# Tests on the Ductility of Stainless Steel and Titanium Alloy Aerospace Fasteners

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## Abstract

This paper presents results from tests aimed to assess the relative ductility of titanium alloy Ti 6Al-4V and stainless steel A286 aerospace fasteners of comparable size and tensile strength. A test procedure is developed and tensile tests are performed on test fasteners. All test fasteners fracture in the threaded region. Elastic and plastic deformation at rupture are extracted from the resulting load versus displacement curves and used to compute the ductility index for each test fastener. The ductility index quantifies the relative ductility between the different fastener materials. The average ductility index for the titanium alloy fasteners is about one-tenth the average value for the A286 fasteners. In addition, the fracture surfaces of the titanium alloy test fasteners fracture perpendicular to the axis of tensile loading, whereas the A286 test fasteners fracture across three or four threads which corresponds to about a 45 degree angle. Both the relative ductility index values and fracture surface characteristics indicate much less ductility in the titanium alloy fasteners. These results are not intended to discourage the use of titanium alloy fasteners, but rather to provide additional data for use in proper joint design when the benefits of lower weight or extreme temperature use are required.

## Introduction and Background

Ductility is generally a desirable characteristic for threaded fasteners since tensile stretch is essential for proper fastener function in a preloaded joint. As a result, traditional fastener materials are designed to provide sufficient ductility to help avoid abrupt and potentially catastrophic failure.

Titanium alloy fasteners are currently available for aerospace applications. They provide lower weight and better performance in extreme temperature than traditional aerospace fastener materials such as A286 stainless steel. However, engineers are reluctant to embrace this material due to uncertainty about its ductility and potential catastrophic failure that can result in brittle materials [1-3]. This concern is valid since fasteners by design are often used close to or at yield. Preload and external load uncertainty compound the problem.

This concern was repeatedly raised during recent meetings of the NASA NESC Standard Development for Spaceflight Fastening Systems Team and is the premise for the work reported in this paper [4].

This paper reports on a series of tests performed to assess titanium alloy fastener failure characteristics compared to a more traditional aerospace fastener material with particular interest in quantifying relative ductility. Tensile tests are performed on both titanium alloy and traditional aerospace fasteners of comparable size and tensile strength. Load versus displacement data are obtained. Elastic deformation and plastic deformation at rupture are extracted from the data and used to compute a ductility index [4-6]. In addition, the fracture surfaces of the different fasteners are examined and documented.

While it is found that titanium alloy fasteners are significantly less ductile than A286 stainless steel fasteners, these results are not intended to disqualify the use of titanium alloy fasteners. Rather, the test procedure and/or resulting data from this work can assist in proper joint design with titanium alloy fasteners for safe use.

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This includes appropriate selection of preload with respect to fastener yield and rupture, minimizing or controlling preload uncertainty, and quantifying worse case external load conditions.

A literature search reveals very little published data on this topic. As a result, the data in this paper helps fill an existing void in the literature.

## Test Specimens

The test fasteners used in this work are aerospace bolts made from Titanium 6Al-4V (i.e., Ti 6-4) and A286. Size and thread are ¼-28 UNJF (M6x1) with length of 1.99 in (50.5 mm) for the Ti 6-4 bolts and 2.03 in (51.5 mm) for the A286 bolts. The heads are 12 point for the Ti 6-4 bolts and hex for the A286 bolts. This difference did not affect the test results in this work since all failures occurred in the threaded section of the bolts. The test fasteners were obtained from aerospace fastener suppliers with full certifications [7]. The Ti 6-4 fasteners meet AMS 4928 Rev: R and AMS 4967 Rev: J specifications. The A286 fasteners meet NAS 1004-24A specifications.

Twelve test specimens for each fastener material are tested. This is found to be a more than adequate sample size based on the mean difference in ductility ratio found for the two different fastener materials [7]. Each test fastener is assigned a number as listed in Table 1. The test order or sequence is randomized as listed in Table 2.

**Table 1. Test fastener number**

| | Fastener number | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Titanium 6-4 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| A286 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |

**Table 2 Randomized test sequence**

| Test sequence | Fastener number | Material |
|---|---|---|
| 1 | 6 | Ti 6-4 |
| 2 | 2 | Ti 6-4 |
| 3 | 12 | Ti 6-4 |
| 4 | 8 | Ti 6-4 |
| 5 | 21 | A286 |
| 6 | 7 | Ti 6-4 |
| 7 | 17 | A286 |
| 8 | 20 | A286 |
| 9 | 13 | A286 |
| 10 | 11 | Ti 6-4 |
| 11 | 24 | A286 |
| 12 | 5 | Ti 6-4 |
| 13 | 9 | Ti 6-4 |
| 14 | 15 | A286 |
| 15 | 18 | A286 |
| 16 | 10 | Ti 6-4 |
| 17 | 4 | Ti 6-4 |
| 18 | 23 | A286 |
| 19 | 14 | A286 |
| 20 | 19 | A286 |
| 21 | 16 | A286 |
| 22 | 1 | Ti 6-4 |
| 23 | 22 | A286 |
| 24 | 3 | Ti 6-4 |

The twenty-four fasteners were visually inspected, coated with spray-on dry-film $MoS_2$ lubricant, allowed to dry, and placed in a sectioned container labeled by fastener number. When a test fastener number came up in the test order, it was picked out of the container, tested to failure, and remains placed back into its cell.

**Equipment and Test Procedure**

An MTS tensile test machine is used for the testing in this work. The tensile tests in this work consist of a bolt in a tapped fixture rather than a bolt and nut configuration. Figure 1 illustrates a test fastener in the tensile machine. The test fastener head is secured by a high strength steel fastener tensile grip fixture and puck per ASTM F606 [8]. The other end of this fastener tensile grip fixture is threaded into the MTS crossbar head.

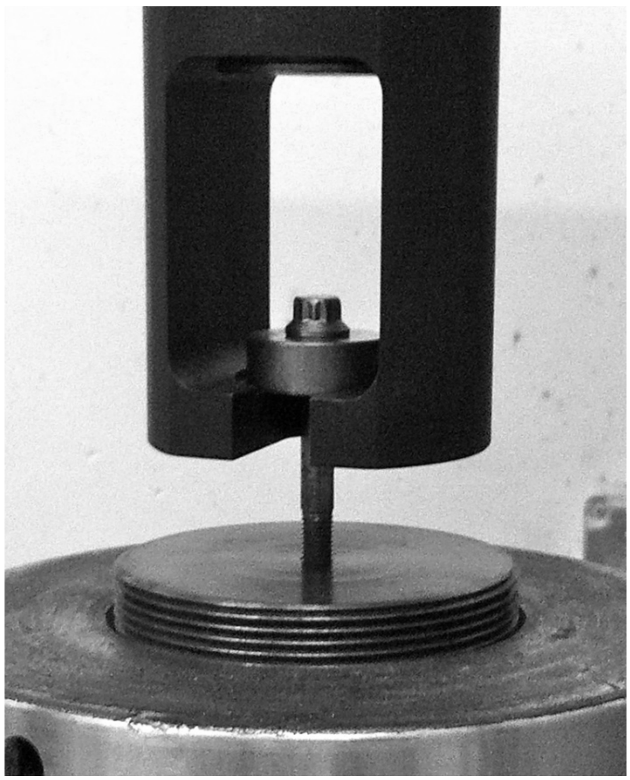

**Figure 1. Sample test fastener in fastener tensile grip with puck and lower test fixture in MTS machine.**

The test fastener threads are secured to the lower steel fixture with a ¼-28 UNJF (M6x1) tapped-hole. This provides $^3/_8$ in (9.5 mm) of thread engagement between the test fastener and the lower fixture. The external threads of this lower fixture are threaded into the MTS hydraulic ram.

Once the fixtures are installed on the tensile test machine, the following test setup is performed for each test fastener:

1. The upper crossbar head is adjusted and locked into a position such that the lower hydraulic ram has sufficient range of motion to fracture the test fastener specimen in tension.
2. The test fastener is inserted through the puck and placed into the recessed area of the upper tensile grip fixture.

3. The lower ram is raised up allowing the test bolt to be fully threaded into the lower test fixture in the ram which provides $^{3}/_{8}$ in (9.5 mm) thread engagement between the test fastener and the lower steel fixture.
4. The ram is slowly lowered until no gap between the washer and head is visible.
5. The ram is further lowered until a 100-lb (445-N) load is placed on the test fastener.

The test procedure for each test fastener is as follows:

1. The ram is lowered at a controlled rate of 2000 lb/min (8.9 kN/min) which is within specification of ASTM F606 [8] for ¼-28 (M6x1) fasteners.
2. Tensile machine load and displacement are sampled and recorded from onset of test at 4.6 Hz providing over 600 data points per test. Test duration was 130 seconds or greater.
3. Test is run until test fastener failure.

**Test Data and Analysis**

A compilation of all twelve A286 test fastener tensile test load versus displacement curves are presented in Figure 2. This reveals minimal scatter in test data across the sample set. The corresponding compilation of all twelve Ti 6-4 test fastener tensile test load versus displacement curves are shown in Figure 3. More scatter is present in this sample set.

Since the displacement scale is different for each fastener material in Figures 2 and 3, sample curves from each fastener material are plotted in Figure 4. This more clearly illustrates the relative displacement to failure of the different fastener materials. The data point at the largest displacement value of each curve corresponds to the test specimen fracture. Since the A286 and Ti 6-4 test fasteners are both ¼-28 UNFJ (M6x1) and have comparable maximum tensile load, the tensile strength for the test fasteners is also comparable.

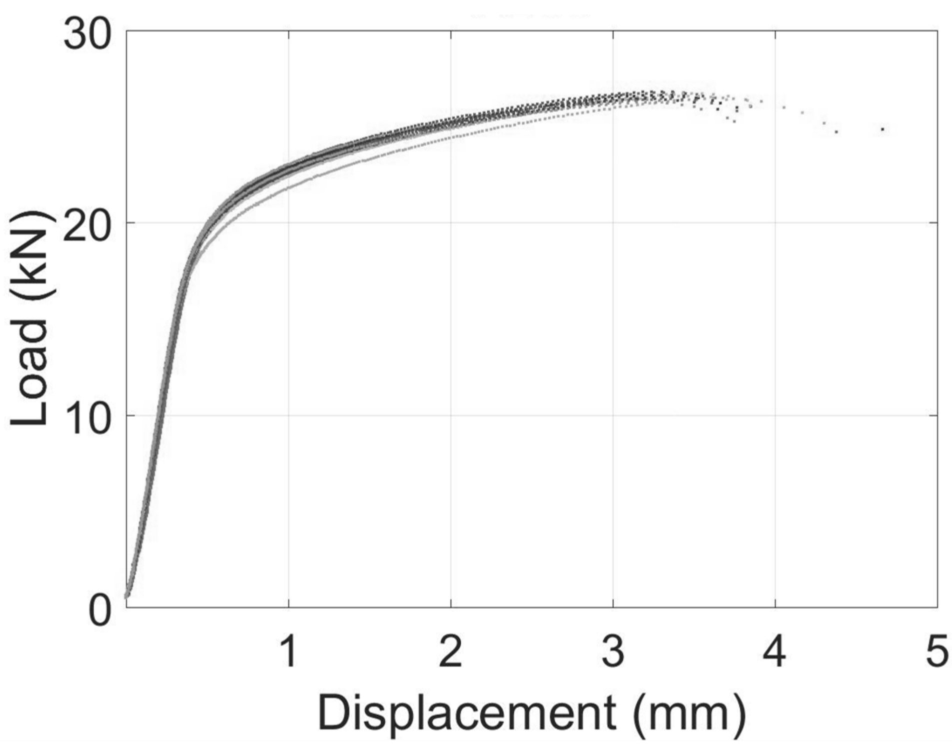


**Figure 2. Load versus displacement data for all twelve A286 test fasteners**

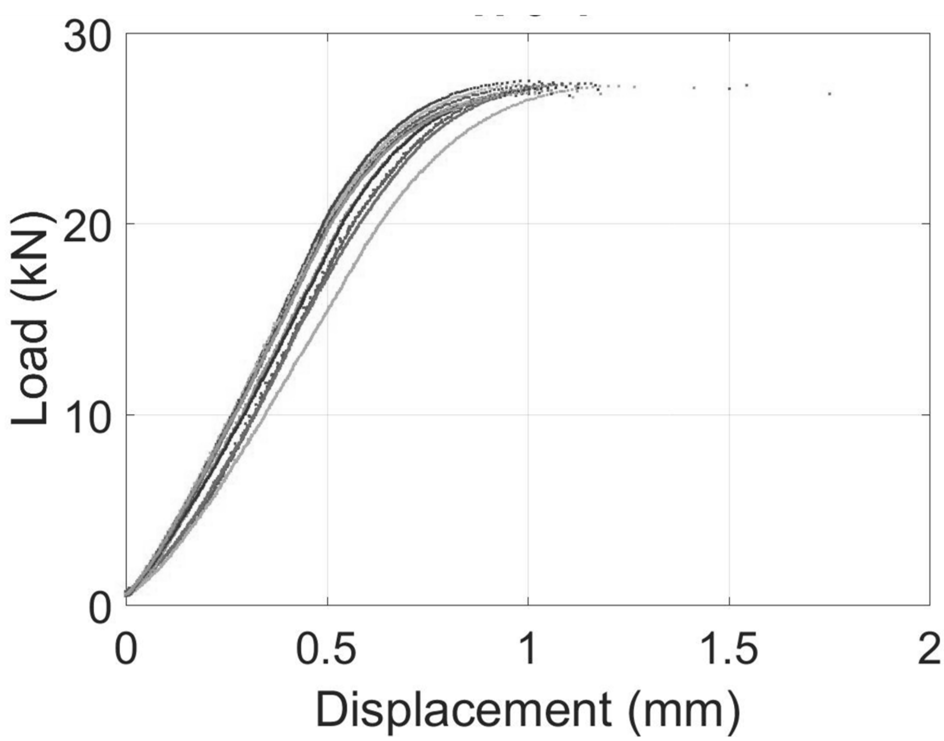


**Figure 3. Load versus displacement data for all twelve titanium 6Al-4V test fasteners**

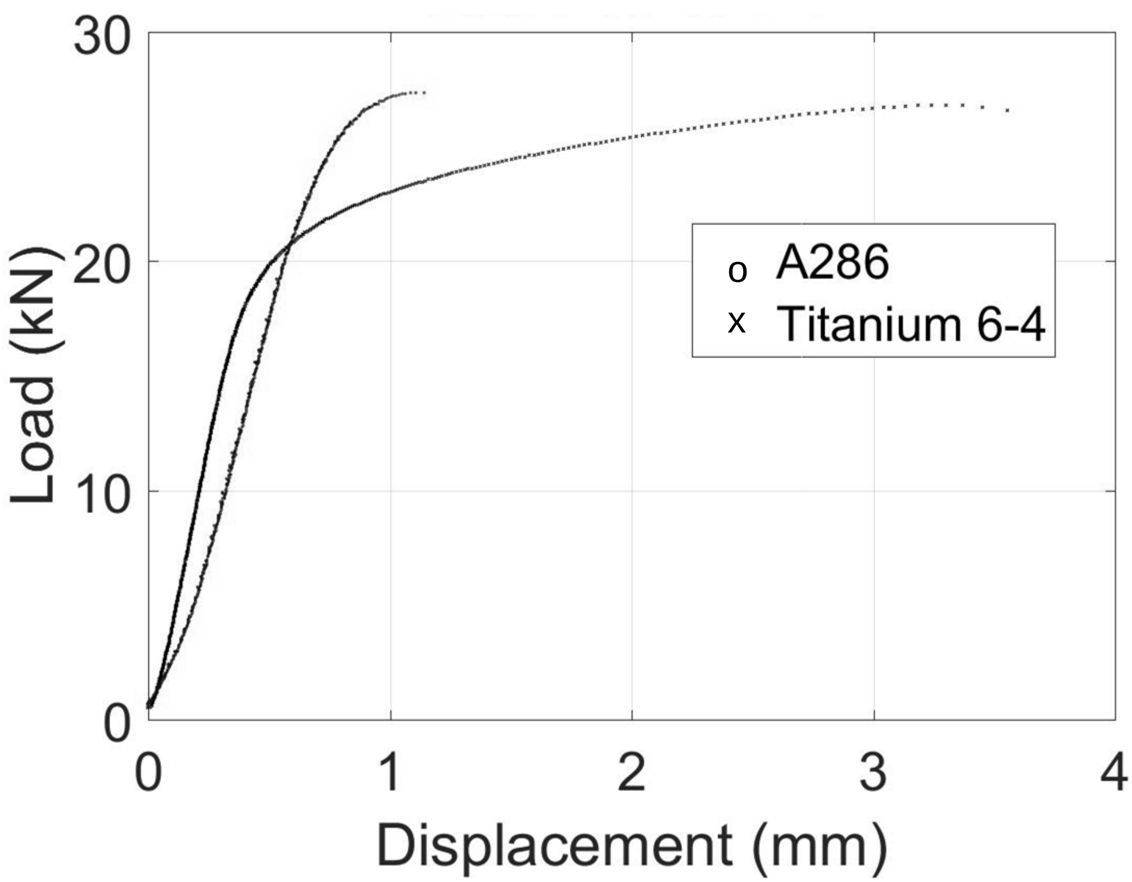


**Figure 4. Load versus displacement data for sample A286 and Ti 6-4 test fasteners**

Although the tensile strength for the test fasteners is comparable, the displacement from yield to fracture is notably different. The ductility index is calculated to assess this characteristic.

The ductility index is quantified by the ratio of plastic deformation at rupture to elastic deformation at rupture [4-6]. Figure 5 illustrates how the ductility index is determined from a sample load versus displacement curve. De represents elastic deformation and Dp represents plastic deformation. The ratio of Dp/De is defined as the ductility index. This index is used to quantify the relative ductility in these two test fastener materials in this work. The ductility index provides a means to quantify ductility of product such as full scale fasteners that are not ideal machined tensile test specimens. The test curves with annotation for ductility index parameters for all 24 test fasteners are provided elsewhere [7].

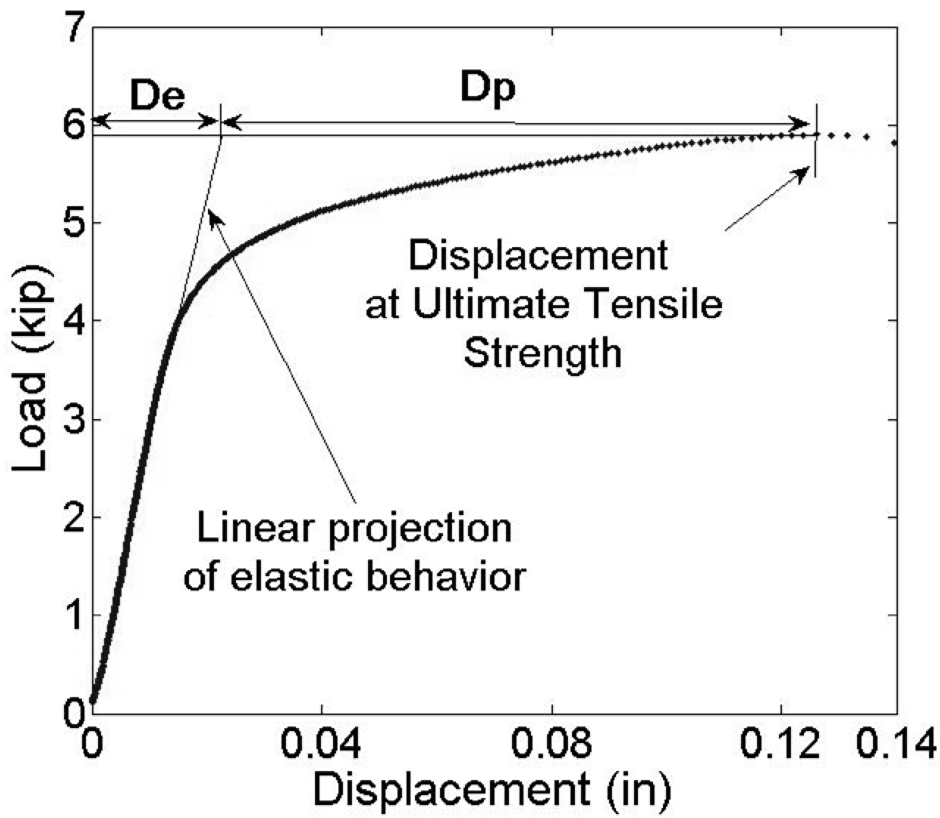


**Figure 5. Calculation of ductility index parameters from sample load vs displacement data**

The ductility index is calculated for all test fasteners. Table 3 lists the ductility index statistics for both the A286 and Ti 6-4 test fasteners. This data reveals that the ductility index for the A286 test fasteners is about ten times larger than the ductility index for the Ti 6-4 test fasteners. In addition, the spread or scatter in the ductility index is modest for each material as indicated by the minimum, maximum and quartile values.

**Table 3. Test fastener ductility index statistics**

| | A286 | Ti 6-4 |
|---|---|---|
| Average | 5.40 | 0.53 |
| Minimum | 5.05 | 0.43 |
| 25th Quartile | 5.12 | 0.51 |
| 75th Quartile | 5.65 | 0.56 |
| Maximum | 5.90 | 0.59 |

Figures 6 and 7 show fracture surfaces from sample Ti 6-4 and A286 test specimens, respectively. The fracture occurs in the threaded region for all test fasteners as expected. However, the Ti 6-4 test fasteners fracture across only one thread (i.e., nearly perpendicular to the axis of tensile loading which is typical for brittle materials), whereas the A286 test fasteners fracture across three or four threads (i.e., approximately at a 45 degree angle to the axis of tensile loading which is typical for ductile materials).

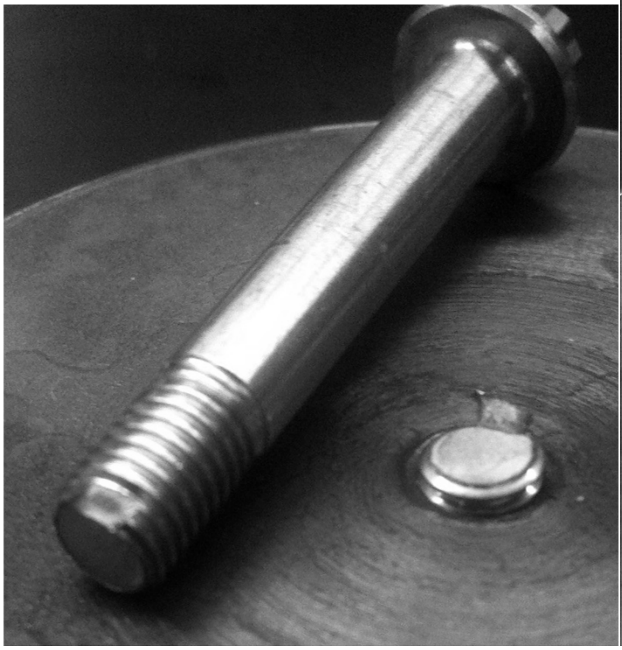

**Figure 6. Sample Ti 6-4 test fastener failure**

**Figure 7. Sample A286 test fastener failure**

## Conclusions

This work assessed the relative ductility of titanium alloy Ti 6-4 aerospace fasteners to stainless steel A286 aerospace fasteners. A test procedure was developed for this assessment. Tests were conducted using an MTS tensile test machine and load versus displacement curves were obtained for 24 test fasteners. The test curves were found to be repeatable for each fastener material, with substantial differences plastic deformation between materials. The tensile strength for the Ti 6-4 and A286 test fasteners were found to be comparable.

Relative ductility was assessed using the ductility index which is the ratio of plastic deformation to elastic deformation from a tensile test. In addition, fracture surfaces of the test specimens were examined for characteristics inherent of ductile and brittle failure.

The results of this work show:

1. The ductility index of the titanium alloy Ti 6-4 aerospace fasteners are about one-tenth of the ductility index of the A286 aerospace fasteners.
2. The average ductility index of the titanium alloy Ti 6-4 aerospace fasteners was found to be 0.53.
3. The average ductility index of the A286 aerospace fasteners was found to be 5.40.
4. The fracture surfaces of the titanium alloy Ti 6-4 aerospace fasteners from tensile testing are perpendicular to the axis of the tensile loading which is characteristic of brittle fracture.

5. The fracture surfaces of the A286 aerospace fasteners from tensile testing are at about 45 degrees to the axis of the tensile loading which is characteristic of ductile fracture.

These results are not intended to discourage the use of titanium alloy fasteners, but rather to provide additional data for use in proper joint design. In cases were weight savings or temperature requirements demand such fasteners, titanium alloy fasteners may be the best option. Proper joint design with titanium alloy fasteners include keeping preloads at or below 65% of yield, minimizing or controlling torque-tension scatter, and accurately quantifying worse case external loads.

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## References

1. Gross, F, “Concerns with the Use of Titanium Fasteners,” *NASA Materials Engineering Branch Technical Information Paper No*. 133, 2003.
2. Stevenson, M, McDougall, J, Cline, K, “Metallurgical Failure Analysis of Titanium Wing Attachment Bolts,” *ASM International - Practical Failure Analysis*, 3 (2003), 75-80.
3. Jha, A, Singh, S, Kiranmayee, M, Sreekumar, K, Sinha, P, “Failure Analysis of Titanium Alloy Ti6Al4V Fastener Used in Aerospace Application,” *Engineering Failure Analysis*, 17 (2010), 1457-1465.
4. NASA-STD-5020, *Requirements for Threaded Fastening Systems in Spaceflight Hardware*, .2012
5. Gerard, G, “Structural Significance of Ductility in Aerospace Pressure Vessels,” *ARS Journal*, 32 (1962), 1216-1221.
6. Samuel, K, “Dependence of Strength and Ductility Ratios in Austenitic Stainless Steels,” *International Journal of Pressure Vessels and Piping*, 83 (2006), 474-476.
7. Whittaker, J, *Ductility and Use of Titanium Alloy and Stainless Steel Aerospace Fasteners*, University of South Florida MS Thesis, 2015.
8. ASTM F606-13, *Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets, 2013*.