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ORIGINAL RESEARCH ARTICLE

Testing and Analysis on the Dynamic Loosening of Jack Bolt Nuts Compared with Heavy Hex Nuts

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Abstract This paper reports on an experimental investigation into the dynamic loosening of jack bolt nuts. Using a Junker type test machine that provides dynamic transverse force loading, tests are performed on jack bolt nuts and heavy hex nuts of the same size to provide a comparative assessment of the dynamic loosening performance. The range of test preload values is selected such that both loosening and non-loosening conditions are observed for each type of nut. The test data reveal jack bolt nuts have a better resistance to loosening than heavy hex nuts. Specifically, under the same transverse loading conditions, the jack bolt nuts are found to require less preload to avoid loosening than the heavy hex nuts. Analysis of the primary locking in both the jack bolt nut and the heavy hex nut shows the jack bolt nut provides 8.5% more locking than the heavy hex nut due to larger effective nut bearing radius and resulting nut friction torque.

Keywords Fastener · Jack bolts · Loosening · Tensioner

Introduction

Jack bolt fasteners [1] are a tensioner type of fastener that have found increased use in applications including aerospace. The components of a jack bolt nut are shown in Figure 1 and include a main body, jack bolts, and a washer. In addition to the main threaded hole, the body has several smaller threaded holes distributed circumferentially for the jack bolts which thread through the body and contact the hardened washer. Jack bolt nuts are produced in metric sizes from M16 to M160 and standard thread sizes from 0.75 to 6 inch.

While a hex nut is assembled [2] onto a bolt by turning it onto a bolt hand-tight and then applying torque, a jack bolt nut is assembled onto a bolt by turning the nut body down hand-tight and then applying torque to the jack bolts in a crisscross pattern. This causes the jack bolts to create a gap between the washer and the body which gives an indication of joint preload.

A benefit of jack bolt nuts over hex nuts is that they require significantly reduced assembly torque. The amount of torque needed to achieve preload for large threaded fasteners is reduced by more than an order of magnitude because the friction and load are distributed to several smaller jack bolts instead of one large nut. This benefit makes them of particular interest for large fastener applications. Despite their increased use in numerous applications, available data on their performance remain quite limited.

DellaCorte et al [3] reported significant loss of preload in several jack bolt nuts during a qualification vibration test of an aerospace mechanism. In this application, the nuts were used in a joint that purposely accommodated some slip. This feature combined with the dynamic loading of the vibration test resulted in the observed loss of preload.

Torque equilibrium analyses [4] of a tensioner nut showed no torsional bolt twist during assembly in contrast to a hex nut. However, analysis of the loosening processes revealed nut body bearing interface slip before thread slip for both the tensioner nut and the hex nut.

The behavior and performance of common threaded fasteners under vibration and shock environments have been studied extensively [2, 5]. This has resulted in an improved understanding of the performance and failure

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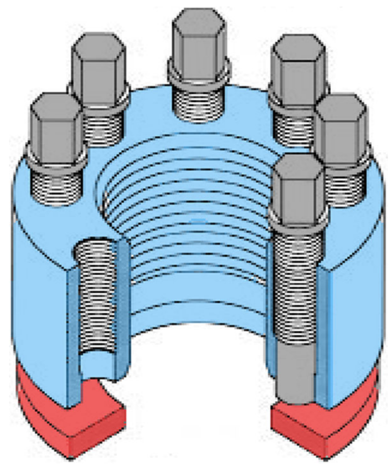

Fig. 1 Jack bolt nut

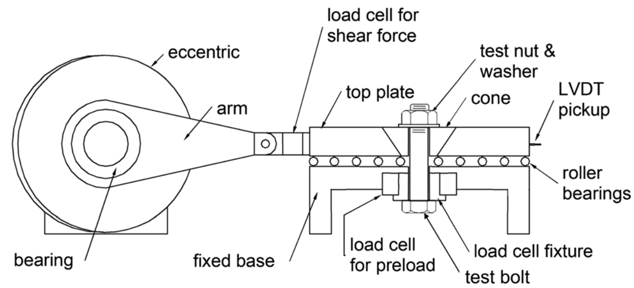

Fig. 2 Schematic of test machine

Fig. 3 Photograph of representative test specimens

mechanisms of threaded fasteners and bolted joints under dynamic conditions. The failure process sequence is often cyclic slip which results in loosening and loss of preload, followed by failure due to joint separation or fatigue [5].

The behavior of jack bolt nuts under dynamic loading has not been adequately studied. It is not clear how their performance compares to hex nuts since no such comparisons exist in the literature. To address this need, this paper provides both comparative test data and analysis of the performance of jack bolt nuts and comparably sized heavy hex nuts under dynamic loading conditions. The tests are performed using a Junker or transverse loading test machine [6, 7] to induce dynamic loosening.

Apparatus

A schematic of the test machine is shown in Figure 2. The test joint comprises a top plate clamped to a lower fixed base with a test nut, washer, and bolt. The top plate and fixed base are fitted with a cone fixture and flanged cylindrical fixture, respectively. The inside diameter of each fixture is sized for the test fasteners. Roller bearings between the top plate and the fixed base minimize friction. Cyclic transverse force is applied to the top plate through an arm connected to a motor driven adjustable eccentric. Load cells are used to measure preload and the shear force applied to the top plate. An LVDT pickup is used to measure the transverse displacement of the top plate.

The test machine provides digital displays for transverse force, preload, and transverse displacement. A multi-channel data acquisition system is used to record the time traces of these variables.

For each test, a test bolt is installed into the load cell fixture in the fixed base up through the cone fixture in the top plate. With a test bolt fully inserted, a test nut and washer are installed on the bolt against the top of the cone fixture. The schematic in Figure 2 shows the machine with a hex nut installed.

Test specimens

The fasteners tested include jack bolt nuts and heavy hex nuts with ¾-10 thread size and the following specifications:

(1) Superbolt jack bolt nut with hardened washer, part # MT-075-10UN
(2) ¾-10 ASTM A194 Grade 2H heavy hex nut with ASTM F436 hardened washer
(3) ¾-10 x 4-1/4 ASTM A193 Grade B7 heavy hex head bolt

Samples of the test specimens are shown in Figure 3.

The jack bolt nuts with hardened washers used were received from the manufacturer lubricated with Molykote P37. The technical datasheet for this lubricant describes it as an extremely pure, solid lubricant paste with applications for threaded fasteners and example coefficient of friction value of 0.11 for fastener thread and bearing interfaces. The safety datasheet states a composition of 33–53% white mineral oil, 19–29% graphite, and 7–13% zirconium oxide. Since this lubricant is specified by the manufacturer, all tests are performed with this lubricant applied to all thread and bearing surfaces of the test nuts, jack bolts, washers, and bolts.

The bolt length used in these tests is based on the following stack-up:

Load cell fixture height = 1.06”
Gap between top of load cell fixture and bottom of cone = 1.30”
Cone fixture height = 0.50”
Jack bolt nut body height + hardened washer height = 0.70” + 0.13” = 0.83”
Heavy hex nut height + hardened washer height = 0.72” + 0.13” = 0.85”
Four bolt threads extending beyond top of nut body = 0.40”
Minimum required bolt length = 1.06 + 1.30 + 0.50 + (0.83 or 0.85) + 0.40 = 4.1”

The test cone and load cell fixture used in these tests are made of 15-5 stainless steel and heat treated to RC35 with flat surfaces finished to 32µin. The cone and load cell fixtures have thru-holes with close-fit clearance for ¾” nominal bolt size.

Prior to testing, all test fasteners and fixtures are cleaned as follows:

(1) Clean in ultrasonic cleaner with MEK for three minutes.
(2) Replace MEK and repeat step 1.
(3) Let the air dry for at least five minutes on clean lint-free wipes before assembly.

Assembly with Jack Bolt Nut

Prior to assembly, Molykote P37 is applied to all thread and bearing surfaces of the test jack bolt nut, washer, and bolt. This includes the nut threads and bearing face, the jack bolt threads, both sides of the hardened washer, the bolt threads, and under the bolt head.

In use, the jack bolts extend beyond the underside nut body against the hardened washer, however, prior to assembly they are retracted into the nut body and the hardened washer is placed against the nut body.

The top plate of the test machine is centered, and the test bolt is installed into the load cell fixture in the fixed base up through the cone fixture in the top plate of the test machine. With the bolt fully inserted, a test jack bolt nut with hardened washer are turned down by hand onto the end of the bolt until contact with the top of the cone fixture. Holding the bolt head stationary, the nut body is loosened one quarter of a turn.

Application of preload with the jack bolt nut is as follows:

(1) Turn all four jack bolts clockwise in a crosswise pattern to eliminate the axial gap.
(2) Use a torque wrench with a 3/16” socket to apply 4in-lb of tightening torque to the four jack bolts in a crosswise pattern.
(3) Apply tightening torque in increasing increments until desired test preload is achieved. Use smaller increments of 2 to 4in-lb of tightening torque for lower preload and as desired value of preload is approached. Use larger increments of 6 to 10in-lb for higher preload.
(4) Repeat step 3 until all jack bolts are equally tightened with respect to tightening torque value and the desired test preload is achieved.

The tightening torque required to achieve the desired preload ranged from as low as 8 to 9in-lb for 1,000 lb preload to as high as 42 to 44in-lb for 6,000 lb preload.

Assembly with Heavy Hex Nut

Prior to assembly, Molykote P37 is applied to all thread and bearing surfaces of the test nut, washer, and bolt. This includes the heavy hex nut threads and bearing face, both sides of the hardened washer, the bolt threads, and under the bolt head.

The top plate of the test machine is centered, and the test bolt is installed into the load cell fixture in the fixed base up through the cone fixture in the top plate of the test machine. With the bolt fully inserted, a test washer is placed over the end of the bolt against the top of the cone fixture. A test heavy hex nut is then turned down by hand onto the end of the bolt until hand tight.

With the bolt head held stationary with a socket wrench, a tightening torque is applied to the heavy hex nut with a torque wrench until the desired preload for the test is achieved. Once the desired preload is achieved, the applied tightening torque is held for four seconds. The tightening torque required to achieve the desired preload ranged from as low as 9 to10ft-lb for 1,000 lb preload to as high as 50 to 55ft-lb for 6,000 lb preload. Both wrenches used 1 1/4” sockets for the bolt head and heavy hex nut.

Preliminary Tests

The goal of this work is to compare the relative dynamic loosening of jack bolts nuts and heavy hex nuts. Preliminary tests were performed for different preload levels for each nut type to identify levels that result in loosening and no-loosening behavior. Initial tests used a preload of 1,000 lb and complete loosening was observed for each type of nut. Then, the preload was increased in increments of 1,000 lb until no loosening was observed. With this approach, loosening was observed for heavy hex nuts for preloads up to 5,000 lb but no loosening was observed for preloads of 6,000 lb and above. For jack bolt nuts, loosening was observed for preloads up to 4,000 lb but no loosening was observed for preloads of 5,000 lb and above. When loosening was observed, complete loosening occurred within about 400 cycles of transverse loading. These results were obtained with a test machine drive frequency of 15 Hz and an eccentric setting of ± 0.06”.

Based on these results and the above-stated goal, the tests in this work are performed at preload levels of 1,000 to 6,000 lb in 1,000 lb increments with a test machine drive frequency of 15 Hz and an eccentric setting of ± 0.06”, and a record length of 40 seconds or 600 cycles. The data were collected at 51.2 samples/second for a total of 2,048 data points for each measured variable for each test. The measured variables for each test include preload, transverse force, and transverse displacement.

Note that a preload of 6,000 lb is about 30% of the maximum capacity of the jack bolt nuts tested. Even though the preload levels used in these tests are below this capacity of the test fasteners, the tests performed meet the goal of comparing the relative dynamic loosening performance of the two nut types which includes observing conditions for loosening and no-loosening behavior for both nut types.

Tests

The number of replicates used in this study for each of the two nut types and six preload levels is six for a total of 72 tests. Table 1 presents the test numbers. The order in which these tests are run is defined by the run number which is randomized according to the test number sequence shown in Table 2.

All bolts, nuts and washers are lubricated before each test. Minimal wear was observed on the test specimens and fixtures due to the use of the Molykote P37 lubricant and relatively low preload in all tests. This is consistent with minimal variation observed in data from replicate tests.

Table 1 Test numbers defined for nut type and preload level

Nut type	Preload (ib)	Test #					
Heavy hex nut	1000	1	2	3	4	5	6
	2000	7	8	9	10	11	12
	3000	13	14	15	16	17	18
	4000	19	20	21	22	23	24
	5000	25	26	27	28	29	30
	6000	31	32	33	34	35	36
Superbolt jack nut	1000	37	38	39	40	41	42
	2000	43	44	45	46	47	48
	3000	49	50	51	52	53	54
	4000	55	56	57	58	59	60
	5000	61	62	63	64	65	66
	6000	67	68	69	70	71	72

Data

Sample preload, transverse force, and transverse displacement data with loosening are shown in Figures 4 and 5. The preload decreases from 4,000 lb to 0 lb with cycles of transverse force loading. The preload data show cyclic fluctuation in preload with the 15 Hz loading cycle as indicated by the width of the blue curve in Figure 4 a. The preload data are also shown with this cyclic variation removed using a centered moving average of n = 10 values which corresponds to about 3 cycles for the 15 Hz variation and 51.2 samples/second sampling rate. This is used to improve clarity in plots with multiple curves such as Figure 6 a.

The sample transverse force data in Figure 5 have an initial amplitude of 321 lb and drops to a final amplitude of 20 lb. The transverse displacement data in Figure 5 have an initial amplitude of 0.013” and increase to a final amplitude of 0.054”. This final displacement amplitude is less than the eccentric amplitude setting of 0.06” due to

Table 2 Run numbers defined by randomized test number sequence

Run #	Test #	Run #	Test #	Run #	Test #	Run #	Test #
1	27	19	15	37	56	55	29
2	64	20	25	38	66	56	65
3	44	21	20	39	23	57	57
4	24	22	4	40	36	58	47
5	48	23	21	41	35	59	26
6	54	24	61	42	31	60	72
7	11	25	50	43	14	61	71
8	19	26	42	44	16	62	45
9	52	27	41	45	69	63	60
10	1	28	13	46	70	64	59
11	7	29	22	47	39	65	68
12	63	30	6	48	55	66	8
13	18	31	3	49	40	67	46
14	2	32	10	50	51	68	5
15	37	33	33	51	62	69	28
16	32	34	67	52	17	70	34
17	12	35	30	53	58	71	9
18	49	36	38	54	53	72	43

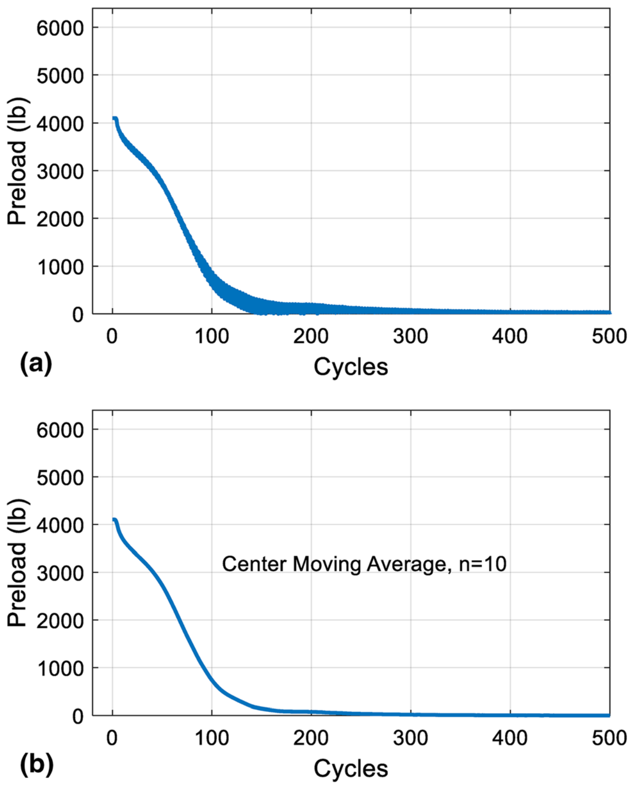

Fig. 4 Sample preload data for a jack bolt nut test with loosening and initial preload of 4,000 lb: (**a**) raw data, and (**b**) data with center moving average of 10 values

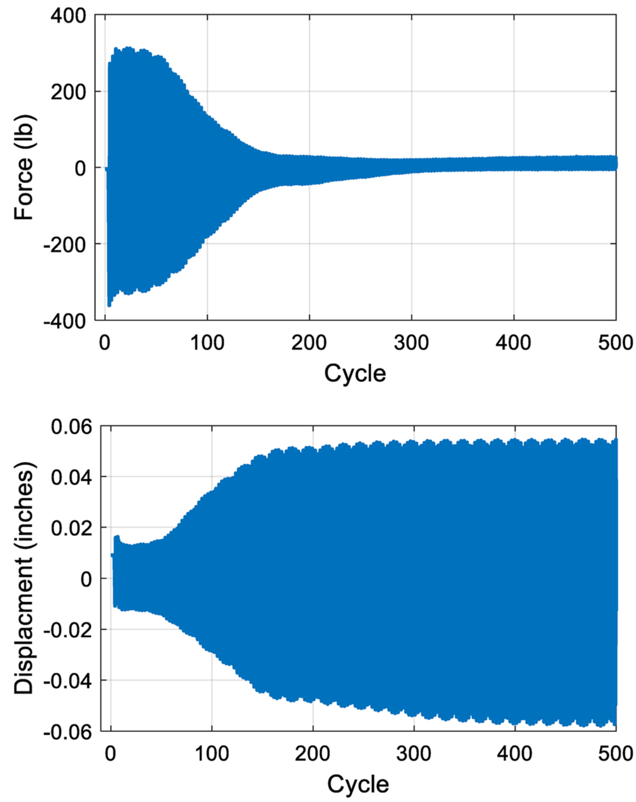

Fig. 5 Sample transverse force and displacement data for a jack bolt nut test with loosening and initial preload of 4,000 lb

deflection within the test machine drive from elasticity and the presence of the test fasteners. These qualitative changes in transverse force and displacement are typical of tests with loosening. However, the initial values are dependent on initial preload. Namely, the initial transverse force increases, and the initial transverse displacement decreases with increasing initial preload.

When no loosening occurs, the preload does not decrease beyond a small amount due to embedment, and the transverse force and displacement amplitudes do not change with loading cycles.

The tightening torque range of values required to achieve the desired preloads are presented in Table 3. These data show the magnitude and variation of tightening torque required to achieve the desired test preload in the tests. The difference in torque required for heavy hex nuts and the jack screws on the jack bolt nuts is remarkable.

The preload data from all six replicate tests for the jack bolt nuts with initial preload of 4,000 lb are presented in Figure 6 a. The variation between these replicate tests is moderate and representative of the variation between replicate tests for the other preload levels for both nut types. This variation in replicate tests is reasonable and typical for such tests. The curve in Figure 6 b is the average of the six replicate curves from Figure 6 a. This reduces the data from six replicate tests for a given initial preload level and nut type to a single curve representing on-average behavior.

Figure 7 summarizes all 36 heavy hex nut tests with data averaged across replicates such that each of the 6 curves represents the average preload for six replicate tests. Figure 8 presents the corresponding data for the jack bolt nut tests. These figures illustrate the preload levels for which loosening, and no-loosening occurs for each nut type. Specifically, Figure 7 illustrates the heavy hex nut tests exhibit loosening for preload levels of 1,000 to 5,000 lb and no-loosening for preload of 6,000 lb. Figure 8 illustrates the jack bolt tests exhibit loosening for preload levels of 1,000 to 4,000 lb and no-loosening for preload levels of 5,000 and 6,000 lb.

These data reveal that the jack bolt nut has better resistance to loosening compared to the heavy hex nut because it does not exhibit loosening for tests with preload of 5,000 lb. These plots concisely illustrate the jack bolt nut has better locking compared to the heavy hex nut. Since no secondary locking is used in either nut type, this difference must result from differences in primary locking which is examined in the Primary Locking Analysis section of this paper.

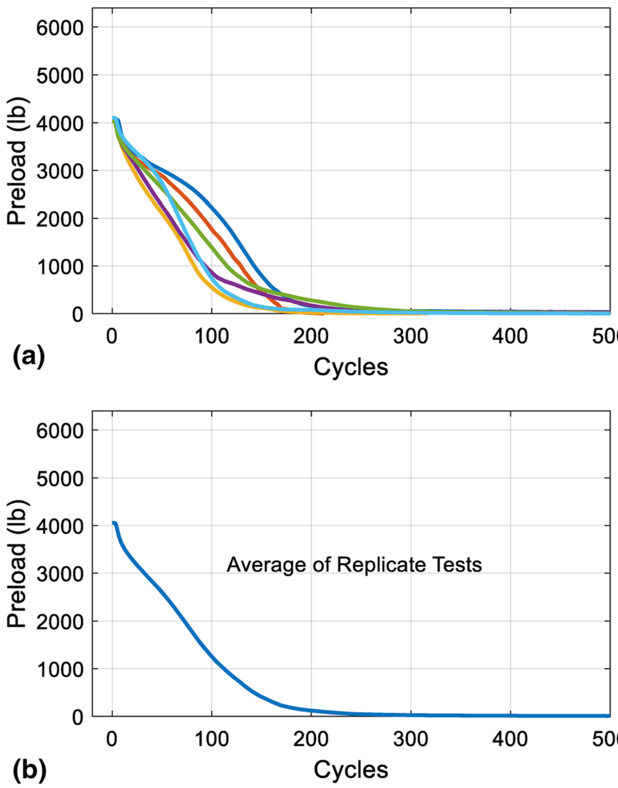

Fig. 6 Preload data for all jack bolt nut tests with initial preload of 4,000 lb: (**a**) six replicate tests, and (**b**) average of replicate tests

Table 3 Tightening torque to achieve desired preload

Preload(lb)	Superbolt nut jack screw tightening torque (in-lb)	Heavy hex nut tightingtorque (ft-lb)
1000	8–9	9–10
2000	16-17	17-18
3000	24-26	25-26
4000	29-32	33-35
5000	35-37	44-46
6000	42-44	51-55

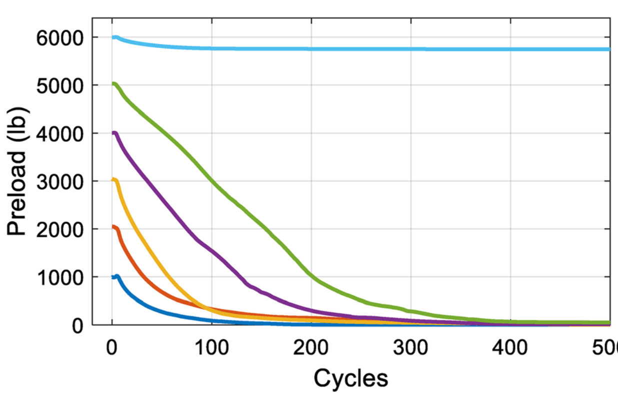

Fig. 7 Heavy hex nut tests averaged across replicates

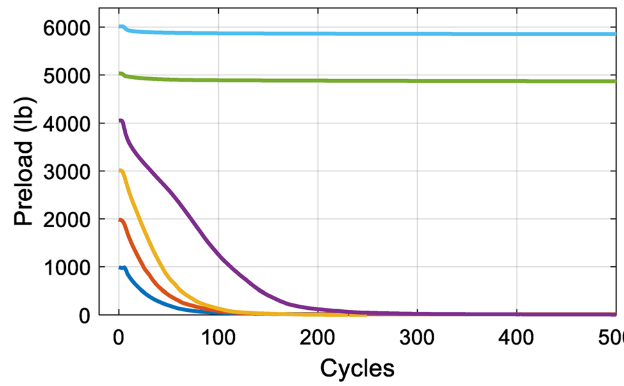

Fig. 8 Jack bolt nut tests averaged across replicates

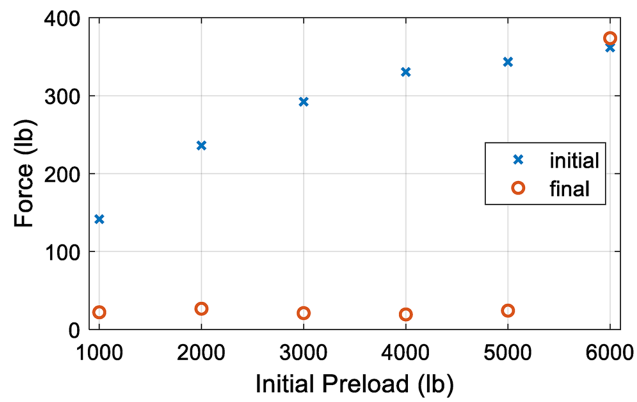

Fig. 9 Initial and final transverse force averaged over replicate tests for heavy hex nut tests

For these tests, the applied dynamic transverse force and transverse displacement vary with initial preload and instantaneous preload. The initial and final transverse force amplitude was extracted from the raw data for all 72 tests and revealed the initial transverse force increases from as low as about 100 lb to as high as about 370 lb with initial preload, whereas the final transverse force amplitude is independent of initial preload with minimum value of about 20 lb when loosening occurs, and a constant maximum value of about 370 lb when no loosening occurs.

The initial and final transverse force values are averaged over the 6 replicate tests for each initial preload level and presented in Figures 9 and 10 for both nut types. This averages out variations in transverse force between replicate tests and shows the increase in initial transverse force with initial preload and constant final transverse force both with and without loosening. It also shows the significant drop in transverse force amplitude from initial to final value when loosening occurs, and that the transverse force amplitude remains constant when no loosening occurs.

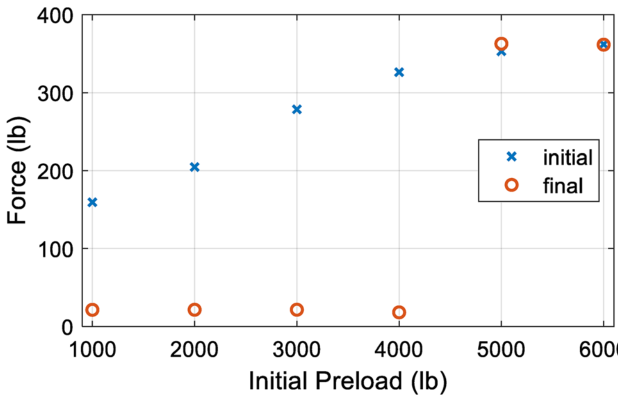

Fig. 10 Initial and final transverse force averaged over replicate tests for jack bolt nut tests

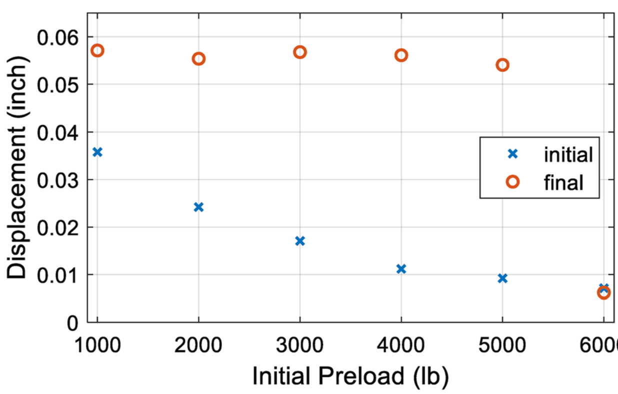

Fig. 11 Initial and final transverse displacement averaged over replicate tests for heavy hex nut tests

The initial and final transverse displacement was extracted from all 72 tests and revealed the initial transverse displacement amplitude decreases from as high as about 0.04” to as low as about 0.007” with increasing initial preload, whereas the final transverse displacement amplitude is independent of initial preload with an average value of about 0.56” when loosening occurs, and a constant value of about 0.007” when no loosening occurs.

The initial and final transverse displacement averaged over the 6 replicate tests for each initial preload level is presented in Figures 11 and 12 for both nut types. This averages variations in transverse displacement between replicate tests and shows the decrease in initial transverse displacement with initial preload and constant final transverse displacement both with and without loosening. These data also show a significant increase in transverse displacement amplitude from initial to final value when loosening occurs, and that the transverse displacement amplitude remains constant when no loosening occurs.

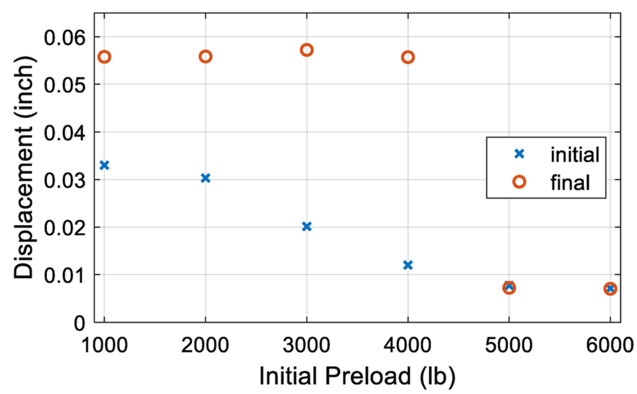

Fig. 12 Initial and final transverse displacement averaged over replicate tests for jack bolt nut tests

Primary Locking Analysis

The test data presented in the previous section show that at a preload of 5,000 lb the jack bolt nut does not loosen whereas the heavy hex nut does loosen. This indicates that the jack bolt nut performs better than the heavy hex nut in terms of resistance to loosening from transverse force loading. Since no secondary locking is used in either nut type, this difference must result from differences in primary locking.

The primary locking [8] with a heavy hex nut with preload F_p, thread pitch radius r_t, effective radius of the nut bearing surface r_n, thread half-angle, β, thread friction coefficient μ_t, and nut bearing friction coefficient μ_n, is

$$T_{\mathrm{pl-hex}} = F_p \left(\frac{\mu_t \, r_t}{\cos \beta} + \mu_n \, r_n \right) \quad \text{(Eq 1)}$$

The primary locking with a jack bolt nut is

$$T_{\mathrm{pl-sb}} = F_p \left(\frac{\mu_t \, r_t}{\cos \beta} + \mu_n \, r_{\mathrm{jb}} \right) \quad \text{(Eq 2)}$$

Here, the preload, thread pitch radius, thread half-angle, and coefficients of friction are defined the same as with the heavy hex nut, however, the radius for nut bearing friction torque is defined by the distance of the jack bolts from the center of the jack bolt nut, r_{jb}. The percent difference in primary locking between a jack bolt nut compared to a heavy hex nut is

$$\frac{100\left(T_{\mathrm{pl-sb}} - T_{\mathrm{pl-hex}}\right)}{T_{\mathrm{pl-hex}}} = \frac{100\left(r_{\mathrm{jb}} - r_n\right)}{\frac{\mu_t \, r_t}{\mu_n \cos \beta} + r_n} \quad \text{(Eq 3)}$$

This change in primary locking is dependent on the distance of the jack bolts from the center of the jack bolt nut, r_{jb}, the effective radius of the heavy hex nut bearing surface, r_n, thread pitch radius r_t, the thread half-angle, β, and the nut bearing and thread friction coefficients, but is independent of preload. It is independent of friction coefficients as well when the nut bearing, and thread friction coefficients are equal.

The values of these parameters for the test nuts used in this work are r_{jb} = 0.5625”, r_n = 0.4875”, r_t = 0.3425”, and β = 30 degrees. Assuming $\mu_t = \mu_n$, the percent change in primary locking of the jack bolt nut compared to the heavy hex nut is an increase of 8.5 percent.

Conclusions

In this study, tests were performed to provide a comparative assessment of the dynamic loosening behavior of jack bolt nuts and heavy hex nuts. The tests were performed on a Junker type test machine which provides dynamic transverse force loading. A range of test preload values were selected to ensure loosening and non-loosening conditions for each type of nut. Thirty-six tests were performed for each nut type.

Preload, transverse force, and transverse displacement data were collected, and representative samples presented to illustrate typical loosening and non-loosening instances. The preload versus loading cycles for all tests was presented concisely with test data averaged across replicate tests at each preload level for each nut type. These data showed jack bolt nuts to have a better resistance to loosening than the heavy hex nuts.

Analysis of the primary locking in both the jack bolt nut and the heavy hex nut was performed and showed the jack bolt nut provides 8.5% more locking than the heavy hex nut due to larger effective nut bearing radius and resulting nut friction torque. This calculation of primary locking supported the observed test results.

References

1. R. Steinbock, (1986) Apparatus to mechanically stress a bolt type fastener, United States Patent 4,622,730
2. J Bickford, (2008) Introduction to the design and behavior of bolted joints, 4th edition, CRC Press
3. C DellaCorte, S Howard, D Hess, (2018) Preload loss in a spacecraft fastener via vibration-induced unwinding, NASA/TP-2018-219787
4. D. Hess, Torque balance, primary locking and loosening in tensioner assembled bolted joints. J. Fail. Anal. Prev. **22**, 542–549 (2022)
5. D. Hess, *Vibration and shock induced loosening, Chapter 40 in Handbook of Bolts and Bolted Joints* (Marcel Dekker, New York, 1998), p.757–824
6. G. Junker, New criteria for self-loosening of fasteners under vibration. Trans. Soc. Automot. Eng. **78**, 314–335 (1969)
7. ISO 16130, (2015) Aerospace series – Dynamic testing of the locking behavior of bolted connections under transverse loading conditions (vibration test), International Standard Organization
8. D. Hess, Threaded fastener secondary locking requirements. J. Fail. Anal. Prev. **17**, 724–730 (2017)