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# LETTERS TO THE EDITOR

## SHOCK-INDUCED LOOSENING OF DIMENSIONALLY NON-CONFORMING THREADED FASTENERS

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### 1. INTRODUCTION AND BACKGROUND

The mechanical performance of threaded components, and of the assemblies in which they are used, is generally determined through evaluation of properties such as axial or tensile strength, torsional strength, shear strength, resistance to vibration-induced loosening, fatigue resistance, resistance to shock-induced loosening, resistance to thermal cycling, and hydraulic pressure integrity. In general, the mechanical performance of threaded components is a function of component material properties, thread geometry, and the environment to which the components are subjected. Other characteristics such as coatings, assembly technique, and thread lubricant will also influence the mechanical performance of a threaded component in an assembly.

Although there are about 30 separate geometrical features and dimensional characteristics in the design and construction of screw threads, the most rigorous standard for threaded components in the United States inspects 11 major thread characteristics. Inspection method A or system 21 is the least rigorous, whereas method C or system 23 is the most rigorous.

Presently, there is a lack of adequate published research on how thread geometry and dimensional conformance affect the overall performance of threaded fasteners. A recent ASME CRTD report [1] concluded that technical documentation on the effect of thread non-conformance on mechanical performance is scarce. This paper presents test results that help fill this void in the technical literature.

Recently, Dong and Hess [2] investigated the affect of thread-dimensional conformance on vibration-induced loosening using a compound cantilever beam apparatus. Data from this work show a significantly degraded resistance to vibration for fastener combinations with undersized pitch and major bolt diameters or oversized pitch and minor nut diameters, compared to fastener combinations within conformance.

In addition, the yield and tensile strength of dimensionally conforming and non-conforming threaded fasteners was recently studied by Leon *et al.* [3]. This work showed that variations in bolt pitch diameter affect the yield and tensile

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strength by about an order of magnitude more than variations in bolt major diameter or nut pitch and minor diameters. The mean tensile strength for conforming product was found to be as much as 20% greater than the tensile strength for non-conforming product.

The focus of this paper is to present results from tests that specifically examine the effect of non-conforming pitch and major diameter of bolts and pitch and minor diameter of nuts on shock-induced loosening. Test specimens include combinations of bolts and nuts within dimensional conformance as specified by ASME Standard B1.1-1992 [4], as well as bolts with undersized pitch and major diameters and nuts with oversized pitch and minor diameters. The tests are performed in accordance with MIL-STD-1312-7A [5]. This test subjects the test fasteners to a repeated shock environment. Shock-induced loosening is an important measure of performance since assemblies that utilize threaded fasteners are often subjected to such dynamic environments [6]. Such conditions can lead to fastener loosening which can result in increased maintenance and/or failure.

## 2. TEST SPECIMENS

In this work, the effect of four-thread parameters on shock-induced loosening is examined. These dimensional thread parameters include bolt major diameter, bolt pitch diameter, nut pitch diameter, and nut minor diameter. The test bolts are nominally 0·3750-16 UNC-3A hex, 50·8 mm (2 in) long and are made of 4140 steel. The test nuts are nominally 0·3750-16 UNC-3B hex and are made of 4140 steel. Table 1 lists the 13 fastener combinations tested. Combinations include bolts and nuts within conformance as well as bolts with 0·127 mm (0·005 in) and 0·254 mm (0·010 in) undersized pitch and major diameters and nuts with 0·127 mm (0.005 in) and 0.254 mm (0.010 in) oversized pitch and minor diameters. A total of 65 bolt and nut combinations were tested, and each combination was tested three times. The deviation of the pitch, major and minor diameters specified in Table 1 is less than 12% for all test specimens. The precise dimensional specifications and certifications of these test bolts and nuts are provided elsewhere [7].

## 3. TEST PROCEDURES

The shock tests are performed in accordance with MIL-STD-1312-7A [5]. This test requires a machine, such as an electromagnetic shaker, that is capable of vibrating the test fixture shown in Figure 1 harmonically at a frequency of 30 Hz with as peak-to-peak amplitude of $11{\cdot}4 \pm 0{\cdot}4$ mm ($0{\cdot}450 \pm 0{\cdot}015$ in). The test fasteners clamp spool-like arbors which are constrained within a slotted fixture (Figure 1). As the fixture vibrates, it subjects each spool to a reciprocating motion with two impacts per cycle. The direction of impact is perpendicular to the fastener axis. Specifications for fixture details are provided in MIL-STD-1312-7A [5] for fasteners ranging in size from 4·8 to 15·9 mm (0·190 to 0·625 in) in diameter.

In this work, one bolt and nut combination is tested at a time. Prior to testing, the fastener specimens and fixture components are cleaned in an ultrasonic bath

TABLE 1

*Test specimens*

| Test specimen group | Number of bolts | Bolt pitch diameter conformance (mm) | Bolt major diameter conformance (mm) | Number of nuts | Nut pitch diameter conformance (mm) | Nut minor diameter conformance (mm) |
|---|---|---|---|---|---|---|
| 1 | 5 | Within | Within | 5 | Within | Within |
| 2 | 5 | Undersized 0·127 | Within | 5 | Within | Within |
| 3 | 5 | Undersized 0·254 | Within | 5 | Within | Within |
| 4 | 5 | Within | Within | 5 | Oversized 0·127 | Within |
| 5 | 5 | Within | Within | 5 | Oversized 0·254 | Within |
| 6 | 5 | Undersized 0·127 | Within | 5 | Oversized 0·127 | Within |
| 7 | 5 | Undersized 0·254 | Within | 5 | Oversized 0·254 | Within |
| 8 | 5 | Undersized 0·127 | Undersized 0·127 | 5 | Within | Within |
| 9 | 5 | Undersized 0·254 | Undersized 0·254 | 5 | Within | Within |
| 10 | 5 | Within | Within | 5 | Oversized 0·127 | Oversized 0·127 |
| 11 | 5 | Within | Within | 5 | Oversized 0·254 | Oversized 0·254 |
| 12 | 5 | Undersized 0·127 | Undersized 0·127 | 5 | Oversized 0·127 | Oversized 0·127 |
| 13 | 5 | Undersized 0·254 | Undersized 0·254 | 5 | Oversized 0·254 | Oversized 0·254 |

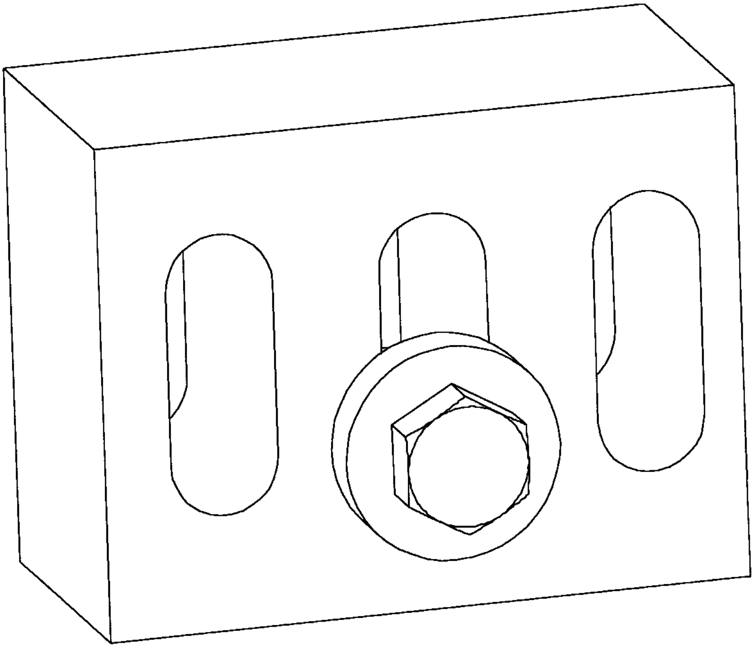

Figure 1. Text fixture.

with acetone for 5 min. The fixture is attached to a 890 N (200 lb) capacity electromagnetic shaker. SAE 20 oil is applied to the surfaces of the spool and washers as specified in MIL-STD-1312-7A [5]. The test bolt and nut are assembled on the spool and fixture, and the nut is tightened to torque of 17·0 N m (150 in lb). A control accelerometer is attached to the base of the test fixture to facilitate shaker control. The test is run until loosening of the test fastner is detected audibly or visually, and time to loosen is recorded. This is repeated three times for each of the 65 test fastener combinations listed in Table 1. The sequence of the 195 tests is completely random.

## 4. DATA ANALYSIS

The data obtained from 195 tests is summarized in Table 2. Fifteen failure times for each of the 13 test configurations are listed. Each test configuration has five test specimens and each test specimen was tested three times.

It is useful to model the failure time distribution for the data in each test configuration. Commonly used life distributions include the normal, exponential, lognormal, Weibull, and extreme value distributions. Goodness-of-fit tests were performed to identify the best distribution model. Two excellent goodness-of-fit tests are probability plots and hazard plots.

The two-parameter Weibull distribution is found to best fit the data for each of the 13 test groups in Table 1. Figures 2 and 3 show the Weibull probability plot and

TABLE 2

*Raw data*

| Test no. | Failure time for test specimen group (s) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 1 | 12 | 15 | 4 | 10 | 8 | 3 | 8 | 15 | 16 | 12 | 12 | 11 | 8 |
| 2 | 14 | 12 | 4 | 7 | 13 | 3 | 8 | 13 | 10 | 12 | 12 | 8 | 5 |
| 3 | 11 | 14 | 8 | 5 | 14 | 3 | 10 | 8 | 10 | 13 | 11 | 8 | 9 |
| 4 | 16 | 10 | 9 | 11 | 14 | 11 | 8 | 14 | 12 | 12 | 5 | 15 | 15 |
| 5 | 20 | 13 | 10 | 15 | 11 | 15 | 8 | 11 | 8 | 15 | 6 | 12 | 18 |
| 6 | 32 | 4 | 12 | 11 | 9 | 10 | 6 | 11 | 18 | 7 | 4 | 10 | 14 |
| 7 | 8 | 6 | 13 | 6 | 14 | 9 | 7 | 13 | 8 | 14 | 8 | 11 | 19 |
| 8 | 17 | 10 | 13 | 9 | 16 | 4 | 10 | 18 | 5 | 5 | 8 | 13 | 11 |
| 9 | 15 | 11 | 15 | 15 | 19 | 6 | 12 | 15 | 8 | 12 | 13 | 15 | 14 |
| 10 | 22 | 12 | 5 | 7 | 9 | 5 | 14 | 6 | 14 | 7 | 13 | 7 | 11 |
| 11 | 20 | 16 | 3 | 8 | 16 | 11 | 12 | 6 | 12 | 11 | 10 | 14 | 17 |
| 12 | 18 | 16 | 8 | 9 | 4 | 14 | 14 | 7 | 11 | 13 | 11 | 20 | 10 |
| 13 | 16 | 19 | 14 | 12 | 11 | 9 | 10 | 9 | 5 | 4 | 13 | 13 | 8 |
| 14 | 20 | 13 | 11 | 12 | 9 | 11 | 14 | 14 | 6 | 5 | 16 | 13 | 15 |
| 15 | 16 | 18 | 8 | 10 | 14 | 14 | 13 | 13 | 6 | 6 | 14 | 7 | 11 |

hazard plot for test group 4 respectively. The Weibull probability plots and Weibull hazard plots for the other test groups are given elsewhere [7]. The closer the data fits to a straight line in each plot, the better the goodness of fit. An $R^2$ value is used to measure how well the data fits a straight line. The $R^2$ value is the percentage reduction in mean-squared error that the model achieves relative to the naive model or null hypothesis. The computed $R^2$ values are all greater than 0·91, which indicates that the two-parameter Weibull model fits the test data well.

The cumulative distribution for the two-parameter Weibull model is defined as

$$F(t) = 1 - \exp[-(t/\beta)^{\gamma}], \quad t > 0. \tag{1}$$

The two parameters of the Weibull model are called the shape parameter $\gamma$ and scale parameter $\beta$, both of which are positive. The scale parameter $\beta$ is also called the characteristic or typical life, has units of time, and is always equal to the 63·2 percentile failure time of the fitted population. Both of these parameters need to be estimated. Once the Weibull distribution model is fitted to each of the 13 data groups in Table 1, equation (1) can be used to estimate the fraction or percent of test specimen failures at any time $t$.

Fitting the model to the data consists of estimating the model shape and scale parameters. There are several methods available for estimating these parameters and associated confidence intervals. The maximum likelihood (ML) method of estimation is considered the most accurate parameter estimation method and is used in this work. Table 3 shows the calculated estimates of the shape and scale parameters together with the lower and upper 90% confidence limits for each of the 13 test fastener groups.

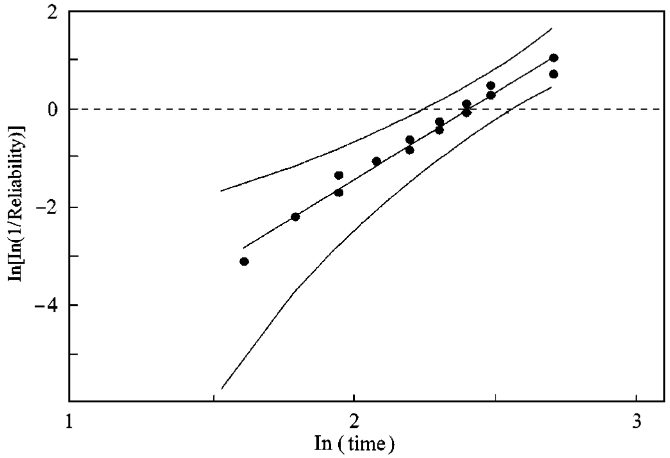

Figure 2. Weibull probability plot with 95% confidence limits for test specimen group 4.

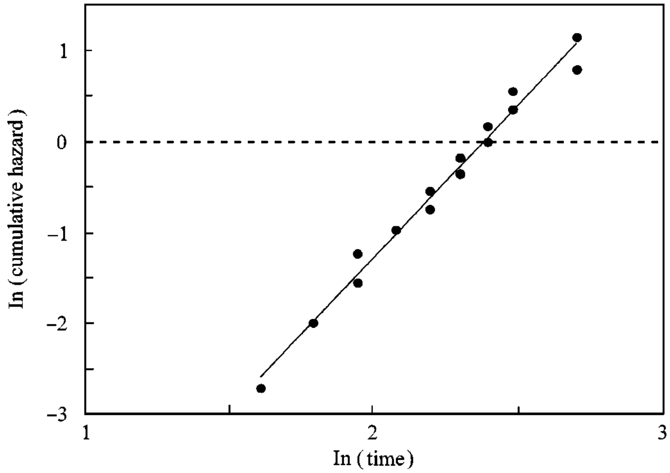

Figure 3. Weibull hazard plot for test specimen group 4.

The expected value of the scale parameter for a particular data sample defines the mean time to failure for that data sample. For example, Table 3 shows that the calculated expected value of the scale parameter for test specimen group 6 is 9·7 s. This means that the mean time to failure of this test specimen group is 9·7 s. Furthermore, the lower and upper 90% confidence limits given in Table 3, provide the range of failure time for 90% of specimens in a given group. For example, 90% of all specimens in group 6 will fail (i.e., loosen) between 8·3 and 11·3 s.

Figure 4 shows a plot of time to failure for each of the 13 test specimen groups. Both the expected time to failure and the 90% confidence limits are presented. The plot shows degradation of resistance to shock-induced loosening for the threaded

Table 3

*Maximum likelihood method estimation of Weibull distribution parameters with* 90% *confidence limits*

| Test specimen group | Weibull scale parameters $\beta$ (s) | | | Weibull shape parameters $\gamma$ | | |
|---|---|---|---|---|---|---|
| | Expected value | Lower 90% confidence limit | Upper 90% confidence limit | Expected value | Lower 90% confidence limit | Upper 90% confidence limit |
| 1 | 19·1 | 17·1 | 21·2 | 3·249 | 2·569 | 4·108 |
| 2 | 14·0 | 12·7 | 15·3 | 3·690 | 2·814 | 4·838 |
| 3 | 10·3 | 9·1 | 11·7 | 2·707 | 2·057 | 3·563 |
| 4 | 10·9 | 9·9 | 11·9 | 3·737 | 2·895 | 4·823 |
| 5 | 13·4 | 12·2 | 14·7 | 3·699 | 2·838 | 4·821 |
| 6 | 9·7 | 8·3 | 11·3 | 2·241 | 1·703 | 2·949 |
| 7 | 11·3 | 10·4 | 12·2 | 4·397 | 3·376 | 5·726 |
| 8 | 12·8 | 11·7 | 14·1 | 3·772 | 2·887 | 4·929 |
| 9 | 11·2 | 9·9 | 12·7 | 2·811 | 2·182 | 3·621 |
| 10 | 11·1 | 9·9 | 12·4 | 3·173 | 2·393 | 4·206 |
| 11 | 11·6 | 10·5 | 12·7 | 3·610 | 2·739 | 4·758 |
| 12 | 13·1 | 11·9 | 14·4 | 3·665 | 2·866 | 4·686 |
| 13 | 13·7 | 12·4 | 15·2 | 3·533 | 2·713 | 4·600 |

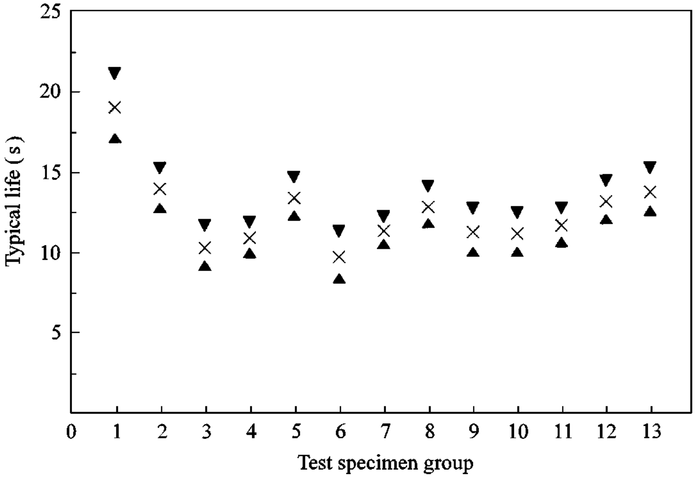

Figure 4. Time to failure for 13 test specimen groups ( ×, expected values; ▲, lower 90% confidence limits; ▼, upper 90% confidence limits).

fastener specimens with non-conforming dimensions compared to the conforming group. Note that the expected time to loosen for the conforming product (i.e., group 1) is highest and about 36% greater than the expected time to loosen for group 2 which is the best-performing non-conforming group tested. The expected time to

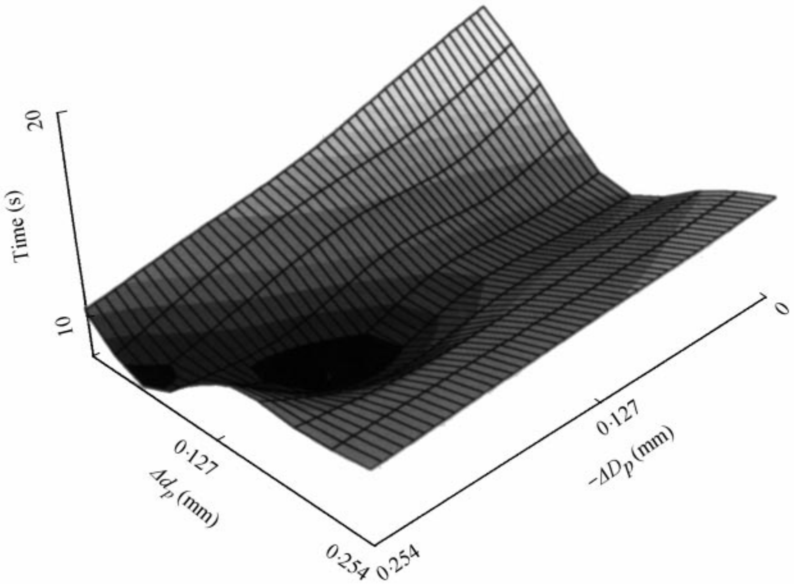

Figure 5. Time to failure versus change in bolt pitch diameter and nut pitch diameter (surface generated using data from test groups 1–7).

loosen for the conforming product is about 97% greater than the expected time to loosen for group 6 which is the worst-performing non-conforming group tested.

Examination of the data in Table 2 and Figure 4 reveals that there is not a simple relationship between the time to loosen under repeated shock conditions and increasing thread clearance. The data shows that decreasing bolt pitch diameter by 0·127 mm and 0·254 mm results in continued reduction in expected time to loosen, whereas increasing nut pitch diameter by 0·127 mm results in a decrease in loosening time but then the loosening time increases when the nut pitch diameter is increased by 0·254 mm. Comparison of the data for non-conforming groups reveals significant interaction between the diameter parameters varied, however, the data shows a general reduction in loosening time for non-conforming product.

Figure 5 illustrates the interaction between bolt pitch diameter and nut pitch diameter. This surface was generated using the data from test groups 1–7. Note that the minimum value in this surface does not occur at the point of largest thread clearance, i.e. $\Delta d_p = 0{\cdot}254$ mm and $\Delta D_p = -0{\cdot}254$ mm. A possible explanation for this behavior is that once the thread clearance reaches a certain level, the threads of the nut actually jam, i.e., load to one side, against the threads of the bolt during tightening. Although this action may result in a slight improvement in shock-induced loosening, it is still inferior to the mechanical shock resistance obtained with the conforming fasteners from group 1.

## 5. CONCLUSIONS

This work has resulted in failure time data from repeated shock loading for fastener combinations within dimensional conformance according to ASME

Standard B1.1-1992 [4] as well as for fastener combinations with non-conforming pitch, minor and major diameters. Statistical models for comparing the test data have been developed. Data from the tests show reduced resistance to mechanical shock for the fastener combinations with undersized pitch and major bolt diameters or oversized pitch and minor nut diameters, compared to fastener combinations within conformance. The expected value for time to loosen for conforming product was found to be as much as 97% greater than the expected value for time to loosen for non-conforming product.

## ACKNOWLEDGMENT

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## APPENDIX A: NOMENCLATURE

| | |
|---|---|
| $\Delta d_p$ | change in nut pitch diameter |
| $\Delta D_p$ | change in bolt pitch diameter |
| $F(t)$ | Weibull cumulative distribution |
| $t$ | time |
| $\beta$ | Weibull sclae parameter |
| $\gamma$ | Weibull shape parameter |