High-Strength Bolts for Steel Bridges

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ABSTRACT

The manufacture and use of substandard, mismatched or bogus bolts have been, and continue to be, a major concern to bridge owners in the U.S. Based on FHWA-sponsored research at the University of Texas, supplemental specifications were developed and issued modifying fastener manufacturing, testing and installation procedures.

Nearly all bridge bolts are designed for dynamic loading. They are designed to resist either tension forces and/or shear forces. Fatigue concerns govern bolts designed for cyclic tension forces. Cyclic shear forces require slip critical connections. Both loading conditions require bolts to be installed to a minimum preload.

The FHWA recommendations were developed in order to assure the ability of bolts to achieve this preload. Minimum nut strength is increased, maximum bolt strength is reduced, thread fit tolerance is reduced, additional rotational-capacity testing is required, and additional testing, documentation, handling and shipping requirements are imposed. The rationale for these new FHWA provisions are discussed.

Finally, slip critical joints depend upon friction between faying surfaces to develop strength. Values of slip resistance or coefficient of friction for various paints and coatings must be determined by testing. Bolt design parameters depend upon minimum values of tested coatings.

Improperly manufactured and installed and poorly inspected high strength fasteners can precipitate structural failures. The behavior of bolted joints depends on a large number of variables many of which are rather difficult to predict. Depending on the usage, and concerns for protection from the environment, different materials and acceptance requirements have been specified by the users depending on their current knowledge. In spite of over 30 years of experience with high strength fasteners, there continue to be problems in ensuring that fasteners are of adequate quality and are installed properly. There are concerns that bolted connections in many bridges built over the past 10 years or so might not meet acceptance criteria if they were subjected to test requirements of today. The October 1989 issue of the Civil Engineering Journal reported (p.61-62) that the Industrial Fastener Institute (IFI) claims that billions of substandard, mismatched or counterfeit products may have entered the country's supply line, threatening the reliability of industrial and consumer products. Besides not meeting the stricter U.S. Engineering Standards, the lower priced foreign manufactured fasteners flooding the market are helping to drive U.S. bolt and nut manufacturers out of business according to IFI.

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Numerous problems have been identified. These include the fact that mismatched fasteners made abroad have been sold in the U.S. market and may have the potential to cause failure and possible serious consequences to the travelling public particularly if these bolts are used in joints subject to tensile or reversible forces. These concerns can be eliminated when fasteners are manufactured to code requirements and subsequent quality control testing is done by the fastener manufacturers, acceptable installation procedures are practiced by the installers, followed by a reliable quality assurance (QA) and traceability program by the owner.

FASTENER REQUIREMENTS AND RATIONALE

Researchers, owners, code writing organizations and the fastener industry have been attempting to constantly improve the quality of fasteners and fastener installation practices to produce a better end product. To ensure that only those fasteners which meet the minimum quality standards are used, the Federal Highway Administration (FHWA) initiated an extensive experimental research program with the Department of Civil Engineering of the University of Texas at Austin to evaluate the performance of both black and galvanized high strength bolts for steel bridge structures. The study was done using ASTM A325 hot dipped or mechanically galvanized bolts and A325/A490 black bolts. Only normal size fasteners commonly used in steel bridge superstructures were tested. Research findings were reported in the FHWA publication FHWA/RD-87/088 "High Strength Bolts for Bridges." Recognizing the need to underscore the various recommendations made in the report and to implement them, the recommendations were compiled, modified in consultation with the researcher and the fastener industry, and later distributed to the field offices via an FHWA memorandum. The objective of the FHWA memorandum was to allow the AASHTO (American Association of State Highway and Transportation Officials) bridge owners to incorporate these high strength bolt specifications in the state standard specifications or contract documents without duplicating the effort of sorting out the recommendations from the report. A copy of the FHWA supplemental specifications contained in the memorandum is included in the appendix. The rationale behind the pertinent specifications is discussed in this paper. The supplemental specifications were written for AASHTO M164 (ASTM A325) bolts but it is recognized that similar specifications are needed for A490 bolts and other alternate fasteners. The supplemental specifications for A325 bolts were written first because those bolts are used most commonly for bolted connections of bridge members.

The following background information should be helpful in understanding the rationale for the various requirements in the memorandum.

Essentially clamping force is needed to prevent fatigue failure of bolts subjected to cyclic tension and to prevent slip and increase fatigue strength in shear connections. Fatigue failure of threaded fasteners is well known. It can be traced to points of stress concentrations such as those locations where there are abrupt geometric changes, a notch or a nick, or locations where the material may have poor fracture toughness. The torque applied to the fastener assembly is not uniformly distributed over the engaged length because fastener materials are not inelastic and there are manufacturing tolerances resulting in less than perfect matching of bolt and nut threads over the engaged length. However, failure in threaded fasteners is often located at the washer face of the nut, at the thread runout or at the junction of the bolt head and shank. This is primarily because of probable high stress concentrations at these locations, although the average stress levels in the body of the bolt may remain well below the endurance limit of the material. Furthermore, cyclic external forces applied to the bolt can reduce the life of the fasteners by fatigue.

As the torque is applied to the nut, a portion of it is resisted by friction between the nut and the gripped material; the remainder is resisted by friction at the thread interface resulting in torsional stresses in the bolt shank. The bolt is thus subjected to a combined torque-tension stress condition. Load deformation characteristics of bolts subject to direct tension compared to torque-tension reveal that specimens subject to torque-tension are less ductile(2) and have strength levels reduced between 5 and 25 percent.

Clamping force is an important consideration if a bolted joint must function as a slip resistant joint. In such a joint the external load component parallel to the faying surface(s) is resisted by the frictional resistance which is dependent on the clamping force of the bolt and the coefficient of friction at the faying surface. In a bearing type connection, slip is allowed and movement stops as the material bears against the bolt. In such joints the critical factors are the permissible bearing stress on the connection material, the axial stress on the net section and the shear stress of the fasteners - not the initial preload of the bolt. Comparative studies of bolts subject to shear stresses under tension or compression show that shear stress deformation characteristic of A325 bolts and A490 bolts are similar; however, A490 bolts have a lesser ability to deform than A325 bolts under similar conditions, and the maximum shear stress experienced by A490 bolts (of higher strength material) is greater than that in A325 bolts. The research also suggests that when the same type of bolt (A325 or A490) is subjected to shear test in tension or compression jigs, samples in tension jigs show lower shear strength, (a tension jig is preferred for testing shear strength of bolts because it produces the lower range of the shear value.) Available data also demonstrate that the shear strength of A325 or A490 bolts is approximately 62 percent of the tensile strength. It is significant to note that unlike bolts subject to tensile loads, the clamping force has no significant effect on the ultimate shear strength of the bolt. Thus, for slip critical joints subjected to dynamic loads, it is apparent that not only should initial preloads as high as practicable be applied to fasteners, but it is also critical that the desired preload is indeed in the bolt after it is installed.

Until 1985, the practice in North America had been to provide as high a preload as practical regardless of whether or not the joint was slip critical and whether or not tensile forces were applied. Though the apparent objective was to achieve uniformity and simplicity in bolt installation, there were inherent economic disadvantages in attempting to accurately preload bolts where preloading was not even necessary. However, since 1985 the requirement has been that high strength fasteners in slip critical joints and connections subject to direct tension or reversible loads need to be preloaded to a predetermined level. Snug tightening in many situations is adequate for bearing type fasteners though generally not used for bridges.

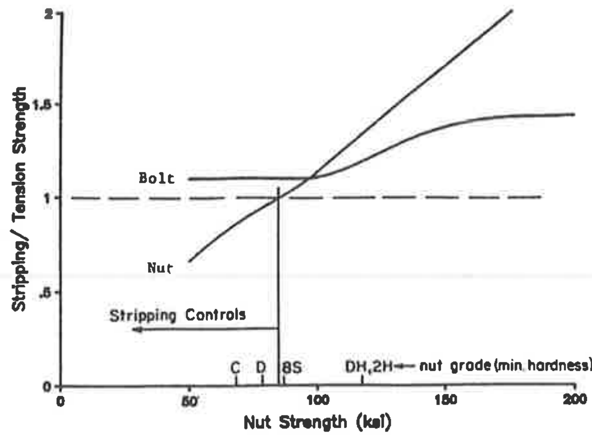
Obviously, an adequate preload is essential within certain tolerances for dynamically loaded structures such as steel bridges. Proper preloading of fasteners in such structures an important critical task faced by bridge engineers and inspectors. There are, however, numerous related problems and issues and hence the need to specify adequate control. Material specifications, e.g., ASTM Specifications, AASHTO Materials Specifications and other specifications provide necessary controls during the manufacturing process. Installation of fasteners for bridges is addressed by AASHTO, in Division II of the "AASHTO Standard Specifications for Highway Bridges;" in addition, AASHTO bridge owners may have their own special requirements and preferred practices.

The FHWA memorandum cited earlier supplements AASHTO Specifications based on the research findings reported in the reference No. 1 "High Strength Bolts for Bridges." It should be understood that except for the proposed supplemental specifications, other ASTM Specifications and AASHTO Material Specifications remain valid. The memorandum amends or revises AASHTO Material Specifications, but does not replace them. These modifications also ensure the strength of the bolts, nuts and washers during manufacturing and cover issues pertaining to testing of fasteners and fastener assemblies, needed documentation, shipping and installation at the job site. As an example, the FHWA supplemental specifications take some exceptions to AASHTO Material Specifications for tensile strength and hardness requirements and modify related specifications.

Some of these are:

1. A325 bolts are available as type 1, 2 and 3 fasteners. These require a minimum strength of 105 ksi for 1 1/8 inch to 1 1/2 inch diameter bolts and 120 ksi minimum strength for 1/2 inch to 1 inch diameter bolts. Though A325 bolt specifications provide a range of hardness, the upper bound of tensile strength is not included in the ASTM or AASHTO Material Specifications. The hardness can generally be converted to an equivalent tensile strength using conversion tables such as those in ASTM Specifications (A370) or other references. Current AASHTO Material Specifications and ASTM Specifications require matching nuts for A325 bolts. These include heat treated nuts as well as non-heat treated nuts with hardness values as low as 78 HRB (Hardness, Rockwell B). Similarly, A490 bolts are available as type 1, 2 and 3. These bolts have required material strength ranges from 150 ksi to 170 ksi with matching nuts of hardness greater than 24 Rc (Rockwell C) which is much greater than 89 HRB. For A490 bolts non-heat treated nuts are not permitted by either ASTM Specifications or AASHTO Material Specifications. An examination of these two specifications reveals an inconsistency in fastener specifications. As noted above, current specifications allow manufacturing A490 bolts with a minimum tensile strength 150 ksi and hardness value of approximately 33 Rc, but these A490 bolts are not permitted to be galvanized. However, using current ASTM Specifications or AASHTO Material Specifications, A325 bolts can be manufactured with hardness as high as 35 Rc which is equivalent to 156 ksi tensile strength, well into the A490 strength range. The current AASHTO Material Specifications and ASTM Specifications do allow galvanizing A325 (M164) bolts. Thus comparing the two situations it does not seem logical to allow galvanizing A325 bolts of 35 Rc hardness when galvanizing A490 bolts of 33 Rc hardness is prohibited. The FHWA supplemental specifications include modified requirements to correct this inconsistency.

2. Thread stripping is controlled by (a) bolt and nut strength and (b) fit of threads at the interface. Prevention of stripping requires proper fit of bolt-nut assemblies and often requires that heat treated nuts be specified. Non-heat treated nuts with lower hardness values have potential for nut stripping. In previous years, AASHTO had been allowing the use of non-heat treated nuts which could have a minimum hardness as low as 78 HRB. The FHWA supplemental specifications require that the minimum hardness of the nut should be 89 HRB to prevent possible stripping of nuts. The need for this minimum hardness can be explained by Alexander's model[1] which was developed based on experimental data. It is illustrated in Figure 1 below:



Effect of nut strength on bolt and nut stripping.

Figure No. 1
(Reproduced from Reference No. 1)

Curves have been plotted for 7/8" diameter bolts of tensile strength 156 ksi (equivalent to 35 Rc hardness). In Figure 1, the ratio of the stripping strength of nut (or stripping strength of bolt) to the tensile strength of the bolt has been plotted against the nut strength. The dotted horizontal line represents those assemblies which have stripping strength equal to the tensile strength of the bolt. Points on the curve which are below this horizontal dotted line are subject to possible failure by thread stripping only. Those above the dotted line will fail by tension in the bolt rather than stripping of threads. From Figure No. 1, it is evident that for those assemblies which have nut strength greater than 87 ksi, neither the bolts nor the nuts will strip since the corresponding points lie above the horizontal dotted line. Since 87 ksi tensile strength is approximately equivalent to 89 HRB hardness, the FHWA supplemental specification requires hardness of nuts not less than 89 HRB. On the abscissa, in Figure No. 1, nut strength and various nut designations have been shown. These nut representations indicate lowest permissible strength (or hardness) as permitted by the current ASTM/AASHTO Material Specifications. From this figure, it is possible to infer that heat treated nuts, 2H, DH, and DH3, have minimum hardness well above 89 HRB, the suggested minimum hardness to prevent nut stripping. However, non-heat treated nuts, if manufactured with minimum hardness as permitted by ASTM and AASHTO Material Specifications, will be prone to nut stripping. The suggested minimum hardness 89 HRB is within the upper and the lower limits of hardness permitted in those specifications. Nut stripping in non-heat treated nuts can be prevented if such nuts are manufactured to a hardness not less than 89 HRB.

A limited study[1] of comparable fasteners produced in accordance with ASTM specifications using traditional U.S. units of measurement with fasteners produced in accordance with ASTM specifications using metric units of measurement seems to suggest that metric fasteners with loose fit and minimum hardness of 89 HRB are less prone to stripping, whereas other fasteners with tighter thread fit tolerances and minimum hardness of 78 HRB are prone to stripping. The study revealed that fasteners made using the metric standard with slightly greater nut strength (approximately 2 percent), as evidenced by hardness numbers, are more forgiving, even with a loose fit. It is important to recognize that failures resulting from thread stripping must be avoided because such failures could go undetected during the service life of the bridge, resulting in possible failure of bridge members and related consequences to the travelling public. However, it may be noted that even though the minimum hardness requirement of 89 HRB for non-heat treated nuts 2, C, C3 and D is specified in the FHWA supplemental specifications, stripping failure can still occur if there are only a few threads in the grip. For that reason it is desirable to ensure that a minimum 3 to 5 complete threads are in the grip. Bolts with more threads in the grip have greater ductility and lower apparent tensile strength.

3. Some of the test requirements for bolts, nuts, washers and fastener assemblies have also been modified by the FHWA supplemental specifications. Proof load testing of bolts and nuts is required. Proof load is the tension applied load which the fasteners must resist without evidence of any permanent deformation. This test provides a check on the yielding behavior of the material since the elongation is measured during testing. If galvanized fasteners are used, proof load testing is required after galvanizing. Wedge testing of bolts and hardness testing of washers is also required, but in the case of galvanized fasteners these tests are required after galvanizing. For galvanized fasteners, zinc thickness measurements are also needed. Zinc thickness measurements on bolts and nuts are important for proper fit and to control overtapping. Performance capability of these fasteners together in an assembly is checked via rotational-capacity testing for either black or galvanized units. Rotational-capacity testing is required prior to shipping as well as at the job site. Job site testing is important but only a minimal amount is needed. Rotational-capacity testing prior to shipping can be done either by the manufacturer or the distributor, as appropriate.

The purpose of the rotational-capacity testing is to verify the torque tension relationship in order to ensure (a) efficiency of lubrication, (b) adequate installation ductility and (c) adequate resistance to stripping. Essentially the rotational-capacity test requires measurement of the bolt tension at the specified minimum rotation (twice the amount of the required installation rotation) from a snug tight condition; and also torque tension values in a Skidmore-Wilhelm Calibrator, at any point above installation rotation, to satisfy the following requirement:

$$\text{Torque (Foot-Pounds)} \leq 0.25 \times P \text{ (Bolt Tension-Pounds)} \times D \text{ (Bolt Dia. Feet)}$$

The FHWA supplemental specification does not allow rotational-capacity testing of long bolts in a steel joint as currently permitted by both ASTM Specifications and AASHTO Material Specifications. Testing in a steel joint does not allow direct measurements of bolt tension during rotational-capacity testing. A Skidmore-Wilhelm Calibrator or similar device is required by the FHWA supplemental specification because such a device allows direct measurement of bolt tension as the rotational-capacity test is performed. The torque-tension relationship curves for these two situations have different slopes at the lower levels of bolt tensioning, but then the curves level out, merge and form a horizontal plateau prior to sloping downwards as the bolt tension is increased. Because the values of tension and torque from this somewhat horizontal portion of the curve are used for acceptance or rejection of the rotational-capacity test, and for determination of the maximum tension in the bolt, the values obtained using a steel joint or a Skidmore-Wilhelm Calibrator will be the same for all practical purposes.

In the case of short bolts which cannot be installed in a Skidmore-Wilhelm Calibrator, the FHWA supplemental specification does not require measurement of the actual maximum tension for the turn test. Anticipated turn test tension as tabulated in the FHWA supplemental specifications, is used to calculate torque using the equation noted above. This calculated torque can then be compared with the measured torque.

4. In addition to job site rotational-capacity tests, calibration tests are also required. This is because for a given tension there can be large variation in bolt torque as measured in the laboratory prior to shipping to the job site and that obtained in the field. Hence, it is required that calibration tests be performed after fasteners are received at the job site using a Skidmore-Wilhelm

Calibrator or an acceptable equivalent tension measuring device to ensure compliance with the minimum installation pretension.

SLIP RESISTANCE OF FAYING SURFACES

As previously noted, the intent of the FHWA supplemental specification is to ensure that the washer/nut/bolt combination functions as a matched unit. It is appropriate to consider the influence of surface preparations and coatings on the faying surfaces in achieving slip critical joints using high-strength fastener assemblies.

The design of a bolted connection may be governed by bearing on the connected material, shear in the shank or thread plane of the fastener or the slip resistance of the contact surfaces of the connection. In nearly all bridge design, because of dynamic loading, slip resistance of the joint is the critical criterion. Bolts are seldom used in tension in bridge structures.

Slip resistance of the contact of faying surfaces is a function of the surface condition. The design specification recognizes three classes of surface conditions:

- Class A - Clean mill scale surfaces and surfaces coated with a Class A coating.
- Class B - Blasted surfaces and surfaces coated with a Class B coating.
- Class C - Galvanized and roughened surfaces.

The most economical joint design generally occurs using Class B surfaces. These are either uncoated blasted surfaces or surfaces coated with a Class B coating. Where the structure is to be unpainted, it makes sense to specify uncoated blasted surfaces. Where the structure is to be painted, the structure should be designed with painted faying surfaces using Class B coatings.

Coatings are classified as Class A or B based on slip coefficient testing performed in accordance with Appendix A of the Specification for Structural Joints Using ASTM A325 or A490 Bolts. The essential variables for the test are paint formulation, cure time, dry film thickness and thinner used. Actual coating application procedures that deviate from the essential variables beyond certain limits require retesting. Because there are many combinations of essential variables, choosing the proper values when performing the test is very important.

Part of the test lasts 42-days; to retest is costly and can delay a project.

As of the summer 1990, very little testing of candidate class B coatings has been performed. Since bridges are currently being designed using the Class B coatings, it is important that testing proceed at a faster rate. Steps are currently underway to increase the number of paints that have been tested. Hopefully, by the spring of 1991, the situation relative to the testing will improve and designers will be using the higher slip values with the full knowledge that there are an adequate number of paints available to meet the need.

REFERENCES

1. J. A. Yura, K. H. Frank, D. Polyzois. High Strength Bolts for Bridges. Publication No. FHWA/RD-87/088. U.S. Department of Transportation. Federal Highway Administration.

2. G. L. Kulak, J. W. Fisher, and J. H. A. Struik. Guide to Design Criteria for Bolted and Riveted Joints. A Wiley-Interscience Publications. John Wiley and Sons, New York.

3. J. H. Bickford. An Introduction to the Design and Behavior of Bolted Joints Marcel Deckker Inc. New York.

4. J. A. MacDonald. For Want of Bolt. Civil Engineering, October 1988.

5. FHWA Memorandum. High Strength Bolts, November 1989.

APPENDIX

November 1989

SUPPLEMENTAL CONTRACT SPECIFICATIONS FOR PROJECTS WITH AASHTO M164 (ASTM A325) HIGH-STRENGTH BOLTS

A. Scope

A1. All AASHTO M164 (ASTM A325) high-strength bolts, nuts and washers shall be furnished in accordance with the appropriate AASHTO Materials Specifications as amended and revised herein.

Additional requirements for field or shop installation of AASHTO M164 (ASTM A325) high-strength bolts are also included. These additional requirements supplement AASHTO Division II, Section 10.

B. Specifications

B1. All bolts shall meet the requirements of AASHTO M164 (ASTM A325) and these revisions.

B2. All nuts shall meet the requirements of AASHTO M292 (ASTM A194) as applicable or AASHTO M291 (ASTM A563) and these revisions.

B3. All washers shall meet the requirements of AASHTO M293 (ASTM F436) and these revisions.

C. Manufacturing

C1. Bolts

1. Hardness for bolt diameters 1/2 inch to 1 inch inclusive shall be as noted below:

Hardness Number

Bolt Size, In.	Brinell		Rockwell C	
	Min.	Max.	Min.	Max.
1/2 to 1 inch	248	311	24	33

C2. Nuts

1. Nuts to be galvanized (hot dip or mechanically galvanized) shall be heat treated grade 2H, DH, or DH3.

2. Plain (ungalvanized) nuts shall be grades 2, C, D or C3 with a minimum Rockwell hardness of 89 HRB (or Brinell hardness 180 HB), or heat treated grades 2H, DH, or DH3. (The hardness requirements for grades 2, C, D and C3 exceed the current AASHTO/ASTM requirements.)

3. Nuts that are to be galvanized shall be tapped oversize the minimum amount required for proper assembly. The amount of overtap in the nut shall be such that the nut will assemble freely on the bolt in the coated condition and shall meet the mechanical requirements of AASHTO M291 (ASTM A563) and the rotational-capacity test herein (the overtapping requirements of AASHTO M291 [ASTM A563] paragraph 7.4 shall be considered maximum values instead of minimum, as currently shown).

4. Galvanized nuts shall be lubricated with a lubricant containing a dye of any color that contrasts with the color of the galvanizing.

C3. Marking - All bolts, nuts and washers shall be marked in accordance with the appropriate AASHTO/ASTM Specifications.

D. Testing

D1. Bolts

1. Proof load tests (ASTM F606 Method 1) are required. Minimum frequency of tests shall be as specified in AASHTO M164 (ASTM A325) paragraph 9.2.4.

2. Wedge tests on full size bolts (ASTM F606 paragraph 3.5) are required. If bolts are to be galvanized, tests shall be performed after galvanizing. Minimum frequency of tests shall be as specified in AASHTO M164 (ASTM A325) paragraph 9.2.4.

3. If galvanized bolts are supplied, the thickness of the zinc coating shall be measured. Measurements shall be taken on the wrench flats or top of bolt head.

D2. Nuts

1. Proof load tests (ASTM F606 paragraph 4.2) are required. Minimum frequency of tests shall be as specified in AASHTO M291 (ASTM A563) paragraph 9.3 or AASHTO M292 (ASTM A194) paragraph 7.1.2.1. If nuts are to be galvanized, tests shall be performed after galvanizing, overtapping and lubricating.

2. If galvanized nuts are supplied, the thickness of the zinc coating shall be measured. Measurements shall be taken on the wrench flats.

D3. Washers

1. If galvanized washers are supplied, hardness testing shall be performed after galvanizing. (Coating shall be removed prior to taking hardness measurements).

2. If galvanized washers are supplied, the thickness of the zinc coating shall be measured.

D4. Assemblies

1. Rotational-capacity tests are required and shall be performed on all black or galvanized (after galvanizing) bolt, nut and washer assemblies by the manufacturer or distributor prior to shipping. Washers are required as part of the test even though they may not be required as part of the installation procedure.

   The following shall apply:

   a. Except as modified herein, the rotational-capacity test shall be performed in accordance with the requirements of AASHTO M164 (ASTM A325).

   b. Each combination of bolt production lot, nut lot and washer lot shall be tested as an assembly. Where washers are not required by the installation procedures, they need not be included in the lot identification.

   c. A rotational-capacity lot number shall be assigned to each combination of lots tested.

   d. The minimum frequency of testing shall be two assemblies per rotational-capacity lot.

   e. The bolt, nut and washer assembly shall be assembled in a Skidmore-Wilhelm Calibrator or an acceptable equivalent device (note - this requirement supersedes the current AASHTO M164 (ASTM A325) requirement that the test be performed in a steel joint). For short bolts which are too short to be assembled in the Skid-more-Wilhelm Calibrator, See Section D4.1i.

   f. The minimum rotation, from a snug tight condition (10% of the specified proof load), shall be:

      240° (2/3 turn) for bolt lengths < 4 diameters

      360° (1 turn) for bolt lengths > 4 diameters and < 8 diameters

      480° (1 1/3 turn) for bolt lengths > 8 diameters

      (Note that these values differ from the AASHTO M164 Table 8/ASTM A325 Table 6 Specifications).

   g. The tension reached at the above rotation shall be equal to or greater than 1.15 times the required installation tension. The installation tension and the tension for the turn test are shown below:

Diameter (In.)	1/2	5/8	3/4	7/8	1	1 1/8	1 1/4	1 3/8	1 1/2
Req. Installation Tension (kips)	12	19	28	39	51	56	71	85	103
Turn Test Tension (kips)	14	22	32	45	59	64	82	98	118

   h. After the required installation tension listed above has been exceeded, one reading of tension and torque shall be taken and recorded. The torque value shall conform to the following:

      Torque≤0.25 PD

      Where

      Torque=measured torque (foot-pounds)

      P=measured bolt tension (pounds)

      D=bolt diameter (feet).

   i. Bolts that are too short to test in a Skidmore-Wilhelm Calibrator may be tested in a steel joint. The tension requirement of Section D4.1g need not apply. The maximum torque requirement of Section D4.1h shall be computed using a value of P equal to the turn test tension shown in the table in Section D4.1g.

D5. Reporting

1. The results of all tests (including zinc coating thickness) required herein and in the appropriate AASHTO specifications shall be recorded on the appropriate document.

2. Location where tests are performed and date of tests shall be reported on the appropriate document.

D6. Witnessing

1. The tests need not be witnessed by an inspection agency; however, the manufacturer or distributor that performs the tests shall certify that the results recorded are accurate.

E. Documentation

E1. Mill Test Report(s) (MTR)

1. MTR shall be furnished for all mill steel used in the manufacture of the bolts, nuts, or washers.

2. MTR shall indicate the place where the material was melted and manufactured.

E2. Manufacturer Certified Test Report(s) (MCTR)

1. The manufacturer of the bolts, nuts and washers shall furnish test reports (MCTR) for the item furnished.

2. Each MCTR shall show the relevant information required in accordance with Section D5.

3. The manufacturer performing the rotational-capacity test shall include on the MCTR:

   a. The lot number of each of the items tested.

   b. The rotational-capacity lot number as required in Section D4.1c.

   c. The results of the tests required in Section D4.

   d. The pertinent information required in Section D5.2.

   e. A statement that MCTR for the items are in conformance to this specification and the appropriate AASHTO specifications.

   f. The location where the bolt assembly components were manufactured.

E3. Distributor Certified Test Report(s) (DCTR)

1. The DCTR shall include MCTR above for the various bolt assembly components.

2. The rotational-capacity test may be performed by a distributor (in lieu of a manufacturer) and reported on the DCTR.

3. The DCTR shall show the results of the tests required in Section D4.

4. The DCTR shall also show the pertinent information required in Section D5.2.

5. The DCTR shall show the rotational-capacity lot number as required in Section D4.1c.

6. The DCTR shall certify that the MCTR are in conformance to this specification and the appropriate AASHTO specifications.

F. Shipping

F1. Bolts, nuts and washers (where required) from each rotational-capacity lot shall be shipped in the same container. If there is only one production lot number for each size of nut and washer, the nuts and washers may be shipped in separate containers. Each container shall be permanently marked with the rotational-capacity lot number such that identification will be possible at any stage prior to installation.

F2. The appropriate MTR, MCTR or DCTR shall be supplied to the contractor or owner as required by the Contract Documents.

G. Installation

The following requirements for installation apply in addition to the specifications in AASHTO Division II, Section 10 when high-strength bolts are installed in the field or shop.

G1. Bolts shall be installed in accordance with AASHTO Division II Article 10.17.4. During installation, regardless of the tightening method used, particular care should be exercised so that the snug tight condition as defined in Article 10.17.4 is achieved.

G2. The rotational-capacity test described in Section D4 above shall be performed on each rotational-capacity lot prior to the start of bolt installation. Hardened steel washers are required as part of the test although they may not be required in the actual installation procedures.

G3. A Skidmore-Wilhelm Calibrator or an acceptable equivalent tension measuring device shall be required at each job site during erection. Periodic testing (at least once each working day when the calibrated wrench method is used) shall be performed to assure compliance with the installation test procedures required in AASHTO Division II, Article 10.17.4.1 for Turn-of-Nut Tightening,Calibrated Wrench Tightening, Installation of Alternate Design Bolts and Direct Tension Indicator Tightening. Bolts that are too short for the Skidmore-Wilhelm Calibrator may be tested using direct tension indicators (DTIs). The DTIs must be calibrated in the Skidmore-Wilhelm Calibrator using longer bolts.

G4. Lubrication

1. Galvanized nuts shall be checked to verify that a visible lubricant is on the threads.

2. Black bolts shall be "oily" to the touch when delivered and installed.

3. Weathered or rusted bolts or nuts not satisfying the requirements of G2 or G3 above shall be cleaned and relubricated prior to installation. Recleaned or relubricated bolt, nut and washer assemblies shall be retested in accordance with G2 above prior to installation.

G5. Bolt, nut and washer (when required) combinations as installed shall be from the same rotational-capacity lot.