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Aerospace Threaded Fastener Strength With Joint Shims

B.E. Steeve
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April 2020

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NOMENCLATURE

d	Nominal bolt diameter
M	Applied bolt moment load
M_{allow}	Bolt allowable bending moment
P	Bolt tensile load
P_{allow}	Bolt allowable tensile strength
R_b	Ratio of bolt moment load to allowable moment load = M/M_{allow}
R_s	Ratio of bolt shear load to allowable shear load = V/V_{allow}
R_t	Ratio of bolt tensile load to allowable tensile load = P/P_{allow}
S	Section modulus
t	Spacer thickness
V	Bolt shear load
V_{allow}	Bolt allowable shear load

TECHNICAL MEMORANDUM

AEROSPACE THREADED FASTENER STRENGTH WITH JOINT SHIMS

1. SUMMARY

Good design practice for bolted joints loaded in shear is to ensure there is no gap between the bolted members. Occasionally a bolted joint incorporates a gap or nonload-carrying member, such as a shim or spacer. This separation of the shear-loading members introduces a bending load into the bolt that affects its loading capability. Various methods exist to account for this additional bending load and provide an ultimate shear- or combined shear- and tension-loading capability; however, there is a lack of test data to validate those methods for typical aerospace fasteners. This Technical Memorandum presents the results of a test series to characterize the strength of a typical high-strength aerospace fastener under shear- or combined shear- and tensile-loading with shims of various thickness. The testing included both steel and aluminum joint members. The results are compared against existing design criteria.

2. INTRODUCTION

Typical aerospace fastener specifications require a minimum ultimate tensile strength and a minimum double shear strength that are lot qualified by tests that load the fasteners in pure tension or pure shear, respectively. Fastener strength under combined shear and tensile loading is typically determined from a load interaction failure criterion. A commonly used historical criterion[1] is given as:

$$\left(\frac{V}{V_{\text{allow}}}\right)^{3}+\left(\frac{P}{P_{\text{allow}}}\right)^{2}\leq 1\ , \tag{1}$$

and a modified criterion used by NASA (for shear planes not in the threads and ignoring bending)[2] is given as:

$$\left(\frac{V}{V_{\text{allow}}}\right)^{2.5}+\left(\frac{P}{P_{\text{allow}}}\right)^{1.5}\leq 1\ , \tag{2}$$

where V and P are the applied bolt shear and tensile loading, respectively, and V_{allow} and P_{allow} are the bolt allowable ultimate shear and tensile strengths, respectively.

When a threaded fastener joint includes a gap or nonloading member in the joint stack, any shear load introduces additional bending load into the fastener that is reacted at the head and nut interfaces, as notionally depicted in figure 1. This additional bending moment reduces the bolt shear capability. Various design failure criteria attempt to account for this reduction in capability. For aerospace joints, there is a lack of test data to assess the accuracy of such criteria. This study aims to investigate the strength behavior of a typical aerospace joint and compare the results against existing design failure criteria.

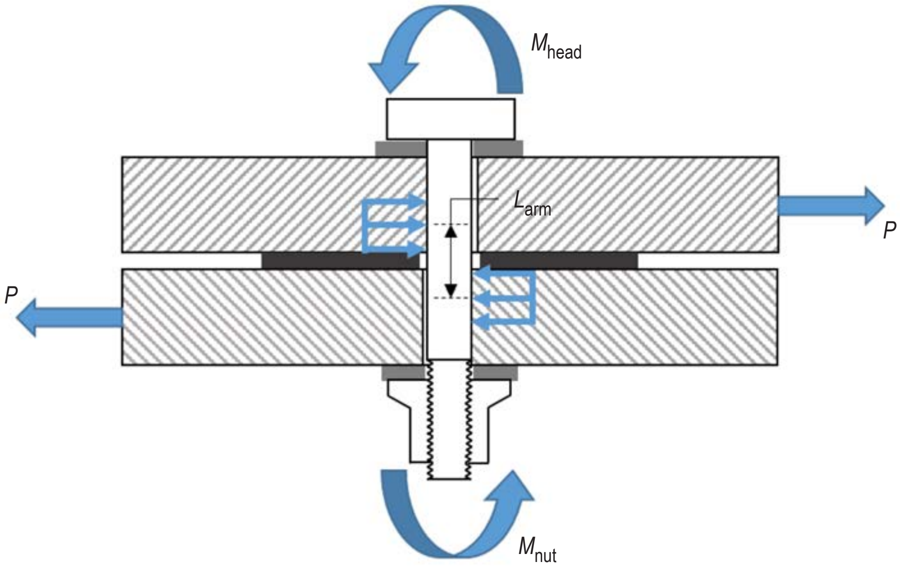

Figure 1. Bolt free-body diagram under combined shear and moment loading.

A series of tests was performed by NASA Marshall Space Flight Center to characterize the shear strength of a typical aerospace corrosion-resistant steel fastener with joint spacers ranging in thickness from zero to one bolt diameter. Testing included a series of bolts loaded in pure shear with both steel and aluminum joint members. Steel joint members were also used to load a series of bolts at an angle of 45° to the bolt axis to apply combined tension and shear. The uniaxial tensile strengths of the bolts were also determined. Table 1 lists the complete test matrix.

Table 1. Test matrix.

Condition No.	Puck Material	Load Orientation	Spacer Thickness (in.)	Quantity Tested
101	Steel	Tension-only 0°	–	3
102	Steel	Shear and Tension 45°	0.000	3
103	Steel	Shear-only 90°	0.000	3
104	Steel	Shear and Tension 45°	0.030	3
105	Steel	Shear-only 90°	0.030	3
106	Steel	Shear and Tension 45°	0.060	3
107	Steel	Shear-only 90°	0.060	3
108	Steel	Shear & Tension 45°	0.090	3
109	Steel	Shear-only 90°	0.090	3
110	Steel	Shear and Tension 45°	0.120	3
111	Steel	Shear-only 90°	0.120	3
112	Steel	Shear-only 90°	0.120	3
113	Steel	Shear and Tension 45°	0.180	3

Table 1. Test matrix (Continued).

Condition No.	Puck Material	Load Orientation	Spacer Thickness (in.)	Quantity Tested
114	Steel	Shear-only 90°	0.180	3
115	Steel	Shear and Tension 45°	0.240	3
116	Steel	Shear-only 90°	0.240	3
201	Aluminum	Tension-only 0°	–	2
203	Aluminum	Shear-only 90°	0.000	3
205	Aluminum	Shear-only 90°	0.030	3
207	Aluminum	Shear-only 90°	0.060	3
209	Aluminum	Shear-only 90°	0.090	3
211	Aluminum	Shear-only 90°	0.120	3
212	Aluminum	Shear-only 90°	0.120	3
214	Aluminum	Shear-only 90°	0.180	3
216	Aluminum	Shear-only 90°	0.240	3

3. DESIGN FAILURE CRITERIA

There are a number of empirical and analytical approaches to predict the failure of a threaded fastener loaded in shear with shims. The NASA criterion adds a bending load ratio term to equation (2) (for shear plane not in the threads and using plastic bending):

$$\left(\frac{V}{V_{\text{allow}}}\right)^{2.5}+\left(\frac{P}{P_{\text{allow}}}\right)^{1.5}+\left(\frac{M}{M_{\text{allow}}}\right)\leq 1\ , \tag{3}$$

where M is the applied bolt moment loading. M_{allow} is the allowable bending moment and is typically determined by the bending stress $S_{\text{allow}}=M_{\text{allow}}/S$, where the allowable stress is chosen as the bolt ultimate stress (when ignoring plastic bending) or the bolt modulus of rupture (when allowing for plastic bending), and S is the section modulus of the full diameter shank or threaded region. The bending moment, M, is typically determined by assuming a line of action for the shear load introduced by the shear members and multiplying the shear load by the distance between the lines of action.

Another method to account for spacers in a joint is described by McCombs.[3] This is an analytical method for bolts loaded in pure shear that is based on the minimum of the bolt shear strength, V_{allow}, or the bolt allowable moment, M_{allow}. A knockdown factor is applied to the allowable moment to account for tension induced in the bolt. The method determines the bending moment by assuming a shear load line of action that is based on the joint member ultimate bearing area required to develop the applied shear load. Weaker materials require a larger area that increases the calculated bending moment.

The steel construction industry for civil structures uses empirically based design criteria to account for joint spacers in a shear critical bolted joint. United States design guides specify a shear strength reduction based on the spacer thickness of $1-0.4\,(t-0.25)$, where t is the total spacer thickness in inches, and no reduction needs to be taken for $t \leq 0.25$ in[4] based on testing by Yura.[5] European design guides specify a strength reduction of $9d/(8d+3t)$, where d is the nominal bolt diameter and t is the thickness of the single thickest spacer, and no reduction needs to be taken for $t \leq d/3$.[6] Another reduction factor was proposed by Dusicka based on experimental results, given as:

$$1+\left[\frac{k_f}{d^2}(0.75t-d)^2-k_f\right]\ , \tag{4}$$

where t is the total spacer thickness and $k_f = 0.10$ for standard size holes and 0.13 for oversize holes.[7] Although these steel construction design criteria are intended to apply to relatively large diameter (0.5–1.5 in) steel bolts in steel joints, they will be compared against the current test results.

4. TEST CONFIGURATION

The testing reported in this paper consisted of 75 individual bolts tested 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 ranging from 0° to 90° relative to the bolt axis, originally developed for the fastener testing described in reference 8. Pure tension corresponds to a loading angle of 0°, and pure shear corresponds to a loading angle of 90°. Figure 2 shows the fixtures installed in the load frame with the loading angle set at 45°.

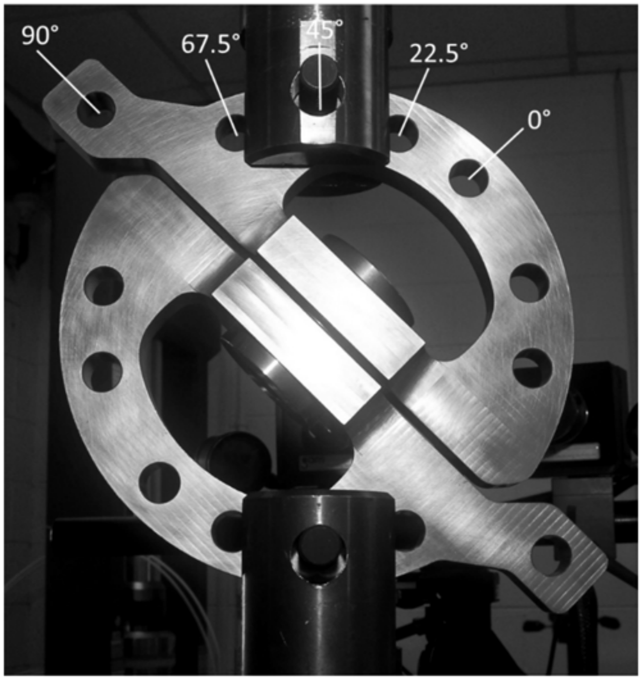

Figure 2. Test fixtures installed in test machine grips.

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. The portion of the puck in the joint stack was 0.25 in thick, and the bolt hole diameter was 0.28 in. The pucks were made from either 2219-T87 aluminum alloy or 15-5PH H1025 stainless steel. One or two stainless steel joint shims were placed between the pucks to introduce the desired joint gap, which required shims placed between the puck lips and test fixture to keep the fastener shear planes centered between the fixtures. Figure 3 shows a cross-section sketch of the test bolted joint configuration.

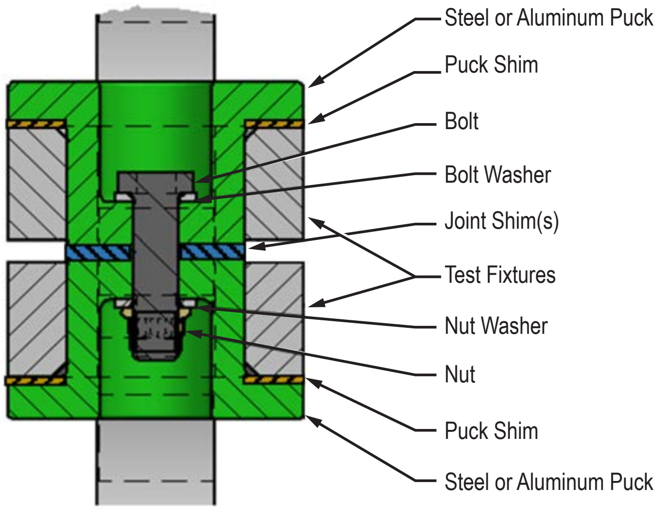

Figure 3. Test bolted joint configuration.

All the bolt specimens were 0.25 in diameter bolts, types NAS1954C9 or C12, from multiple manufacturing lots. The bolt material was A-286 corrosion resistant steel heat-treated to a minimum of 180 ksi tensile strength and 108 ksi shear strength.[9] Testing utilized two bolt lengths. The shorter bolts, referred to as C9, have a nominal grip length of 0.562 in; and the longer bolts, referred to as C12, have a nominal grip length of 0.75 in. The washers were types NAS1857-4 or 4C. Three types of nuts were used. The pure shear tests used types NAS1291-4 or NAS1805-4, the tension only tests used type H20-4, and the combined tension-shear tests used NAS1805-4.

5. TEST PROCEDURE

The bolts were installed into the puck/spacer joint and torqued to 80 in•lb. The bolts were loaded by a tensile load frame operating under displacement control. The loading rate was approximately 0.024 in/min for all tests. The data collected for each test included the load frame load-cell force, cross-head displacement, and the displacement of each test fixture in the loading direction measured by a pair of displacement gauge arms.

The bolt hole region of the aluminum pucks deformed significantly at the edge of the shear bearing interface. However, each aluminum puck was used for two tests by rotating the pucks 180° between tests. The same two steel pucks were used for all the steel puck testing.

6. TEST RESULTS

A summary of the test results is listed in table 2. The maximum load listed is the maximum applied load that was achieved during the test. The displacement is the measured relative displacement of the test fixtures in the loading direction at the maximum load. The uniaxial tension test of sample 101-2 attempted to reuse a nut, and the test resulted in a thread shear failure mode, so the results were not valid. The zero shim shear tests of samples 103-X used the longer C12 bolts with extra washers at the bolt head and nut.

Table 2. Test result summary.

Sample ID	Puck Material	Bolt Specification	Loading Angle (deg)	Spacer Thickness (in)	Max Load (lb)	Displacement (in)	Failure Location
101-1	Steel	NAS1954C12	0	0	8,950	0.047	Thread
101-2	Steel	NAS1954C12	0	0	–	–	–
101-3	Steel	NAS1954C12	0	0	9,046	0.038	Thread
102-1	Steel	NAS1954C9	45	0	6,840	0.064	Shank
102-2	Steel	NAS1954C9	45	0	6,744	0.060	Shank
102-3	Steel	NAS1954C9	45	0	6,729	0.068	Shank
103-1	Steel	NAS1954C12	90	0	6,058	0.050	Shank
103-2	Steel	NAS1954C12	90	0	6,010	0.043	Shank
103-3	Steel	NAS1954C12	90	0	6,015	0.045	Shank
104-1	Steel	NAS1954C9	45	0.03	6,725	0.076	Shank
104-2	Steel	NAS1954C9	45	0.03	6,707	0.085	Shank
104-3	Steel	NAS1954C9	45	0.03	6,746	0.081	Shank
105-1	Steel	NAS1954C9	90	0.03	5,725	0.057	Shank
105-2	Steel	NAS1954C9	90	0.03	5,670	0.055	Shank
105-3	Steel	NAS1954C9	90	0.03	5,729	0.054	Shank
106-1	Steel	NAS1954C9	45	0.06	6,661	0.092	Shank
106-2	Steel	NAS1954C9	45	0.06	6,725	0.083	Shank
106-3	Steel	NAS1954C9	45	0.06	6,749	0.083	Shank
107-1	Steel	NAS1954C9	90	0.06	5,785	0.089	Shank
107-2	Steel	NAS1954C9	90	0.06	5,747	0.093	Shank
107-3	Steel	NAS1954C9	90	0.06	5,787	0.080	Shank
108-1	Steel	NAS1954C9	45	0.09	6,184	0.053	Combo
108-2	Steel	NAS1954C9	45	0.09	6,095	0.056	Combo
108-3	Steel	NAS1954C9	45	0.09	6,006	0.052	Combo
109-1	Steel	NAS1954C9	90	0.09	5,630	0.100	Shank
109-2	Steel	NAS1954C9	90	0.09	5,643	0.099	Shank
109-3	Steel	NAS1954C9	90	0.09	5,675	0.095	Shank

Table 2. Test result summary (Continued).

Sample ID	Puck Material	Bolt Specification	Loading Angle (deg)	Spacer Thickness (in)	Max Load (lb)	Displacement (in)	Failure Location
110-1	Steel	NAS1954C9	45	0.12	5,525	0.038	Combo
110-2	Steel	NAS1954C9	45	0.12	5,503	0.038	Combo
110-3	Steel	NAS1954C9	45	0.12	5,641	0.045	Combo
111-1	Steel	NAS1954C9	90	0.12	5,470	0.099	Shank
111-2	Steel	NAS1954C9	90	0.12	5,535	0.099	Shank
111-3	Steel	NAS1954C9	90	0.12	5,409	0.090	Shank
112-1	Steel	NAS1954C12	90	0.12	5,576	0.097	Shank
112-2	Steel	NAS1954C12	90	0.12	5,417	0.081	Shank
112-3	Steel	NAS1954C12	90	0.12	5,513	0.084	Shank
113-1	Steel	NAS1954C12	45	0.18	6,150	0.106	Shank
113-2	Steel	NAS1954C12	45	0.18	6,188	0.116	Shank
113-3	Steel	NAS1954C12	45	0.18	6,181	0.113	Shank
114-1	Steel	NAS1954C12	90	0.18	5,408	0.123	Shank
114-2	Steel	NAS1954C12	90	0.18	5,286	0.110	Shank
114-3	Steel	NAS1954C12	90	0.18	5,315	0.117	Shank
115-1	Steel	NAS1954C12	45	0.24	6,199	0.122	Thread
115-2	Steel	NAS1954C12	45	0.24	6,309	0.112	Shank
115-3	Steel	NAS1954C12	45	0.24	6,258	0.122	Thread
116-1	Steel	NAS1954C12	90	0.24	5,148	0.124	Shank
116-2	Steel	NAS1954C12	90	0.24	4,640	0.104	Thread
116-3	Steel	NAS1954C12	90	0.24	5,189	0.121	Shank
201-1	Alum	NAS1954C9	0	0	9,046	0.044	Thread
201-2	Alum	NAS1954C9	0	0	9,039	0.044	Thread
201-3	Alum	NAS1954C9	0	0	9,118	0.045	Thread
203-1	Alum	NAS1954C9	90	0	6,508	0.097	Shank
203-2	Alum	NAS1954C9	90	0	6,344	0.100	Shank
203-3	Alum	NAS1954C9	90	0	6,374	0.089	Shank
205-1	Alum	NAS1954C9	90	0.03	6,007	0.098	Shank
205-2	Alum	NAS1954C9	90	0.03	6,123	0.105	Shank
205-3	Alum	NAS1954C9	90	0.03	6,248	0.113	Shank
207-1	Alum	NAS1954C9	90	0.06	5,972	0.133	Shank
207-2	Alum	NAS1954C9	90	0.06	5,907	0.121	Shank
207-3	Alum	NAS1954C9	90	0.06	5,881	0.117	Shank
209-1	Alum	NAS1954C9	90	0.09	5,966	0.149	Thread
209-2	Alum	NAS1954C9	90	0.09	5,973	0.157	Shank
209-3	Alum	NAS1954C9	90	0.09	5,869	0.156	Shank
211-1	Alum	NAS1954C9	90	0.12	5,264	0.104	Thread
211-2	Alum	NAS1954C9	90	0.12	5,312	0.113	Thread
211-3	Alum	NAS1954C9	90	0.12	5,404	0.114	Thread

Table 2. Test result summary (Continued).

Sample ID	Puck Material	Bolt Specification	Loading Angle (deg)	Spacer Thickness (in)	Max Load (lb)	Displacement (in)	Failure Location
212-1	Alum	NAS1954C12	90	0.12	5,844	0.154	Shank
212-2	Alum	NAS1954C12	90	0.12	5,861	0.146	Shank
212-3	Alum	NAS1954C12	90	0.12	6,096	0.163	Shank
214-1	Alum	NAS1954C12	90	0.18	5,018	0.137	Thread
214-2	Alum	NAS1954C12	90	0.18	5,090	0.134	Thread
214-3	Alum	NAS1954C12	90	0.18	4,965	0.121	Thread
216-1	Alum	NAS1954C12	90	0.24	4,972	0.135	Thread
216-2	Alum	NAS1954C12	90	0.24	4,095	0.113	Thread
216-3	Alum	NAS1954C12	90	0.24	4,034	0.102	Thread

Pictures of the fractured specimens from select cases are shown in figures 4–6. Bolts loaded in pure shear with steel pucks are shown in figure 4, bolts loaded in pure shear with aluminum pucks are shown in figure 5, and bolts loaded at a 45° angle with steel pucks are shown in figure 6. The post-test conditions of the steel and representative aluminum pucks are shown in figures 7 and 8, respectively.

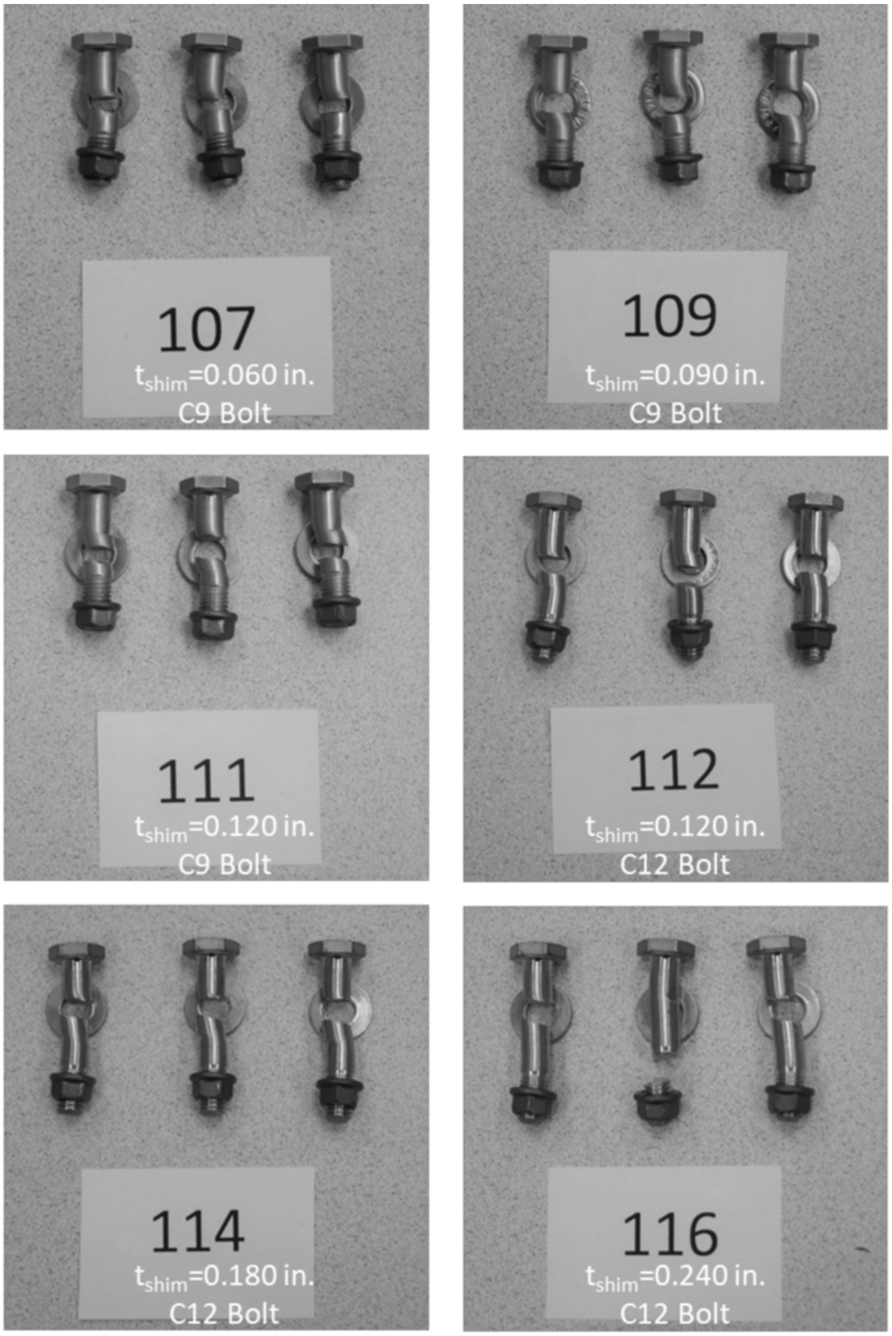

Figure 4. Fractured bolt specimens from select cases loaded in pure shear with steel pucks.

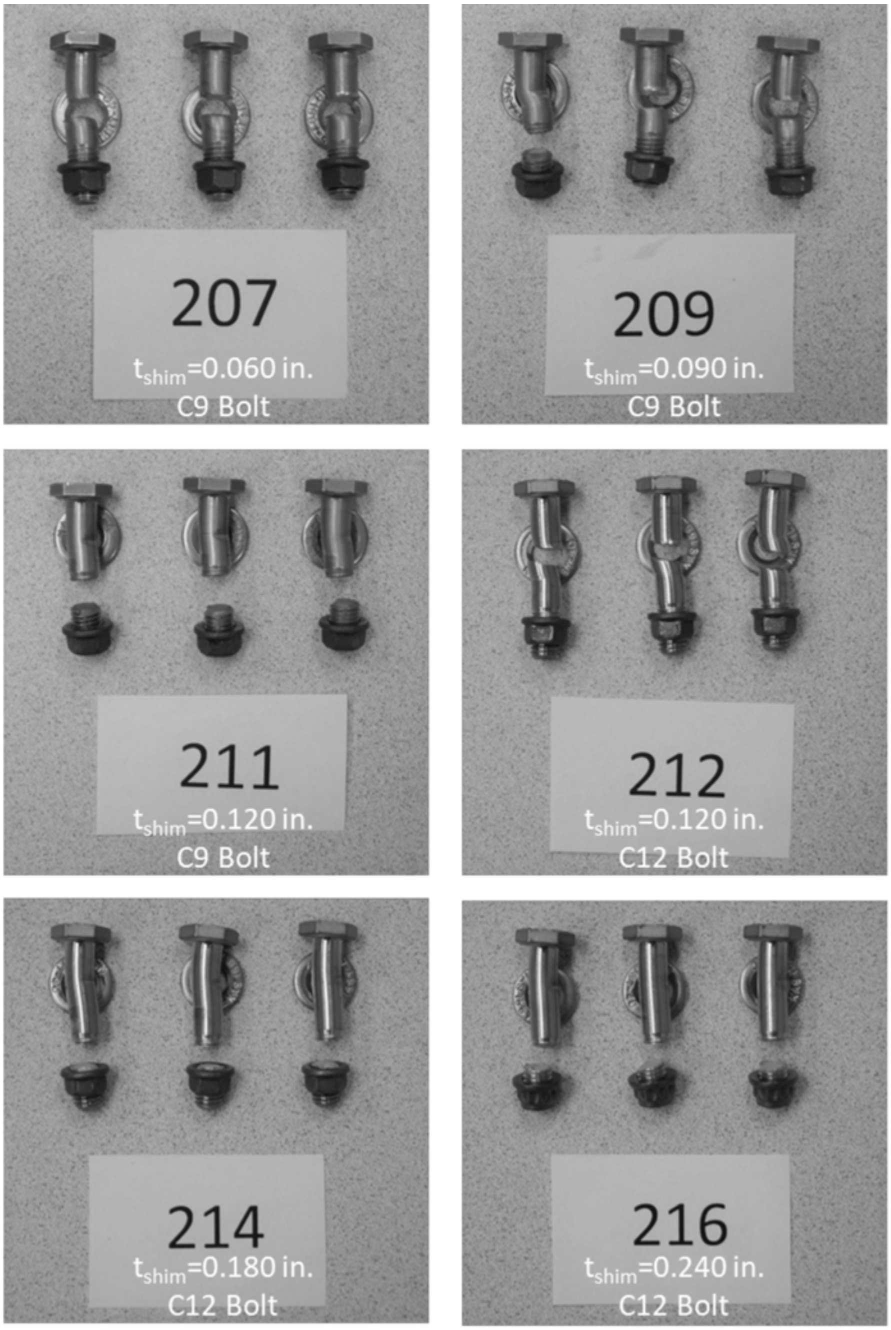

Figure 5. Fractured bolt specimens from select cases loaded in pure shear with aluminum pucks.

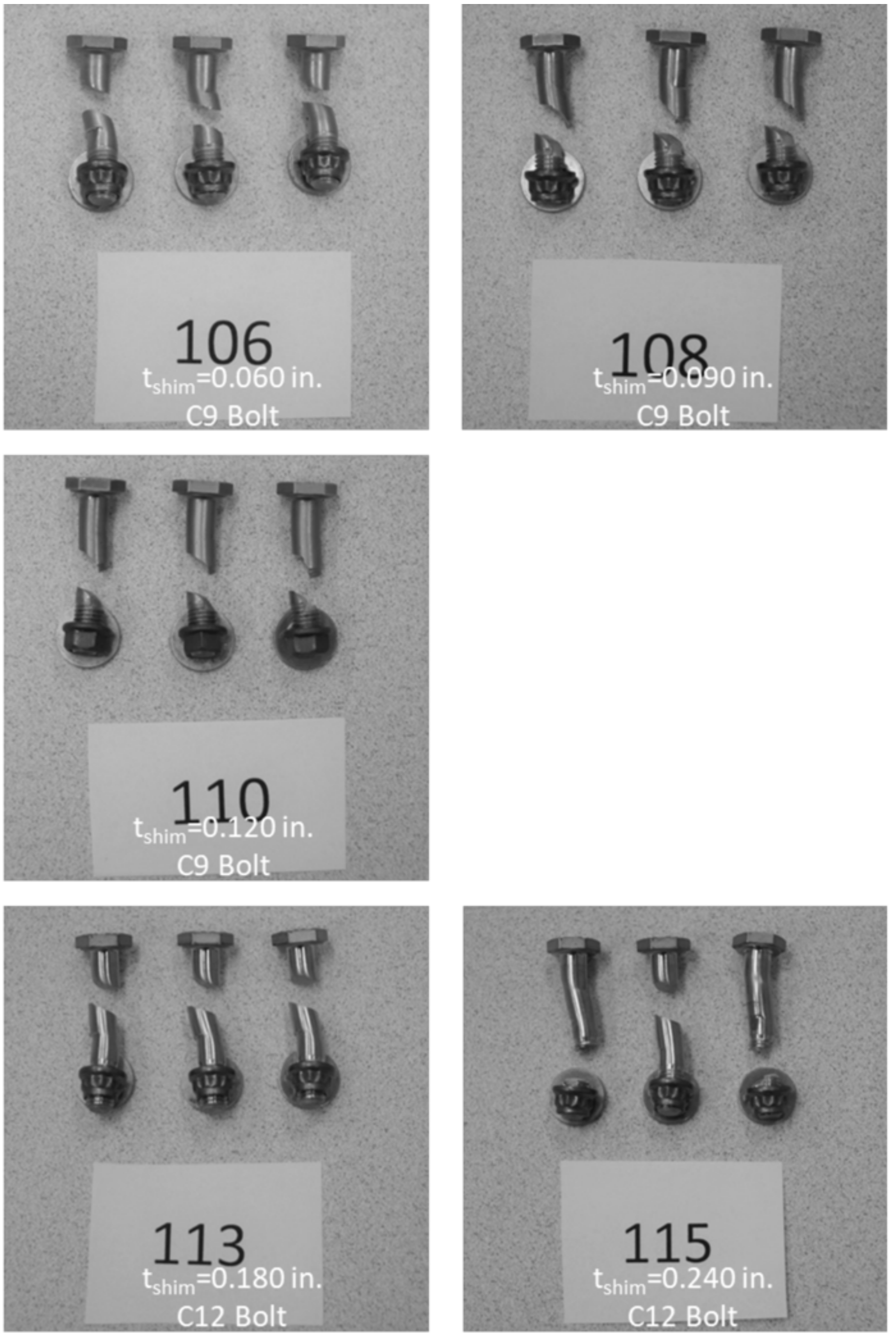

Figure 6. Fractured bolt specimens from select cases loaded at 45° with steel pucks.

Figure 7. Steel pucks after all steel puck testing.

Figure 8. Representative aluminum pucks after use for two load cases (top: cases 111-1 and 111-2; bottom: cases 105-2 and 105-3).

7. DATA ASSESSMENT

7.1 Fastener Strength

The tensile and shear strength of the test fasteners were determined by testing five bolts in tension and six in pure shear with no shims. The tensile test results had relatively low scatter across the three C9 bolts tested with aluminum pucks and the two C12 bolts tested with steel pucks. The average tensile strength is 9,040 lb and all the bolts broke in the threaded region. For comparison, the NAS1954 bolt specification required tensile strength is 6,980 lb.

The shear failure load results show a difference between the C9 bolts tested with aluminum pucks and the C12 bolts tested with steel pucks. All of the bolts broke in the shank region, but the C9/aluminum puck bolt average shear failure load is 6,409 lb, and the C12/steel puck bolt average shear failure load is 6,028 lb. Given the similarity in the bolt tensile strengths, the difference is likely due to puck deformation and/or friction behavior. For comparison, the NAS1954 specification required double shear strength is 10,600 lb, or 5,300 lb for single shear.

7.2 Combination Loading Results

The individual ultimate load results for the steel and aluminum puck series loaded in pure shear and the steel puck series loaded at a 45° angle are shown in figures 9 and 10, respective to the various shim thicknesses. As expected, the ultimate load generally decreases with increasing shim thickness. The three repeat data points for each test condition show relatively good agreement, with the exception of one of the steel and aluminum puck shear loading tests with a 0.24-in shim thickness.

The loading shear plane(s) for every test were in the bolt full diameter shank region. While most tests failed in the shank region, some failed in the threads or a combination of the shank and threads as listed in table 2. The filled symbols in figures 9 and 10 indicate the specimens that failed in the threads or shank and threads combination. Only one of the steel puck tests failed in the threaded region and that was with a 0.24-in shim thickness, which explains why it has a lower failure load than the other two companion tests.

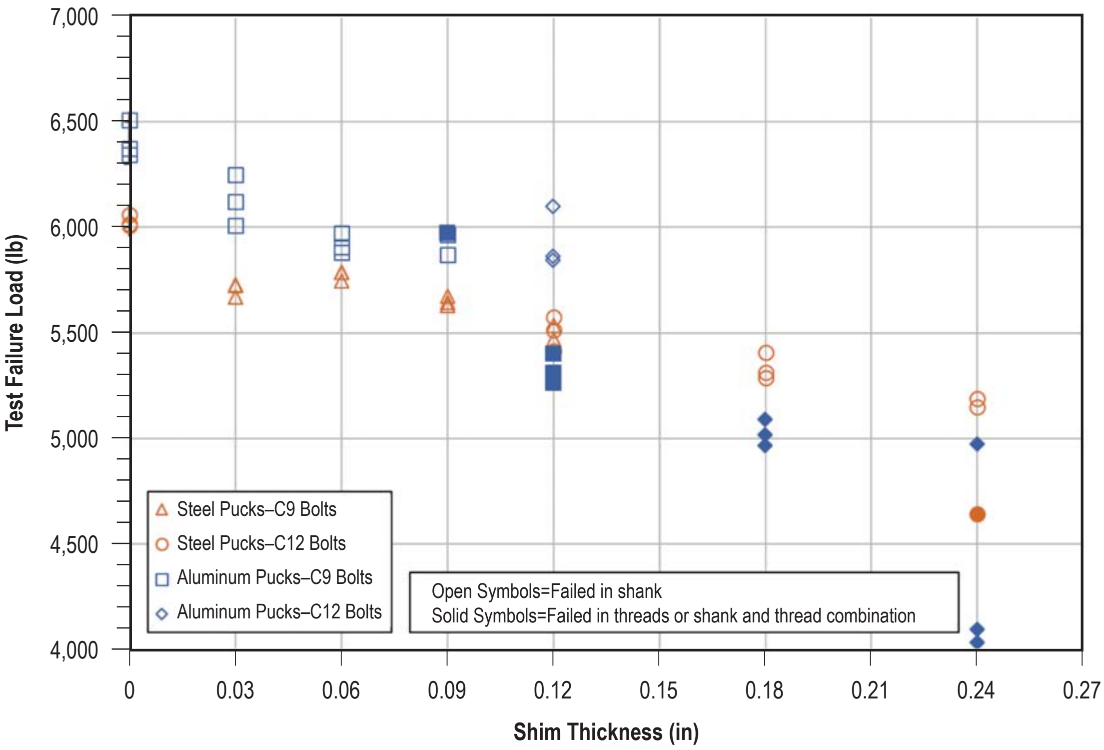

Figure 9. Bolt ultimate load results (shear loading).

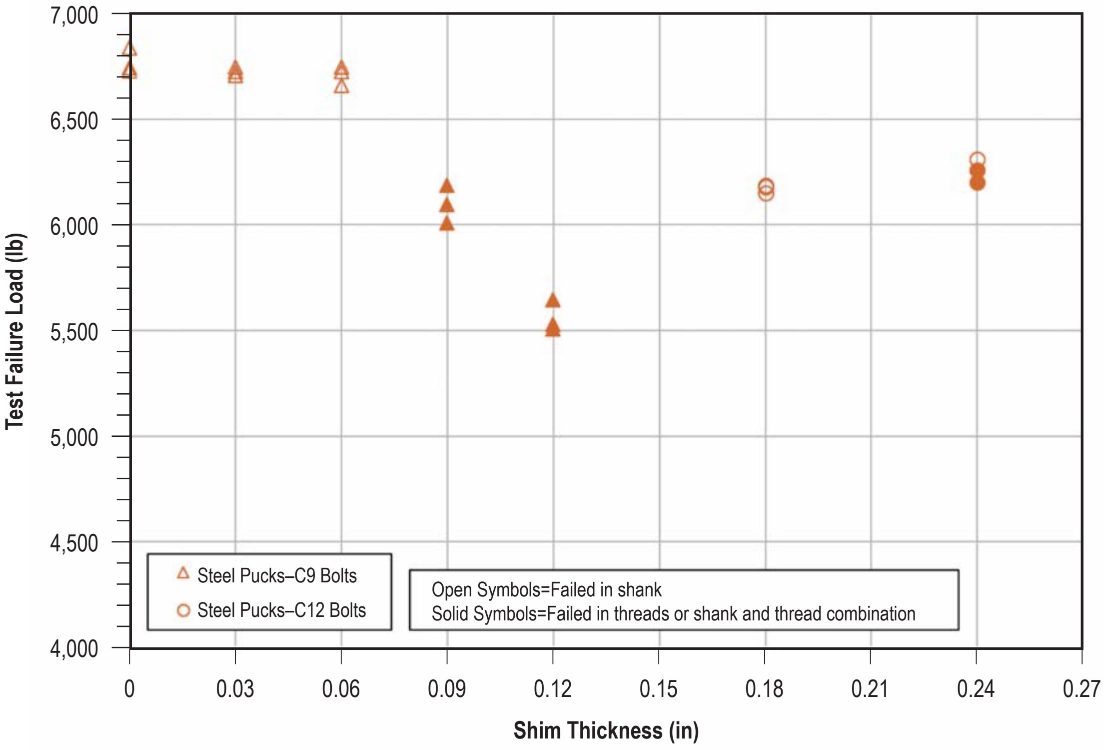

Figure 10. Bolt ultimate load results (45° loading).

The aluminum puck test specimens failed in the threaded region for all of the C9 bolts with a 0.12-in shim and all of the longer C12 bolts with a 0.18- and 0.24-in shim. This explains the lower strength results observed for those conditions compared to the other aluminum puck results and the steel puck results with the same shim thickness. One of the specimens with a 0.09-in shim thickness failed in the threads, but the failure load was in-line with the other two specimens that failed in the shank.

All of the 45° loading steel puck tests with the C9 bolts and a 0.09- and 0.12-in shim failed in a combination of the shank and threads. This likely explains the sharp drop in strength seen in those tests compared to the other 45° loading results. Two of the specimens with a 0.24-in shim thickness failed in the threads, but the failure loads were similar to the third specimen that failed in the shank.

The higher failure loads exhibited in the aluminum puck shear strength (no shim) tests compared to the steel pucks were also seen in the tests with shims (excluding the three aluminum puck conditions that resulted in thread failure for all three specimens). As noted in section 7.1, this difference is likely due to puck deformation and/or friction behavior. The friction coefficient for aluminum is often reported as higher than steel. However, casual inspection of the pucks did not note an obvious difference in surface finish or friction behavior.

The higher deformation behavior of the aluminum pucks was visibly obvious around the hole-bearing surface as shown in figure 8. The difference is also apparent in the measured displacement at failure load for the shear-loaded specimens as plotted in figure 11. The aluminum pucks produced approximately 0.04–0.05 in more deflection for cases with the same failure mode.

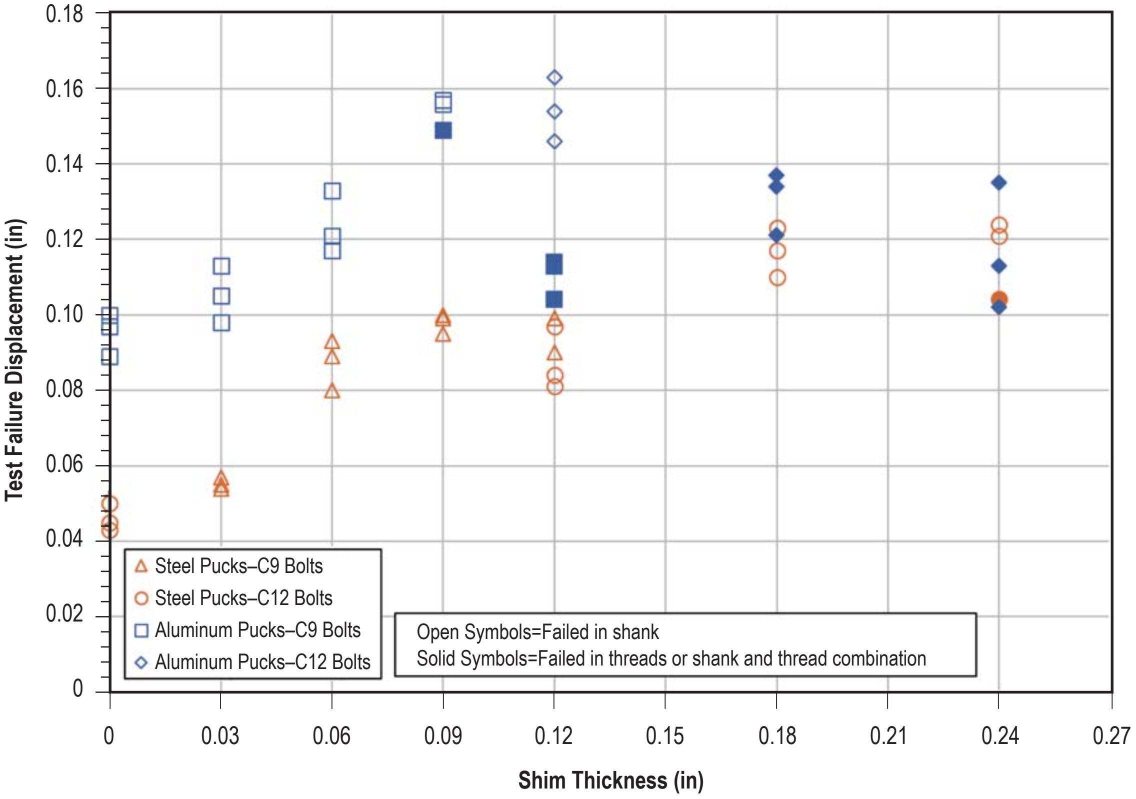

Figure 11. Bolt ultimate load displacement results (shear loading).

The joint members prevent any appreciable axial length reduction of the bolt under lateral load. Therefore the lateral displacement stretches the bolt and increases the tensile load in the bolt above the initial preload. As plastic strain zones develop in the bolt near failure, some of that tensile load is reduced. The larger deformation of the aluminum pucks may allow higher tensile load to develop or remain that would require higher shear load to overcome the faying surface friction.

The lower deformation of the steel pucks may also work to introduce higher stress concentration in the bolt as the edge of the steel puck hole bears into the bolt.

7.3 Failure Locations

These test results highlight that the failure of a bolt loaded in shear with shims can occur in either the shank or threads, even when the shear plane is in the full diameter shank region. Failure in the threads is more likely with aluminum joint members and with thicker shims. The relative distance of the threads to the shear plane may also be a factor, as indicated by the aluminum puck 0.12-in shim results that failed in the threads for the shorter C9 bolt but in the shank for the longer C12 bolt. For reference, the range of relative locations of the bolt threads to the nearest shear plane is shown in figure 12.

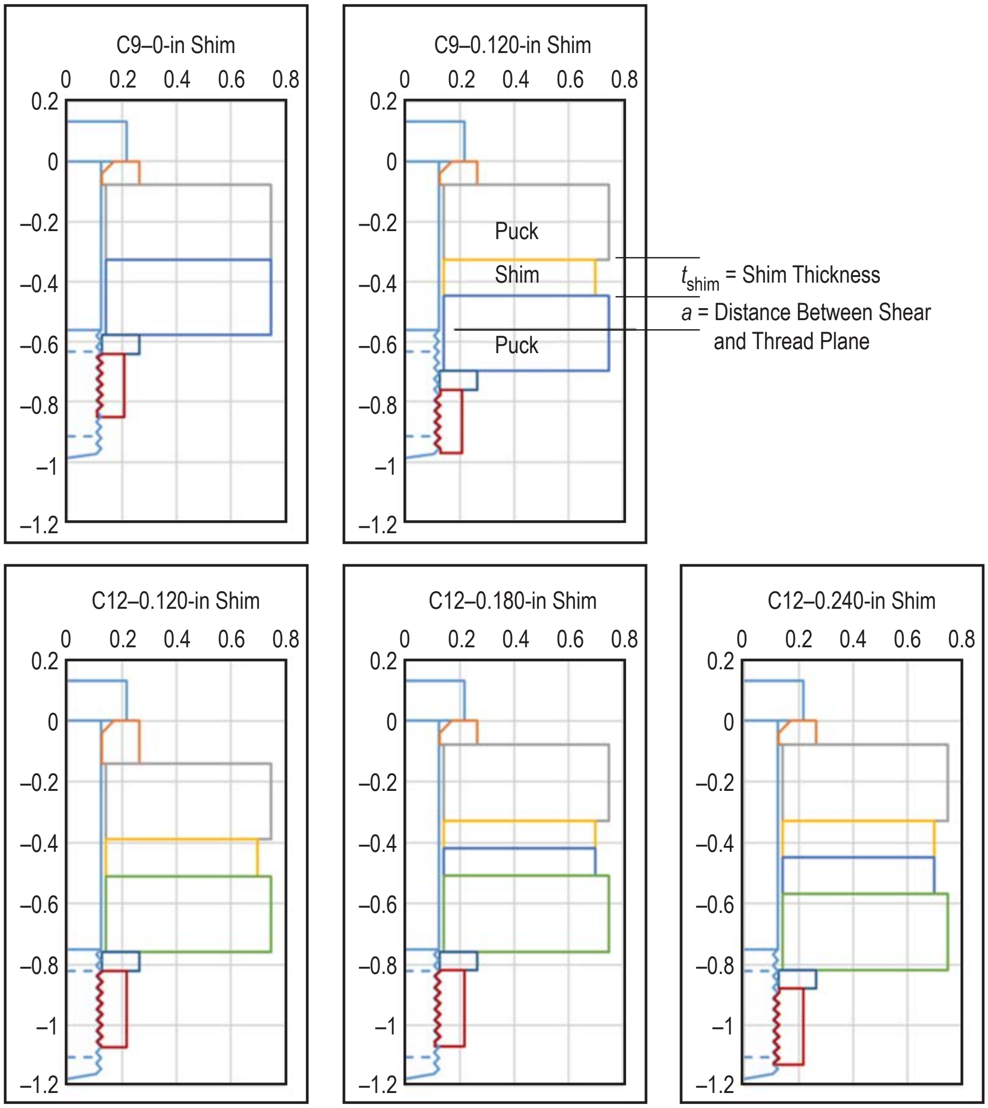

Figure 12. Sketch of select test conditions showing distance between shear plane and threads.

Shear loading of a bolt introduces a distribution of shear, moment, and tensile force along the length of the bolt. The shear load peaks at the shear plane and then drops to near zero at the head and nut. On the other hand, the moment is near zero at the shear planes and increases toward the head and nut where it is reacted by bearing of the bolt head and nut against the joint members. The moment on the head side is higher than the nut side due to the difference in bending stiffness. As the moment increases toward the nut, the bolt capability steps down at the transition from the shank to the threads due to the reduced cross section. For a given bolted joint configuration loaded in shear, it is a race between failure at the shear load dominated shear plane or at the moment load dominated and reduced capability thread region. Three of the test conditions highlight this race by exhibiting failure in both the shank and threads.

Finite element simulation was used to determine the bolt axial, shear, and moment distribution with a shim thickness of 0.12 in for both steel and aluminum 0.25-in-thick joint members, assuming an initial preload of 2,500 lb. The results are shown in figure 13 at a load near failure. The moment peaks approximately where the shear is almost zero. The shear distribution with aluminum members is wider and the resulting moment is greater than the steel results. The axial load has increased overall and is higher with the aluminum members. Interestingly, the effect of friction and bearing against the laterally displaced bolt shank reduces the bolt tensile load in the shim region. This secondary effect would make failure in the threads more likely.

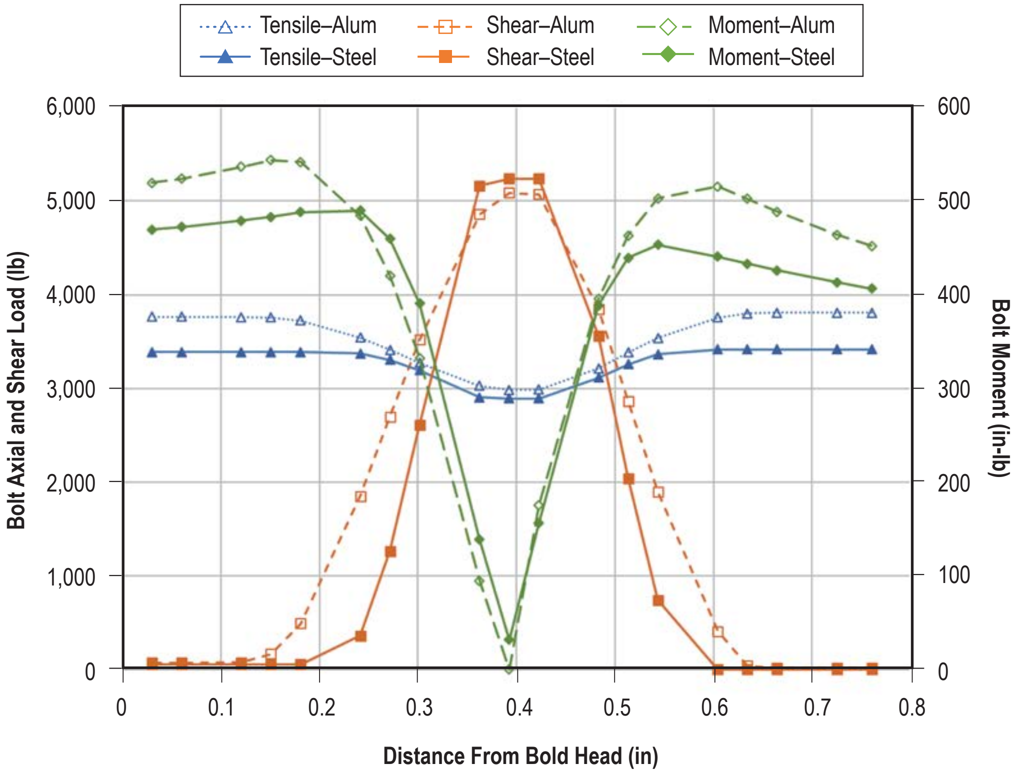

Figure 13. Finite element simulation bolt axial, shear, and moment distribution example with steel and aluminum joint members.

Typically, a bolt analysis does not explicitly consider the possibility of failure at different locations in a bolt. Instead, the intent is to use a single failure criterion that considers possible tensile, shear, and moment loads and corresponding bolt capabilities, combining them into a failure equation that envelopes the possible bolt failure behavior. For example, bolt shear capability is normally based on the full diameter shank (for a joint with shear planes in the shank), while the tensile capability is based on the threads. This approach is used by all of the design criteria considered in this study, except for the McCombs criterion, which effectively considers the shear plane and bolt shank near the head or nut separately.

7.4 Design Criteria Comparison

The average test data for the pure shear tests is shown in figure 14, normalized with respect to the bolt shear strength for each of the puck materials. This figure also includes the normalized design criteria of NASA, McCombs, Yura, the European Design Guide, and Dusicka. The NASA criteria uses a shear load line of action equal to the shim thickness to determine the induced moment.

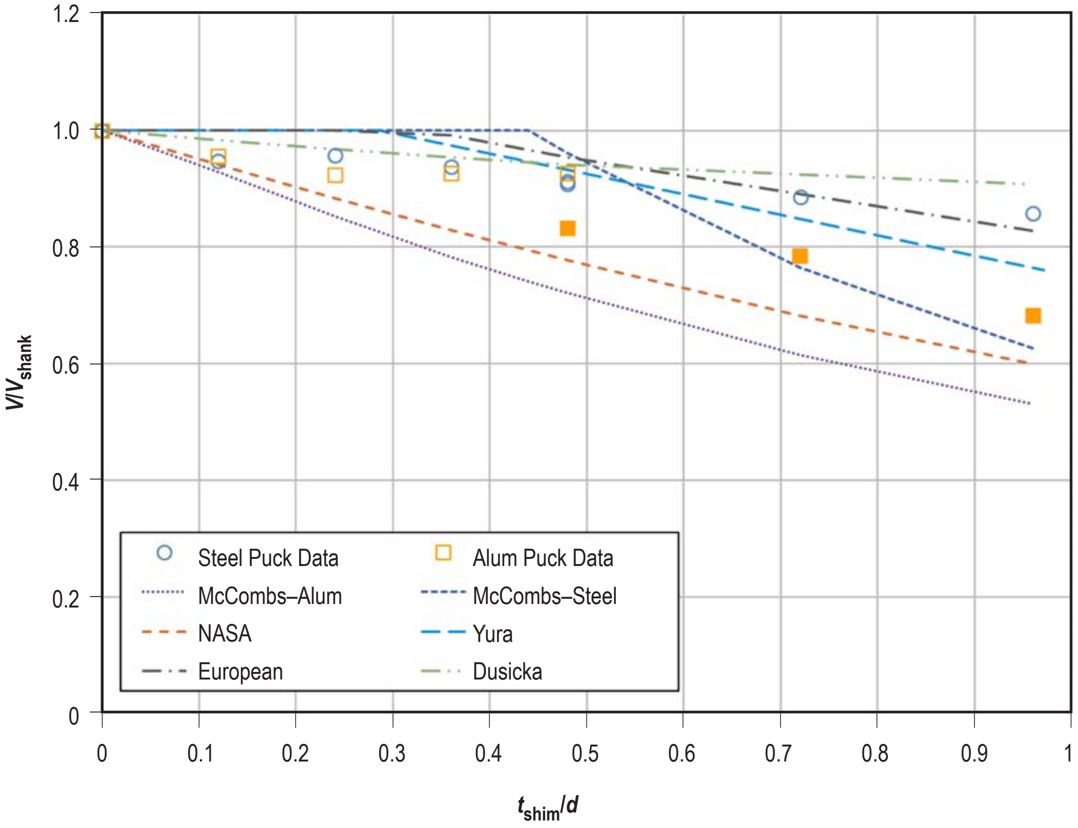

Figure 14. Normalized pure shear load averaged results and design failure criteria.

If only the test data associated with failure in the bolt shank is considered, the shear carrying capability of the bolt decreases to roughly 85%, as the shim thickness approaches one diameter. This is a modest reduction in strength, and the steel construction design criteria of Yura, the European Design Guide, and Dusicka are in fairly good agreement with the test data, with the American Design Guide criteria of Yura providing the more conservative estimate of shear strength.

The steel design code criteria and the McCombs criteria (using Fbru (ultimate bearing strength) = 332 ksi for the steel members) for steel bearing members do not reduce the bolt shear strength for shim thicknesses out to approximately 25% of the bolt diameter. The test data show a drop in shear strength when going from no shims to the smallest shim of 0.03 in or 12% of the diameter, but then the test data are relatively flat out to a shim thickness of 0.09 in or 36% of the diameter, which is consistent with the criteria. The reduction in shear strength below the no-shim value for the smaller shim thicknesses suggests that a small knockdown should be used for shims up to approximately 30% of the bolt diameter. More testing is needed to support this, and it would be of interest to repeat this testing with no preload to see if this same behavior is observed.

When all of the test data are considered, regardless of failure location, the steel design criteria overestimate the shear strength compared to these test data. Even though no shear planes were in-line with the bolt threads for any of the test configurations, the induced loads did cause failure in the threads, which produced significantly lower strengths.

The bolts in the aluminum pucks were much more likely to experience failure in the threads. This must be caused by the greater bearing deformation of the aluminum puck holes. As the pucks deform under the shear bearing load, the shear load is distributed over a larger area. This increases the effective shear load line of action distance, which in turn increases the induced moment. The increase is small at the shear planes and is greatest near the bolt head and nut. Combined with the increased tensile load due to lateral deformation, aluminum joints loaded in shear are more prone to cause failure in the threads.

The NASA criterion adequately envelopes all the test data. This criterion assumes a shear load line of action distance equal to the shim thickness, and the moment allowable considers plastic bending with the modulus of rupture equal to the measured tensile strength of 233 ksi multiplied by a plastic bending factor of 1.7. The addition of the bending term in equation 3 proves to be conservative compared to the aluminum puck results. The criterion is very conservative compared to the steel puck results (or results that failed in the shank). Since the bolt moment is based on the shim thickness, it is apparent this criterion is unable to accommodate the difference in behavior due to the different member materials. The single equation bolt-centric nature of the criterion also ignores the varying nature of the bolt loading and capability along the length of the bolt. Nevertheless, the criteria provides a reasonable prediction for the aluminum member results with the accompanying failures in the threads.

The McCombs aluminum member criterion (using Fbru = 126 ksi for the aluminum members) also envelops the data but is more conservative. The McCombs criterion considers failure at both the shear plane and at the moment dominated shank region (curiously, the criterion does not consider the reduced capability thread region). The capability of the shear plane is based on the bolt single shear capability without any knockdown. It also checks the bolt moment capability based on a plastic moment allowable with a 0.88 knockdown to account for tensile loads that may develop due to the lateral loading. The moment-based capability is the limiting factor for the aluminum member cases. The conservative nature of the results compared to the test data indicate that the calculated shear load line of action and induced moment is overestimated.

The average test data for bolts loaded in combined shear and tension at a 45° angle is plotted in figure 15. All of these tests used the steel pucks. Every case with a shim thickness of 0.09 and 0.12 in, the two conditions with the threads closest to the shear plane, experienced a failure that was primarily located in the shank region but also extended into the threads. Ignoring these two conditions, the drop in shear capability was modest, including the 0.24-in shim condition that experienced two out of three failures in the threads. There is virtually no loss in capability with shims up to 0.06 in thick.

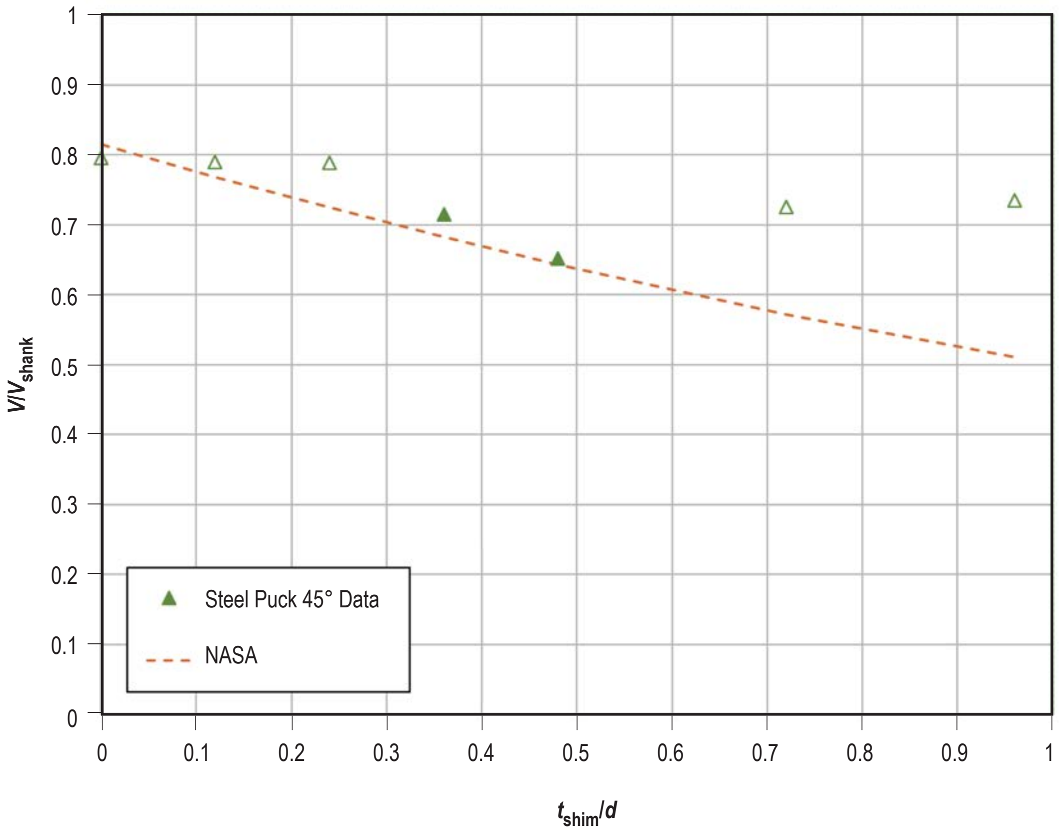

Figure 15. Normalized 45° load averaged results and NASA design failure criterion.

The NASA criterion is also plotted for this loading condition using the shim thickness as the shear load line of action distance. The criterion adequately bounds the test data.

8. CONCLUSIONS

The strength of typical 0.25-in aerospace bolts loaded in shear with shims up to one diameter in thickness was determined using both aluminum and steel joint members. The data shows a drop in the shear capability with increasing shim thickness. Failure was observed in the full diameter shank and thread region. Failure in the threads was more likely with the aluminum joint members and thicker shims.

The steel joint member tests failed in the shank except for one case with the largest shim thickness. The failure criteria of the steel building codes captured the behavior relatively well. However, the test data showed a small loss of capability with shim thickness less than 25% of the bolt diameter where the criteria would produce no reduction in shear capability. However, with the possibility of failure occurring in the threads, particularly with aluminum joint members, a more comprehensive criterion is needed for aerospace joints.

The NASA criterion adequately bounded the test data with the simple assumption that the induced bending moment is equal to the shear load times the shim thickness. The single equation nature of the criterion does not capture the actual varied loading or capability in the bolt or the difference caused by joint members of different strength. This makes the criterion very conservative for bolts and joints limited by shear failure of the shank. A criterion that can account for these differences would potentially be more accurate. The McCombs criterion is a simple example.

Yet, the McCombs criterion also proved to be conservative compared to the test results. This criterion considers shear failure at the shank and moment failure at the head/nut. It also has the ability to capture the effect of joint member strength on the bolt loading and failure. With some additional study and testing, a more accurate multilocation criterion is likely attainable.

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14. ABSTRACT

Bolted joints with a nonload-carrying member, like a shim or spacer, and loaded in shear introduce bending moment into the bolt that reduces the bolt shear load-carrying capability. Various design criteria are available that attempt to account for the additional bending and provide reduced allowable bolt loads. The actual shear load-carrying capability of a typical aerospace fastener with various thickness shims was determined by test using both aluminum and steel joint members. The results are compared against existing design criteria, which are shown to be adequate for their intended purposes.

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threaded fastener, bolt, strength criteria, shim, shear, bending

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