Aerospace Threaded Fastener Strength in Combined Shear and Tension Loading

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NOMENCLATURE

A_{body}	area of full diameter body section of a bolt
A_t	tensile stress area of the threaded section of a bolt
F_{ult_test}	maximum applied test load at rupture
K	ratio of bolt allowable shear load to allowable tensile load
k	ratio of ultimate shear stress to ultimate tensile stress
P	axial tensile load applied to a bolt as a result of tensile load applied to a joint
P_{allow}	bolt allowable ultimate tensile load
P_{allow_thread}	bolt allowable ultimate tensile load based on failure in the threaded section
P_{ult}	bolt tensile load at failure
R_s	ratio of applied shear load to allowable ultimate shear load $= V/V_{allow}$
R_{s_body}	ratio of applied shear load to bolt body allowable ultimate shear load $= V/V_{allow\_body}$
R_t	ratio of applied tensile load to bolt allowable ultimate tensile load (neglecting preload) $= P/P_{allow}$
R_{t_thread}	ratio of applied tensile load to thread allowable tensile load $= P/P_{allow\_thread}$
V	shear load applied to a bolt as a result of shear load applied to a joint
V_{allow}	bolt allowable ultimate shear load $= V_{allow\_body}$ or V_{allow_thread}
V_{allow_body}	bolt allowable ultimate shear load based on failure in the full diameter body section
V_{allow_thread}	bolt allowable ultimate shear load based on failure in the threaded section
V_{ult}	bolt shear load at failure
θ	loading angle relative to the bolt axis
σ	normal stress
τ	shear stress

TECHNICAL MEMORANDUM

**AEROSPACE THREADED FASTENER STRENGTH IN COMBINED
SHEAR AND TENSION LOADING**

1. INTRODUCTION

The strength capability of aerospace threaded fasteners is typically specified as a minimum tensile strength or minimum double shear strength in either a standard part or procurement specification. These values are usually derived by multiplying the thread tensile stress area by the design allowable ultimate tensile stress of the fastener material or by multiplying the area of the full diameter body (herein referred to as the body) by the design allowable ultimate shear stress, respectively. Acceptance testing is performed on manufacturing lots to verify that each lot of bolts is at least as strong as the minimum specification values.

The specification strength values are only applicable to fasteners that are loaded in either pure tension or pure shear. For bolted joints that do not have a design feature to react applied shear loads, the bolts are required to carry a combination of shear and tension loading. Load interaction failure criteria exist for members in combined shear and tension loading,[1] including a commonly used criterion specifically for threaded fasteners.[1–4] However, a survey of literature reveals that there is little data available to validate these failure criteria for aerospace bolts in a typical preloaded joint installation. Furthermore, these existing failure criteria are intended for instances where the shear plane is at a smooth, constant cross section and do not necessarily apply to a threaded fastener with the shear plane through the threads.

A test program was initiated by Marshall Space Flight Center and sponsored by the NASA Engineering and Safety Center to validate existing combined loading failure criteria and to quantify the effect of threads in the shear plane. The testing consisted of a series of 46 tests of individual bolts. The bolts were loaded to failure at several angles relative to the bolt axis, similar to test method MIL-STD-1312-2,[5] using a custom designed test fixture. The testing included a group of fasteners with the shear plane passing through the full diameter body and a group of fasteners with the shear plane passing through the threads. Both of these groups were further divided into fasteners that were installed with zero preload and fasteners that were installed with a high initial preload. Table 1 lists the complete test matrix.

Table 1. Test matrix.

Condition	Shear Plane	Load Orientation	Assembly Preload	Quantity Tested
1	Body	Tension-only 0°	None	6
2	Body	Shear-only 90°	None	3
3	Threads	Shear-only 90°	None	3
4	Body	Shear-only 90°	High	3
5	Threads	Shear-only 90°	High	3
6	Body	Shear and tension 45°	None	3
7	Threads	Shear and tension 45°	None	3
8	Body	Shear and tension 45°	High	3
9	Threads	Shear and tension 45°	High	3
10	Body	Shear and tension 22.5°	None	2
11	Threads	Shear and tension 22.5°	None	2
12	Body	Shear and tension 22.5°	High	2
13	Threads	Shear and tension 22.5°	High	2
14	Body	Shear and tension 67.5°	None	2
15	Threads	Shear and tension 67.5°	None	2
16	Body	Shear and tension 67.5°	High	2
17	Threads	Shear and tension 67.5°	High	2

2. DESIGN FAILURE CRITERIA

The criterion typically used to predict the ultimate failure of a member in combined shear and tension is based on the maximum normal stress and maximum shear stress theories.[1] For the case of combined shear and uniaxial tension loading, the maximum principal and shear stresses are given as follows:

$$\sigma_{max} = \frac{\sigma}{2} + \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \tag{1a}$$

and

$$\tau_{max} = \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \quad . \tag{1b}$$

If the allowable stresses in shear and tension are given as τ_{ult} and σ_{ult}, respectively, then let $R_s = \tau/\tau_{ult}$, $R_t = \sigma/\sigma_{ult}$, and $k = \tau_{ult}/\sigma_{ult}$. If failure is defined when the maximum shear stress is τ_{ult} or the maximum principal stress is σ_{ult}, the above equations can then be written as the following failure criteria:

$$1 = \frac{R_t}{2} + \sqrt{\left(\frac{R_t}{2}\right)^2 + \left(kR_s\right)^2} \tag{2a}$$

and

$$1 = \sqrt{\left(\frac{R_t}{2k}\right)^2 + \left(R_s\right)^2} \quad . \tag{2b}$$

These two equations are plotted in figure 1 for k values of 0.5, 0.6, and 0.7. For values of k greater than 0.5, the bounding failure envelope consists of a combination of the maximum normal and shear stress curves. It is convenient and conservative to use the maximum shear stress criterion equation with $k = 0.5$, and this is the criterion usually cited for a member loaded in combined shear and tension. When $k = 0.5$, the maximum shear stress failure criterion simplifies to the following single interaction equation, where R_s and R_t are the shear and tension load ratios, respectively:

$$R_s^2 + R_t^2 = 1 \quad . \tag{3}$$

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The failure criterion given by equation (3) is a stress-based criterion for a material at a given point. Often the form of this criterion is used as a load-based criterion for compact sections by changing the normal stress σ to a normal load P, the shear stress τ to a shear load V, and material stress allowables σ_{ult} and τ_{ult} to load allowables P_{allow} and V_{allow}, respectively, as shown in equation (4):

$$R_s^2 + R_t^2 = \left(\frac{V}{V_{allow}} \right)^2 + \left(\frac{P}{P_{allow}} \right)^2 = 1 \ . \tag{4}$$
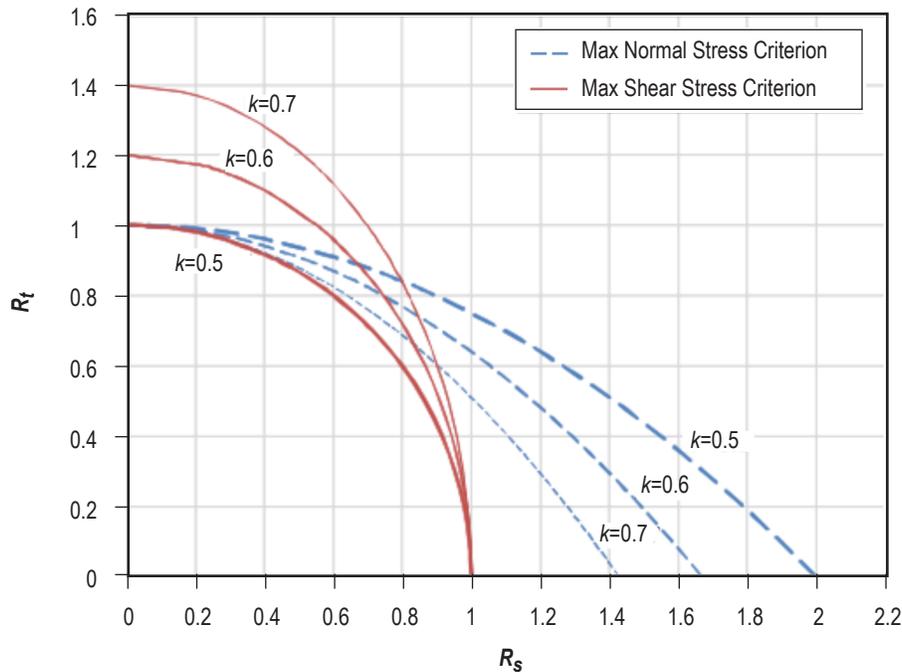

Figure 1. Maximum normal and shear stress failure criteria.

The failure behavior of a threaded fastener with the shear plane passing though the body of the fastener is determined by the shear strength of the body and the tensile strength of the threads. Since the tensile strength of the threads is less than the tensile strength of the body, and the shear and tensile failures occur at different locations, the criterion of equation (4) cannot be used as a single equation criterion for threaded fasteners with the shear plane through the body.

The failure criterion commonly used for threaded fasteners in combined shear and tension loading is given by equation (5). References 1–3 indicate that this criterion was originally developed for the AN series aircraft bolts, and references 1 and 3 indicate it is based on testing; however, the test data have not been located in a survey of the available literature. Equation (5) is the failure criterion that will be used to compare against the test data herein for the test configuration with the shear plane through the body:

$$R_{s\_body}^3 + R_{t\_thread}^2 = \left(\frac{V}{V_{allow\_body}}\right)^3 + \left(\frac{P}{P_{allow\_thread}}\right)^2 = 1 \ . \tag{5}$$

The criterion of equation (5) can be compared against the maximum normal and maximum shear stress criteria by introducing an effective shear to tensile allowable load ratio, $K = V_{allow}/P_{allow}$. For a threaded fastener, the ratio of the tensile strength of the body to the tensile strength of the threads is given by the ratio of tensile area of the body to the tensile stress area of the threads, which for a 0.375-24 UNJ bolt is given as 1.161.[6–8] If the material shear to tensile allowable stress ratio is 0.5, as assumed for equation (4), then the bolt shear to tensile allowable load ratio $K = 0.5 \times 1.161 = 0.581$. The maximum normal and maximum shear stress failure curves for $k = 0.581$ are shown in figure 2. Equation (5) is also plotted in figure 2, and it can be seen that this equation approximately follows the failure envelope defined by the $K = 0.581$ maximum normal and maximum shear failure curves. Therefore, while equation (5) is an empirically-based, single equation failure criterion, it is similar to the failure envelope predicted by the maximum normal and maximum shear stress theories.
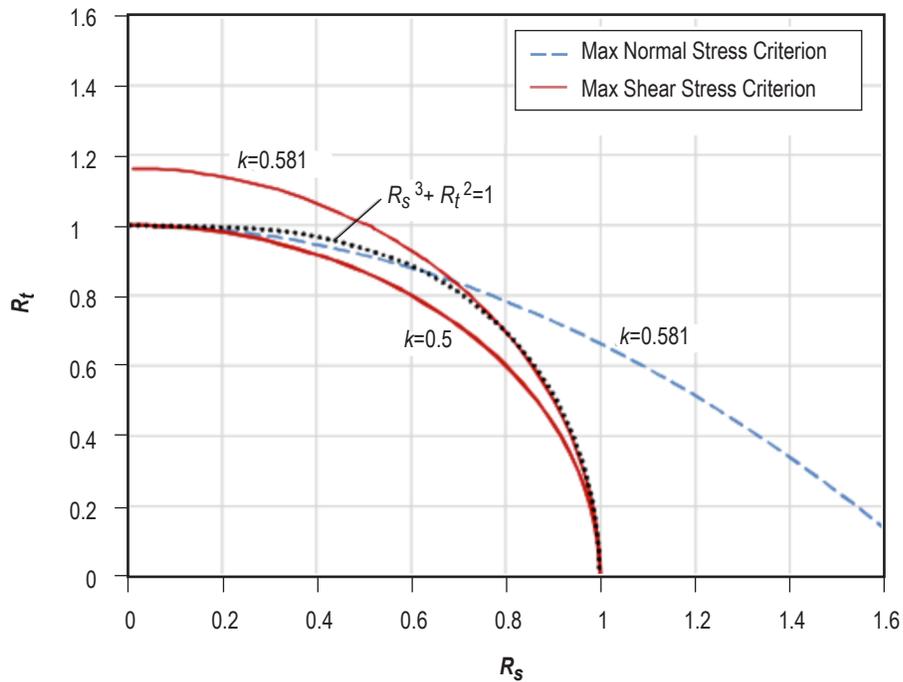

Figure 2. Threaded fastener failure criterion.

There is no unique combined shear and tension load failure criterion intended specifically for threaded fasteners when the shear plane passes through the threads. For this condition, it is often assumed the criterion of equation (4) applies, where the allowable loads are the shear and tensile strength of the threaded region as shown in equation (6). Equation (6) will be used to compare against the test data herein for the test configuration with the shear plane through the threads:

$$R_{s\_thread}^2 + R_{t\_thread}^2 = \left(\frac{V}{V_{allow\_thread}} \right)^2 + \left(\frac{P}{P_{allow\_thread}} \right)^2 = 1 \ . \tag{6}$$

The combined shear and tension load failure criterion in reference 4 has the same form as equation (5) but the shear and tensile load allowables are "based on the cross section at which the combined loads occur." The resulting failure criterion is given in equation (7). This criterion is not in agreement with the maximum normal and maximum shear stress theories, nor is it based on test, and it is less conservative than equations (4) or (5). The use of this criterion with shear and tensile load allowables from the same cross section is not recommended.

$$R_s^3 + R_t^2 = \left(\frac{V}{V_{allow}} \right)^3 + \left(\frac{P}{P_{allow}} \right)^2 = 1 \ . \tag{7}$$

The failure criteria presented above assume the only significant loading at the failure cross section is shear and tension. Bending moment is assumed to be zero or insignificant. For bolts under shear loading, moment does develop within the length of the bolt but it is nearly zero at the shear plane. Since the failure plane of all the test bolts with shear loading occurred at the shear plane, moment is not considered. If moments are not insignificant at the shear plane due to the nature of the applied loading, or if the configuration of the joint includes shims or gaps, then moment should be considered. However, it is outside the scope of this Technical Memorandum (TM) to determine the influence of moment on the combined loading failure criteria.

3. TEST CONFIGURATION

The testing reported in this TM consisted of 46 tests of individual bolts to failure. The testing was performed using a load frame with a set of fixtures that can orient the load over a range of discrete angles from 0° to 90° relative to the bolt axis. Pure tension corresponds to a loading angle of 0° and pure shear corresponds to a loading angle of 90°. Figure 3 shows the fixtures installed in the load frame with the loading angle set at 45°.
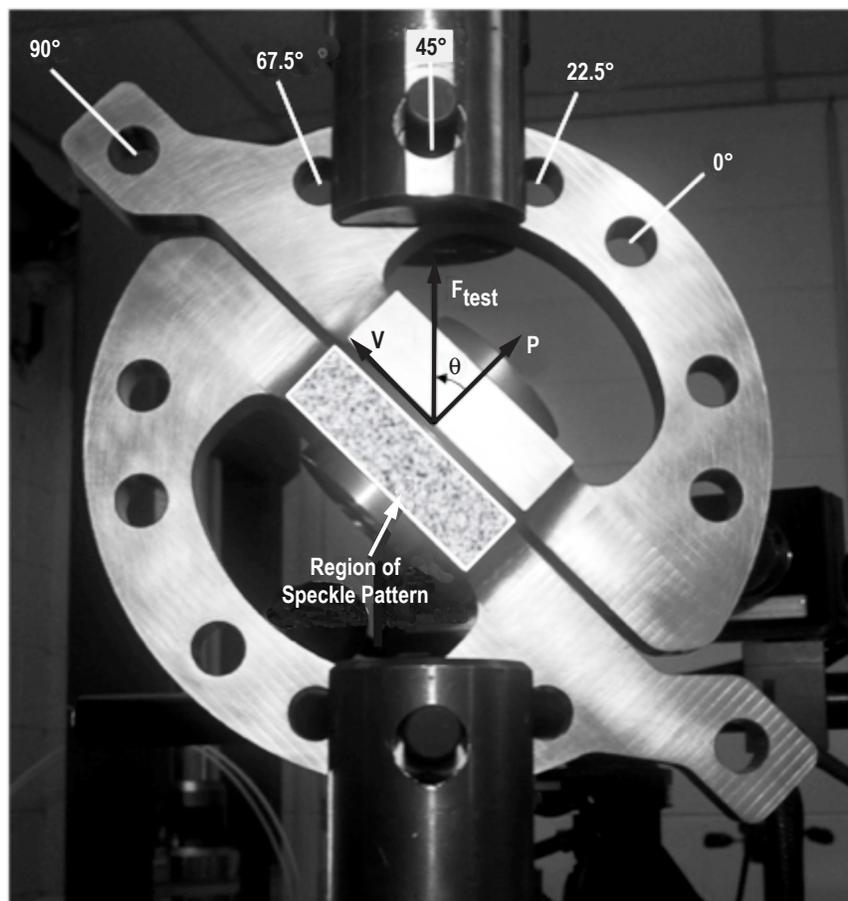

Figure 3. Test fixtures installed in test machine grips.

The bolts were installed into the test fixtures using interfacing pucks as the bolted joint members. The pucks transferred the load from the test fixture to the bolt and were sized to be able to install the same size diameter and length bolt with either a nut or with an insert. The pucks in the nut configuration were sized to place the shear plane through the body of the bolt, and the pucks in the insert configuration were sized to place the shear plane through the threads of the

bolt. For the insert configuration, a threaded heavy-duty, key-locked insert was installed into an aluminum 7075 alloy puck. All other pucks were made from 440C stainless steel. Figure 4 shows a cross-section sketch of the bolt and nut configuration, and figure 5 shows the bolt and insert configuration.
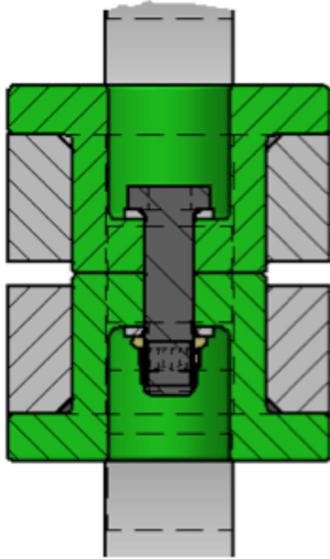

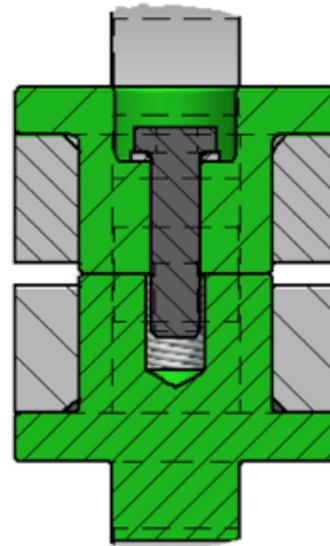Figure 4. Bolt and nut configuration.   Figure 5. Bolt and insert configuration.

All of the bolt specimens were 3/8-in bolts of type NAS1956C14 and were procured from the same manufacturing lot. The bolt material was A-286 corrosion-resistant steel heat treated to a minimum of 180 ksi ultimate tensile strength and 108 ksi ultimate shear strength. The nuts were of type NAS1805-6, and the inserts were of type NAS1395C6L. The washers were of type NAS1587-6 or -6C. A lubricant was applied to the faying surfaces of the pucks to minimize the transfer of shear load by friction.

4. TEST PROCEDURE

The loading of the bolts was performed by the tensile load frame operating under displacement control. The loading rate was ≈0.024 in/min for all tests. The data collected for each test included the load frame load cell force and the cross head displacement. Additional displacement data were obtained using a video displacement measuring system. This system measured displacement of the test fixture face adjacent to the pucks by monitoring a speckle pattern of paint applied to the surface of both fixtures as indicated in figure 3.

The bolts were installed into the pucks with either no preload or a high preload. In the no-preload tests, the bolts were installed by hand until the bolt was just seated. In the high-preload tests, the bolts were intended to be installed with a torque wrench until the torque reached a value corresponding to a preload level of ≈8,000 lb (47% of the bolt minimum specified ultimate tensile strength) based on results from previously performed torque-tension testing (see appendix). The target torque was 400 in-lb for the nut configuration, and the target torque was 1,200 in-lb for the insert configuration. During bolt installation into the second insert test article, the fastener broke before reaching 1,200 in-lb. The failure was attributed to tensile overload thought to be a result of large variability in the torque-preload relationship for this fastening system. Subsequent insert configurations were then installed to a torque value of 600 in-lb.

5. TEST RESULTS

A summary of the test results is listed in table 2. The ultimate load listed is the maximum applied load that was achieved during the test, F_{ult_test}. The bolt ultimate tension load P_{ult} is $F_{ult\_test} \times \cos(\theta)$, and the bolt ultimate shear load V_{ult} is $F_{ult\_test} \times \sin(\theta)$. Figures 6 and 7 show representative fractured bolts with the shear plane through the body and through the threads, respectively, at four loading angles.

Table 2. Test result summary.

Condition	Load Orientation, θ (deg)	Shear Plane	Installation Torque (in-lb)	Ultimate Load, F_{ult_test} (lb)	Failure Location
1	0	Body	0	17,366	<1>
1	0	Body	0	17,679	<1>
1	0	Body	0	17,465	<1>
1	0	Body	0	20,164	Threads
1	0	Body	0	20,529	Threads
1	0	Body	0	20,229	Threads
10	22.5	Body	0	18,829	Body
10	22.5	Body	0	19,081	Body
6	45	Body	0	15,267	Body
6	45	Body	0	15,319	Body
6	45	Body	0	15,316	Body
14	67.5	Body	0	13,626	Body
14	67.5	Body	0	13,615	Body
2	90	Body	0	13,339	Body
2	90	Body	0	13,346	Body
2	90	Body	0	13,489	Body
11	22.5	Threads	0	15,084	Threads
11	22.5	Threads	0	15,100	Threads
7	45	Threads	0	11,997	Threads
7	45	Threads	0	12,046	Threads
7	45	Threads	0	<2>	<2>
15	67.5	Threads	0	10,415	Threads
15	67.5	Threads	0	10,377	Threads
3	90	Threads	0	10,163	Threads
3	90	Threads	0	9,995	Threads
3	90	Threads	0	<2>	<2>
12	22.5	Body	400	18,746	<1>

Table 2. Test result summary (Continued).

Condition	Load Orientation, θ (deg)	Shear Plane	Installation Torque (in-lb)	Ultimate Load, F_{ult_test} (lb)	Failure Location
12	22.5	Body	400	18,423	<1>
8	45	Body	400	15,382	Body
8	45	Body	400	15,343	Body
8	45	Body	400	15,292	Body
16	67.5	Body	400	13,599	Body
16	67.5	Body	400	<2>	<2>
4	90	Body	400	13,337	Body
4	90	Body	400	13,373	Body
4	90	Body	400	13,302	Body
13	22.5	Threads	600	15,170	Threads
13	22.5	Threads	600	15,122	Threads
9	45	Threads	600	12,070	Threads
9	45	Threads	600	12,088	Threads
9	45	Threads	600	11,636	Threads
17	67.5	Threads	600	10,255	Threads
17	67.5	Threads	600	10,529	Threads
5	90	Threads	1,200	9,706	Threads
5	90	Threads	600	9,785	Threads
5	90	Threads	<3>	<3>	<3>

<1> Specimen failure mode was stripping of the threads.
<2> Test data file lost.
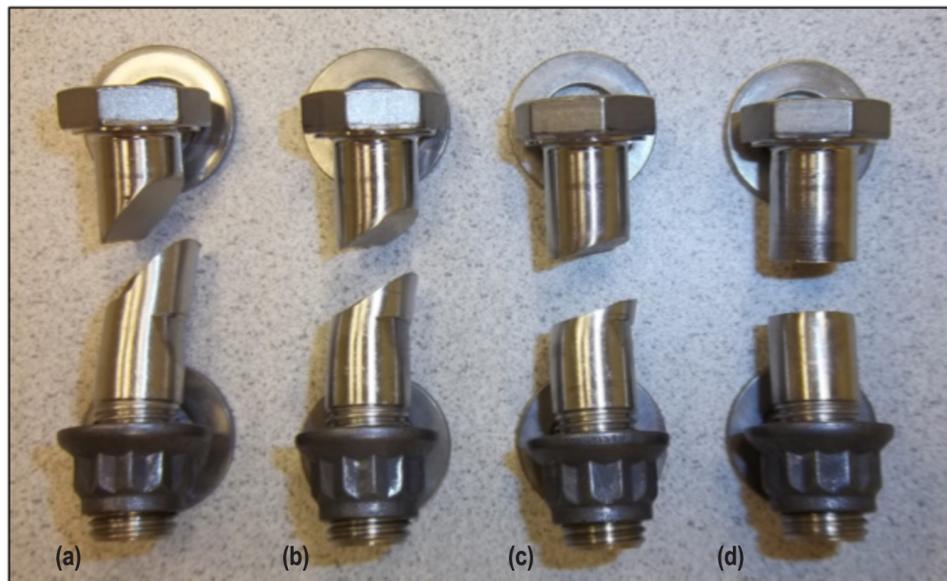<3> Specimen failed during application of 1,200 in-lb of torque.

Figure 6. Fractured bolts with the shear plane in the body. Loading angles of (a) 22.5°, (b) 45°, (c) 67.5°, and (d) 90°.
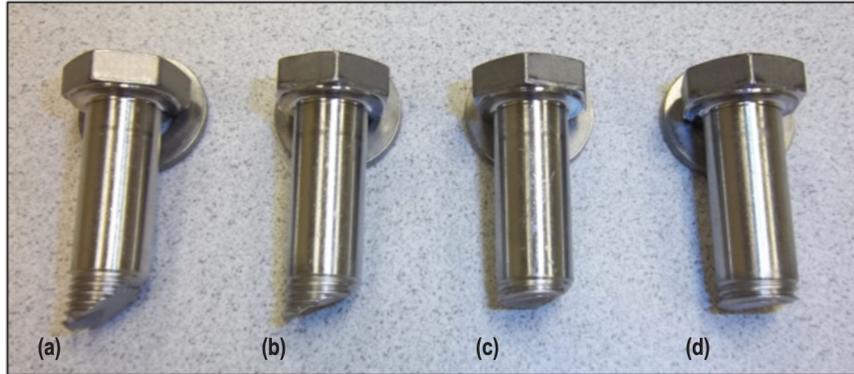
Figure 7. Fractured bolts with the shear plane in the threads. Loading
angles of (a) 22.5°, (b) 45°, (c) 67.5°, and (d) 90°.

5.1 Thread Stripping Failure Mode

Five of the tests resulted in a combined bolt and nut thread stripping failure mode. The five tests were the first three tension-only tests and the two tests with high preload, shear plane in the body, and loaded at 22.5°. The three tension-only tests failed at an average value of 17,503 lb when using the NAS1805 nut. Figure 8 shows these failed bolts and nuts.

Figure 8. Tension load only bolts with thread shear failure.

The tensile-only tests were repeated using higher strength H20-6 220 ksi alloy steel nuts. These tests resulted in the tensile failure of the bolts in the threads at an average load of 20,307 lb. Figure 9 shows the failed bolts. For comparison, the specification minimum tensile strength is 17,100 lb, and the lot acceptance tensile strength is 21,871 lb.

Figure 9. Tension load only bolts with bolt failure in the threads.

The two tests that failed by thread stripping and loaded at 22.5° also had the NAS1805 nuts and failed at an average load of 18,584 lb. This corresponds to an average tensile load of 17,170 lb and an average shear load of 7,112 lb. The minimum failure load was 18,423 lb, which corresponds to a tensile load of 17,021 lb and a shear load of 7,050 lb. This minimum tensile load is just under the specification tensile strength of the bolt and nut of 17,100 lb.

6. DATA ASSESSMENT

6.1 Effect of Preload

The bolt shear and tension ultimate load for each test is plotted in figure 10. It can be seen that the addition of preload did not affect the ultimate external load capability of the bolts. This result is consistent with the findings of other studies.[9,10] The mechanisms behind this behavior are understood to be joint separation prior to bolt failure under tensile loading and relaxation of preload due to plastic deformations under shear loading.
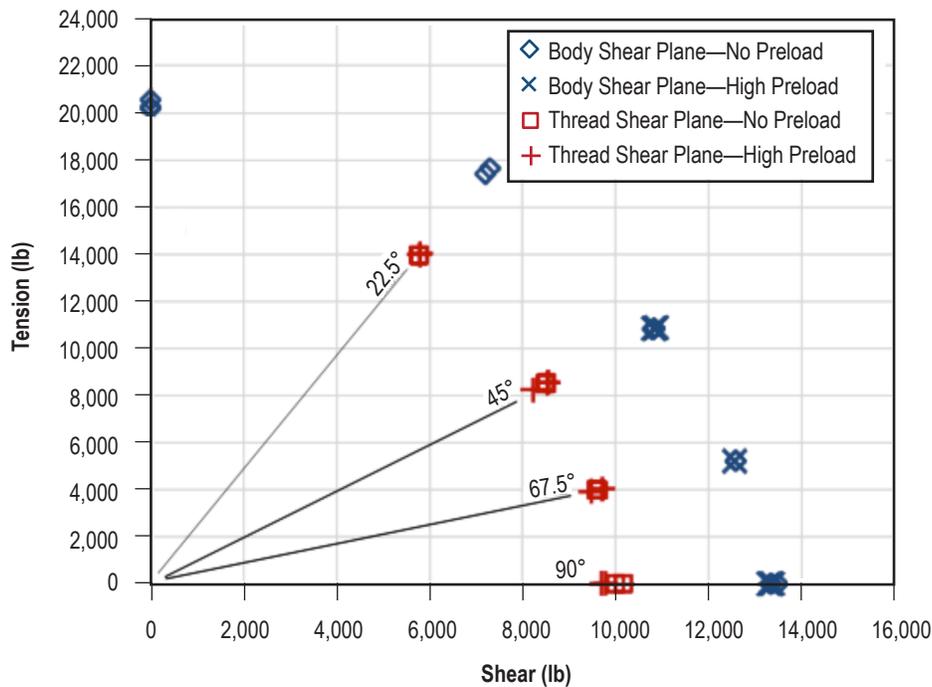

Figure 10. Ultimate bolt shear and tension load results.

6.2 Shear Plane Location

Based on the 90° test results, the average shear strength of the body section is 13,364 lb, and the average shear strength of the threaded section is 9,912 lb. The ratio between the thread and body shear strength values is 0.742. The cross-sectional area of the body is 0.1093 in^2 based on the minimum diameter of the body,[6] and the cross-sectional area of the threads is 0.0811 in^2 based on the minimum minor diameter of the threads.[8] The ratio between the thread and body minimum cross-sectional areas is 0.742. Therefore, the difference between the thread and body

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shear strengths can be completely explained by the difference between the cross-sectional areas when using the minimum body and thread minor diameters.

The net section stress at failure for each of the tests is plotted in figure 11, where the failure stress is determined by dividing the failure load by the original area of the failure plane. The failure behavior of the bolts with the shear plane in the threads is consistent with the behavior of the bolts with the shear plane in the body under combined shear and tension loading. Simply accounting for the reduced cross-sectional area of the threads is sufficient to determine the ultimate capability of fasteners with the shear plane in the threads under all combinations of shear and tension loading. No additional adjustment to the strength of bolts with the shear plane in the threaded section is necessary.
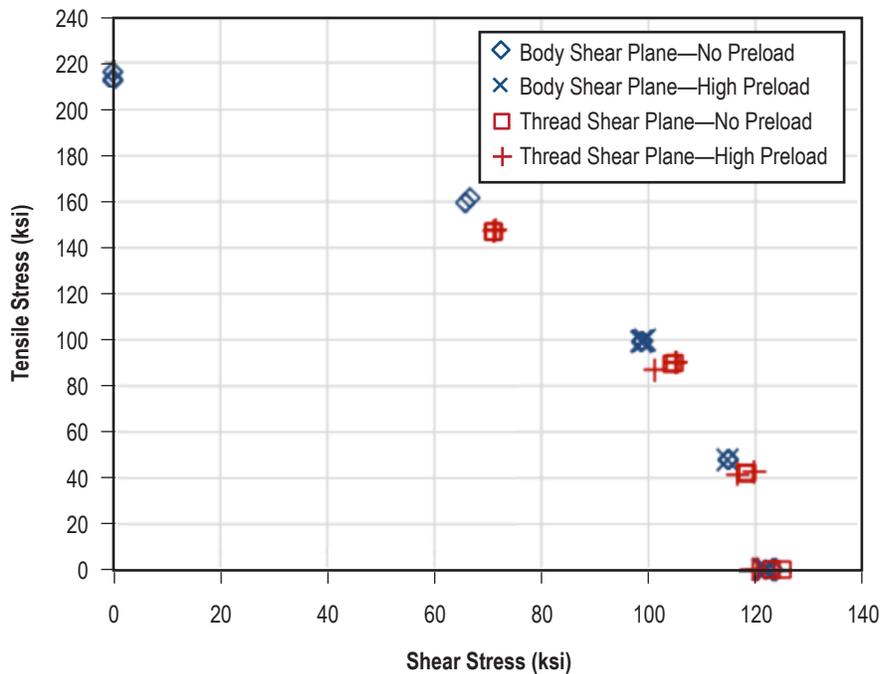

Figure 11. Ultimate bolt shear and tension stress results.

6.3 Existing Failure Criteria

Based on the average of the test results, the following allowable shear and tensile strengths are determined for the body and threaded sections of the test bolts: $P_{allow\_thread} = 20,307$ lb, $V_{allow\_body} = 13,364$ lb, and $V_{allow\_thread} = 9,912$ lb.

The loading ratio results are plotted in figure 12 using the allowable loads listed above. The failure criteria of equations (5) and (6) are also plotted. The combined loading data points for the body shear plane tests fall within the relevant failure criterion of equation (5). The combined loading data points for the thread shear plane tests fall within the relevant failure criterion
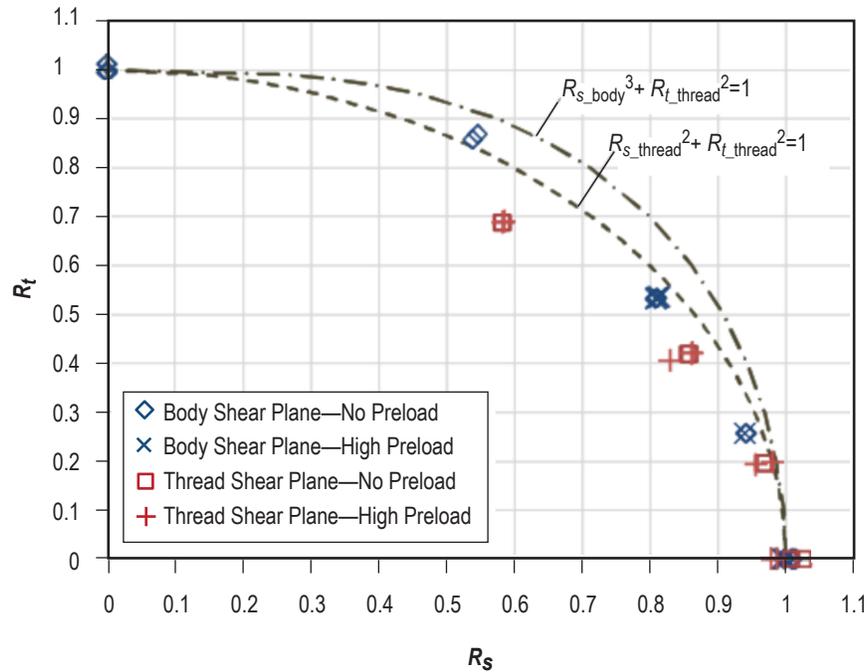
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Figure 12. Ultimate shear and tension ratios.

of equation (6). Therefore, the existing combined loading failure criteria overpredict the strength of the bolts in this test program.

It is proposed that the source for this discrepancy is bending that developed during the testing. The application of tension loads caused the joint to separate before the bolt ruptured, which allowed some bending to develop due to the simultaneously applied shear load. Joint separation was observed during some of the tests. The displacement of the faying surfaces was not directly measured during testing, but the video photogrammetry measurements of the fixture faces indicated relative displacement along the bolt axial direction of up to 0.079 in at failure for the 22.5° loading angle. Figure 13 shows the relative displacement between the two fixtures in the bolt axial direction for each loading angle from representative tests without preload. During the pure shear load tests, the fixture faces moved towards each other, so there was likely no separation for the 90° loading angle.
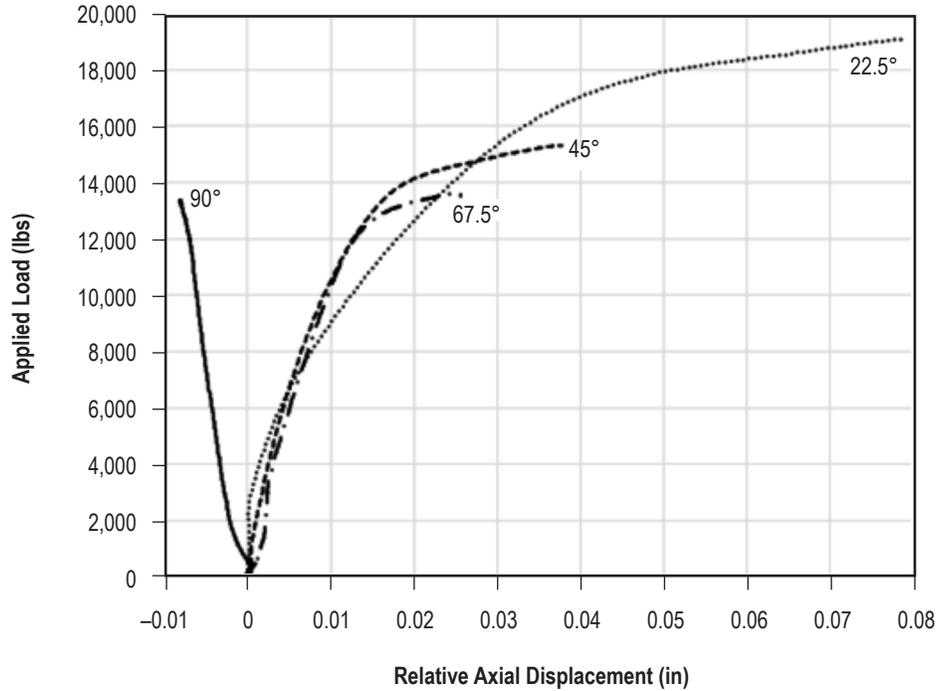
Figure 13. Relative displacement of test fixture faces in bolt axial direction.

The testing performed by Olson subjected smooth titanium and steel bars to combined tension and double shear loading.[9] The failure criterion of equation (4) matched the results from Olson's testing quite well. Olson's double shear test configuration does not allow joint separation, which indicates that the discrepancy between the results of this TM and the failure criteria of equations (5) and (6) is likely due to the joint separation and bending that occurs under the single shear configuration.

6.4 Modified Failure Criteria

The test ultimate loading ratios for the bolts with the shear plane in the body are plotted against the failure criterion of equation (5) in figure 14. Equation (5) overpredicts the test results for the combined shear and tension loading conditions by as much as 7%. A modification of the criterion of equation (5) that better matches the data with the shear plane in the body is given by equation (8) and is also plotted in figure 14:

$$R_{s\_body}^{2.5} + R_{t\_thread}^{1.5} = \left(\frac{V}{V_{allow\_body}} \right)^{2.5} + \left(\frac{P}{P_{allow\_thread}} \right)^{1.5} = 1 \ . \tag{8}$$
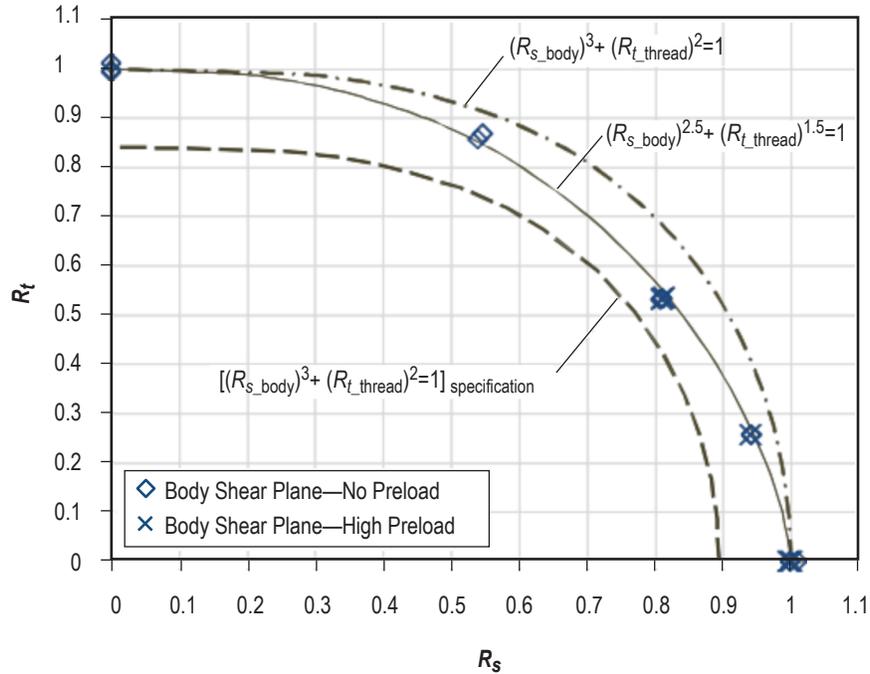
Figure 14. Test data versus failure criteria for shear plane in the body.

Similar combined single shear and tension testing was performed by Chesson et al. using high-strength A325 bolts.[11] The test data from both Chesson and the results reported herein, with the shear plane in the body, are plotted in figure 15. Both sets of data fall short of the capability predicted by equation (5) but match equation (8).

The modified failure criterion of equation (8) is a potential criterion for all bolts in joints with no gaps or shims, a single shear plane in the body, and loaded in combined shear and tension, where the joint is expected to separate before the bolt ruptures. This criterion accounts for the bending that develops after joint separation and does not require the determination of the applied or allowable bending moment. For bolts in joints that are not expected to separate prior to rupture, the criterion of equation (5) is expected to apply.
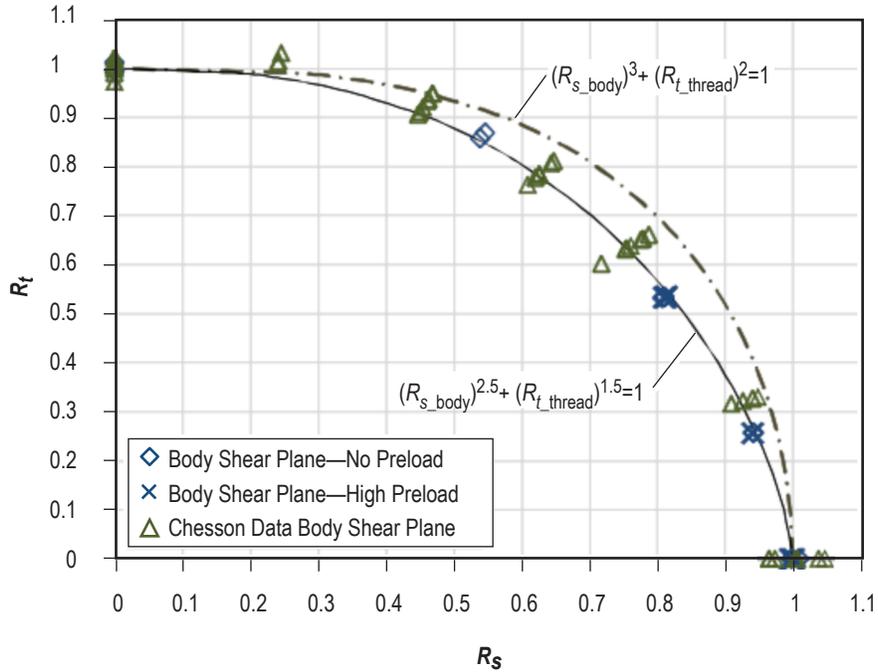
Figure 15. Chesson and test data versus failure criteria for shear plane
in the body.

The test ultimate loading ratios for the bolts with the shear plane in the threads are plotted against the criteria of equations (6) and (7) in figure 16. The failure criteria given by equations (6) and (7) overpredict the ultimate load capability of the bolts by as much as 10% for equation (6) and 16% for equation (7) at the 22.5° loading angle. A modified failure criterion that provides a good match to the test data is given by equation (9), which is also plotted in figure 16:

$$R_{s\_\text{thread}}^{1.2} + R_{t\_\text{thread}}^{2} = \left(\frac{V}{V_{\text{allow\_thread}}} \right)^{1.2} + \left(\frac{P}{P_{\text{allow\_thread}}} \right)^{2} = 1 \ .$$

(9)

Like equation (8), the modified failure criterion of equation (9) is a potential criterion for all bolts in joints with no gaps or shims, a single shear plane in the threads, and loaded in combined shear and tension, where the joint is expected to separate before the bolt ruptures. For bolts in joints that are not expected to separate prior to rupture, the criterion of equation (6) is expected to apply.
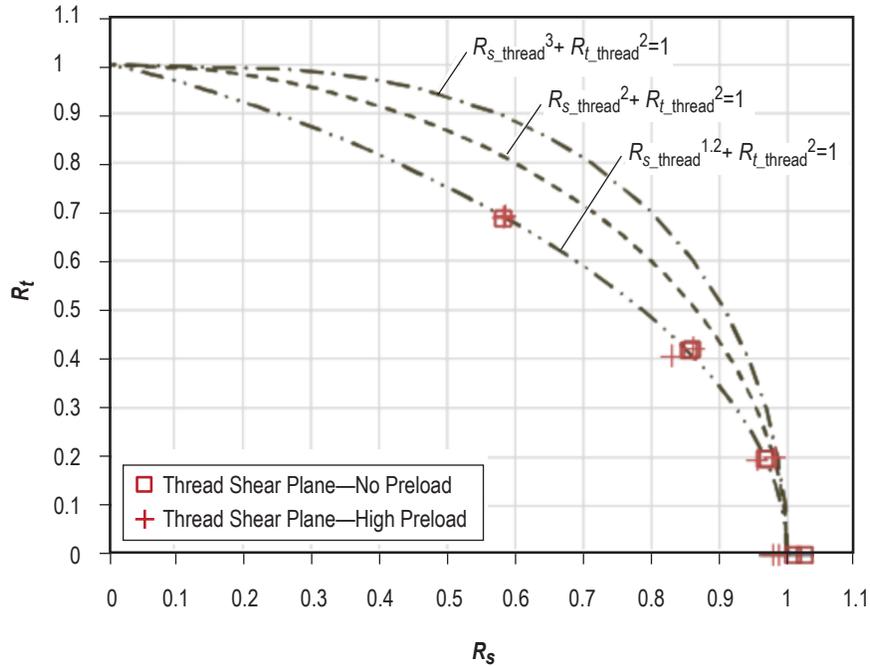
Figure 16. Test data versus failure criteria for shear plane in the threads.

6.5 Specification Versus Actual Strength

While the failure criteria of equations (5)–(7) overpredict the capability of the bolts under combined shear and tension loads when the actual strength of the test bolts is used as the allowable, the criteria are conservative when the minimum specified strengths of the bolts are used as the allowable. Figure 14 shows the failure curve for equation (5) using the minimum shear and tension strengths from the bolt specification, normalized to the average measured strengths from the test specimens.

7. CONCLUSIONS

The results of this test program confirm that the application of an initial preload does not affect the ultimate strength capability of a bolt in shear, tension, or combined shear and tension loading when the joint separates before the bolt ruptures under pure tension loading.

The decrease in shear strength when the failure plane is in the threaded section compared to the body section is accounted for by the change in cross-sectional area between the body and the area of the threaded section based on the minor diameter. No other strength adjustment is required.

The common existing failure criteria used to assess bolt strength overpredicted the strength of the test bolts in combined shear and tension loading when using the actual fastener strengths. The likely cause is due to separation of the joint, which allowed bending to develop within the fastener under the simultaneously applied shear load.

Modifications to the existing failure criteria are proposed that match the results of this test program and can be considered candidate criteria to be used for bolts under combined single shear and tension loading when joint separation before rupture is predicted. The modified criteria account for any bending that occurs under combined loading, thus avoiding the need to estimate the applied and allowed bending load.

The common existing combined loading failure criteria have extensive successful use in the aerospace industry. One contributing factor to this success was demonstrated in the test results: the actual shear and tensile strength of the test bolts were significantly higher than the minimum specified strengths. All of the common criteria would conservatively underpredict the capability of the test bolts, under all load combinations, when using the specification strengths.

APPENDIX—TORQUE-TENSION TEST DATA

The torque-tension test data for a fastener for a with nut is shown in figure 17 and for a fastener with insert in figure 18.
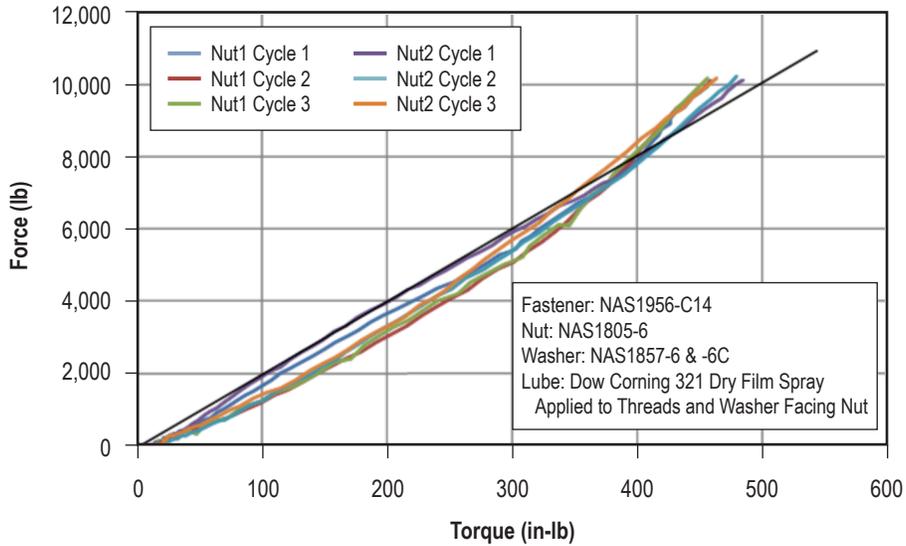

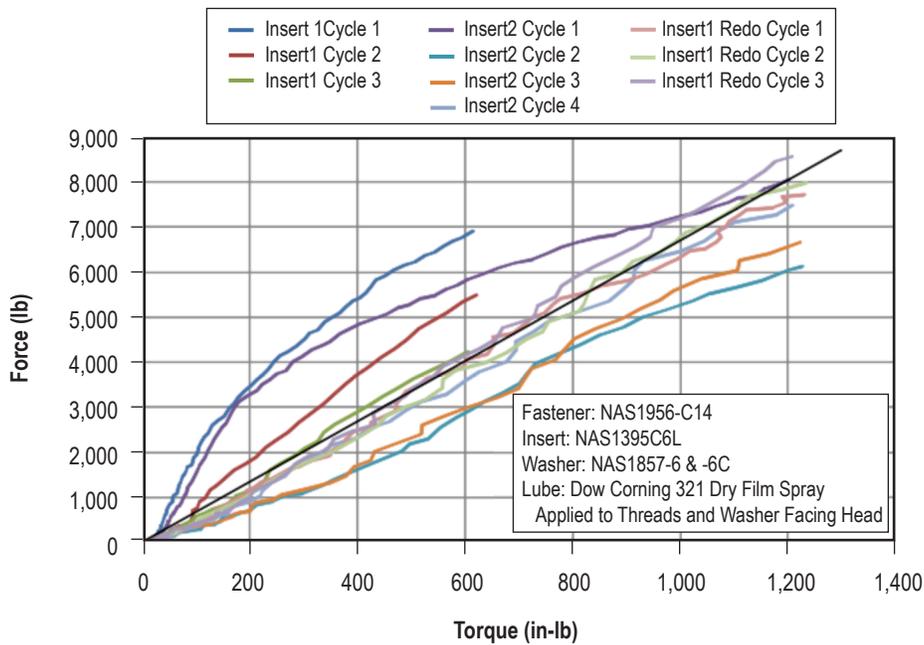Figure 17. Fastener with nut torque-tension data.

Figure 18. Fastener with insert torque-tension data.

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14. ABSTRACT
A test program was initiated by Marshall Space Flight Center and sponsored by the NASA Engineering and Safety Center to characterize the failure behavior of a typical high-strength aerospace threaded fastener under a range of shear to tension loading ratios for both a nut and an insert configuration where the shear plane passes through the body and threads, respectively. The testing was performed with a customized test fixture designed to test a bolt with a single shear plane at a discrete range of loading angles. The results provide data to compare against existing combined loading failure criteria and to quantify the bolt strength when the shear plane passes through the threads.

15. SUBJECT TERMS
threaded fastener, bolt, strength criteria, combined loading, shear, tension

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