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2014 WSEAT X-Prize

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Experimental Work Package (EWP): SML0287

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Introduction

The 2014 WSEAT X-Prize is modeled as a double blind study to challenge the computational and material mechanics communities methodologies to develop better capabilities in modeling and experimentation to predict the failure in ductile metals. The challenge is presented as a distinct, yet relatively, simple geometry with all reported modeling predictions blind to each of the modeling teams. The experimental testing is validated by two independent test labs to confirm the experimentally observed behavior and results are unbiased and repeatable.

The WSEAT X-Prize was issued to both external participants and internal participants as the Sandia Fracture Challenge 2 (SFC2) on May 30, 2014. A Challenge Supplemental Information Packet was sent to participants on August 13, 2014 to Prior years SFCs focused on the ability to predict failures under a quasi-static loading condition that focused on either a shear or tensile-dominated failure mode. This year's challenge focuses on a geometry with a shear and/or tensile-dominated failure mode influenced by a moderate strain-rate ductile fracture in a metallic alloy.

Purpose

Support, evaluate and further advance the predictive ductile fracture modeling for moderate strain-rate loading through experimental testing. The projects goal is critical in aiding numerical modeling predictions through supportive experimental results. In addition, this will lead to the refinement of computational modeling and experimental testing to enhance and promote future capabilities in predicting failure in ductile materials.

The main objective of this year's challenge is to issue the Sandia Fracture Challenge (referred to as "the challenge") to the computational community by May 30, 2014. With an overall objective of the challenge to determine if and what kind of predictive modeling methodology is best suited to modeling ductile fractures with applied transient rate loading and to assess what types of material characterization test methods are necessary to support a computational model regarding transient rate loading failure.

Challenge Geometry

Material & Trial Geometry

The challenge material was selected based on prior knowledge and experience of a moderate ductile metallic alloy exhibiting properties with a propensity to show moderate strain-rate characteristics. Ti-6Al-4V was selected as the challenge material to be used for fabricating the challenge geometry. The challenge geometry has a material nominal thickness of 3.112 mm.

The challenge geometry was based upon testing several trial geometries, to determine if the geometry and material selected produced a noticeable shift when a quasi-static and moderate-stain rate loading was applied by an instantaneous stroke velocity. The results of the original and modified test geometries based on loading rates of 0.0254 mm/s and 25.4 mm/s is shown below in **Figure 1 and 2**, respectively. The rate of 25.4 mm/s is at the upper bound of the Structural Mechanics Labs servo-hydraulic system.

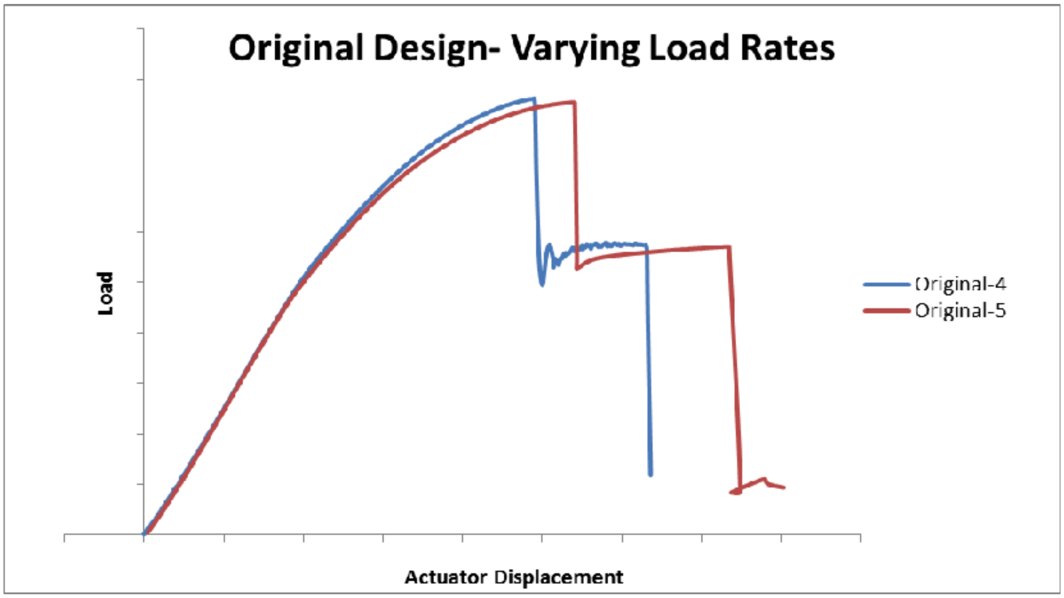


Figure 1-Original Trial Geometry Rate Loading

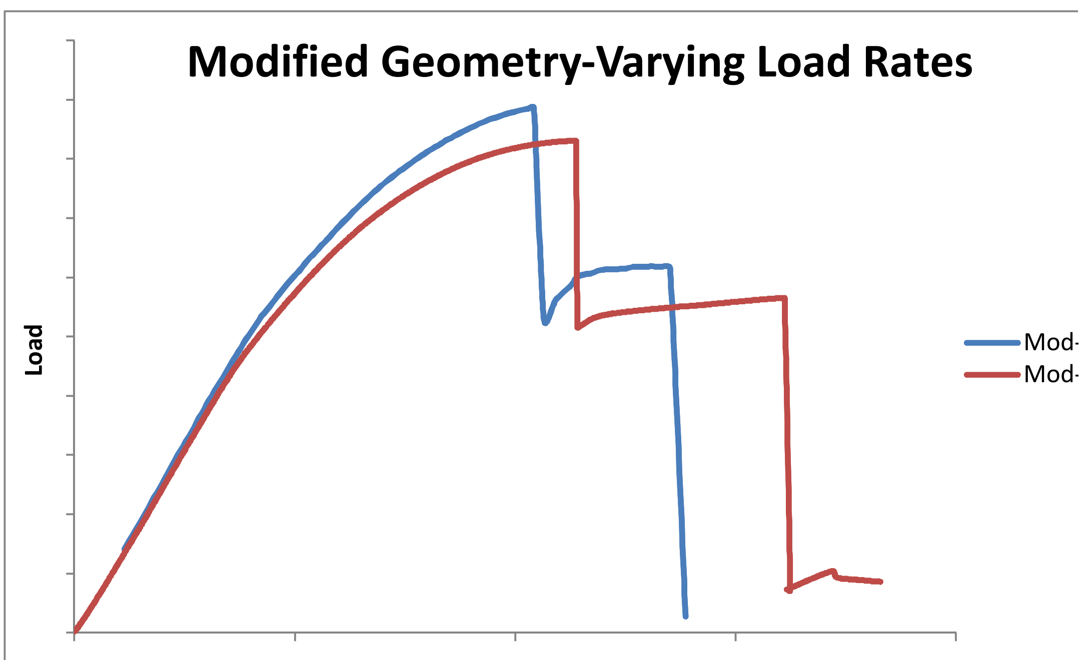


Figure 2-Modified Trial Geometry Rate Loading

Challenge Geometry

The challenge geometry selected for the SFC2 is shown in **Figure 3**. The challenge geometry consists of a S-shaped sheet specimen with two slots and 3 holes tested in axial tension. The two larger holes are used for the loading pins. The geometry was mechanically challenging because 1) the multiple failure modes based on the multiple hole locations and sizes along with the applied loading rates 2) no pre-existing crack tip to influence a crack path and 3) a material thickness that could influence either a plane strain or plane stress dominance. The geometric characteristic of the challenge have not been experimentally or computationally before.

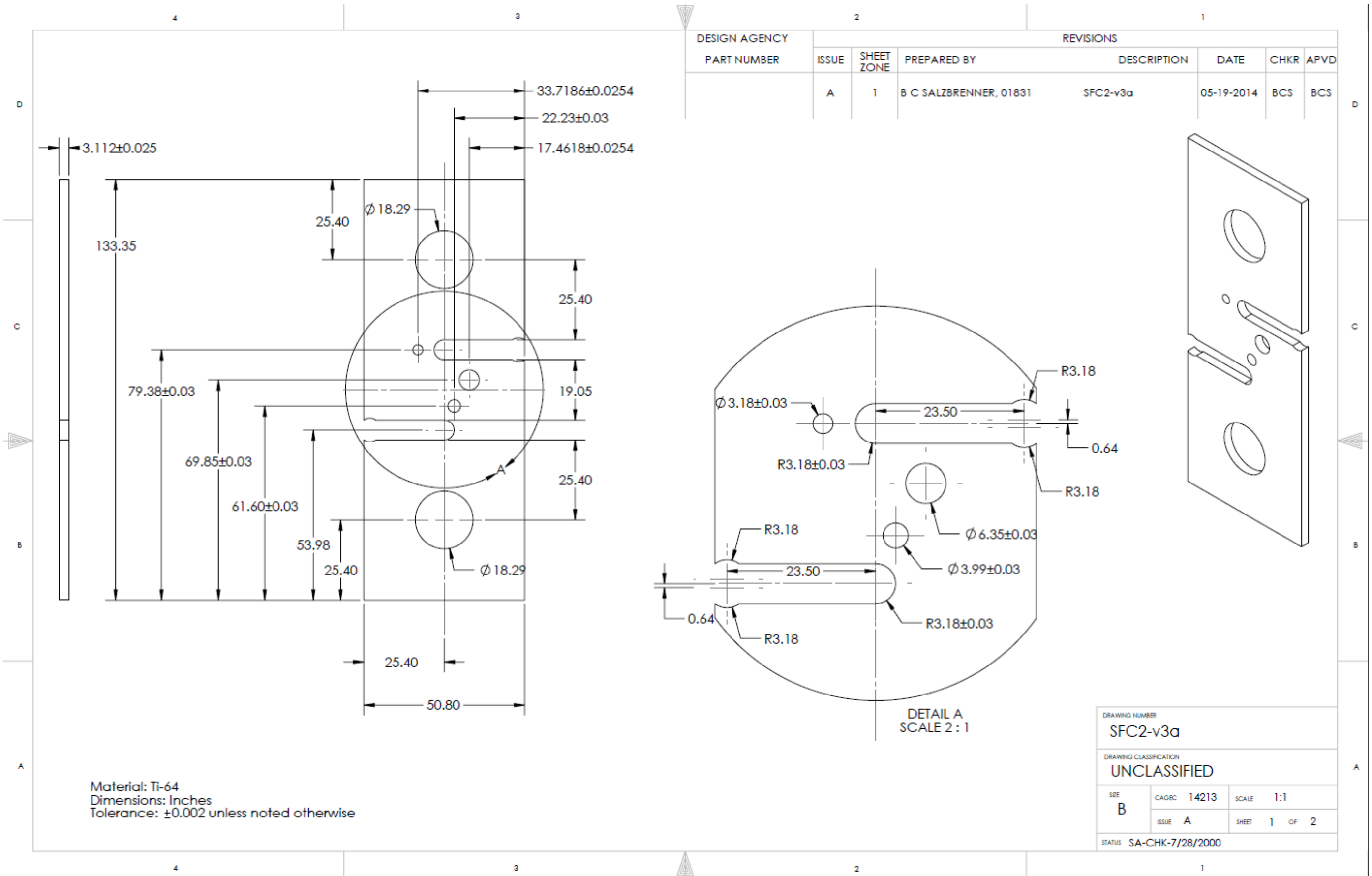


Figure 3-Challenge Geometry

Experimental Characterization

Material characterization for the challenge consisted of the following experimental tests 1) tensile 2) shear and 3) hardness. For the tensile and shear testing, the Structural Mechanics Lab (SML) tested the specimens at two rates of 25.4 mm/s and 0.0254 mm/s, respectfully, and in two plate related orientations referred to as the rolling and transverse directions.

Tensile Test

Tensile specimens for material characterization were fabricated in the "dog bone" configuration to meet ASTM E8/E8M-13: "Standard Test Methods for Tension Testing of Metallic Materials" specifications as shown below in **Figure 4**. The tensile tests conducted by the SML included eight (8) specimens in the rolling direction and ten (10) specimens in the transverse direction for a total of eighteen test specimens. Three specimens were tested at the higher rate and five at the lower rate in the rolling direction, while five specimens were tested at each rate in the transverse direction. A table of tensile specimens consisting of measurements, orientation and rates is shown in **Table 1**.

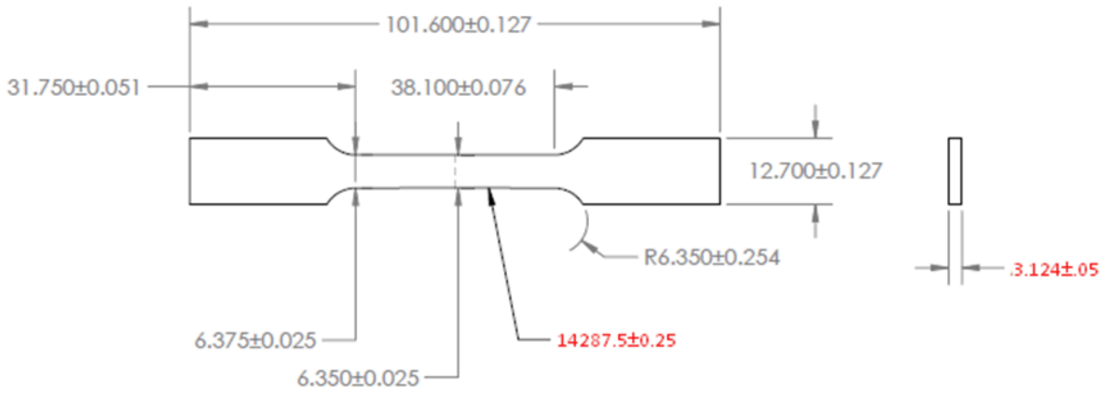


Figure 4-Tensile Specimen Geometry (mm)

ID	orientation	Thickness	Width	Area	Location Broke	Nominal Rate
		mm	mm	mm^2		
RD8	rolling direction	3.175	6.35	20.16	with in extensometer	0.0254 mm/s
RD2	rolling direction	3.1623	6.35	20.08	with in extensometer	0.0254 mm/s
RD9	rolling direction	3.175	6.35	20.16	with in extensometer	25.4 mm/s
RD7	rolling direction	3.1496	6.35	20.00	with in extensometer	0.0254 mm/s
RD6	rolling direction	3.175	6.35	20.16	with in extensometer	0.0254 mm/s
RD5	rolling direction	3.1623	6.35	20.08	with in extensometer	0.0254 mm/s
RD4	rolling direction	3.1623	6.35	20.08	with in extensometer	25.4 mm/s
RD10	rolling direction	3.1623	6.35	20.08	with in extensometer	25.4 mm/s
TD1	transverse direction	3.1496	6.35	20.00	within exten	25.4 mm/s
TD2	transverse direction	3.1496	6.35	20.00	within exten	0.0254 mm/s
TD3	transverse direction	3.1496	6.35	20.00	within exten	0.0254 mm/s
TD4	transverse direction	3.1242	6.35	19.84	within exten	0.0254 mm/s
TD5	transverse direction	3.1496	6.35	20.00	within exten	25.4 mm/s
TD6	transverse direction	3.1242	6.35	19.84	within exten	0.0254 mm/s
TD7	transverse direction	3.1242	6.35	19.84	within exten	0.0254 mm/s
TD8	transverse direction	3.1242	6.35	19.84	within exten	25.4 mm/s
TD11	transverse direction	3.1369	6.35	19.92	within exten	25.4 mm/s
TD12	transverse direction	3.1496	6.35	20.00	within exten	25.4 mm/s

Table 1-Actual Tensile Specimen Identification and Measurements

The related load versus strain plots for both orientations and rates are shown in **Figure 5**. A noticeable difference in the ultimate tensile strength and maximum elongation, with respect to orientation and rate, is visible in the data plots of load versus strain.

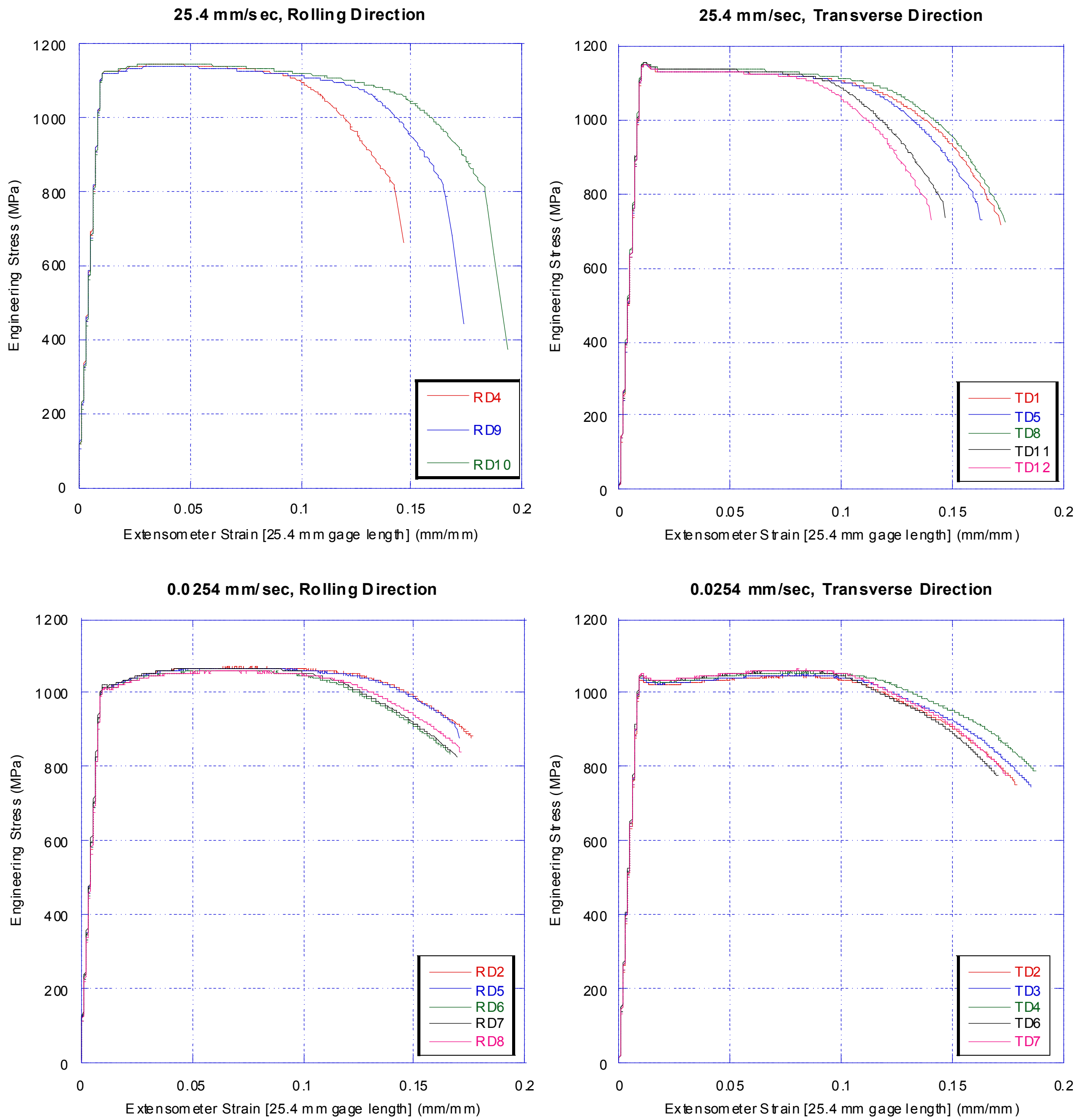


Figure 5-Actual Tensile Test Data Plotted as Load vs. Strain

The tensile test measurements consisted of applied loading data collected from the load cell of the 22-kip MTS load frame and a 25.4 mm extensometer. Validation of the applied fast-rate was accomplished by using images of the high-speed pull tests that were captured using the high-speed Phantom 611 camera. These images were analyzed in a computer vision software package (VIC 2D) to determine the relative change in distance between a pair of fiducials placed on the grips (see **Photo A**). The software output data is compiled as a total change in distance between the fiducials in terms of pixels. A pixels-per-inch ratio was determined by knowing the size of the fiducial, allowing for a determination of change of location per image. The velocity was determined by knowing the time-step between images. Because of the relatively small change in displacement per image, this data was quite noisy. Therefore, a 30-point (central difference) rolling average of the velocity data was utilized. This data was compared to data collected by the MTS testing software, where the difference between displacement values was divided by the difference in the timestamp on the data for each line of data (referred to as the "forward difference"). Good agreement was seen in this data reduction methodology.

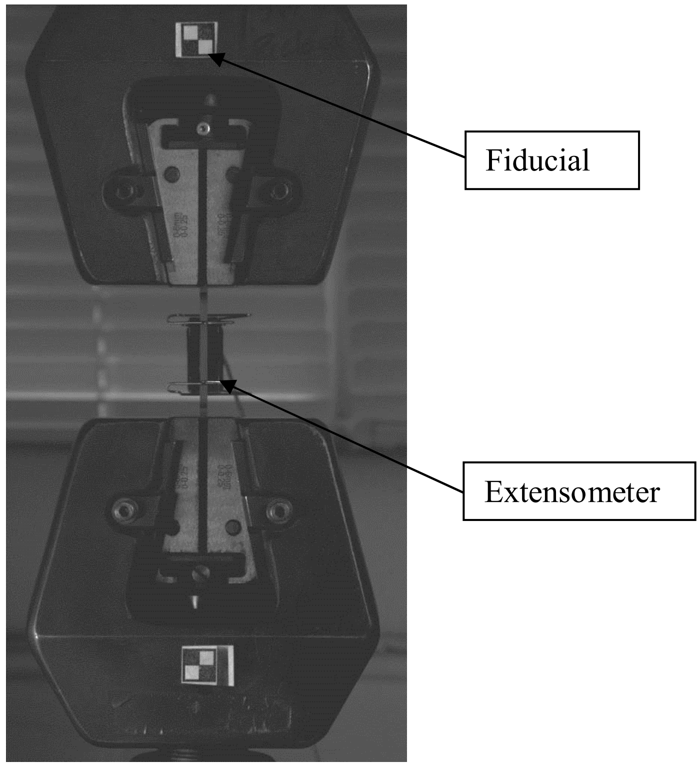


Photo A-Extensometer and Optical Fiducials for High-Speed Confirmation

Post-test specimens are shown below in **Photo B** for each material orientation.

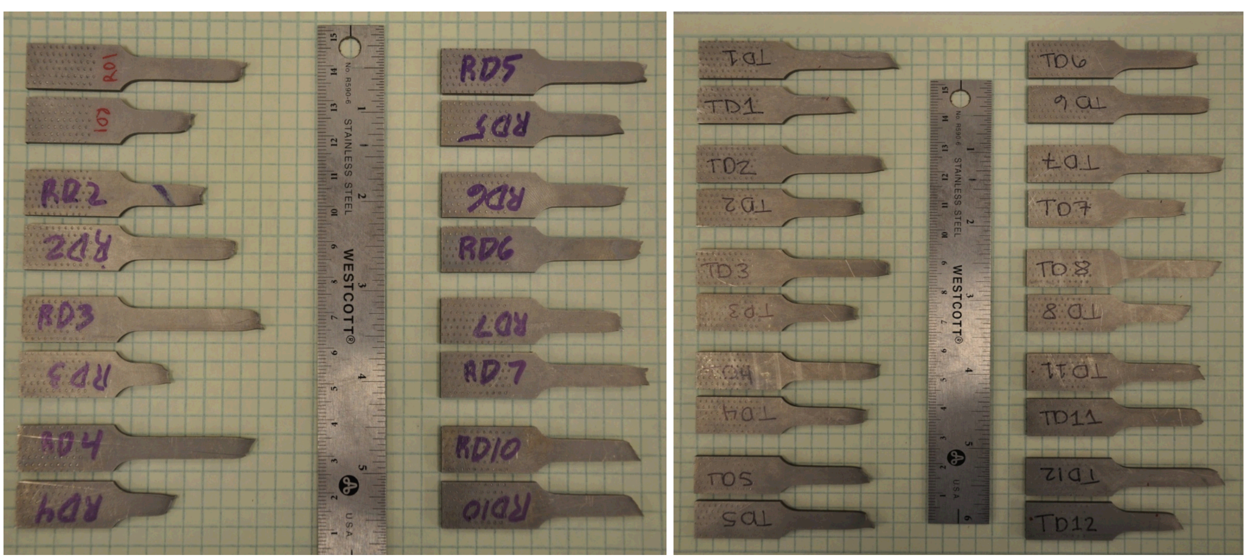


Photo B- Post-Test Tensile Specimens (Left-Rolling Orientation, Right-Transverse Direction)

Shear Test

The shear specimens for material characterization were originally fabricated to meet ASTM D7078/D7078M-05 "Standard Test Methods for Shear Properties of Composite Materials by V-Notched Rail Shear Method" specifications, since a specific ASTM standard does not appear to exist for characterization of shear failure in ductile metals. There are numerous shear test methods in the literature, each with advantages and disadvantages. For this challenge, we will provide test data on a specimen geometry based on ASTM D 7078 with the V-notched rail shear geometry modified (deeper notch than the standard) to reduce the stress area by more than half and allow induced failure at lower forces, minimize grip rotation, and eliminate the potential for grip slippage. This modification to the specimens arose from the initial shear tests on standard size specimens that required higher than expected loads to shear the specimens along with compliance issues encountered with the unique fixturing used for the test.

Test specimen geometry for the shear test is shown in **Figure 6**. The shear tests conducted by the SML included four (4) specimens parallel to the plate rolling direction and four (4) specimens in the transverse direction for a total of eighteen test specimens. Two specimens were tested at each rate parallel to the plate rolling direction, while two specimens were tested at each rate in the transverse direction. A table of shear specimens consisting of plate rolling orientation and geometrical measurements is shown in **Table 2**.

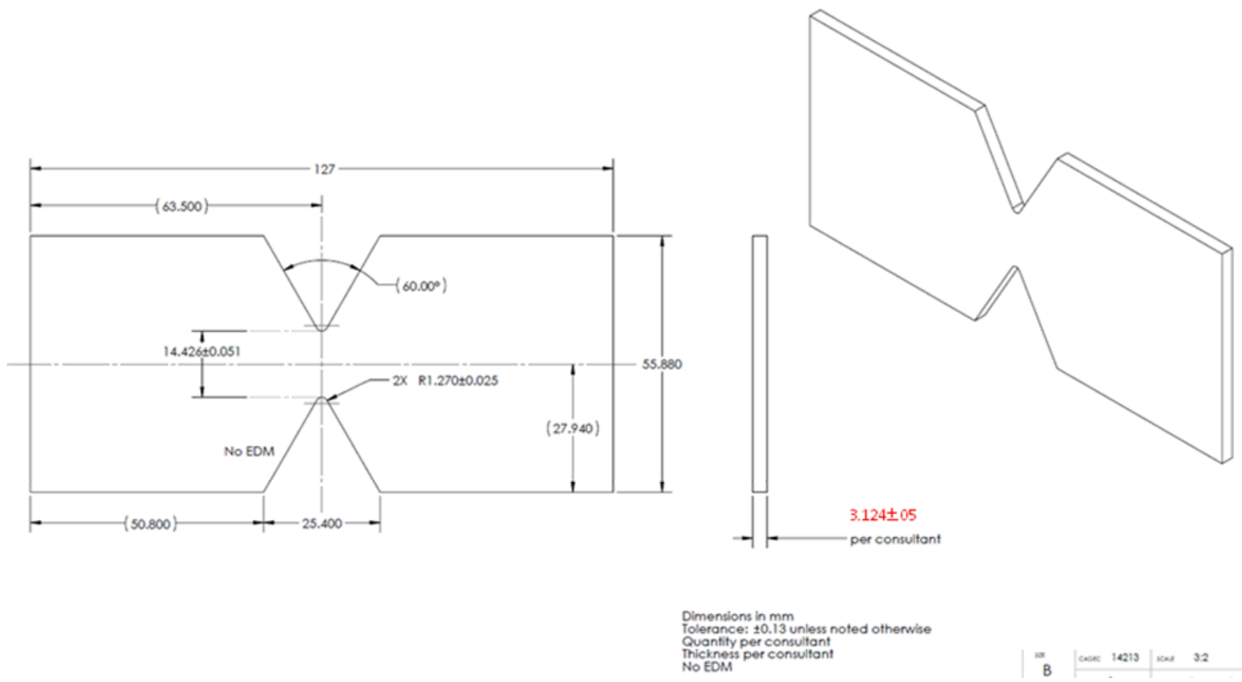
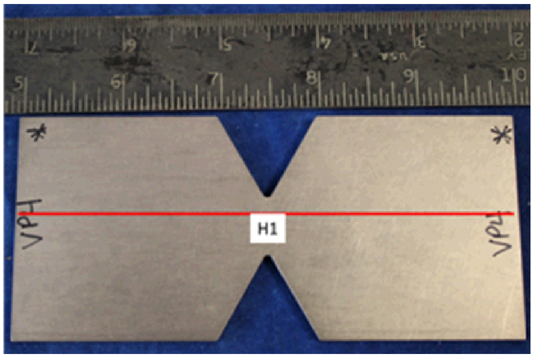
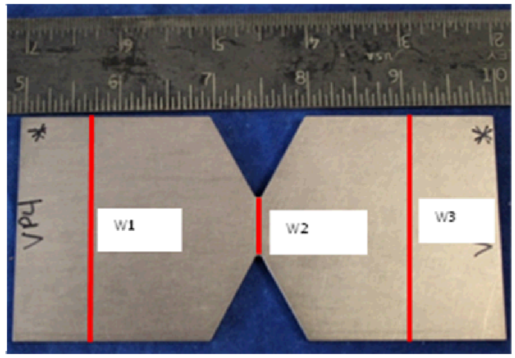


Figure 6-Shear Test Specimen Geometry





Specimen Name	Plate Rolling Direction Relative to Long Direction of Specimen (H1)	Thickness mm	H1 mm	W1 mm	W2 mm	W3 mm	L1 mm	L2 mm	L3 mm	L4 mm
VP2	Parallel	3.129	126.95	55.97	14.37	55.96	51.19	51.08	51.08	51.07
VP3	Parallel	3.087	126.94	55.96	14.37	55.96	51.08	51.08	51.09	51.12
VP4	Parallel	3.086	126.92	55.96	14.37	55.96	51.18	51.22	51.24	51.27
VP6	Parallel	3.091	126.97	55.94	14.37	55.94	51.05	51.05	50.95	51.16
VA1	Against	3.090	126.95	55.96	14.39	55.96	51.27	51.30	51.21	51.19
VA2	Against	3.073	126.95	55.96	14.385	55.96	51.24	51.23	51.27	51.23
VA3	Against	3.122	126.95	55.96	14.37	55.96	51.35	51.09	51.19	51.28
VA4	Against	3.122	126.96	55.97	14.36	55.97	51.19	51.18	51.18	51.19

Table 2-Shear Test Specimen Rolling Direction Orientation and Measurements

The fixturing for the shear test is unique and utilizes a hybrid fixture called the "Adjustable Combined Loading Shear (CLS) Fixture" for the V-notch Rail Shear Test from Wyoming Test Fixtures as shown in **Photo C**. The CLS fixture is fabricated from 17-4PH stainless steel and allows a higher shear load to be imparted into the specimen by minimizing the rotation of the specimen, when loaded, due to slippage.

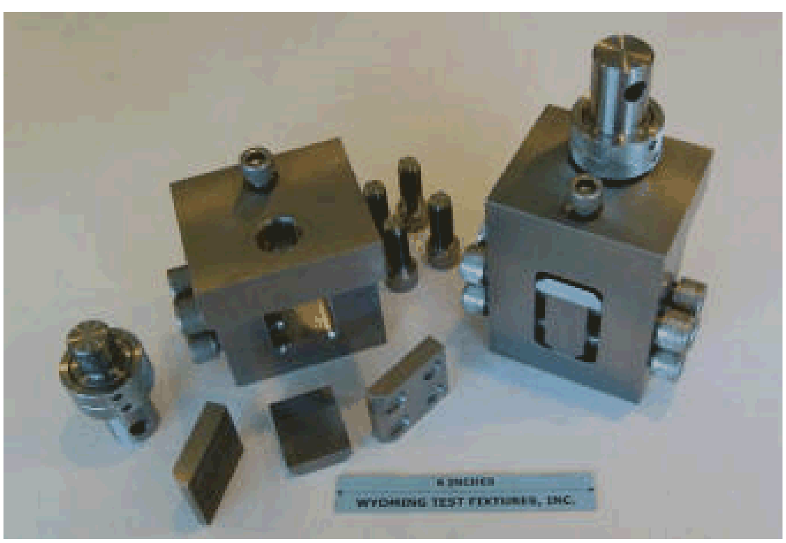


Photo C - Adjustable Combined Loading Shear (CLS) Fixture

As a result from the initial shear testing, before modifying the specimen geometry, compliance issues in the fixture were assessed to determine a path forward. The resulting additional experimental measurements were implemented to qualify the testing methodology.

LVDT measurement data of grip displacement was provided, in addition to strain gages as described in the standard, due to the compliance issues with grip slip and fixturing experienced in the initial shear test specimens. Therefore, LVDT placement was critical to insure compliance with respect to grip slippage and rotation. To account for grip slip, LVDT 1 was placed in the axial direction while the lateral LVDT 2 and 3 were installed to measure rotation in the fixture. Shown below, in **Photo D**, is the LVDT test setup for the shear test. The lateral LVDTs have a 38.1-mm (1.5-inch) gap between their mounts and their reference blocks, and their mounts are directly on the inner edge of each grip. The lateral centerline of LVDT 2 is 38.849 mm (1.5295 inch) above the lateral centerline of the specimen. The lateral centerline of LVDT 3 is 44.387 mm (1.7475 inch) below the lateral centerline of the specimen. The Axial LVDT 1 is mounted such that the open gap between the mount and its reference block at the start of the test is 83.82 mm (3.30 inch). The Axial LVDT mount and reference block are 12.7-mm (0.50-in) thick.

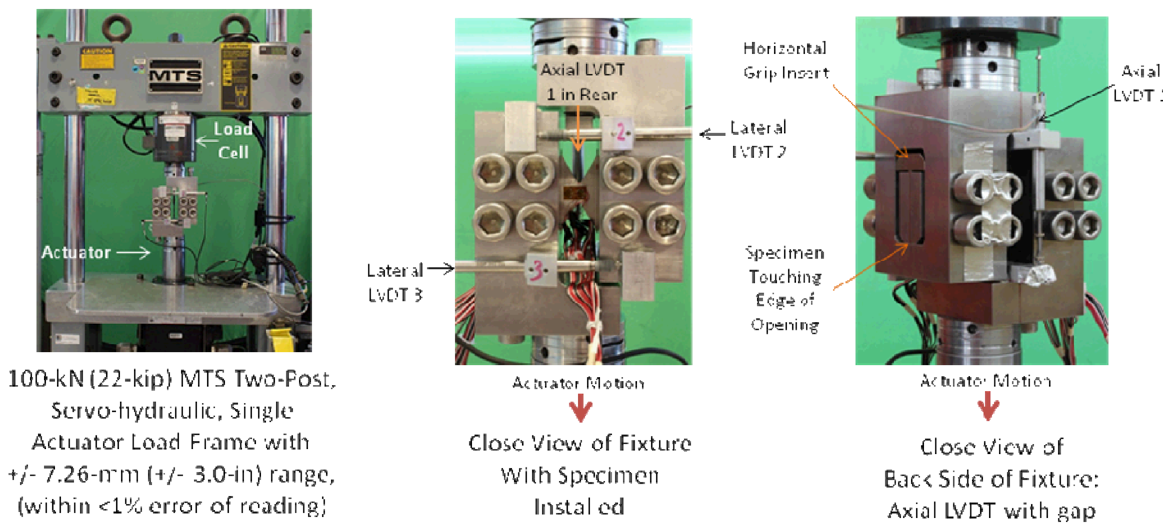


Photo D –Shear Test Setup

Strain gages were applied to the specimens to aide in calculating the shear stress and provide compliance data. The two types of strain gages utilized for the test were the 3.18mm rectangular rosette and stacked rosette. The strain gage information for each rosette is shown in **Appendix A**.

The strain gage configuration for VP2, VP3, VA1 and VA3 is shown below in **Photo E**. Stacked rosette strain gages from Micro-Measurements (Model CA2-06-125WW-350) were applied to the center of the V-notch specimens and to the left (relative to the front surface) of the center. The rosette gages on the front were paired with gages on the back. Horizontal and vertical surface scribe lines were added to the specimen surface for gage alignment.

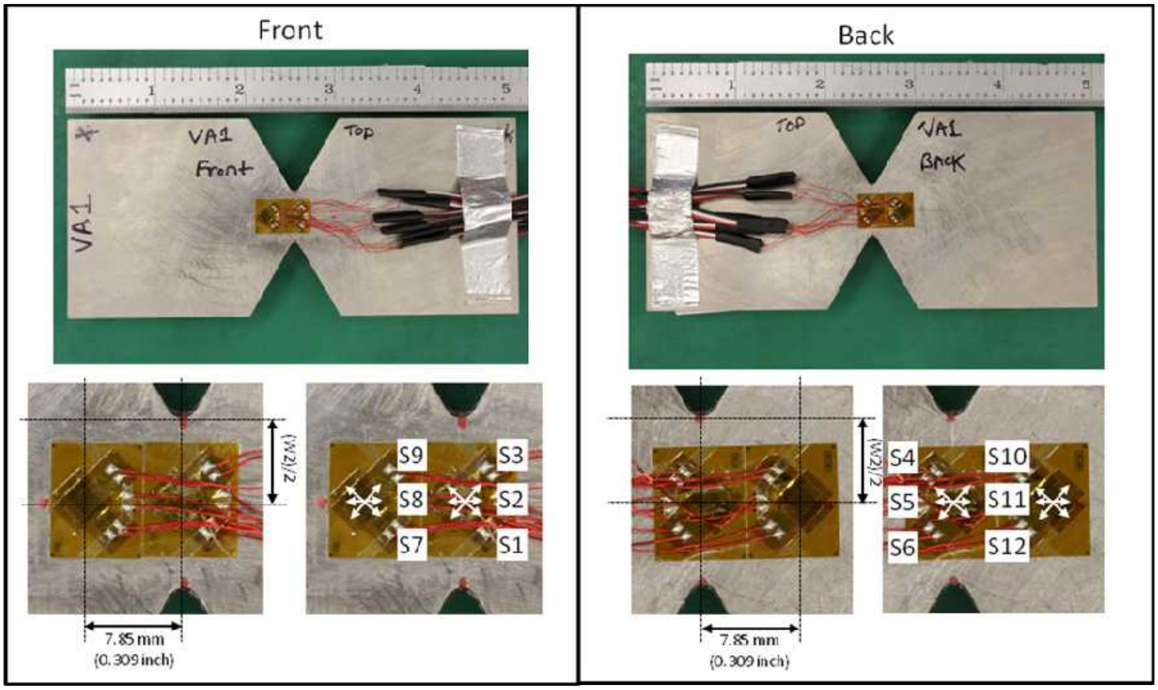


Photo E-Strain Gages for Specimens VP2, VP3, VA1, and VA3

The strain gage configuration for VP4, VP6, VA2 and VA4 are shown below in **Photo F**. Stacked rosette strain gages from Micro-Measurements (Model CA2-06-125WW-350) were applied to the center of the V-notch specimens. Rectangular rosette Strain Gages from Micro-Measurements (Model CA2-06-125LR-350) were applied to the left (relative to the front surface) of the center. The rosette gages on the front were paired with gages on the back. Horizontal and vertical surface scribe lines were added to the specimen surface for gage alignment.

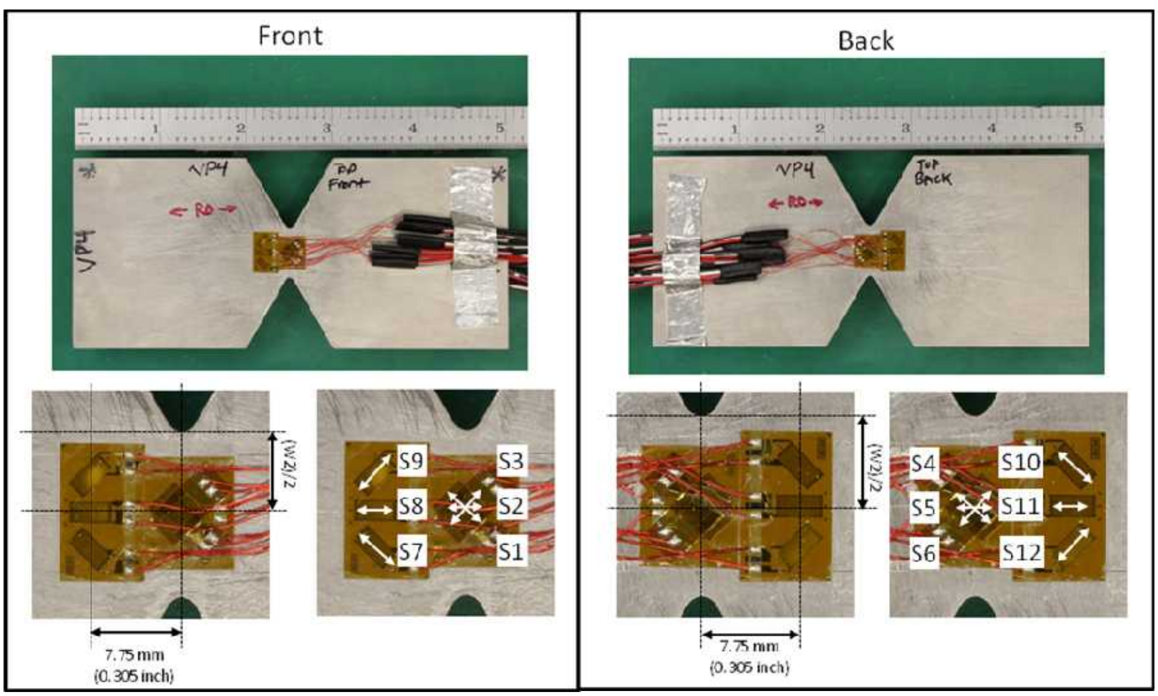


Photo F- Strain Gages for Specimens VP4, VP6, VA2 and VA4

Quasi-static loading of 0.0254 mm/s was applied to specimens VP2, VP6, VA1 & VA2. The faster rate loading of 2.54 mm/s was applied to specimens VP3, VP4, VA3 & VA4. The calculation for central engineering shear strain is based on an average of the front and back gages at 45-degrees, leading to a formula of [(S3+S4)-(S1+S6)]/2 for the stacked gage rosettes. Test data for the shear test is shown below in **Figures 7 and 8**. Figure 7 shows a plot of the shear stress versus central shear strain and Figure 8 shows a plot of the load versus axial LVDT displacement. In Figure 7b, data acquisition is missing for gages S7 through S12 on specimen VP2. Due to the large strain gage length relative to the plastic zone of the central shear area, the calculated engineering strain past yield does not reflect the actual engineering strain in the plastic zone. The estimated shear modulus in both of the plate rolling directions of the tested Ti-6Al-4V specimens is 44 GPa, which is consistent with literature values. The Axial LVDT 1 measurements in each test include contributions related to the compliance issues with the fixture and specimen slip in the grips. At 20 kN, the combined effects contribute ~0.27 mm to the axial LVDT 1 value. It is possible that these two factors can be taken into account by applying a first-order linear correction to this dataset so that the modulus matches the values shown in the strain-gage data. In **Appendix B,** an independent assessment using stiff plates of steel and Ti-6Al-4V was implemented to measure the effect from the compliance issues on the specimens. The data included in Appendix A offers another more detailed possibility to account for the effect of specimen slip and fixture compliance.

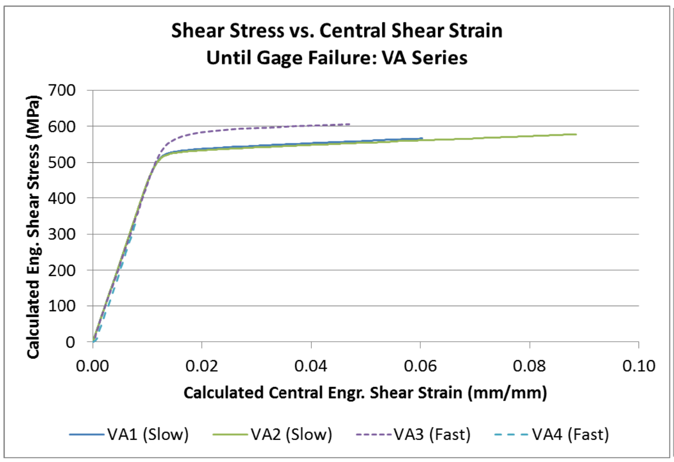


Figure 7a-VA Series Shear Stress vs Central Shear Strain

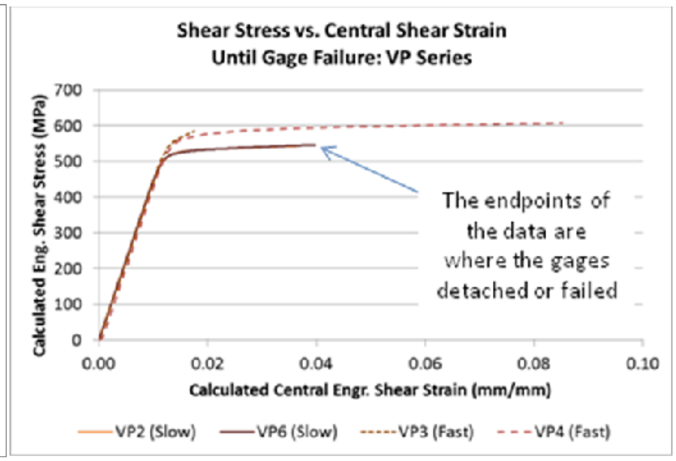


Figure 7b-VP Series Shear Stress vs Central Shear Strain

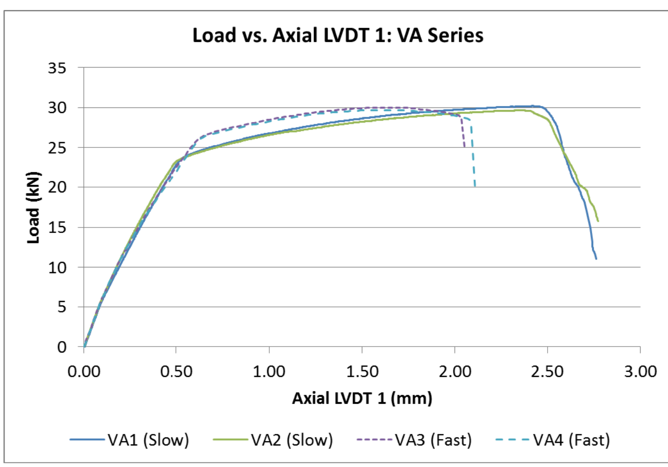


Figure 8a-VA Series Load vs Axial LVDT 1

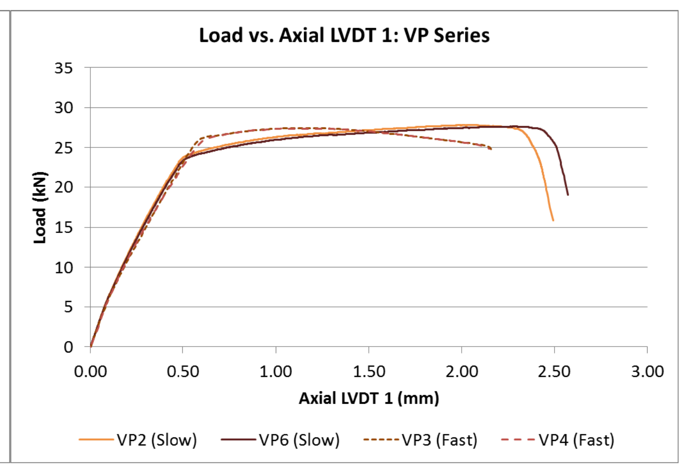


Figure 8b-VA Series Load vs Axial LVDT 1

Photos of the post tests for each specimen were documented and are shown below in **Photos G through J**. Cracks, in general, did not form at the original V-notch root, because the cracks do not align with the original surface scribe line that was used to mark the center of the specimen for strain gage alignment. It should be noted that the axial LVDT 1 data shows that there is little fixture rotation and there was no visible evidence of rotational galling on the grip surfaces of the specimen. So, these inclined failure surfaces are not due to large rotation of the specimen relative to the axial pull direction, but due to some other phenomena. All the specimens tested at the fast test rate show a noticeable inclined shear fracture, while the slow test rate specimens show either a jagged step type inclined fracture (VA1 and VA2) or a vertical shear fracture (VP2 and VP6). This would suggest that the direction of rolling in quasi-static loading has a impact on the type of fracture that will form.

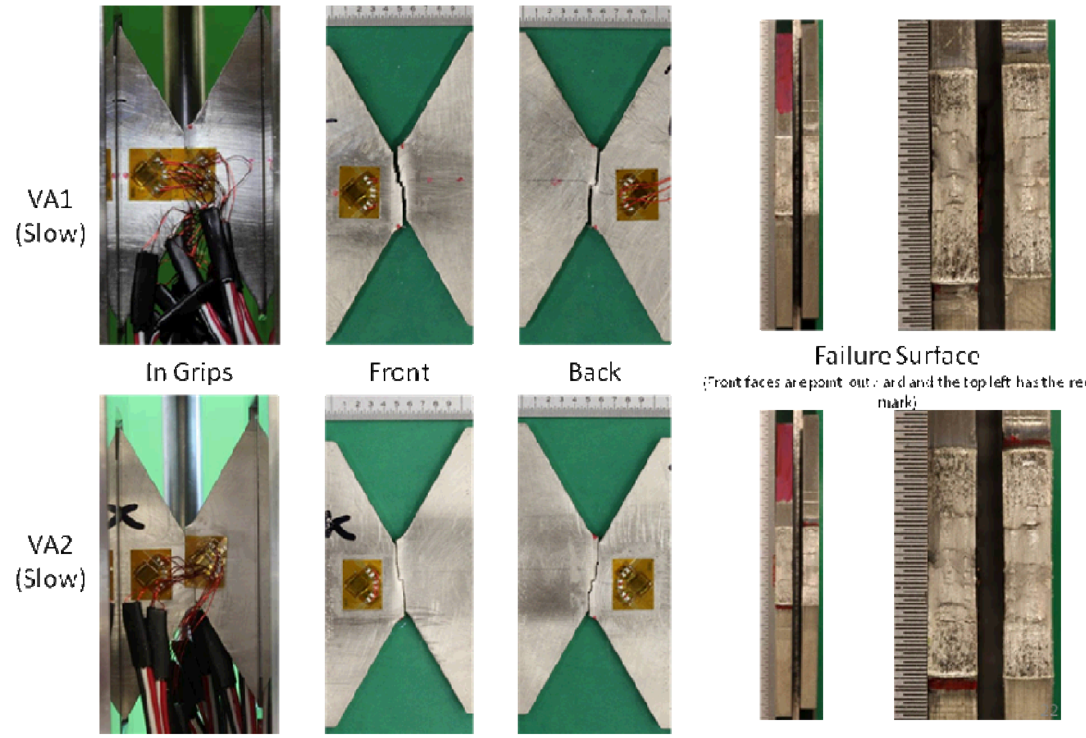


Photo G-Post-Test Specimens VA1 and VA2

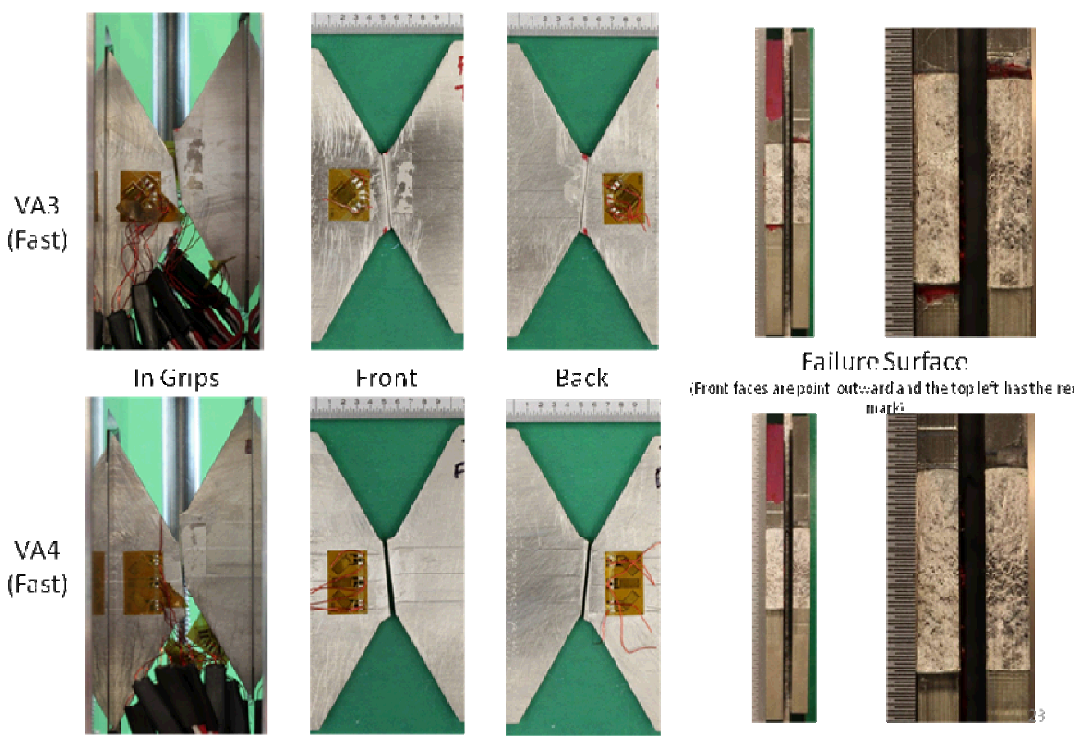


Photo H-Post-Test Specimens VA3 and VA4

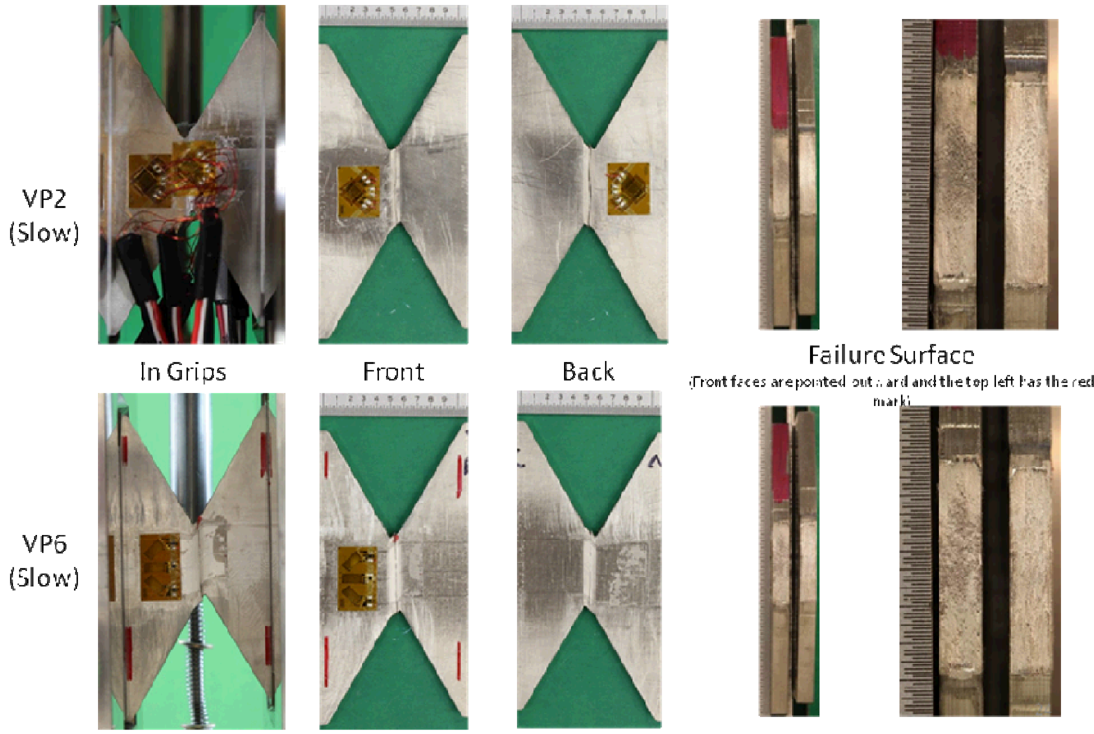


Photo I-Post-Test Specimens VP2 and VP6

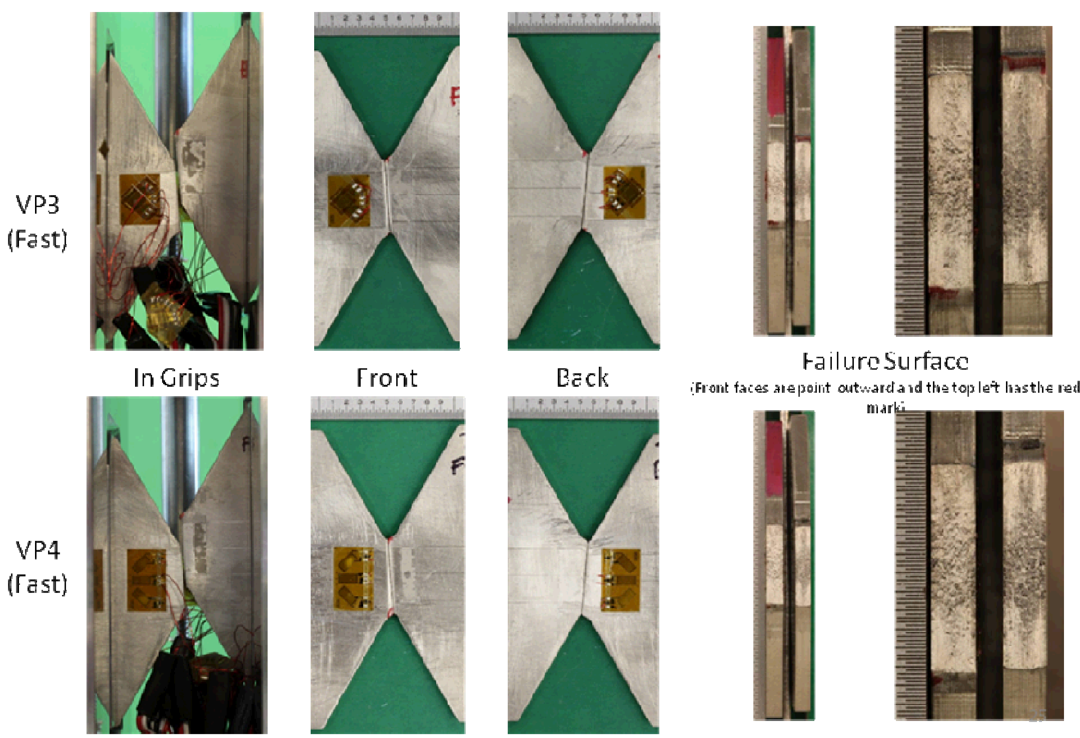


Photo J-Post-Test Specimens VP3 and VP4

Hardness Test

The average of 6 measurements from the Ti-6AL-4V plate for SFC2 was 36.1 HRC (Rockwell C) that is consistent with mill annealed Ti-6Al-4V.

Challenge Geometry Test

The challenge geometry is referred to as the "S-Shape" and thirty-two (32) specimens were fabricated for the test. SML will test a total of twenty specimens (20) and provide ten (10) specimens to the other independent testing lab to verify data and repeatability of the tests. Of the twenty specimens to be tested, ten specimens will be tested at the slow loading rate of 0.0254 mm/s and the other ten will be tested at the fast loading rate of 2.54 mm/s. The testing orientation is critical to achieve repeatability and is shown below in **Figure 9**. The orientation shown in Fig. 9 is considered the front side of the specimen.

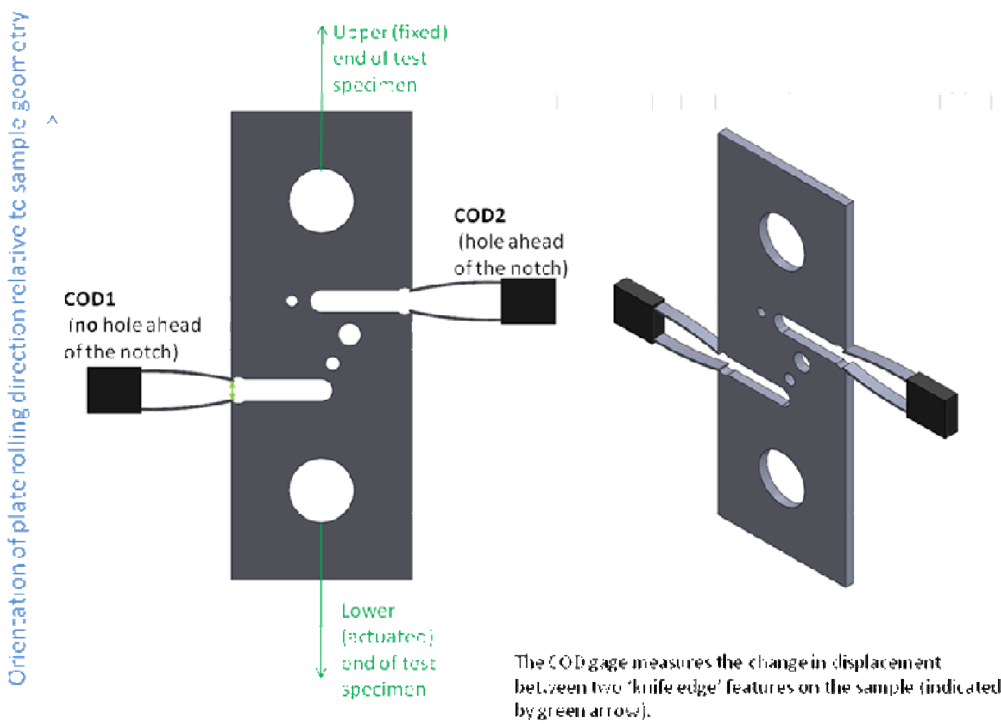


Figure 9-S-Shape Test Configuration

The fixturing for the test consists of clevis grips that are fabricated from 17-4PH stainless steel and manufactured in accordance with standard ASTM E 399. The grips were purchased from Materials Testing Technology (www.mttusa.net), model number ASTM.E0399.08. The clevis grip pin hole is 17.93 mm and has a flat bottom consistent with ASTM E399. The clevis grips are shown in **Photo K**.

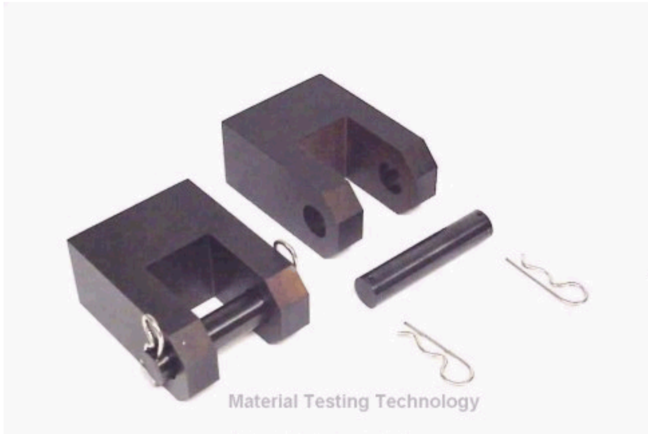


Photo K-Clevis Grips

The measurement devices used for the test consists of the 100 kN load cell and crack opening displacement (COD) gages. Because of the possible deformation characteristics of the geometry under loading and the high rate of loading, validation of the COD displacement data will be analyzed using fiducial images. These images will be analyzed in a computer vision software package (VIC 2D) to determine the relative change in distance between a pair of fiducials placed on either side of the two slots where COD1 and COD2 are located. For the slow rate test, the four (4) fiducials on the front side of the specimen are paired with fiducials on the back. Imaging for this test will be captured using two Point Grey Grasshopper digital cameras. The high rate load tests will only utilize the fiducials on the front side and capture high speed images with the high-speed Phantom 611 camera.

S-Shape testing is currently undergoing a compliance evaluation with the clevis grips. There appears to be some fabrication compliance issues with the two pin holes. The twenty tests are anticipated to be completed by the beginning of October.

Issuance of the Challenge

The SFC2 was issued to participants on May 30, 2014 via a MS PowerPoint e-mail invitation with supplemental information regarding the shear test issued on 8/14/2014 via a MS PowerPoint e-mail. The deadline for submission of the predictions and answers for the six questions is 10/01/2014.

Included in the SFC2 was detailed information and data for calibrating the computational models. This data included detailed tensile and shear test data along with compliance data generated for the shear tests.

The challenge questions to be addressed by the participants are as follows:
For each of the two loading rates, please predict the following outcomes:
Question 1: Report the force at following COD displacements:
COD1= 1-mm, 2-mm, and 3-mm. (COD1 and COD2 are defined on slide 7)
Note: COD1 and COD2 = 0 at the start of the test; the COD values refer to the change in length from the beginning of the test.
Question 2: Report the peak force of the test.
Question 3: Report the COD1 and COD2 values after peak force when the force has dropped by 10% (to 90% of the peak value).
Question 4: Report the COD1 and COD2 values after peak force when the force has dropped by 70% (to 30% of the peak value).
Question 5: Report the crack path (see slide 9 for examples on how to report crack path)

Question 6: Report the expected force-COD1 and force-COD2 curves as two separate ASCII data files with column 1 as force (in N) and column 2 as COD (in mm).

Conclusions

The 2014 Sandia Fracture Challenge (SFC2) was issued under the FY14 WSEAT X-Prize as a double blind study to challenge the computational and material mechanics communities to develop better capabilities in modeling and experimentation to predict the failure in ductile metals. The intent of the FY14 X-Prize was to issue a metallic alloy "challenge geometry" that exhibits a moderate strain-rate ductile fracture. The SFC2 was issued on May 30, 2014.

This year's challenge expanded on the availability of calibration data by the inclusion of the V-notch shear test. The development of the shear test methodology proved to be very revealing and educational for the experimental team. The test challenged the team on the fundamental methods of test development to ensure the quality of the test produces relevant and meaningful data. Extensive research into the data resulted in modifications to the test to more accurately resolve compliance issues experienced in the test.

By the beginning of October, the computational modeling participants will have submitted there models and answers to the challenge questions. In addition, the testing of the challenge geometry will be complete, allowing the other independent testing lab (Material Mechanics Lab) to conduct validation experiments while the Structural Mechanics Lab (SML) performs data reduction and assessments. In November, both SML and MML will assess the computational model predictions against the experimental data. A formal paper will be issued in FY15 documenting the SFC2 and related re-evaluation to better develop the modeling and experimentation methods used to predict the failure in ductile metals.

Recommendations and Future Work

FY15 X-Prize project will not issue a modeling challenge, but will focus on completing the FY14 Challenge, re-evaluating experimental testing methodologies and modeling inconsistencies for overall improvements. The project scope will consists of: 1) Complete the FY14 X-Prize Challenge – Evaluate results 2) Re-evaluate/identify areas of strength and weakness for ductile failure predictive capability to aide in developing a FY16 Challenge. FY15 X-Prize will improve our understanding of the experimental methodologies and capabilities applied to ductile factures, as well as, investigating best practices for computational modeling to allow advancements in predictive modeling. These modeling methods would benefit from more extensive calibration data beyond traditional material property tests. The prior SFC identified the need for a suite of test geometries spanning different degrees of stress concentrations, stress state, mode mixity, post-necking behavior, etc. that could be useful to calibrate models prior to using them on an 'unknown' problem.

Appendix A -Additional Details of Shear Test Method

Shear Failure Calibration Test Procedure

1. **Lateral Grip LVDT Alignment Measurements**: With no specimen in place before each test, the actuator is moved through the range of displacement of the test to measure the no-load alignment of the lateral LVDTs. These LVDTs do have some slight misalignment with the vertical motion due to mounting alignment and roughness of the reference blocks (see slide 16). These lateral misalignments are on the order of 0.025-0.050 mm (0.001-0.002 inch) over 2.5-mm (0.1-inch) of vertical actuator motion. [Note: This step was not performed before each specimen, but sporadically through the test series.]
2. **Specimen Installation**
   a. Place specimen between grip inserts without tightening bolts.
   b. Set electrical zero offset on strain gages when in this zero-load condition.
   c. Torque the four right front face bolts on the vertical grip inserts up to 67.8 N-m (50 ft-lbs) each in a pattern such that the strain gage values do not rise above 100 micro-strain on any particular gage (note: the right rear grip insert and bolts had been set with a gage block for parallelism and is not adjusted during the test series – see tape over these bolts in image on slide 20). The bottom edge (L4) is touching the bottom horizontal edge of the opening of the upper fixture.
   d. Set electrical zero on strain gages with right grip engaged.
   e. Adjust the vertical alignment of the left (lower) grip relative to the right (upper) such that there is no load on the specimen, but the top left of the specimen (L1) is in contact with the top of the opening of the left grip.
   f. Slowly finger-tighten the eight bolts of the left grip inserts using a guideline that the strain gage values do not rise above 100 micro-strain on any particular gage. Place the fixture in load control to zero load.
   g. Slowly torque the eight bolts of the left grip inserts up to 67.8 N-m (50 ft-lbs) each in a pattern using a guideline that the strain gage values do not rise above 100 micro-strain on any particular gage, adjusting the rotational alignment of the bottom actuator to minimize the rotational bending of the specimen. This procedure overall helps to minimize twisting and bending of the specimen and the grips. [Note: The bolt torque value of 67.8 N-m (50 ft-lbs) each is a practical limit discovered through trial-and-error. Greater than that led to uncontrolled specimen bending and fixture rotation during specimen installation.]
   h. Hand-tighten vertical bolt that places the horizontal grip insert snugly against the edge of the specimen on each side of the grips. This should not affect the strain gage values.
3. **Pre-test Alignment Check (i.e. "Response" Procedure)**: With specimen installed, precycle the actuator in a sinusoidal motion from +/- 4.448 kN (+/-1000 lbs) at a rate of 0.1 Hz for three cycles to determine if the strain gages are behaving linearly through this initial elastic region. If they are not, then the specimen installation must be repeated to reduce the twist and bending in the specimen (note: this re-installation was not required on any specimen.) For some specimens, a second response cycle set was performed from 0 to 4.448 kN (1000 lbs) at a rate of 0.1 Hz for three cycles .
4. **Test to Failure**
   a. Reset electrical zero for the LVDTs and strain gages prior to the start of the test and record the offset values.
   b. Precycle actuator from 0 to 4.448 kN (1000 lbs) at a rate of 0.1 Hz for three cycles.
   c. After the 0 to 4.448-kN precycles, hold the load at zero before operator selects a button to begin the monotonic pull to failure.

d. After the operator command, pull to failure at a nominal rate of 0.0254 mm/s (0.001 in/s) or 25.4 mm/s (1.0 in/s) under load frame actuator stroke control. (Note: Due to the servo-hydraulic control nature of the load frame with these grips, the faster rate tests did not achieve a constant 25.4 mm/s (1.0 in/s) rate, but all pull rates were close to the goal over the course of each test. Modelers are advised to check the actuator stroke velocity history for each fast rate test to apply the appropriate displacement boundary condition.)

Pre-test Geometry and Experimental Measurements

1. Pre-test Geometry Measurements (mm & in)
2. Strain Gage Electrical Offsets after Right Grip Engaged on Specimen (micro-strain)
3. Segment Count (different loading, unloading, and hold segments of the load-frame command)
4. Test Time (s)
5. Actuator Stroke (mm & in)
6. Axial LVDT 1 (mm & in)
7. Lateral LVDT 2 (mm & in)
8. Lateral LVDT 3 (mm & in)
9. Load (N & kip)
10. Strain Gages 1-12 (micro-strain)

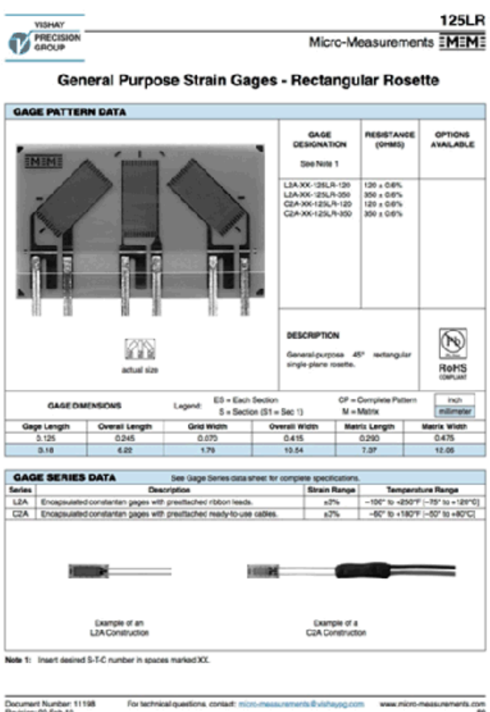
Calculated Measurements – For V-notch specimens only:

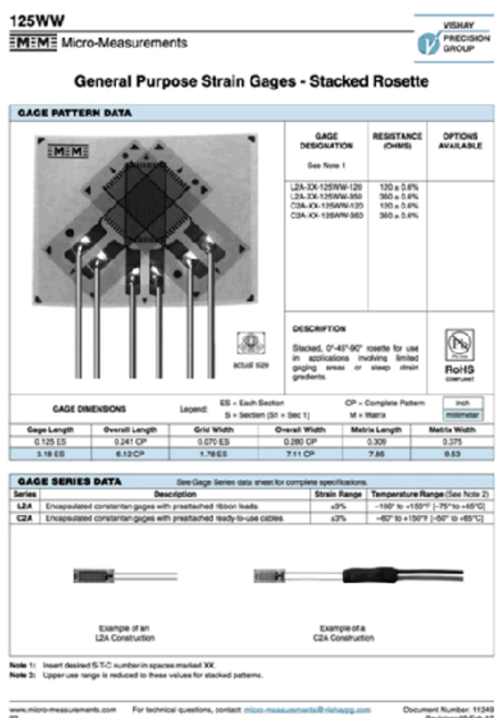
1. Average Center Shear Strain Over 3.18-mm (0.125-inch) Gage Length (micro-strain)
2. Nominal Engineering Shear Stress (MPa & ksi)
3. Axial LVDT 1 Displacement with Suggested Specimen Slip Removal (mm & in)
4. Instantaneous Stroke Velocity (mm/s & in/s)

Data Sets for Each Specimen:

1. Fixture Alignment Check with No Specimen Installed (if completed)
2. Responses – Cyclic Loading in Elastic Region (+/-4.448-kN and 0 to 4.448-kN type)
3. 0 to 4.448-kN Precycles and Monotonic Loading to Failure

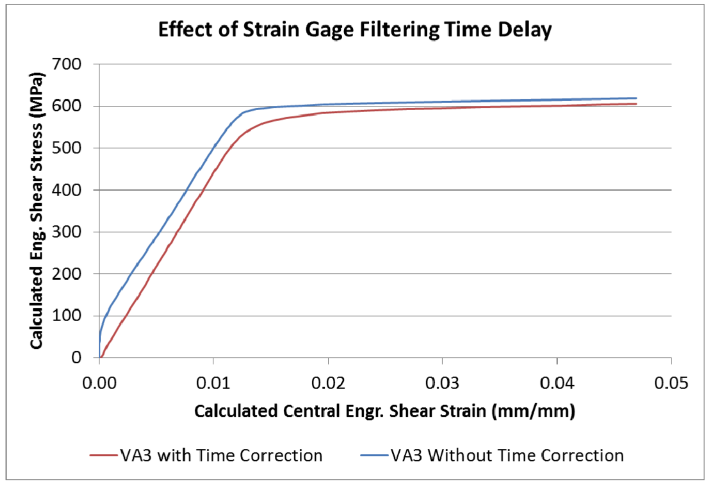
Strain Gage Cutsheets





Rectangular Rosette Model: CA2-06-125LR-350 & Stacked Rosette Model: CA2-06-125WW-350

Data Acquisition Filtering for Specimen VA3 and VP3: The filtering on the strain gage amplifier boxes and in the MTS FlexTest DAQ system resulted in delayed strain signals estimated to be 3.8 ms for S1-6 and 5.1 ms for S7-12 for specimen VA3 and VP3, with a range of +/- 0.5ms, due to a Butterworth-type filtering in the system. This filtering was compensated for in the test data by shifting the strain signals relative to the other data signals. This shift could only be done in increments for 0.488 ms (2048 Hz), which is the time interval between lines of data. Therefore, the applied time shift was 3.90 ms for S1-6 and 5.37 ms for S7-12 for specimen VA3 and VP3. This filtering setup was changed for specimens VA4 and VP4, so these strain values did not exhibit a time delay relative to the other data and therefore is reported without any time shift. *The time shift correction for specimens VA3 and VP3 aligns the data with specimen VA4 and VP4. Without the time correction, the initial elastic response would appear significantly incorrect, giving credence to the correction.*

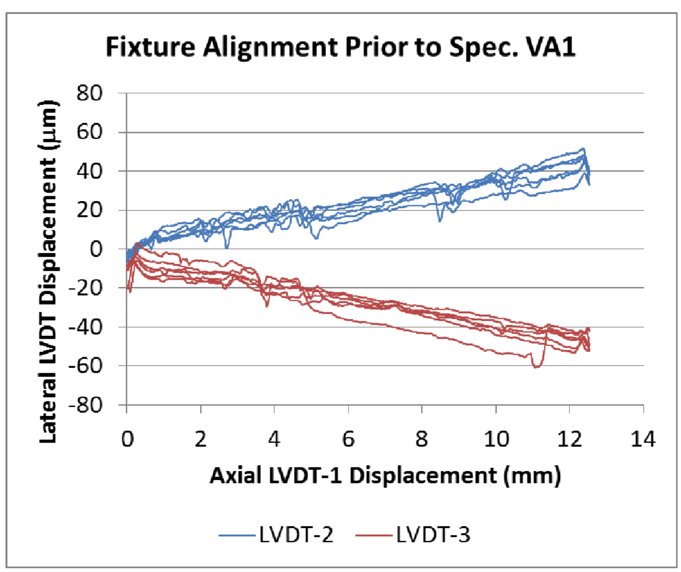


Strain Gage Factor:
During the test series, the strain gage factor (essential a gain factor on the strain gage amplifier) was set to 2.0, even though these values ranged from 2.08 to 2.16 for the actual gages. The original strain gage data required adjustment to compensate for the incorrect strain gage factor. This was accomplished by multiplying the recorded strain gage value by a ratio of (2.0/[Actual Strain Gage Factor]). *All of the strain gage values reported have been corrected already.*

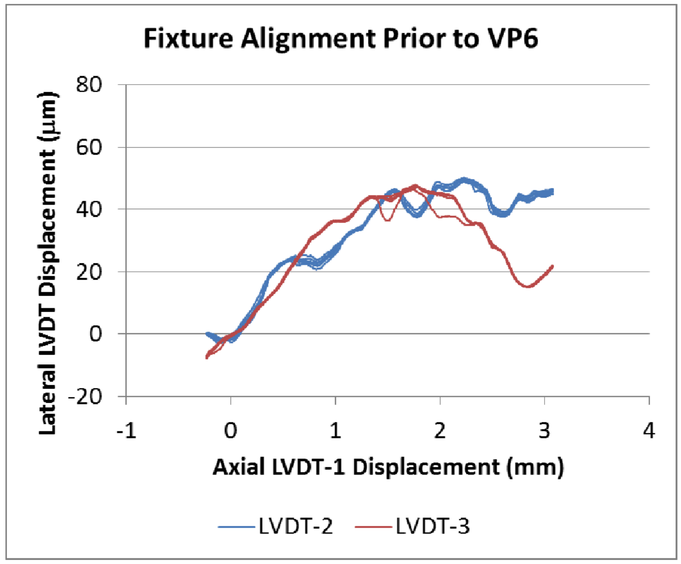
<u>LVDT Considerations: Nonlinearities and Alignment on Fixture</u>

LVDT Nonlinearities: LVDTs are inherently nonlinear measurement devices, but with highly repeatable behavior over their measurement range. These are calibrated against a known calibration micrometer. The errors are on the order of +/-1% of measurement for the Axial LVDT and +/-0.1% of measurement for the lateral LVDTs. Electrical Offsets for each run are provided to determine which portion of the range was used in each run.

Alignment on Fixture: During the shear tests, the lateral LVDTs travel transverse to their measurement direction, so parallelism of the lateral LVDT mounts is an error source. The lateral LVDT mounts were adhered to the outer surface of the fixture using dental cement without a determinate perpendicular mounting surface, and the surfaces of the blocks were not ground smooth. Parallelism of the lateral LVDT mounts was difficult to achieve, and the nature of this alignment could vary through the test series due to the lateral compliance of the fixture. The combination of this variation and the surface roughness of the mounts is on the order of 50



micrometers in LVDT 2 and 3 values over 6-mm of vertical travel, as seen in two no-specimen fixture alignment runs to the right.



Recommendation – Lateral LVDTs: During the shear tests, LVDT2 and LVDT3 were used to record any unintended parasitic rotation of the grips due to load frame torsional and lateral compliance. The values of these measurements were confirmed to be relatively small (LVDT2 or LVDT3 typically changed by 50 micrometers during the course of a 30 kN and 2-mm vertical travel shear tests). These values are provided in the raw data files. The error due to the fixture alignment in these shear tests are on the order of the measurements; thus*, modelers are cautioned from using LVDT 2 and 3 measurements as a lateral boundary condition, but rather use them as qualitative confirmation of the minimal grip rotation during the shear tests.* On the other hand, during the lateral fixture compliance test, there was no vertical motion of the grips; therefore, the predominant error source for the lateral fixture compliance test is the inherent nonlinearity of the lateral LVDT. *Modelers may use the lateral LVDT data for the lateral fixture compliance test since the inherent measurement error of these LVDTs is small.*

Recommendation – Axial LVDT: The axial LVDT error is small relative to the range of the axial measurements; therefore, *the axial LVDT measurements can be used as a boundary condition measurement, assuming that specimen slip and fixture compliance is accounted for.*

MTS Systems Corporation
14000 Technology Drive
Eden Prairie, MN 55344-2290

Calibration Report

 CALIBRATION CERT #1145.01

Customer Name: Sandia National Labs | Report Number: 2511-1789
System: 931.13 | Site: 507350
System ID: S559752 | Location: 126 Lab | Country Code: US

Equipment
Device Type: Force | Model: 661.21A-03 | Serial No.: 5204_(FT)
Controller/Conditioner Model: 493.25 DC | Serial No.: Slot 4-3 J6
Readout Device Model: 493.10 | Serial No.: 02010206F | Channel: Axial

Procedure
MTS Procedure: FS-CA 2122 Rev. C | ACS Version: 8.4
Calibration has been performed in accordance with: ASTM E4-13
Method of Verification: Set-the-Force Method using Elastic Calibration Devices

Calibration Equipment Asset No.
Dead Weight Set: | HighLevel Board: | LowLevel Board: | Standard Asset No.: 12559
DW Compensation: | DMM: 16994 | Digital Indicator: 16708 | Lower Limit: .4 kip
Temperature Readout: 15514 | Additional Equipment: | Standardizer: 16679

Conditions
Ambient Temperature: 71.80 °F | Polarity(+): Tension | Bidirectional: | Cable Length: 25 Feet

In Tolerance X | **As Found:** X | **Tolerance: +/-1.0% of Applied Force**
Out of Tolerance | **As Adjusted:** | **As Found System Condition: Good**

Conditioner Parameters
Excitation: 7.0000 | Delta K: | Zero Offset: 0.0000 | Multiplier: | Cal Res: kohms
Shunt Cal: Positive: | Negative: | Range Gain: | PreAmp Gain: 480 | Post Amp/FineGain: 1.11969 | Polarity: Normal

Calibration Data **Range:** 1
Compression **Resolution:** 0.00025 **Full Scale:** 22.5
Report Units: kip

Applied	Series 1		Series 1 Errors				Series 2		Series 2 Errors				Repeatability	
Percent of Full Scale Force	Indicated Reading Ascending	Indicated Reading Descending	Units Error Asc	Percent Error Asc	Units Error Desc	Percent Error Desc	Indicated Reading Ascending	Indicated Reading Descending	Units Error Asc	Percent Error Asc	Units Error Desc	Percent Error Desc	Percent Error Asc	Percent Error Desc
0	0.0000	0.0008	0.0000	0.00	0.0008	0.00	0.0000	0.0008	0.0000	0.00	0.0008	0.00	0.00	0.00
-2.5	-0.5644		0.0019	0.34			-0.5644		0.0019	0.34			0.00	
-5	-1.1280		0.0030	0.27			-1.1276		0.0026	0.23			0.04	
-7.5	-1.6898		0.0023	0.14			-1.6895		0.0020	0.12			0.02	
-10	-2.2523		0.0023	0.10			-2.2518		0.0018	0.08			0.02	
-25	-5.6262		0.0012	0.02			-5.6255		0.0005	0.01			0.01	
-50	-11.2500		0.0000	0.00			-11.2490		0.0010	-0.01			0.01	
-75	-16.8730		0.0020	-0.01			-16.8730		0.0020	-0.01			0.00	
-100	-22.5010		0.0010	0.00			-22.5010		0.0010	0.00			0.00	

Tension **Range:** 1
Report Units: kip

Applied	Series 1		Series 1 Errors				Series 2		Series 2 Errors				Repeatability	
Percent of Full Scale Force	Indicated Reading Ascending	Indicated Reading Descending	Units Error Asc	Percent Error Asc	Units Error Desc	Percent Error Desc	Indicated Reading Ascending	Indicated Reading Descending	Units Error Asc	Percent Error Asc	Units Error Desc	Percent Error Desc	Percent Error Asc	Percent Error Desc
0	0.0000	0.0000	0.0000	0.00	0.0000	0.00	0.0000	0.0000	0.0000	0.00	0.0000	0.00	0.00	0.00
2.5	0.5639		0.0014	0.25			0.5639		0.0014	0.25			0.00	
5	1.1274		0.0024	0.21			1.1270		0.0020	0.18			0.04	
7.5	1.6897		0.0022	0.13			1.6893		0.0018	0.11			0.02	
10	2.2515		0.0015	0.07			2.2512		0.0012	0.05			0.01	
25	5.6256		0.0006	0.01			5.6256		0.0006	0.01			0.00	
50	11.2530		0.0030	0.03			11.2540		0.0040	0.04			0.01	
75	16.8830		0.0080	0.05			16.8830		0.0080	0.05			0.00	
100	22.5080		0.0080	0.04			22.5090		0.0090	0.04			0.00	

Errors at Zero are computed in % of Range.
Uncertainty of the data supplied is equal to or less than ±0.25% of reading for a confidence level of 95%.
This report shall not be reproduced except in full, without the written approval of the laboratory.
Calibrations are performed with standards whose values and measurements are traceable to the National Institute of Standards and Technology.
American Association of Laboratory Accreditation Certificate Number: 1145.01

Out of Tolerance in % column

Notes: Customer is aware of .25% Uncertainty and is OK with special 1 % data point in Compression.

Performed By: Brad R. Schroenghamer | Field Service Engineer | Date: 9-Jul-13

Signature: Brad R. Schroenghamer | Next Customer Agreed Upon Calibration Date: 9-Jul-14 | ACSRepRevAJ

Load Cell Calibration Report

MTS Systems Corporation
14000 Technology Drive
Eden Prairie, MN 55344-2290

Calibration Report

Page: 2 of 3 CALIBRATION CERT #1145.01

Customer Name: Sandia National Labs | Report Number: 2511-1788
System: 931.13 | Site: 507350
System ID: S559752 | Location: 126 Lab | Country Code: US

Equipment
Device Type: Length | Model: ACTUATOR_LVDT | Serial No.: 263_(FT)
Controller/Conditioner Model: 493.25 AC | Serial No.: Slot 4-2
Readout Device Model: 493.10 | Serial No.: 02010206F | Channel: 22 kIP

Procedure
MTS Procedure: FS-CA 2124 Rev. C | ACS Version: 8.4
Calibration has been performed in accordance with: ASTM E2309/E2309M-05(2011)
Method of Verification:

Calibration Equipment Asset No.
Dead Weight Set: | HighLevel Board: | LowLevel Board: | Standard Asset No.: 20506
DW Compensation: | DMM: 16994 | Digital Indicator: | Lower Limit:
Temperature Readout: 15514 | Additional Equipment: | Standardizer:

Conditions
Ambient Temperature: 73.90 °F | Polarity(+): Retraction | Bidirectional: | Cable Length: 30 Feet

In Tolerance X | **As Found:** X | **ASTM E2309 Classification: B >=10% of Range, B <10% of Range**
Out of Tolerance | **As Adjusted:** | **As Found System Condition: Good**

Conditioner Parameters
Excitation: 5.0000 | Delta K: | Zero Offset: 0.0000 | Multiplier: | Phase: 45.78097
Cal Factor: Positive: | Negative: | Range Gain: | PreAmp Gain: 2 | Post Amp/FineGain: 1.09369 | Polarity: Normal

Calibration Data Range: 1
Extension Resolution: 0.00005 | Full Scale: 6
Report Units: inch | 0.0000

Applied Percent of Full Scale Length	Series 1 Indicated Reading Ascending	Series 1 Indicated Reading Descending	Series 1 Errors Units Error Asc	Series 1 Errors Percent Error Asc	Series 1 Errors Units Error Desc	Series 1 Errors Percent Error Desc	Series 2 Indicated Reading Ascending	Series 2 Indicated Reading Descending	Series 2 Errors Units Error Asc	Series 2 Errors Percent Error Asc	Series 2 Errors Units Error Desc	Series 2 Errors Percent Error Desc	Repeatability Percent Error Asc	Repeatability Percent Error Desc
0	0.00000	-0.00030	0.00000	0.00	0.00030	-0.01	0.00000	-0.00020	0.00000	0.00	0.00020	0.00	0.00	0.00
-1	-0.06040		0.00040	0.67			-0.06031		0.00031	0.52			0.15	
-2.5	-0.15040		0.00040	0.27			-0.15031		0.00031	0.21			0.06	
-5	-0.30040		0.00040	0.13			-0.30031		0.00031	0.10			0.03	
-7.5	-0.45080		0.00080	0.18			-0.45071		0.00071	0.16			0.02	
-10	-0.60170		0.00170	0.28			-0.60161		0.00161	0.27			0.02	
-25	-1.49540		0.00460	-0.31			-1.49540		0.00460	-0.31			0.00	
-50	-3.01310		0.01310	0.44			-3.01280		0.01280	0.43			0.01	
-55	-3.29240		0.00760	-0.23			-3.29220		0.00780	-0.24			0.01	

Retraction Range: 1
Report Units: inch

Applied Percent of Full Scale Length	Series 1 Indicated Reading Ascending	Series 1 Indicated Reading Descending	Series 1 Errors Units Error Asc	Series 1 Errors Percent Error Asc	Series 1 Errors Units Error Desc	Series 1 Errors Percent Error Desc	Series 2 Indicated Reading Ascending	Series 2 Indicated Reading Descending	Series 2 Errors Units Error Asc	Series 2 Errors Percent Error Asc	Series 2 Errors Units Error Desc	Series 2 Errors Percent Error Desc	Repeatability Percent Error Asc	Repeatability Percent Error Desc
0	0.00000	-0.00009	0.00000	0.00	0.00009	0.00	0.00000	-0.00019	0.00000	0.00	0.00019	0.00	0.00	0.00
1	0.05991		0.00009	-0.15			0.06001		0.00001	0.02			0.17	
2.5	0.15012		0.00012	0.08			0.15021		0.00021	0.14			0.06	
5	0.30112		0.00112	0.37			0.30112		0.00112	0.37			0.00	
7.5	0.45273		0.00273	0.61			0.45274		0.00274	0.61			0.00	
10	0.60395		0.00395	0.66			0.60395		0.00395	0.66			0.00	
25	1.50450		0.00450	0.30			1.50450		0.00450	0.30			0.00	
50	3.01840		0.01840	0.61			3.01810		0.01810	0.60			0.01	
55	3.30730		0.00730	0.22			3.30700		0.00700	0.21			0.01	

Errors at Zero are computed in % of Range.
Uncertainty of the calibration data supplied is equal to or less than the greater of, ±0.25% of reading or ±50μ inches, for a confidence level of 95%. | Out of Tolerance in % column
This report shall not be reproduced except in full, without the written approval of the laboratory.
Calibrations are performed with standards whose values and measurements are traceable to the National Institute of Standards and Technology.
American Association of Laboratory Accreditation Certificate Number: 1145.01

Notes:

Performed By: Brad R. Schroenghamer | Field Service Engineer | Date: 9-Jul-13

Signature: | Next Customer Agreed Upon Calibration Date: 9-Jul-14 | ACSRepRevAJ

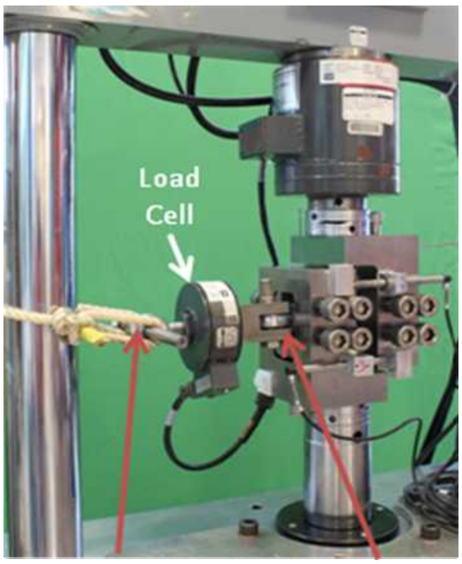
Actuator Stroke Calibration Report

Appendix B –Assessment of Shear Fixture Compliance

Shear Fixture Lateral Compliance Test

Setup: A 2.224-kN (0.50-kip) load cell was attached to a manual pull rod and a clevis. The clevis was attached to a rod end bearing gripped in one half of the fixture. The manual pull rod allowed the operator to apply a lateral load to each half of the fixture to measure the lateral displacements of fixture. The lateral stiffness of the upper fixture (attached to the stationary part of the load frame) is greater than the lower fixture (attached to the actuator). The upper fixture has more rotation for a given load than the lower fixture as seem in the difference between LVDT 2 and LVDT 3.

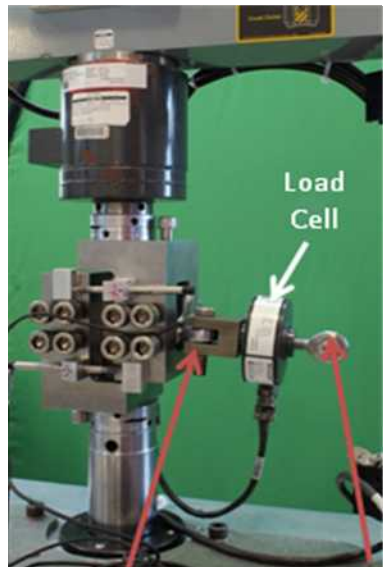
Setup for Lower Fixture



Rod for Manual Application of Lateral Load

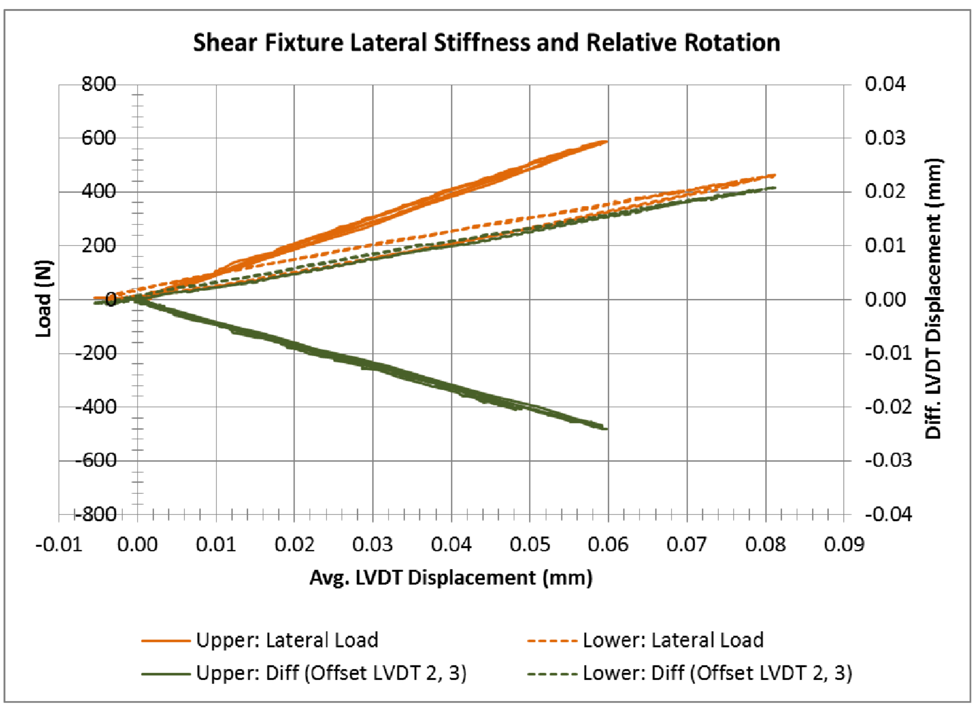
Gripped Rod End Bearing and Clevis

Setup for Upper Fixture

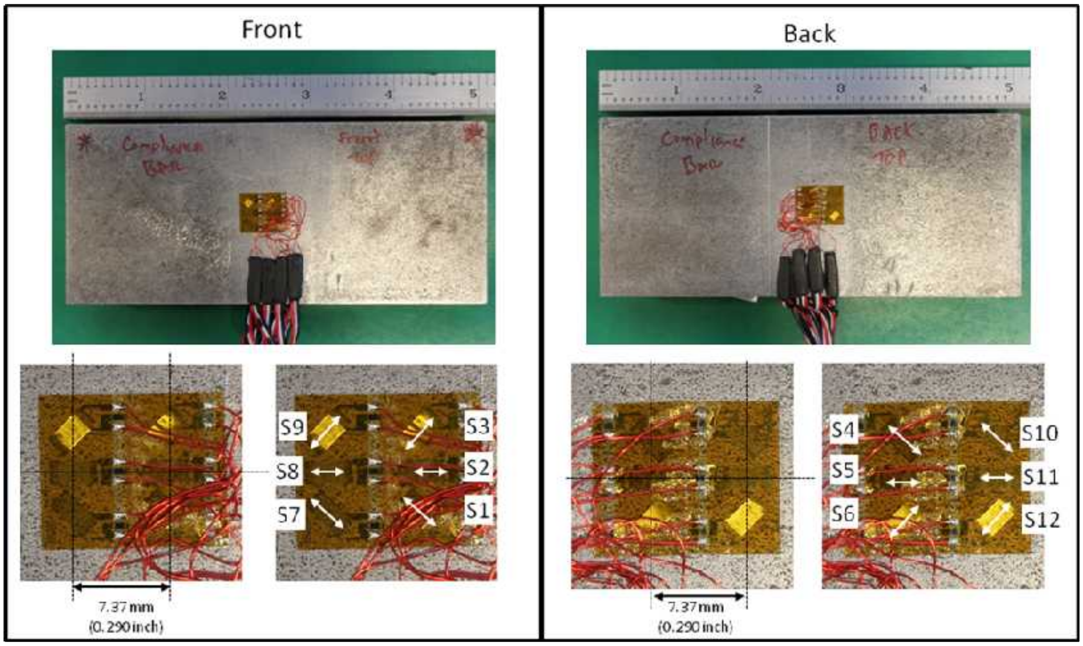


Gripped Rod End Bearing and Clevis

Rod for Manual Application of Lateral Load

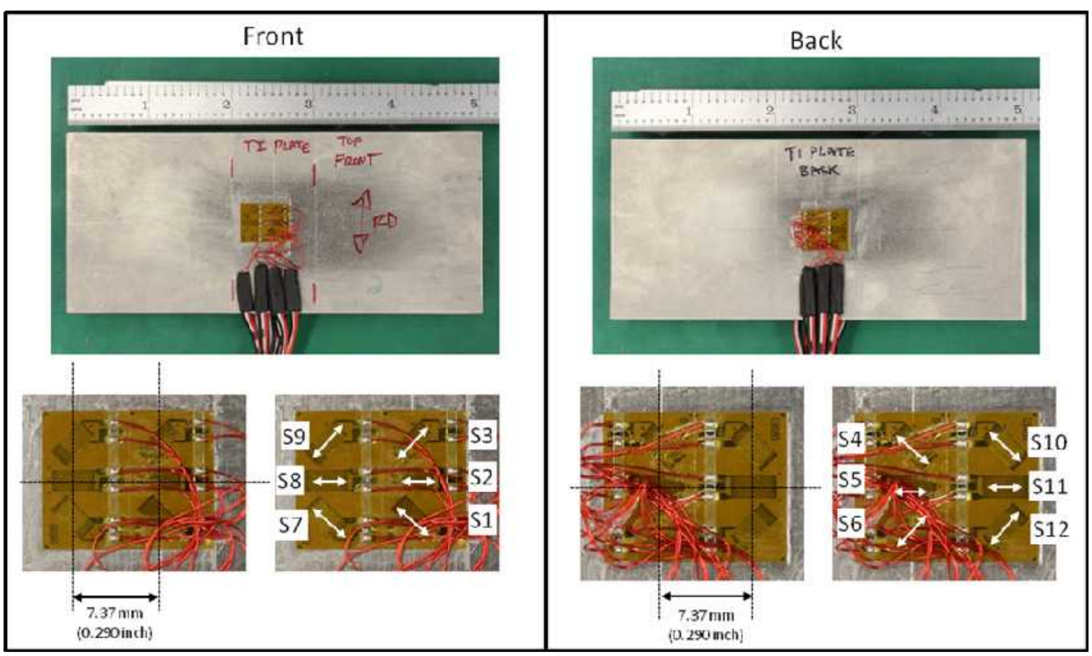


Shear Fixture Compliance Tests - Strain Gages for Alloy Steel Plate



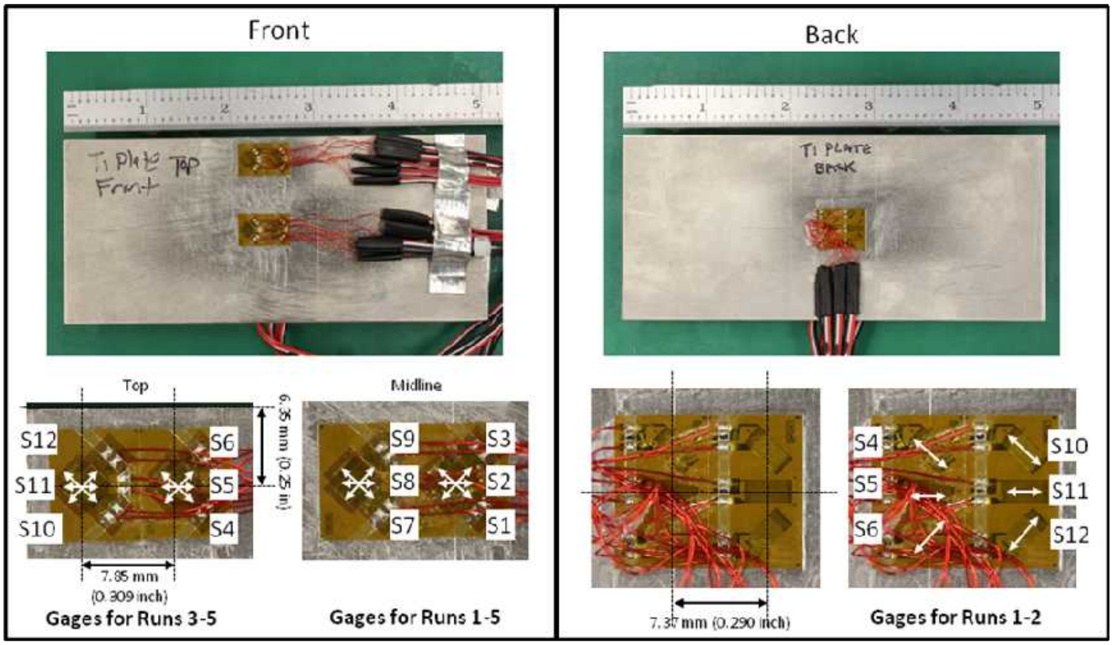
Adjacent strain gages from Micro-Measurements (Model CA2-06-125LR-350), with gage length 3.18 mm (0.125 inch), were applied in the center and to the left (relative to the front surface) of the center, with gages S2, S5, S8, and S11 aligned with the centerline of the plate. The gages on the front were paired with gages on the back.

Shear Fixture Compliance Tests - Strain Gages for Ti-6Al-4V Plate Series 1



Adjacent strain gages from Micro-Measurements (Model CA2-06-125LR-350), with gage length 3.18 mm (0.125 inch), were applied in the center and to the left (relative to the front surface) of the center, with gages S2, S5, S8, and S11 aligned with the centerline of the plate. The gages on the front were paired with gages on the back. The rolling direction of the plate is perpendicular to the long side of the plate like the VA-series specimens.

Shear Fixture Compliance Tests - Strain Gages for Ti-6Al-4V Plate Series 2



On the front face of the plate, stacked rosette strain gages from Micro-Measurements (Model CA2-06-125WW-350), with gage length 3.18 mm (0.125 inch), were applied to the center and to the left (relative to the front surface) of the center on both the midline and top of the specimen (6.35 mm (0.25in) from top). On the back face, the same adjacent strain gages in the midline of the specimen from Micro-Measurements (Model CA2-06-125LR-350), with gage length 3.18 mm (0.125 inch), were maintained from the Ti-6AL-4V compliance Series 1. There were only 12 strain gage channels, so different gages were monitored for the 5 runs of this series as indicated above.

Shear Fixture Compliance Tests

Shear fixture compliance characterization tests were completed using two different plates: a generic alloy steel with dimensions 55.766-mm X 129.29-mm X 9.385-mm (2.1955-in X 5.090-in X 0.36975-in) and the Challenge material Ti-6Al-4V with dimensions 55.88-mm X 127.36-mm X 3.061-mm (2.200-in X 5.014-in X 0.1205-in). Each plate had four sets of three strain gages as previously described.
The compliance tests revealed two main effects: nonlinear compliance of the test fixture and specimen slip in the grips. The compliance seen in the tests also includes the elastic deformation of the plates since the compliance of the test fixture was of comparable magnitude of the stiffness of the plates.
The slip behavior of the steel plate was less pronounced than that of the Ti-6Al-4V plate because the grip surfaces were rough. The slip behavior of the Ti-6Al-4V plate is assumed to be the same as that of the V-notch specimens since this plate and the V-notch specimens have the same surface roughness; thus, these Ti-6Al-4V plate compliance tests allow for empirical characterization of the slip behavior. This empirical characterization can then be applied to the V-notch specimen tests to remove the effect of slip in the Axial LVDT 1 data, as will be explained.

Procedure for Steel Plate Compliance Tests:

1. **Plate installation**: same as with V-notch specimens
2. **Pre-test Alignment Check:** same as with V-notch specimens
3. **Cyclic loading:**
    a. Without zeroing the measurements after the Pre-test Alignment Check, the actuator is cycled from 0 to 4.448 kN (1000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.

b. Upon an operator command, the actuator is cycled from 0 to 8.896 kN (2000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
c. Upon an operator command, the actuator is cycled from 0 to 18.793 kN (4000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
d. Upon an operator command, the actuator is cycled from 0 to 26.689 kN (6000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
e. Upon an operator command, the actuator is cycled from 0 to 35.586 kN (8000 lbs) at a rate of 0.1 Hz for three cycles.

4. **Repeat of cyclic loading procedure in step 3**
5. **After zeroing of the measurements, repeat of cyclic loading procedure in step 3**

Procedure for Ti-6Al-4V Plate Compliance Tests Series 1:

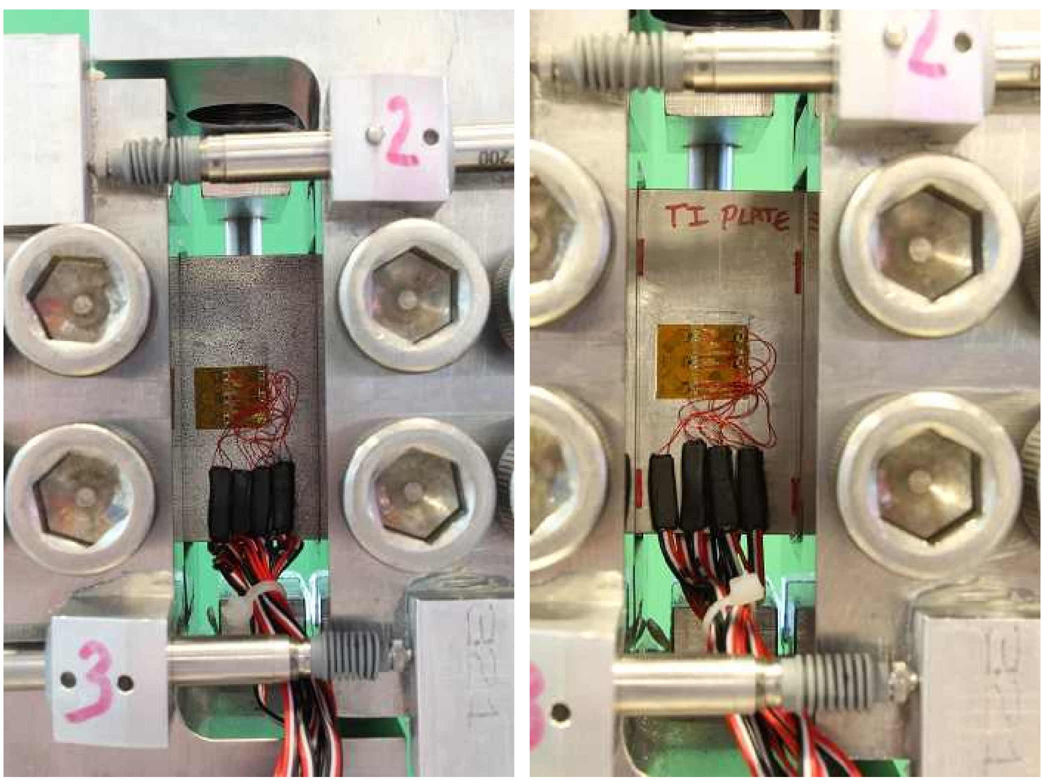
1. **Plate installation**: same as with V-notch specimens
2. **Cyclic loading pattern 1:**
   a. With zeroing the measurements after the plate installation, the actuator is cycled from 0 to 4.448 kN (1000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   b. Upon an operator command, the actuator is cycled from 0 to 8.896 kN (2000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   c. Upon an operator command, the actuator is cycled from 0 to 13.345 kN (3000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   d. Upon an operator command, the actuator is cycled from 0 to 18.793 kN (4000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   e. Upon an operator command, the actuator is cycled from 0 to 22.241 kN (5000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
3. **Cyclic loading pattern 2:**
   a. With zeroing the measurements after cyclic loading pattern 2, the actuator is cycled from 0 to 4.448 kN (1000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   b. Upon an operator command, the actuator is cycled from 0 to 8.896 kN (2000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   c. Upon an operator command, the actuator is cycled from 0 to 13.345 kN (3000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   d. Upon an operator command, the actuator is cycled from 0 to 18.793 kN (4000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   e. Upon an operator command, the actuator is cycled from 0 to 22.241 kN (5000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   f. Upon an operator command, the actuator is cycled from 0 to 26.689 kN (6000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   g. Upon an operator command, the actuator is cycled from 0 to 31.138 kN (7000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
   h. Upon an operator command, the actuator is cycled from 0 to 35.586 kN (8000 lbs) at a rate of 0.1 Hz for three cycles.
4. **After zeroing of the measurements, repeat of cyclic loading procedure in step 3**

The purpose of Ti-6Al-4V Plate Compliance Tests Series 2 was (1) to evaluate the effect of using adjacent vs. stacked strain gages on the strain measurements in Runs 1-2, (2) check the slip behavior of the Ti-6Al-4V plate again in Run 1, and, (3) to evaluate the difference in strain magnitude in the midline and top edge of the compliance plate in Runs 3-5.

Procedure for Ti-6Al-4V Plate Compliance Tests Series 2:

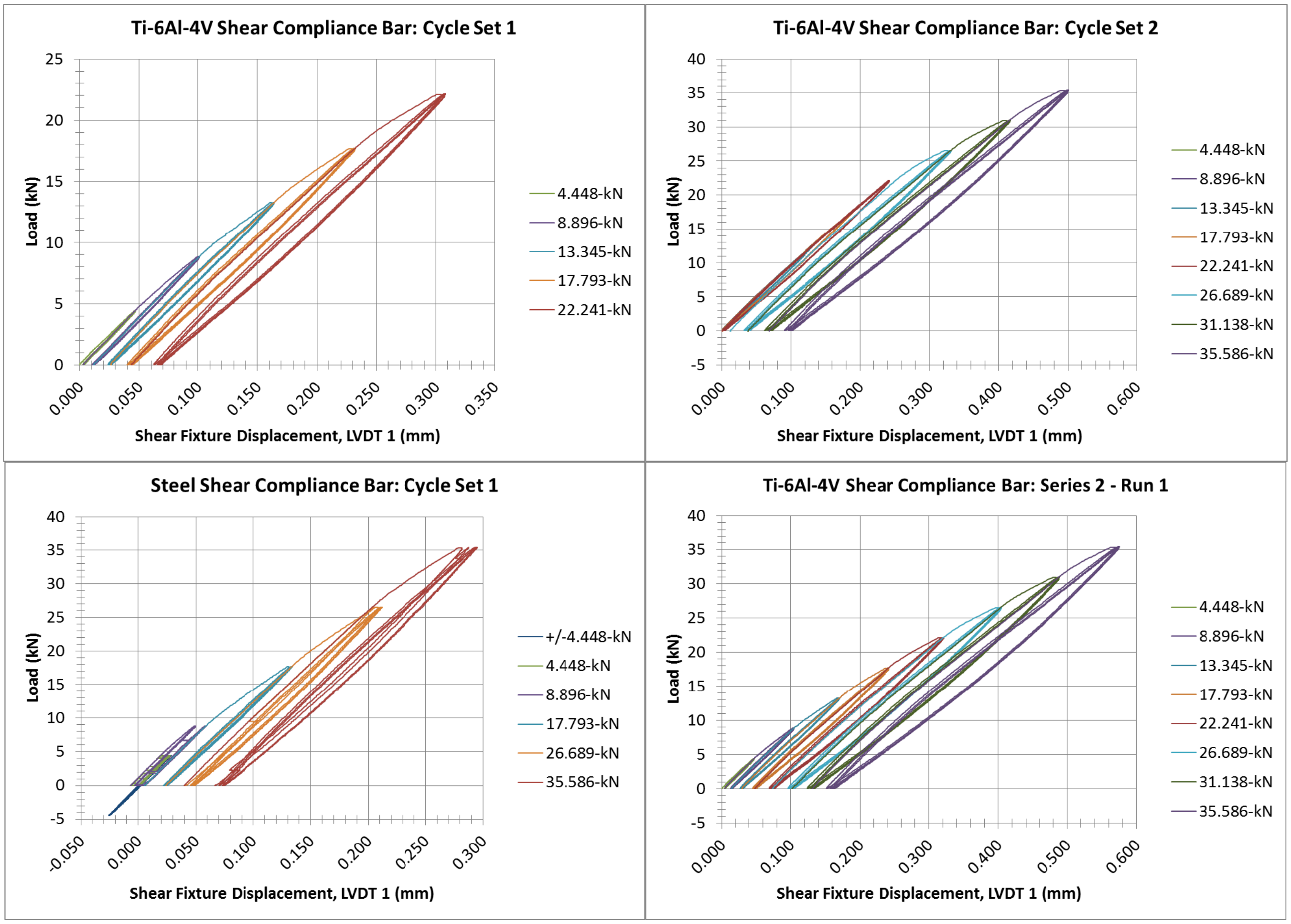
1. **Plate installation**: same as with V-notch specimens

2. **Cyclic loading pattern – Run 1 with Midline Strain Gages, Front and Back**
    a. The actuator is cycled from 0 to 4.448 kN (1000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
    b. Upon an operator command, the actuator is cycled from 0 to 8.896 kN (2000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
    c. Upon an operator command, the actuator is cycled from 0 to 13.345 kN (3000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
    d. Upon an operator command, the actuator is cycled from 0 to 18.793 kN (4000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
    e. Upon an operator command, the actuator is cycled from 0 to 22.241 kN (5000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
    f. Upon an operator command, the actuator is cycled from 0 to 26.689 kN (6000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
    g. Upon an operator command, the actuator is cycled from 0 to 31.138 kN (7000 lbs) at a rate of 0.1 Hz for three cycles. The load is held at zero load.
    h. Upon an operator command, the actuator is cycled from 0 to 35.586 kN (8000 lbs) at a rate of 0.1 Hz for three cycles.
3. **Cyclic loading pattern – Run 2 with Midline Strain Gages, Front and Back**
    a. The actuator is cycled from 0 to 35.586 kN (8000 lbs) at a rate of 0.1 Hz for three cycles.
4. **Cyclic loading pattern – Run 3 with Top and Midline Strain Gages in the Front**
    a. The actuator is cycled from 0 to 35.586 kN (8000 lbs) at a rate of 0.1 Hz for three cycles.
5. **Cyclic loading pattern – Run 4 with Top and Midline Strain Gages in the Front**
    a. The actuator is cycled from 0 to 35.586 kN (8000 lbs) at a rate of 0.1 Hz for three cycles.
6. **Cyclic loading pattern – Run 5 with Top and Midline Strain Gages in the Front**
    a. The actuator is cycled from 0 to 35.586 kN (8000 lbs) at a rate of 0.1 Hz for three cycles.

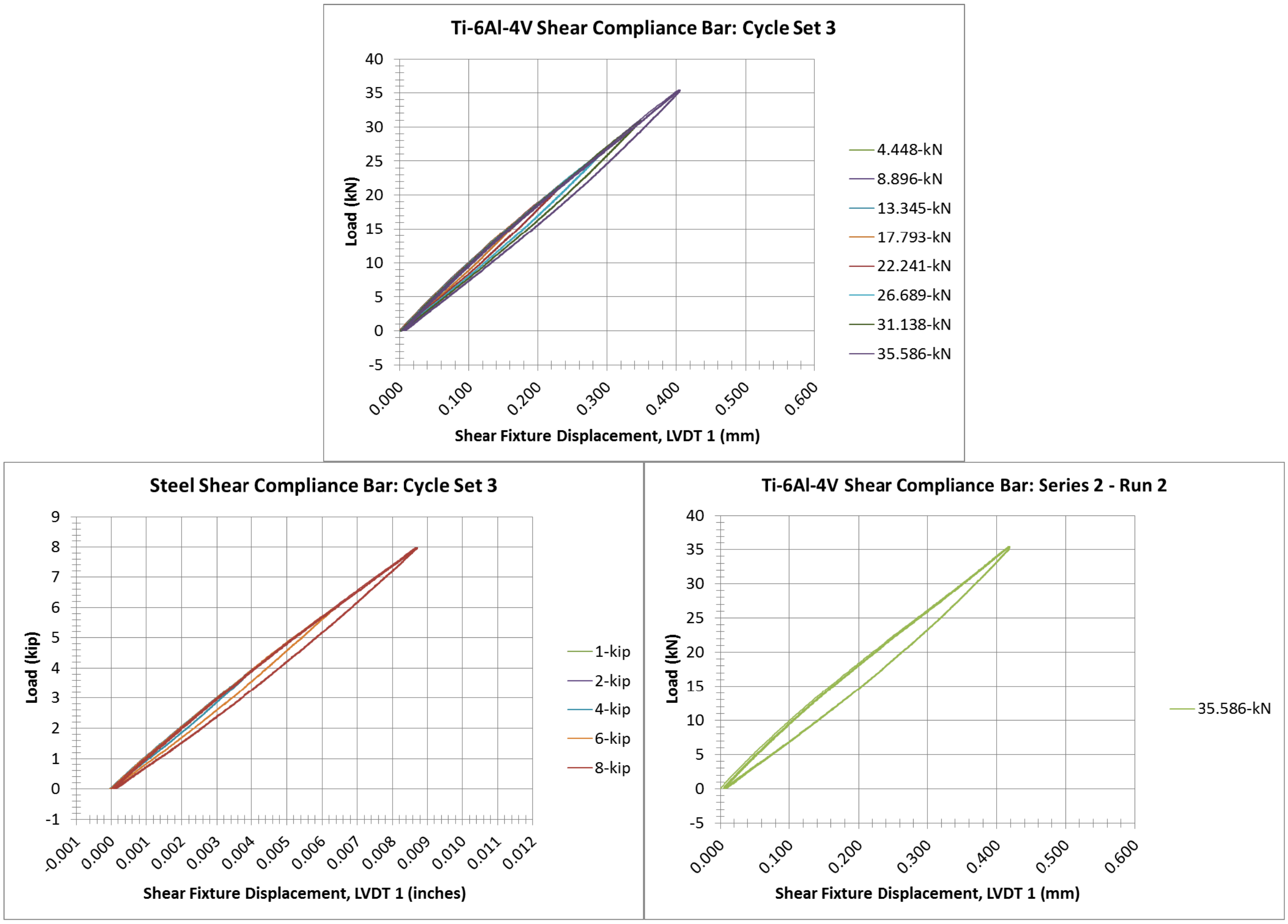


Alloy Steel Plate (left) and Ti-6Al-4V Plate (right) installed in the fixture

Typical Shear Fixture Compliance Tests Data: Cycles with Evident Slip



Typical Shear Fixture Compliance Tests Data: Cycles with Evident Slip
(Specimen slip is evident non-zero LVDT 1 measurement upon unload)

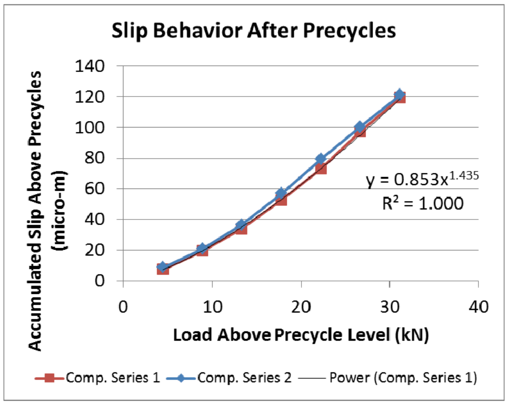


Typical Shear Fixture Compliance Tests Data: Cycles Without Further Slip Accumulation
(Negligible specimen slip accumulates here because these cycles occurred after the initial cycles up to the precycle upper load levels seen on the prior slide. This shows that slip accumulates only on the *first* load increase.)

Shear Fixture Ti-6AL-4V Specimen Slip Characterization

The Ti-6Al-4V compliance plate exhibited slip in the grips, seen in the Axial LVDT 1 data. This slip predominately occurred upon the initial positive loading through a load regime; this implies that cyclic loading exhibits considerable slip on the first portion of increasing load with little accumulation of additional slip in subsequent cycles between the same two load end-points. This also implies that after a set of precycles has been completed, a subsequent load segment would have minimal slip accumulation through the precycles load regime, but considerable slip above the upper precycle load. Therefore, to remove the accumulated slip from the Axial LVDT 1 data for the monotonic pull to failure portion of the V-notch data, an empirical formula based on the slip seen in the Ti-6Al-4V plate compliance test needs to be applied to the V-notch monotonic pull data above the 4.448-kN (1000-lbs) precycle level.
The slip accumulated on the initial monotonic pull between two load levels (the maximum load of the prior precycle and the new maximum load of the current precycle), as seen by Axial LVDT 1, is assumed to be the difference in the Axial LVDT 1 values at zero load for the first complete cycle of the current precycle set. This taken at zero load because there is no fixture compliance at zero load, and thus the difference in the Axial LVDT 1 measurement after one cycle is assumed to be due to specimen slip on the increasing load segment. [Note: there are implicit assumptions that no slip is reversed in unloading segments or for decreasing load in the monotonic pull segment.] For example, to calculate the slip between 4.448 kN and 8.896 kN, one would subtract the Axial LVDT 1 values at the end and start of the first cycle of the 0 to 8.896-kN precycle set. In other words, one assumes the slip between 0 and 4.448 kN has already occurred in the prior 0 and 4.448-kN

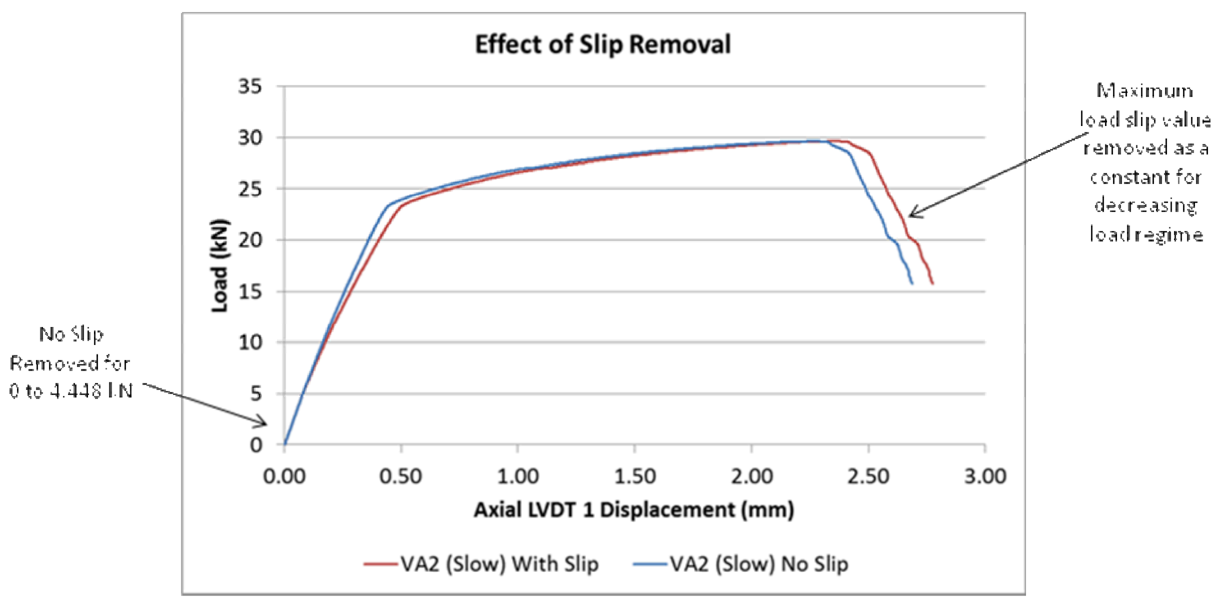
precycle set, so comparing the end values of the Axial LVDT 1 of the first cycle of the 0 to 8.896-N precycle set should provide the slip between 4.448 kN and 8.896 kN. This exercise was repeated for each precycle set in increments of 4.448 kN (1000 lbs) up to 35.586 kN (8000 lbs), and then a power-law curve was fit to the accumulated-slip-in-Axial-LVDT-1 vs. Load-above-the-precycle-set curve. This curve fit was the applied to the Axial LVDT 1 values for increasing loads above the 4.448 kN (1000 lbs) load level for the monotonic pull of each V-notch specimen. See SFC2-SupplementalData-v02.xlsx for the calculation. *Note: this compensation for slip does not remove the fixture compliance, which is evident in the non-linear behavior of the load vs. Axial LVDT 1 curve in the elastic region.*



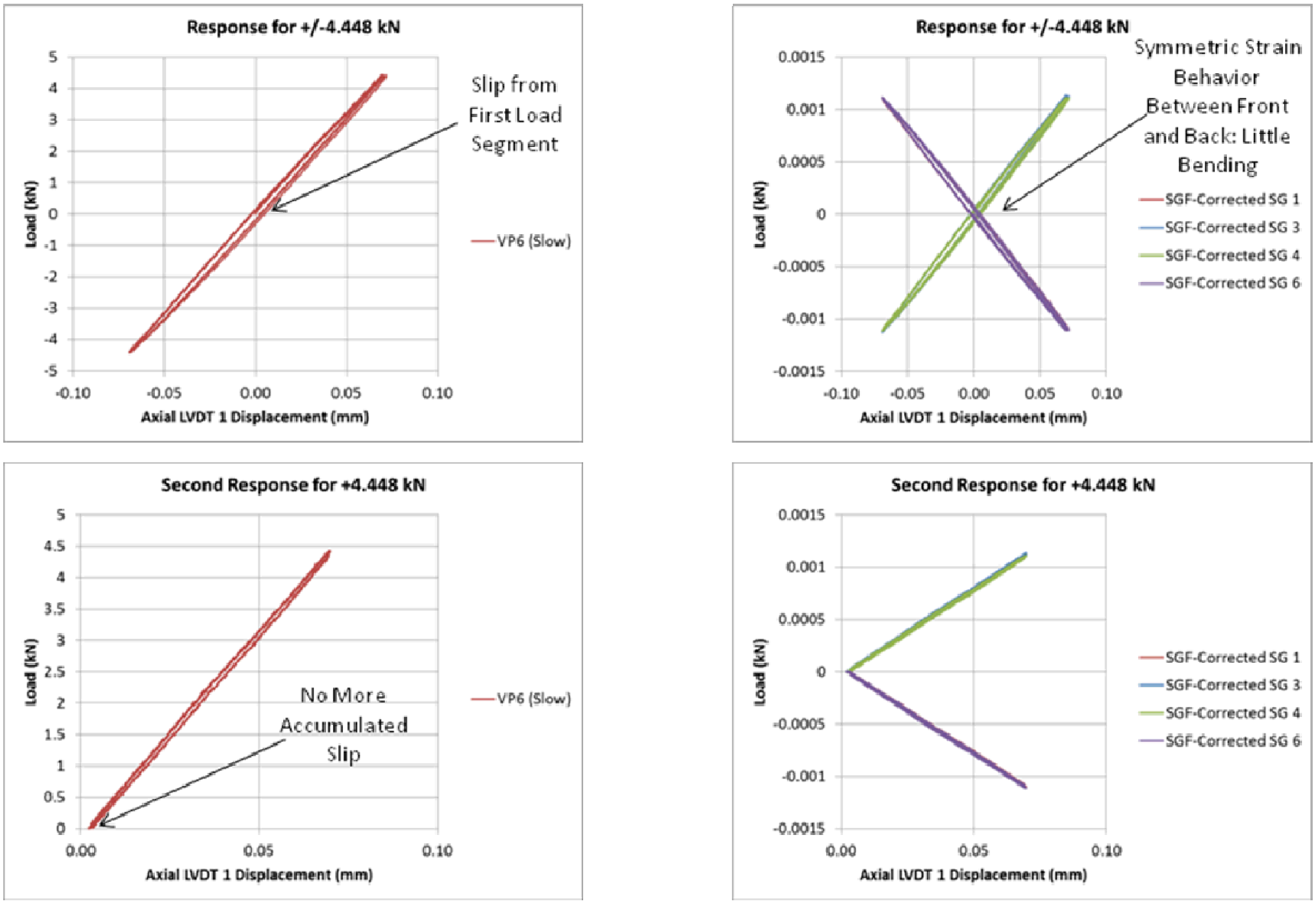
From TI-6Al-4V Compliance Series 1:
(Slip) = 8.528 * 10^{-4} * $(\text{Load}-4.448)^{1.435}$ mm
From TI-6Al-4V Compliance Series 2:
(Slip) = 1.076* 10^{-4} * $(\text{Load}-4.448)^{1.377}$ mm
Since Compliance Series 1 had unblemished surfaces , this is a recommended calculation to use for slip removal, even though the second series is very similar.

One Potential Shear Fixture Ti-6Al-4V Specimen Slip Removal Method

The formula of (Slip) = 8.528 * 10^{-4} * $(\text{Load}-4.448)^{1.435}$ mm is applied for loads greater than 4.448 kN up through maximum load. Once maximum load is reached, it is assumed that the slip does not decrease with the load drop, so the maximum slip value is subtracted from the Axial LVDT 1 reading for decreasing loads after maximum loads. For example, in specimen VA2, the maximum load is 29.658 kN with an associated slip of 0.0876 mm, and that amount of slip was removed from the Axial LVDT 1 for all loads after maximum load has been achieved.



Shear Test – Data Summary



Shear Test – Data Summary: Typical Response Data Before Monotonic Pull to Failure
(Note: The Axial LVDT 1 measurement here includes the slip (no slip removal) and fixture compliance.)