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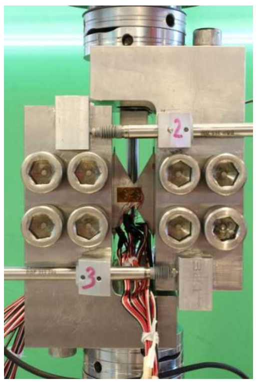

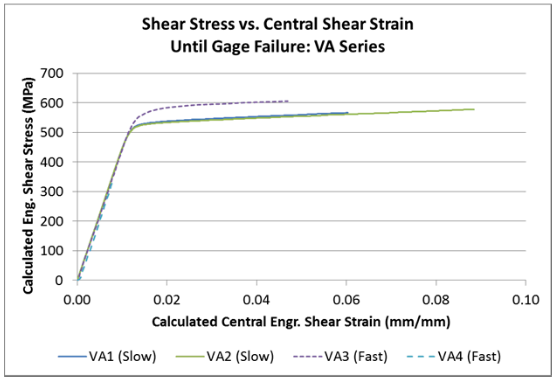

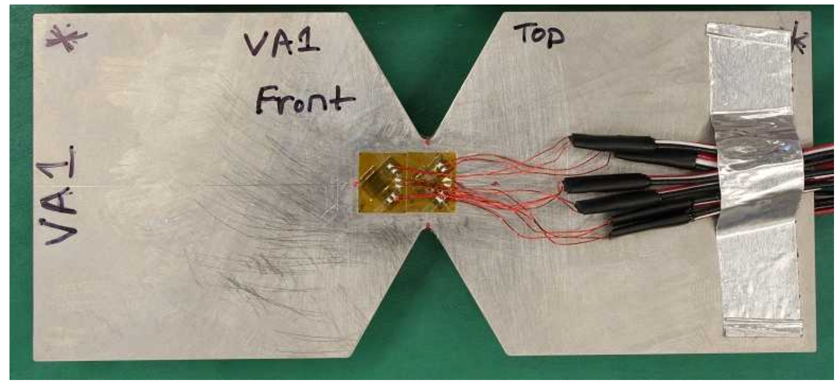

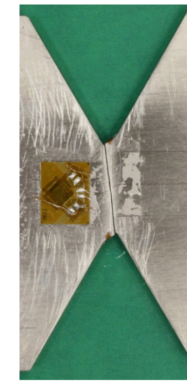

V-Notched Rail Test for Shear-Dominated Deformation of Ti-6Al-4V

Sharlotte Kramer, John Laing, Thomas Bosiljevac, Jhana Gearhart, and Brad Boyce

9 June 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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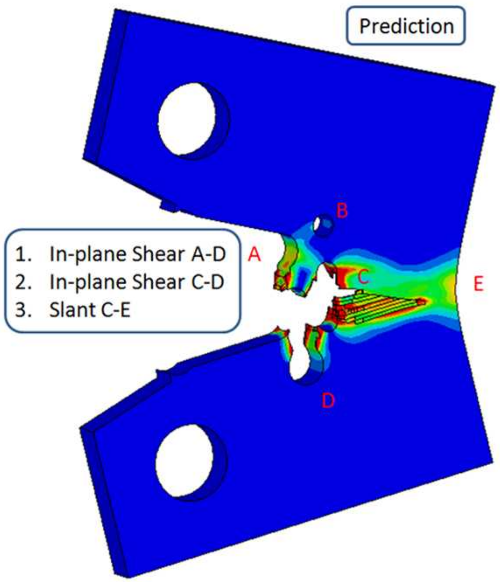
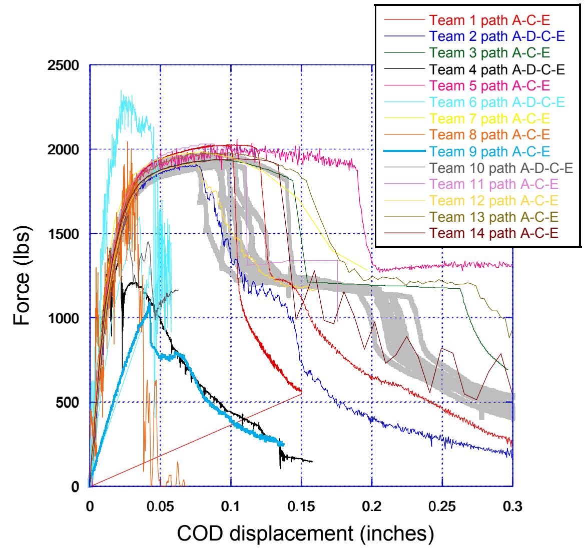
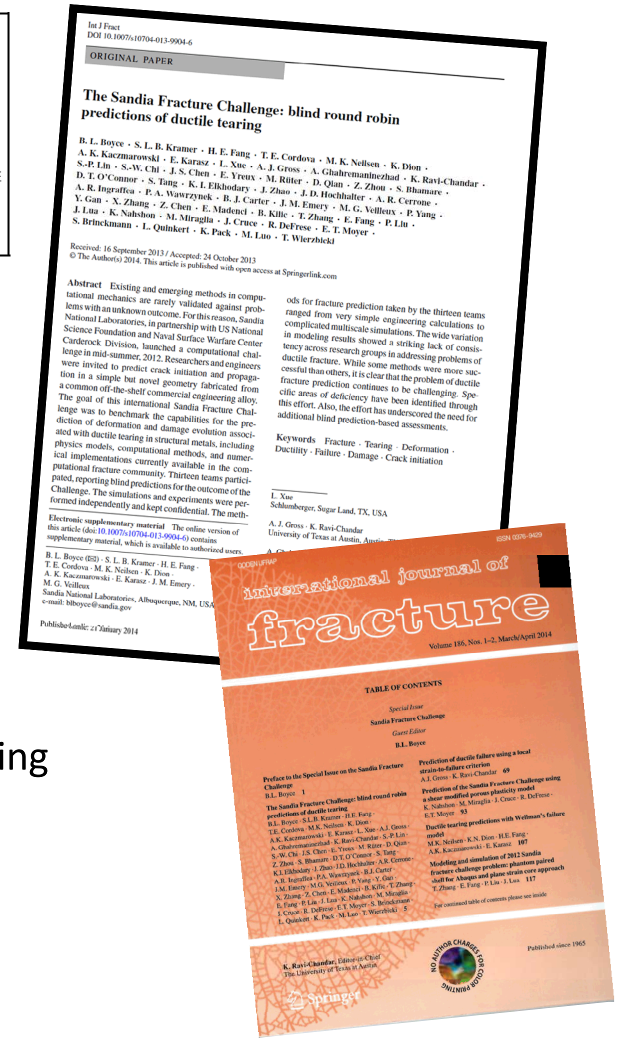
Motivation: Sandia Fracture Challenge

- In 2012, Sandia hosted a blind assessment challenge of predicting ductile fracture, open to the international solid mechanics community.



Overlay: Predictions (colors) compared to experiments (gray)

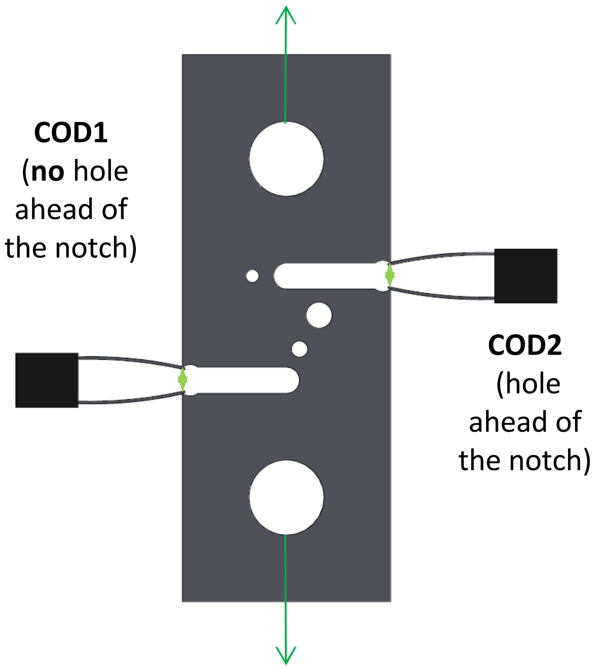


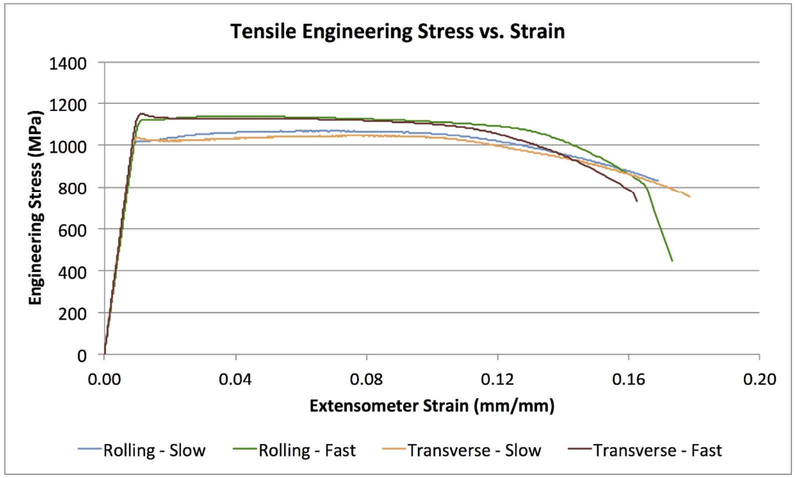


- This detailed study revealed several common deficiencies, including:
  - The lack of shear calibration data
  - Discrepancies caused by imperfections in specimen manufacturing
  - Many models could not capture shear failure
  - Difficulties in regularization / mesh sensitivity
  - Difficulty setting length scale in non-local models
  - Prediction bounds typically based off parameter 'uncertainty'
  - Trade-off between expedience and accuracy.

Motivation: 2014 Sandia Fracture Challenge

SFC Specimen Geometry (right); Anisotropic, Rate-Dependent Tensile Properties of Ti-6Al-4V (bottom)





Challenge Definition:

- S-shaped Ti-6Al-4V specimen with holes and notches loaded with a set of clevis pins at two displacement rates (25.4 mm/s and 0.0254 mm/s)
- Predict
  - Failure path
  - Force at particular COD gage values
  - Force-COD curves
- Provided Information
  - Specimen geometry and pre-test measurements
  - Tensile test data for rolling and transverse material directions
  - Shear test data of rolling and transverse material directions

Issues:

- **No standard shear testing protocol for ductile metals**
- **Need method that can be easily done in a regular experimental testing lab at two loading rates**

Shear Testing Techniques

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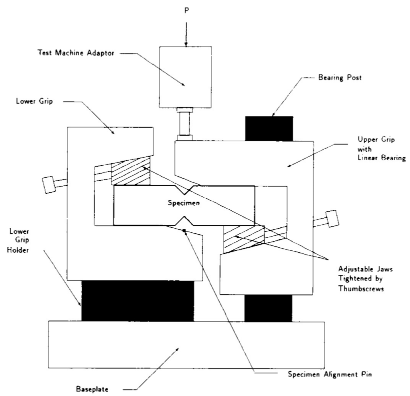
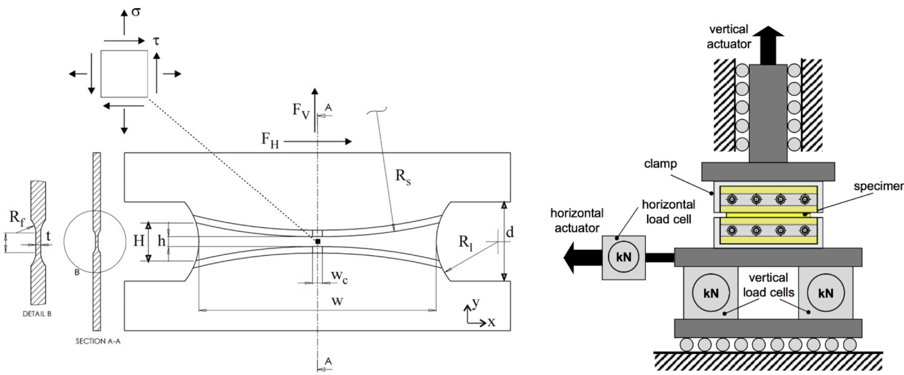
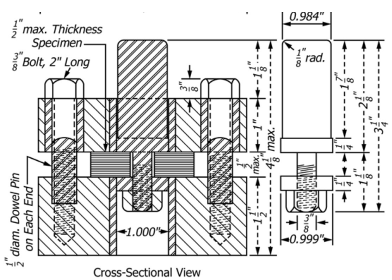


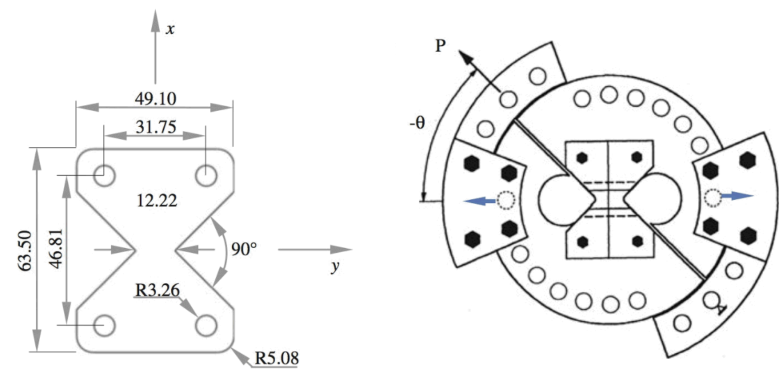
Iosipescu (V-Notched Beam) Test (ASTM D5379) for Composites



Dunand and Mohr (2013) Butterfly Geometry for Multi-Axial Ductile Fracture Testing



Punch Geometry (ASTM D732) for Plastics



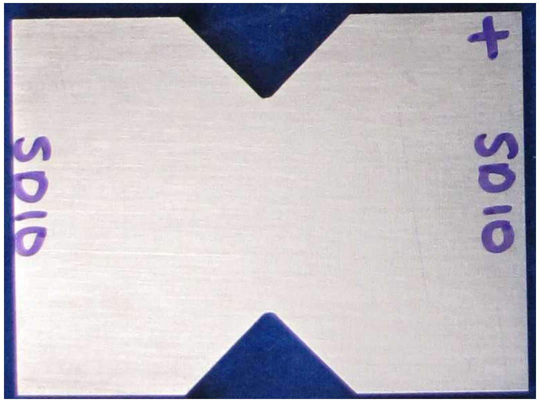
Arcan Multi-Axial Testing (Ghahremaninezhad and Ravi-Chandar, 2013)

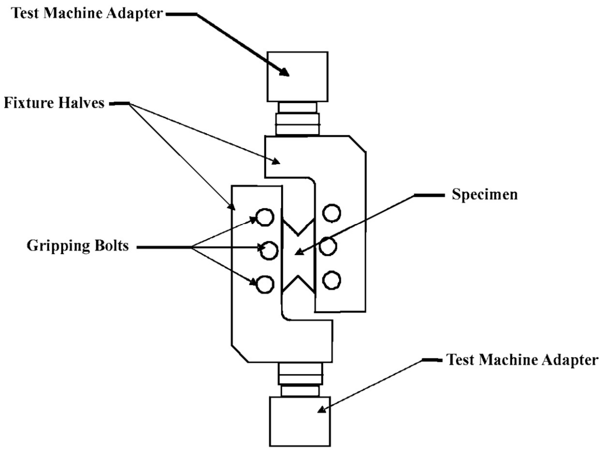
These methods are either difficult to implement for sheet Ti-6AL-4V or not straightforward to implement in a regular experimental testing lab

V-Notched Rail Test

ASTM D7078:
Shear testing for composite materials

76.2-mm Long, 90° V-notch Standard Specimen (right); Standard V-Notched Rail Fixture (Bottom)



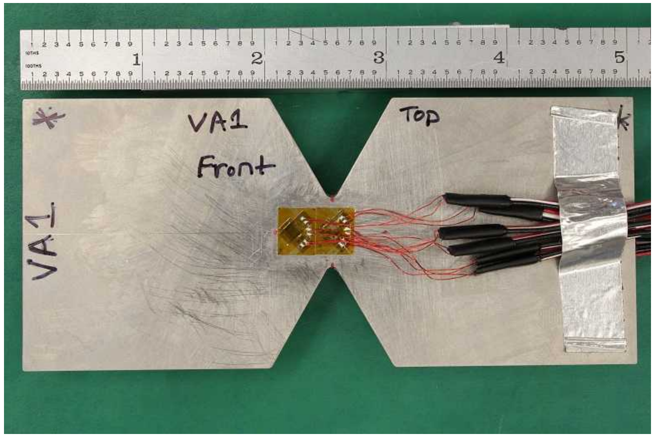


- Advantages:
  - Large area of gripping
  - Easy-to-machine specimen geometry
  - Ease of testing sheet material
  - Useful geometry for anisotropic materials
  - Testing in a common uniaxial load frame
  - Testing at a large range of displacement rates
  - Commercially available standard grips
- Disadvantages:
  - No literature on test used for metals
  - Non-negligible system compliance when testing metals
  - Non-trivial grip alignment of two independent grip halves
  - Potential for insufficient gripping pressure of metal specimens

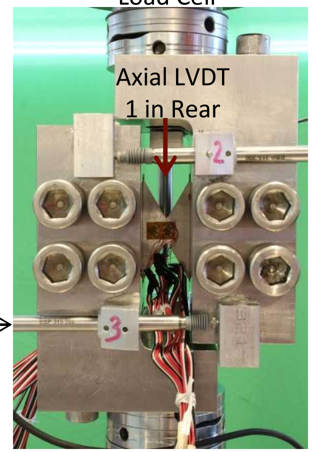
V-notch rail test had the most promise for the Ti-6Al-4V shear test, requiring a few modifications

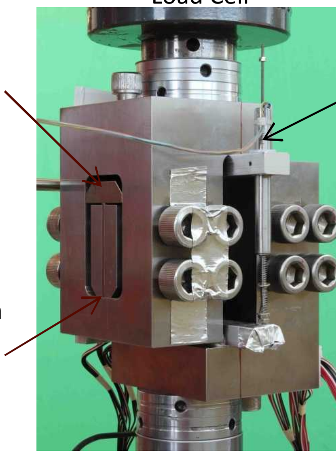
Modified Setup for Testing Ti-6Al-4V

Modified V-Notched Specimen



Adjustable Combined Loading Shear (CLS) Fixture for the V-notch Rail Shear Test from Wyoming Test Fixtures

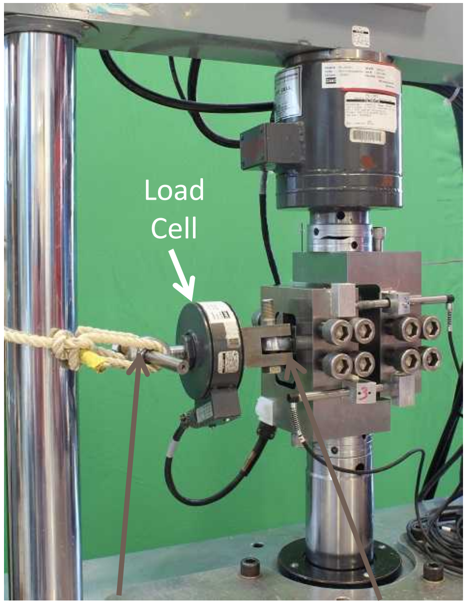


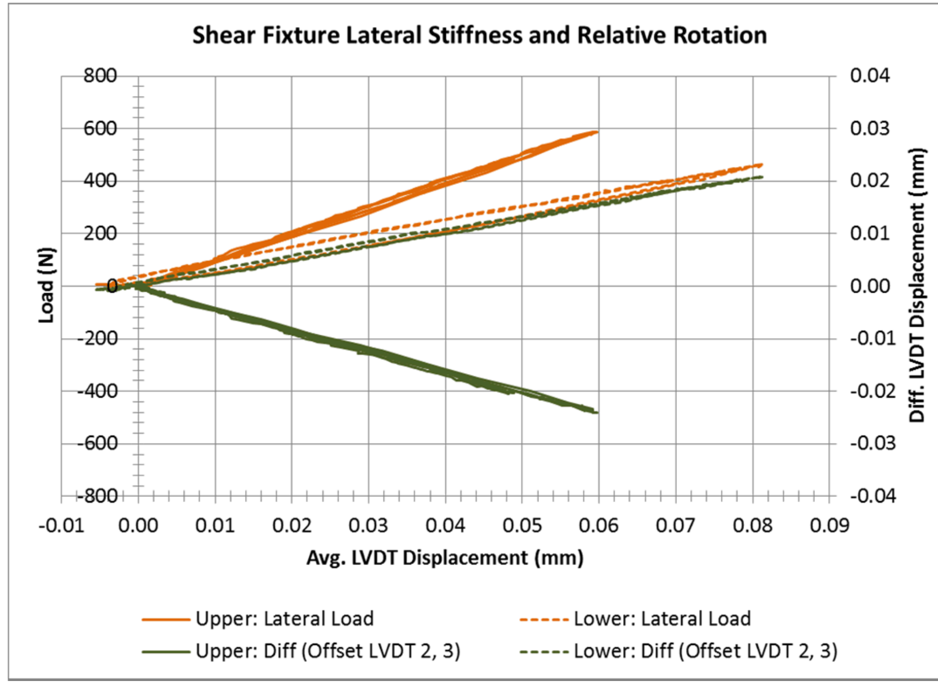


- **Specimen Modification**:
  - **60º notch** to reduce central shear area
  - **Longer grip section** allowing for more gripping area and higher grip pressures
- **Test Setup Enhancements**:
  - **Axial LVDT** for local displacement measurement
  - **Lateral LVDTs** to monitor potential rotations of the fixture
  - **Strain gage rosettes** on front and back of each specimen
  - **Specimen installation procedure**: tighten bolts incrementally up to 67.8 N-M (50 ft-lbs) each, not allowing any strain gage to rise above 100-microstrain

Lateral Compliance Characterization

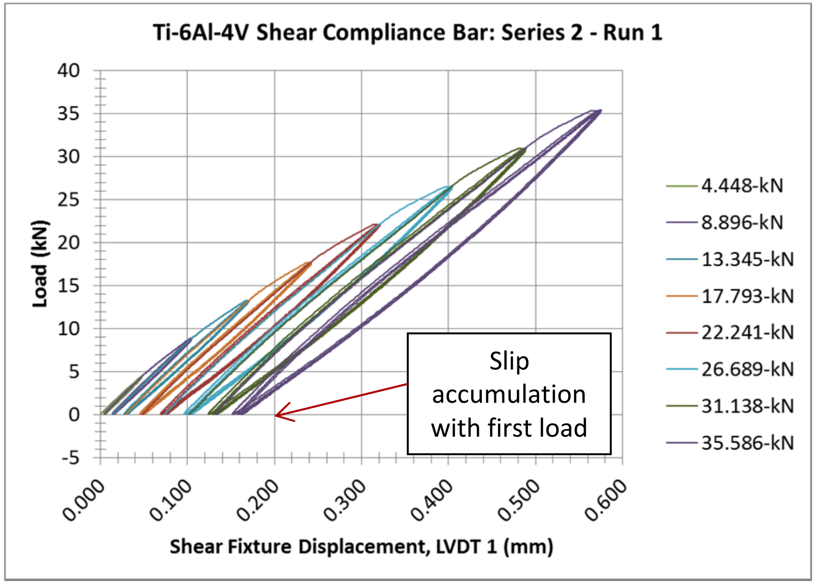
Setup for Lower Fixture

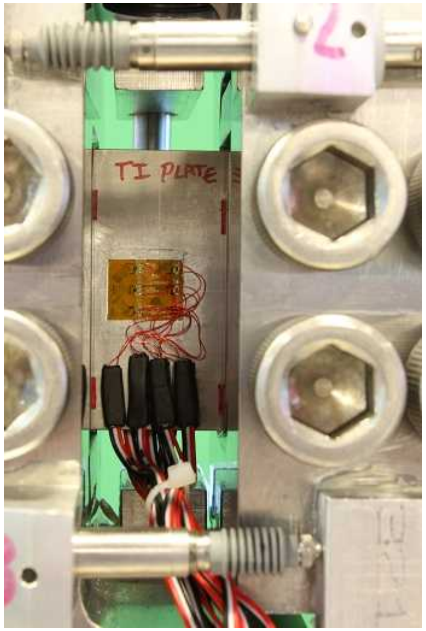




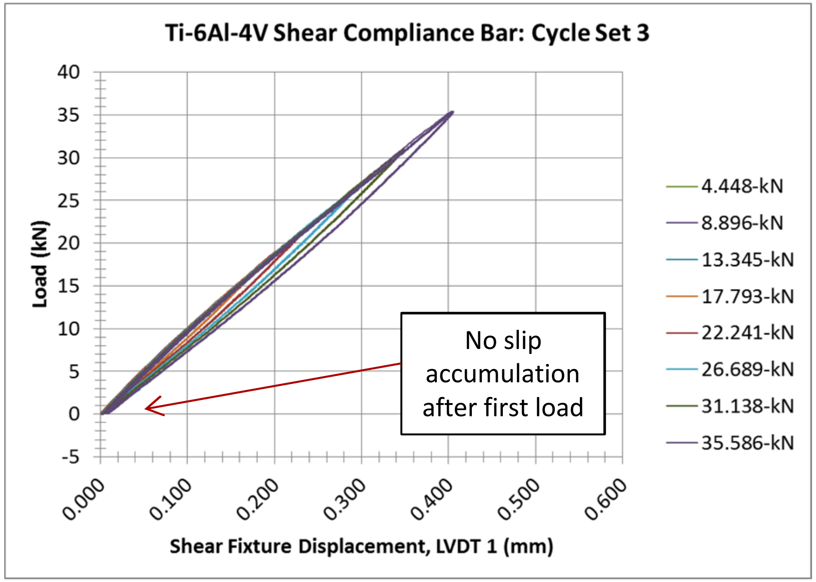
- The lateral stiffness of the upper fixture is greater than the lower fixture.
- The upper fixture has more rotation for a given load than the lower fixture as seen in the difference between LVDT 2 and LVDT 3.
- The V-notched specimen tests had negligible lateral displacements, implying that the specimens did not exhort significant lateral loads on the fixture.

Axial Compliance Characterization



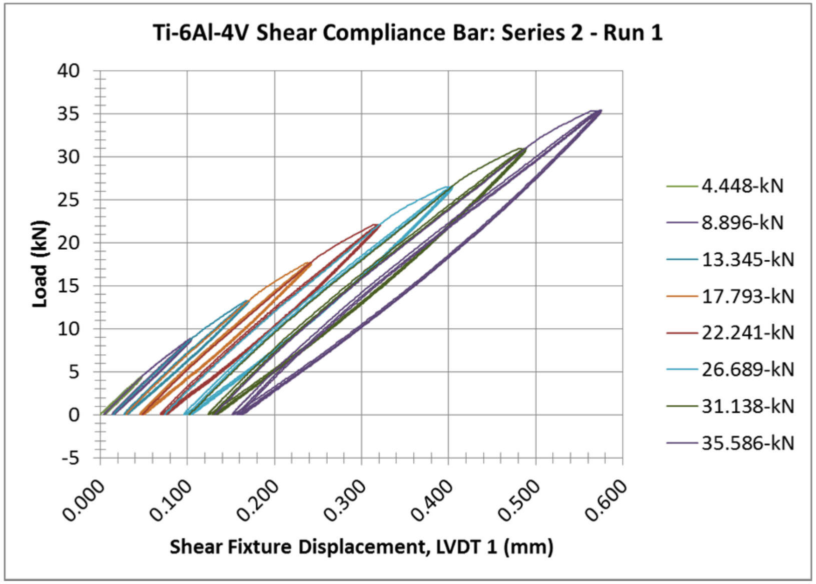


First run compliance test with Ti-6Al-4V plate (upper left); Subsequent compliance test with same Ti-6Al-4V plate (lower left); Ti-6Al-4V solid plate in fixture (right)

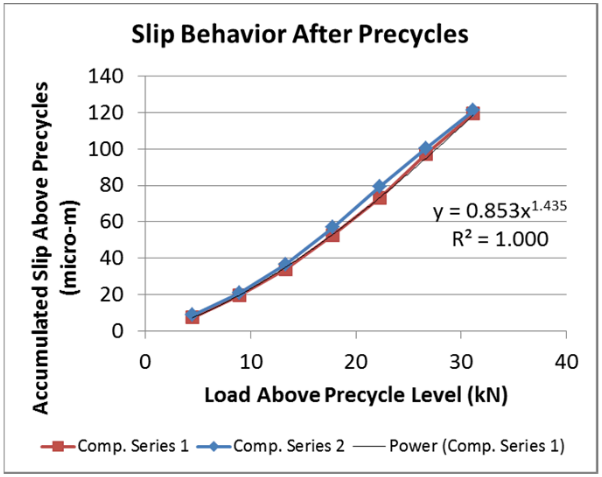


- Performed cyclic loading of an solid alloy steel plate and a solid Ti-6Al-4V plate at increments of 4.448 kN (1000-lbf)
- The fixture exhibited significant compliance
- Noticed considerable slip of the plates in the grips (displacement did not return to zero upon unload)
- Negligible slip accumulation after first load increment for each load level

Specimen Slip Characterization

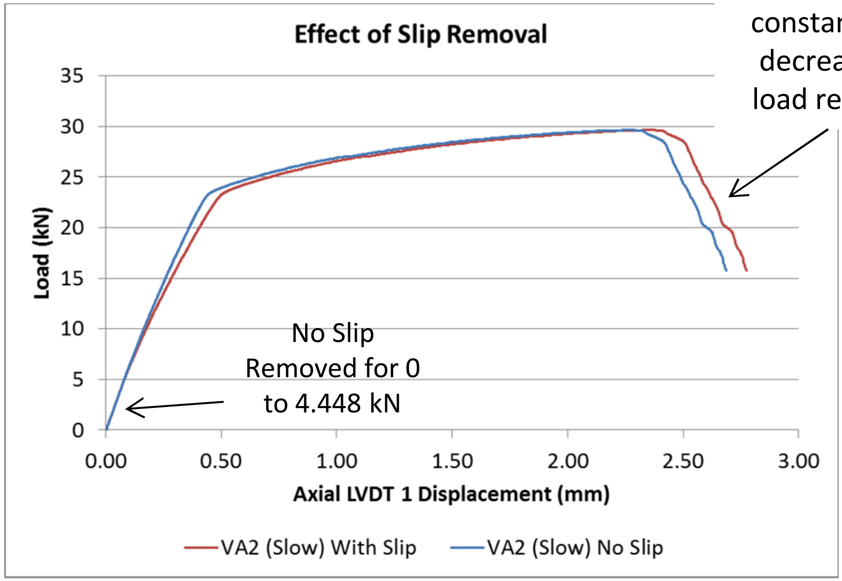


$$(\text{Slip}) = 8.528 * 10^{-4} * (\text{Load}-4.448)^{1.435} \text{ mm}$$



Suggested Slip Removal Approach

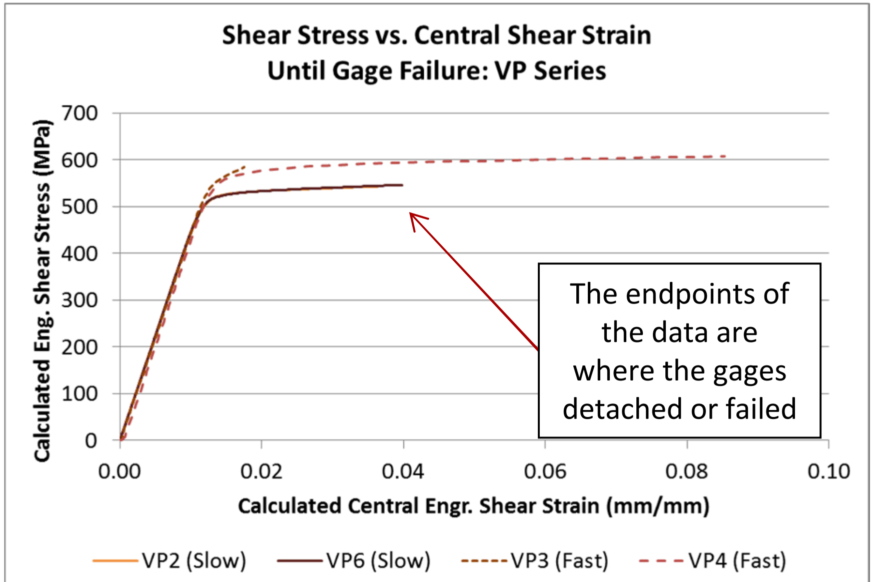
- During testing, all specimen underwent pre-cycling up to 4.448 kN, effectively removing the specimen slip prior to the monotonic pull to failure.
- Slip could be removed from the axial LVDT data for loads after the 4.448-kN level using the empirical slip formula.
- No slip should be removed from decreasing loads: assumption that slip does not occur upon unload



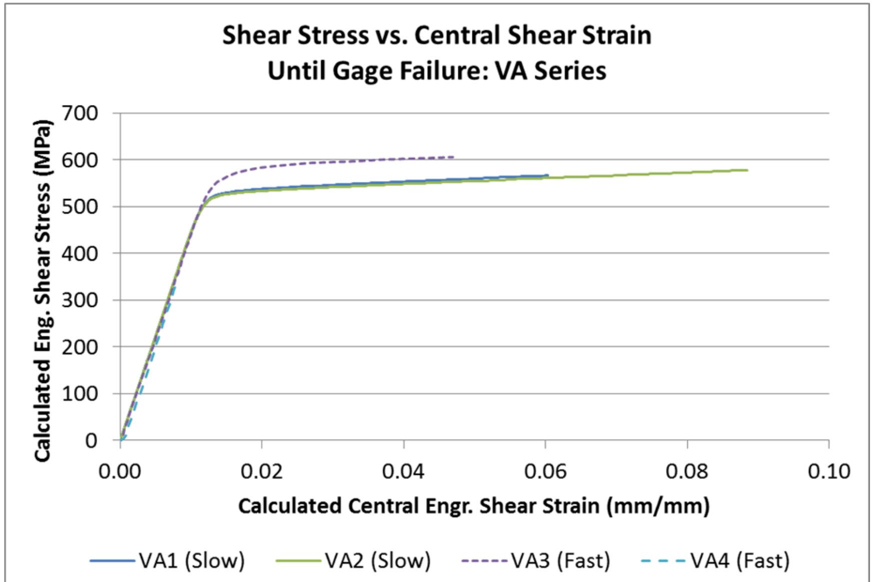
Maximum load slip value removed as a constant for decreasing load regime

Ti-6Al-4V Results: Strain Gages

These strain-gage tests estimate a shear modulus of Ti-6Al-4V of 44 GPa, consistent with literature values.



VP Series: Rolling Direction Transverse to Shear Direction

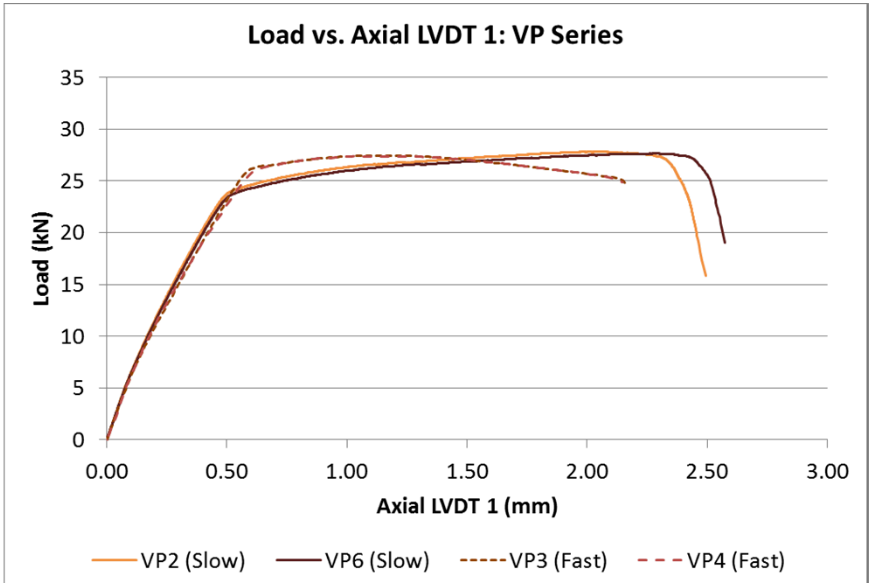


VA Series: Rolling Direction Aligned with Shear Direction

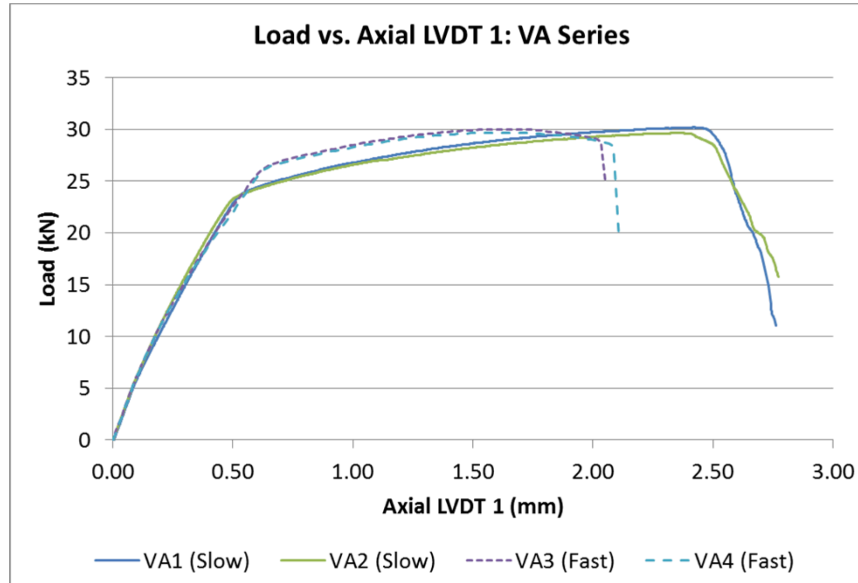
- Engineering shear strain calculated from strain gage rosettes as per ASTM D7078 prescribes
- Ti-6Al-4V exhibits rate dependence in shear: stiffer response from fast rate tests (25.4 mm/s) as compared to the slow rate tests (0.0254 mm/s)
- Rate dependence has a greater effect on the early plastic behavior than material direction

Ti-6Al-4V Results: Load-Displacement

Both material direction and rate dependent affect large-deformation plasticity seen in the global load-displacement behavior.



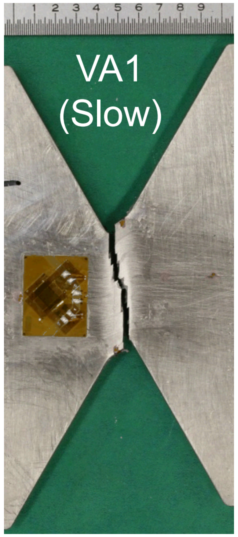
VP Series: Rolling Direction Transverse to Shear Direction



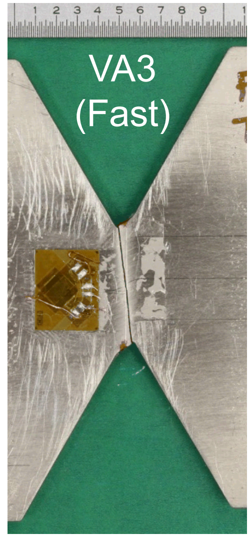
VA Series: Rolling Direction Aligned with Shear Direction

- Note: The Axial LVDT 1 measurement here includes contributions from fixture compliance and specimen slip. At 20 kN, the combined effects contribute ~0.27 mm to the axial LVDT 1 value.
- Approaches to removal of effects of fixture compliance and specimen slip:
  - Apply a first-order linear correction so that the modulus matches the strain-gage data
  - Explicitly remove the specimen slip using the empirical formula previously derived, and also remove compliance by determining fixture displacement-load behavior from modeling the setup and subtract the elastic behavior of the plate

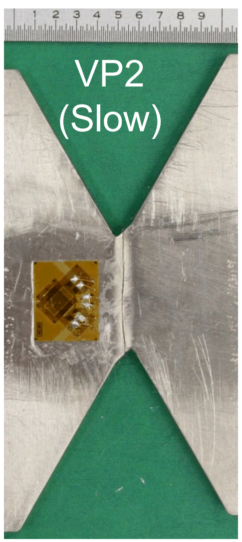
Ti-6Al-4V Fracture Surfaces



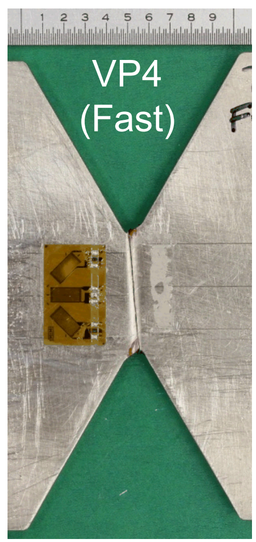
Failure Surface



Failure Surface



Failure Surface



Failure Surface

Ruler Scale: Smallest Division is 0.254 mm (0.01 in)

- Cracks did not intersect the root of the 60° notch
- Failure surfaces for the fast rate tests (25.4 in/s) are similar for the rolling (VA) and transverse (VP) directions
- Failure surfaces for the slow rate tests (0.0254 in/s) are dissimilar for the rolling and transverse directions

Failure of each rolling direction and displacement rate had repeatable behavior

Conclusions and Future Work

- Demonstrated V-notched rail test for shear characterization of Ti-6Al-4V
  - Performed tests at two loading rates (quasi-static and moderate rates)
  - Measured shear modulus consistent with literature
  - Performed repeatable tests, showing rigorous testing procedures
  - Characterized fixture compliance and specimen slip in the grips
- Improvements / Future Work
  - Develop improved gripping technique to prevent specimen slip
  - Perform full-field Digital Image Correlation measurements to provide shear strain measurements to failure
  - Team with computationalists to
    - Characterize fixture behavior
    - Establish testing protocol for ease of constitutive model calibration