Dimensional Tolerances and Length Determination of High-Strength Bolts

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ABSTRACT

Structural engineers and detailers are often removed from the process of manufacturing bolts and, thus, the tolerances and variances that go along with common manufacturing processes. While this does not represent a problem in most cases, being familiar with the manufacturing processes and tolerances associated with high-strength bolts can help prevent some problems from occurring before the design process even begins, particularly when shorter bolt lengths are needed. This lack of familiarity, in some circumstances, might lead to mistaken assumptions regarding the location of the shear plane relative to the threads of the bolt, which may lead to incorrect designs. While an engineer might presume that bolt strength would not control in such short grips, this paper will discuss the cases in which this can become an issue. This paper summarizes the major variances between nominal and actual dimensions, evaluates some of the consequences that those variances can have on design, presents solutions to those issues, and culminates with a proposed design procedure for proper length determination of high-strength bolts with several illustrative examples.

Keywords: Structural bolt, high-strength bolt, fastener, A325, A490, F1852, F2280, F3125, F3148, threads excluded, ASME B18.2.6.

INTRODUCTION

Bolts, like any other manufactured product, are specified by nominal values but have acceptable variances or tolerances from those baseline values that are needed during manufacturing. Because the governing standards for high-strength bolts are maintained by ASTM International, which references several American Society of Mechanical Engineers (ASME) standards, the details of bolt manufacturing are often steps removed from the day-to-day attention of most structural engineers and connection detailers. The objective of this paper is to provide a summary of the dimensional tolerances that are associated with the manufacture of bolts, evaluate some of the consequences that those tolerances can have on structural steel design, and present solutions to those issues.

Carter, in a 1996 *Engineering Journal* paper, presented an analysis of tolerances associated with high-strength bolting with an emphasis on developing expedient methods of determining bolt length and when the threads of a bolt can be excluded from the shear plane of a bolted joint, thus increasing the design strength of the bolt. The paper focused on the length tolerance of the bolts and the thickness tolerances of the washers and nuts that are used to complete the bolting assembly, and culminated with a series of design tables for commonly used bolt sizes that are useful tools for structural engineers and detailers. Carter's paper identified that the tolerance on bolt length is more critical than the washer and nut thickness tolerances and that while additional tolerances on the shank length and thread transition region of bolts were considered, they were thought at the time to be small enough so as to be inconsequential.

BOLT, NUT, AND WASHER GEOMETRY AND MANUFACTURING TOLERANCES

High-strength structural bolts are required by ASTM F3125/3125M-15a (2015) and F3148-17a (2017) to conform to the ASME Standard B18.2.6-19 (2019). Two types of dimensions, shown in Figures 1 and 2, are used in the latter standard: control dimensions and reference dimensions. Control dimensions are those dimensions that are used during manufacture to ensure quality control and conformance with standards. Reference dimensions, on the other hand, are dimensions that are typically provided for information only or for the purpose of calculating control dimensions, and not for quality control or demonstration of conformance to standards.

Bolt Diameter

ASTM F3125 high-strength structural fasteners are generally available in diameters ranging from ½ in. to 1½ in. in ⅛-in.-diameter increments, with the exception of 1⅜-in.

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Table 1. Diameters and Tolerances for Standard Size High-Strength Bolts (ASME B18.2.6-19)				
Nominal Bolt Diameter, *E* or d_b (in.)	**Maximum Body Diameter (in.)**	**Minimum Body Diameter (in.)**	**Permitted Swell or Fin (in.)**	**Max Diameter plus Max Swell (in.)**
½	0.515	0.482	0.030	0.545
⅝	0.642	0.605	0.050	0.692
¾	0.768	0.729	0.050	0.818
⅞	0.895	0.852	0.060	0.955
1	1.022	0.976	0.060	1.082
1⅛	1.149	1.098	0.060	1.209
1¼	1.277	1.223	0.060	1.337
1⅜	1.404	1.345	0.090	1.494
1½	1.531	1.470	0.090	1.621

bolts, which are not widely produced. ASTM F3148 high-strength bolts are currently available in diameters ranging from ⅝ in. to 1⅛ in. in ⅛-in. increments. The diameter of a bolt, specified as *E* in Figures 1 and 2 and in ASME B18.2.6, but more commonly referred to as d_b in structural engineering contexts, is a control dimension and has an over/under tolerance ranging from approximately 0.015 in. for small bolts to approximately 0.030 in. for large bolts. Actual values of diameters permitted are shown in Table 1. In addition to the diameter tolerance, an allowance is included for a swell or fin under the head of the fastener that may occur during manufacturing.[1] As can be deduced from the table, a bolt produced at the maximum body diameter with the maximum permitted swell may have a final measured diameter

1 Swells and fins result primarily during hot forging of fastener heads. Hot forging is used in the manufacture of relatively few common bolt sizes, however—mostly for larger diameter or longer bolts. Bolts up to approximately 6 in. long are typically cold formed.

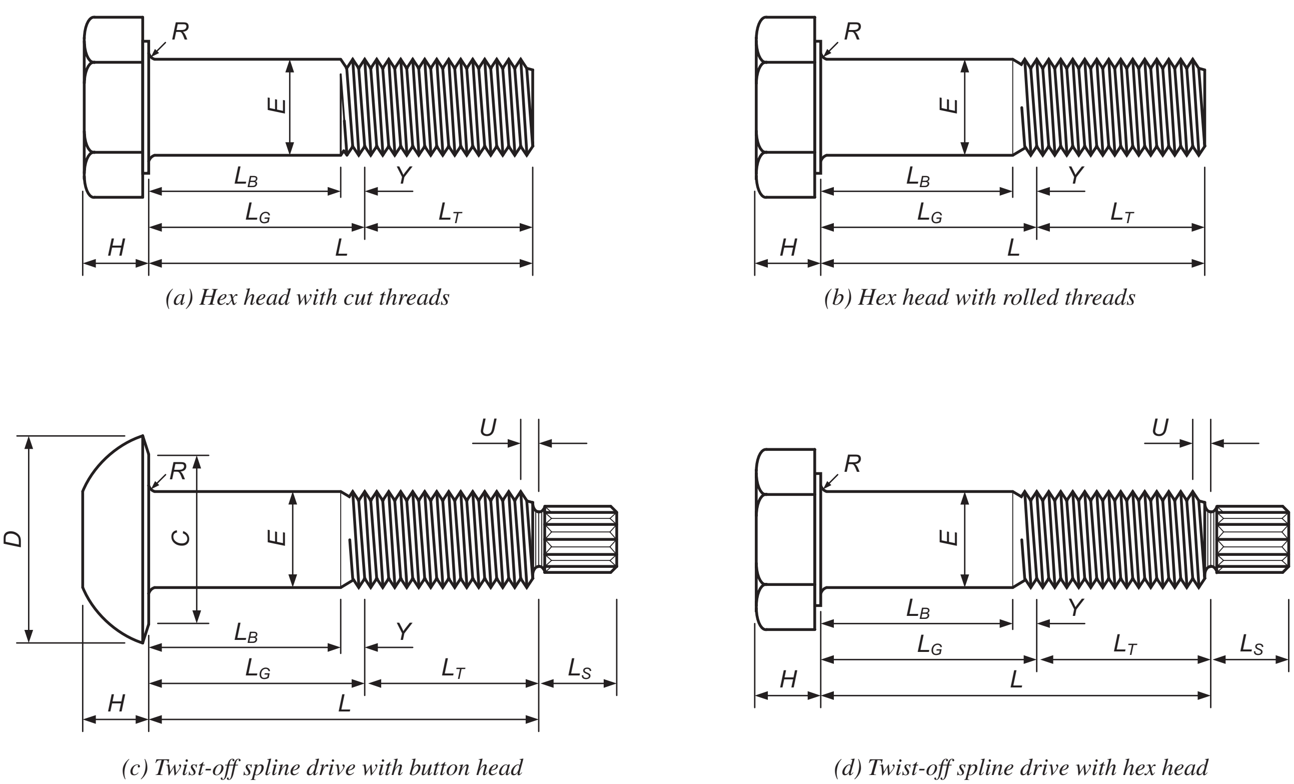

Fig. 1. Geometry of ASTM F3125 bolts (ASME B18.2.6-19).

Table 2. Tolerances on Bolt Length		
Nominal Bolt Diameter, *E* or d_b (in.)	**Nominal Bolt Length, $L \le 6$ (in.)**	**Nominal Bolt Length, $L > 6$ (in.)**
½	+0.00, −0.12	+0.00, −0.19
⅝	+0.00, −0.12	+0.00, −0.25
¾ to 1	+0.00, −0.19	+0.00, −0.25
1⅛ to 1½	+0.00, −0.25	+0.00, −0.25

that is more than 1⁄16 in. larger than its nominal diameter and, in the case of a 1½-in. bolt, is nearly ⅛ in. larger than the nominal diameter. As Shaw points out (2015), this, in part, led to the increase in the size of standard holes for 1-in.-diameter and larger bolts in the 2016 AISC *Specification* (AISC, 2016) and in the 8th edition of the AASHTO *LRFD Specification* (AASHTO, 2017) and has been approved for inclusion in the next edition of the RCSC *Specification*, expected to be published in 2020.

Bolt Length, Shank Length, and Thread Length

The length of the bolt, specified as L in Figure 1, is a control dimension and for bolts without splines (ASTM F3125 Grades A325 and A490) is measured parallel to the axis of the bolt from the underside of the head of the bolt—the bearing surface of the head—to the end of the bolt. For bolts with twist-off splines (ASTM F3125 Grades F1852 and F2280), the length, L, is measured from the bolt bearing surface to the center point of the groove between the threaded portion of the bolt and the spline drive (ASME B18.2.6-19). For F3148 spline drive bolts (ASTM F3148-17a), the length, L, is measured from the bolt bearing surface to the first indication of thread near the spline, as shown in Figure 2. The tolerances on the overall length of a bolt, shown in Table 2, range from +0 in. to approximately −⅛ in. or −¼ in. depending on the diameter and nominal length of the bolt. A looser tolerance for bolts longer than 6 in. reflects once-common manufacturing methods but is likely no longer required due to improved production practices, while methods vary from one manufacturer to another and even one machine to another.

ASME B18.2.6 provides specifications for bolts ranging in length from 1½ in. to 10 in. in ¼-in.-long increments. However, the AISC *Steel Construction Manual* (2017) states that high-strength bolts are generally furnished in length increments of ¼-in. only up to a length of 5 in. and then in length increments of ½-in. for longer bolts. The RCSC *Specification* (2015), however, notes that the transition from ¼-in. to ½-in. increments occurs at a length of 6 in. In practice, availability of bolts of specific length is a function of several variables, including manufacturing methods, tooling, and market factors. A good rule of thumb is that bolt lengths up to four diameters are generally stocked for all diameters up to 1½ in. and bolt lengths up to eight diameters are commonly stocked for the more commonly used diameters of ¾ in. to 1⅛ in. Longer bolts or bolts in ¼-in. length increments are available given sufficient lead time and appropriate coordination with a supplier.

The thread length, L_T, is the distance from the last complete thread near the shank to the extreme end of the bolt for Grades A325 and A490 bolts, to the center point of the groove for Grades F1852 and F2280 bolts, or to the first indication of thread for F3148 bolts, as is shown in Figures 1 and 2. The thread length of structural bolts is generally shorter than that of similar nonstructural bolts so as to more easily allow the threads of the bolt to be excluded from the shear plane, thus increasing the strength of the bolt when it is subjected to shear. Although many resources, including the AISC *Manual* and the RCSC *Specification*, include

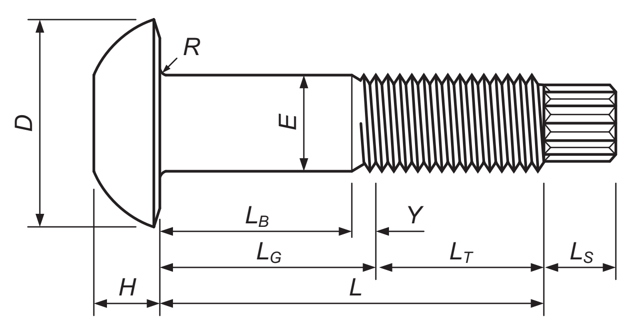

Fig. 2. Geometry of ASTM F3148 bolts.

Table 3. Bolt Lengths, Thread Lengths, and Shortest Lengths Routinely Produced			
Nominal Bolt Diameter, E or d_b (in.)	Thread Length, L_T (in.)	Transition Length, Y (in.)	Shortest Length Produced (in.)*
½	1.00	0.19	1¼
⅝	1.25	0.22	1½
¾	1.38	0.25	1¾
⅞	1.50	0.28	2
1	1.75	0.31	2¼
1⅛	2.00	0.34	2¾
1¼	2.00	0.38	2¾
1⅜	2.25	0.44	Special order
1½	2.25	0.44	See text

* Bolts are occasionally produced in shorter lengths for special orders.

tables detailing the length of threads, L_T, also shown here in Table 3, the thread length is a reference dimension in ASME B18.2.6, intended for calculation purposes only, and may actually vary from published nominal values.

Instead of controlling the thread length of a bolt, the geometry of the bolt is controlled by the overall length of the bolt, L, the grip gaging length, L_G, and the body length, L_B. The grip gaging length, L_G, is a control dimension measured from the bearing surface of the head to the face of a thread ring gage (Figure 3) that is threaded onto the bolt by hand until it stops at the thread runout. The bolt body length, L_B, which is also a control dimension, is basically the length of the shank or body of the bolt. The body length is more precisely defined as the distance measured from the bearing surface of the head to the last scratch of thread for bolts with cut threads, as shown in Figure 1(a), or to the top of the extrusion angle for bolts with rolled threads, as shown in Figures 1(b)–1(d). The transition length, Y, is a reference dimension that represents the length of the transition region between the threads and body.

The grip gage length and body length are used as control dimensions by specifying a maximum grip gage length, $L_{G,max}$, and a minimum body length, $L_{B,min}$, which are calculated as shown in Equations 1 and 2 using the nominal overall length and the reference dimensions L_T and Y. Values of $L_{G,max}$ and $L_{B,min}$ are tabulated in ASME B18.2.6 for each diameter and length of fastener and are also shown herein (in part) as Table A1. Because L_T and Y are reference dimensions, no tolerances are provided for these dimensions and actual measured dimensions on finished product may vary from these published values.

$$L_{G,max} = L_{nom} - L_T \quad (1)$$

$$L_{B,min} = L_{G,max} - Y \quad (2)$$

ASME B18.2.6 states that when the minimum body length, $L_{B,min}$, is short enough, that the bolt shall be threaded full length. Specifically, it says that when $L_{B,min} \le 2.5p$ for $d_b \le 1$ in. or when $L_{B,min} \le 3.5p$ for $d_b > 1$ in., the bolt shall be threaded full length, where p is the pitch of the threads on the bolt. However, ASME B18.2.6 also says that bolts that are threaded full length are permitted to have an unthreaded length under the head that is not longer than $2.5p$ for bolts 1 in. in diameter or smaller and $3.5p$ for bolts larger than 1 in. in diameter. One implication of this is that there are some lengths of bolts an engineer may expect to be fully threaded that may, in fact, have a short unthreaded length under the head. Another implication is that there are some lengths of bolts an engineer may expect to definitely have a shank but may, in fact, be fully (or mostly) threaded. The former case is generally of little concern in most cases, but the latter case may lead to a serious design issue.

With two exceptions, bolts that are fully threaded do not carry a special designation identifying them as such. The first exception is for bolts manufactured with nonstandard dimensions, which are designated with an S—A490S, for example. The second exception is that Grade A325 bolts up

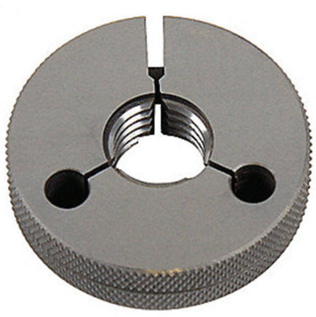

Fig. 3. A thread ring gage.

to a length of four times their diameter may be manufactured as fully threaded and are designated with a T—A325T, for example. Bolts with the "T" designation are for users who may want a longer bolt that is fully threaded so they do not need to order or inventory multiple shorter sizes. These bolts are common in markets such as the metal building industry and are used in multiple grip ranges and in the threads included condition. The fully threaded T bolts are also permitted to have an unthreaded length under the head that is not longer than 2.5p for bolts 1 in. in diameter or smaller and 3.5p for bolts larger than 1 in. in diameter.

Illustrative Cases

The next several cases consider ⅞-in.-diameter bolts of varying length. For all ⅞-in.-diameter structural bolts, there are 9 threads per in. (TPI); thus the pitch of these bolts is $p = 1/9$ in. and $2.5p = (2.5)/(9 \text{ in.}) = 0.28$ in. Further, all ⅞-in.-diameter structural bolts have a threaded length, L_T, a reference dimension, equal to 1½ in. Finally, the transition length, Y, also a reference dimension, has a value of 0.28 in. for all ⅞-in.-diameter structural bolts.

Case 1

First, consider a ⅞ in.-9×1½ in. bolt. The maximum grip gage length, $L_{G,max}$, is calculated using Equation 1 and the minimum body length, $L_{B,min}$, is calculated using Equation 2:

$$L_{G,max} = L_{nom} - L_T \tag{1}$$
$$= 1\tfrac{1}{2} \text{ in.} - 1\tfrac{1}{2} \text{ in.}$$
$$= 0.00 \text{ in.}$$

$$L_{B,min} = L_{G,max} - Y \tag{2}$$
$$= 0.00 \text{ in.} - 0.28 \text{ in.}$$
$$= -0.28 \text{ in.}$$

Therefore, use $L_{B,min} = 0.00$ in.

Because $L_{B,min}$ is less than 2.5p, however, $L_{G,max}$ is taken as $2.5p = 0.28$ in. Because the value of $L_{B,min}$ is less than 2.5p, the bolt is considered to be fully threaded. Because the nominal thread length for a ⅞-in.-diameter bolt is 1½ in., which is equal to the nominal overall bolt length, the bolt would simply be considered as fully threaded.

Based on the ASME B18.2.6 standard, the ⅞ in.-9×1½ in. diameter bolt may be produced without an unthreaded body, or the bolt may have a small unthreaded and transition length that could be as long as 2.5p. The diameter of this unthreaded and transition length may be as large as the full nominal diameter (over/under tolerances) but may be as small as the pitch diameter of the bolt. These two alternatives, both of which are in compliance with ASME B18.2.6, are shown as Figures 4(a) and 4(b), respectively. (The tolerance for overall bolt length is not illustrated in Figure 4.)

Case 2

Next, consider a ⅞ in.-9×1¾ in. bolt with

$$L_{G,max} = 1\tfrac{3}{4} \text{ in.} - 1\tfrac{1}{2} \text{ in.}$$
$$= 0.25 \text{ in.}$$

$$L_{B,min} = 0.25 \text{ in.} - 0.28 \text{ in.}$$
$$= -0.03 \text{ in.}$$

Therefore use $L_{B,min} = 0.00$ in.

Because $L_{B,min}$ is less than 2.5p, $L_{G,max}$ is taken as $2.5p = 0.28$ in. Because the value of $L_{B,min}$ is less than 2.5p, this bolt, despite having a nominal thread length of $L_T = 1\tfrac{1}{2}$ in. and a nominal shank or body length of $L_B = 1\tfrac{3}{4}$ in. − 1½ in. = ¼ in., would be considered fully threaded according to ASME B18.2.6 and, like Case 1, may indeed be produced as fully threaded, or it may have a small unthreaded and transition length that could be as long as 0.28 in. These two alternatives, both of which are in compliance with ASME B18.2.6, are shown as Figures 4(c) and 4(d), respectively.

Case 3

Next, consider a ⅞ in.-9×2 in. bolt with

$$L_{G,max} = 2 \text{ in.} - 1\tfrac{1}{2} \text{ in.}$$
$$= 0.50 \text{ in.}$$

$$L_{B,min} = 0.50 \text{ in.} - 0.28 \text{ in.}$$
$$= 0.22 \text{ in.}$$

Because $L_{B,min}$ is less than 2.5p, $L_{G,max}$ is taken as $2.5p = 0.28$ in. Because this value of $L_{B,min}$ is less than 2.5p, this bolt, despite having a nominal thread length of $L_T = 1\tfrac{1}{2}$ in. and a nominal shank or body length of $L_B = 2$ in. − 1½ in. = ½ in., would be considered fully threaded according to ASME B18.2.6. Like Cases 1 and 2, the ⅞-in.-9×2-in. bolt may be produced as fully threaded, or it may have a small unthreaded and transition length that could be as long as 0.28 in. These two alternatives, both of which are in compliance with ASME B18.2.6, are shown in Figures 4(e) and 4(f), respectively.

Three different variants of ⅞-in.-9×2-in. bolts made by different manufacturers are shown in Figure 5. The bolt on the left has a short unthreaded body with a diameter that is less than the nominal diameter of the bolt, the bolt in the middle is basically all transition up to the body diameter, and the bolt on the right has a short body with a diameter equal to the nominal diameter of the bolt and a short transition. All three bolts are in compliance with ASME B18.2.6.

Case 4

Now, consider a ⅞-in.-9×2¼ in. bolt with

$$L_{G,max} = 2\tfrac{1}{4}\text{ in.} - 1\tfrac{1}{2}\text{ in.}$$
$$= 0.75\text{ in.}$$

$$L_{B,min} = 0.75\text{ in.} - 0.28\text{ in.}$$
$$= 0.47\text{ in.}$$

Because this value of $L_{B,min}$ is greater than 2.5p, this bolt will have a shank that is at least 0.47 in. long with a diameter equal to the nominal body diameter (±tolerances) and a transition region that may be as long as 0.28 in. This bolt, which is in compliance with ASME B18.2.6, is shown as Figure 4(g).

It should be noted that the ⅞-in.-9×2-in. is the shortest ⅞-in.-diameter high-strength bolt that is routinely produced. Because the ⅞-in. × 2-in. is considered to be fully threaded, there is little demand for a ⅞-in.-diameter bolt shorter than 2 in., although shorter ones are occasionally manufactured upon request. The ⅞-in. × 2¼-in. is the shortest ⅞-in.-diameter high-strength bolt that is guaranteed to have a shank.

The case of the ⅞-in.-9×2 in. represents a potentially serious design issue. A structural engineer or connection detailer would likely review tables in the RCSC *Specification* (RCSC, 2015) or AISC *Manual* (AISC, 2017), see that the thread length is listed as L_T = 1½ in. for a bolt that is 2 in. long, and, expecting the bolt to have a ½-in.-long shank, may design the bolt as if the threads are excluded from the shear plane, as is shown in Figure 6(a). The ⅞-in.-9×2 in. bolt as supplied by the manufacturer in full compliance with ASME B18.2.6 may however have a shank much shorter than ½ in. or have no shank at all, resulting in a significant deviation from the engineer's or detailer's expectations, as is shown in Figure 6(b).

The shortest length bolts that are routinely produced for each diameter are shown in Table 3. With the exceptions of 1⅜-in.- and 1½-in.-diameter bolts, bolts with the lengths shown in the table may or may not have a shank or unthreaded body depending on the tooling and preferences of the manufacturer. Bolts with lengths greater than those shown in the table will have a shank.

A direct application of the formulas for L_b and L_g in ASME B18.2.6 to 1⅜-in.- and 1½-in.-diameter bolts would show that 1⅜-in.- and 1½-in.-diameter bolts with lengths

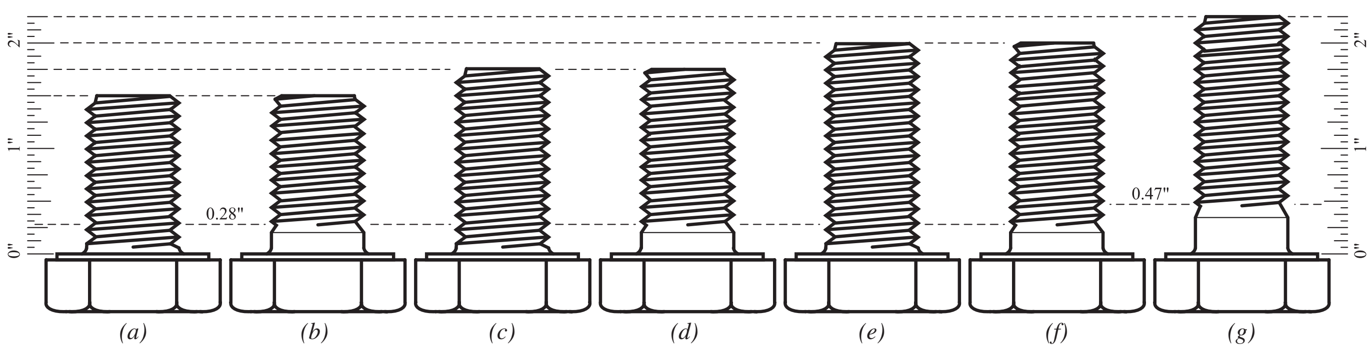

Fig. 4. Conforming variants of ⅞-in.-9×1½-in., ⅞-in.-9×1¾-in., ⅞-in.-9×2-in., and ⅞-in.-9×2¼-in. bolts.

Fig. 5. Three ⅞-in.-9 × 2-in. bolts manufactured by three different manufacturers.

3¼ in. and shorter would be fully threaded. In Table 2 of ASME B18.2.6-10 (2010), however, 1⅜-in.- and 1½-in.-diameter bolts with lengths 3 in. and shorter were both shown as fully threaded. Going back to the 2006 edition, in Table 2 of ASME B18.2.6-06 (2006), 1⅜-in.-diameter bolts with lengths 3 in. and shorter were shown as fully threaded but 1½-in.-diameter bolts with lengths 3¾ in. and shorter were shown as fully threaded. This discrepancy has been resolved in ASME B18.2.6-19 (2019), and the corresponding table has been updated to be consistent with the equations. As was stated earlier, 1⅜-in.-diameter bolts are not routinely produced and are available by special order only; they are included in this discussion for the sake of completeness only.

Case 5

Finally consider a ⅞-in.-9×4-in. bolt, where

$$L_{G,max} = 4 \text{ in.} - 1\tfrac{1}{2} \text{ in.}$$
$$= 2.50 \text{ in.}$$

$$L_{B,min} = 2.50 \text{ in.} - 0.28 \text{ in.}$$
$$= 2.22 \text{ in.}$$

Note that the transition length can vary from manufacturer to manufacturer; thus, depending on the actual values of Y and L (including tolerances for L), the thread length, L_T, for this bolt could range anywhere from L_T = (4.00 in. − 0.19 in.) − 2.50 in. = 1.31 in. to L_T = (4.00 in. − 0.00 in.) − 2.22 in. = 1.78 in., despite having a nominal reference value of L_T = 1½ in. In all cases, though, the body of the bolt will be at least 2.22 in. long, and the grip gage length will not exceed 2.50 in.

Four different variations of the ⅞-in.-9×4-in. bolt are shown in Figure 7. Figures 7(a) and 7(b) show the bolt with its maximum permitted length, L = 4.00 in., and Figures 7(c) and 7(d) show the bolt with its minimum permitted length L = 4.00 − 0.19 in. = 3.81 in. Additionally, Figures 7(a) and 7(c) show the bolt with its minimum body length of L_B = $L_{B,min}$ = 2.22 in., while Figures 7(b) and 7(d) show the bolt with a slightly longer body length of L_B = 2.38 in. that could result with a shorter transition length of Y = 0.22 in. instead of the reference value of Y = 0.28 in. All four variations are within the ASME B18.2.6 tolerances for a ⅞-in.-9×4-in. bolt, and consideration of these variations is essential when selecting a bolt with appropriate length for a joint.

Nut and Washer Thickness Dimensions

ASME B18.2.6 also includes dimensions for heavy hex nuts and hardened washers. While dimensions and tolerances are given for the width across the flats and the width across the corners for nuts and for outer and inner diameters for washers, the tolerances on thickness for both the nuts and washers are of primary concern for this paper and are shown in Table 4. Nominal thicknesses are not provided for washers in ASME B18.2.6, but 5⁄32 in. is often used as the nominal thickness for all diameter washers (RCSC, 2015).

BOLT LENGTH DETERMINATION

Two design criteria that must be satisfied in selecting the length of a bolt for a given joint are (1) the bolt must be short enough that the nut can be either snug tightened or pretensioned without the threads of the nut running out onto the transition region of the bolt (“shanking out”), and (2) the bolt must be long enough that the nut can be threaded completely onto the bolt (zero or positive stick-out). These two cases are illustrated in Figures 8(a) and 8(b), which show a bolting assembly consisting of a 1-in.-8×6-in. bolt, a nut, and

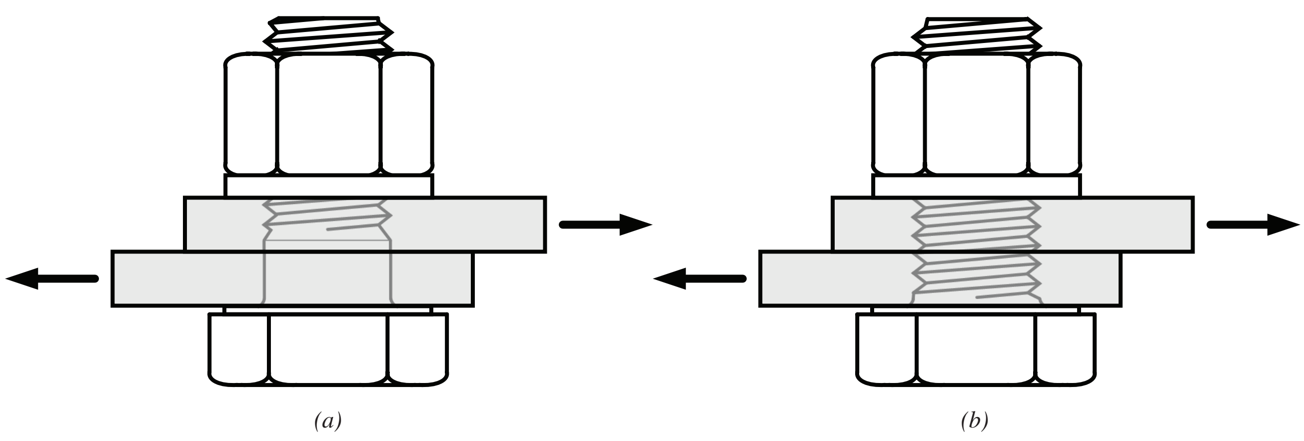

Fig. 6. Illustration of a joint with ⅞-in.-9×2-in. bolts (a) as might be expected by the engineer of record and (b) as provided.

Table 4. Nut and Washer Thicknesses					
Nominal Bolt Diameter (in.)	Heavy Hex Nut Thickness			Washer Thickness	
	Maximum (in.)	Nominal (in.)	Minimum (in.)	Minimum (in.)	Maximum (in.)
½	0.504	31⁄64	0.464	0.097	0.177
⅝	0.631	39⁄64	0.587	0.122	0.177
¾	0.758	47⁄64	0.710	0.122	0.177
⅞	0.885	55⁄64	0.833	0.136	0.177
1	1.012	63⁄64	0.956	0.136	0.177
1⅛	1.139	1 7⁄64	1.079	0.136	0.177
1¼	1.251	1 7⁄32	1.187	0.136	0.177
1⅜	1.378	1 11⁄32	1.310	0.136	0.177
1½	1.505	1 15⁄32	1.433	0.136	0.177

two F436 washers.[2] Figure 8(a) illustrates the first criterion, which leads to the minimum grip for a given bolt length, while Figure 8(b) illustrates the second criterion, which leads to the maximum grip for a given bolt length.[3] These two criteria can be written mathematically as

$$\text{Minimum grip} = L_{G,max} - \Sigma t_{washers} - \delta_{pretension} \quad (3)$$

$$\text{Maximum grip} = L - \Sigma t_{washers} - t_{nut} \quad (4)$$

Considering a 1-in.-8×6-in. bolt, the maximum grip gage length can be computed as

$$L_{G,max} = 6 \text{ in.} - 1\tfrac{3}{4} \text{ in.}$$
$$= 4.25 \text{ in.}$$

For this bolt, with $L < 8d_b$, the change in length during pretensioning, based on a half turn past snug being required, can be estimated as

$$\delta_{pretension} = 0.5/8$$
$$= 0.0625 \text{ in.}$$

It should be noted that most of this elongation is expected to occur within the threaded region of the bolt. Thus,

2 The case of a bolting assembly with two washers—one under the head and one under the nut—has been used in this paper because it represents a situation that is useful for illustrating the calculations that are presented. It should be noted, however, that while the use of two washers is necessary in some situations, it is more common to use just a single washer.

3 Care should be taken to not confuse the "grip gage length" of a bolt with the "grip" of a joint. The former is a control dimension used in the manufacturing of bolts while the latter is the total thickness of a joint between the bearing surfaces of the bolt and nut, which, in this work, excludes the thickness of F436 washers included with the bolting assembly. This is consistent with the definition of found in the RCSC *Specification* (2015) but not with the definition found in the AISC *Specification* (2016).

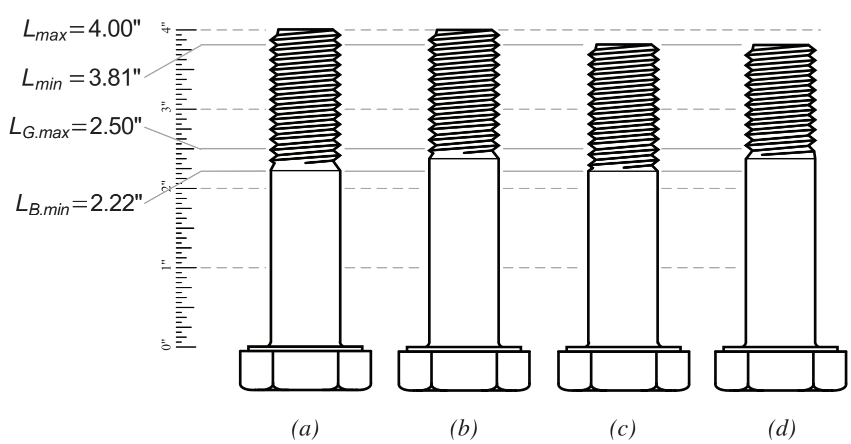

Fig. 7. Different variations of ⅞-in.-9×4-in. high-strength bolts per ASME B18.2.6-19.

assuming that two washers are used and using the minimum washer thickness permitted in ASME B18.2.6, the minimum grip can be determined using Equation 3:

$$\text{Minimum grip} = L_{G,max} - \Sigma t_{washers} - \delta_{pretension} \quad (3)$$
$$= 4.25 \text{ in.} - (2)(0.136 \text{ in.}) - 0.0625 \text{ in.}$$
$$= 3.92 \text{ in.}$$

Again, assuming that two washers are used, but using the maximum washer thickness, maximum nut thickness, and minimum overall bolt length permitted in ASME B18.2.6, the maximum grip can be determined using Equation 4:

$$\text{Maximum grip} = L - \Sigma t_{washers} - t_{nut} \quad (4)$$
$$= (6.00 \text{ in.} - 0.19 \text{ in.}) - (2)(0.177 \text{ in.}) - 1.012 \text{ in.}$$
$$= 4.44 \text{ in.}$$

Values for the minimum and maximum grip for all common diameter and length high-strength bolts are tabulated in Table A2. The values shown in Table A2 for the minimum grip include an elongation during pretensioning based on a half-turn of the nut for bolts where $L \leq 8d_b$ and two-thirds turn of the nut for bolts where $L > 8d_b$. This is largely consistent with the RCSC *Specification* for joints where outer faces of the gripped material are normal to the axis of the bolt but is slightly conservative for bolts where $L \leq 4d_b$ where one-third turn would be required.

A third design criterion that is implemented in some cases is that the bolt should be long enough so as to exclude the threads of the bolt from the shear plane(s) of the joint. Considering the joint shown in Figure 9, where four plies are joined, the bolt can be designed with the threads excluded from the shear plane so long as none of the faying surfaces between plies intersects the threaded portion of the bolt. This is true when

$$\Sigma t_{(n-1)} + \Sigma t_{washers\ under\ head} \leq L_{B,min} + f(Y) \quad (5)$$

where $\Sigma t_{(n-1)}$ is used as short hand for $\sum_{i=1}^{n-1} t_i$ and $f(Y)$ is some fraction of thread transition length, Y. The threads can be excluded from the shear plane as long as

$$\Sigma t_{(n-1)} \leq L_{B,min} - \Sigma t_{washers\ under\ head} + f(Y) \quad (6)$$

A fraction of the thread transition length, $f(Y)$, is included in Equations 5 and 6 because commentary to Section 2.3 of the RCSC *Specification* (RCSC, 2015) can be interpreted as permitting a bolt to be considered in the threads excluded or X condition when the shear plane passes through the transition region of the bolt, though this section of the RCSC *Specification* is under review as of the writing of this paper. Knowing that the actual value of Y may vary from one manufacturer to another, however, there is merit to simply and conservatively taking $f(Y) = 0$.

If the $\Sigma t_{(n-1),max}$ is defined as

$$\Sigma t_{(n-1),max} = L_{B,min} - \Sigma t_{washers\ under\ head} + f(Y) \quad (7)$$

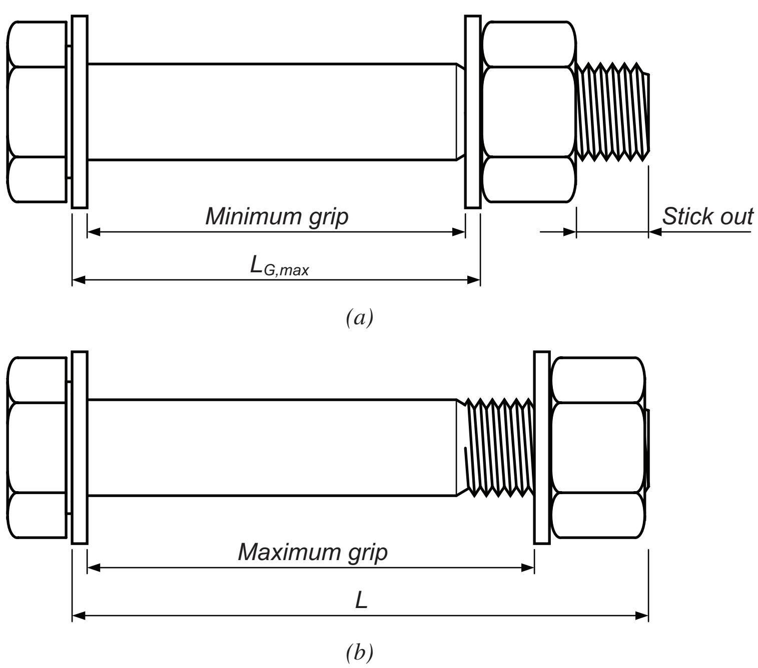

Fig. 8. Minimum and maximum grip for a given bolt length.

then it can be stated that when $\Sigma t_{(n-1)}$ for a joint is less than $\Sigma t_{(n-1),max}$ for a bolting assembly, then the bolt can be treated as if it is in the threads excluded or X condition. Again, considering a bolting assembly consisting of a 1-in.-8×6-in. bolt, a nut, and two F436 washers—one under the head and one under the nut—the $\Sigma t_{(n-1),max}$ can be computed as

$$\Sigma t_{(n-1),max} = L_{B,min} - \Sigma t_{washers\ under\ head} + f(Y) \quad (7)$$

$$= 3.94 \text{ in.} - 0.177 \text{ in.} + 0 \text{ in.}$$

$$= 3.76 \text{ in.}$$

where the maximum thickness of the washer was used and $f(Y)$ was conservatively taken as zero. Values of $\Sigma t_{(n-1),max}$ for common configurations of bolting assemblies computed with $f(Y)$ conservatively taken as zero are provided in Table A2.

In the past, other authors have related the location of the shear plane relative to the thread transition as a function of the bolt length and the thickness of the last ply in the joint, t_n (i.e., the ply closest to the nut). Because the thread length, L_T, is a reference dimension, however, there is little assurance that the transition will be where it is expected when its location is based on L_T. In this work, the location of the thread transition is determined as a function of the minimum body length, $L_{B,min}$, which is a control dimension, and is thus more reliable than the thread length.

Use of Washers

The AISC *Specification* (AISC, 2016) refers to the RCSC *Specification* regarding the use of washers. According to the RCSC *Specification* (RCSC, 2015), washers are not required for snug-tightened joints except when a slotted hole is used, in which case an F436 washer or a 5⁄16-in.-thick common plate washer is required to completely cover the hole, or when sloping surfaces are joined, where a beveled washer is required. When pretensioned or slip-critical joints are employed, an F436 washer or a 5⁄16-in.-thick common plate washer is again required to completely cover slotted holes, a beveled washer is required for sloping surfaces, and an F436 washer is required under both the head and the nut when material with a yield strength of less than 40 ksi is joined using Grade A490 or F2280 bolts, except that a washer is not needed under the head of an F2280 when it has a button head like that shown in Figure 1(c). Further, when twist-off bolts are used in a pretensioned or slip-critical joint, an F436 washer is required under the nut of the assembly, and when the calibrated wrench method of installation is used, an F436 washer must be used under the turned element (either the nut or head of the bolt), regardless of bolt grade or material strength. Finally, there are additional washer requirements when direct-tension-indicators are used for pretensioning.

Given these requirements for washers, common bolting assembly configurations include no washers, a single washer under either the nut or head, or two washers with one under the nut and another under the head. Occasionally, multiple washers are used to allow more margin for nut rotation and thread engagement during pretensioning. In those cases, the washers are generally added under the nut. With few exceptions, there is little to be gained from using washers under the head of the bolt, since doing so makes it more challenging to exclude the threads of the bolt from the shear plane. One exception is when the head of the bolt is the turned element during tightening using the calibrated wrench method of installation, in which case a single washer under the head will suffice. Another exception is when Grade A490 or hex headed Grade F2280 bolts are used to connect material with a yield stress less than 40 ksi. In other cases, washers other than F436 are used, including 5⁄16-in.-thick common washers, plate washers, direct-tension-indicating washers, or shims. In these cases, the thicknesses of those washers, shims, and/or washer plates must be included in the bolt length calculations.

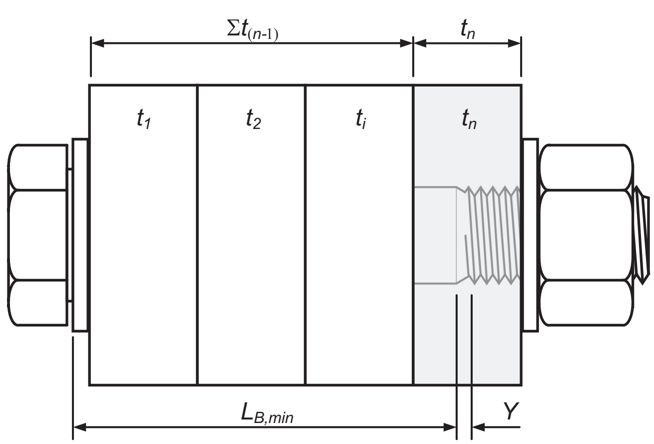

Fig. 9. Illustration of plies and threads in the grip of a bolt.

Procedure for Determination of Bolt Length

A procedure for the determination of bolt length for a joint is summarized here.

Step 1. Determine the type and location of washer(s) required for the particular joint specified, taking care to consider washer requirements in the RCSC and AISC *Specifications* related to hole type, location, material strength, and method of installation.

Step 2. Compute the required grip for the joint. The required grip should include all materials between the bearing surfaces of the bolt head and the nut except for F436 hardened washers addressed in Step 1.

Step 3. Unless bolts are not subject to shear or are predetermined to be designed in the threads not excluded or N condition, determine the cumulative thickness of all but the last plate within the grip of the bolt, $\Sigma t_{(n-1)}$ (i.e., the thickness of all of the plates within the grip except for the plate closest to the nut). This quantity may depend on the way in which the bolt is installed in joints that are not symmetric about the mid-length of the joint grip and should include all materials between the bearing surface of the nut and last faying surface of the joint except for F436 washers, which are included in Table A2.

Step 4. Enter Table A2 on the appropriate page for the bolt diameter specified, and using the appropriate columns for the washer configuration determined in Step 1, select a bolt length that has both (1) a minimum grip that is shorter than the required grip and (2) a maximum grip that is longer than the required grip. Rarely, a bolt cannot be identified that satisfies both criteria. In that case, try either adding washer(s) to the bolting assembly or selecting a bolt that meets only the first criterion (i.e., a bolt that has a minimum grip that is shorter than the required grip).

Step 5. Unless bolts are not subject to shear or are predetermined to be designed in the threads not excluded or N condition, determine the maximum cumulative thickness of all but the last plate within the grip of the bolt, $\Sigma t_{(n-1),max}$, and compare this value to $\Sigma t_{(n-1)}$ that was determined in Step 3. If $\Sigma t_{(n-1)}$ is not greater than $\Sigma t_{(n-1),max}$ then the bolt can be designed in the threads excluded or X condition.

Note that there is sometimes more than one bolt length that will satisfy the design criteria for a given joint. It is up to the engineer to decide which one is desired. On one hand, choosing a longer bolt will result in more thread stick out past the exposed face of the nut and will make it more likely that the threads will be excluded from the shear plane, resulting in higher strength from the fastener. On the other hand, though, choosing a shorter bolt will result in less thread stick out and more threads within the grip of the bolt, which can improve the rotational capacity of the bolt during pretensioning and can improve the ductility of the bolt under tension. Note that the values shown for minimum grip in Table A2 include the *minimum* required turn of nut for most cases. As such, when the required grip for a joint is close to the minimum grip for a bolt shown in Table A2, an engineer may wish to select the next shorter bolt, if possible, to avoid potential problems with the nut "shanking out" on the transition region due to over-rotation of the nut during pretensioning. Alternatively, an additional washer can often be added to the bolting assembly to reduce the likelihood of shanking out.

DESIGN EXAMPLES

Six examples are presented in this section to illustrate the use of the proposed procedure for determining the appropriate length of bolts. Examples 1–4 are adapted from examples that were presented by Carter (1996). Examples 5 and 6 are intended to illustrate less commonly encountered design issues.

Example 1

Determine the bolt length for ¾-in.-diameter ASTM F3125 Grade A325 snug-tight bolts in standard holes in a ⅜-in. single-plate connection supporting a W21×50 beam (nominal t_w = ⅜ in.)

Recommended Solution

The required grip for the joint is ⅜ in. + ⅜ in. = ¾ in. Because the thickness of either of the plies joined is t = ⅜ in., $\Sigma t_{(n-1)}$ = ⅜ in. for the joint regardless of whether the bolt is installed through the single plate first or through the beam web first. No washers are required for a snug-tightened joint using Grade A325 fasteners. Table A2 is used to select ¾-in.-diameter bolts with a minimum grip less than or equal to ¾ in. and a maximum grip greater than or equal to ¾ in. The following options are available:

1. ¾-in.-10×1¾-in. with no washers
   Min grip = 0.20 in.
   Max grip = 0.80 in.
   Fully threaded

2. ¾-in.-10×2-in. with no washers
   Min grip = 0.57 in.
   Max grip = 1.05 in.
   $\Sigma t_{(n-1),max} = 0.37$ in.

3. ¾-in.-10×2-in. with one washer
   Min grip = 0.45 in.
   Max grip = 0.88 in.
   $\Sigma t_{(n-1),max} = 0.37$ in.

4. ¾-in.-10×2¼-in. with one washer
   Min grip = 0.70 in.
   Max grip = 1.13 in.
   $\Sigma t_{(n-1),max} = 0.62$ in.

5. ¾-in.-10×2¼-in. with two washers[4]
   Min grip = 0.58 in.
   Max grip = 0.95 in.
   $\Sigma t_{(n-1),max} = 0.44$ in.

Based on the options available for this joint, a ¾-in.-10×2-in. bolt is recommended because it would be of an acceptable length to work either without washers or with a single washer. Because $\Sigma t_{(n-1),max} = 0.37$ in. in either case, which is smaller than $\Sigma t_{(n-1)} =$ ⅜ in., the bolt would need to be designed in the threads not excluded or N condition regardless of whether it is inserted through the shear plate first or through the beam web first.

If it is required to exclude the threads from the shear plane, then a ¾-in.-10×2¼ in. bolt would work, though this assembly would need at least one washer included to avoid shanking out the nut during installation (even for a snug-tight installation).

RCSC Method

Because washers are not required for this joint, the grip + washer thickness is ¾ in. Per RCSC *Specification* Table C2.2, the length of the bolt is determined by adding 1 in. to the grip + washer thickness. Thus, the length of the bolt can be determined as

$$L_{req} = \tfrac{3}{4} \text{ in.} + 1 \text{ in.}$$
$$= 1\tfrac{3}{4} \text{ in.}$$

Therefore, use $L_{req} = 1\tfrac{3}{4}$ in.

For the ¾-in.-diameter bolt, $L_T = 1\tfrac{3}{8}$-in., thus the shank would be expected to be 1¾-in. − 1⅜-in. = ⅜ in. long, and the engineer may expect the bolt to be in the threads excluded or X condition. Note, however, that according to Table A1, the ¾-in.-10×1¾-in. bolt is considered to be fully threaded and would have an unthreaded and transition length that would be no longer than 0.25 in.

4 In the design examples presented in this work, when one washer is included, it will be under the nut, and when two washers are included, one will be under the nut and one will be under the head.

Example 2

Determine the bolt length for ¾-in.-diameter ASTM F3125 Grade A325 snug-tightened bolts in standard holes in a double-angle connection with 2L5×3×5⁄16-in. angles supporting a W27×84 beam (nominal t_w = 7⁄16-in.).[5]

Recommended Solution

The required grip for this joint is 5⁄16 in. + 7⁄16 in. + 5⁄16 in. = 1 1⁄16 in. Regardless of which direction the bolt is installed, $\Sigma t_{(n-1)}$ for the joint would be 5⁄16 in. + 7⁄16 in. = ¾ in. Washers are not required for a snug tightened joint. Table A2 is used to select ¾-in.-diameter bolts with a minimum grip less than or equal to 1 1⁄16 in. and a maximum grip greater than or equal to 1 1⁄16 in. The following options are available:

1. ¾-in.-10×2¼-in. with no washers
   Min grip = 0.82 in.
   Max grip = 1.30 in.
   $\Sigma t_{(n-1),max}$ = 0.62 in.

2. ¾-in.-10×2¼-in. with one washer
   Min grip = 0.70 in.
   Max grip = 1.13 in.
   $\Sigma t_{(n-1),max}$ = 0.62 in.

3. ¾-in.-10×2½-in. with one washer
   Min grip = 0.95 in.
   Max grip = 1.38 in.
   $\Sigma t_{(n-1),max}$ = 0.87 in.

4. ¾-in.-10×2½-in. with two washers
   Min grip = 0.83 in.
   Max grip = 1.20 in.
   $\Sigma t_{(n-1),max}$ = 0.69 in.

Based on the options available for this joint, a ¾-in.-10×2¼-in. bolt is recommended because it would be of an acceptable length either without washers or with a single washer. Because $\Sigma t_{(n-1),max}$ = 0.62 in. in either case, which is smaller than $\Sigma t_{(n-1)}$ = ¾ in., the bolt would need to be designed in the threads not excluded or N condition.

If a threads excluded or X condition is required, a ¾-in.-10×2½-in. bolt would be acceptable, though this assembly would require one washer under the nut to avoid shanking out the nut during installation (even for a snug-tight installation). Putting the washer under the head, however, may cause the threads to be not excluded from the shear plane.

RCSC Method

When no washers are required, as would be the case for snug-tightened Grade A325 bolts, the grip + washer thickness is 5⁄16 in. + 7⁄16 in. + 5⁄16 in. = 1 1⁄16 in. Thus, the length of the bolt can be determined using RCSC *Specification* Table C2.2 as

$$L_{req} = 1\tfrac{1}{16}\text{ in.} + 1\text{ in.}$$
$$= 2\tfrac{1}{16}\text{ in.}$$

Therefore, use L_{req} = 2¼ in.

5 It is noted that 2L4×32×5⁄16 angles may be more commonly used than 2L5×3×5⁄16. However, the 2L5×3×5⁄16 angles were selected for this example to maintain consistency with the paper by Carter (1996), where it first appeared.

For the ¾-in.-diameter bolt, L_T = 1⅜ in.; thus, the shank would be expected to be 2¼ in. − 1⅜ in. = ⅞ in. long, and the engineer would expect the bolt to be in the threads excluded or X condition. Note from Table A1, however, that the shank or body length of a ¾-in.-10×2¼-in. bolt is guaranteed only to be 0.62 in. As a result, the 2¼-in.-long bolt might actually be in the threads not excluded or N condition. If the engineer considers a bolt with the shear plane passing through the thread transition to be treated as if it is in the threads excluded or X condition, then from Table A1 it can be observed that the maximum grip gage length of a 2¼-in.-long bolt is 0.87 in, and the bolt could be treated as if the threads were excluded. This is a maximum length, however, and the actual grip gage length may be anywhere between 0.62 in. and 0.87 in.

Example 3

Determine the bolt length for pretensioned ¾-in.-diameter ASTM F3125 Grade A490 bolts connecting a ½-in.-thick angle to a W14×500 column flange (nominal t_w = 3½ in.). The calibrated wrench method will be used to pretension the bolts.

Recommended Solution

The required grip for this joint is 3½ in. + ½ in. = 4 in. If the bolt is installed through the column flange first, then $\Sigma t_{(n-1)}$ = 3½ in. but if the bolt is installed through the angle leg first, then $\Sigma t_{(n-1)}$ = ½ in. Because the calibrated wrench method of installation is to be used, at least one F436 washer is required under the turned element. A Grade A490 bolt was specified, so an F436 washer is also required between the angle and the bearing surface of the head or nut since the angle would be made of 36-ksi material unless otherwise designated.

Assuming that the bolt is installed through the column flange first and that the nut is the turned element, then a single washer under the nut is required and from Table A2 a 5½-in.-long bolt can be selected. For a ¾-in.-10×5½ in. bolting assembly with one washer under the nut, the minimum grip is 3.95 in. and the maximum grip is 4.38 in. In that case, $\Sigma t_{(n-1),max}$ = 3.87 in. and because this is larger than $\Sigma t_{(n-1)}$ = 3½ in., the bolt can be considered to be in the threads excluded or X condition. Note that a ¾-in.-10×5¼-in. bolting assembly with one washer under the nut could be specified, but this would likely be available only by special order.

Alternatively, assuming that the bolt is installed through the angle leg first and the nut is the turned element, then two washers are required—one under the nut and one under the head of the bolting assembly. A 5½-in.-long bolt can again be selected, but in this case, the minimum grip would be 3.83 in.; the maximum grip would be 4.20 in.; the $\Sigma t_{(n-1),max}$ would be 3.69 in.; and because this is larger than $\Sigma t_{(n-1)}$ = ½ in., the bolt can be considered to be in the threads excluded or X condition.

RCSC Method

With a washer under the turned element, the grip + washer thickness is 3½ in. + ½ in. + 5⁄32 in. = 4 5⁄32 in. Thus, the length of the bolt can be determined as

$$L_{req} = 4\tfrac{5}{32} \text{ in.} + 1 \text{ in.}$$
$$= 5\tfrac{5}{32} \text{ in.}$$

Therefore, use L_{req} = 5½ in.

For the ¾-in.-diameter bolt, L_T = 1⅜ in.; thus, the shank would be expected to be 5½ in. − 1⅜ in. = 4⅛ in. long, and the engineer would expect the bolt to be in the threads excluded or X condition.

Example 4

Determine the bolt length for ⅞-in.-diameter ASTM F3125 Grade F2280 bolts in standard holes in an extended endplate moment connection (1-in.-thick plate) to a W14×132 column flange (nominal t_f = 1 in.) The column and endplate are both made of material with F_y = 50 ksi.

Recommended Solution

The required grip for this joint is 1 in. + 1 in. = 2 in. Because both plates joined are 1 in. thick, the $\Sigma t_{(n-1)}$ is 1 in. regardless of whether the bolt is installed through the column flange first or through the endplate first. Grade F2280 bolts are to be used, so an F436 washer is required under the nut. Because 50-ksi material is gripped by the F2280 bolts, a washer is not required under the head. Table A2 is used to select ⅞-in.-diameter bolts with a minimum grip less than or equal to 2 in. and a maximum grip greater than or equal to 2 in. The following options are available:

1. ⅞-in.-9×3¼-in. with one washer
   Min grip = 1.56 in.
   Max grip = 2.00 in.
   $\Sigma t_{(n-1),max}$ = 1.47 in.

2. ⅞-in.-9×3½-in. with one washer
   Min grip = 1.81 in.
   Max grip = 2.25 in.
   $\Sigma t_{(n-1),max}$ = 1.72 in.

3. ⅞-in.-9×3½-in. with two washers
   Min grip = 1.67 in.
   Max grip = 2.07 in.
   $\Sigma t_{(n-1),max}$ = 1.54 in.

4. ⅞-in.-9×3¾-in. with two washers
   Min grip = 1.92 in.
   Max grip = 2.32 in.
   $\Sigma t_{(n-1),max}$ = 1.79 in.

Based on the options available for this joint, a ⅞-in.-9×3½-in. bolt is recommended because it would be of an acceptable length either with one washer or with two washers. Because the smallest value of $\Sigma t_{(n-1),max}$ for this bolt is 1.54 in., which is greater than $\Sigma t_{(n-1)}$ = 1 in., the bolt can be designed in the threads excluded or X condition, in either case.

RCSC Method

With a washer under the nut of the bolting assembly, the grip + washer thickness is 1 in. + 1 in. + 5⁄32 in. = 2 5⁄32 in. Thus, the length of the bolt can be determined as

$$L_{req} = 2\tfrac{5}{32}\text{ in.} + 1\tfrac{1}{8}\text{ in.}$$
$$= 3\tfrac{9}{32}\text{ in.}$$

Therefore, use $L_{req} = 3\tfrac{1}{2}$ in.

For the ⅞-in.-diameter bolt, L_T = 1½ in.; thus the shank would be expected to be 3½ in. − 1½ in. = 2 in. long, and the engineer would expect the bolt to be in the threads excluded or X condition.

Example 5

Determine the length for 1-in.-diameter ASTM F3148 bolts in standard holes connecting a flange plate (1 in. thick) to the flange of a W24×76 beam (nominal t_f = 11⁄16 in.) in a moment connection. The beam and flange plate are both made of material with F_y = 50 ksi.

Recommended Solution

F3148 bolts ship as matched bolting assemblies with one washer that is to be used under the nut. The required grip for this joint is 1 in. + 11⁄16 in. = 1 11⁄16 in. To account for the tolerances in the depth of the beam, however, which are ±⅛ in. per ASTM A6 (AISC, 2017), the connection will be detailed allowing for the beam depth plus ⅛ in. Shims will be provided to accommodate a gap of up to (2)(⅛ in.) between one beam flange and the adjacent flange plate. Thus the required grip for the bolts could be as large as 1 in. + 11⁄16 in. + (2)(⅛ in.) = 1 15⁄16 in. If the bolts are installed though the beam flange first, the $\Sigma t_{(n-1)}$ would be 11⁄16 in. without shim plates and could be as large as 15⁄16 in. with shim plates. If the bolts are installed through the flange plate first, the

$\Sigma t_{(n-1)}$ would be 1 in. without shim plates and could be as large as 1¼ in. with shim plates.

Table A2 is used to select 1-in.-diameter bolts with a minimum grip less than or equal to 111⁄16 in. and a maximum grip greater than or equal to 1 15⁄16 in. Based on these criteria, the following options are available:

1. 1-in.-8×3½-in. with one washer
   Min grip = 1.55 in.
   Max grip = 2.12 in.
   $\Sigma t_{(n-1),max}$ = 1.44 in.

2. 1-in.-8×3½-in. with two washers
   Min grip = 1.42 in.
   Max grip = 1.94 in.
   $\Sigma t_{(n-1),max}$ = 1.26 in.

3. 1-in.-8×3¾-in. with two washers
   Min grip = 1.67 in.
   Max grip = 2.19 in.
   $\Sigma t_{(n-1),max}$ = 1.51 in.

Based on the options available for this joint, a 1-in.-8×3½-in. bolting assembly with one washer is selected. This assembly will accommodate a grip ranging from 1.55 in. to 2.12 in. with either one washer or two and will work in the joint either with or without shims. Using just one washer would eliminate the need for and the added cost of the second washer. It can be further noted that the minimum value of $\Sigma t_{(n-1),max}$ for the options shown is 1.26 in. Thus, because this is greater than the maximum considered $\Sigma t_{(n-1)}$, the bolts can be designed in the threads excluded or X condition regardless of which of the options is selected, regardless of the direction in which the bolts are installed, and regardless of whether or not shim plates are used. If for some reason the 1-in.-8×3½-in. bolting assembly was unavailable, the 1 in.-8×3¾ in. bolting assembly with two washers would also work, though this would require additional washers to be provided.

Example 6

Determine the appropriate length for ⅝-in.-diameter ASTM F3125 Grade F1852 bolts that are used in a double lap splice shear joint where two 1½-in.-thick splice plates are used to connect a 2½-in. main member.

Recommended Solution

The required grip for this joint is 1½ in. + 2½ in. + 1½ in. = 5½ in. The $\Sigma t_{(n-1)}$ is 1½ in. + 2½ in. = 4 in. regardless of the direction in which the bolts are installed. Because Grade F1852 bolts are specified, one hardened washer is required under the nut of the bolting assembly.

Using a required grip of 5½ in., Table A2 is used and it is noted that there is not a solution for a ⅝-in.-diameter assembly with one washer tabulated. Despite this, there are several options for this joint.

Option 1. From Table A2, select a ⅝-in.-11×7-in. bolting assembly with two washers. From the table, the minimum grip is 5.45 in. and the maximum grip is 5.77 in. If both washers are installed under the nut of the assembly, $\Sigma t_{(n-1),max}$ would be 5.53 in. Alternatively if one washer was installed under the head and one washer under the nut, then $\Sigma t_{(n-1),max}$ would be 5.35 in. In either case, $\Sigma t_{(n-1),max}$ would be larger than $\Sigma t_{(n-1)}$, indicating that the bolt could be designed in the threads excluded or X condition.

Option 2. Investigate the use of an assembly with tighter overall length tolerances: Using a required grip of 5½ in., Table A2 is used to select a bolt with one washer that has a minimum grip that is smaller than the required grip. A ⅝-in.-11×6½-in. bolting assembly is selected with a minimum grip of 5.07 in. and from Equation 4, the required length of the bolt can be determined as

$$L_{Rqd} = \text{Maximum grip} + \Sigma t_{washers} + t_{nut} \quad (8)$$

$$L_{Rqd} = 5\tfrac{1}{2}\text{ in.} + (1)(0.177\text{ in.}) + 0.631\text{ in.}$$
$$= 6.31\text{ in.}$$

As long as the bolt has an actual length of at least 6.31 in., even with a washer and nut that are both as thick as they can be while still within tolerance, the bolting assembly will work. The standard tolerance for overall length for this bolting assembly is −0.25 in. To be acceptable, the tolerance would need to be 6.31 in. − 6½ in. = −0.19 in. This is certainly achievable and can be accommodated by discussing needs with a reputable bolt supplier. In this case, $\Sigma t_{(n-1),max}$ would be 5.03 in., and because this is larger than $\Sigma t_{(n-1)}$ = 4.00 in., the bolt could again be designed in the threads excluded or X condition.

Option 3. Investigate the use of a ⅝-in.-11×6¾-in. bolting assembly with one washer under the nut: Though this bolt length is not included in Table A2, it would likely be available by special order given proper coordination with a bolt supplier. For the ⅝-in.-11×6¾-in. bolt,

$$
\begin{aligned}
L_{G,max} &= L_{nom} - L_T \\
&= 6\tfrac{3}{4}\text{ in.} - 1\tfrac{1}{4}\text{ in.} \\
&= 5.50\text{ in.}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
L_{B,min} &= L_{G,max} - Y \\
&= 5.50\text{ in.} - 0.22\text{ in.} \\
&= 5.28\text{ in.}
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
\text{Minimum grip} &= LG,max - \Sigma t_{washers} - \delta_{pretension} \\
&= 5.50\text{ in.} - (1)(0.177\text{ in.}) - (\tfrac{1}{2}\text{ turn})/(11) \\
&= 5.28\text{ in.}
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
\text{Maximum grip} &= L - \Sigma t_{washers} - t_{nut} \\
&= (6.75\text{ in.} - 0.25\text{ in.}) - (1)(0.177\text{ in.}) - 0.631\text{ in.} \\
&= 5.69\text{ in.}
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
\Sigma_{t(n-1)} &\leq L_{B,min} - \Sigma t_{washers\ under\ head} + f(Y) \\
&= 5.28\text{ in.} - (0\text{ in.}) + (0\text{ in.}) \\
&= 5.28\text{ in.}
\end{aligned} \tag{6}
$$

With these values, it can be seen that that the ⅝-in.-11×6¾-in. assembly with one washer under the nut would be acceptable and could be designed in the threads excluded or X condition.

SUMMARY AND CONCLUSIONS

The dimensional tolerances in ASME B18.2.6, to which F3125 and F3148 bolts must conform, consist of control dimensions and reference dimensions. Control dimensions and their tolerances are those that bolt manufacturers must meet in order for their product to be in conformance with published ASME and, by extension, ASTM standards. Resources that structural engineers and detailers commonly have available, however, typically provide reference dimensions for bolts. This inconsistency can lead to variances between the expectations of the engineer or detailer and what is actually built, possibly in ways that are unconservative.

It should be noted that this inconsistency has existed for nearly four decades. Prior to the introduction of ASME B18.2.6, the dimensions of high-strength fasteners were maintained in ASME B18.2.1 (1981). The dimensional requirements in ASME B18.2.619 can be traced back to at least the 1981 edition of ASME B18.2.1. Despite the fact that this misunderstanding has occurred in the design of numerous structures since at least 1981, the authors are not aware of a structural failure that has resulted from this specific issue. While this misunderstanding can certainly lead to unconservative designs, it might be considered only less conservative compared to actual demand. It should be noted that the application of resistance factors, documented overstrength of fasteners (Moore et al., 2010), and other factors mitigate the risk associated with these incorrect design assumptions.

Based on an analysis of available bolt diameters and lengths, a series of tables was generated to aid in the length determination of bolts for joints, considering the most punitive combination of dimensional tolerances of high-strength bolts, hardened washers, and heavy hex nuts. The tables present ranges of grip lengths that bolting assemblies can accommodate based on bolt diameter, bolt length, and washer configuration and also provide a tool for quickly determining whether the threads in a bolting assembly can be considered as "excluded" from the shear plane or whether they should be considered as "not excluded." Several design examples are presented demonstrating the use of these tables in determining the length of bolts and comparing the results with traditional methods presented in engineering and detailing resources.

The proposed design tables represent a departure from the approach presented by Carter (1996), where acceptable bolt lengths were tabulated for given grips. A similar approach was considered in the current work, but the resulting tables were substantially larger than those proposed, including some redundancies. Instead of centering on the required grip, the tables proposed in this work focus on acceptable grips for practically all available bolting assemblies. One notable difference between the tables presented by Carter and those proposed herein is that Carter's tables provide the minimum ply thickness closest to the nut ($t_{n,min}$) that is required to ensure that the threads are excluded from the shear plane. The tables proposed herein instead provide the maximum thickness of the plies closest to the head ($\Sigma t_{(n-1),max}$) that can be used to ensure that the threads are excluded from the shear plane. This latter approach was chosen because $\Sigma t_{(n-1),max}$ is not dependent on the number of washers used under the nut. For the example joints presented, bolt lengths determined using Carter's method match those determined using the method proposed herein, for the most part. In some cases, however, such as for ¾-in.-10×1¾-in. and ⅞-in.-9×2-in. bolts, Table 2 in Carter indicates that the bolts can be designed in the threads excluded or X condition for some ply thickness when, in fact, the bolts would be considered as fully threaded according to ASME B18.2.6.

It was observed that when the most punitive combination of tolerances for the bolt, washer, and nut were assumed to occur simultaneously, the minimum grip for a given bolt length was actually larger than the maximum grip for the next shorter bolt of the same diameter and washer configuration. This generally occurred for bolting assemblies ranging from ½ in. to ⅞ in. in diameter that are longer than 6-in. nominal length, although cases were observed for bolting assemblies of all diameters with multiple washers. Bolts longer than 6 in. have looser tolerances for nominal length than bolts 6 in. long and shorter. This, combined with the shorter threaded length of smaller-diameter bolts and the standard practice of producing bolts longer than 5 in. in ½-in.-long increments, leads to a situation where it may be difficult to determine an appropriate bolt length for a given joint. This potential situation is not likely to lead to too many difficulties in the field, but it could be eliminated if the rather permissive lower tolerance on bolt length was tightened up.

The design examples included illustrate potential situations where bolts selected using traditional methods of length determination might be designed in the threads excluded or X condition when they may actually be in the threads not excluded or N condition. Examples were also presented illustrating situations where an engineer or detailer may expect bolts to have a small, but predictable, shank when, in fact, they may—in full compliance with ASME B18.2.6—be manufactured fully threaded with no shank at all. It was shown that this second situation generally occurs for the shortest length of each diameter bolt that is routinely produced. While this represents a small percentage of the bolt lengths available, it should be noted that approximately 90% of bolts sold have a length less than four times their diameter, and bolts that are considered to be fully threaded per ASME B18.2.6 represent a disproportionately high percentage—possibly in excess of 35% for some diameters—of bolts sold.[6]

The ambiguous case of the ⅞-in.-9×2-in. bolt is encountered quite commonly. If ⅞-in.-diameter bolts were used to join two ⅜-in.-thick plates, a bolt with a length of 2 in. would be appropriate. The engineer, based on tables in resources readily available to him or her, may expect that the bolts would be in the threads excluded condition, as is shown in Figure 5(a). The bolts, however, would be considered as fully threaded according to ASME B18.2.6 and would actually be in the threads not excluded condition, as is shown in Figure 5(b). Note that selecting a ⅞-in.-9×2¼-in. bolt instead of a ⅞-in.-9×2-in. bolt would also be appropriate, but since this bolt is not considered to be fully threaded, it would have a minimum body length of $L_{B,min} = 0.47$ in. and could reliably be considered to be in the threads excluded condition.

Based on the analysis and examples included in this work, the authors recommend that bolts that are considered to be fully threaded per ASME B18.2.6 be designed for shear strength only in the threads not excluded or N condition. Bolts in this category are those that are the shortest produced for each diameter as is shown in Table 3 (in addition to 1⅜-in.- and 1½-in.-diameter bolts up to and including 3¼ in. long), which are those bolts shown above the solid lines in Tables A1 and A2.

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APPENDIX

Table A1. Maximum Grip Gage Length and Minimum Body Length for Common Structural Bolt Sizes

Bolt Length	Nominal Diameter and Threads per Inch																	
	½ in.-13		⅝ in.-11		¾ in.-10		⅞ in.-9		1 in.-8		1⅛ in.-7		1¼ in.-7		1⅜ in.-6		1½ in.-6	
L (in.)	$L_{G,max}$ (in.)	$L_{B,min}$ (in.)	$L_{G,max}$ (in.)	$L_{B,min}$ (in.)	$L_{G,max}$ (in.)	$L_{B,min}$ (in.)	$L_{G,max}$ (in.)	$L_{B,min}$ (in.)	$L_{G,max}$ (in.)	$L_{B,min}$ (in.)	$L_{G,max}$ (in.)	$L_{B,min}$ (in.)	$L_{G,max}$ (in.)	$L_{B,min}$ (in.)	$L_{G,max}$ (in.)	$L_{B,min}$ (in.)	$L_{G,max}$ (in.)	$L_{B,min}$ (in.)
1¼	0.19	0.06	0.23	0.00	0.25	0.00	0.28	0.00	0.31	0.00	0.50	0.00	0.50	0.00	0.58	0.00	0.58	0.00
1½	0.50	0.31	0.23	0.03	0.25	0.00	0.28	0.00	0.31	0.00	0.50	0.00	0.50	0.00	0.58	0.00	0.58	0.00
1¾	0.75	0.56	0.50	0.28	0.25	0.12	0.28	0.00	0.31	0.00	0.50	0.00	0.50	0.00	0.58	0.00	0.58	0.00
2	1.00	0.81	0.75	0.53	0.62	0.37	0.28	0.22	0.31	0.00	0.50	0.00	0.50	0.00	0.58	0.00	0.58	0.00
2¼	1.25	1.06	1.00	0.78	0.87	0.62	0.75	0.47	0.31	0.19	0.50	0.00	0.50	0.00	0.58	0.00	0.58	0.00
2½	1.50	1.31	1.25	1.03	1.12	0.87	1.00	0.72	0.75	0.44	0.50	0.16	0.50	0.12	0.58	0.00	0.58	0.00
2¾	1.75	1.56	1.50	1.28	1.37	1.12	1.25	0.97	1.00	0.69	0.50	0.41	0.50	0.37	0.58	0.06	0.58	0.06
3	2.00	1.81	1.75	1.53	1.62	1.37	1.50	1.22	1.25	0.94	1.00	0.66	1.00	0.62	0.58	0.31	0.58	0.31
3¼	2.25	2.06	2.00	1.78	1.87	1.62	1.75	1.47	1.50	1.19	1.25	0.91	1.25	0.87	0.58	0.56	0.58	0.56
3½	2.50	2.31	2.25	2.03	2.12	1.87	2.00	1.72	1.75	1.44	1.50	1.16	1.50	1.12	1.25	0.81	1.25	0.81
3¾	2.75	2.56	2.50	2.28	2.37	2.12	2.25	1.97	2.00	1.69	1.75	1.41	1.75	1.37	1.50	1.06	1.50	1.06
4	3.00	2.81	2.75	2.53	2.62	2.37	2.50	2.22	2.25	1.94	2.00	1.66	2.00	1.62	1.75	1.31	1.75	1.31
4¼	3.25	3.06	3.00	2.78	2.87	2.62	2.75	2.47	2.50	2.19	2.25	1.91	2.25	1.87	2.00	1.56	2.00	1.56
4½	3.50	3.31	3.25	3.03	3.12	2.87	3.00	2.72	2.75	2.44	2.50	2.16	2.50	2.12	2.25	1.81	2.25	1.81
4¾	3.75	3.56	3.50	3.28	3.37	3.12	3.25	2.97	3.00	2.69	2.75	2.41	2.75	2.37	2.50	2.06	2.50	2.06
5	4.00	3.81	3.75	3.53	3.62	3.37	3.50	3.22	3.25	2.94	3.00	2.66	3.00	2.62	2.75	2.31	2.75	2.31
5½	4.50	4.31	4.25	4.03	4.12	3.87	4.00	3.72	3.75	3.44	3.50	3.16	3.50	3.12	3.25	2.81	3.25	2.81
6	5.00	4.81	4.75	4.53	4.62	4.37	4.50	4.22	4.25	3.94	4.00	3.66	4.00	3.62	3.75	3.31	3.75	3.31
6½	5.50	5.31	5.25	5.03	5.12	4.87	5.00	4.72	4.75	4.44	4.50	4.16	4.50	4.12	4.25	3.81	4.25	3.81
7	6.00	5.81	5.75	5.53	5.62	5.37	5.50	5.22	5.25	4.94	5.00	4.66	5.00	4.62	4.75	4.31	4.75	4.31
7½	6.50	6.31	6.25	6.03	6.12	5.87	6.00	5.72	5.75	5.44	5.50	5.16	5.50	5.12	5.25	4.81	5.25	4.81
8	7.00	6.81	6.75	6.53	6.62	6.37	6.50	6.22	6.25	5.94	6.00	5.66	6.00	5.62	5.75	5.31	5.75	5.31
8½	7.50	7.31	7.25	7.03	7.12	6.87	7.00	6.72	6.75	6.44	6.50	6.16	6.50	6.12	6.25	5.81	6.25	5.81
9	8.00	7.81	7.75	7.53	7.62	7.37	7.50	7.22	7.25	6.94	7.00	6.66	7.00	6.62	6.75	6.31	6.75	6.31
9½	8.50	8.31	8.25	8.03	8.12	7.87	8.00	7.72	7.75	7.44	7.50	7.16	7.50	7.12	7.25	6.81	7.25	6.81
10	9.00	8.81	8.75	8.53	8.62	8.37	8.50	8.22	8.25	7.94	8.00	7.66	8.00	7.62	7.75	7.31	7.75	7.31

Notes: Cells above the solid line represent bolt lengths that are considered to be fully threaded per ASME B18.2.6. These bolts may or may not have a shank.
Shaded cells represent bolt lengths that are rarely produced. Italics values represent bolt lengths that are available by special order only.

Table A2. Minimum Grip, Maximum Grip, and Thread Condition for High-Strength Bolts								
	½-in.-Diameter Bolts							
	0 Washers		1 Washer		2 Washers		$\Sigma t_{(n-1),max}$	
Bolt Length (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	0 Washers (in.)	1 Washer (in.)
1¼	0.15	0.63	0.06	0.45	0.00	0.27	N	N
1½	0.46	0.88	0.36	0.70	0.27	0.52	0.31	0.13
1¾	0.71	1.13	0.61	0.95	0.52	0.77	0.56	0.38
2	0.96	1.38	0.86	1.20	0.77	1.02	0.81	0.63
2¼	1.21	1.63	1.11	1.45	1.02	1.27	1.06	0.88
2½	1.46	1.88	1.36	1.70	1.27	1.52	1.31	1.13
2¾	1.71	2.13	1.61	1.95	1.52	1.77	1.56	1.38
3	1.96	2.38	1.86	2.20	1.77	2.02	1.81	1.63
3¼	2.21	2.63	2.11	2.45	2.02	2.27	2.06	1.88
3½	2.46	2.88	2.36	2.70	2.27	2.52	2.31	2.13
3¾	2.71	3.13	2.61	2.95	2.52	2.77	2.56	2.38
4	2.96	3.38	2.86	3.20	2.77	3.02	2.81	2.63
4¼	3.20	3.63	3.10	3.45	3.00	3.27	3.06	2.88
4½	3.45	3.88	3.35	3.70	3.25	3.52	3.31	3.13
4¾	3.70	4.13	3.60	3.95	3.50	3.77	3.56	3.38
5	3.95	4.38	3.85	4.20	3.75	4.02	3.81	3.63
5½	4.45	4.88	4.35	4.70	4.25	4.52	4.31	4.13
6	4.95	5.38	4.85	5.20	4.75	5.02	4.81	4.63
6½	5.45	5.81	5.35	5.63	5.25	5.45	5.31	5.13
7	5.95	6.31	5.85	6.13	5.75	5.95	5.81	5.63
7½	6.45	6.81	6.35	6.63	6.25	6.45	6.31	6.13
8	6.95	7.31	6.85	7.13	6.75	6.95	6.81	6.63
8½	7.45	7.81	7.35	7.63	7.25	7.45	7.31	7.13
9	7.95	8.31	7.85	8.13	7.75	7.95	7.81	7.63
9½	8.45	8.81	8.35	8.63	8.25	8.45	8.31	8.13
10	8.95	9.31	8.85	9.13	8.75	8.95	8.81	8.63

Notes: For Min Grip and Max Grip, consider the total number of F436 washers used under the head and under the nut.
For the $\Sigma t_{(n-1),max}$, consider only the number of F436 washers under the head of the bolt.
"N" indicates bolts that should be designed in the "threads not excluded" or "N" condition only.
Cells above the heavy line represent bolt lengths that are considered to be fully threaded per ASME B18.2.6.

Table A2. Minimum Grip, Maximum Grip, and Thread Condition for High-Strength Bolts (continued)								
	⅝-in.-Diameter Bolts							
	0 Washers		1 Washer		2 Washers		$\Sigma t_{(n-1),max}$	
Bolt Length (in.)	**Min Grip (in.)**	**Max Grip (in.)**	**Min Grip (in.)**	**Max Grip (in.)**	**Min Grip (in.)**	**Max Grip (in.)**	**0 Washers (in.)**	**1 Washer (in.)**
1¼	0.18	0.50	0.06	0.32	0.00	0.15	N	N
1½	0.18	0.75	0.06	0.57	0.00	0.40	N	N
1¾	0.45	1.00	0.33	0.82	0.21	0.65	0.28	0.10
2	0.70	1.25	0.58	1.07	0.46	0.90	0.53	0.35
2¼	0.95	1.50	0.83	1.32	0.71	1.15	0.78	0.60
2½	1.20	1.75	1.08	1.57	0.96	1.40	1.03	0.85
2¾	1.45	2.00	1.33	1.82	1.21	1.65	1.28	1.10
3	1.70	2.25	1.58	2.07	1.46	1.90	1.53	1.35
3¼	1.95	2.50	1.83	2.32	1.71	2.15	1.78	1.60
3½	2.20	2.75	2.08	2.57	1.96	2.40	2.03	1.85
3¾	2.45	3.00	2.33	2.82	2.21	2.65	2.28	2.10
4	2.70	3.25	2.58	3.07	2.46	2.90	2.53	2.35
4¼	2.95	3.50	2.83	3.32	2.71	3.15	2.78	2.60
4½	3.20	3.75	3.08	3.57	2.96	3.40	3.03	2.85
4¾	3.45	4.00	3.33	3.82	3.21	3.65	3.28	3.10
5	3.70	4.25	3.58	4.07	3.46	3.90	3.53	3.35
5½	4.19	4.75	4.07	4.57	3.95	4.40	4.03	3.85
6	4.69	5.25	4.57	5.07	4.45	4.90	4.53	4.35
6½	5.19	5.62	5.07	5.44	4.95	5.27	5.03	4.85
7	5.69	6.12	5.57	5.94	5.45	5.77	5.53	5.35
7½	6.19	6.62	6.07	6.44	5.95	6.27	6.03	5.85
8	6.69	7.12	6.57	6.94	6.45	6.77	6.53	6.35
8½	7.19	7.62	7.07	7.44	6.95	7.27	7.03	6.85
9	7.69	8.12	7.57	7.94	7.45	7.77	7.53	7.35
9½	8.19	8.62	8.07	8.44	7.95	8.27	8.03	7.85
10	8.69	9.12	8.57	8.94	8.45	8.77	8.53	8.35

Notes: For Min Grip and Max Grip, consider the total number of F436 washers used under the head and under the nut.
For the $\Sigma t_{(n-1),max}$, consider only the number of F436 washers under the head of the bolt.
"N" indicates bolts that should be designed in the "threads not excluded" or "N" condition only.
Cells above the heavy line represent bolt lengths that are considered to be fully threaded per ASME B18.2.6.
Shaded cells represent bolt lengths that are rarely produced.

Table A2. Minimum Grip, Maximum Grip, and Thread Condition for High-Strength Bolts (continued)								
	¾-in.-Diameter Bolts							
	0 Washers		1 Washer		2 Washers		$\Sigma t_{(n-1),max}$	
Bolt Length (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	0 Washers (in.)	1 Washer (in.)
1¼	*0.20*	*0.30*	*0.08*	*0.13*	—	—	*N*	*N*
1½	0.20	0.55	0.08	0.38	0.00	0.20	N	N
1¾	0.20	0.80	0.08	0.63	0.00	0.45	N	N
2	0.57	1.05	0.45	0.88	0.33	0.70	0.37	0.19
2¼	0.82	1.30	0.70	1.13	0.58	0.95	0.62	0.44
2½	1.07	1.55	0.95	1.38	0.83	1.20	0.87	0.69
2¾	1.32	1.80	1.20	1.63	1.08	1.45	1.12	0.94
3	1.57	2.05	1.45	1.88	1.33	1.70	1.37	1.19
3¼	1.82	2.30	1.70	2.13	1.58	1.95	1.62	1.44
3½	2.07	2.55	1.95	2.38	1.83	2.20	1.87	1.69
3¾	2.32	2.80	2.20	2.63	2.08	2.45	2.12	1.94
4	2.57	3.05	2.45	2.88	2.33	2.70	2.37	2.19
4¼	2.82	3.30	2.70	3.13	2.58	2.95	2.62	2.44
4½	3.07	3.55	2.95	3.38	2.83	3.20	2.87	2.69
4¾	3.32	3.80	3.20	3.63	3.08	3.45	3.12	2.94
5	3.57	4.05	3.45	3.88	3.33	3.70	3.37	3.19
5½	4.07	4.55	3.95	4.38	3.83	4.20	3.87	3.69
6	4.57	5.05	4.45	4.88	4.33	4.70	4.37	4.19
6½	5.05	5.49	4.93	5.32	4.81	5.14	4.87	4.69
7	5.55	5.99	5.43	5.82	5.31	5.64	5.37	5.19
7½	6.05	6.49	5.93	6.32	5.81	6.14	5.87	5.69
8	6.55	6.99	6.43	6.82	6.31	6.64	6.37	6.19
8½	7.05	7.49	6.93	7.32	6.81	7.14	6.87	6.69
9	7.55	7.99	7.43	7.82	7.31	7.64	7.37	7.19
9½	8.05	8.49	7.93	8.32	7.81	8.14	7.87	7.69
10	8.55	8.99	8.43	8.82	8.31	8.64	8.37	8.19

Notes: For Min Grip and Max Grip, consider the total number of F436 washers used under the head and under the nut.
For the $\Sigma t_{(n-1),max}$, consider only the number of F436 washers under the head of the bolt.
"N" indicates bolts that should be designed in the "threads not excluded" or "N" condition only.
Cells above the heavy line represent bolt lengths that are considered to be fully threaded per ASME B18.2.6.
Shaded cells represent bolt lengths that are rarely produced.
Italics values indicate bolt lengths that are available by special order only.
"—" indicates bolt assemblies where the nut may not be able to be threaded fully onto the bolt.

Table A2. Minimum Grip, Maximum Grip, and Thread Condition for High-Strength Bolts (continued)								
	⅞-in.-Diameter Bolts							
	0 Washers		1 Washer		2 Washers		$\Sigma t_{(n-1),max}$	
Bolt Length (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	0 Washers (in.)	1 Washer (in.)
1¼	*0.22*	*0.18*	—	—	—	—	*N*	*N*
1½	*0.22*	*0.43*	*0.09*	*0.25*	*0.00*	*0.07*	*N*	*N*
1¾	0.22	0.68	0.09	0.50	0.00	0.32	N	N
2	0.22	0.93	0.09	0.75	0.00	0.57	N	N
2¼	0.69	1.18	0.56	1.00	0.42	0.82	0.47	0.29
2½	0.94	1.43	0.81	1.25	0.67	1.07	0.72	0.54
2¾	1.19	1.68	1.06	1.50	0.92	1.32	0.97	0.79
3	1.44	1.93	1.31	1.75	1.17	1.57	1.22	1.04
3¼	1.69	2.18	1.56	2.00	1.42	1.82	1.47	1.29
3½	1.94	2.43	1.81	2.25	1.67	2.07	1.72	1.54
3¾	2.19	2.68	2.06	2.50	1.92	2.32	1.97	1.79
4	2.44	2.93	2.31	2.75	2.17	2.57	2.22	2.04
4¼	2.69	3.18	2.56	3.00	2.42	2.82	2.47	2.29
4½	2.94	3.43	2.81	3.25	2.67	3.07	2.72	2.54
4¾	3.19	3.68	3.06	3.50	2.92	3.32	2.97	2.79
5	3.44	3.93	3.31	3.75	3.17	3.57	3.22	3.04
5½	3.94	4.43	3.81	4.25	3.67	4.07	3.72	3.54
6	4.44	4.93	4.31	4.75	4.17	4.57	4.22	4.04
6½	4.94	5.37	4.81	5.19	4.67	5.01	4.72	4.54
7	5.44	5.87	5.31	5.69	5.17	5.51	5.22	5.04
7½	5.93	6.37	5.79	6.19	5.65	6.01	5.72	5.54
8	6.43	6.87	6.29	6.69	6.15	6.51	6.22	6.04
8½	6.93	7.37	6.79	7.19	6.65	7.01	6.72	6.54
9	7.43	7.87	7.29	7.69	7.15	7.51	7.22	7.04
9½	7.93	8.37	7.79	8.19	7.65	8.01	7.72	7.54
10	8.43	8.87	8.29	8.69	8.15	8.51	8.22	8.04

Notes: For Min Grip and Max Grip, consider the total number of F436 washers used under the head and under the nut.
For the $\Sigma t_{(n-1),max}$, consider only the number of F436 washers under the head of the bolt.
"N" indicates bolts that should be designed in the "threads not excluded" or "N" condition only.
Cells above the heavy line represent bolt lengths that are considered to be fully threaded per ASME B18.2.6.
Shaded cells represent bolt lengths that are rarely produced.
Italics values indicate bolt lengths that are available by special order only.
"—" indicates bolt assemblies where the nut may not be able to be threaded fully onto the bolt.

Table A2. Minimum Grip, Maximum Grip, and Thread Condition for High-Strength Bolts (continued)								
	1-in.-Diameter Bolts							
	0 Washers		1 Washer		2 Washers		$\Sigma t_{(n-1),max}$	
Bolt Length (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	0 Washers (in.)	1 Washer (in.)
1¼	—	—	—	—	—	—	—	—
1½	—	—	—	—	—	—	—	—
1¾	*0.25*	*0.55*	*0.11*	*0.37*	*0.00*	*0.19*	*N*	*N*
2	0.25	0.80	0.11	0.62	0.00	0.44	N	N
2¼	0.25	1.05	0.11	0.87	0.00	0.69	N	N
2½	0.69	1.30	0.55	1.12	0.42	0.94	0.44	0.26
2¾	0.94	1.55	0.80	1.37	0.67	1.19	0.69	0.51
3	1.19	1.80	1.05	1.62	0.92	1.44	0.94	0.76
3¼	1.44	2.05	1.30	1.87	1.17	1.69	1.19	1.01
3½	1.69	2.30	1.55	2.12	1.42	1.94	1.44	1.26
3¾	1.94	2.55	1.80	2.37	1.67	2.19	1.69	1.51
4	2.19	2.80	2.05	2.62	1.92	2.44	1.94	1.76
4¼	2.44	3.05	2.30	2.87	2.17	2.69	2.19	2.01
4½	2.69	3.30	2.55	3.12	2.42	2.94	2.44	2.26
4¾	2.94	3.55	2.80	3.37	2.67	3.19	2.69	2.51
5	3.19	3.80	3.05	3.62	2.92	3.44	2.94	2.76
5½	3.69	4.30	3.55	4.12	3.42	3.94	3.44	3.26
6	4.19	4.80	4.05	4.62	3.92	4.44	3.94	3.76
6½	4.69	5.24	4.55	5.06	4.42	4.88	4.44	4.26
7	5.19	5.74	5.05	5.56	4.92	5.38	4.94	4.76
7½	5.69	6.24	5.55	6.06	5.42	5.88	5.44	5.26
8	6.19	6.74	6.05	6.56	5.92	6.38	5.94	5.76
8½	6.67	7.24	6.53	7.06	6.39	6.88	6.44	6.26
9	7.17	7.74	7.03	7.56	6.89	7.38	6.94	6.76
9½	7.67	8.24	7.53	8.06	7.39	7.88	7.44	7.26
10	8.17	8.74	8.03	8.56	7.89	8.38	7.94	7.76

Notes: For Min Grip and Max Grip, consider the total number of F436 washers used under the head and under the nut.
For the $\Sigma t_{(n-1),max}$, consider only the number of F436 washers under the head of the bolt.
"N" indicates bolts that should be designed in the "threads not excluded" or "N" condition only.
Cells above the heavy line represent bolt lengths that are considered to be fully threaded per ASME B18.2.6.
Shaded cells represent bolt lengths that are rarely produced.
Italics values indicate bolt lengths that are available by special order only.
"—" indicates bolt assemblies where the nut may not be able to be threaded fully onto the bolt.

Table A2. Minimum Grip, Maximum Grip, and Thread Condition for High-Strength Bolts (continued)								
	1⅛-in.-Diameter Bolts							
	0 Washers		1 Washer		2 Washers		$\Sigma t_{(n-1),max}$	
Bolt Length (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	0 Washers (in.)	1 Washer (in.)
1¼	—	—	—	—	—	—	—	—
1½	—	—	—	—	—	—	—	—
1¾	—	—	—	—	—	—	—	—
2	*0.43*	*0.61*	*0.29*	*0.43*	*0.16*	*0.26*	*N*	*N*
2¼	*0.43*	*0.86*	*0.29*	*0.68*	*0.16*	*0.51*	*N*	*N*
2½	0.43	1.11	0.29	0.93	0.16	0.76	N	N
2¾	0.43	1.36	0.29	1.18	0.16	1.01	N	N
3	0.93	1.61	0.79	1.43	0.66	1.26	0.66	0.48
3¼	1.18	1.86	1.04	1.68	0.91	1.51	0.91	0.73
3½	1.43	2.11	1.29	1.93	1.16	1.76	1.16	0.98
3¾	1.68	2.36	1.54	2.18	1.41	2.01	1.41	1.23
4	1.93	2.61	1.79	2.43	1.66	2.26	1.66	1.48
4¼	2.18	2.86	2.04	2.68	1.91	2.51	1.91	1.73
4½	2.43	3.11	2.29	2.93	2.16	2.76	2.16	1.98
4¾	2.68	3.36	2.54	3.18	2.41	3.01	2.41	2.23
5	2.93	3.61	2.79	3.43	2.66	3.26	2.66	2.48
5½	3.43	4.11	3.29	3.93	3.16	3.76	3.16	2.98
6	3.93	4.61	3.79	4.43	3.66	4.26	3.66	3.48
6½	4.43	5.11	4.29	4.93	4.16	4.76	4.16	3.98
7	4.93	5.61	4.79	5.43	4.66	5.26	4.66	4.48
7½	5.43	6.11	5.29	5.93	5.16	5.76	5.16	4.98
8	5.93	6.61	5.79	6.43	5.66	6.26	5.66	5.48
8½	6.43	7.11	6.29	6.93	6.16	6.76	6.16	5.98
9	6.93	7.61	6.79	7.43	6.66	7.26	6.66	6.48
9½	7.40	8.11	7.27	7.93	7.13	7.76	7.16	6.98
10	7.90	8.61	7.77	8.43	7.63	8.26	7.66	7.48

Notes: For Min Grip and Max Grip, consider the total number of F436 washers used under the head and under the nut.
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Cells above the heavy line represent bolt lengths that are considered to be fully threaded per ASME B18.2.6.
Shaded cells represent bolt lengths that are rarely produced.
Italics values indicate bolt lengths that are available by special order only.
"—" indicates bolt assemblies where the nut may not be able to be threaded fully onto the bolt.

Table A2. Minimum Grip, Maximum Grip, and Thread Condition for High-Strength Bolts (continued)								
	1¼-in.-Diameter Bolts							
	0 Washers		1 Washer		2 Washers		$\Sigma t_{(n-1),max}$	
Bolt Length (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	0 Washers (in.)	1 Washer (in.)
1¼	—	—	—	—	—	—	—	—
1½	—	—	—	—	—	—	—	—
1¾	—	—	—	—	—	—	—	—
2	*0.43*	*0.50*	*0.29*	*0.32*	—	—	*N*	*N*
2¼	*0.43*	*0.75*	*0.29*	*0.57*	*0.16*	*0.40*	*N*	*N*
2½	0.43	1.00	0.29	0.82	0.16	0.65	N	N
2¾	0.43	1.25	0.29	1.07	0.16	0.90	N	N
3	0.93	1.50	0.79	1.32	0.66	1.15	0.62	0.44
3¼	1.18	1.75	1.04	1.57	0.91	1.40	0.87	0.69
3½	1.43	2.00	1.29	1.82	1.16	1.65	1.12	0.94
3¾	1.68	2.25	1.54	2.07	1.41	1.90	1.37	1.19
4	1.93	2.50	1.79	2.32	1.66	2.15	1.62	1.44
4¼	2.18	2.75	2.04	2.57	1.91	2.40	1.87	1.69
4½	2.43	3.00	2.29	2.82	2.16	2.65	2.12	1.94
4¾	2.68	3.25	2.54	3.07	2.41	2.90	2.37	2.19
5	2.93	3.50	2.79	3.32	2.66	3.15	2.62	2.44
5½	3.43	4.00	3.29	3.82	3.16	3.65	3.12	2.94
6	3.93	4.50	3.79	4.32	3.66	4.15	3.62	3.44
6½	4.43	5.00	4.29	4.82	4.16	4.65	4.12	3.94
7	4.93	5.50	4.79	5.32	4.66	5.15	4.62	4.44
7½	5.43	6.00	5.29	5.82	5.16	5.65	5.12	4.94
8	5.93	6.50	5.79	6.32	5.66	6.15	5.62	5.44
8½	6.43	7.00	6.29	6.82	6.16	6.65	6.12	5.94
9	6.93	7.50	6.79	7.32	6.66	7.15	6.62	6.44
9½	7.43	8.00	7.29	7.82	7.16	7.65	7.12	6.94
10	7.93	8.50	7.79	8.32	7.66	8.15	7.62	7.44

Notes: For Min Grip and Max Grip, consider the total number of F436 washers used under the head and under the nut.
For the $\Sigma t_{(n-1),max}$, consider only the number of F436 washers under the head of the bolt.
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"—" indicates bolt assemblies where the nut may not be able to be threaded fully onto the bolt.

Table A2. Minimum Grip, Maximum Grip, and Thread Condition for High-Strength Bolts (continued)								
	1⅜-in.-Diameter Bolts							
	0 Washers		1 Washer		2 Washers		$\Sigma t_{(n-1),max}$	
Bolt Length (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	0 Washers (in.)	1 Washer (in.)
1¼	—	—	—	—	—	—	—	—
1½	—	—	—	—	—	—	—	—
1¾	—	—	—	—	—	—	—	—
2	—	—	—	—	—	—	—	—
2¼	*0.50*	*0.62*	*0.36*	*0.45*	*0.23*	*0.27*	*N*	*N*
2½	*0.50*	*0.87*	*0.36*	*0.70*	*0.23*	*0.52*	*N*	*N*
2¾	*0.50*	*1.12*	*0.36*	*0.95*	*0.23*	*0.77*	*N*	*N*
3	*0.50*	*1.37*	*0.36*	*1.20*	*0.23*	*1.02*	*N*	*N*
3¼	*0.50*	*1.62*	*0.36*	*1.45*	*0.23*	*1.27*	*N*	*N*
3½	*1.17*	*1.87*	*1.03*	*1.70*	*0.89*	*1.52*	*0.81*	*0.63*
3¾	*1.42*	*2.12*	*1.28*	*1.95*	*1.14*	*1.77*	*1.06*	*0.88*
4	*1.67*	*2.37*	*1.53*	*2.20*	*1.39*	*2.02*	*1.31*	*1.13*
4¼	*1.92*	*2.62*	*1.78*	*2.45*	*1.64*	*2.27*	*1.56*	*1.38*
4½	*2.17*	*2.87*	*2.03*	*2.70*	*1.89*	*2.52*	*1.81*	*1.63*
4¾	*2.42*	*3.12*	*2.28*	*2.95*	*2.14*	*2.77*	*2.06*	*1.88*
5	*2.67*	*3.37*	*2.53*	*3.20*	*2.39*	*3.02*	*2.31*	*2.13*
5½	*3.17*	*3.87*	*3.03*	*3.70*	*2.89*	*3.52*	*2.81*	*2.63*
6	*3.67*	*4.37*	*3.53*	*4.20*	*3.39*	*4.02*	*3.31*	*3.13*
6½	*4.17*	*4.87*	*4.03*	*4.70*	*3.89*	*4.52*	*3.81*	*3.63*
7	*4.67*	*5.37*	*4.53*	*5.20*	*4.39*	*5.02*	*4.31*	*4.13*
7½	*5.17*	*5.87*	*5.03*	*5.70*	*4.89*	*5.52*	*4.81*	*4.63*
8	*5.67*	*6.37*	*5.53*	*6.20*	*5.39*	*6.02*	*5.31*	*5.13*
8½	*6.17*	*6.87*	*6.03*	*6.70*	*5.89*	*6.52*	*5.81*	*5.63*
9	*6.67*	*7.37*	*6.53*	*7.20*	*6.39*	*7.02*	*6.31*	*6.13*
9½	*7.17*	*7.87*	*7.03*	*7.70*	*6.89*	*7.52*	*6.81*	*6.63*
10	*7.67*	*8.37*	*7.53*	*8.20*	*7.39*	*8.02*	*7.31*	*7.13*

Notes: For Min Grip and Max Grip, consider the total number of F436 washers used under the head and under the nut.
For the $\Sigma t_{(n-1),max}$, consider only the number of F436 washers under the head of the bolt.
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Shaded cells represent bolt lengths that are rarely produced.
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"—" indicates bolt assemblies where the nut may not be able to be threaded fully onto the bolt.

Table A2. Minimum Grip, Maximum Grip, and Thread Condition for High-Strength Bolts (continued)								
	1½-in.-Diameter Bolts							
	0 Washers		1 Washer		2 Washers		$\Sigma t_{(n-1),max}$	
Bolt Length (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	Min Grip (in.)	Max Grip (in.)	0 Washers (in.)	1 Washer (in.)
1¼	—	—	—	—	—	—	—	—
1½	—	—	—	—	—	—	—	—
1¾	—	—	—	—	—	—	—	—
2	—	—	—	—	—	—	—	—
2¼	—	—	—	—	—	—	—	—
2½	*0.50*	*0.75*	*0.36*	*0.57*	*0.23*	*0.39*	*N*	*N*
2¾	*0.50*	*1.00*	*0.36*	*0.82*	*0.23*	*0.64*	*N*	*N*
3	*0.50*	*1.25*	*0.36*	*1.07*	*0.23*	*0.89*	*N*	*N*
3¼	0.50	1.50	0.36	1.32	0.23	1.14	N	N
3½	1.17	1.75	1.03	1.57	0.89	1.39	0.81	0.63
3¾	1.42	2.00	1.28	1.82	1.14	1.64	1.06	0.88
4	1.67	2.25	1.53	2.07	1.39	1.89	1.31	1.13
4¼	1.92	2.50	1.78	2.32	1.64	2.14	1.56	1.38
4½	2.17	2.75	2.03	2.57	1.89	2.39	1.81	1.63
4¾	2.42	3.00	2.28	2.82	2.14	2.64	2.06	1.88
5	2.67	3.25	2.53	3.07	2.39	2.89	2.31	2.13
5½	3.17	3.75	3.03	3.57	2.89	3.39	2.81	2.63
6	3.67	4.25	3.53	4.07	3.39	3.89	3.31	3.13
6½	4.17	4.75	4.03	4.57	3.89	4.39	3.81	3.63
7	4.67	5.25	4.53	5.07	4.39	4.89	4.31	4.13
7½	5.17	5.75	5.03	5.57	4.89	5.39	4.81	4.63
8	5.67	6.25	5.53	6.07	5.39	5.89	5.31	5.13
8½	6.17	6.75	6.03	6.57	5.89	6.39	5.81	5.63
9	6.67	7.25	6.53	7.07	6.39	6.89	6.31	6.13
9½	7.17	7.75	7.03	7.57	6.89	7.39	6.81	6.63
10	7.67	8.25	7.53	8.07	7.39	7.89	7.31	7.13

Notes: For Min Grip and Max Grip, consider the total number of F436 washers used under the head and under the nut.
For the $\Sigma t_{(n-1),max}$, consider only the number of F436 washers under the head of the bolt.
"N" indicates bolts that should be designed in the "threads not excluded" or "N" condition only.
Cells above the heavy line represent bolt lengths that are considered to be fully threaded per ASME B18.2.6.
Shaded cells represent bolt lengths that are rarely produced.
Italics values indicate bolt lengths that are available by special order only.
"—" indicates bolt assemblies where the nut may not be able to be threaded fully onto the bolt.