Quantifying Threaded Fastener Locking

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Abstract

A mechanism for loosening of threaded fasteners is explained and defined in terms of the self-loosening moment inherent to threaded fasteners and an external load induced loosening moment. Equations for these loosening moments are defined. The locking moment needed to prevent loosening due to the self-loosening moment and an external load loosening moment in threaded fastener joints is quantified. This together with secondary locking moment data provide a basis for specifying secondary locking in threaded fasteners to prevent loosening. An example is presented for an aerospace fastener.

Introduction and Background

Assembly of a bolted joint generally involves application of a tightening torque to threaded fasteners with resulting relative angular motion and stretch defined by the thread helix. After assembly, this stretch and associated potential energy is often held by the inherent friction at the thread and bearing interfaces. This friction is the primary locking mechanism or feature in preloaded threaded fasteners and is proportional to preload.

In many cases, a secondary locking feature is added to a threaded fastener [1]. These include mechanical locking (e.g., cotter pin or safety wire), prevailing torque locking (e.g., deformed thread or polymer patch), adhesive locking (e.g., anaerobic adhesive), and free spinning locking (e.g., serrated bearing surface or lock washer).

Use of a secondary locking feature may be required as in some aerospace applications [2] to provide redundancy and to counter possible loosening and failure in the event of unexpected loads. Often it is added to correct an observed or documented fastener loosening problem. In cases of fasteners without preload, it provides the only form of locking in fasteners.

Despite the widespread availability and use of secondary locking features, very little quantitative design guidelines exist. This paper aims to quantify locking and to help answer the question “What moment does a secondary locking feature need to provide to prevent loosening?”

Self-Loosening Moment

Threaded fasteners exhibit an inherent self-loosening moment. This self-loosening moment is evident from the torque equation for a bolted joint. The tightening torque for a threaded fastener in a bolted joint is generally [3-5] defined as shown in Eq. 1.

$$T_t = F_p \left(\frac{p}{2\pi} + \frac{\mu_t \, r_t}{\cos\beta} + \mu_n \, r_n \right) \tag{1}$$

Here T_t is the tightening torque, F_p is the preload, p is the thread pitch, μ_t is the thread interface friction coefficient, r_t is the nominal thread interface radius, μ_n is the nut interface friction coefficient, and r_n is the

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nominal nut interface radius. The first term in Eq. 1 is the torque required to stretch the bolt and the remaining two terms are the torque required to overcome thread and nut friction.

The removal torque is shown in Eq. 2.

$$T_r = F_p \left(-\frac{p}{2\pi} + \frac{\mu_t\, r_t}{\cos\beta} + \mu_n\, r_n \right) \tag{2}$$

This removal torque is the torque required to overcome thread and nut friction minus the torque from bolt stretch. This negative term (Eq. 3) defines the self-loosening moment.

$$M_{self-l} = \frac{F_p\, p}{2\pi} \tag{3}$$

This results from the bolt stretch torque and associated potential energy in the bolt. It is inherent to the threaded fastener and is proportional to preload and thread pitch.

Loosening Moment from External Loads

In addition to the inherent self-loosening moment in fasteners due to bolt stretch, external loads introduce loosening moments. An external transverse load on a bolted joint is illustrated in Figure 1.

Since threaded fasteners are made with lateral clearance for assembly, the nut can be moved sideways by an amount equal to this lateral clearance. Consider the cross section of a bolted joint as shown in Figure 1 with a force applied to the front of the nut. Since the right side will move with greater difficulty, it acts as a pivot point about which the nut slips and turns loose. When a force is applied to the back of the nut as shown in Figure 2, the left side becomes the pivot point about which the nut slips and rotates loose. The net effect of a dynamic or cyclic transverse force is a ratcheting loosening motion, and the amount of slip and resulting loosening increases with lateral thread clearance.

Taking the pivot points on the thread pitch diameter and the external transverse load applied at the center of the fastener, the moment arm is the thread pitch radius r_t and the loosening moment from front and back external transverse loads is shown in Eq. 4.

$$M_{ext-l} = F_{front}\, r_t = F_{back}\, r_t \tag{4}$$

Similar loosening moments can result from other external loads such as axial loads, bending loads, and combined loads.

Primary locking

The friction terms in the tightening and removal torque (Equations (1) and (2)) define the primary locking moment in a bolted joint as shown in Eq. 5.

$$M_{primary\ locking} = F_p \left(\frac{\mu_t\, r_t}{\cos\beta} + \mu_n\, r_n \right) \tag{5}$$

This primary locking moment is dependent on preload and friction. Unfortunately, if sustained cyclic slip occurs in a bolted joint, this primary locking moment is ineffective and locking must be provided by a secondary locking feature.

Secondary Locking Moment

In a joint subjected to only an external transverse load, the total loosening moment is shown in Eq. 6.

$$M_l = M_{self-l} + M_{ext-l} = \frac{F_p\, p}{2\pi} + F_{ext-trans}\, r_t \qquad (6)$$

In cases with sustained cyclic slip where thread and nut friction are ineffective, this total loosening moment from combined self-loosening moment and external load loosening moment defines the needed locking moment from a secondary locking feature. Specifically, the needed secondary locking feature locking moment is shown in Eq. 7.

$$M_{locking} \geq M_l = M_{self-l} + M_{ext-l} \qquad (7)$$

Prevailing Torque Locking

The tightening torque equation with secondary locking prevailing torque feature added is shown in Eq. 8.

$$T_t = F_p \left(\frac{p}{2\pi} + \frac{\mu_t\, r_t}{\cos\beta} + \mu_n\, r_n \right) + T_{pv} \qquad (8)$$

Here T_{pv} is the prevailing torque. It is independent of preload F_p.

The removal torque equation with secondary locking prevailing torque feature added is shown in Eq. 9.

$$T_r = F_p \left(-\frac{p}{2\pi} + \frac{\mu_t\, r_t}{\cos\beta} + \mu_n\, r_n \right) + T_{pv} \qquad (9)$$

Even without friction and preload, a locking moment equal to the prevailing torque T_{pv} remains. Prevailing torque locking features provide locking even with complete loss of preload. As a result, prevailing torque locking is often used in applications where complete disassembly and loss of components must not occur.

Well-defined standards exist for fasteners with prevailing torque locking [6-11]. These provide allowable minimum and maximum prevailing torque for a given thread size.

Secondary Locking Measurement

The locking moment provided by a secondary locking feature can be measured with a torque wrench or sensor on test specimens or actual hardware. This measurement should be taken as a separate test with the fastener in a state of zero preload. This is routinely performed in practice for prevailing torque locknuts, but can also be performed for adhesives, safety lock wire, cotter pins in castle nuts, and other secondary locking features.

Aerospace Fastener Example

As an example, consider an NAS1004 0.25-28 UNJF (approx. M6x1) thread fastener in a joint with a 2400-lb (10.7-kN) preload. The thread pitch is 1/28 inch. The self-loosening moment is shown in Eq. 10.

$$M_{self-l} = \frac{F_p\, p}{2\pi} = \frac{2,400}{2\pi(28)} = 13.6 \text{ in-lb (1.54 N-m)} \qquad (10)$$

For a 0.25-28 UNJF thread fastener, the prevailing torque locking standards [6-11] list an allowable 3.5 in-lb (0.40 N-m) minimum and 30 in-lb (3.4 N-m) maximum prevailing torque. Since the self-loosening moment for the thread is 13.6 in-lb (1.54 N-m), meeting the minimum 3.5 in-lb (0.40 N-m) is not enough to counter the self-loosening moment.

If a prevailing torque locking feature is used with a measured prevailing torque of 20 in-lb (2.3 N-m), then the locking moment is 20 in-lb (2.3 N-m) which is in excess the self-loosening moment.

Data [12] exists from dynamic transverse load tests with NAS1004 0.25-28 UNJF threaded fasteners. Minimum and maximum pitch diameter are 0.2243 (5.697 mm) and 0.2268 inch (5.761 mm) for an average of 0.2256 inch (5.730 mm). The dynamic transverse force is 200 lb (890 N) and the preload is 2400 lb (10.7 kN). Therefore, the loosening moment from this external transverse load is shown in Eq. 11.

$$M_{ext-l} = F_{front}\, r_t = F_{back}\, r = (200)(0.1128) = 22.6 \text{ in-lb (2.55 N-m)} \tag{11}$$

This 200-lb (890-N) external transverse force is the amount that acts on the fastener. The dynamic transverse test machine [12] used is designed with bearings between the clamped components of the joint. This intentionally puts the applied external transverse force on the fastener which makes the test severe. In practice with a typical joint, additional friction between the clamped components of the joint would counter the external transverse load. This joint friction force would need to be subtracted from the external load to determine the transverse force on the fastener that is used in the previous equation. An estimate of this joint friction force is the product of clamping force and coefficient of friction at the joint interface.

At a preload of 2400 lb (10.7 kN), the test fasteners were subjected to a dynamic external transverse load of 200 lb (890 N), and a total loosening moment shown in Eq. 12.

$$M_l = M_{self-l} + M_{ext-l} = 13.6 + 22.6 = 36.2 \text{ in-lb (4.09 N-m)} \tag{12}$$

A set of tests [13] for a variety of secondary locking features provide measured locking moment data for 0.25-28 UNJF (similar to M6) thread fasteners. Specifically, the following locking moment data was obtained: 16-23 in-lb (1.8-2.6 N-m) for metal and nonmetal prevailing torque locknuts, 15-18 in-lb (1.7-2.0 N-m) for medium strength Loctite, 55-65 in-lb (6.2-7.3 N-m) for high strength Loctite, 50-60 in-lb (5.6-6.8 N-m) for cotter pins with castle nuts, and 36-42 in-lb (4.0-4.7 N-m) for 0.032-inch (0.813-mm) Inconel safety lock wire through bolt heads. This data indicates only high-strength Loctite, cotter pins, and safety lock wire provide sufficient locking to overcome the loosening moment due to combined self-loosening and the severe external transverse loading. However, in the absence of the external load, all of the locking features tested provide locking moments in excess of the self-loosening moment.

Conclusions

This paper provides some guidance for specifying secondary locking features in threaded fasteners to provide sufficient locking and prevent loosening.

A mechanism for loosening of threaded fasteners is provided and defined in terms of a self-loosening moment inherent to threaded fasteners and an external load loosening moment.

Equations for loosening moments are defined. Secondary locking feature moments are quantified in terms of these loosening moments.

An example is provided. Some sample data for measured locking moments is given for one thread size.

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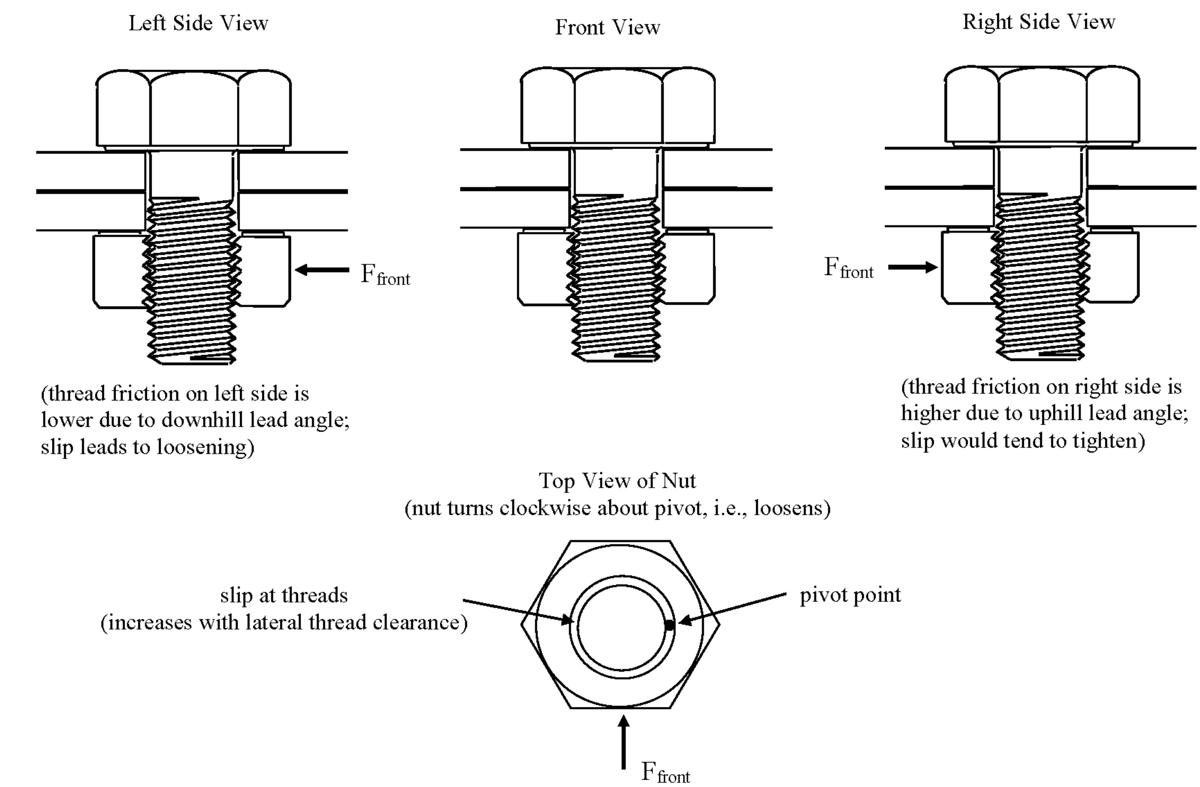

Figure 1. Bolted joint with force applied to nut from front.

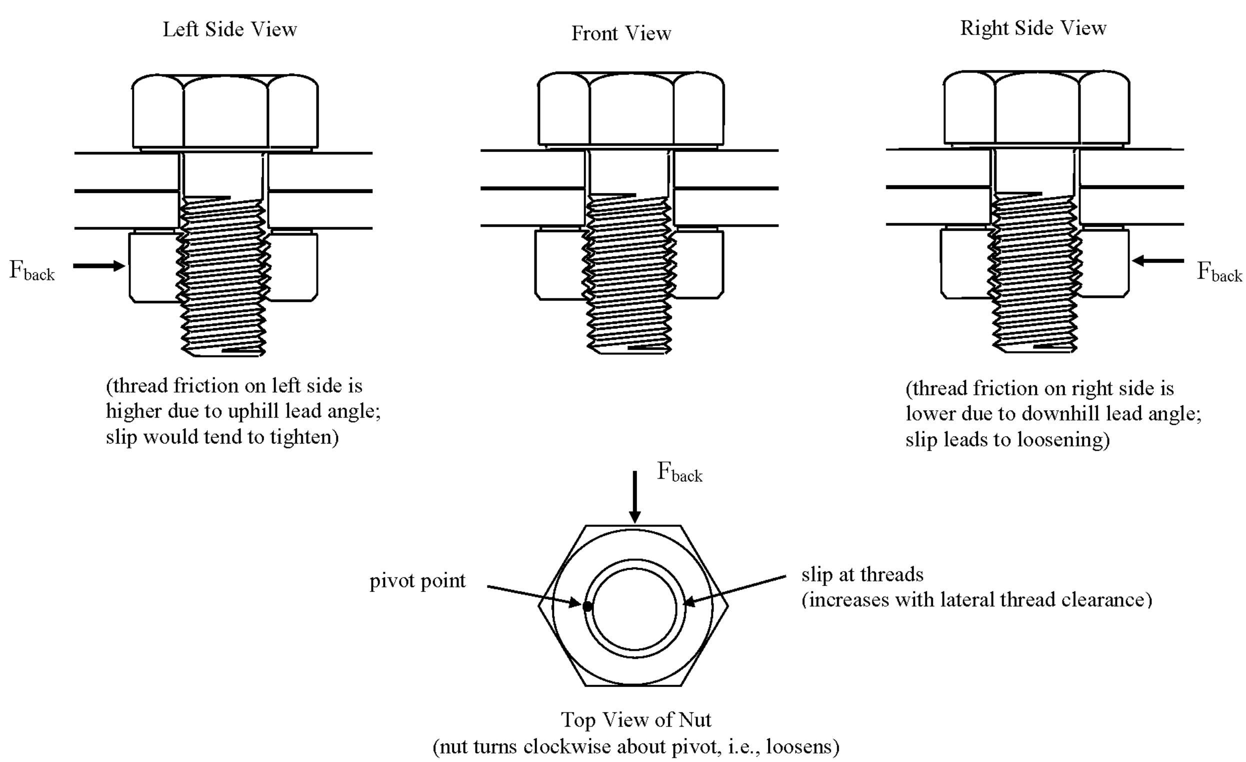

Figure 2. Bolted joint with force applied to nut from back.