# Elastic-Plastic Behavior of Threaded Fasteners Under Multi-Axial Loads

**Joseph Erwin, Laith Alqawasmi, Tariq Khraishi**
Mechanical Engineering Department
University of New Mexico

## Abstract

Fasteners play an essential role in securely connecting separate components in practically any product. Since these components are generally made of ductile metals, their behavior under non-yielding loads should predictably follow the relationship between stress and strain defined by the Young's Modulus of the material. To better understand the behavior of fasteners under multi-axial loading, tensile tests were conducted on aerospace grade fasteners. The fasteners were loaded in pure tension, pure shear, and in mixed loading between 0° and 90° in 15° increments. The normal and shear displacement of the fasteners were recorded along with the corresponding force applied to the test fixture. The data collected from these experiments showed that the fasteners in tension dominated loads failed at significantly higher loads as compared to fasteners in shear dominated loading.

## Introduction

The importance of fasteners in mechanical assemblies cannot be understated [5]. However, this significance is not reflected in the reasonably limited published works and technical papers on quasi-statically induced failure of fasteners under multiaxial loading [1,2,6,8]. There do also exist a reasonable number of papers on fatigue failure of fasteners under cyclical multiaxial loading. [3,4,7] This area of research is certainly not entirely groundbreaking, but it is undoubtedly in need of further exploration. One of the largest issues in attempting to understand the behavior of fasteners in multiaxial loading is the complex geometry of the threads. The effect of threading upon stress concentrations developed within a fastener under multiaxial loading are very difficult to accurately predict, especially at varying angles. Therefore, it is necessary to be able to experimentally characterize the elastic-plastic behavior of fasteners with reasonably high resolution in their angle of loading. In this experiment, fasteners were inserted in a testing fixture with loading applied by an Instron. The testing fixture could be configured to load the fastener in pure tension, pure shear or mixed loading in 15° increments (0, 15, 30, 45, 60, 75, 90). Since local strain in the fasteners could not be measured, linear voltage differential transformers (LVDTs) attached to the fixture recorded the horizontal and vertical displacement of the fastener with respect to the fixture. Instron displacement, load, and the two dimensions of the fastener's displacement were recorded. As was predicted, the fasteners failed under significantly lower loads as loading moved from pure tension to pure shear.

## Experimental Setup

Depicted below is the Instron used to apply loading to the fixture. Loading and displacement data was recorded independently of the Instron System.

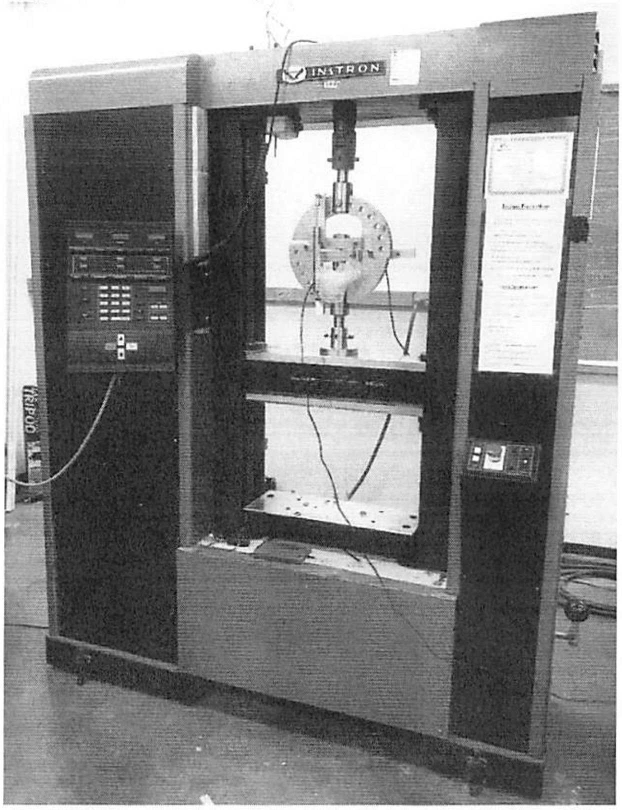

Figure 1: An Instron 4400R Load Frame for Tension/Compression

The testing fixture is pictured below in Figure 2. The LVDT (LVDTB) in the front measured vertical displacement, and the LVDT (LVDTA) hidden behind the fixture measured horizontal displacement at 0 degrees. The bushing pictured at the top had no threading, while the bottom bushing was threaded. The fixture halves were connected only by the fastener passing through both bushings. To change the angle of loading of the fastener, the clevis pins were removed, the fixture was rotated, and the clevis pins were placed in the holes corresponding to the desired angle.

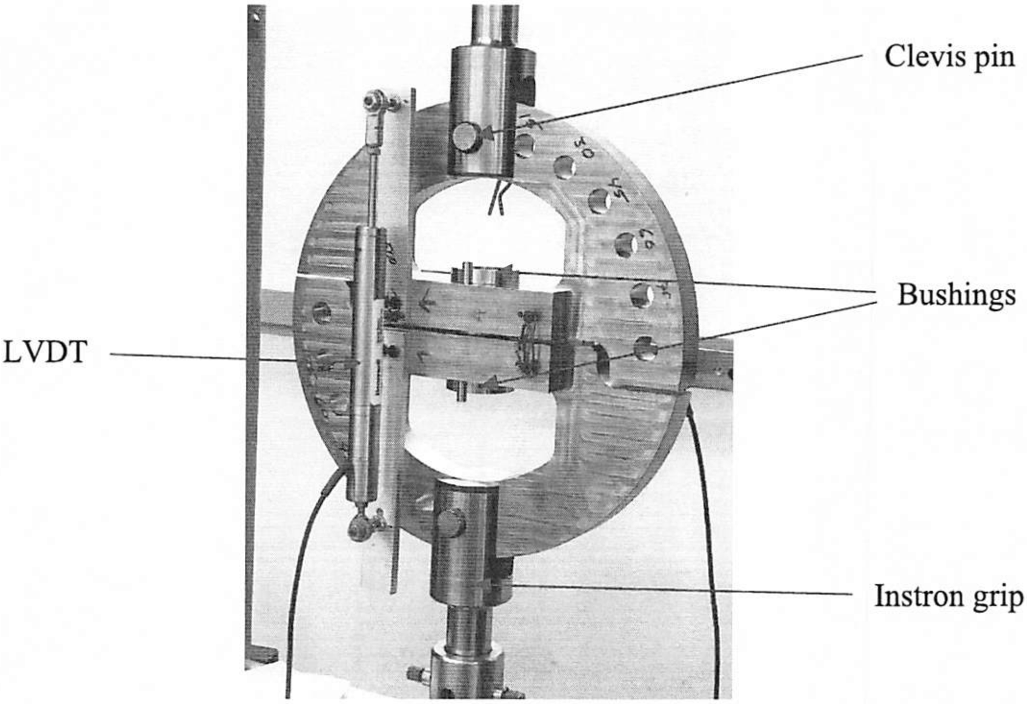

Figure 2. Testing Fixture

Finally, the MTS controller used to record the loading and LVDT data is pictured below.

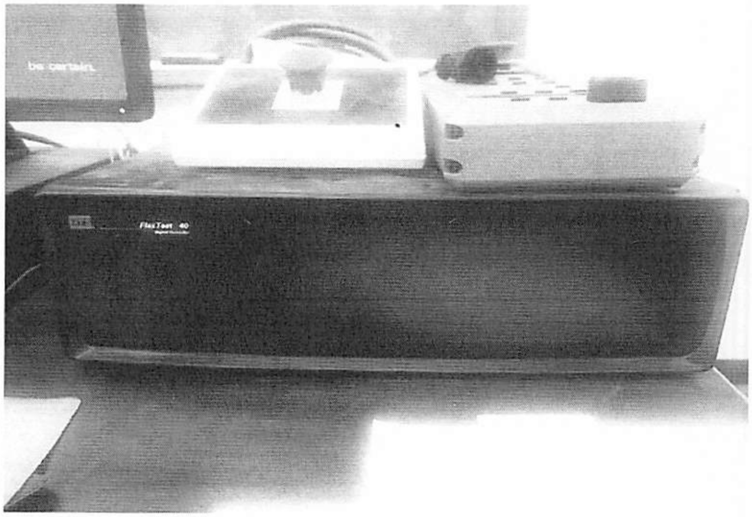

Figure 3. MTS FlexTest 40 controller used to record load-displacement and LVDT data

## Procedure

1. Place the bushings in the fixture.
2. Screw the fastener in the bushings to 2.5 N-m torque.
3. Fix the test fixture at the desired angle of loading.
4. Zero the strain and load readings on the extensometer.
5. Eyeball the LVDTs to make sure they are square with the test fixture.
6. Jog down the extensometer to preload the test fixture at 175 lbf.
7. Initiate collection of data from LVDTs.
8. Start the test using the Instron controller.
9. Stop data collection immediately after fastener failure.
10. Collect all loading and displacement data.

## Results and Calculations

Of course, a stress vs strain curve could not be used in this context because the stress and strain will not be uniform across the fastener. This made it necessary to plot the load exerted on the test fixture as a function of the Instron crosshead's displacement. As can be seen below in Figure 4, the maximum load and maximum displacement decrease as the angle at which the fastener was loaded increases. The general behavior of the plots illustrates what should be expected of a ductile material under these loading conditions.

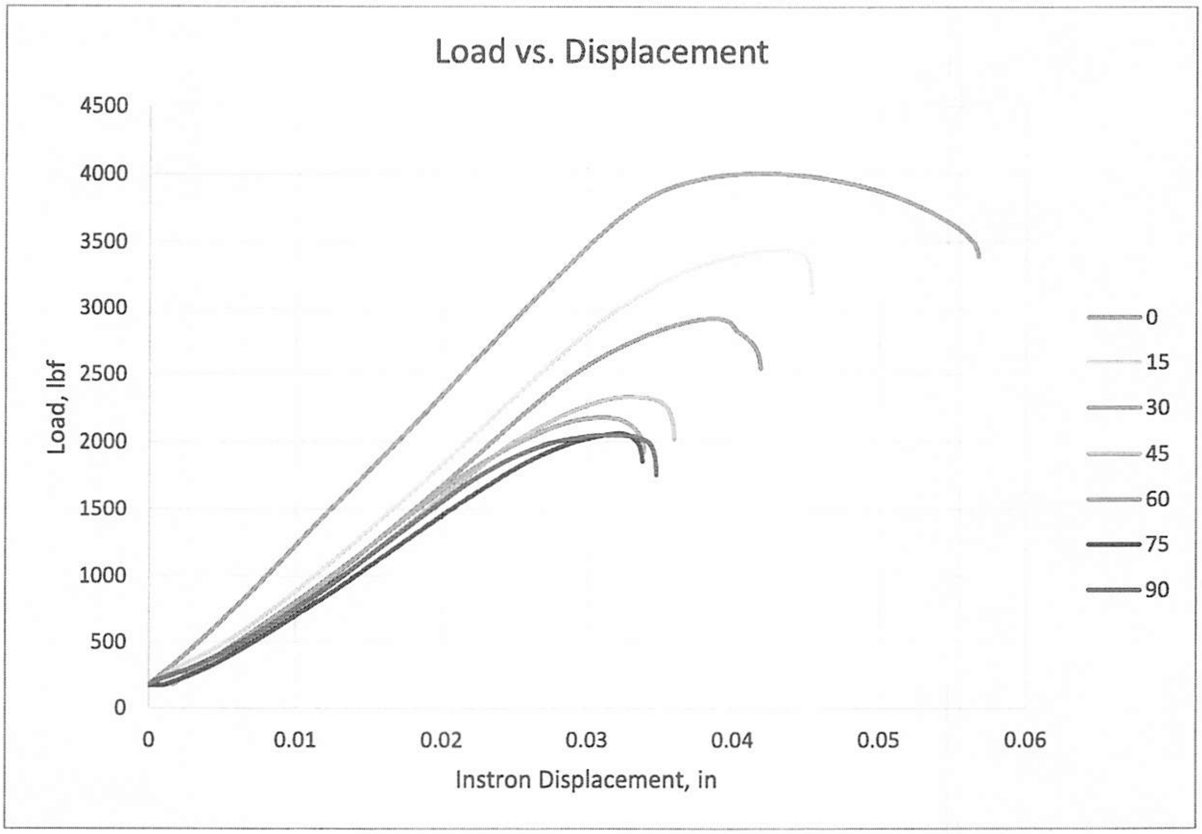

Figure 4. Load vs. Displacement Curves for Fasteners Loaded at Varying Angles

The graphs below illustrate the reliability of the experimental methods. With the strain rate at a set value, 0.01 inches per minute in this case, the force versus time plots for all specimens at any given angle should overlap as seen below.

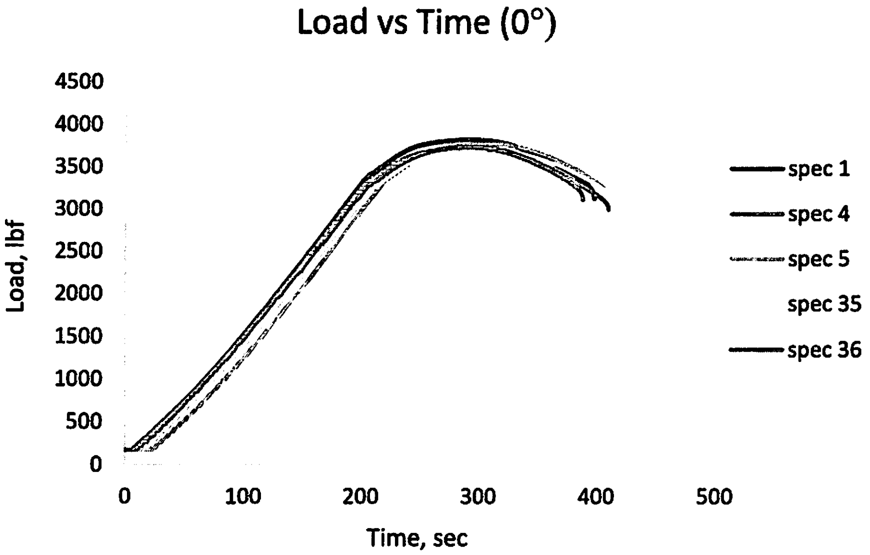

Figure 5. Instron Load as a Function of Time for Specimens Loaded at 0°

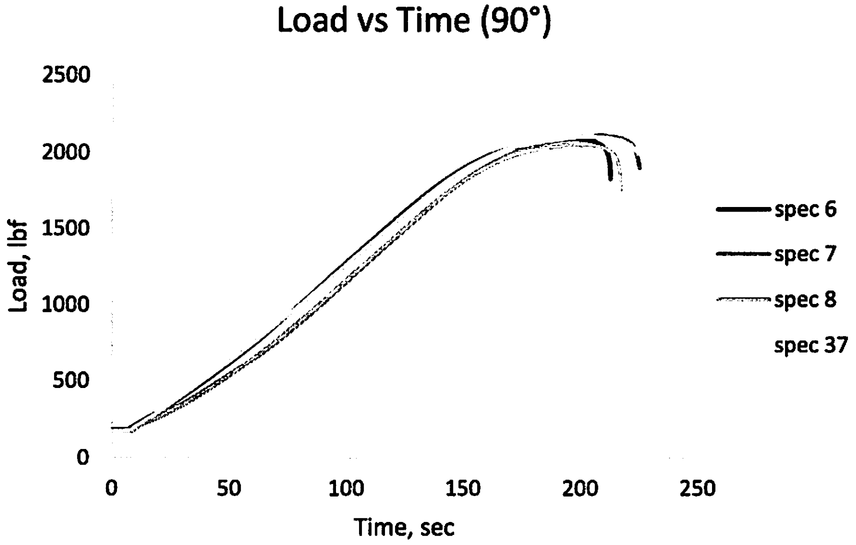

Figure 6. Instron Load as a Function of Time for Specimens Loaded at 90°

The LVDT displacement readings for a specimen loaded at 0° are plotted as a function of the Instron displacement below in Figures 7 and 8. As expected, the horizontal displacement (LVDT A) is negative since, in pure tension, the specimen will decrease in diameter.

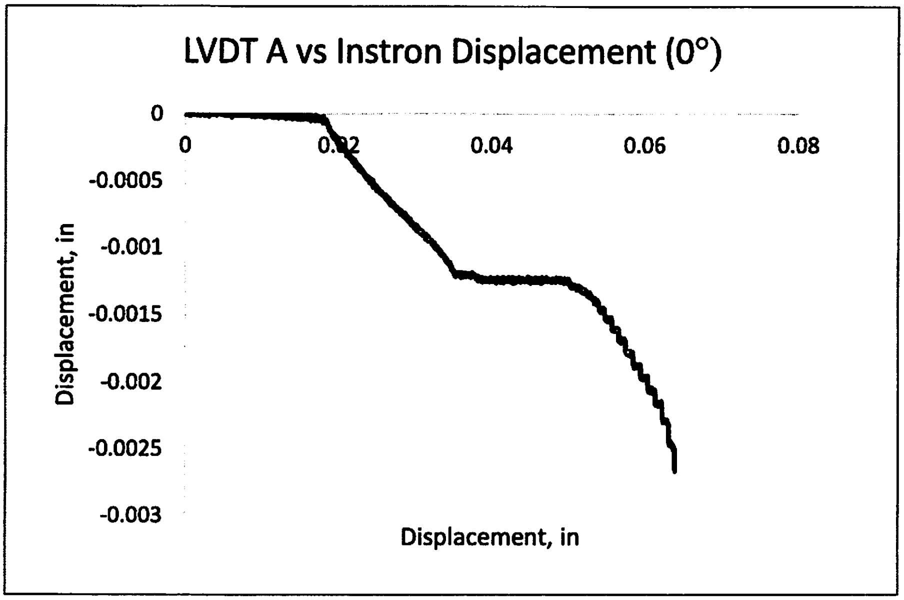

Figure 7. Horizontal Displacement vs. Instron Displacement at 0°

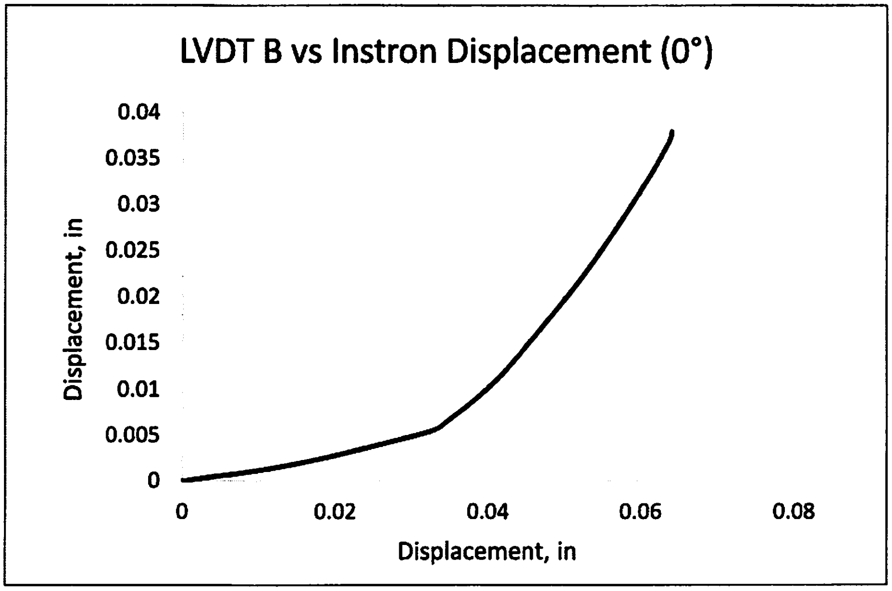

Figure 8. Vertical Displacement vs. Instron Displacement 0°

When the specimen is put under loading at 30°, the horizontal displacement should be expected to be positive and much larger in magnitude due to the shearing component of loading. As can also be seen by comparing Figure 8 to Figure 10, the maximum vertical displacement is lower at 30° loading, as is anticipated.

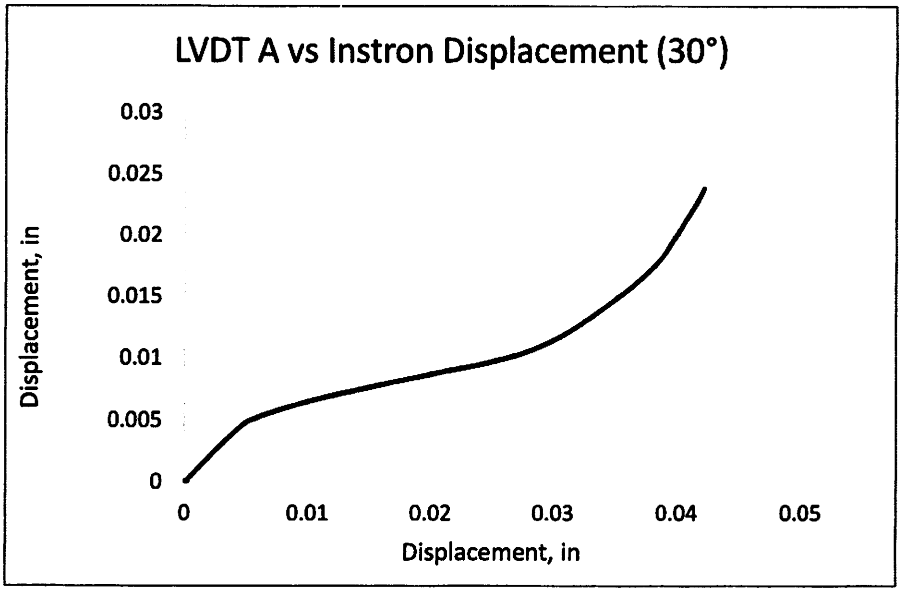

Figure 9. Horizontal Displacement vs. Instron Displacement at 30°

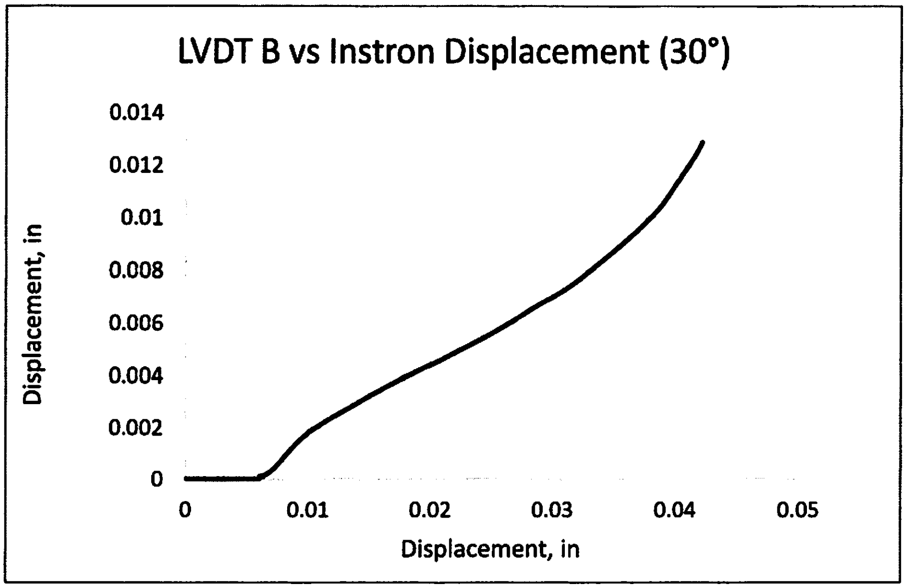

Figure 10. Vertical Displacement vs. Instron Displacement at 30°

Finally, at 90°, the inverse of the 0° case should be seen with large, positive horizontal displacement values and relatively small vertical displacement values.

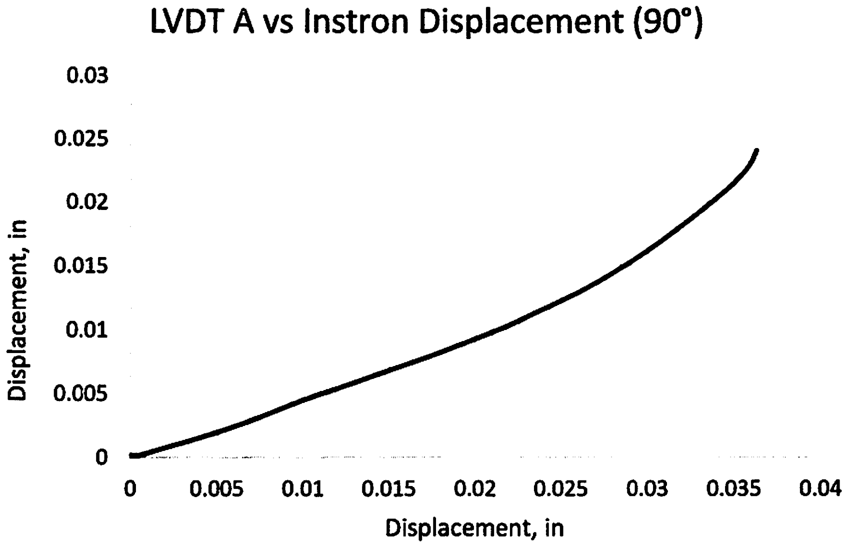

Figure 11. Horizontal Displacement vs. Instron Displacement at 90°

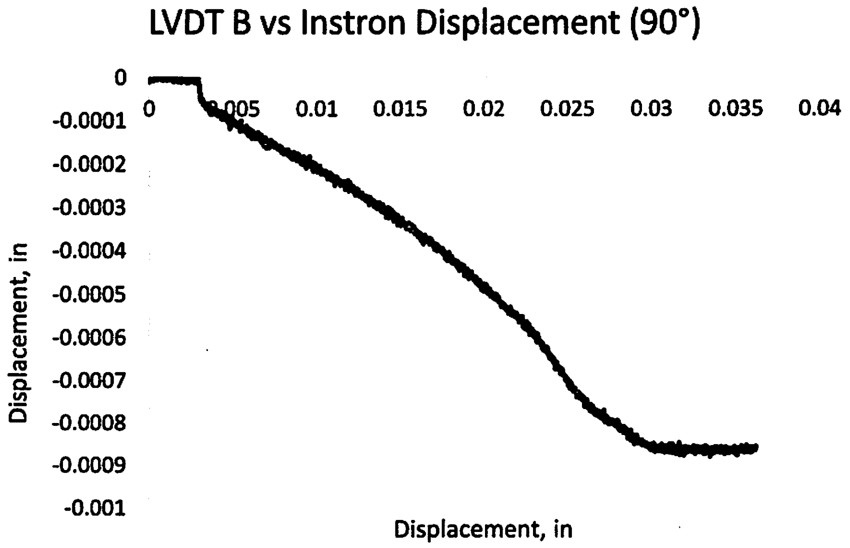

Figure 12. Vertical Displacement vs. Instron Displacement at 90°

## Summary and Conclusions

Data collection proved to be very difficult, especially at angles above 30°. Thankfully, as is shown in the results, the data collected agrees with previous research and fundamental solid mechanics theories. This coherence between experimental data, established research from reputable sources, and theory establishes credibility for the methods utilized for data collection. This research adds to the knowledge base on fastener testing that is currently available in the literature.

## References

1. Camarena E., Quintana A., V. Yim, P., Grimmer, J. Mersch, J. Smith, J. Emery, G. Castelluccio, "Analysis of Multiaxial Loading of Threaded Fasteners" Sandia National Lab, Albuquerque, SAND2018-12364C, 2018.
2. Cao Z., Brake M., and Zhang D., "The failure mechanisms of fasteners under multi-axial loading," *Engineering Failure Analysis*, vol. 105, pp. 708–726, 2019.
3. Kazemi, A., and Nassar, S. A., "Principal stress-based equation for multi-axial fatigue analysis of preloaded threaded fasteners," *Journal of Pressure Vessel Technology*, vol. 140, 2018.
4. Kazemi, A., Wu, Z., and Nassar, S. A., "Multiaxial fatigue of preloaded threaded fasteners," *Volume 2: Computer Technology and Bolted Joints*, 2015.
5. Mersch, J. P., Smith, J. A., Johnson, E. P., and Bosiljevac, T., "Evaluating the performance of fasteners subjected to multiple loadings and loadings rates and identifying sensitivities of the modeling process," *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2018.
6. Moreno K., Murugesan A., Sheng M., Alqawasmi L., Khraishi T., and Hubbard N.B., "Correlation of reduced-order models of a threaded fastener in multi-axial loading," *Volume 9: 17th International*, 2021.
7. Ross, M., Stevens, B., Khan, M., Brink, A., and Freymiller, J., "Fastener Fatigue Analysis using time domain methods for multiaxial random vibration," *Special Topics in Structural Dynamics, Volume 5*, 2018, pp. 17–36.
8. Steev, B.E., Wingate, R.J., "Aerospace Threaded Fastener Strength in Combined Shear and Tension Loading," Marshall Space Flight Center, Huntsville, NASA/TM—2012–217454, 2012, March 2012.

JOSEPH C. ERWIN
Joseph is an undergraduate student in the Mechanical Engineering Department at UNM. He is graduating with his undergraduate degree in the Spring of 2023 and will go on to pursue a master's degree in Mechanical Engineering with a focus on solid mechanics and materials science.

LAITH ALQAWASMI

Laith Alqawasmi is a master's student in the Mechanical Engineering Department at the University of New Mexico. His research interests are material science and mechanics of materials. He is currently a process engineer at Jabil's Albuquerque site working on additive manufacturing of medical implants.

TARIQ A. KHRAISHI

Dr. Khraishi currently serves as a Professor of Mechanical Engineering at the University of New Mexico. His general research interests are in theoretical, computational, and experimental solid mechanics and materials science. He has taught classes in Dynamics, Materials Science, Advanced Mechanics of Materials, Elasticity and Numerical Methods. For the last several years he has engaged himself in the scholarship of teaching and learning.