steelwise

STRENGTH AND ENGAGEMENT

BY JAMES LABELLE, PE, DocE

Notes on thread strength and partial engagement of anchor rod nuts.

EVERY ANCHOR ROD has its limit.

Here, we'll discuss the limit state of thread stripping in threaded steel anchor rods (anchor bolts), used with nuts, for diameters, *D*, from 0.5 in. to 4 in.

Internal threads (nuts) or external threads (threaded rod) could strip under certain conditions. This limit state can usually be avoided by having a suitable type of nut fully engaged with the threaded fastener. A thread's strip strength depends on both its geometry and material. An external unified coarse thread (UNC), whose cross section is approximately triangular, is wrapped as a helix around a solid cylinder. The number of threads that resist load depends on the thread spacing, or pitch, and the engaged length of the nut with the fastener, parallel to the fastener's longitudinal axis.

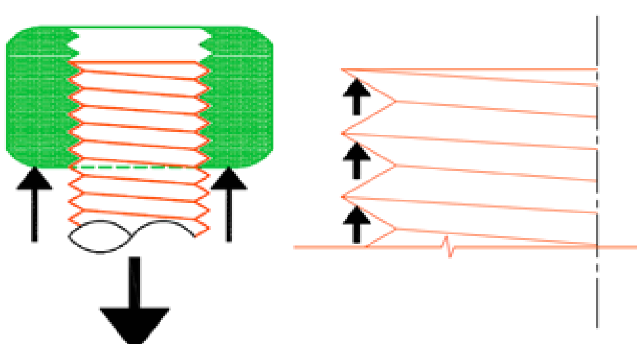

Figure 1a and 1b

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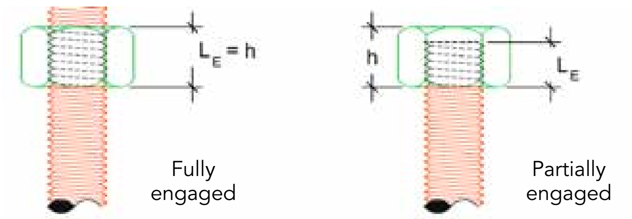


Figure 2. (Note: While protrusion through the nut is shown in the fully engaged example above, it is not necessary for full engagement.)

Load Path

The load path for a tension-loaded threaded fastener with a heavy-hex nut is shown in Figures 1a and 1b. For example, a base plate pushes up against a washer which then pushes against a nut. The nut's threads then push against the corresponding threads of the anchor rod. The anchor threads in turn transmit most of the load into the root diameter portion of the rod—the solid cylinder portion—producing tension stress. However, some of the tension force remains in the threads because they are integral with the root cylinder. For tension, the effective stress area of the anchor rod is its tensile stress area A_T, which is less than the gross area A_G but greater than the root area. See Equation 1, (per references 1, 2, 3 and 6) and Equation 2 (per references 3 and 5). The ratio of A_T to A_G is not a constant, and ranges from 0.72 to 0.88, as shown in Figure 3. Thread spacing *n*, in threads per inch, varies from 13 to 4 for this diameter range (see Table 1).

Table 1

Diam. (in.)	n (threads/in.)	Diam. (in.)	n (threads/in.)	Diam. (in.)	n (threads/in.)
½	13	1¼	7	2¾	4
9⁄16	12	1	6	3	4
⅝	11	1½	6	3¼	4
¾	10	1¾	5	3½	4
⅞	9	2	4.5	3¾	4
1	8	2¼	4.5	4	4
1⅛	7	2½	4		

$$A_T = (\pi/4)\,(D - [0.9743/n])^2 \qquad (1)$$

$$A_G = (\pi/4)D^2 \qquad (2)$$

Figure 3. Ratio A_T/A_G vs. Diameter, for UNC Threaded Fasteners

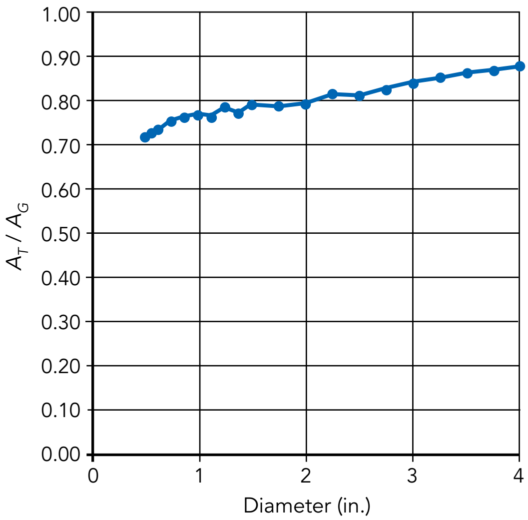


Figure 4. Strip Area per Thread vs. Diameter (UNC Thread)

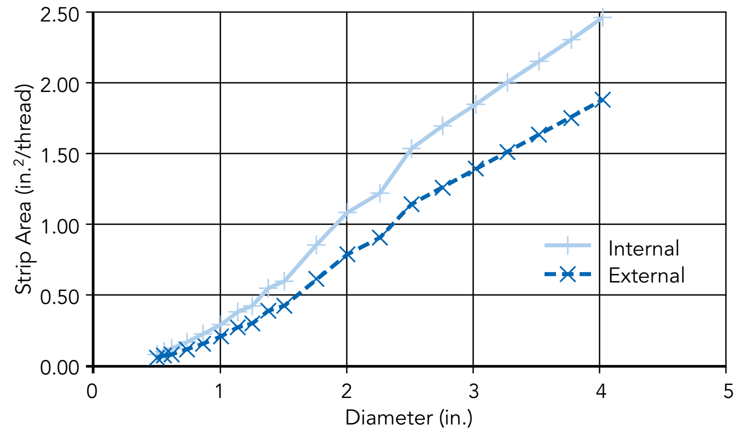


Figure 6. Safety Factor S_F vs. Diameter, for UNC Threaded Fasteners (Tension; Ω = 2.0)

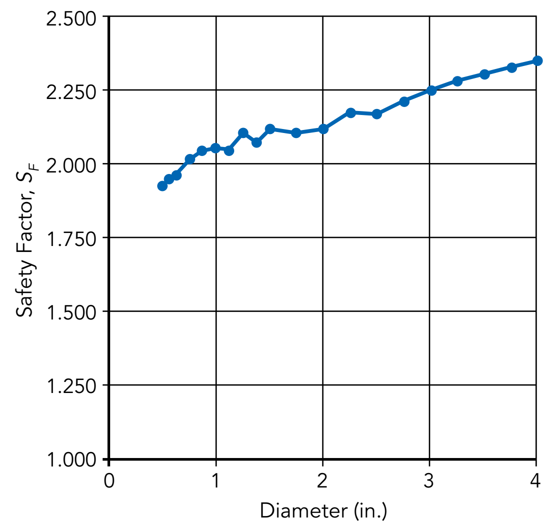
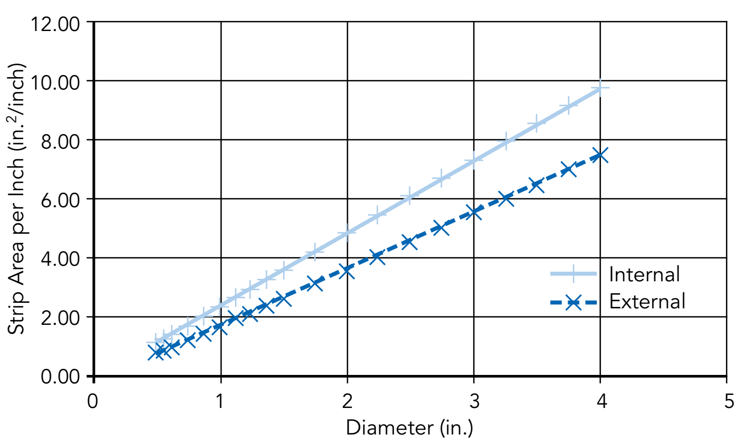


Figure 5. Strip Area per in. vs. Diameter (UNC Thread)



Thread Stripping

The engaged threads of the nut and rod are resisting load via local shear stress along the engaged length. Stripping occurs if the shear stress in the nut or the rod threads reaches the ultimate shear stress. A thread's shear stress depends on the force per thread and the stripping area per thread. Prior to stripping, shear yielding will typically occur. See Eq. 3 and Eq. 4 for stripping areas, per thread, for external and internal threads.

$$A_{TSE} = \pi c \left[(1/(2n)) + (1/\sqrt{3})(b-c)\right], \text{ ext. thread} \qquad (3)$$

$$A_{TSI} = \pi a \left[(1/(2n)) + (1/\sqrt{3})(a-d)\right], \text{ int. thread} \qquad (4)$$

where
c = maximum minor diameter of internal thread
b = minimum pitch diameter of external thread
a = minimum major diameter of external thread
d = maximum pitch diameter of internal thread

The preceding variables for bolts and nuts are given in references 1, 2 and 3. Figure 4 is a plot of the strip area per thread, and Figure 5 illustrates the strip area per inch, for external and internal threads.

To better understand thread stripping, it is helpful to know that an external thread's strip area per thread is significantly smaller than that of the corresponding internal thread. Thus as long as the bolt material's tensile ultimate stress F_U does not exceed that of the nut, the bolt threads' strip strength governs the stripping failure mode. The ratio of A_{TSE} to A_{TSI} ranges from 0.70 to 0.77.

In an idealized simple model, engaged threads would contact uniformly along the full length of the helix. The bolt would be rigid and the force on each thread would be the same for a given bolt tension. In reality though, there is variation. Steel's elasticity and ductility, tolerances in fabricated threads and the geometric details of a nut and anchor rod all contribute to variation in the force per thread. For example, the threads closest to the loaded face of the nut resist a disproportionately high fraction of the total load. Within limits, a sufficiently high tension will cause local yielding of some threads and allow for partial redistribution of force among threads.

One aspect of nut behavior is the dilation, or increase in diameter, that occurs as the applied tension force increases. This response is due to the radial component of force per thread that is caused by the sloping contact faces of the triangular cross-section threads. Proper nut design limits this behavior.

Partial Engagement

If a nut is not fully engaged with an anchor rod (see Figure 2) and the required tension is less than the rod's full allowable, then there are design methods that can be used to evaluate structural adequacy.

Method 1 (AISC Design Guide 1: *Base Plate and Anchor Rod Design*, 2nd ed.) conservatively limits the engagement length L_E to a minimum of half of the nut's height h. At this minimum engagement, the reduced allowable rod tension T_{A1} is considered to be half of its full (basic) allowable T_A. Partial-engagement lengths in between 50% and 100% of the nut height result in linear reductions of T_A:

$$T_{A1} = (L_E/h)T_A \quad (5)$$
where $0.5\ h \le L_E \le h$

Method 2 (AAMA *Design Guide for Metal Cladding Fasteners*) involves the use of an approximate equation for allowable bolt tension T_{A2}, which is based on external thread strength and the average load per engaged thread:

$$T_{A2} = F_{SU}A_{TSE}nL_E/S_{F2} = F_{SU}A_{TSEU}L_E/S_{F2} \quad (6)$$

where
F_{SU} = ultimate shear stress for anchor, ksi
A_{TSE} = stripping area per external thread, in.^{2}
S_{F2} = safety factor for Method 2
A_{TSEU} = stripping area per unit length of external thread, in.^{2}/in.

Use $F_{SU} = F_U/\sqrt{3}$ and $S_{F2} = 2.5$ per reference 3.

Heavy-hex Nut

A suitable heavy-hex nut (HHN, fully engaged) will, without thread stripping, allow a matching bolt or anchor to develop its tensile ultimate at the threaded cross-section. By calculation, using the external threads' minimum strip-strength and the average force per bolt thread, a HHN can develop at least 1.5 times the minimum tensile ultimate of the threaded bolt.

Here's an example: UNC thread series, $D = 1.25$ in., $n = 7$ threads/in.; anchor rod is ASTM F1554 Gr. 36 ($F_U = 58$ ksi); heavy-hex nut (Grade A) for which $F_U > 58$ ksi, height $h = 1.25$ in. (A regular-hex nut for this diameter has a height of ⅞ in., which is 70% of the HHN's height. Also, a Grade A ASTM A563 heavy-hex nut must be able to support a proof load due to a fully-engaged threaded fastener stressed in tension to 100 ksi, based on A_T). Eq. 7 from reference 5 gives the basic allowable tension T_A for the anchor rod.

$$\begin{aligned} T_A &= 0.75F_UA_G/\Omega \quad (7) \\ &= 0.75(58\text{ ksi})(1.227\text{ in.}^2)/2.0 \\ &= 26.7\text{ kips, the basic allowable tension of anchor rod} \end{aligned}$$

Method 1. Assume that the nut can be engaged with the rod for only ⅞ in. Use Method 1 to find the reduced allowable tension. Verify that at least half of the nut height is engaged:
(⅞ in.)/(1.25 in.) = 70% > 50% OK

$$\begin{aligned} T_{A1} &= (L_E/h)T_A \\ &= (7/8\text{ in.}/1.25\text{ in.})(26.7\text{ k}) \\ &= 18.7\text{ kips; Method 1} \end{aligned}$$

Method 2. In this case, the nut has a total of 8.75 threads (1.25 in. × 7 threads/in.), but only 6.125 threads are engaged. Now use Method 2 to find the reduced allowable tension.

$$\begin{aligned} T_{A2} &= F_{SU}A_{TSE}nL_E/S_{F2} \\ &= (58\text{ ksi}/\sqrt{3})(0.301\text{ in.}^2/\text{thread})(7\text{ threads/in.})(0.875\text{ in.})/2.5 \\ &= 24.7\text{ kips; Method 2} \end{aligned}$$

This value exceeds the reduced value of 18.7 k from Method 1, but in this case is less than the rod's basic allowable of 26.7 k. This illustrates that Method 1 is the more conservative method.

Safety factor and Ω

The design method for allowable tension in a threaded fastener, as given in reference 5, results in a variable value of the actual safety factor S_F against tensile rupture. That is, Ω usually does not equal S_F. This is due to the simplification provided by use of the gross diameter A_G and to the variable ratio A_T/A_G. S_F equals the ratio of the minimum rupture strength (A_TF_U) to the allowable tension (given by Eq. 7):

$$S_F = A_TF_U/(0.75F_UA_G/\Omega) \quad (8)$$

As the diameter increases, both (A_T/A_G) and S_F increase in most cases (see Figures 3 and 6). The safety factor S_F ranges from 1.93 to 2.35. Threaded rods with $D \ge$ ¾ in. each have a minimum tensile ultimate that exceeds 2.0 times the corresponding allowable tension T_A. While conservative for basic tensile strength, this also means that a nut might be subjected to a larger tensile force than would otherwise be the case.

In conclusion, it is recommended that Method 1 be used in the case of a partially engaged nut and anchor rod. In addition to ensuring greater resistance to thread stripping, this will reduce or avoid inelastic shear deformation, at service load, in the most highly stressed threads. ■

References

1. *Fastener Standards*, 6th ed. Industrial Fasteners Institute (IFI), 1988
2. *Inch Fastener Standards*, 8th ed., Industrial Fasteners Institute (IFI), 2011
3. *Design Guide for Metal Cladding Fasteners*, TIR A9-14, American Architectural Manufacturers Association (AAMA), 2014
4. Steel Design Guide 1: *Base Plate and Anchor Rod Design*, 2nd ed., American Institute of Steel Construction (AISC), 2006; (section 2.11.3)
5. *Specification for Structural Steel Buildings*, ANSI/AISC 360-10, 2010; (section J3, including Commentary)
6. *Steel Construction Manual*, 14th ed., AISC, 2011; (Part 7, tables 7-17 and 7-19)