of structural steel.

Commentary:
Test reports provided by the *Manufacturer* or *Supplier* of *bolting components* and *matched bolting assemblies* are required to verify that the components are identifiable and meet the requirements of the applicable ASTM standard or appropriate consensus standard.

2.10. Storage and Lubrication

2.10.1. Once received at the installation site, *bolting components* and *bolting assemblies* shall be kept in *protected storage*.

2.10.2. Only as many *bolting components* and *bolting assemblies* as are anticipated to be installed during the work shift shall be taken from *protected storage*.

2.10.3. *Bolting components* and *bolting assemblies* that are not incorporated into the work shall be returned to *protected storage* at the end of the work shift.

Commentary:
Bolting components and *bolting assemblies* placed in the steel are considered incorporated into the work even if a full *snug-tight condition* or *pretensioning* has not yet been achieved. See the Commentary to 7.1.

2.10.4. *Bolting components* (including some *bolting assemblies*) may be field lubricated to help with installation as deemed practical or necessary, except that the following *matched bolting assemblies* and *bolting components* shall only be relubricated by, or under the direction of the *Manufacturer*:

(1) *Spline end twist-off matched bolting assemblies*;
(2) *Spline end fixed matched bolting assemblies*; and
(3) *Matched bolting assemblies* when using the *combined method* and alternative design *bolting components* or *matched bolting assemblies* (see Section 2.12).

2.10.5. Heavy hex head bolting components for *snug-tightened joints* that accumulate rust or dirt shall not be incorporated into the work unless they are cleaned and lubricated, if necessary.

2.10.6. *Bolting components* and *bolting assemblies* intended for *pretensioned* or *slip-critical joints* that accumulate rust or dirt shall not be incorporated into the work unless they are cleaned and lubricated, if necessary, and then retested as specified in Section 7. See Section 2.10.4 for prohibitions on relubrication.

2.10.7. *Temporary bolts* shall be exempt from this Section's storage requirements.

> **Commentary:**
> *Protected storage* requirements are specified for *high-strength bolts*, nuts, washers, and other *bolting components* so that the components' as-manufactured conditions are maintained as nearly as possible until they are incorporated in the work.
>
> Because *Manufacturers* may apply various coatings and lubricants to prevent corrosion or to facilitate manufacture or installation, the condition of supplied *bolting components* and *bolting assemblies* should not be altered.
>
> If *bolting components* or *bolting assemblies* become dirty, rusty, or otherwise have their as-received condition altered, they may be unsuitable for *pretensioned* installation. It is also possible that a *bolting assembly* may not pass the pre-installation verification test requirements of Section 7. Some *components* can be cleaned and lubricated by the fabricator or the erector.
>
> The limitations in Section 2.10.4 apply because proper installation in those situations is dependent on specific lubrication.

2.11. Reuse

2.11.1. Plain finish Groups 120 and 144 heavy hex bolts may be *reused* (1) in *snug-tightened joints* without *Engineer of Record* approval and (2) in *pretensioned joints* and *slip-critical joints* with *Engineer of Record* approval.

2.11.2. Coated bolts of any Group or grade, or coated *spline end bolting assemblies* of any Group or grade, and Group 150 heavy hex bolts shall not be *reused*.

2.11.3. *Touching up* shall not be considered a *reuse*.

> **Commentary:**
> *Pretensioned* installation involves the inelastic elongation of the portion of the threaded length between the nut and the thread run-out. Plain finish Group 120 bolts possess sufficient ductility to undergo more than one *pretensioned* installation as suggested in the *Guide* (Kulak et al., 1987). As a simple rule of thumb, a plain finish Grade A325 bolt is suitable for *reuse* if the nut can be run all the way up the threads by hand.
>
> Group 144 heavy hex bolts share the same ductility requirements as Group 120 bolts in ASTM F3125; therefore, they are suitable for *reuse*.
>
> On the other hand, while Group 150 bolts possess sufficient ductility to undergo one *pretensioned* installation, they are not consistently ductile enough to undergo a second pretensioned installation. The *Guide* also indicates that the coating on galvanized Group 120 bolts reduces their nut rotation capacity and thus are not to be *reused*. For additional guidance, see Bowman and Betancourt (1991).

2.12. Alternative-Design Bolting Components, Assemblies, and Methods

The Specification allows for innovation in *bolting components* and *assemblies* in *joints* that transmit forces through shear, tension, combined tension and shear, or friction on *faying surfaces* and that meet the requirements in this Section. Other mechanical fasteners are not covered in this Specification. The provisions in this Specification that are not explicitly covered by the relevant consensus standard of an alternative-design *bolting component* or *assembly* shall still apply.

2.12.1. When approved by the *Engineer of Record*, alternative-design *bolting components*, *assemblies*, or installation methods are permitted to replace or supplement *bolting components*, *assemblies*, or installation methods described elsewhere in this Specification under the following conditions:

(1) *Bolting components* or *assemblies* shall meet the minimum manufacturing, material, and mechanical properties of the grade and type being substituted;
(2) When used in *pretensioned* or *slip-critical joints*, the alternative-design product or method must meet minimum *pretension* requirements set in Table 5.2 for the Group being substituted; and
(3) When required by a product or consensus standard or the installation method, the alternative-design *bolting components* shall be supplied and used in the work as a *matched bolting assembly*.

2.12.2. When approved by the *Engineer of Record*, the use of consensus standards that are not referenced in Section 2 is permitted, under the following conditions:

(1) Alternative design *bolting components* or *assemblies* must meet the minimum manufacturing, material, and mechanical properties of an approved consensus standard;
(2) When considering strength levels other than those provided in this Specification, the consensus standard or *Manufacturer* shall provide, or the *Engineer of Record* shall determine, the minimum (and maximum, when applicable) specified values for at least:

a. Proof load and tensile strength;
b. *Nominal strength* values for Table 5.1;
c. Minimum *pretension* values for Table 5.2, as required; and
d. Fatigue strength values for Section 5.5, as required.

In addition, the consensus standard or *Manufacturer* shall provide:

e. Washer requirements, as required or if different than Section 6; and
f. Pre-installation verification test, installation, and inspection requirements, if applicable.

(3) When required by a consensus standard or the installation method, the *bolting components* shall be supplied and used in the work as a *matched bolting assembly*.

2.12.3. Alternative coatings shall meet the performance criteria as specified in the alternative coating standard and shall not have a detrimental effect on the *bolting components* or *assemblies*, specifically in conformance to Sections 2.12.1(1) and (2).

2.12.4. Alternative-design *bolting components* or *assemblies* are permitted to differ in dimensions from those specified in Section 2 with the following limitations:

(1) Bolts shall have a body diameter and bearing area under the head equal to or greater than that provided by an equivalent bolt in Section 2.7;
(2) Bolt thread lengths that differ from those in Section 2.7 shall be clearly identified and communicated to the *Engineer of Record*; and
(3) Nuts and washers shall have a bearing area that is equal to or greater than that provided by a nut or washer of the same nominal dimensions specified in Section 2.7, as applicable.

2.12.5. Installation methods shall be provided in the relevant consensus standard or by the *Manufacturer* and shall be approved by the *Engineer of Record*. These instructions shall provide, as a minimum:

(1) For *pretensioned* and *slip-critical joints*, the procedure and frequency of pre-installation verification testing;
(2) The alignment of bolt holes to permit insertion of the bolt without undue damage to the threads;
(3) The placement of *bolting assemblies* in all types and sizes of holes, including placement and orientation of the alternative design devices (and ASTM F436 washers or F3394 washers, if any);
(4) The systematic assembly of the *joint* to the *snug-tight condition*, progressing from the most rigid part of the *joint* until the connected plies are in *firm contact*; and
(5) For *pretensioned* and *slip-critical joints*, the subsequent systematic *pretensioning* of all bolting *assemblies* in the *joint*, progressing from the most rigid part of the *joint* in a manner that will minimize relaxation of previously *pretensioned* bolts.

2.12.6. Inspection instructions shall be provided in the relevant consensus standard or by the *manufacturer* and shall be approved by the *Engineer of Record*. These instructions shall provide, as a minimum:

(1) Required observation of the pre-installation verification testing, when performed; and
(2) Subsequent *routine observation* to verify the proper use of the alternative-design product or method.

Commentary:

RCSC's policy has been to recognize only *bolting components* and *matched bolting assemblies* that meet approved ASTM standards. Other consensus standards that could be considered by the *Engineer of Record* include EN, JIS, and ISO standards. However, alternate products, standards, and installation methods (known collectively as "alternative designs") may be used when approved by the *Engineer of Record*. Alternative designs fall into two categories:

(1) Product made as an alternative design to an ASTM standard referenced in this document and installed using RCSC installation methods or an alternate installation method. See Section 2.12.1; and
(2) Product made to an ASTM standard that is *not* referenced in this document or made to another consensus standard and installed using RCSC installation methods or an alternate installation method. See Section 2.12.2.

When using alternative designs it is important that the strength of the component and geometry be fully considered so that the requirements of *joint* design are met as intended by this Specification. Particularly important are strength requirements, such as tensile strength, shear strength, and minimum *pretension*, along with certain dimensional characteristics vital to proper *joint* loading, such as bearing area and bolt body diameter.

Alternative-design provisions are intended to provide flexibility to address unique needs and design challenges and to enable the use of alternate technology, standards, and practices. This includes products or technology the Council may not have had the time or opportunity to fully consider, or products with a frequency of use that might not compel the Council to detail such use in this document.

SECTION 3. BOLTED PARTS

This section addresses the fabrication of steel connections, including the treatment of faying surfaces.

The section is organized as follows:

3.1. Connected Plies

Unless otherwise approved by the *Engineer of Record,* all connected plies in a *joint* that are within the *grip* of the bolt and any materials that are used under the bolt head or nut shall be steel with *faying surfaces* that are *uncoated*, *coated*, or *galvanized.* See Section 3.2.

The slope of the surfaces of parts in contact with the bolt head and nut shall be equal to or less than 1:20 with respect to a plane that is normal to the bolt axis.

Commentary:
The presence of gaskets, insulation, or any compressible materials other than the specified coatings within the grip will preclude the development or retention of the installed pretensions in the bolts, when required. See the Commentary to Section 1.1.

Structural bolting assemblies are generally 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. Greater slopes are undesirable because the resultant localized bending decreases both the strength and the ductility of the bolt.

3.2. Faying Surfaces

Faying surfaces and surfaces adjacent to the bolt head and nut shall be free of dirt and other foreign material.

3.2.1. **Snug-Tightened Joints and Pretensioned Joints:** The *faying surfaces* of *snug-tightened joints* and *pretensioned joints* are permitted to be *uncoated*, *coated* with coatings of any formulation, or *galvanized*.

Commentary:
In both *snug-tightened joints* and *pretensioned joints*, the ultimate strength is dependent upon shear transmitted by the bolts and bearing of the bolts against the connected material. It is independent of any frictional resistance that may exist on the *faying surfaces*. Consequently, since slip resistance is not an issue, the *faying surfaces* are permitted to be *uncoated*, *coated*, or *galvanized* without regard to the resulting slip coefficient obtained.

For *pretensioned joints*, caution should be used in the specification and application of thick coatings within the *faying surface*, on ply surfaces under the bolt head, and under the nut or washer. Although slip resistance is not required, *bolting assemblies* in *joints* with thick or multilayer coatings may exhibit significant loss of *pretension* because of compressive creep in softer coatings such as epoxies, alkyds, vinyls, acrylics, and urethanes. Previous bolt relaxation studies have been conducted using uncoated steel with plain finish bolts or galvanized steel with galvanized bolts. *Galvanized faying surfaces* ranged up to approximately 4 mils of thickness, of which approximately half the thickness was the compressible soft pure zinc surface layer. The underlying zinc-iron layers are very hard and would exhibit little creep. See *Guide*, Section 4.4. Tests have indicated that significant bolt *pretension* may be lost when the total coating thickness within the *joint* approaches 15 mils per surface and that soft surface coatings beneath the bolt head and nut can contribute to additional reduction in *pretension*.

3.2.2. **Slip-Critical Joints:** The *faying surfaces* of *slip-critical joints*, including those of filler plates and finger shims, shall meet the following requirements:

(1) *Uncoated faying surfaces*:
   a. Shall be free of scale (except tight mill scale), coatings, and overspray:
      (i) In areas closer than one bolt diameter, but not less than 1 in. from the edge of any hole; and
      (ii) In all areas within the bolt pattern; or
   b. Shall be blast cleaned prior to assembly.

(2) *Coated faying surfaces* shall first be blast cleaned and subsequently coated with a coating that is qualified in accordance with Appendix A as a Class A or Class B coating (see Section 5.4). Alternatively, when approved by the *Engineer of Record*, coatings that provide a *mean slip coefficient* that differs from Class A or Class B are permitted when:
   a. The *mean slip coefficient* μ is established by testing in accordance with the requirements in Appendix A; and
   b. The design slip resistance is determined in accordance with Section 5.4 using this coefficient, except that, for design purposes, a value of μ greater than 0.50 shall not be used.

The plies of *slip-critical joints* with *coated faying surfaces* shall not be assembled before the coating has fully *cured*, or the longer of:
   (i) The minimum time that was used in the qualifying tests, or
   (ii) The time provided in the Coating Manufacturer's application instructions.

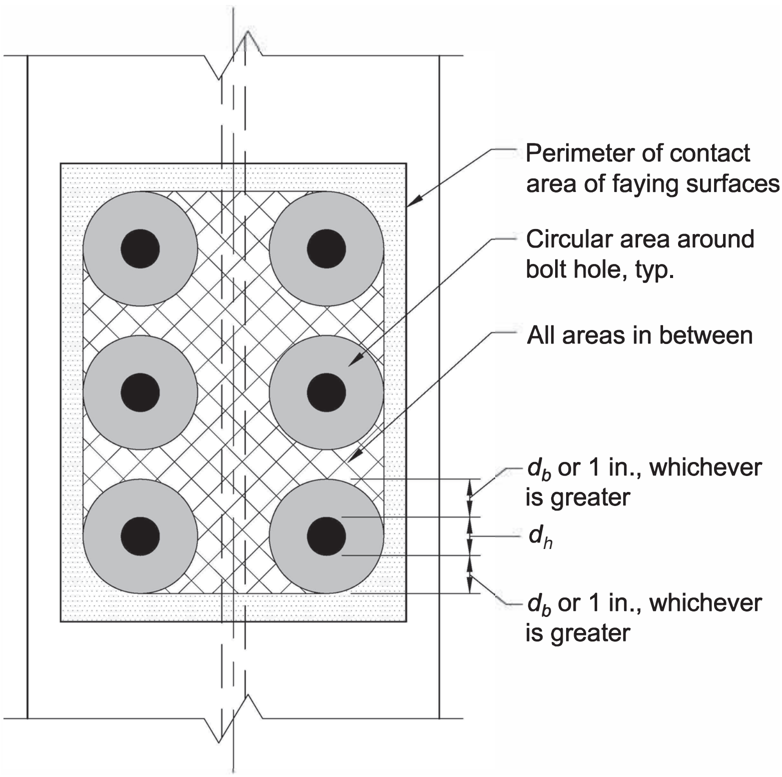
On members coated with non-qualified coatings, the *faying surfaces* shall be free of coating and overspray:
   (i) In areas closer than one bolt diameter but not less than 1 in. from the edge of any hole, and
   (ii) In all areas within the bolt pattern. See Figure C-3.1.

(3) *Galvanized faying surfaces* shall be hot-dip galvanized in accordance with the requirements of ASTM A123. Power or hand wire brushing is not permitted. *Galvanized faying surfaces* are designated as Class A for design.

Commentary:

Slip-critical joints are those *joints* that have specified *faying surface* conditions that, in the presence of the clamping force provided by *pretensioned bolting assemblies*, resist a design load solely by friction and without displacement at the *faying surfaces*. Consequently, it is necessary to prepare the *faying surfaces* in a manner such that the desired slip performance is achieved.

Clean mill scale steel surfaces (Class A, see Section 5.4) and blast-cleaned steel surfaces (Class B, see Section 5.4) can be used within *slip-critical joints*. When used, it is necessary to keep the *faying surfaces* free of unintentional coatings, including inadvertent overspray.



(d_b = *bolt diameter,* d_h = *nominal hole diameter).*

Fig. C-3.1. Areas of faying surfaces of slip-critical joints to remain uncoated with unqualified coatings.

Corrosion often occurs on uncoated blast-cleaned steel *faying surfaces* (Class B, see Section 5.4) due to exposure between the time of fabrication and subsequent erection. In normal atmospheric exposures, this corrosion is not detrimental and may actually increase the slip resistance of the *joint*. Yura et al. (1981) found that the Class B slip coefficient could be maintained for up to one year prior to *joint* assembly.

Polyzois and Frank (1986) demonstrated that for plate material with thickness in the range of ⅜ in. to ¾ in., the contact pressure caused by bolt *pretension* is concentrated on the *faying surfaces* in annular rings around and close to the bolts. In this study, unqualified paint on the *faying surfaces* away from the edge of the bolt hole by at least one bolt diameter but not less than 1 in. did not reduce the slip resistance. However, this would not likely be the case for *joints* involving thicker material, particularly those with a large number of bolts on multiple gage lines; the minimum bolt *pretension* in Table 5.2 might not be adequate to completely flatten and pull thicker material into tight contact around every bolt. Instead, the bolt *pretension* would be balanced by contact pressure on the regions of the *faying surfaces* that are in contact. To account for both possibilities, it is required in this Specification that for unqualified coatings all areas between the bolts be free of coatings, including overspray, as illustrated in Figure C-3.1.

As a practical matter, the smaller coating-free area can be laid out and protected more easily using masking located relative to the bolt-hole pattern than relative to the limits of the complete area of *faying surface* contact with varying and uncertain edge distance. Furthermore, the narrow coating strip around the perimeter of the *faying surface* minimizes the required field touch-up of uncoated material outside of the *joint*.

Polyzois and Frank (1986) also investigated the effect of various degrees of inadvertent overspray on slip resistance. It was found that even a small amount of overspray of unqualified paint (i.e., not qualified as a Class A or Class B coating) within the specified coating-free area on clean mill scale can reduce the slip resistance significantly. On blast-cleaned surfaces, however, the presence of a small amount of overspray was not as detrimental. For simplicity, this Specification requires that all overspray be prohibited from areas that are required to be free of coatings in *slip-critical joints* regardless of whether the surface is clean mill scale steel or blast-cleaned steel.

When the *faying surfaces* of a *slip-critical joint* are to be protected against corrosion, a qualified coating must be used. A qualified coating is one that has been tested in accordance with Appendix A, the sole basis for qualification of any coating to be used in conjunction with this Specification. Coatings can be qualified as follows:

(1) As a Class A coating as defined in Section 5.4;
(2) As a Class B coating as defined in Section 5.4; or
(3) As a coating with a *mean slip coefficient* μ of at least 0.30 (Class A) but not greater than 0.50 (Class B).

Retesting is required if any essential variable associated with *cure*, coating composition, or method of manufacture is changed. See Appendix A.

For *slip-critical joints*, coating testing as prescribed in Appendix A includes creep tests, which incorporate relaxation in the *bolting assembly* and the effect of the coating itself. Specifiers should verify the coating thicknesses used in the Appendix A testing and verify that the actual maximum average coating thickness is at least 2 mils less than the coating thickness tested. See Appendix A and Section A1.2.2.

Frank and Yura (1981) also investigated the effect of varying the time between coating the *faying surfaces* and assembly of the *joint* and *pretensioning* the bolts in order to ascertain if partially cured paint continued to *cure* within the assembled *joint* over a period of time. The results indicated that all curing effectively ceased at the time the *joint* was assembled, and paint that was not fully cured at that time acted as a lubricant. The slip resistance of a *joint* that was assembled after a time less than the curing time used in the qualifying tests was severely reduced. Thus, the *degree of cure* prior to mating the *faying surfaces* is an essential parameter to be specified and controlled during construction.

Prior versions of this Specification included a requirement to hand wire-brush galvanized surfaces in *slip-critical joints*, but research in combination with current galvanizing practices has revealed that such brushing does not improve slip resistance capacity and may reduce it (Donahue et al., 2014).

Field experience and test results have indicated that galvanized assemblies may continue to slip under sustained loading (Kulak et al., 1987). Tests of hot-dip galvanized *joints* subjected to sustained loading show a creep-type behavior that was not observed in short-duration or fatigue-type load application. See Appendix A and Commentary to A4.2.

3.3. Bolt Holes

The nominal dimensions of standard, oversized, short-slotted, and long-slotted holes for *high-strength bolts* shall be as shown in Table 3.1. Any restrictions on the use of hole types permitted in this section shall be specified in the *design documents*.

Mechanically guided thermally cut holes are permitted in all statically loaded *joints* and in cyclically loaded *slip-critical joints.* The surface roughness profile of the hole shall not exceed 1,000 microinches as defined in ASME B46.1. Occasional gouges not more than 1⁄16 in. in depth are permitted.

Commentary:

The footnotes in Table 3.1 provide for slight variations in the dimensions of bolt holes from the nominal dimensions. When the dimensions of bolt holes are such that they exceed these permitted variations, the bolt hole must be treated as the next larger type.

Table 3.1
Nominal Bolt Hole Dimensions

Nominal Bolt Diameter, d_b, in.	Nominal Bolt Hole Dimensions,[a,b] in.			
	Standard (diameter)	Oversized (diameter)	Short Slotted (width × length)	Long Slotted (width × length)
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 × 15⁄16	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 shall not exceed the nominal. The fabricated hole dimension shall not exceed the nominal +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.

Slots longer than standard long slots may be required to accommodate construction tolerances or expansion joints. Larger oversized holes may be necessary to accommodate construction tolerances or misalignments. In these two cases, the Specification provides no guidance for further reduction of *design strengths* or allowable loads. 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.

For thermally cut holes produced freehand, it is usually necessary to grind the hole's interior surface after thermal cutting in order to achieve a maximum surface roughness profile of 1,000 microinches.

Slotted holes in statically loaded *joints* are often produced by punching or drilling the hole ends and thermally cutting the sides of the slots by mechanically guided means. The sides of such slots should be ground smooth, particularly at the junctures of the thermal cuts to the hole ends.

For cyclically loaded *joints*, test results have indicated that when no major slip occurs in the *joint*, fretting fatigue failure usually occurs in the gross section prior to fatigue failure in the net section (Kulak et al., 1987). Conversely, when slip occurs in the *joints* of cyclically loaded *connections*, failure usually occurs in the net section and the edge of a bolt hole becomes the point of crack initiation (Kulak et al., 1987). Therefore, for cyclically loaded *joints* designed as slip-critical, the method used to produce bolt holes (either thermal cutting or drilling) should not influence the ultimate failure load, as failure usually occurs in the gross section when no major slip occurs.

3.3.1. **Standard Holes:** Standard holes are permitted to be used in all plies of bolted *joints*.

> **Commentary:**
> The use of bolt holes 1⁄16 in. larger than the bolt installed in them has been permitted since the first publication of this Specification. The increase in bolt hole diameter in recent editions for standard holes and the width of short- and long-slotted holes is to facilitate entry of larger diameter bolts into holes. For bolts of 1⅜ in. and 1½ in. diameter, the permitted tolerance for swell or fin under the head or any die seam on the body exceeds the previous hole clearance of 1⁄16 in. For bolts of ¾ in. through 1¼ in. diameter, these tolerances would allow only 0.02 in. clearance. Smaller diameter bolts are commonly cold-formed with little swell, fins, or seams. Larger bolt diameters are commonly hot-forged where these issues are more common. Based upon typical production and use, the hole diameter and slot width clearance were increased to ⅛ in. for bolts 1 in. diameter and greater, and clearances for smaller bolts remained unchanged. The increase is also intended to reduce the need for reaming during *joint* assembly and the use of oversized holes for large diameter bolts that requires *joints* to be designed as *slip-critical joints*, as well as to bring bolt hole diameters into closer alignment with other major international steel construction standards. The change was supported by research by Allan (1967), Allan and Fisher (1968), Fisher and Beedle (1964), Chesson et al. (1964), Hoyer (1960), and Borello et al. (2009). Allan and Fisher (1968) showed that even larger holes could be permitted for *high-strength bolts* without adversely affecting the bolt shear or member bearing strength. However, the slip resistance can be reduced by the failure to achieve adequate *pretension* initially or by the relaxation of the bolt *pretension* as the highly compressed material yields at the edge of the hole or slot.

3.3.2. **Oversized Holes:** For *snug-tightened* or *pretensioned joints* subject to shear or combined shear and tension, oversized holes are not permitted.

> **Commentary:**
> The provisions for oversized holes in this Specification are based upon the findings of Allan and Fisher (1968) and the additional concern for the consequences of a slip of significant magnitude that can occur as permitted by the oversized hole.

3.3.3. **Short-Slotted Holes**

3.3.3.1. For *snug-tightened* or *pretensioned joints*, short-slotted holes are permitted in only one ply at any individual *faying surface* of any *joint*, provided the applied load is approximately perpendicular (between 80 and 100 degrees) to the axis of the slot. When complete *connection* design is not shown in the structural design drawings, the *Engineer of Record* shall be notified when short-slotted holes are used in this manner.

3.3.3.2. For *snug-tightened* or *pretensioned joints*, upon approval by the *Engineer of Record*, short-slotted holes are permitted in more than one or all plies, provided the applied load is approximately perpendicular (between 80 and 100 degrees) to the axis of the slot(s).

3.3.3.3. For *slip-critical joints*, upon approval by the *Engineer of Record*, short-slotted holes are permitted in any or all plies without regard for the direction of the applied load.

Commentary:

For beam end *connections*, the use of short-slotted holes approximately perpendicular to the applied load in conjunction with snug-tight bolts can provide the shear capacity and may allow the beam to rotate consistently with the design assumptions. Deformation of *connections* can be a concern where the beam is not laterally or torsionally restrained by floor, roof, or other framing.

Short slots are used to account for minor adjustments in main members such as web thickness differences and member length. This practice is prevalent enough that this Specification permits it unless it is specifically prohibited by the *Engineer of Record* in the *design documents*. This specification requires the *Engineer of Record* to be notified of the hole types and dimensions by showing this information on shop detail drawings or by obtaining prior approval of the *Engineer of Record*.

The provision limiting 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.

3.3.4. Long-Slotted Holes

3.3.4.1. For *snug-tightened* or *pretensioned joints*, upon approval by the *Engineer of Record*, long-slotted holes are permitted in only one ply at any individual *faying surface*, provided the applied load is approximately perpendicular (between 80 and 100 degrees) to the axis of the slot.

3.3.4.2. For *slip-critical joints*, upon approval by the *Engineer of Record*, long-slotted holes are permitted in only one ply at any individual *faying surface*, without regard for the direction of the applied load.

3.3.4.3. 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 shall have the same *surface preparation* as the plies.

Commentary:
See the Commentary to Section 3.3.1. Finger shims are devices that are often used to permit the alignment and plumbing of structures. When these devices are fully and properly inserted, they do not have the same effect on bolt *pretension* relaxation or the *connection* performance as do long-slotted holes in an outer ply. When fully inserted, the shim provides support around approximately 75 percent of the perimeter of the bolt in contrast to the greatly reduced area that exists with a bolt that is centered in a long slot. Furthermore, finger shims are always enclosed on both sides by the connected material, which should be effective in bridging the space between the fingers.

3.4. Burrs

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

Commentary:
Polyzois and Yura (1985) and McKinney and Zwerneman (1993) demonstrated that the slip resistance of *joints* was either unchanged or slightly improved by the presence of burrs. Therefore, small (1⁄16 in. or less in height) burrs need not be removed. On the other hand, parallel tests in the same program demonstrated that large burrs (over 1⁄16 in. in height) could cause a small increase in the required nut rotation from the *snug-tight condition* to achieve the specified *pretension* with the *turn-of-nut method*. Therefore, the Specification requires that all large burrs be removed or reduced in height.

Note that prior to *pretensioning*, the snug-tightening procedure is required to bring the plies into *firm contact*. If *firm contact* has not been achieved after snugging due to the presence of burrs, additional snugging is required to flatten them and bring the plies into *firm contact*.

SECTION 4. JOINT TYPE

This section addresses the three types of joints, their limitations, and their respective requirements.

The section is organized as follows:

4.1. Snug-Tightened Joints
4.2. Pretensioned Joints
4.3. Slip-Critical Joints

For joints with bolts that are loaded in shear or combined shear and tension, the *Engineer of Record* shall specify the joint type in the contract documents, if other than snug-tightened, as pretensioned or slip-critical. For slip-critical joints, the required class of slip resistance in accordance with Section 5.4 shall also be specified. For joints with bolts that are loaded in tension only, the *Engineer of Record* shall specify the joint type in the contract documents if other than snug-tightened, as pretensioned. Table 4.1 summarizes the applications and requirements of the three joint types.

Commentary:
When first approved by the Research Council on Structural Connections in January 1951, the *Specification for Assembly of Structural Joints Using High-Strength Bolts* merely permitted the substitution of a like number of ASTM A325 bolts for hot-driven ASTM A141* steel rivets of the same nominal diameter. Additionally, it was required that all bolts be *pretensioned* and that all *faying surfaces* be free of paint—hence satisfying the requirements for a *slip-critical joint* by the present-day definition. As revised in 1954, the omission of paint was required to apply only to "*joints* subject to stress reversal, impact or vibration, or to cases where stress redistribution due to *joint* slippage would be undesirable." This relaxation of the earlier provision recognized the fact that, in many applications, movement of the connected parts that brings the bolts into bearing against the sides of their holes is in no way detrimental. Bolted *joints* were then designated as "bearing type," "friction type," or "direct tension." With the 1985 edition of this Specification, these designations were changed to "shear/bearing," "slip-critical," and "direct tension," respectively, and snug-tightened installation was permitted for many *shear/bearing joints*. *Snug-tightened joints* are also permitted for qualified applications involving Group 120 bolts in direct tension. It is important that the snug-tightened *bolting assemblies* are tightened uniformly to ensure that all *bolting assemblies* participate equally in carrying the load to match the design assumption.

If non-*pretensioned* bolts are used in the type of *joint* that places the bolts in 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. On the other hand, 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,

**ASTM A141 (discontinued in 1967) became identified as ASTM A502 Grade 1.*

Table 4.1
Summary of Applications and Requirements for Bolted Joints

Load Transfer	Application	Joint Type[a,b]	Faying Surface Prep.	Install per Section	Inspect per Section	Arbitrate per Section 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	3.2.2	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.[c]**	ST	No	8.1	9.1	No
	Resistance to shear 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	3.2.2	8.2	9.3	If required to resolve dispute
Tension only	**Static loading only.[c]**	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]Under *Joint* Type: ST = *snug-tightened*, PT = *pretensioned*, and SC = *slip-critical*; see Section 4.
[b]See Sections 4 and 5 for the design requirements for each *joint* type.
[c]Per Section 4.2, the use of Group 144 and 150 bolts in *snug-tightened joints* with tensile loads is not permitted.

just as was the case when non-*pretensioned* bolts were used. Since 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.

Because the consequences of slip into bearing vary from application to application, the determination of whether a *joint* can be designated as *snug-tightened* or as *pretensioned*, or rather must be designated as *slip-critical*, is best left to judgment and a decision on the part of the *Engineer of Record*. In the case of *joints* with three or more bolts in holes with only a small clearance, the freedom to slip generally does not exist. It is probable that normal fabrication tolerances and erection procedures are such that one or more bolts are in bearing even before additional load is applied. Such is the case for standard holes and for slotted holes loaded transversally to the axis of the slot.

Joints that are required to be *slip-critical joints* include:

(1) Those cases where slip movement could theoretically exceed an amount deemed by the *Engineer of Record* to affect the serviceability of the structure, or through excessive distortion cause a reduction in strength or stability, even though the resistance to fracture of the *connection* and yielding of the member may be adequate; and
(2) Those cases where slip of any magnitude must be prevented, such as in *joints* subject to significant load reversal and *joints* between elements of built-up compression members in which any slip could cause a reduction of the flexural stiffness, which is required for the stability of the built-up member.

In this Specification, the provisions for the design, installation, and inspection of bolted *joints* are dependent upon the type of *joint* that is specified by the *Engineer of Record*. Consequently, it is required that the *Engineer of Record* identify the *joint* type in the *contract documents*.

4.1. Snug-Tightened Joints

Except as required in Sections 4.2 and 4.3, *snug-tightened joints* are permitted.

Bolts in *snug-tightened joints* shall be designed in accordance with the applicable provisions 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 shall not apply to *snug-tightened joints*.

Commentary:
Recognizing that the ultimate strength of a *connection* is independent of the bolt *pretension* and slip movement, there are numerous practical cases in the design of structures where, if slip occurs, it will not be detrimental to the serviceability of the structure. Additionally, there are cases where slip of the *joint* is desirable to permit rotation in a *joint* or to minimize the transfer of moment. To provide for these cases while at the same time making use of the shear strength of *high-strength bolts*, *snug-tightened joints* are permitted.

The maximum amount of slip that can occur in a *joint* is, theoretically, equal to twice the hole clearance. In practical terms, it is observed in laboratory and field experience to be much less; usually, about one-half the hole clearance. Acceptable inaccuracies in the location of holes within a pattern of bolts usually cause one or more bolts to be in bearing in the initial, unloaded condition. Furthermore, even with perfectly positioned holes, the usual method of erection causes the weight of the connected elements to put some of the bolts into direct bearing at the time the member is supported on loose bolts and the lifting crane is unhooked. Additional loading in the same direction would not cause additional *joint* slip of any significance.

4.2. Pretensioned Joints

Pretensioned joints are required in the following applications:

(1) *Joints* in which bolt *pretension* is required in the specification or code that invokes this Specification;
(2) *Joints* that are subject to significant load reversal;
(3) *Joints* that are subject to fatigue load with no reversal of the loading direction;
(4) *Joints* with Group 120 *bolting assemblies* that are subject to tensile fatigue; and
(5) *Joints* with Group 144 or Group 150 *bolting assemblies* that are subject to tension or combined shear and tension, with or without fatigue.

Bolts in *pretensioned joints* subject to shear shall be designed in accordance with the applicable provisions 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* subject to tension or combined shear and tension shall be designed in accordance with the applicable provisions 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 shall not apply to *pretensioned joints*.

Commentary:

Certain shear *connections* had previously been listed in other specifications that were required to be *pretensioned* but were not required to be *slip-critical joints*, regardless of whether the potential for slip was a concern (AISC, 2010). Those *connections* included:

(1) Column splices in buildings with high ratios of height to width;
(2) *Connections* of members that provide bracing to columns in tall buildings;
(3) Various *connections* in buildings with cranes over 5-ton capacity; and
(4) *Connections* for supports of running machinery and other sources of impact or stress reversal.

When *pretension* is desired for reasons other than the necessity to prevent slip, a *pretensioned joint* should be specified in the contract documents.

4.3. Slip-Critical Joints

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

(1) *Joints* that are subject 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 (within 80 to 100 degrees) to the direction of the long dimension of the slot; and
(4) *Joints* in which slip at the *faying surfaces* would be detrimental to the performance of the structure.

Bolts in *slip-critical joints* shall be designed in accordance with the applicable provisions 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.

Commentary:
In certain cases, slip of a bolted *joint* in shear under service loads would be undesirable or must be precluded. Clearly, *joints* that are subject to reversed fatigue load must be *slip-critical joints* since slip may result in back-and-forth movement of the *joint* and have potential for accelerated fatigue failure. Unless slip is intended, as desired in a sliding expansion *joint*, slip in *joints* with long-slotted holes that are parallel to the direction of the applied load might be large enough to invalidate structural analyses that are based upon the assumption of small displacements.

For *joints* subject to fatigue load with respect to shear of the bolts that do not involve a reversal of load direction, there are two alternatives for fatigue design. The designer can provide either a *slip-critical joint* that is proportioned on the basis of the applied stress range on the gross section or a *pretensioned joint* that is proportioned on the basis of the applied stress range on the net section.

SECTION 5. LIMIT STATES IN BOLTED JOINTS

This section addresses the design of bolted connections under various loading conditions.

The section is organized as follows:

The available shear strength and available tensile strength of bolts shall be determined in accordance with Section 5.1. The interaction of combined shear and tension on bolts shall be limited in accordance with Section 5.2. The available bearing strength of the connected parts at bolt holes shall be determined in accordance with Section 5.3. Each of these *available strengths* shall be equal to or greater than the *required strength*. The axial load in bolts that are subject to tension or combined shear and tension shall 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 required at the *faying surfaces* subject to shear or combined shear and tension, slip resistance shall be checked at either the *LRFD-load* level or *ASD-load* level, at the option of the *Engineer of Record*. 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 shall be equal to or greater than the *required strength*. In addition, *slip-critical joints* shall meet the strength requirements of *shear/bearing joints*. Therefore, the strength requirements of Sections 5.1, 5.2, and 5.3 shall also be met.

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

Commentary:
This section of the Specification provides the design requirements for *high-strength bolts* in bolted *joints*. However, this information is not intended to provide comprehensive coverage of the design of *high-strength 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 Specification and Commentary.

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 must also be checked.

Parameters that influence the shear strength of bolted *joints* include:

(1) Geometric parameters—the ratio of the net area to the gross area of the connected parts, the ratio of the net area of the connected parts to the total shear-resisting area of the bolts, and the length of the *joint*; and

(2) Material parameter—the ratio of the yield strength to the tensile strength of the connected parts.

Using both mathematical models and physical testing, it was possible to study the influences of these parameters (Kulak et al., 1987). These showed that under the rules that existed at that time, the longest (and often the most important) *joints* had the lowest factor of safety, about 2.0 based on ultimate strength.

In general, bolted *joints* that are designed in accordance with the provisions of this Specification 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. Additionally, the controlling strength limit state in the structural member, such as yielding or deflection, is usually reached well before the strength limit state in the *connection*, such as bolt shear strength or bearing strength of the connected material. The installation requirements vary with *joint* type and influence the behavior of the *joints* within the service-load range; however, this influence is ignored in all strength calculations. Secondary tensile stresses that may be produced in bolts in *shear/bearing joints*, such as through the flexing of double-angle *connections* to accommodate the simple-beam end rotation, need not be considered.

It is sometimes necessary to use *high-strength bolts* and fillet welds in the same *connection*, particularly as the result of remedial work. When these fastening elements act in the same shear plane, it is recommended to make reference to the *Guide* or AISC 360 Section J1.8 for guidance.

5.1. Nominal Shear and Tensile Strengths

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

The *design strength* in shear or tension for a Group 120, 144, or 150 bolt is ϕR_n, where $\phi = 0.75$, and the *allowable strength* in shear or tension is R_n/Ω, where $\Omega = 2.00$ and

$$R_n = F_n A_b \tag{5.1}$$

where

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

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 required below

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

Bolts with lengths indicated in Table 2.5 are considered to be fully threaded in accordance with ASME B18.2.6. The shear strength of these bolts shall be determined based on the assumption that the threads are included in the shear plane.

Table 5.1
Nominal Strengths per Unit Area of Bolts

Applied Load Condition			*Nominal Strength* per Unit Area, F_n, ksi		
			Group 120	Group 144	Group 150
Tension[a]	Static		90	108	113
	Fatigue		See Section 5.5		
Shear[a,b]	Threads included in shear plane	$L_s \leq 38$ in.	54	65	68
		$L_s > 38$ in.	45	54	56
	Threads excluded from shear plane	$L_s \leq 38$ in.	68	81	84
		$L_s > 38$ in.	56	68	70

[a]Except as required 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.

When a bolt that carries load passes through fillers or shims in a shear plane that are equal to or less than ¼ in. thick, F_n from Table 5.1 shall be used without reduction. When a bolt that carries load passes through fillers or shims that are greater than ¼ in. thick, the *connection* shall be designed in accordance with one of the following procedures:

(1) F_n from Table 5.1 shall be multiplied by the factor $[1 - 0.4(t' - 0.25)]$, which shall not be taken as greater than 1.00 nor smaller than 0.85, where t' is the total thickness of fillers or shims, in.; or
(2) The fillers or shims shall be extended beyond the *joint* and the filler or shim extension shall 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; or
(3) The size of the *joint* shall be increased to accommodate a number of bolts that is equivalent to the total number required in (2) above; or
(4) The *joint* shall be designed as a *slip-critical joint* using Class A *faying surfaces* with the *turn-of-nut method*; or
(5) The joint shall be designed as a *slip-critical joint* using Class B *faying surfaces*.

Commentary:
The nominal shear and tensile strengths of ASTM F3125 Grades A325, F1852, A490, and F2280 *high-strength bolts* as well as ASTM F3148 Grade 144 *matched bolting assemblies* are given in Table 5.1. These values are based upon the work of a large number of researchers throughout the world, as reported in the *Guide* and by others (Kulak et al., 1987; Tide, 2010; Roenker et al., 2017).

The nominal shear strength of a single high-strength bolt is taken as 0.625 times the tensile strength of that bolt (Kulak et al., 1987). In addition, a reduction factor of 0.90 is applied to 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 accounts for both the nonuniform force distribution between the bolts in a long joint and the minor secondary effects discussed above. 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.

The average ratio of nominal shear strength for bolts with threads included in the shear plane to the nominal shear strength for bolts with threads excluded from the shear plane is 0.83 with a standard deviation of 0.03 (Frank and Yura, 1981). Conservatively, a reduction factor of 0.80 is used 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. The case of a bolt in double shear with a nonthreaded section in one shear plane and a threaded section in the other shear plane is not covered in this Specification for two reasons. First, the manner in which load is shared between these two dissimilar shear areas is uncertain. Second, the detailer's lack of certainty as to the orientation of the bolt placement might leave both shear planes in the threaded section. Thus, if threads are included in one shear plane, the conservative assumption is made that threads are included in all shear planes.

The tensile strength of a *high-strength bolt* is the product of its ultimate tensile strength per unit area and some area through the threaded portion. This area, called the tensile stress area, is a derived quantity that is a function of the relative thread size and pitch. For the usual sizes of structural bolts, it is about 75 percent of the nominal cross-sectional area of the bolt. Hence, the nominal tensile strengths per unit area given in Table 5.1 are 0.75 times the tensile strength of the bolt material. According to Equation 5.1, the nominal area of the bolt is then used to calculate the *design strength* or *allowable strength* in tension. 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.

Reliability studies of bolts and bolted *joints* in shear have shown that the reliability indices for bolted *joints* is approximately 4.0 to 5.0 in most cases, at a ratio of live load to dead load of $L/D = 3$ (Moore et al., 2008; Taylor et al., 2008; Tide, 2010; Roenker et al., 2017). The reliability is slightly higher for compact bolted *joints* than it is for intermediate length or long bolted *joints*, and the reliability of bolts with threads excluded from the shear plane is slightly higher than that of bolts with threads not excluded from the shear plane.

If *pretensioned* bolts are used in a *joint* that loads the bolts in tension, the question arises as to whether the *pretension* and the applied tension are additive. Because the compressed parts are being unloaded during the application of the external tensile force, the increase in bolt tension is minimal until the parts separate (Kulak et al., 1987). Thus, there will be little increase in bolt force above the *pretension* load under service loads. After the parts separate, the bolt acts as a tension member, as expected.

Pretensioned bolts have torsion present during the installation process. Once the installation is completed, any residual torsion is quite small and will disappear entirely when the bolt is loaded to the point of plate separation. Hence, there is no question of torsion-tension interaction when considering the ultimate tensile strength of a *high-strength bolt* (Kulak et al., 1987).

When required, *pretension* is induced in a bolt by imposing a small axial elongation during installation. When the *joint* is subsequently loaded in shear, tension, or combined shear and tension, the bolts will undergo significant deformations prior to failure that have the effect of overriding the small axial elongation that was introduced during installation, thereby removing the *pretension*. Measurements taken in laboratory tests confirm that the *pretension* that would be sustained if the applied load were removed is essentially zero before the bolt fails in shear (Kulak et al., 1987). Thus, the shear and tensile strengths of a bolt are not affected by the presence of an initial *pretension* in the bolt.

See also the Commentary to Section 5.5.

Tests of *connections* with 24 1-in.-diameter A490 bolts indicated the reduction factor for bolt shear strength in *connections* with fillers as required in Section 5.1 (1) is limited to a minimum of 85 percent. (Borello et al., 2009).

5.2. Combined Shear and Tension

When combined shear and tension loads are transmitted by a Group 120, 144, or 150 bolt, the factored limit-state interaction shall be:

$$\left[\frac{T_u}{(\phi R_n)_t}\right]^2 + \left[\frac{V_u}{(\phi R_n)_v}\right]^2 \le 1 \tag{5.2a}$$

where

T_u = *required strength* in tension (factored tensile load) per bolt, kips
V_u = *required strength* in shear (factored shear load) per bolt, 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 by a Group 120, 144, or 150 bolt, the allowable limit-state interaction shall be:

$$\left[\frac{T_a}{\left(R_n/\Omega\right)_t}\right]^2+\left[\frac{V_a}{\left(R_n/\Omega\right)_v}\right]^2\leq 1 \tag{5.2b}$$

where

T_a = *required strength* in tension (service tensile load) per bolt, kips

V_a = *required strength* in shear (service shear load) per bolt, 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

Commentary:
When both shear forces and tensile forces act on a bolt, the interaction can be conveniently expressed as an elliptical solution (Chesson et al., 1965) that includes the elements of the bolt acting in shear alone and the bolt acting in tension alone. Although the elliptical solution provides the best estimate of the strength of bolts subject to combined shear and tension and is thus used in this Specification, the nature of the elliptical solution is such that it can be approximated conveniently using three straight lines (Carter et al., 1997). Earlier editions of this Specification have used such linear representations for the convenience of design calculations. The elliptical interaction equation in effect shows that, for design purposes, significant interaction does not occur until either force component exceeds 20 percent of the limiting strength for that component.

5.3. Nominal Bearing Strength at Bolt Holes

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

The design bearing strength is ϕR_n, where $\phi = 0.75$, and the allowable bearing strength is R_n/Ω, where $\Omega = 2.00$ of the connected 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 and:

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

$$R_n = 1.2L_ctF_u \leq 2.4d_btF_u \tag{5.3}$$

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

$$R_n = 1.5L_ctF_u \leq 3d_btF_u \tag{5.4}$$

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

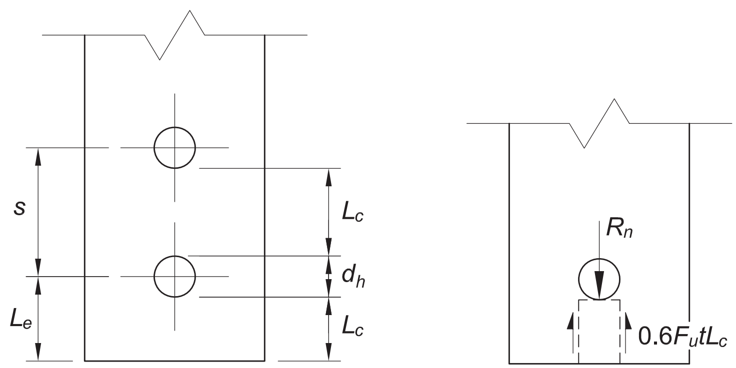
$$R_n = L_ctF_u \leq 2d_btF_u \tag{5.5}$$

In Equations 5.3, 5.4, and 5.5,

R_n = *nominal strength* (bearing strength of the connected material), kips
F_u = specified minimum tensile strength per unit area of the connected material, ksi
L_c = clear distance, in the direction of load, between the edge of the hole and the edge of the adjacent hole or the edge of the material, in.
d_b = nominal diameter of bolt, in.
t = thickness of the connected material, in.

Commentary:
The contact pressure at the interface between a bolt and the connected material can be expressed as a bearing stress on the bolt or on the connected material. The connected material is always critical. For simplicity, the bearing area is expressed as the bolt diameter times the thickness of the connected material in bearing. The governing value of the bearing stress has been determined from extensive experimental research, and a further limitation on strength was derived from the case of a bolt at the end of a tension member or near another bolt.

The design equations are based upon the models presented in the *Guide* (Kulak et al., 1987), except that the clear distance to another hole or edge is used in the Specification formulation rather than the bolt spacing or end distance as used in the *Guide* (see Figure C-5.1). Equation 5.3 is derived from tests (Kulak et al., 1987) that showed that the total elongation, including local bearing deformation, of a standard hole that is loaded to obtain the ultimate strength equal to $3d_btF_u$ in Equation 5.4 was on the order of the diameter of the bolt.



$L_c = s - d_h$ (interior bolts)
$L_c = L_e - ½d_h$ (exterior bolts)

$R_n = 2(0.6F_utL_c)$
$= 1.2F_utL_c$

(a) Dimensions *(b) Strength formulation (per bolt)*

Fig. C-5.1. Bearing strength formulation.

This apparent hole elongation results largely from bearing deformation of the material that is immediately adjacent to the bolt. The lower value of $2.4d_btF_u$ in Equation 5.3 provides a bearing strength limit-state that is attainable at reasonable deformation (¼ in.). Strength and deformation limits were thus used to jointly evaluate bearing strength test results for design.

When long-slotted holes are oriented with the long dimension perpendicular to the direction of load, the bending component of the deformation in the material between adjacent holes or between the hole and the edge of the plate is increased. The nominal bearing strength is limited to $2d_btF_u$, which again provides a bearing strength limit-state that is attainable at reasonable deformation.

5.4. Design Slip Resistance

Slip-critical joints shall 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 shall 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 below.

The nominal slip resistance per bolt for the limit state of slip shall be 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

μ = *mean slip coefficient* for Class A or B surfaces, as applicable, and determined as follows, or as established by tests:

(1) For Class A surfaces (unpainted clean mill scale steel surfaces, or surfaces with Class A coatings on blast-cleaned steel, or hot-dipped galvanized)

$$\mu = 0.30$$

(2) For Class B surfaces (unpainted blast-cleaned steel surfaces or surfaces with Class B coatings on blast-cleaned steel)

$$\mu = 0.50$$

D_u = 1.13 for building structures, 1.00 for bridge structures. Other values may be used with the approval by the *Engineer of Record* or by a Specification body.
T_m = minimum bolt pretension given in Table 5.2, kips
h_f = factor for fillers, determined as follows:

(1) Where there are no fillers or 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

$$h_f = 0.85$$

n_s = number of slip planes required to permit the *connection* to slip

$$k_{sc} = 1 - \frac{T_u}{D_u T_m n_b} \geq 0 \quad \text{(LRFD)} \tag{5.7a}$$

$$k_{sc} = 1 - \frac{1.5T_a}{D_u T_m n_b} \geq 0 \quad \text{(ASD)} \tag{5.7b}$$

where
T_a = required tension force using *ASD load* combinations, kips
T_u = required tension force using *LRFD load* combinations, kips
n_b = number of bolts carrying the applied tension

Commentary:
The slip resistance of a *joint* is a function of the coefficient of friction, the bolt *pretension* (clamping force), the number of *faying surfaces*, and the number of bolts. In the equation for the nominal slip resistance per bolt (Equation 5.6), the clamping force is calculated as the product of the specified minimum *pretension*, T_m, and of a coefficient D_u. The specified minimum *pretensions* shown in Table 5.2 are based on 70 percent of the tensile strength of Group 120 or 150 fasteners computed as the product of their tensile strengths and tensile stress areas, rounded to the nearest kip. For the sake of simplicity, Group 144 bolts are required to be installed to the same minimum *pretensions* as Group 150 bolts.

The multiplier D_u in Equation 5.6 accounts for the statistical relationship between mean historical measured installed bolt *pretension* and the specified minimum bolt *pretension*, T_m. For the design of building structures, the value of D_u = 1.13 is based on installation data by the *calibrated wrench method* (Kulak et al., 1987; Grondin et al., 2007). The calibrated wrench method was removed in the 2025 edition of this standard. In the absence of other field test

Table 5.2
Minimum Bolt Pretension, Pretensioned and Slip-Critical Joints

Nominal Bolt Diameter, d_b, in.	Specified Minimum Bolt Pretension, T_m, kips	
	Group 120	Group 144 and Group 150
½	12	15
⅝	19	24
¾	28	35
⅞	39	49
1	51	64
1⅛	64	80
1¼	81	102
1⅜	97	121
1½	118	148

data, this value is used for all installation methods. *Turn-of-nut pretensioning* results in mean *pretensions* that are about 1.35 times the specified minimum *pretension* for ASTM F3125 Grade A325 bolts, and about 1.26 for Grade A490 bolts (Kulak et al., 1987; Grondin et al., 2007). *Twist-off tension control*- and *direct tension indicator*-installed *pretensions* are similar to those of a *calibrated wrench* (Grondin et al., 2007). The *combined method* of installation results in a D_u value of 1.37 for F3148 bolts (Roenker et al., 2017). The bolt clamping force data indicate that bolt *pretensions* are distributed normally for each *pretensioning* method. Field studies (Kulak and Birkemoe, 1993) of installed bolts in various structural applications indicate that the *pretensions* in Table 5.2 have been achieved as anticipated in the laboratory research.

For the design of bridge structures, a value of $D_u = 1.00$ is typically used. However, it is noted that in the AASHTO-LRFD Specification (AASHTO, 2020), the slip resistance of bolted *joints* is compared to loads that are computed using a different load combination than those used for checking the strength of main members and components.

In any of the foregoing installation methods, it can be expected that a portion of the bolt assembly (the threaded portion of the bolt within the *grip* length and/or the engaged threads of the nut and bolt) will reach the inelastic region of behavior. This permanent distortion has no undesirable effect on the subsequent performance of the bolt.

For most applications, the assumption that the slip resistance at each bolt is equal and additive with that at the other bolts is based on the fact that all locations must develop the slip force before a total *joint* slip can occur at that plane. Similarly, the forces developed at various slip planes do not necessarily develop simultaneously, but one can assume that the full slip resistances must be mobilized at each plane before full *joint* slip can occur.

Section 3.2.2(2) permits the *Engineer of Record* to authorize the use of *faying surfaces* with a *mean slip coefficient*, μ, that is less than 0.50 (Class B) and other than 0.30 (Class A). This authorization requires that the *mean slip coefficient*, μ, be determined in accordance with Appendix A.

In built-up compression members, such as double-angle struts in trusses, a small relative slip between the elements, especially at the end *connections*, can increase the effective length of the combined cross section to that of the individual components and significantly reduce the compressive strength of the strut. Therefore, the *connection* between the elements at the ends of built-up members should be checked to prevent slip, whether or not a *slip-critical joint* is required for serviceability. As given by Sherman and Yura (1998), the required slip resistance is $0.08P_uLQ/I$, where P_u is the axial compressive force in the built-up member, kips; L is the total length of the built-up member, in.; Q is the first moment of area of one component about the axis of buckling of the built-up member, in.^{3}; and I is the moment of inertia of the built-up member about the axis of buckling, in.^{4}.

In *joints* with long-slotted holes that are parallel to the direction of the applied load, the *joint* is designed to prevent slip; however, the effect of the factored loads acting on the deformed structure (deformed by the maximum amount of slip in the long slots at all locations) should be included in the structural analysis.

In *joints* subject to fatigue, design should be based upon service-load criteria and the design slip resistance of the governing cyclic design specification because fatigue is a function of the service load performance rather than that of the factored load.

5.5. Tensile Fatigue

The tensile stress range on the tensile stress area of the bolt due to the total applied cyclic load and moment, plus the effects of any prying action, shall not exceed the allowable stress range computed as,

$$F_{sr} = 1{,}000\left(\frac{C_f}{n_{sr}}\right)^{\frac{1}{3}} \geq F_{TH} \qquad (5\text{-}8)$$

where

F_{sr} = allowable stress range, ksi
C_f = constant-amplitude fatigue constant, ksi^3
n_{sr} = number of stress range cycles in the design life
F_{TH} = constant-amplitude fatigue threshold stress range for infinite life, ksi

For Group 120, 144, and 150 bolts, $C_f = 0.39$ ksi^3 and $F_{TH} = 7.0$ ksi.

Joints that are subject to tensile fatigue loading shall be specified as *pretensioned joints* in accordance with Section 4.2 or *slip-critical joints* in accordance with Section 4.3. An analysis of the relative stiffness of the connected parts and bolts is permitted to 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 shall be assumed to be equal to the stress on the tensile stress area due to 20% of the absolute value of the total applied cyclic load and moment, plus the effects of any prying action. The tensile stress area shall be calculated as,

$$A_s = \frac{\pi}{4}\left(d_b - \frac{0.9743}{n}\right)^2 \tag{5-9}$$

where

A_s = tensile stress area of bolt, in.^{2}
d_b = nominal diameter of bolt, in.
n = threads per inch

Commentary:
Fatigue provisions in this specification were updated in the 2025 edition to be consistent with provisions in AISC 360-22 that were applicable to high-strength bolts. It is worth noting that the scope of this specification is much narrower than the scope of AISC 360, and as such, the fatigue provisions in this specification are much briefer than those in AISC 360.

The fatigue strength of individual bolts subjected to tension is predictable in the absence of pretension and prying action because the stress range is directly and solely related to the applied tension. In pretensioned joints subjected to tension, however, only a small portion of the externally applied tension and associated prying are reflected in the stress range with the remaining externally applied tension acting to reduce the clamping force between the plies. In non-pretensioned joints subjected to tension, the stress range includes the entire combined effect of the externally applied tension and associated prying, and as a result, the fatigue resistance of the bolts is greatly reduced. However, this specification requires all joints that are subjected to fatigue loads to be either pretensioned joints or slip-critical joints.

SECTION 6. USE OF WASHERS

This section addresses where hardened washers and plate washers are required for various bolt diameters, bolt styles, hole types, joint types, and base material strength.

The section is organized as follows:

6.1. Snug-Tightened Joints Using Group 120, 144, or 150 Bolting Assemblies

Washers are not required in *snug-tightened joints* with standard holes, except as required in Section 6.1.2. Use of ASTM F436 or ASTM F3394 washers is permitted even when not required.

6.1.1. **Oversized and Slotted Holes:** When a slotted hole occurs in an outer ply, an ASTM F436, ASTM F3394 washer, or a 5⁄16-in.-thick plate washer shall be used as required to completely cover the hole. For extra-thick or plate washers, Section 6.2.5 shall also apply.

6.1.2. **Sloped Surfaces:** 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, a beveled washer through-hardened to the requirements of ASTM F436 shall be used to compensate for the lack of parallelism.

6.2. Pretensioned Joints and Slip-Critical Joints Using Group 120, 144, or 150 Bolting Assemblies

Washers are not required in *pretensioned joints* and *slip-critical joints* with standard holes, except as required in Sections 6.2.1, 6.2.2, 6.2.3, 6.2.4, and 6.3. Use of ASTM F436 hardened washers is permitted, even when not required. Use of ASTM F3394 reaction washers is permitted, even when not required, in accordance with Section 6.4. When used, washers shall completely cover the hole, or a plate washer shall be used to completely cover the hole.

6.2.1. **Specified Minimum Yield Strength of Connected Material Less Than 40 ksi:** When Group 144 or Group 150 bolts are used in connected material with specified minimum yield strength less than 40 ksi, ASTM F436 washers shall be used under both the bolt head and the nut.

6.2.2. **Oversized and Short-Slotted Holes:** When oversized or slotted holes occur in an outer ply in a *pretensioned joint*, the washer requirements shall be as follows:

6.2.2.1. For Group 120 bolts of all diameters and Group 144 and 150 bolts up through 1 in. diameter, ASTM F436 washers shall be used.

6.2.2.2. For Group 144 and 150 bolts with diameters greater than 1 in., ASTM F436 extra thick washers or ⅜ in. plate washers with ordinary thickness ASTM F436 washers shall be used.

6.2.3. **Long-Slotted Holes:** When long-slotted holes occur in an outer ply in a *pretensioned joint,* the washer requirements shall be as follows:

6.2.3.1. For Group 120 bolts, all sizes, and Group 144 and 150 bolts up through 1 in. diameter: 5⁄16 in. plate washers or continuous bars shall be used.

6.2.3.2. For Group 144 and 150 bolts with diameters greater than 1 in., ⅜ in. plate washers or continuous bars with ordinary thickness ASTM F436 washers shall be used.

6.2.4. **Sloped Surfaces:** 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, a beveled washer through-hardened to the requirements of ASTM F436 shall be used to compensate for the lack of parallelism.

6.2.5. **Extra-Thick Washers, Plate Washers, and Continuous Bars:** When extra thick washers, plate washers, or continuous bars are required, the following shall apply:

6.2.5.1. Extra thick washers, plate washers, and continuous bars shall be of sufficient size to completely cover the bolt holes or slots,

6.2.5.2. Plate washers and continuous bars shall have standard sized holes,

6.2.5.3. Plate washers and continuous bars shall be of structural grade material of at least 40 ksi yield strength, but need not be hardened,

6.2.5.4. Plate washers and continuous bars shall meet or exceed the required corrosion resistance of the connected plies.

6.2.5.5. Stacking multiple washers, plates, and bars thinner than the specified minimum thickness do not satisfy the requirements for specified thickness.

6.3. Washer Requirements Unique to Certain Pretensioning Methods

6.3.1. **Twist-Off Tension-Control Bolt Method:** An ASTM F436 washer shall be used under the nut. When ASTM F3125 Gr 120TC, Gr 144TC, or Gr 150TC bolting assemblies with round heads that meet ASME B18.2.6 are used, washers are not required under the head as indicated in 6.2.1 and 6.2.2.

6.3.2. **Combined Method:** When the *combined method* of *pretensioning* is used, an ASTM F436 washer shall be used under the nut. When ASTM F3148 bolting assemblies with round heads that meet ASME B18.2.6 are used, washers are not required under the head as indicated in 6.2.1 and 6.2.2.

6.3.3. **Direct Tension Indicator Method:** When the *direct tension indicator method* of *pretensioning* is used, and the *direct tension indicator* is located under the turned element, an ASTM F436 washer shall be used between the turned element and the *direct tension indicator protrusions.*

6.4. Use of ASTM F3394 Reaction Washers and Backup Washers

6.4.1. When the *turn-of-nut method* or the *combined method* of *pretensioning* is used, ASTM F3394 *reaction washers* may be used under the turned element.

6.4.2. When the *turn-of-nut method* or the *combined method* of *pretensioning* is used, ASTM F3394 *backup washers* may be used under the unturned element to prevent the unturned element from turning, with or without the use of ASTM F3394 Reaction Washers.

6.4.3. When the *direct tension indicator method* of pretensioning is used, ASTM F3394 *backup washers* may be used under the unturned element to prevent the unturned element from turning.

6.4.4. When ASTM *reaction washers* or *backup washers* are permitted by 6.4.1 through 6.4.3, they may be used in lieu of ordinary thickness ASTM F436 washers.

Commentary:
It is important that shop and erection drawings and *connection* details clearly reflect the number and disposition of washers when they are required, especially extra-thick hardened washers or plate washers that are required for some oversized and slotted hole applications. The total thickness of washers and *direct tension indicators* used in a *bolting assembly* affects the length of bolt that must be supplied and used. Table C-6.1 indicates sections where washer requirements are provided.

Additional washers may be stacked under the bolt head and/or nut to accommodate bolt lengths longer than needed. Using additional washers under the head could change the shear plane location from threads excluded to a threads-included condition. If designed as threads-excluded, care must be taken to maintain the shear location on the bolt body when adding washers.

The primary function of washers is to provide a hardened non-galling surface under the turned element, particularly for torque-based *pretensioning methods* such as the *twist-off tension control method*, and the *combined method*. Circular flat washers that meet the requirements of ASTM F436 or ASTM F3394 *reaction washers* provide an increase in bearing area that is approximately 50 percent larger than that provided by a heavy hex bolt head or nut. However, tests have shown that washers of the standard thickness have a minor influence on the pressure distribution of the induced bolt *pretension*. Furthermore, they showed that a larger thickness and surface bearing area is required when Group 150 bolts are used with material that has a minimum specified yield strength less than 40 ksi. This is necessary to mitigate the effects of local yielding of the material in the vicinity of the contact area of the head and nut. This requirement has been extended to Group 144 bolts, as the minimum specified pretensions are the same.

Extra thick ASTM F436 washers are required to cover oversized and short-slotted holes in external plies when Group 144 or Group 150 bolts of diameter larger than 1 in. are used, except as permitted by 6.3.1 and 6.3.2. This was found to be necessary to distribute the high clamping pressure to prevent collapse of the hole perimeter and enable the development of the desired clamping force. Preliminary investigation has shown that a similar but less severe deformation occurs when oversized or slotted holes are in the interior plies. The reduction in clamping force may be offset by "keying," which tends to increase the resistance to slip. These effects are accentuated in *joints* of thin plies. When a long-slotted holes occurs in an outer ply, a 5⁄16-in.-thick plate washer or continuous bar and one ASTM F436 washer are required. This requirement can be satisfied with material of any structural grade that matches the strength and material type of the base material. Alternatively, either of the following options can be used:

(1) The use of material with F_y equal to or greater than 40 ksi will eliminate the need to also provide washers in accordance with the requirements of Section 6.2.1 for Group 144 or Group 150 bolts of any diameter; or
(2) Material with F_y equal to or less than 40 ksi can be used with ASTM F436 washers in accordance with the requirements of Section 6.2.1.

Tests indicate that the *pretension* achieved with a bolt having the minimum ASTM F3125 Grade F1852 or Grade F2280 bearing circle diameter is the same as that of a bolt with the larger bearing circle diameter equal to the size of an ASTM F436 washer, provided that the hole size meets the RCSC Specification limitations (Schnupp and Murray, 2003). Similar considerations apply to ASTM F3148 Grade 144 bolts with round heads.

With the 2025 version of this Specification, ASTM F3394 washers were introduced. ASTM F3394 covers two types of washers, *reaction washers* and *backup washers*.

These washers are meant to facilitate tensioning via the *turn-of-nut method*, *combined method*, and *direct tension indicator method* of pretensioning. With these three methods, ASTM F3394 washers may be substituted for ASTM F436 washers.

When used, a *reaction washer* is installed under the turned element. When used, a *backup washer* is installed under the unturned element (see Section 6.4). When using *reaction washers*, additional rotation above the minimum requirement may be needed to compensate for the embedment of the knurls into the base material and underside of the bolt head.

Table C-6.1
Washer Requirements[a] for Snug-Tightened (ST), Pretensioned (PT), and Slip-Critical (SC) Bolted Joints

Bolt Group	Joint Type and Bolt Size Range	Bolt Hole and Joint Conditions in Outer Ply					
		Standard	**Oversized**	**Short-Slotted**	**Long-Slotted**	**Minimum Specified Yield Strength <40 ksi**	**Sloped Surface >1:20**
120 **144** **150**	**ST** ½ thru 1½ in.	See 6.1	See 6.1.1, 6.2.5			Not required	See 6.1.2, 6.2.4
120	**PT or SC** ½ thru 1½ in.	See 6.2	See 6.2.2.1		See 6.2.3.1, 6.2.5	Not required	
144 **150**	**PT or SC** ½ thru 1 in.	See 6.2	See 6.2.2.1		See 6.2.3.1, 6.2.5	See 6.2.1	
	PT or SC 1⅛ thru 1½ in.	See 6.2	See 6.2.2.2, 6.2.5		See 6.2.3.2, 6.2.5	See 6.2.1	

[a]See 6.3 for washer requirements unique to certain *pretensioning* methods.
[b]See 6.4 for use of reaction washers and backup washers.

SECTION 7. PRE-INSTALLATION VERIFICATION TESTING

This section addresses the requirements and methods for testing bolting assemblies to verify their suitability, the pretensioning method, and the equipment to be used.

This section is organized as follows:

7.1. Required Testing
7.2. Test Procedure
7.3. Nonconformance

The requirements in this section shall apply only when required in Section 8.2.

Commentary:
Pre-installation verification (PIV) testing provides a practical means for ensuring that nonconforming *bolting assemblies* are not incorporated into the work. Experience on many projects 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*. 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 personnel* 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 need for lubrication (when permitted) to prevent failure of bolts by combined high torque with tension; under-strength assemblies resulting from excessive overtapping of hot-dip galvanized nuts; or other failures to meet strength or geometry requirements of applicable ASTM standards, such as the use of mismatched *bolting components* (e.g., a Grade C nut on an F3125 Grade A490 bolt).

Pre-installation verification testing can be used for:

(1) Providing the *Inspector* and other interested entities with an opportunity to verify the *Contractor's* compliance with the requirements applicable to *pretensioning* of *bolting assemblies.*
(2) Confirming that the *Contractor* recognizes the specified *connections* on the project that require *pretensioning* of *bolting assemblies.*
(3) Confirming the *Contractor* recognizes that testing and segregation of *bolting components* and *bolting assemblies* by *lot* is required.
(4) Demonstrating the suitability of the *bolting assembly*, including the lubrication that is applied by the *Manufacturer*, or specially applied to develop the specified minimum *pretension*;
(5) Verifying that the *Contractor* has a suitable means to achieve the *snug-tight condition*;
(6) When the *combined method* of installation is used, verifying the *initial torque* applied achieves at least the required *initial tension*;

(7) When the *turn-of-nut method* or *combined method* is used, verifying the correct nut rotation for the bolt length and disposition of outer faces of bolted parts has been selected; and
(8) When the *direct tension indicator method* is used, verifying the use of the feeler gauge and the associated criteria for checking the gap.

7.1. Required Testing

Pre-installation verification testing shall be performed in compliance with all of the following:

(1) At the site of installation, unless otherwise approved by the *Engineer of Record*;
(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, grade, and assembly *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 washers positioned in accordance with Section 6.2; and
(6) In accordance with the test procedure in Section 7.2.

For *pretensioned* installation in accordance with Section 8.2.4 (*combined method*), this testing shall be performed at least weekly to verify that each installation tool continues to produce the torque required to reach or exceed the minimum initial tension in Table 7.1 for the *bolting assemblies* that are being installed. For each installation tool, testing need only be performed on three *bolting assemblies* of a single *lot*. Alternatively, if there is a means to measure the torque output of the tool while in use, this testing can be performed during installation.

Commentary:

The *bolting assemblies* and *bolting components* listed in Section 2 are manufactured under separate ASTM standards, each of which includes tolerances that are appropriate for the individual component covered. While these tolerances are intended to provide for a reasonable and workable fit between the components when used in an assembly, the cumulative effect of the individual tolerances permits a significant variation in the installation characteristics of the complete *bolting assembly*. It is the intent of this Specification that the responsibility rests with the *Supplier* for the proper performance of the *bolting assembly*, the components of which may have been produced by more than one *Manufacturer*.

When *pretensioned* installation is required, it is essential that the effects of the accumulation of tolerances, surface condition, and lubrication be taken into account. Hence, pre-installation verification testing of the complete *bolting assembly* is required as indicated in Section 8 to ensure that the *bolting assemblies* and installation method to be used in the work will provide a *pretension* that exceeds those specified in Table 5.2. It is not, however, intended to verify conformance with the individual ASTM standards.

The pre-installation verification testing requirements in this section presume that *bolting assemblies* so verified will be *pretensioned* before the condition of the *bolting assemblies*, the equipment, and the steelwork have changed significantly. Research by Kulak and Undershute (1998) and Tan et al. (2005) *on spline end twist-off bolt assemblies* from various *Manufacturers* showed that installed *pretensions* could be a function of the time and environmental conditions of storage and exposure. The reduced performance of these bolts was caused by a deterioration of the lubricity of the assemblies.

All bolt *pretensioning* that is achieved through rotation of the nut (or the bolt head) is affected by the reliance upon torque for tightening. *Bolting assemblies* that require high installation torque have demonstrated an adverse effect on the development of the desired *pretension*. Thus, it is required that the condition of the *bolting assemblies* must be replicated in pre-installation verification testing. When the time of exposure between the placement of bolting assemblies in the fieldwork and the subsequent *pretensioning* of those bolting assemblies is of concern, pre-installation verification testing can be performed on *bolting assemblies* removed from the work or on extra *bolting assemblies* that, at the time of placement, were set aside to experience the same degree of exposure.

The *rotational capacity test* is not covered by this specification. When required, the *rotational capacity test* procedure in ASTM F3125 or ASTM F3148 should be used as applicable.

7.2. Test Procedure

The *bolting assembly* shall 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 equal to or greater than that specified in Table 7.1. The accuracy of the *bolt tension measurement device* shall be confirmed through calibration at least annually.

Impact wrenches, if used, shall 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.

Pre-installation verification testing shall be performed as follows:

(1) For the *turn-of-nut method* in accordance with Section 8.2.1, pre-installation verification testing shall be in accordance with Section 7.2.1;
(2) For the *twist-off tension control bolt method* in accordance with Section 8.2.2, pre-installation verification testing shall be in accordance with Section 7.2.2;
(3) For the *direct tension indicator method* in accordance with Section 8.2.3, pre-installation verification testing shall be in accordance with Section 7.2.3; and
(4) For the *combined method* in accordance with Section 8.2.4, pre-installation verification testing shall be in accordance with Section 7.2.4.

Table 7.1
Minimum Bolt Pretension for Pre-Installation Verification Testing

Nominal Bolt Diameter, d_b, in.	Minimum Bolt Pretension for Pre-Installation Verification Testing, kips	
	Group 120	Group 144 and Group 150
½	13	16
⅝	20	25
¾	29	37
⅞	41	51
1	54	67
1⅛	67	84
1¼	85	107
1⅜	102	127
1½	124	155

7.2.1. **Turn-of-Nut Method**

Step 1: Snug-Tightening

The *bolting assembly* shall be installed 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* shall be matchmarked.

Step 3: Pretensioning

The applicable rotation specified in Table 8.1 shall be applied to the *bolting assembly*.

Step 4: Final Verification

If the actual *pretension* developed in the *bolting assembly* is less than that specified in Table 7.1, the cause(s) shall be determined and resolved before the *bolting assemblies* are used in the work. Cleaning, lubrication, and retesting of these *bolting assemblies* is permitted provided that all *bolting assemblies* are treated in the same manner.

7.2.2. **Twist-Off Tension Control Bolt Method**

Step 1: Snug-Tightening

The *bolting assembly* shall be installed to the *snug-tight condition* using the tools, *bolting components*, assembly configuration, and installation methods to be used in the work.

Step 2: Intermediate Verification
It shall be verified that the splined end is not severed.

Step 3: Pretensioning
The *twist-off tension control bolt* installation wrench shall be used to sever the splined end from the bolt.

Step 4: Final Verification
It shall be verified that the splined end is severed. If the actual *pretension* developed in the *bolting assembly* is less than that specified in Table 7.1, the cause(s) shall be determined and resolved before the *bolting assemblies* are used in the work. Cleaning, lubrication, and retesting of these *bolting assemblies* is not permitted, except as allowed in Section 2.10.4, provided that all *bolting assemblies* are treated in the same manner.

7.2.3. **Direct Tension Indicator Method**

Step 1: Snug-Tightening
The *bolting assembly* shall be installed to the *snug-tight condition* using the tools, *bolting components*, assembly configuration, and installation methods to be used in the work. *Snug-tightening* shall not exceed the *pretension* specified in Table 7.1.

Step 2: Pretensioning
The *bolting assembly* shall be tightened to a *pretension* equal to the value indicated in Table 7.1. A feeler gauge provided by the *direct tension indicator Manufacturer*, and of the correct thickness for the *direct tension indicator* being installed, shall be inserted into the spaces between the *direct tension indicator* protrusions as indicated in the “Minimum Feeler Gauge Entries—Preinstallation Verification” column of Table 7.2. The feeler gauge must touch the bolt shank to be considered a feeler gauge entry.

If the feeler gauge cannot meet the minimum feeler gauge entries in Table 7.2, the cause shall be determined and resolved before the *bolting assemblies* are used in the work. Cleaning, lubrication, and retesting of these *bolting assemblies* are permitted, provided that all *bolting assemblies* are treated in the same manner.

Step 3: Further Tensioning
The *bolting assembly* shall be further tensioned until the feeler gauge is refused (i.e., cannot be inserted) in at least one additional space between *direct tension indicator* protrusions.

Step 4: Final Verification
It shall be verified that the *bolting assembly* still satisfies the requirement for pretension in Table 7.1.

Table 7.2
Direct Indicator Feeler Gauge Entry Requirements— Pre-Installation Verification Testing

Spaces between Direct Tension Indicator Protrusions	Minimum Feeler Gauge Entries— Pre-Installation Verification Testing
	All Other Cases
4	2
5	3
6	3
7	4
8	4
9	5

7.2.4. Combined Method

Step 1: Initial Tensioning

The *bolting assembly* shall be installed in the *bolt tension measurement device* using the tools, *bolting components*, assembly configuration, and installation methods to be used in the work. The *initial torque* shall be applied to the nut. If the *initial torque* has not been provided by the *Supplier*, then the user shall establish a torque that produces a minimum initial tension that meets or exceeds the value in Table 7.3 and does not exceed the torque value in Table 7.4. Tools used shall demonstrate or have certified output that does not vary by more than ±10 percent during use.

Step 2: Intermediate Verification

If the actual tension developed in the *bolting assembly* is less than the *initial tension* specified in Table 7.3, the cause(s) shall be determined and resolved before the *bolting assemblies* are used in the work. Cleaning, lubrication, and retesting of these *bolting assemblies* is permitted, except as restricted in Section 2.10.4, provided that all *bolting assemblies* are treated in the same manner.

Step 3: Pretensioning

If matchmarking is to be used in the work, the *bolting assembly* shall be matchmarked. The rotation specified in Table 8.2 shall be applied to the *bolting assembly*.

Step 4: Final Verification

If the actual *pretension* developed in the *bolting assembly* is less than that specified in Table 7.1, the cause(s) shall be determined and resolved before the *bolting assemblies* are used in the work.

Table 7.3
Minimum Initial Tension for Pre-Installation Verification Testing of Installation in Accordance with Section 8.2.4 (Combined Method)

Nominal Bolt Diameter, d_b, in.	Minimum Initial Tension[a] for Pre-Installation Verification Testing, kips	
	Group 120	Group 144 and Group 150
½	5	7
⅝	9	11
¾	13	16
⅞	17	22
1	23	29
1⅛	29	36
1¼	37	46
1⅜	44	55
1½	53	66

[a]Minimum installation tension is based on 0.45 times the minimum bolt pretension in Table 5.2, rounded to the nearest kip.

Commentary:

A *bolt tension measurement device (BTMD)* must be readily available whenever *high-strength bolts* are to be *pretensioned*.

Hydraulic *BTMDs* undergo a slight deformation during bolt *pretensioning*. Hence, when bolts are *pretensioned* according to Section 8.2.1, 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*.

Direct tension indicators (*DTIs*) may be used as *BTMDs*, except in the cases of the *turn-of-nut method* and the *combined method*. This method is especially useful for, but not restricted to, bolts that are too short to fit into a hydraulic *BTMD*. The *DTIs* to be used for pre-installation verification testing must first have the average gap determined for the specific level of *pretension* required by Table 7.1, measured to the nearest 0.001 in. This is termed the "*calibrated gap*." Such measurements should be made for each *lot* of *DTIs* being used for pre-installation verification testing, termed the "verification *lot*." The *bolting assembly* may then be installed in a standard size hole with the additional

Table 7.4
Maximum Torque for Pre-Installation Verification Testing of Initial Tension in Accordance with Section 8.2.4 (Combined Method)

Nominal Bolt Diameter, d_b, in.	Torque Range for Pre-Installation Verification Testing, lb-ft[a]	
	Group 120	Group 144[b] and Group 150
	Max	Max
½	55	65
⅝	110	135
¾	195	245
⅞	315	395
1	475	595
1⅛	675	845
1¼	950	1190
1⅜	1250	1560
1½	1655	2070

[a]This table shall not be used in lieu of *Supplier*-provided torque values and shall only be used when torque has not been provided for a *bolting assembly* by the *Supplier*.
[b]ASTM F3148 Group 144 *bolting assemblies* are only available up to 1¼ in. diameter.
[c]The torque required to reach minimum initial tension (P) in Table 7.3 shall not exceed 0.25 PD, where P = tension in pounds, and D = diameter (in.)/12 = bolt diameter in feet.

verification *DTI*. The prescribed *pretensioning* procedure is followed, and it is verified that the average gap in the verification *DTI* is equal to or less than the *calibrated gap* for the verification *lot*. For *twist-off tension control bolt method* installation, the verification *DTI* must be placed beneath the bolt head, with an additional ASTM F436 washer between the bolt head and verification *DTI*, and the bolt head is not permitted to turn. For *DTI* installation, the verification *DTI* must be placed at the end opposite the placement of the production *DTI*.

This technique cannot be used for the *turn-of-nut method* or for the *combined method* because the deformation of the *DTI* consumes a portion of the rotation provided. For *turn-of-nut method*, pre-installation verification testing of bolts too short to fit into a *bolt tension measurement device*, installing the *bolting assembly* in a steel plate with the proper size hole and applying the required turns is adequate. The assembly is then to be removed from the steel plate using a wrench to confirm that stripping has not occurred. No verification is required for achieved *pretension* to meet Table 7.1. This test demonstrates that the *bolting assembly* will not fracture or strip during tightening, and the *turn-of-nut method* ensures a strain that will produce the minimum required *pretension*.

It is recognized in this Specification that a natural scatter is found in the results of the pre-installation verification testing that is required in Section 8.2. Furthermore, it is recognized that the *pretensions* developed in tests of a representative sample of the *bolting components* that will be installed in the work must be slightly higher to provide confidence that the majority of *bolting assemblies* will achieve the minimum required *pretension* as given in Table 5.2. Accordingly, the minimum *pretension* to be used in pre-installation verification testing is 1.05 times that required for installation and inspection, rounded to the nearest kip.

Pre-installation verification testing in accordance with Section 8.2.4 has been written so the *combined method* could be applied to any bolting assembly. If the supplier does not provide a torque value, the user must determine a torque value that produces an initial tension that meets or exceeds the value in Table 7.2 while not exceeding the maximum torque in Table 7.3. In the 2020 edition of this Specification, Table 7.3 provided a torque range, but the lower bound of the torque range was eliminated to accommodate very efficient lubricants.

The minimum initial tension values in Table 7.2 ensure that the subsequent rotation will develop the minimum required pretension. Users should determine a torque that provides an initial tension in excess of the minimum required in Table 7.3 to provide tolerance for installation variables.

7.3. Nonconformance

Identification and rejection of *lot*, procedure, or workmanship that is not in conformance with the provisions of Sections 7.1 and 7.2 is permitted at any time during the pre-installation verification testing process.

The nonconforming *lot*, procedure, or workmanship shall be brought into conformance prior to any retesting of product.

If the root cause is determined and corrected, then the pre-installation verification testing shall be performed on additional samples at the original sample size or greater. If this additional testing results in nonconforming test results, then it shall be determined whether additional modifications are required to be made to the material, process, or workmanship.

If all corrections or modifications to the *lot*, procedure, or workmanship continue to yield nonconforming results, then that *bolting assembly lot* shall be considered nonconforming, and the following steps shall be followed:

(1) Segregate nonconforming *bolting components* or *bolting assemblies* that have been subjected to the specific jobsite conditions experienced with the nonconforming test;
(2) Perform rework on site in compliance with this standard to correct the nonconforming characteristic; or
(3) Return *bolting components* or *bolting assemblies* to the supplier for rework or replacement.

(4) After any rework or segregation of the *bolting components* or *bolting assemblies*, the *lot* shall be reinspected in the original sample quantity for the nonconforming characteristic.

(5) If the material or workmanship cannot be brought into conformance, the *Engineer of Record* may consider the degree to which the characteristic deviates from specified requirements and the significance of the effect on the structure or performance of the *bolting assemblies* in service.

Commentary:

Testing performed in accordance with ASTM F3125 is required to be performed in controlled environments at a qualified laboratory and these conditions may differ from the jobsite. There are reasons that nonconforming pre-installation verification test results may be seen at a jobsite compared to testing performed by the *Manufacturer*, distributor, or other responsible party such as a laboratory. The *Supplier* or *Manufacturer* should be contacted to assist in determining a resolution for nonconforming pre-installation verification test results.

Below are some potential conditions that should be evaluated if the pre-installation verification test results are nonconforming:

(1) Ensure that the *bolt tension measurement device (BTMD)* is in good working condition and the calibration is current. If the *BTMD* has been stored for extended periods without use, or is in extreme environmental conditions, this may affect the performance of the *BTMD*, consult with *BTMD Manufacturer* for limiting conditions. It is good practice to run a few assemblies in the *BTMD* before those to be used in pre-installation verification testing.

(2) Ensure the proper size faceplates and bushings are used and seated and oriented correctly in the *BTMD*, and that they are in good condition.

(3) Verify that hole sizes of the *BTMD* conform to Section 3.3 of this specification. Features such as chamfers are not permitted.

(4) Verify that there is no residual oil or other contaminants on the faying surfaces of the *BTMD*.

(5) Verify that the tools utilized for the testing are in good working condition and adequate supply of power is used.

(6) Verify that the test had sufficient thread engagement in the *bolting assembly*. This can be achieved in the *BTMD* by using the proper faceplates, head bushings, and hardened spacers. Stacking of washers is not recommended.

(7) Verify that the *bolting assembly* was in *snug-tightened condition* prior to *pretensioning*. Finger/hand tight is not an acceptable practice.

(8) Verify that the surface condition or lubrication of the *bolting components* has not been altered from the as-manufactured condition and that *protective storage* in accordance with Section 2.10 is followed. Alterations in condition include, but are not limited to, contamination, improper handling and storage, environmental conditions, and addition of unauthorized lubrication.

SECTION 8. INSTALLATION

This section addresses the requirements for installing bolting assemblies to the snug-tight condition and the methods of pretensioning bolting assemblies.

The section is organized as follows:

The storage and lubrication of *bolting assemblies* and *bolting components* shall comply with the requirements of Section 2.10. For *joints* that are designated in the contract documents as *snug-tightened joints*, the *bolting assemblies* shall 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* shall be *pretensioned* in accordance with Section 8.2.

8.1. Snug-Tightened Joints

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

(1) All bolt holes shall be aligned to permit insertion of the bolts without undue damage to the threads;
(2) Bolts shall be placed in all holes with washers positioned as required in Section 6.1 and nuts threaded to complete the assembly;
(3) Compacting the *joint* shall progress systematically from the most rigid part of the *joint*; and
(4) The *joint* shall be installed to the *snug-tight condition* with *sufficient thread engagement*.

Commentary:
As discussed in the Commentary to Section 4, the bolted *joints* in most shear *connections* and in many tension *connections* can be specified as *snug-tightened joints*. The *snug-tightened condition* is typically achieved with a few impacts of an impact wrench, application of an electric torque wrench until the wrench begins to slow, or the full effort of a worker on an ordinary spud wrench. More than one cycle through the bolt pattern may be required to achieve the *snug-tightened condition*.

The splines on *spline end twist-off bolts* may be twisted off or left in place in *snug-tightened joints*.

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 joint’s performance.

As used in Section 8.1, the term “undue damage” is intended to mean damage that would render the product unfit for its intended use.

With the 2025 edition of the Specification, recognition of the Calibrated Wrench method has been withdrawn because of the large variability of torque-to-tension relationship for seemingly similar bolts and conditions. The Specification now requires that the inspecting torque wrench, to be used only in arbitration of disputes, be calibrated specifically for the individual case at issue, using a *bolt tension measurement device* to measure the actual tension produced by a given wrench effort applied to a representative sample.

8.2. Pretensioned Joints and Slip-Critical Joints

The pre-installation verification testing procedures specified in Section 7 shall be performed using *bolting assemblies* that are representative of the condition of those that will be *pretensioned* in the work.

(1) *Pretensioning methods*

One of the following methods shall be used to *pretension* the *bolting assemblies* in the *joint*:

(i) For Group 120, 144 or 150 *bolting assemblies*, one of the *pretensioning* methods in Sections 8.2.1 through 8.2.4 shall be used;

(ii) For ASTM F3148 Grade 144 *matched bolting assemblies*, the *pretensioning* method in Section 8.2.4 shall be used;

(iii) For ASTM F1852 and F2280 *matched bolting assemblies*, the *pretensioning* method in Section 8.2.2 shall be used; and

(iv) For ASTM F959 *direct tension indicators*, the *pretensioning* method in Section 8.2.3 shall be used.

Alternative-design *bolting components* or *assemblies,* including self-indicating *direct tension indicators*, shall meet the requirements of Section 2.12.

(2) For *pretensioned* installation in accordance with Sections 8.2.1 through 8.2.3:

(i) All *bolting assemblies* shall be installed to the *snug-tight condition* in accordance with the requirements of Section 8.1, with washers positioned as required in Section 6.2; and

(ii) Subsequently, the *pretensioning* method verified for the *bolting assemblies* shall be used as specified in Sections 8.2.1 through 8.2.3.

(3) For *pretensioned* installation in accordance with Section 8.2.4:

(i) All *bolting assemblies* shall be installed in accordance with the requirements of Section 8.1(1), (2), and (3) with washers positioned as required in Section 6.2. Each *bolting assembly* shall have been tightened by application of the *initial torque* used in the pre-installation verification testing, and the plies shall have been brought into *firm contact* with *sufficient thread engagement*. The *initial torque* shall be applied only by turning the nut.

(ii) Subsequently, the *bolting assemblies* shall be *pretensioned* as specified in Section 8.2.4.

For all methods, the part not turned by the wrench shall 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 of Section 6.2 are met. Upon completion of the *pretensioning*, it is not permitted to turn the nut or the head in the loosening direction except for the purpose of complete removal of the individual *bolting assembly*. Removed *bolting assemblies* shall not be *reused* except as permitted in Section 2.11.

Commentary:
Four *pretensioning methods* are provided, without preference, in this Specification. Each method may be relied upon to provide satisfactory results when conscientiously implemented with the specified *bolting components* or *assemblies* in good condition. However, it must be recognized that misuse or abuse is possible with any method. 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 reduced by the *pretensioning* of adjacent *bolting assemblies*. The resulting reduction in total clamping force will reduce the slip resistance.

In the case of galvanized coatings, especially if the *joint* consists of many plies of thickly coated material, relaxation of bolt *pretension* may be significant and re-*pretensioning* of the *bolting assemblies* may be required subsequent to the initial *pretensioning*. Munse (1967) showed that a loss of *pretension* of approximately 6.5 percent occurred with galvanized plates and bolts due to relaxation as compared with 2.5 percent for *uncoated joints*. This loss of bolt *pretension* occurred in five days; loss recorded thereafter was negligible. Either this loss can be allowed for in design, or *pretension* may be brought back to the prescribed level by re-*pretensioning* the bolts after an initial period of “settling-in.” If re-*pretensioning* of galvanized *joints* is required by the *Engineer of Record*, this must be clearly specified in the contract documents.

As stated in the *Guide* (Kulak et al., 1987), "…it seems reasonable to expect an increase in bolt force relaxation as the *grip* length is decreased. Similarly, increasing the number of plies for a constant *grip* length might also lead to an increase in bolt relaxation."

8.2.1. **Turn-of-Nut Method Pretensioning:** After the snug-tightening operation has been performed, the nut or head rotation specified in Table 8.1 shall 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*.

Commentary:
The *turn-of-nut method* of *pretensioning* results in more reliable bolt *pretensions* than are generally provided with torque-controlled *pretensioning methods*. Strain-control that reaches the inelastic region of bolt behavior is inherently more reliable than a method that is completely dependent upon torque control. However, proper implementation is dependent upon ensuring that the *joint* is properly compacted prior to application of the required rotation and that the bolt head (or nut) remains stationary when the nut (or bolt head) is being turned.

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

As indicated in Table 8.1, there is no available research that establishes the required nut rotation for bolt lengths exceeding $12d_b$. The required turn for such bolts can be established on a case-by-case basis using a *bolt tension measurement device*. When the *turn-of-nut method* is to be used, and the bolt length exceeds 12 bolt diameters, Table 8.1 note c requires testing in a *bolt tension measurement device* to establish the required nut rotation, similar to pre-installation verification testing as described in Section 7. The following procedure may be used:

(1) Test three samples of each combination of bolt and nut *lot* to be used in the work.
(2) Place the bolt in the *bolt tension measurement device*. The manufacturer's instructions of the selected *bolt tension measurement device* should be properly followed and should include requirements for the proper placement of spacers and/or bushings to reduce the *prying action* that results from excessive stick-out at the turned element so that accurate tension testing for long bolts can be achieved.
(3) Install the *bolting assembly* to the requirements of Section 8.1 using the tools and installation methods to be used in the work.
(4) Determine the rotation from the *snug-tight condition* required to develop a *pretension* in the *bolting assembly* equal to or greater than that specified in Table 7.1.

Table 8.1
Nut Rotation from Snug-Tight Condition for Turn-of-Nut Method Pretensioning[a,b,e]

Bolt Length[c]	Disposition of Outer Faces of Bolted Parts		
	Both Faces Normal to Bolt Axis	One Face Normal to Bolt Axis, Other Sloped Not More Than 1:20[d]	Both Faces Sloped Not More Than 1:20 from Normal to Bolt Axis[d]
Not more than $4d_b$	⅓ turn	½ turn	⅔ turn
More than $4d_b$ but not more than $8d_b$	½ turn	⅔ turn	⅚ turn
More than $8d_b$ but not more than $12d_b$	⅔ turn	⅚ turn	1 turn

[a]Nut rotation is relative to bolt regardless of the element (nut or bolt) being turned. For all required nut rotations, the tolerance is plus 60 degrees (⅙ turn) and minus 0 degrees.
[b]Applicable only to joints in which all material within the *grip* is steel.
[c]When the bolt length exceeds $12d_b$, the required nut rotation shall be determined by actual testing in a suitable *bolt tension measurement device*; see *turn-of-nut* Commentary.
[d]Beveled washer not used.
[e]When F3394 *backup washers*, *reaction washers*, or both, are used, nut rotations shall be increased by 60 degrees.

(5) For the convenience of the installer, round the rotation up to the next higher ⅙ turn increment [e.g., if 270 degrees (¾ turn) is required, round up to ⅚ turn].

(6) If the resultant rotation requirement is less than that provided in Table 8.1, use the value for $12d_b$) as provided in Table 8.1.

Significant research indicates that, at rotations exceeding those specified in Table 8.1, the level of *pretension* in the bolt will still be above the specified minimum *pretension*. In addition, the *pretension* is likely to remain high until just prior to failure of the bolt. The rotational margin before bolt failure is large. A325 and A490 bolts ⅞ in. diameter and 5½ in. long with ⅛ in. of thread in the *grip* were tested. The installation condition for bolts of this length and diameter is ½ turn past snug. The A325 bolts did not fail until about 1¾ turns past snug, and the A490 bolts did not fail until about 1¼ turns past snug. Bolts with additional threads in the *grip* would exhibit additional ductility and tolerance for over-rotation.

Research (Swanson and Rassati, 2025) indicates that when ASTM F3394 *backup washers, reaction washers,* or both are installed following the *turn-of-nut method,* a portion of the specified turn is consumed by the embedment of the knurls during pretensioning. ASTM F3394 specifies an upper limit on the height of the knurls, and therefore, the effects of knurl embedment can be quantified. Accordingly, the specified nut rotations in Table 8.1 for use with ASTM F3394 washers are increased, and the tolerances remain the same.

Non-heat-treated nuts (ASTM A563 Grades C, C3, and D) manufactured near the lower range of permitted strength and hardness may strip if the bolt is tightened far beyond the specified level of *pretension*. For Group 120 bolts, nuts with a hardness of 89 HRB or higher should have adequate resistance to thread stripping. For Group 144 and 150 bolts, only heat-treated nuts are used. Deliberate over-rotation should be avoided to minimize risk of inducing nut stripping with low-hardness nuts or inducing nut cracking with high-hardness heat-treated nuts. Nut stripping or cracking would be considered cause for rejection of the installed *bolting assembly*.

8.2.2. **Twist-Off Tension Control Bolt Method Pretensioning:** After the snug-tightening operation is performed, the installer shall verify that the splined end has not been severed, and if this has occurred, the *bolting assembly* shall be removed and replaced.

All bolts in the *joint* shall be *pretensioned* with the *spline end twist-off bolt* installation wrench, progressing systematically from the most rigid part of the *joint* in a manner that will minimize relaxation of previously *pretensioned* bolts.

Commentary:

Spline end twist-off matched bolting assemblies have a splined end that extends beyond the threaded portion of the bolt. During installation, this splined end is gripped by a specially designed wrench chuck and provides a means for turning the nut relative to the bolt. This product is, in fact, based upon a torque-controlled installation method to which the *bolting assembly* variables affecting torque that were discussed in the Commentary to Section 8.2.2 apply, except for wrench calibration, because torque is controlled within the *bolting assembly*.

Spline end twist-off matched bolting assemblies must be used in the as-delivered, clean, lubricated condition as specified in Section 2. Adherence to the requirements in this Specification, especially those for storage, cleanliness, and verification, is necessary for their proper use.

8.2.3. **Direct Tension Indicator Method Pretensioning:** After the snug-tightening operation is performed, the installer shall verify that the feeler gauge, of the thickness used in pre-installation verification testing, can be inserted into the spaces between the *direct tension indicator* protrusions as indicated in the "Minimum Feeler Gauge Entries—Snug Tight Condition" column of Table 8.2. If the feeler gauge cannot be inserted per Table 8.2, the bolt and nut combination shall be checked to verify that the assembly is suitable for reuse, as prescribed in 2.11, and the direct tension indicator shall be removed and replaced, and the snug-tightening operation performed again.

All bolts in the *joint* shall be *pretensioned*, progressing systematically from the most rigid part of the *joint* in a manner that will minimize relaxation of previously *pretensioned* bolts. The installer shall verify that the maximum number of feeler gauge entries does not exceed the entries indicated in Table 8.2.

Table 8.2
Direct Tension Indicator Feeler Gauge Entry Requirements—Installation

Spaces between Direct Tension Indicator Protrusions	Minimum Feeler Gauge Entries—Snug-Tight Condition	Maximum Feeler Gauge Entries—Installation in Work
4	2	1
5	3	2
6	3	2
7	4	3
8	4	3
9	5	4

Commentary:
Direct tension indicators are a *bolt tension measurement device*. *Direct tension indicators* are washer-shaped devices incorporating small arch-like protrusions on the bearing surface that are designed to deform in a controlled manner when subjected to compressive load.

During installation, care must be taken to ensure that the *direct tension indicator* protrusions are oriented to bear against the hardened bearing surface of the bolt head or nut or against a hardened flat washer if used under the turned element, whether that turned element is the nut or the bolt. Proper use and orientation is illustrated in Figure C-8.1.

Provided the connected plies are in *firm contact*, partial compression of the *direct tension indicator* protrusions is commonly taken as an indication that the *snug-tight condition* has been achieved.

8.2.4. **Combined Method Pretensioning:** After the plies have been brought into firm contact, and the initial torque determined in 7.4 has been applied, the rotation specified in Table 8.3 shall 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*.

Commentary:
The *combined method* relies on an established relationship between fastener torque and tension to achieve or surpass the prescribed *initial tension*. Next, the bolt or nut is rotated by a designated additional amount relative to the bolt 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

Table 8.3
Nut Rotation from Initial Torque for Combined Method Pretensioning[a,b]

Bolt Length[c]	Rotation
Not more than $4d_b$	90° (¼ turn)
More than $4d_b$ but not more than $8d_b$	120° (⅓ turn)

[a]Nut rotation is relative to bolt. For all required nut rotations, the tolerance is plus 45 degrees and minus 0 degrees.
[b]Applicable only to *joints* in which all material within the *grip* is steel.
[c]When the bolt length exceeds $8d_b$, the required nut rotation shall be determined by actual testing in a suitable *bolt tension measurement device*; see *combined method* Commentary.

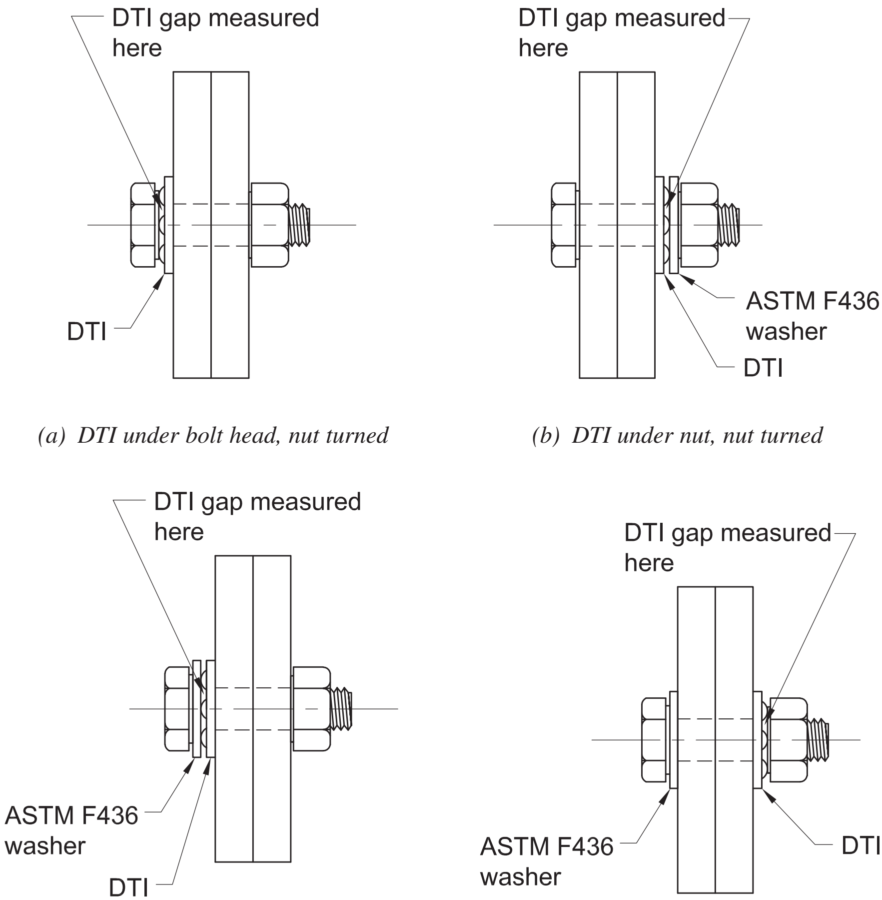
likely less because it is relative to the *initial tension* condition of the *combined method*, which is usually higher than the minimum snug condition required for the *turn-of-nut method*. Matchmarking of the nut and protruding end of the bolt after initial tensioning can be helpful in subsequent installation and as an aid to inspection.

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

As indicated in Table 8.3, there is no available research that establishes the required nut rotation for bolt lengths exceeding $8d_b$. In the absence of procedures provided by the *Manufacturer*, the required turn for such bolts can be established on a case-by-case basis using a *bolt tension measurement device*.

When the *combined method* is to be used and the bolt length exceeds $8d_b$, Table 8.3. note *c* requires testing in a *bolt tension measurement device* to establish the required nut rotation, similar to pre-installation verification testing as described in Section 7.

(1) Test three samples of each *bolting assembly* to be used in the work.
(2) Place the bolt in the *bolt tension measurement device*. The manufacturer's instructions of the selected *bolt tension measurement device* should be properly followed and should include requirements for the proper placement of spacers and/or bushings to reduce the *prying action* that results from excessive stick-out at the turned element, so that accurate tension testing for long bolts can be achieved.
(3) Install the *bolting assembly* to the *initial tension* requirements of Section 7.2.4 using the tools and installation methods to be used in the work.
(4) Determine the rotation from the *initial tension* condition required to develop a *pretension* in the *bolting assembly* equal to or greater than that specified in Table 7.1.
(5) For the convenience of the installer, round the rotation up to the next higher ⅙-turn increment (e.g., if 150 degrees is required, round up to ½ turn).
(6) If the resulting rotation requirement is less than that provided in Table 8.3, use the value for a bolt length up to 8 bolt diameters as provided in Table 8.3.



(a) DTI under bolt head, nut turned

(b) DTI under nut, nut turned

(c) DTI under bolt head, bolt head turned

(d) DTI under nut, bolt head turned

Fig. C-8.1. Proper use and orientation of ASTM F959 direct tension indicators.
Note: See Section 6 for general requirements for the use of washers.

SECTION 9. INSPECTION

This section addresses inspection requirements for the three types of bolted joints applicable to the Contractor's Inspection and, if required, Third-Party Inspection.

The section is organized as follows:

9.1. Snug-Tightened Joints
9.2. Pretensioned Joints
9.3. Slip-Critical Joints

Inspection tasks prior to bolting and during bolting shall be performed in accordance with the invoking specification or standard and as required in this section.

Commentary:
For buildings, Chapter N, Section 6 of AISC 360 contains requirements for inspection of high-strength bolting. In particular, inspection tasks prior to, during, and after bolting are summarized in Tables N5.6-1, N5.6-2, and N5.6-3 of AISC 360, respectively.

Generally, torque measurements do not provide consistent results for inspection, as they are greatly dependent on the friction between the turned element (bolt head or nut) and the steel or washer, as applicable, and the friction between the bolt threads and nut threads, both influenced by the lubrication conditions of the *bolting components*. *Routine observation* of installation methods is always preferred.

9.1. Snug-Tightened Joints

Prior to the *start of work*, it shall be verified that all *bolting components* to be used in the work meet the requirements of Section 2. Subsequently, it shall be verified that all connected plies meet the requirements of Section 3.1 and all bolt holes meet the requirements of Sections 3.3 and 3.4. After the *connections* have been assembled to the requirements of Section 8.1, it shall be visually verified that the plies of the connected elements have been brought into *firm contact*, where the plies are solidly seated against each other, but not necessarily in continuous contact, and that washers have been used as required of Section 6. No further evidence of conformity is required for *snug-tightened joints*.

Commentary:
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 required for the proper performance of a *snug-tightened joint*, the installed bolts should not be inspected to determine the actual installed *pretension*. Likewise, the arbitration procedures described in Section 10 are not applicable.

9.2. Pretensioned Joints

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

(1) When the *turn-of-nut method* is used for *pretensioning*, the inspection shall be in accordance with Section 9.2.1;
(2) When the *twist-off tension control bolt method* is used for *pretensioning*, the inspection shall be in accordance with Section 9.2.2;
(3) When the *direct tension indicator method* is used for *pretensioning*, the inspection shall be in accordance with Section 9.2.3;
(4) When the *combined method* is used for *pretensioning*, the inspection shall be in accordance with Section 9.2.4; and
(5) When alternative-design *bolting components*, *assemblies*, or installation methods that meet the requirements of Section 2.12 are used, the inspection shall be in accordance with inspection instructions provided by the consensus standard or *Manufacturer* and approved by the *Engineer of Record*.

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

9.2.1. **Turn-of-Nut Method Pretensioning:** The *Inspector* shall:

(1) Observe the pre-installation verification testing required in Section 7;
(2) Verify by *routine observation* that the *snug-tight condition* has been achieved in accordance with Section 8.1; and
(3) Verify by *routine observation* that the bolting crew subsequently rotates the turned element relative to the unturned element by the amount specified in Table 8.1. Alternatively, when *bolting assemblies* are matchmarked 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 required.

A *pretension* that is greater than the value specified in Table 5.2 shall not be cause for rejection. A rotation that exceeds the required values, including tolerance, specified in Table 8.1 shall not be cause for rejection.

Commentary:
Matchmarking of the assembly during installation as discussed in the Commentary to Section 8.2.1 improves the ability to inspect bolts that have been *pretensioned* with the *turn-of-nut method*. When impact tools are used, the sides of nuts and bolt heads that have been impacted sufficiently to induce the minimum *pretension* in Table 5.2 will appear slightly peened.

Proper inspection of the *bolting assemblies pretensioned* with this method calls for the *Inspector* to observe the required pre-installation verification testing of the *bolting assemblies* and the method to be used, followed by monitoring of the work in progress to verify that the method is routinely and properly applied, or visual inspection of matchmarked assemblies.

Some problems with the *turn-of-nut method* have been encountered with galvanized or coated bolts. In some cases, the problems have been attributed to especially effective lubricants applied by the *Manufacturer* to ensure that bolts and nuts from stock will meet the ASTM Standard requirements for rotational capacity of galvanized and coated *bolting assemblies*. Jobsite testing in a *bolt tension measurement device* demonstrated that the lubricant reduced the coefficient of friction between the bolt and nut to the degree that "the full effort of an ironworker using an ordinary spud wrench" to snug-tighten the *joint* actually induced the full required *pretension*. Well-lubricated *high-strength bolts* may require significantly less torque to induce the specified *pretension*. The required pre-installation verification test will reveal this.

Conversely, the absence of lubrication or lack of proper overtapping of galvanized or coated bolts can cause seizing of the nut and bolt threads, which will result in a twisting failure of the bolt at less than the specified *pretension*. For such situations, the use of a *bolt tension measurement device* to check the bolt assemblies to be installed will be helpful in establishing the need for lubrication.

9.2.2. **Twist-Off Tension Control Bolt Method Pretensioning:** The *Inspector* shall:

(1) Observe the pre-installation verification testing required in Section 7;
(2) Verify by *routine observation* that the *snug-tight condition* has been achieved in accordance with Section 8.1 and that splined ends are intact after snug-tightening; and
(3) Verify by *routine observation* that the splined ends are subsequently twisted off during *pretensioning* by the bolting crew. No further evidence of conformity is required.

A *pretension* that is greater than the value specified in Table 5.2 shall not be cause for rejection.

Commentary:
The sheared-off splined end of an installed *twist-off tension control bolting assembly* merely signifies that at some time, the bolt was subjected to a torque that was sufficient to cause the separation of the spline. If all *bolting assemblies* are individually *pretensioned* in a single continuous operation without first properly snug-tightening all *bolting assemblies*, relaxation of previously tightened bolts may occur, and this may give a misleading indication that the bolts have been properly *pretensioned*. Therefore, it is necessary that the *Inspector*

verify by *routine observation* that the *snug-tight condition* has been achieved in the *joints* in accordance with Section 8.1. This is followed by monitoring of the work in progress to verify that the method is routinely and properly applied within the limits on time between removal from *protected storage* and final twist-off of the splined end.

9.2.3. **Direct Tension Indicator Method Pretensioning:** The *Inspector* shall:

(1) Observe the pre-installation verification testing required in Section 7.
(2) Before pretensioning, verify by *routine observation* that the *snug-tight condition* has been achieved in accordance with Section 8.1, and that the feeler gage used in Section 7.2.3 can be inserted per Table 8.2's Minimum Feeler Gage Entries, properly oriented against the bolt head, the nut, or a hardened washer in compliance with the bolting procedure. If the assembly does not meet this criterion, the *direct tension indicator* shall be removed and replaced.
(3) After pretensioning, verify by *routine observation* that the maximum number of feeler gauge entries does not exceed the entries indicated in Table 8.2.

A *pretension* that is greater than that specified in Table 5.2 or feeler gage refusals in all locations shall not be cause for rejection.

Commentary:
When the *joint* is initially snug-tightened, the *direct tension indicator* arch-like protrusions will generally partially compress. Whenever the snug-tightening operation causes one-half or more of the gaps between these arch-like protrusions to close to less than the inspection gap, the *direct tension indicator* must be replaced. Only after this initial operation should the bolts be *pretensioned* in a systematic manner. If the *bolting assemblies* are installed and *pretensioned* in a single continuous operation, *direct tension indicators* may give the *Inspector* a misleading indication that the *bolting assemblies* have been properly *pretensioned*. Therefore, it is necessary that the *Inspector* observe that the *snug-tight condition* has been achieved before final *pretensioning*. Following this operation, the *Inspector* should monitor the work in progress to verify that the method is routinely and properly applied.

9.2.4. **Combined Method Pretensioning:** The *Inspector* shall:

(1) Observe the pre-installation verification testing required in Section 7;
(2) Verify by *routine observation* that the bolting crew applies to the nut the *initial torque* used in pre-installation verification testing, that the plies have been brought into *firm contact*, and that the requirements of Section 8.1 have been met; and

(3) Verify by *routine observation* that the bolting crew properly rotates the turned element relative to the unturned element by the amount specified in Table 8.3. Alternatively, when *bolting assemblies* are matchmarked 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 Table 5.2 shall not be cause for rejection. A rotation that exceeds the required values, including tolerance, in Table 8.3 shall not be cause for rejection.

Commentary:
Matchmarking of the nut and protruding end of the bolt after snug-tightening can be helpful in the subsequent pretensioning process. It improves the ability to inspect *bolting assemblies* that have been *pretensioned* with the *combined method* of *pretensioning*. The sides of nuts and bolt heads that have been *pretensioned* using impact wrenches sufficiently to induce the minimum *pretension* in Table 5.2 may appear slightly peened.

Proper inspection of the *bolting assemblies pretensioned* with this method is for the *Inspector* to observe 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* shall observe that the prescribed rotation was applied.

9.3. Slip-Critical Joints

Prior to assembly, it shall be visually verified that the *faying surfaces* of *slip-critical joints* meet the requirements of Section 3.2.2. Subsequently, the inspection required in Section 9.2 shall be performed.

Commentary:
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. Accordingly, the inspection requirements for *slip-critical joints* are identical to those specified in Section 9.2, with additional *faying surface* condition inspection requirements.

SECTION 10. ARBITRATION

This section provides a method for resolving uncertainty in recently installed and inspected bolting assemblies suspected of failing to achieve the minimum pretension.

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

(1) A representative sample of five bolt and nut assemblies of each combination of diameter, length, grade, and *lot* in question shall be installed in a *bolt tension measurement device*. The material under the turned element shall be the same as in the actual installation—that is, structural steel or hardened washer. The bolt shall be partially tightened to approximately 15 percent of the *pretension* specified in Table 5.2. Subsequently, the bolt shall be *pretensioned* to the minimum value specified in Table 5.2.

(2) A calibrated 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, shall be applied to the *pretensioned* bolt. The torque that is necessary to rotate the nut or bolt head five degrees (approximately 1 in. at 12 in. radius) relative to its mating component in the tightening direction shall be determined.

(3) The *arbitration torque* shall be determined by rejecting the high and low values and averaging the remaining three.

(4) Bolts represented by the above sample shall be tested by applying the *arbitration torque* in the tightening direction to 10 percent 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* shall be accepted as properly *pretensioned*.

If verification of bolt *pretension* is required 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 shall 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* shall be tested. Those bolts whose nut or head is turned relative to its mating component by the application of the *arbitration torque* shall be further *pretensioned* by the fabricator or erector and reinspected. Alternatively, the fabricator or erector, at their option, is permitted to further *pretension* all of the bolts in the *joint* and subsequently resubmit the *joint* for inspection.

Commentary:

The variability in any torque-tension relationship used for the arbitration of disputes can be significant. The variables that affect the relationship between torque and bolt pretension include:

(1) The finish and tolerance on the bolt and nut threads;
(2) The uniformity, degree, and condition of lubrication on the bolting components;
(3) The shop or job-site conditions that contribute to dust, dirt, or corrosion on the threads, mating nut, and washer surfaces;

(4) The friction that exists to a varying degree between the turned element (the nut face or bearing area of the bolt head) and the steel surface or hardened washer, as applicable;
(5) The repeatability of the performance of any wrench that senses or responds to the level of the applied torque; and
(6) The uncertainty of the effect of passage of time and exposure in the installed condition.

Furthermore, in many cases such arbitration may have to be based upon an *arbitration torque* that is determined either using bolts that can only be assumed to be representative of the bolts used in the actual job or using bolts that are removed from completed *joints*. Ultimately, such arbitration may wrongly reject *bolting assemblies* that were subjected to a properly implemented installation procedure or accept *bolting assemblies* that were not properly installed. The arbitration procedure contained in this Specification is provided, in spite of its limitations, as the most feasible available at this time.

Arbitration using an ultrasonic extensometer or a mechanical one capable of measuring changes in bolt length can be performed on a sample of *bolting assemblies* that is representative of those that have been installed in the work. Several manufacturers produce equipment specifically for this application. The use of appropriate techniques, which includes calibration, can produce a very accurate measurement of the actual *pretension*. The method involves measurement of the change in bolt length during the release of the nut, combined with either a load calibration of the removed *bolting assembly* or a theoretical calculation of the force corresponding to the measured elastic release or "stretch." Reinstallation of the released *bolting assembly* or installation of a replacement *bolting assembly* is required.

The required release suggests that the direct use of extensometers as an inspection tool be used in only the most critical cases. The problem of reinstallation may require *bolting assembly* replacement unless torque can be applied slowly using a manual or hydraulic wrench, which will permit the restoration of the original elongation.

Because the reliability of the *turn-of-nut method* is not dependent upon the presence or absence of washers under the turned element, washers are not generally required, except for other reasons as indicated in Section 6. Thus, in the absence of washers, after-the-fact, torque-based arbitration is particularly unreliable when the turn-of-nut method has been used for installation.

APPENDIX A. TESTING METHOD TO DETERMINE THE SLIP COEFFICIENT FOR COATINGS USED IN BOLTED JOINTS

SECTION A1. GENERAL PROVISIONS

This Appendix provides test methods to determine the mean slip coefficient of a coating for use in the design of slip-critical joints.

The Appendix is organized as follows:

A1. General Provisions
A2. Test Plates and Coating of the Specimens
A3. Short-Term Compression Slip Tests
A4. Tension Creep Tests

A1.1. Purpose and Scope

The purpose of this testing procedure is to determine the *mean slip coefficient* of a coating for use in the design of *slip-critical joints*. The *mean slip coefficient* is determined upon successful completion of both short-term compression tests and long-term tension creep tests.

Commentary:

The Research Council on Structural Connections first approved the testing method developed by Yura and Frank (1985) that tested bare steel *faying surfaces* with adherent mill scale, blast cleaned bare steel *faying surfaces*, and blast cleaned *faying surfaces* with liquid applied coatings. It has since been revised to incorporate changes resulting from the intervening years of experience with the testing method and is included as an Appendix to this Specification.

Testing programs using the methods in this Appendix have already assessed the mean slip resistance of clean mill scale, blast-cleaned bare steel, and hot-dip galvanized *faying surfaces*. This Appendix presents a generic test method for assessing coatings or combinations of coatings other than these three commonly adopted.

It is noted that this Appendix describes a method to determine the certification of a slip coefficient of a *faying surface* or coating and does not address how that certification should be applied. Coating reducer, percent coating reduction, coating dry film thickness, *cure* time, temperature, relative humidity, and *degree of cure* are variables measured during testing. Satisfactory *degree of cure* can be achieved using a reducer, percent reduction, *cure* time, temperature, and relative humidity other than those recorded at time of test as long as they are within the Coating Manufacturer's recommendations. *Degree of cure* may be evaluated using one or more of the following: sclerometer hardness (ISO 4586-2), pencil hardness (ASTM D3363), MEK double rub test (ASTM D4752), and/or by other means as recommended by the Coating Manufacturer. Coating dry film thickness and *degree of cure* are essential variables as recorded on the certification.

A1.2. Definition of Essential Variables

Essential variables are those that, if changed, will require retesting of the coating to determine its *mean slip coefficient*. The essential variables and the relationship of these variables to the limitations of application of the coating for structural *joints* are given below. The slip coefficient testing shall be repeated if there is any change in these essential variables.

A1.2.1. *Degree of Cure: Degree of cure* is an essential variable. *Cure* shall be performed according to Coating Manufacturer's published recommendations. The *degree of cure* of the coating shall be evaluated using one or more of the following: (a) sclerometer hardness, (b) pencil hardness, (c) MEK double rub test, or (d) by other means as recommended by the Coating Manufacturer. Each evaluation method recommended by the Coating Manufacturer shall be performed at the time of test and shall be recorded on the certification.

A1.2.2. **Coating Thickness:** The coating thickness is an essential variable. The maximum average coating thickness, as per SSPC-PA 2, 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.

A1.2.3. **Coating Composition and Method of Manufacture:** The composition of the coating and its method of manufacture are essential variables.

A1.3. Retesting

A coating that fails to meet the creep requirements of Section A4 may be retested in accordance with methods in Section A4 at a lower slip coefficient without repeating the static short-term tests specified in Section A3. Essential variables shall remain unchanged in the retest.

A1.4. Duration of Coating Slip Certificate

Any coating slip certificate issued under this Appendix for a coating is valid for a term of 84 months after the certificate has been issued. After 84 months, the coating shall be fully retested according to this Appendix and reissued a new certificate.

SECTION A2. TEST PLATES AND COATING OF THE SPECIMENS

A2.1. Test Plates

The test specimen plates for the short-term static tests are shown in Figure A-1. The plates are 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 A-2. The plates are 4 in. × 7 in. × ⅝ in. thick with two 1-in.-diameter holes drilled 1½ in. ± 1⁄16 in. from each end. The edges of the plates may be milled, as-rolled, or saw-cut; thermally cut edges are not permitted. The contact surfaces shall be flat enough to ensure that they will be in reasonably full contact over the *faying surface*. All burrs, lips, or rough edges shall be removed. The arrangement of the specimen plates for the testing is shown in Figure A-2. The plates shall be fabricated from a steel with a specified minimum yield strength that is between 36 and 50 ksi, inclusive.

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

Commentary:
The use of 1-in.-diameter bolt holes in the specimens is to ensure that adequate clearance is available for slip. Fabrication tolerances, coating buildup on the holes, and assembly tolerances tend to reduce the apparent clearances.

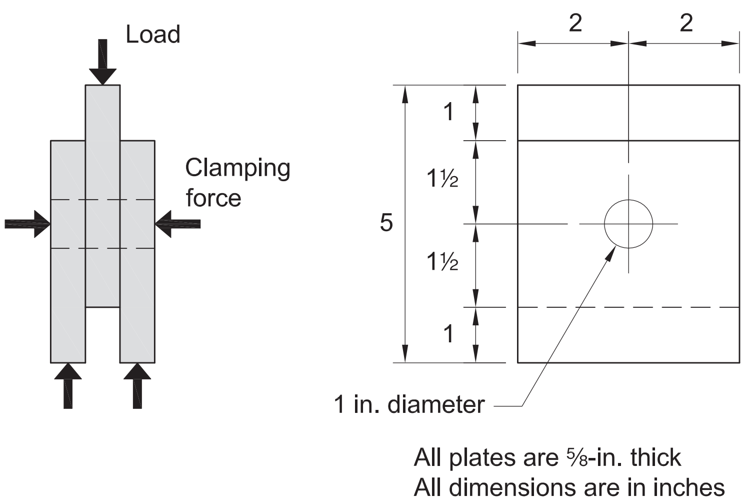


Fig. A-1. Compression slip test specimen.

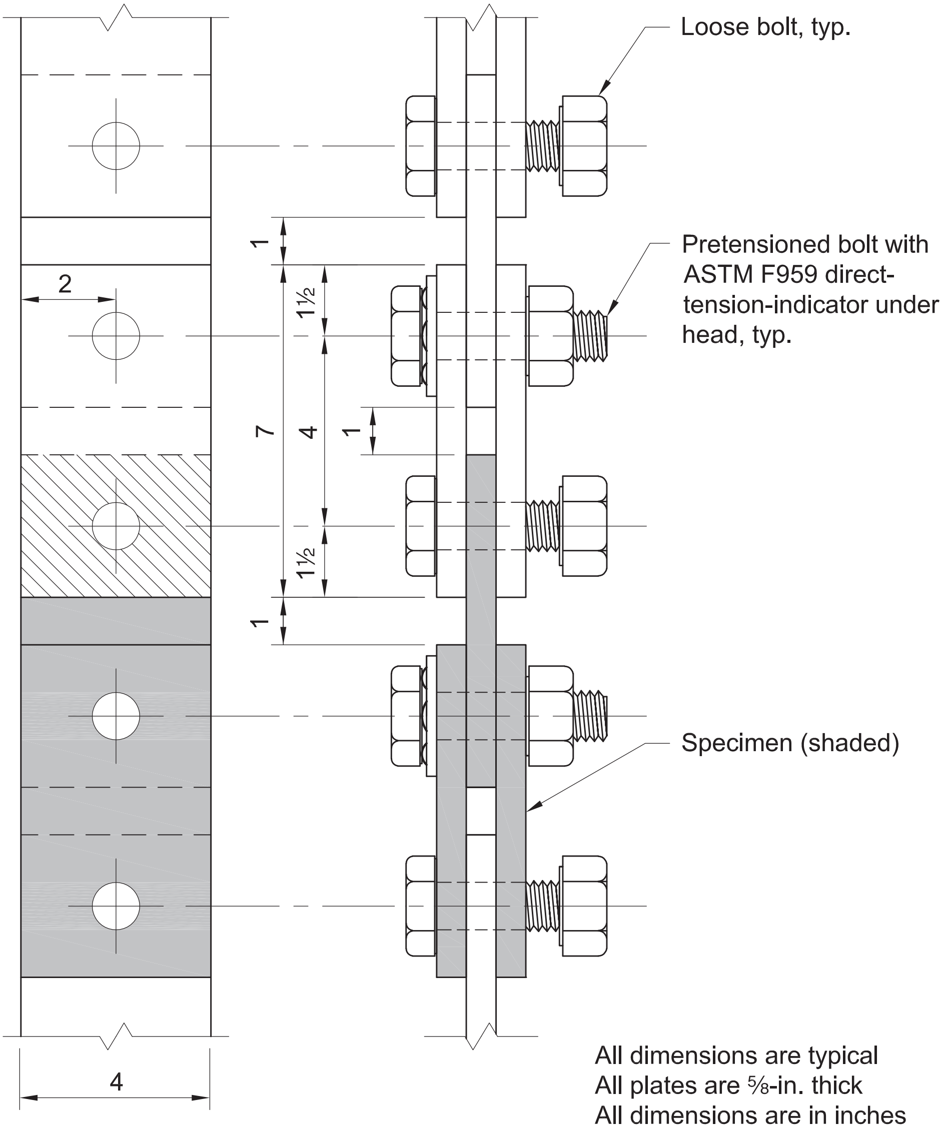


Fig. A-2. Creep test specimen assembly.

A2.2. Specimen Coating

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 shall 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, shall be measured on the contact surface of the specimens. The thickness shall be measured in accordance with SSPC-PA 2. Two spot readings (six gage readings) shall 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 shall be reported for each specimen. The average coating thickness of the creep specimens shall be calculated and reported.

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

SECTION A3. SHORT-TERM COMPRESSION SLIP TESTS

The methods and procedures described herein are used to experimentally determine the *mean slip coefficient* under short-term static loading for *slip-critical joints*. The *mean slip coefficient* shall be determined by testing one set of five specimens and then verified for long-term tension creep loading covered in Section A4.

Commentary:
The test method is designed to provide the necessary information to evaluate the suitability of a coating for *slip-critical joints* and to determine the *mean slip coefficient* to be used in the design of the *joints*. 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 found to be independent of the magnitude of the clamping force, normal variation in applied coating thickness, and bolt hole diameter.

A3.1. Compression Test Setup

The test setup shown in Figure A-3 has two major loading components, one to apply a clamping force to the specimen plates and another to apply a compressive load to the specimen so that the load is transferred across the *faying surfaces* by friction.

Commentary:
The slip coefficient can be easily determined using the hydraulic bolt test setup included in this Specification. The clamping force system simulates the clamping action of a *pretensioned high-strength bolt* through a controlled and directly measurable way.

A3.1.1. **Clamping Force System:** The clamping force system consists of a ⅞-in.-diameter threaded rod that passes through the specimen and a centerhole compression ram. An ASTM A563 Grade DH nut is used at both ends of the rod and a hardened washer is used at each side of the test specimen. Between the ram and the specimen is a specially modified ⅞-in.-diameter ASTM A563 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 shall have a capability to apply a load of at least 49 kips.

Commentary:
The loading rod should be made of steel with a strength greater than or equal to an ASTM F3125 Grade A490 bolt. Understrength rods may fracture under loading causing flying debris that could injure test operators. 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.

A3.1.2. **Compressive Load System:** A compressive load shall be applied to the specimen until slip occurs. This compressive load shall be applied with a compression test machine or a reaction frame using a hydraulic loading device. The loading device and the necessary supporting elements shall be able to support a force of 120 kips.

A3.1.3. **Load Train Alignment:** The testing agency shall ensure that the loading system is constructed such that the lines of action from the spherical head and the center-hole ram intersect at the theoretical center of the three test plates. A tolerance of ±⅛ in. is considered allowable in any direction. This alignment shall be checked every time a new specimen is installed.

A3.2. Instrumentation

A3.2.1. **Clamping Force:** The clamping force may be measured by pressure in the ram or placing a load cell in series with the ram. The device measuring clamping load shall be calibrated annually and be accurate within ±0.5 kip.

A3.2.2. **Compression Load:** The compression load shall 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 shall be calibrated annually and be accurate within ±1.0 kip.

A3.2.3. **Slip Deformation:** The displacement of the center plate relative to the two outside plates shall be measured. This displacement, called "slip" for simplicity, shall be the average of the displacement gauges on each side of the specimen. Deflections shall be measured by dial gauges or any other calibrated device that has a resolution of at least 0.001 in. and shall be calibrated annually.

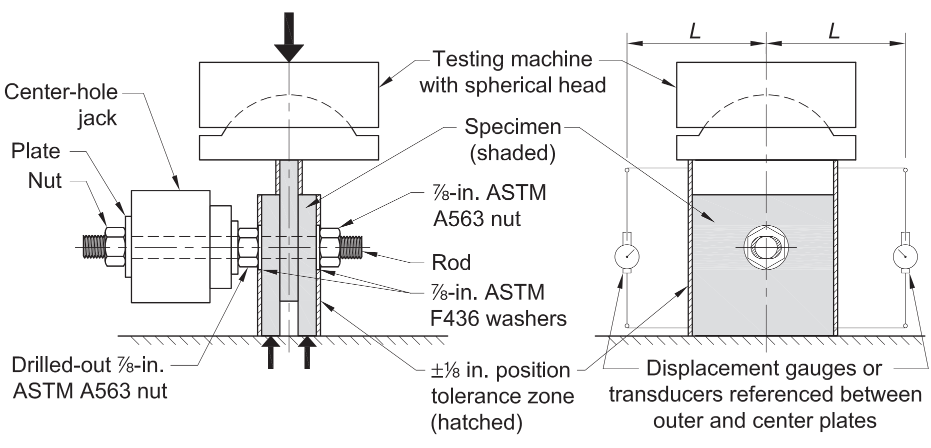


Fig. A-3. Compression slip test setup.

Commentary:
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 A3.3. The low stiffness may erroneously affect determination of the slip load described in Section A3.4. More details about the initial displacement response and means to mount displacement gauges can be found in Ocel et al. (2014).

A3.3. Test Procedure

The specimen shall be installed in the test setup as shown in Figure A-3. Before the hydraulic clamping force is applied, the individual plates shall 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 ensure obvious slip deformation. Care shall be taken in positioning the two outside plates so that the specimen is perpendicular to the base with both plates in contact with the base. After the plates are positioned, the centerhole ram shall be engaged to produce a clamping force of 49 kips. The applied clamping force shall be maintained within ±0.5 kip during the test until slip occurs.

The spherical head of the compression loading machine shall be brought into contact with the center 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 shall be engaged, attached, or zeroed at a compressive load of 5.0 kips.

When the slip gauges are in place, the compression load shall be applied at a rate that does not exceed 25 kips per minute nor 0.003 in. of slip displacement per minute until the slip load is reached. The test shall be terminated when a slip of 0.04 in. or greater is recorded. The load-slip relationship shall be continuously recorded in a manner sufficient to evaluate the slip load defined in Section A3.4.

Commentary:
It is helpful 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. It is the intent of these limits to provide a test that will take approximately 5 minutes to attain the failure load.

A3.4. Slip Load

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

Curve (a) Slip load is the maximum load, provided this maximum occurs before a slip of 0.02 in. is recorded.

Curve (b) Slip load is the load at which the slip rate increases suddenly.

Curve (c) Slip load is the load corresponding to a deformation of 0.02 in. This definition applies when the load versus slip curves show a gradual change in response.

A3.5. Slip Coefficient

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

$$k_s = \frac{\text{slip load}}{2 \times \text{clamping force}} \tag{A3.1}$$

The *mean slip coefficient*, μ, for one set of five specimens shall be 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 passes the following criteria:

$$\frac{\mu - k_{s_{\text{min.}}}}{\sigma} \geq 1.71 \tag{A3.2}$$

where

μ = the average of the five k_s values attained
σ = the standard deviation of the five k_s values attained
$k_{s_{\text{min.}}}$ = lowest k_s value in five samples

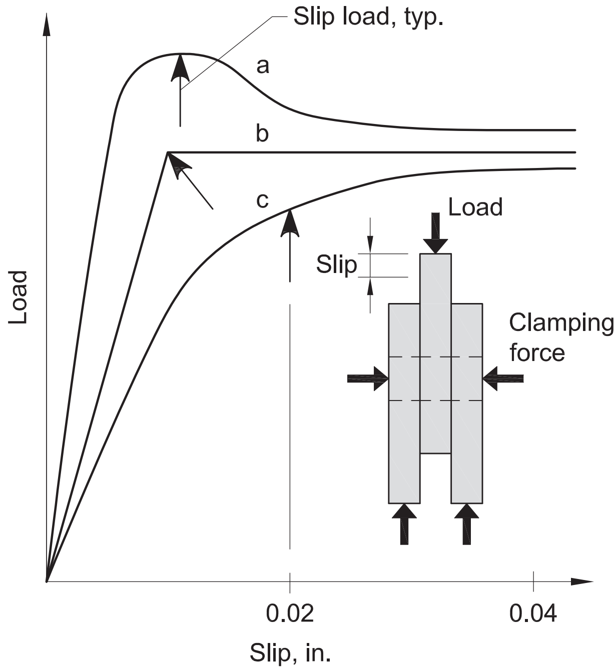


Fig. A-4. Definition of slip load.

Commentary:
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 with a critical value of 5 percent based on a two-tailed Student's T-distribution. This effectively means the outlier passing the criterion in Equation A3.2 falls outside the 95 percent confidence limits of an assumed normal distribution. Grubbs' test is only valid for the removal of one outlier, and rejection of more than one outlier is not used since 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. Additionally, for sample populations with small scatter (i.e., coefficient of variation <1%), the outlier criterion may identify good data as an outlier, and some discretion must be used on whether it is appropriate to screen for an outlier.

To demonstrate the outlier analysis, consider the slip curves attained in testing five replicates of a liquid-applied coating shown in Figure C-A-1. Test 2 is a suspected outlier and using Equation A3.2 determines that (0.44 − 0.34)/0.058 = 1.72 is greater than 1.71; therefore, it may be disregarded as an outlier. And, thus, 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 gleaned from plots of load versus slip. In the plot shown in Figure C-A.1, Test 2 has a double plateau response, which is characteristic of a specimen that is not seated correctly—that is, only one of the two outer plates was initially in contact with

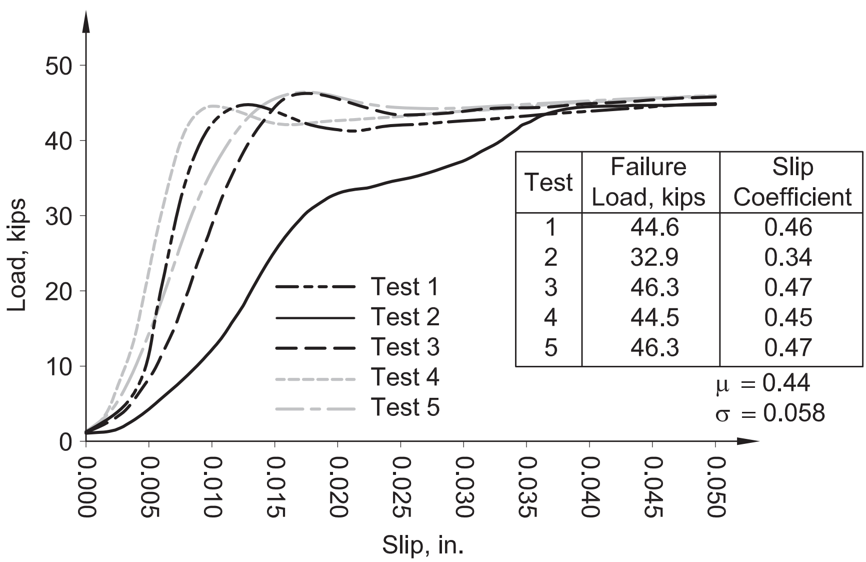


Fig. C-A.1. Example load versus slip plots.

the platen. Additionally, it is possible to distinguish if slip is occurring or if the plates are bearing on the loading rod. Figure C-A.2 shows a response of a slip test where load continuously increases as slip is occurring. 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*.

A3.6. Alternative Test Methods

Alternative test methods to determine slip are permitted, provided the accuracy of load measurement and clamping satisfies 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 as long as the contact surface area per bolt of the test specimen is the same as that shown in Figure A-1. The clamping force of at least 49 kips may be applied by any means, provided the force can be accurately established within ±0.5 kip.

Commentary:

Alternative test procedures and specimens may be used as long as the accuracy of load measurement and specimen geometry are maintained as prescribed. For example, strain-gauged bolts can usually provide the desired accuracy. However, bolts that are *pretensioned* by the *turn-of-nut method*, alternative-design *bolting assembly*, or *direct tension indicator method* usually show too much variation to meet the ±0.5 kip accuracy of the slip test.

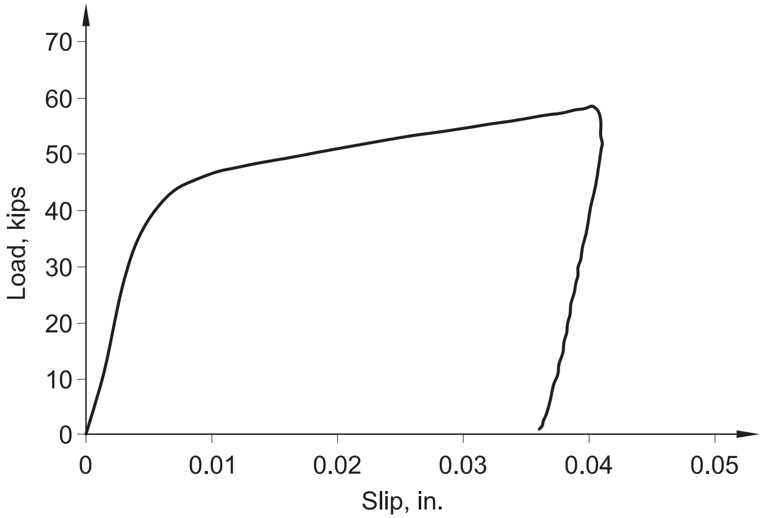


Fig. C-A.2. Example load versus slip curve bearing on loading rod.

SECTION A4. TENSION CREEP TEST

The test method outlined is intended to ensure that the coating will not undergo significant creep deformation under sustained service loading. The test also indicates the loss in clamping force in the bolt due to the compression or creep of the coating. Three replicate specimens are to be tested. Adherence to this testing method provides that the creep deformation of the coating due to both the clamping force of the bolt and the service-load *joint* shear are such that the coating will provide satisfactory performance under sustained loading.

Commentary

Tests of bolted specimens revealed that the clamping force may not be constant but decreases with time due to the compressive creep of the coating on the *faying surfaces* and under the nut and bolt head. Thicker coatings tend to creep more than thinner coatings.

The reduction in clamping force can be considerable for *joints* with high clamping force and thick coatings (as much as a 20 percent loss). This reduction in clamping force causes a corresponding reduction in the slip load. The resulting reduction in slip load must be considered in the overall test procedure. The loss in clamping force is a characteristic of the coating. Consequently, it cannot be accounted for by an increase in the factor of safety or a reduction in the clamping force used for design without unduly penalizing coatings that do not exhibit this behavior.

A4.1. Test Setup

Tension-type specimens, as shown in Figure A-2, shall be used. The replicate specimens shall be linked together in a single chain-like arrangement, using loose pin bolts, so the same load is applied to all specimens. The specimens shall be assembled so the specimen plates are bearing against the bolt in a direction opposite to the applied tension loading. Care shall 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 A4.2, shall be maintained constant within ±1 percent by springs, load maintainers, servo controllers, dead weight, or other suitable equipment. The bolts used to clamp the specimens together shall be ⅞-in.-diameter ASTM F3125 Grade A490 bolts. All bolts shall come from the same *lot*.

The clamping force in the bolts shall be a minimum of 49 kips. The clamping force shall be determined by calibrating the bolt force with bolt elongation, if standard bolts are used. Alternatively, special *bolting assemblies* that control the clamping force by other means, such as calibrated bolt torque, strain gauges, or direct tension indicating washers are permitted. A minimum of three bolt calibrations shall be performed using the technique selected for bolt force determination. The average of the three-bolt calibration shall be calculated and reported. The method of measuring bolt force shall ensure the clamping force is within ±2 kips of the average value.

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

A4.2. Test Procedure

The load placed on the creep specimen is as follows:

$$R_s = \frac{2\mu_t T_t}{1.5} \tag{A4.1}$$

where

μ_t = *mean slip coefficient* for the particular slip coefficient category under consideration

T_t = average clamping force from the three-bolt calibrations ≥ 49 kips

The load shall be placed on the specimen and held for 1,000 hours. The creep deformation of a specimen is calculated using the average reading of the two displacements on either side of the specimen. The difference between the average after 1,000 hours and the initial average reading taken within one-half hour after loading the specimens is defined as the creep deformation of the specimen. This value shall be reported for each specimen. If the creep deformation of any specimen exceeds 0.005 in., the coating has failed the test for the slip coefficient used. The coating may be retested using new specimens in accordance with this section at a load corresponding to a lower value of slip coefficient.

Commentary:

The mean slip coefficient, μ_t, used to determine the creep test load shall be the slip coefficient corresponding to the design classification or, in the case of coating specific slip coefficient, the average of the short-term slip tests.

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; rather, it decreases with time. After about 1,000 hours of loading, the additional creep deformation is negligible.

REFERENCES

Allan, R.N. (1967), "The Effect of Oversize and Slotted Holes on the Behavior of a Bolted Joint," Thesis and Dissertation, Lehigh University, Bethlehem, Pa.

Allan, R.N. and Fisher, J.W. (1968), "Bolted Joints with Oversize or Slotted Holes," *Journal of the Structural Division*, Vol. 94, No. ST9, September, ASCE, Reston, Va.

AASHTO (2020), *AASHTO LRFD Bridge Design Specifications* (9th Ed.), American Association of State Highway and Transportation Officials, Washington, D.C.

AISC (2010), *Specification for Structural Steel Buildings*, ANSI/AISC 360-10, American Institute of Steel Construction, Chicago, Ill.

AISC (2022), *Specification for Structural Steel Buildings*, ANSI/AISC 360-22, American Institute of Steel Construction, Chicago, Ill.

Birkemoe, P.C. and Herrschaft, D.C. (1970), "Bolted Galvanized Bridges—Engineering Acceptance Near," *Civil Engineering*, April, ASCE, Reston, Va.

Borello, D., Denavit, M., and Hajjar, J. (2009), "Behavior of Bolted Steel Slip Critical Connections with Fillers," Report No. NSEL-017, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Champaign, Ill.

Bowman, M. and Betancourt, M. (1991), "Reuse of A325 and A490 High-Strength Bolts," *Engineering Journal,* Vol. 28, No. 3, AISC, Chicago, Ill.

Brahimi, S. (2006), "Qualification of Dacromet for Use with ASTM A490 High-Strength Structural Bolts—An Investigation per IFI-144," ASTM Committee F16 on Fasteners, IBECA Technologies Research Report.

Brahimi, S. (2011), "Qualification of ASTM F2833 Coatings for Use on ASTM A490 High Strength Structural Bolts," ASTM Committee F16 on Fasteners, IBECA Technologies Research Report.

Brahimi, S. (2014), "Qualification of ASTM F1136 Non-Chrome (GEOMET 321) for Use with ASTM A490 High-Strength Structural Bolts—An Investigation per IFI-144," ASTM Committee F16 on Fasteners, IBECA Technologies Research Report.

Brahimi, S. (2017), "Qualification of F3019/F3019M Coatings DELTA PROTEKT®KL 105 for Use on ASTM A490 High Strength Structural Bolts," ASTM Committee F16 on Fasteners, IBECA Technologies Research Report.

Carter, C.J. (1996), "Specifying Bolt Length for High-Strength Bolts," *Engineering Journal*, Vol. 33, No. 2, AISC, Chicago, Ill.

Carter, C.J., Tide, R.H.R., and Yura, J.A. (1997), "A Summary of Changes and Derivation of LRFD Bolt Design Provisions," *Engineering Journal*, Vol. 34, No. 3, AISC, Chicago, Ill.

Chesson, Jr., E., Faustino, N.L., and Munse, W.H. (1964), "Static Strength of High-Strength Bolt under Combined Tension and Shear," SRS No. 288, University of Illinois at Urbana-Champaign, Urbana, Ill.

Chesson, Jr., E., Faustino, N.L., and Munse, W.H. (1965), "High-Strength Bolts Subjected to Tension and Shear," *Journal of the Structural Division*, Vol. 91, No. ST5, October, ASCE, Reston, Va.

Donahue, S., Helwig, T., and Yura, J. (2014), "Final Report for Study: Slip Coefficients for Galvanized Surfaces," University of Texas at Austin, Austin, Tex.

Fisher, J.W. and Beedle, L.S. (1964), "High Strength Bolting in the USA," IABSE Congress Report.

Frank, K.H. and Yura, J.A. (1981), "An Experimental Study of Bolted Shear Connections," FHWA/RD-81/148, December, Federal Highway Administration, Washington, D.C.

Grondin, G., Jin, M., and Josi, G. (2007), "Slip-Critical Bolted Connections—A Reliability Analysis for the Design at Ultimate Limit State," Preliminary Report prepared for the American Institute of Steel Construction, University of Alberta, Edmonton, Alberta, Canada.

Grubbs, F.E. (1950), "Sample Criteria for Testing Outlying Observations," *The Annals of Mathematical Statistics*, Vol. 21, No. 1, pp. 27–28, doi: 10.1214/aoms/1177729885.

Hamel S. and White S. (2016), "Thermo-Mechanical Modeling and Testing of Thermal Breaks in Structural Steel Point Transmittances," Research Report for the American Institute of Steel Construction, University of Alaska Anchorage, Alaska.

Hoyer, W. (1960) *Uber Gleitfeste Schraubenverbindungen (3 Bericht) Hochfeste Schrauben mit Verschiedenem Lochspiel [On Slideproof Bolted Connections (3rd Report) High-Strength Bolts with Different Hole Clearance]*, Wissenschaftliches Zeitschrift der Hochschule fuer Bauwesen, Cottbus, 1959/1960, Vol. 1, Cottbus, Germany.

ISO: International Organization for Standardization, ISO 4586-2:2018, High-Pressure Decorative Laminates (HPL, HPDL)—Sheets Based on Thermosetting Resins (usually called laminates)—Part 2: Determination of Properties.

Kulak, G.L. and Birkemoe, P.C. (1993), "Field Studies of Bolt Pretension," *Journal of Constructional Steel Research*, No. 25, pp. 95–106.

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

Kulak, G.L. and Undershute, S.T. (1998), "Tension Control Bolts: Strength and Installation," *Journal of Bridge Engineering*, Vol. 3, No. 1, February, ASCE, Reston, Va.

McKinney, M. and Zwerneman, F.J. (1993), "The Effect of Burrs on the Slip Capacity in Multiple Bolt Connections," Final Report to the Research Council on Structural Connections, August.

Moore, A.M., Rassati, G.A., and Swanson, J.A. (2008), "Evaluation of the Current Resistance Factors for High-Strength Bolts," Research Report to the Research Council on Structural Connections, Chicago, Ill.

Munse, W.H. (1967), "Structural Behavior of Hot Galvanized Bolted Connections," *Proceedings of the 8th International Conference on Hot-Dip Galvanizing*, June, London, United Kingdom.

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.

Peterman, K.D., Kordas, J., Moradei, J., Coleman, K., Hajjar, J.F., D’Aloisio, J.A., Webster, M.D., and Der Ananian, J. (2017), “Thermal Break Strategies for Cladding Systems in Building Structures,” Research Report to the Charles Pankow Foundation, Vancouver, Wash.

Peterman, K.D., Webster, M.D., D’Aloisio, J.A., and Hajjar, J.F., (2020), “Structural Performance of Steel Shelf Angles with Thermally-Improved Detailing,” *Journal of Structural Engineering*, ASCE, Reston, Va.

Polyzois, D. and Frank, K.H. (1986), “Effect of Overspray and Incomplete Masking of Faying Surfaces on the Slip Resistance of Bolted Connections,” *Engineering Journal*, Vol. 23, No. 2, AISC, Chicago, Ill.

Polyzois, D. and Yura, J.A. (1985), “Effect of Burrs on Bolted Friction Connections,” *Engineering Journal*, Vol. 22, No. 3, AISC, Chicago, Ill.

Rassati, G.A. and Swanson, J.A. (2025), “Testing of ASTM F3394-23 Backup & Reaction Washers Used on Pretensioned Structural Bolting Assemblies,” University of Cincinnati, Cincinnati, Ohio.

Roenker, A., Rassati, G.A., and Swanson, J.A. (2017) “Testing of Torque-and-Angle High-Strength Fasteners,” University of Cincinnati, Cincinnati, Ohio.

Schnupp, K.O. and Murray, T.M. (2003), “Effects of Head Size on the Performance of Twist-Off Bolts,” CC/VTI-ST 03/09, Virginia Polytechnic Institute and State University, July, Blacksburg, Va.

Sherman, D.R. and Yura, J.A. (1998), “Bolted Double-Angle Compression Members,” *Journal of Constructional Steel Research*, Vol. 47, pp. 1–3, Paper No. 197, Elsevier Science Ltd., Kidlington, Oxford, United Kingdom.

Swanson, J.A., Rassati, G.A., and Larson, C.M. (2020a), “Dimensional Tolerance and Length Determination of High-Strength Bolts,” *Engineering Journal*, Vol. 57, No. 1, AISC, Chicago, Ill.

Swanson, J.A., Rassati, G.A., and Larson, C.M. (2020b), “Reliability Study of Joints with Bolts Designed as X but Installed as N,” *Engineering Journal*, Vol. 57, No. 1, AISC, Chicago, Ill.

Tan, W., Maleev, V.V., and Birkemoe, P.C. (2005), “Installation Characteristics of ASTM F1852 Twist-Off Type Tension Control Structural Bolt/Nut/Washer Assemblies,” Final Report Phase 1, June 2005, University of Toronto, Canada.

Taylor, A.T., Rassati, G.A., and Swanson, J.A. (2008), “Evaluation of the Resistance Factors for Fully Threaded High Strength Fasteners,” Research Report to the Metal Building Manufacturers Association, Cleveland, Ohio.

Tide, R.H.R. (2010), “Bolt Shear Design Considerations,” *Engineering Journal*, Vol. 47, No. 1, AISC, Chicago, Ill.

Yura, J.A. and Frank, K.H. (1985), "Testing Method to Determine Slip Coefficient for Coatings Used in Bolted Joints," *Engineering Journal*, Vol. 22, No. 3, AISC, Chicago, Ill.

Yura, J.A., Frank, K.H., and Cayes, L. (1981), "Bolted Friction Connections with Weathering Steel," *Journal of the Structural Division*, Vol. 107, No. ST11, November, ASCE, Reston, Va.

INDEX

boltcouncil
RESEARCH COUNCIL ON STRUCTURAL CONNECTIONS
rcsc
boltcouncil.org