CRASHWORTHINESS OF COMPOSITE FUSELAGE STRUCTURES – MATERIAL DYNAMIC PROPERTIES

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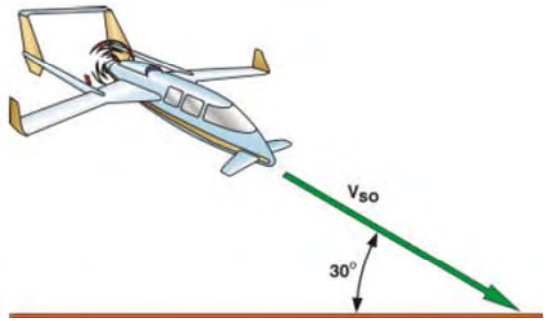
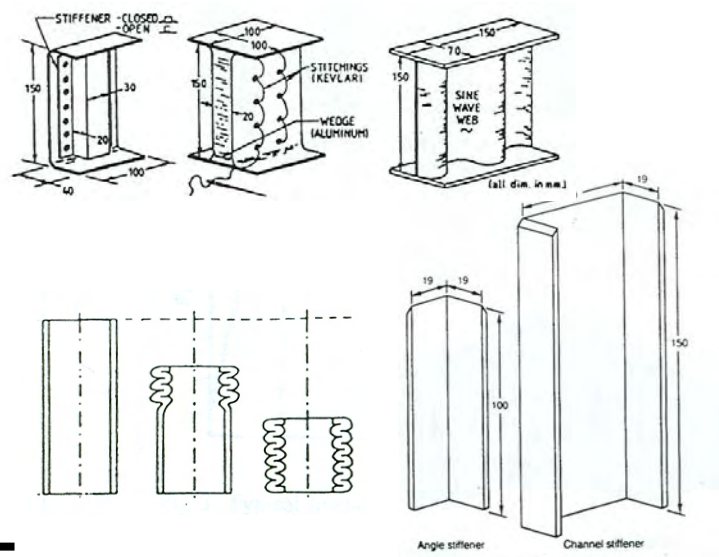
The Joint Advanced Materials and Structures Center of Excellence

Crashworthiness of Composite Fuselage Structures – Material Dynamic Properties

- Motivation and Key Issues
  - Crashworthiness
    - Maintain survivable volume
    - Alleviate occupant loads
  - Energy Absorption
    - Metals – Plastic deformation
    - Composites – controlled failure modes
  - Factors affecting energy absorption
    - Geometry (?)
    - **Strain rate (?)**
  - Experiments – expensive & expansive
  - Analysis – requires data for material properties





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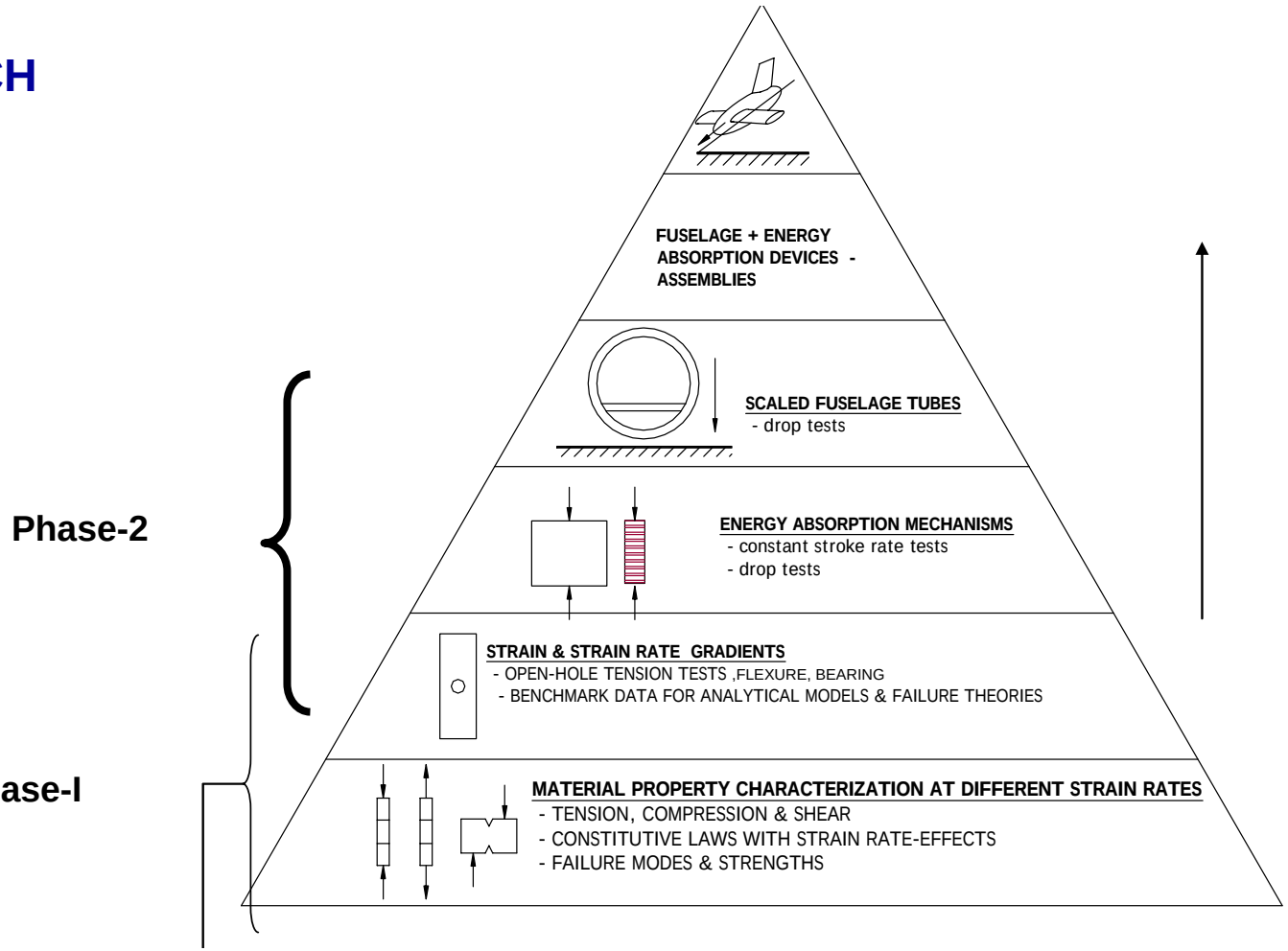
CRASHWORTHINESS OF COMPOSITE FUSELAGE STRUCTURES – MATERIAL DYNAMIC PROPERTIES

- APPROACH



Crashworthiness of Composite Fuselage Structures – Material Dynamic Properties

– Objectives: Material property characterization at different strain rates (10^{-4} s^{-1} to 10^{3} s^{-1})/dynamic loading

- Phase-1
  - Development of test apparatus & fixtures for high strain rate testing
    - » MTS high stroke rate system
    - » Split Hopkinson Pressure Bar (SHPB) Apparatus
  - Tension, Compression & Shear
  - Open Hole Tension
- Phase-2
  - » Interlaminar Shear
  - » Pin Bearing
  - » Flexure
  - » Honeycomb core

FAA-Sponsored Project Information

- Principal Investigators & Researchers
  - K.S. Raju
  - C.K. Thorbole, H. Lankarani
  - GRA - J.F.Acosta, V.B. Mariyanna, A.B. Deshpande, S. Dandayudhapani
- FAA Technical Monitor
  - Alan Abramowicz
- Other FAA Personnel Involved
  - John Zvanya, Peter Shyprykevich, Curtis Davis
- Industry Participation
  - Spirit Aerosystems
  - Raytheon
  - Cessna
  - Sikorsky
  - Bell Helicopter

Material Systems

- Newport NB321/3k70P
- Newport NB321/7781 Fiberglass*
- Newport NCT321/G150 Unitape

- Toray T800S/3900-2B[P2352W-19] BMS8-276 Rev-H- Unitape*
- Toray T700G-12K-50C/3900-2 Plain Weave Carbon Fabric*

- Fibercote E-765/PW Carbon Fabric /Epoxy
- Cytec PWC T300 3KNT Plain Weave Carbon Fabric

- Plascore Nomex Honeycomb core PN2-3/16-3.0

* ***Investigated through NIS funding (2005-06)***

Material Properties

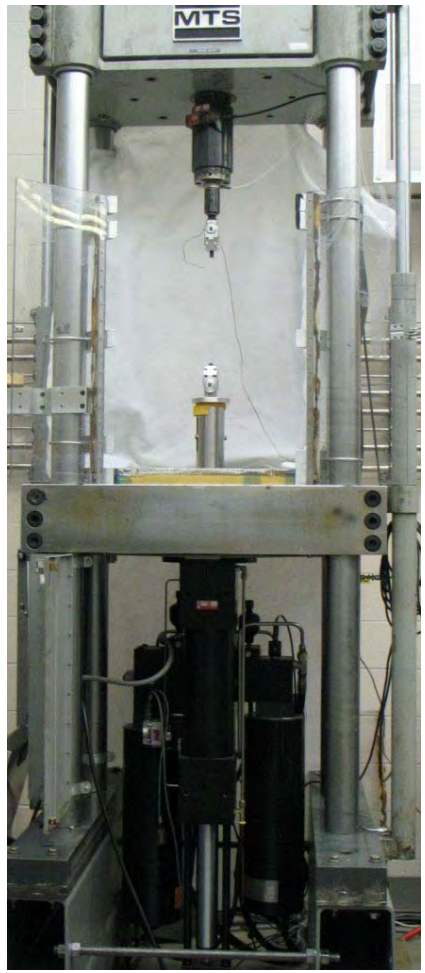
- In-Plane Tensile Properties (Strength & Modulus)
  - $[0°]_n$, $[\pm 15°]_{ns}$,$[\pm 30°]_{ns}$, $[\pm 45°]_{ns}$
- In-Plane Compressive Properties (Strength & Modulus)
  - $[0°]_n$, $[\pm 15°]_{ns}$,$[\pm 30°]_{ns}$, $[\pm 45°]_{ns}$
- In-Plane Shear Properties (Strength & Modulus)
  - $[0°/90°]_{ns}$
- Open- Hole Tension

Test Apparatus

- TENSION MODE TESTING
  - MTS servo hydraulic testing machine
    - Tension, shear and flexure tests
- COMPRESSION MODE TESTING
  - Split- Hopkinson Pressure Bar Apparatus (SHPB)
    - Compressive strength
  - MTS servo hydraulic testing machine
    - Honeycomb core

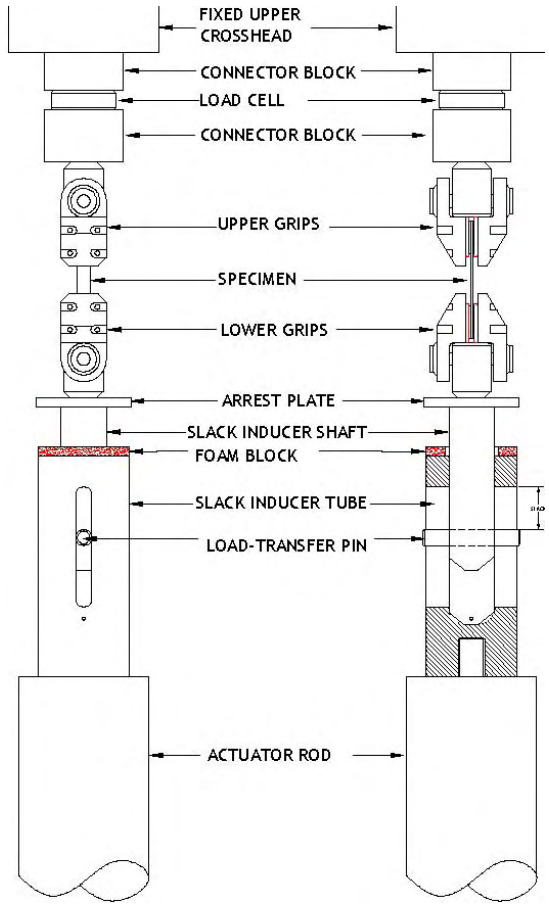
Test Apparatus

- MTS High Stroke Rate System (MTS-HSRS)
  - Stroke rate ~ 500 in/sec
  - +/- 7 inches stroke
  - Load capacity
    - 5 kips @ rated speed
    - 9 kips maximum
  - Load measurement
    - Piezoelectric load cell (+/-10 kips)
  - Data Acquisition
    - National Instruments PCI 6110 DAQ
    - 4 Channels
    - 5 MHz (simultaneous sampling)
    - 12 bits resolution
  - Test control
    - MTS MultipurposeTestware computer program



Test Apparatus

- SLACK INDUCER MECHANISM
  - allows actuator acceleration to desired speed prior to loading the specimen
- LOW-MASS GRIPS
  - mechanical wedge grips
  - 2.4 lbs
  - 15 kip capacity



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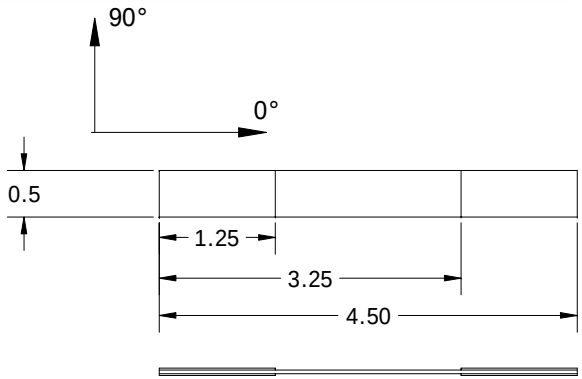
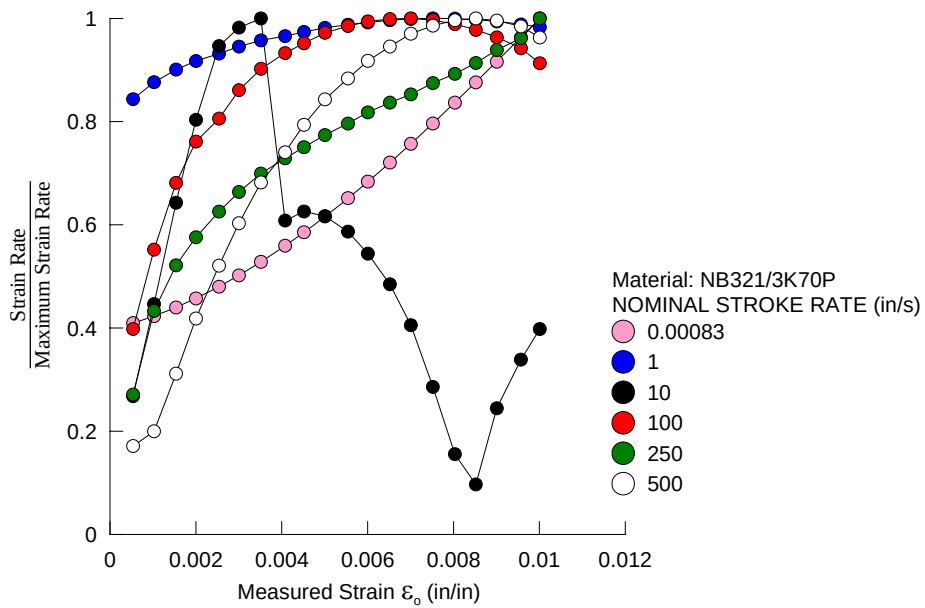
Tension Testing

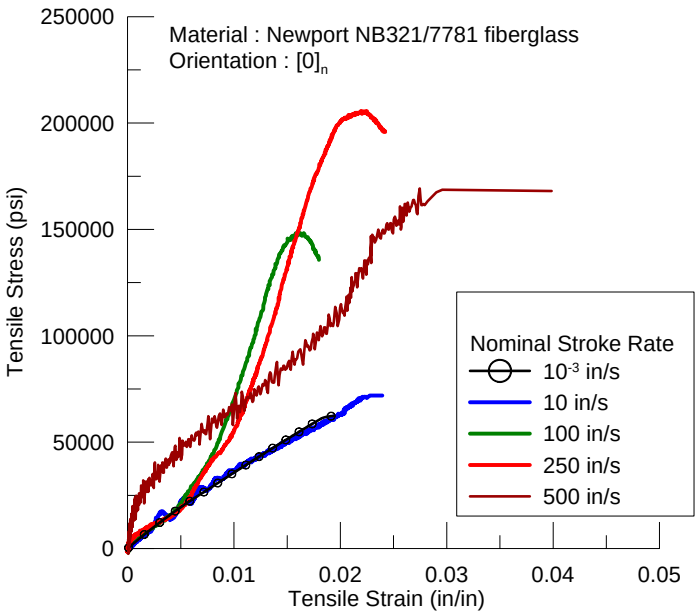
- SPECIMEN GEOMETRY
  - 2 inch gage length
  - 0.5 inch width
  - Thickness limited by loading capacity of the testing machine
- TEST RATES
  - $1x10^{-4}$ in/s (quasi-static)
  - 1, 10 , 100, 250 and 500 in/s
  - 3 specimens each
- CONSTANT STROKE RATE TESTS
  - Based on actuator displacement
  - Strain rate varies throughout the test
    - Variation of strain rate is dependent on slack inducer element (s) characteristics (stiffness and mass)

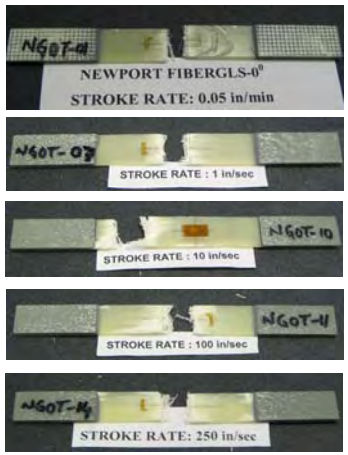


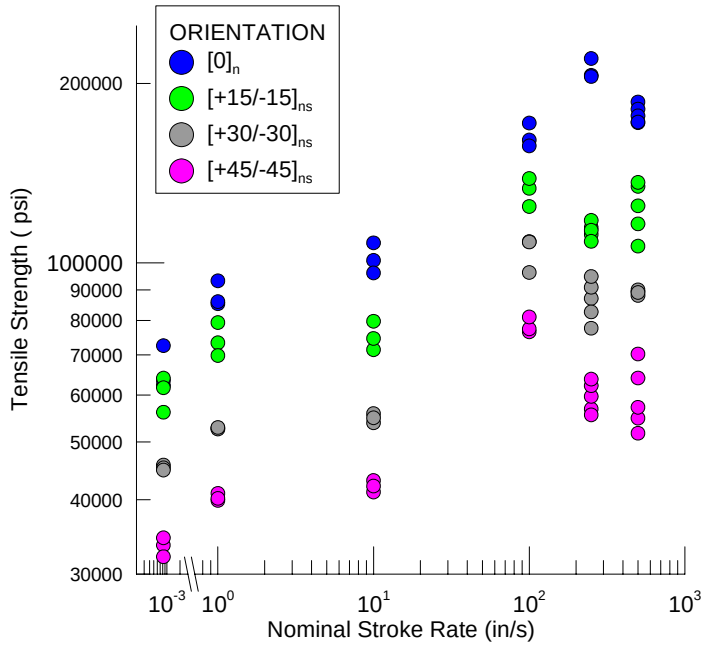


Tension Testing - Results

- Newport NB321/7781 Fiberglass/epoxy

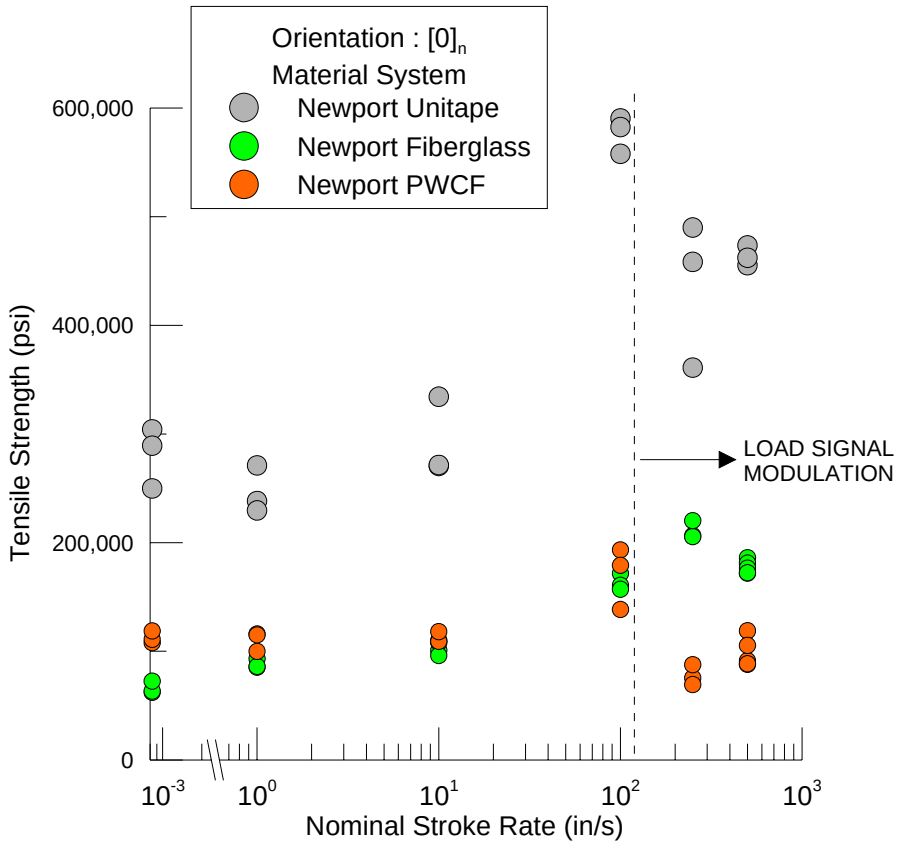






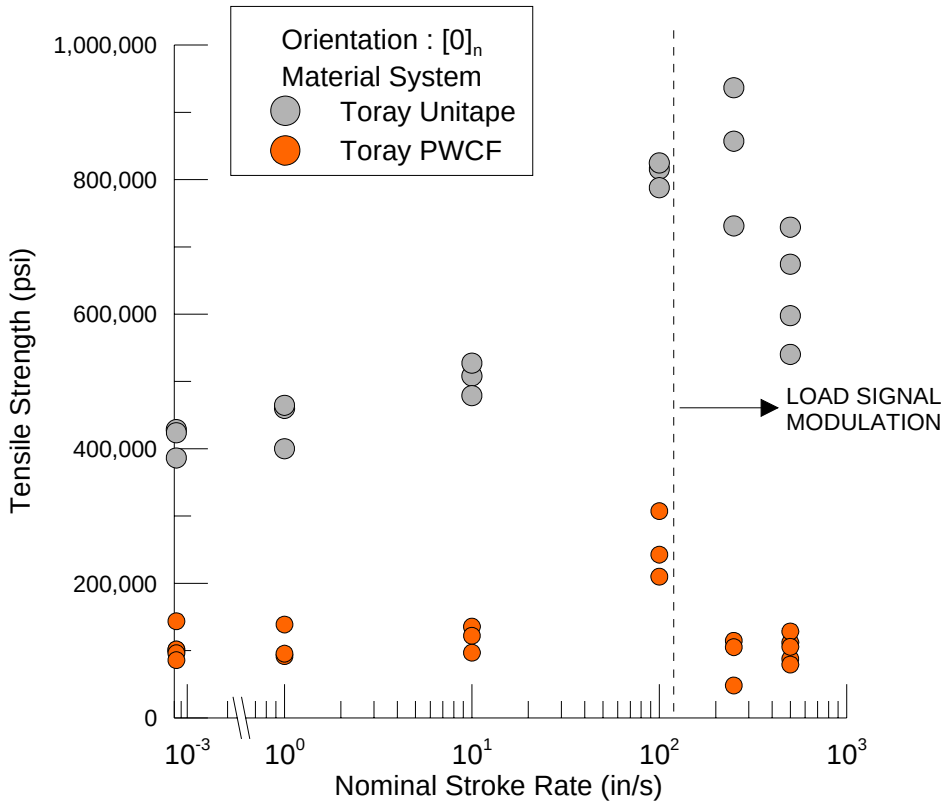
Tension Testing - Results

- Newport Material Systems
  - Increase in tensile strength observed for stroke rates up to 100 in/s, irrespective of reinforcement type
  - Fiberglass (NB321/7781) was observed to be more sensitive to strain rate, with increase in tensile strength by a factor of 3.
  - At stroke rates above 100in/s, modulation of load signal occurs. Load signal must be corrected using experimentally determined transfer function (under progress)



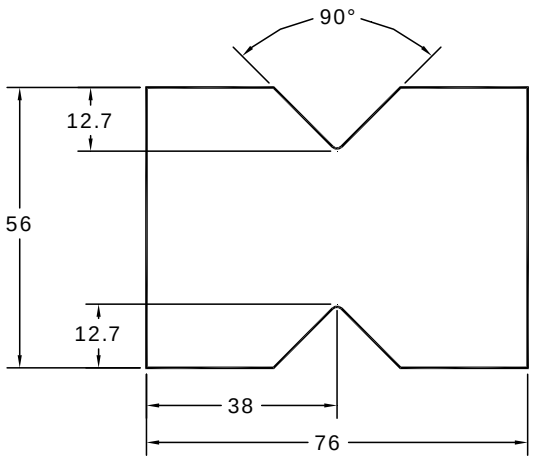
Tension Testing - Results

- Toray Material Systems
  - Increase in tensile strength observed for stroke rates up to 100 in/s, irrespective of reinforcement type
  - Tensile strengths of PWCF material observed to drop to quasi-static levels at stroke rates of 250 and 500 in/s
  - At stroke rates above 100in/s, modulation of load signal occurs. Load signal must be corrected using experimentally determined transfer function (under progress)

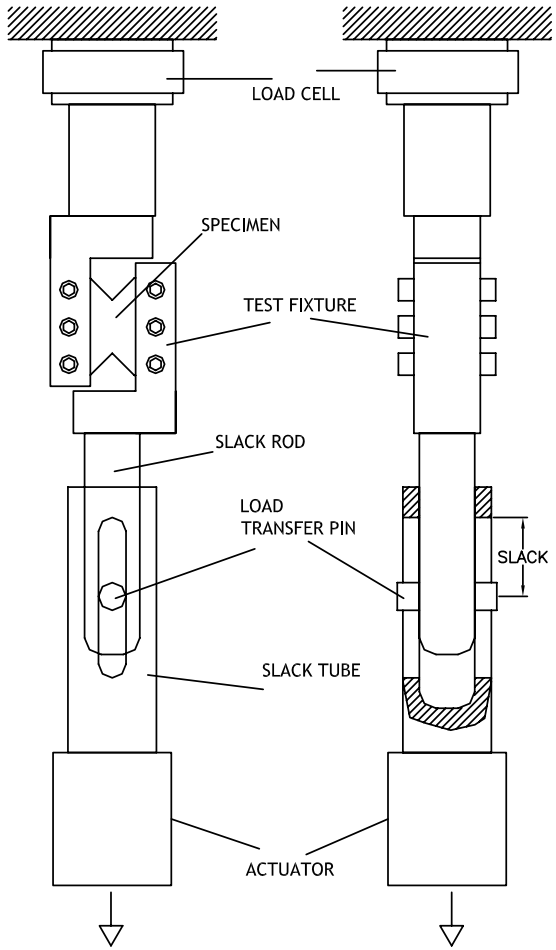


In-Plane Shear Tests

- **TEST METHOD**
  - **ASTM D 7078 V-Notch Rail Shear**
- **TEST RATES**
  - **1x10^{-4} in/s (quasi-static)**
  - **1, 10 , 100, 250 and 500 in/s**
  - **3 specimens each**

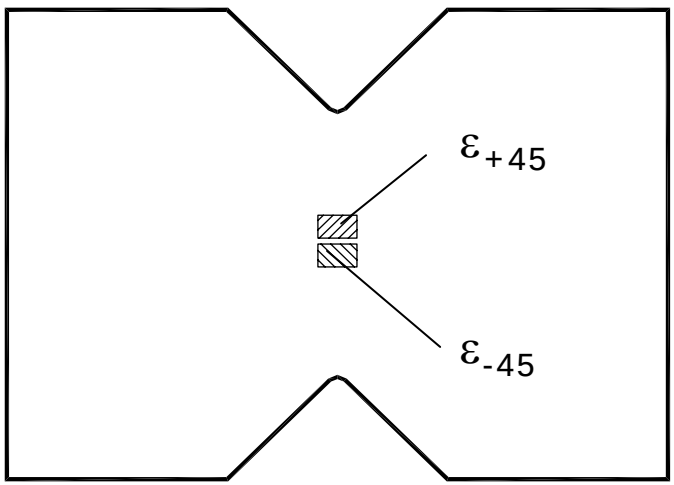


All dimensions in mm

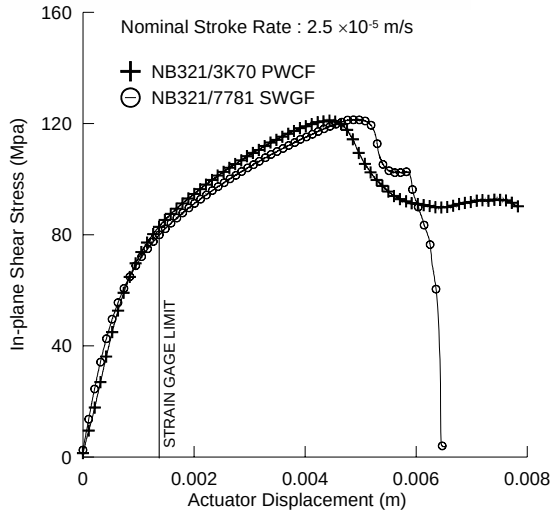


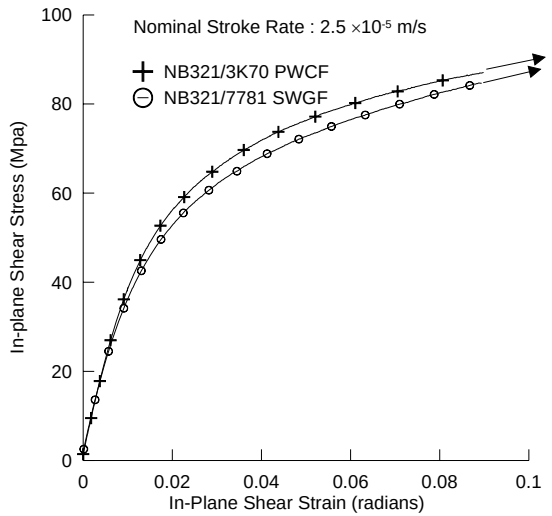
In-Plane Shear Tests

- **SHEAR STRAIN MEASURMENT**

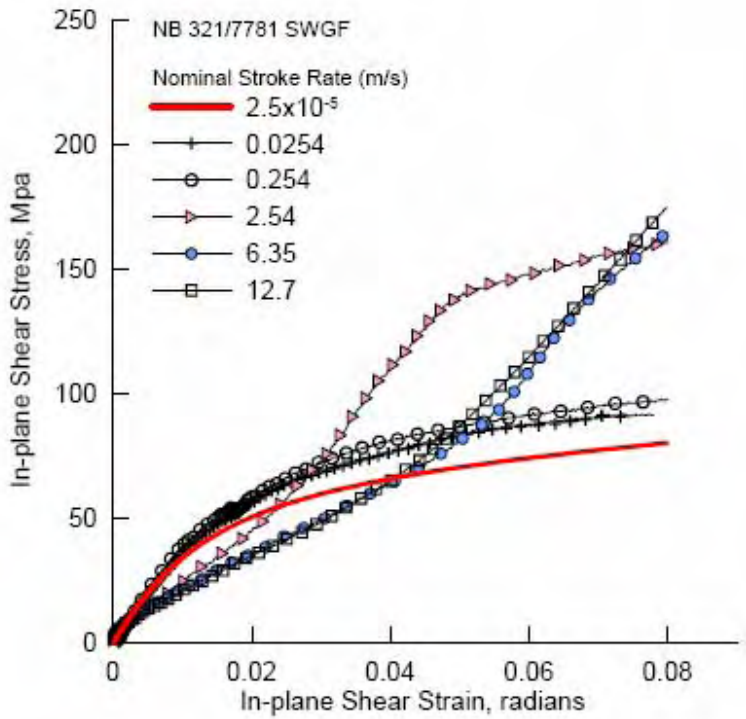


$$\gamma_{12} = \left|\varepsilon_{+45}\right| + \left|\varepsilon_{-45}\right|$$





Shear Stress-Strain Behavior



- **Shape of Shear Stress-strain curves similar for stroke rates up to 10 in/s**
  - **Stress levels increase with stroke rate**
- **Shear stress strain behavior changes at stroke rates of 100 in/s and beyond**
  - **Reduction in shear stiffness**
  - **Dynamic effects**
  - **NB321/7781 & NB321/PWCF material exhibit similar behavior up to strain levels of 0.05**
  - **Beyond shear strain of 0.05, NB321/7781 observed to stiffen at 250 and 500in/s**

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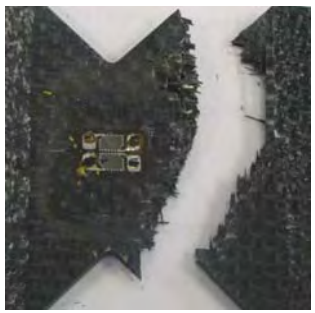
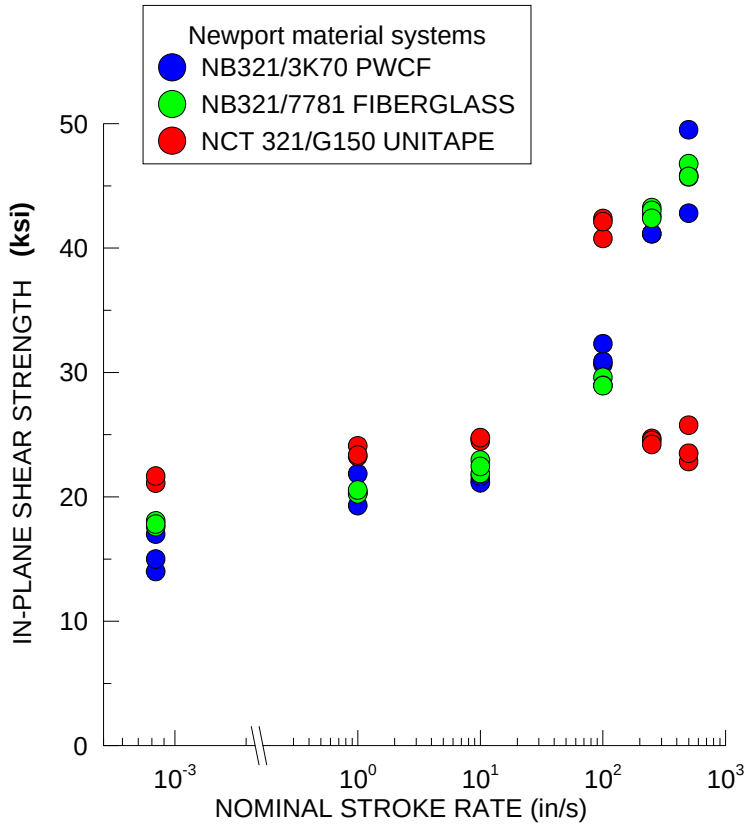
In-Plane Shear Strength

- **NEWPORT MATERIAL SYSTEMS**
  - **Fabric reinforced systems (3k70P and 7781)**
    - **Shear strength increases with stroke rate**
    - **Failure mode changes at higher rates**
  - **Unitape system**
    - **Shear strength increases up to stroke rate of 100in/s, but decrease at 250 and 500 in/s**
    - **No change in failure mode**

Quasi-static



500 in/s



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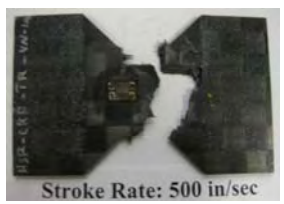
In-Plane Shear Strength

- **TORAY MATERIAL SYSTEMS**
  - **Fabric reinforced systems ()**
    - **Shear strength increases with stroke rate**
    - **Failure mode changes at higher rates**
  - **Unitape system**
    - **Shear strength increases up to stroke rate of 250 in/s, but decreases at 500 in/s**
    - **No change in failure mode**

UNITAPE



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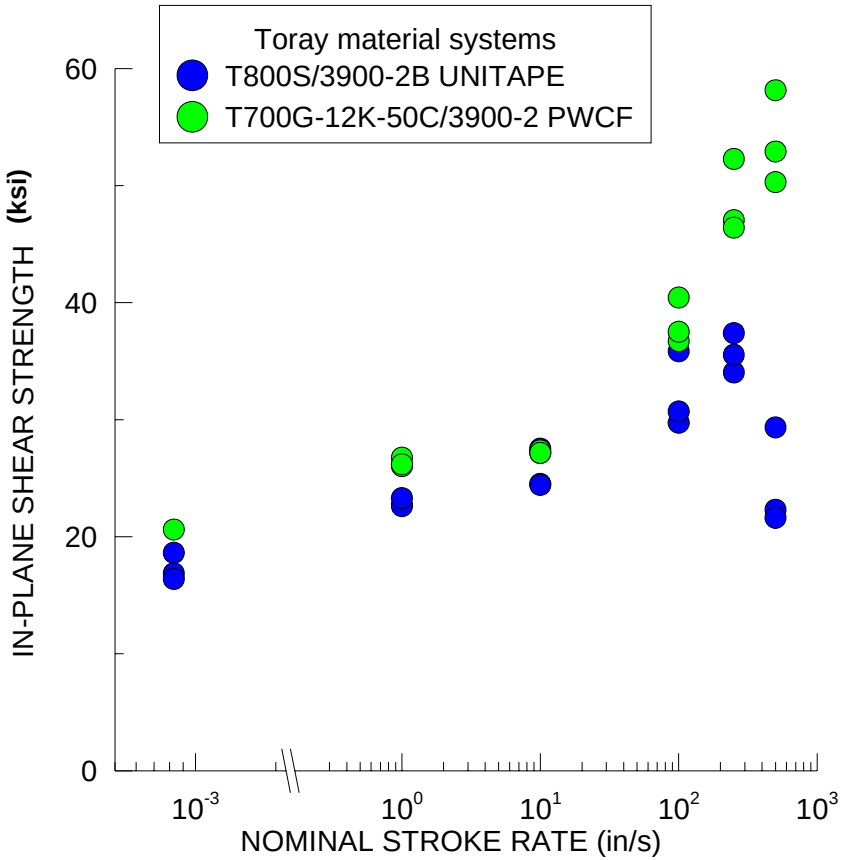
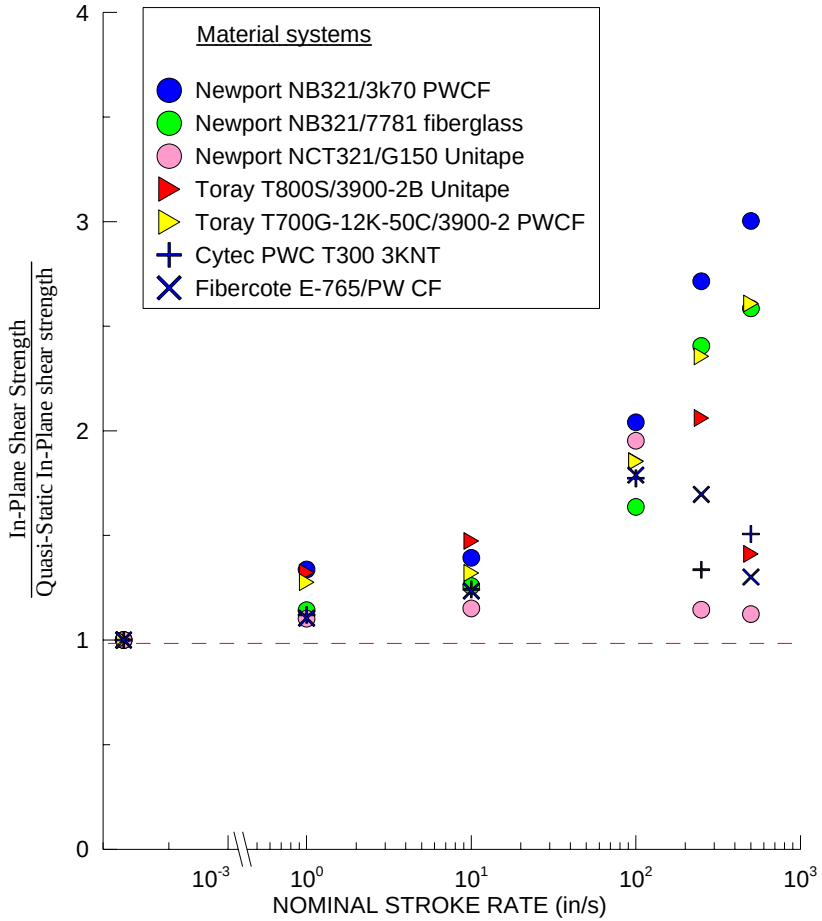


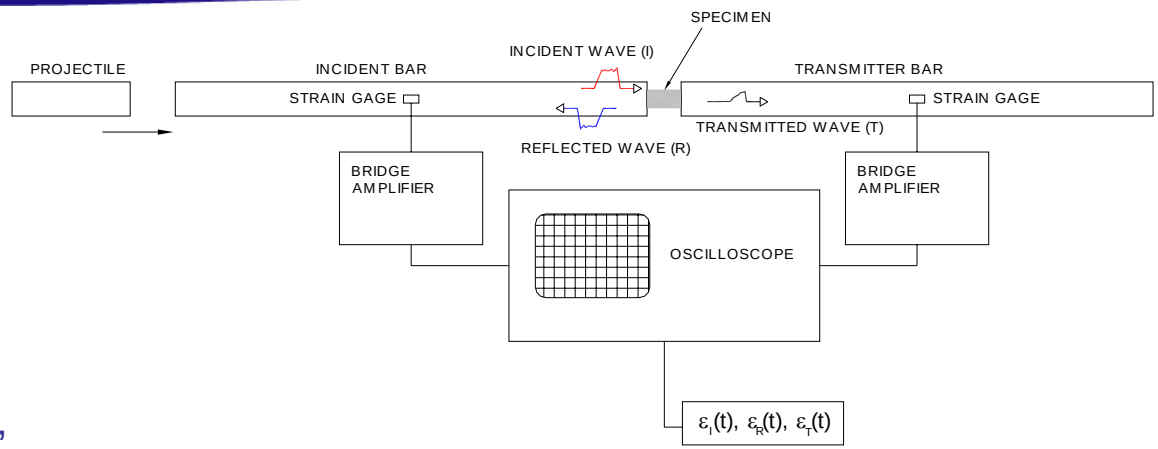
In-Plane Shear Strength

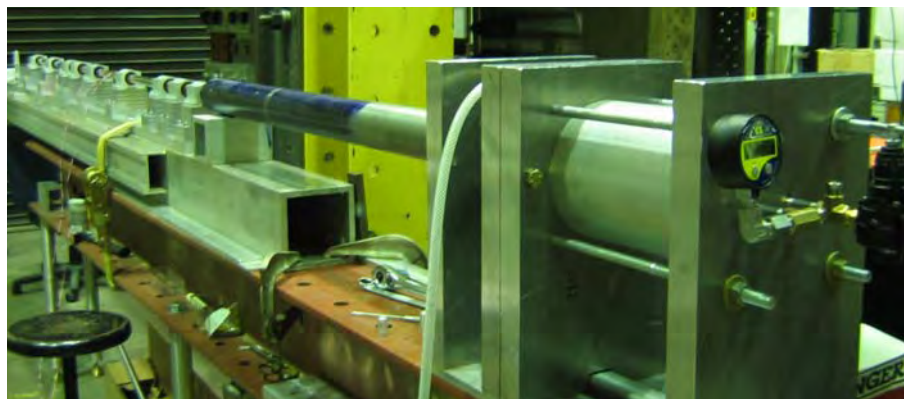
- **COMPARISON OF SHEAR STRENGTHS**
  - **Fabric reinforced systems**
    - **Shear strength increases with stroke rate**
    - **Failure mode changes at higher rates**
  - **Unitape system**
    - **Shear strength increases up to stroke rate of 250 in/s, but decreases at 500 in/s**
    - **No change in failure mode**
- **Corrections for modulation of load signal**
  - **Transfer function (under progress)**



Split-Hopkinson Pressure Bar Apparatus (SHPB)

- SPECIFICATIONS
  - Bar diameter : 1.00 inch
  - Bar Material : Vascomax 350
  - Bar lengths
    - Incident bar : 48”
    - Transmitter bar : 36”
  - Barrell length : 48 inches
  - Projectiles : 1”, 2”, 4”, 6” & 12”
    - Pneumatically driven (100 psi)
    - Velocities ~ 2000 in/s
  - PULSE SHAPING
    - Copper discs
  - DATA ACQUISITION
    - Tektronix TDS 3034 Digital Oscilloscope
  - SIGNAL CONDITIONING
    - Ectron model 778 (3 MHz bandwidth)



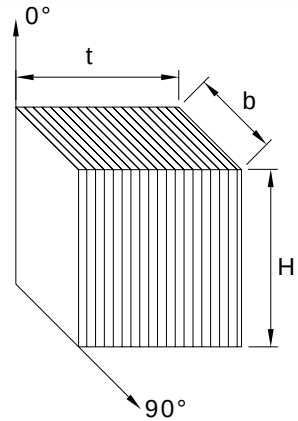


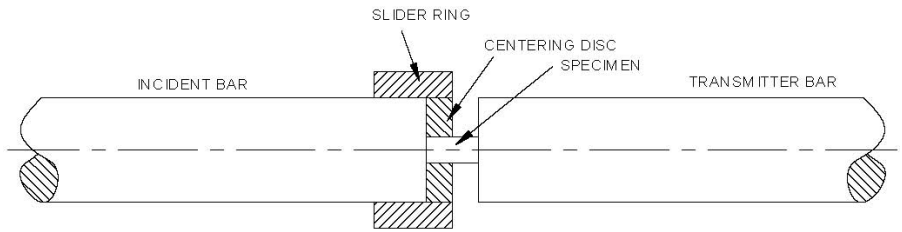
P.S.Follansee, Metals Handbook, vol.8, American Society for Metals, 1985
K.F. Graff, Wave Motion in Elastic Solids, Dover Pub., Inc.1991

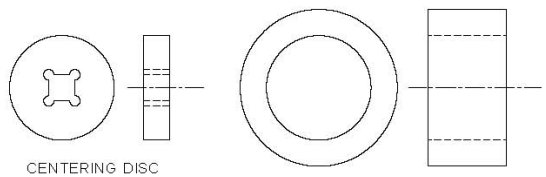
Split-Hopkinson Pressure Bar Apparatus (SHPB)

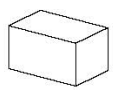
- SPECIMEN GEOMETRY*
  - Rectangular cross-section
  - Laminate thickness (t) ~ 0.17 to 0.25 inches
  - Specimen width (b) ~ 0.25 inches
  - Specimen height (H) ~ 0.25 inches

- SPECIMEN ALIGNMENT
  - Centering disc & slider ring







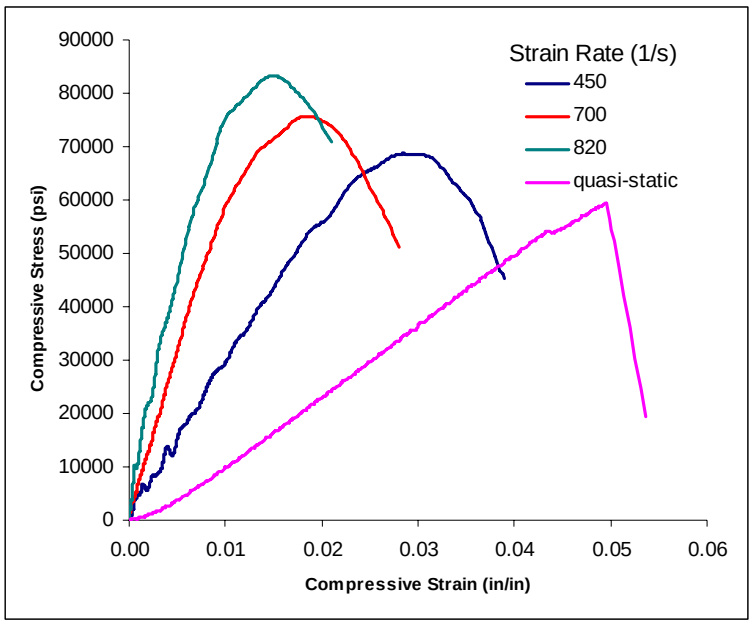


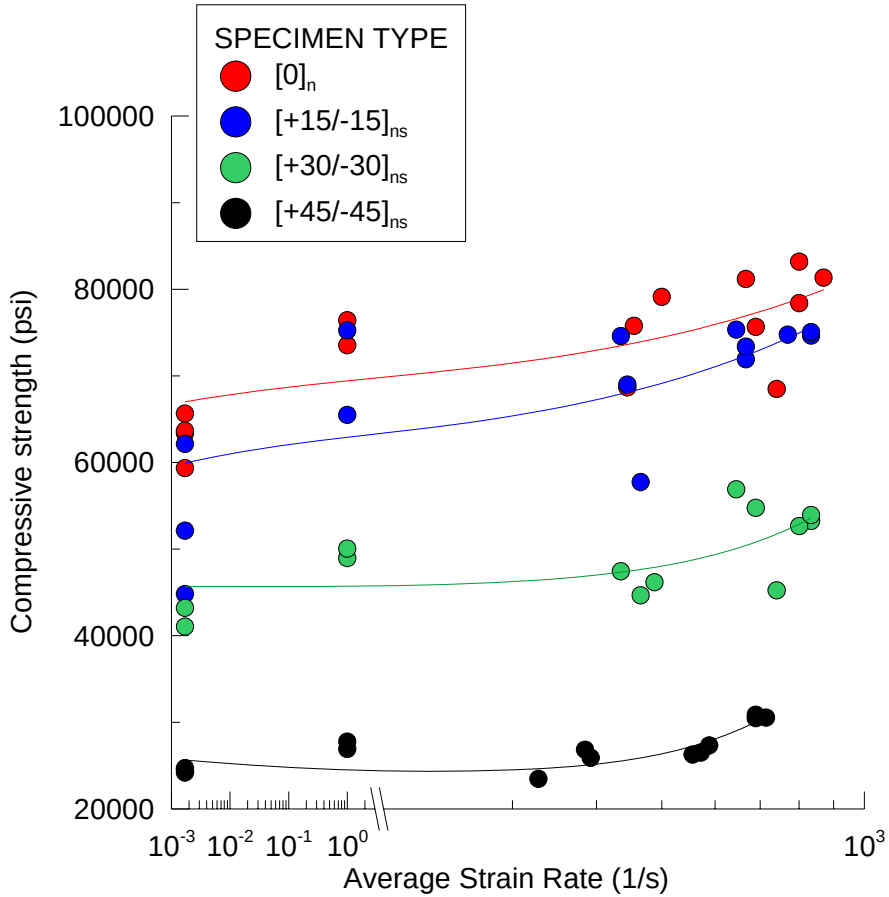
** E. Woldesenbet & J.R. Vinson, AIAA Journal, Vol.37, Sept. 1999.*

** P.S.Follansee, Metals Handbook, vol.8, American Society for Metals, 1*

Compression Test Results

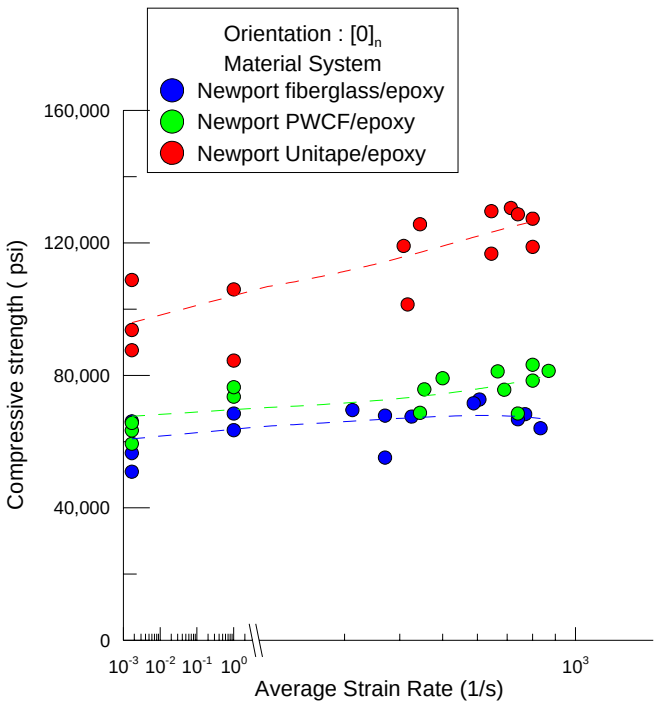
- Newport NB321/7781 fiberglass
  - Increasing trend observed for all laminate types
  - Strength increase less pronounced compared to tensile loading.
    - Maximum strength increase at strain rate of ~800 s^{-1} is about 1.25 times the quasi-static value

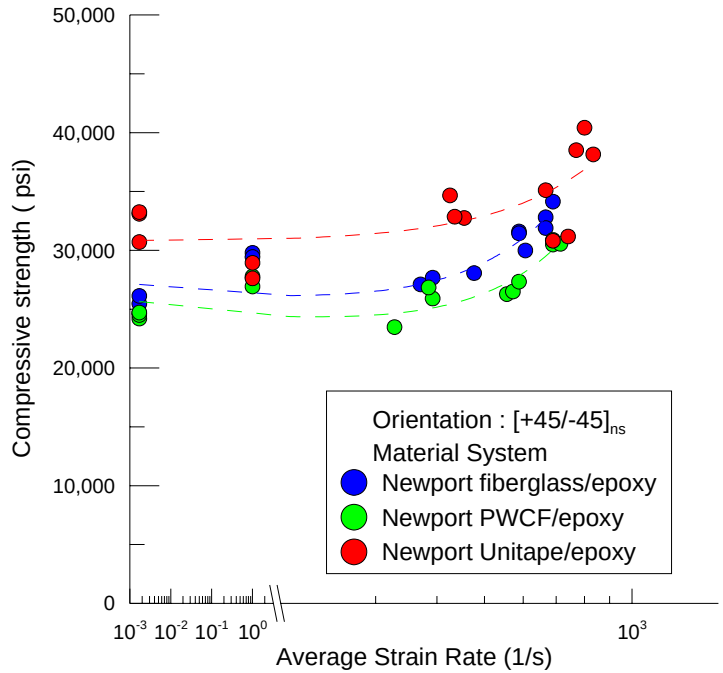




Compression Test Results

- Newport NB32/xxxx material systems
  - Unidirectional tape more rate sensitive than fabric reinforced system
  - Compresive strength tends to reach a limit as strain rate approaches 10^3 s^{-1}



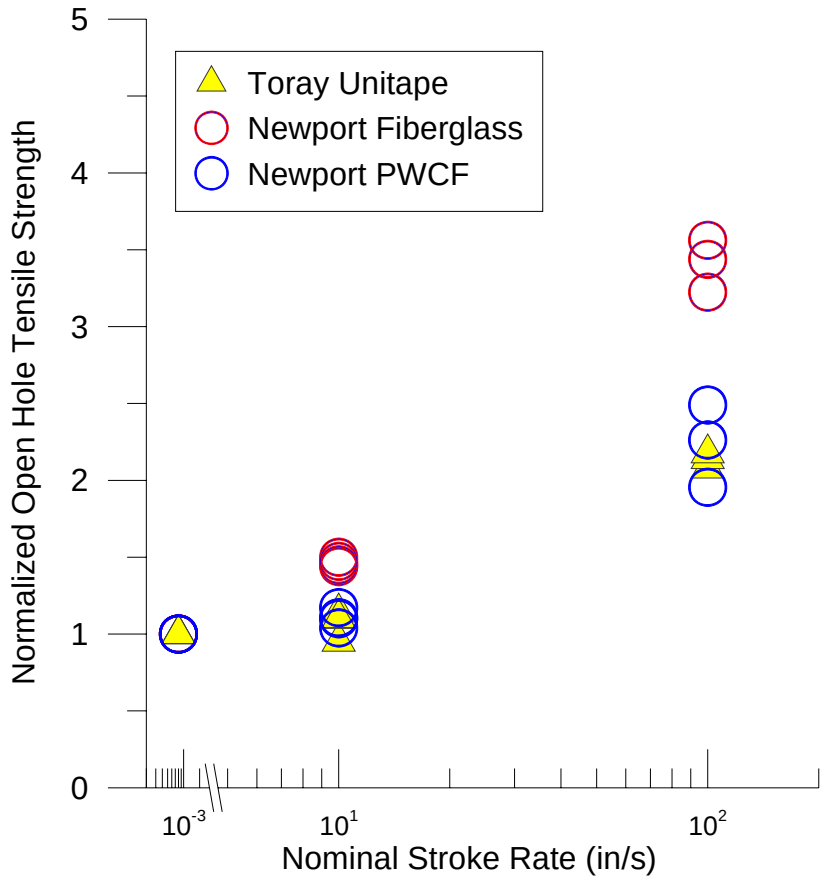


- Newport NB321/xxxx material systems
  - Rate sensitivity of $[+45/-45]_{ns}$ specimens follow similar trends for different reinforcement types
  - Compressive strength exhibits an increasing trend as strain rate approaches 10^3 s^{-1}

Open-Hole Tension

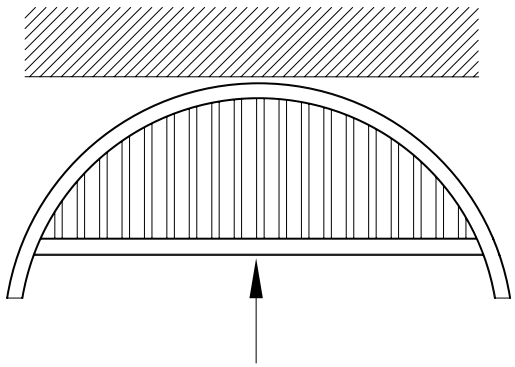
- **Material Systems**
  - Newport NB321/7781 fiberglass
  - Newport NB321/3k70 PWCF
  - Toray T700G-12K-50C/3900-2 PWCF
- **Hole diameter : 0.25 inches (w/d = 3)**
- **Test speeds : quasi-static, 1 in/s and 100 in/s**

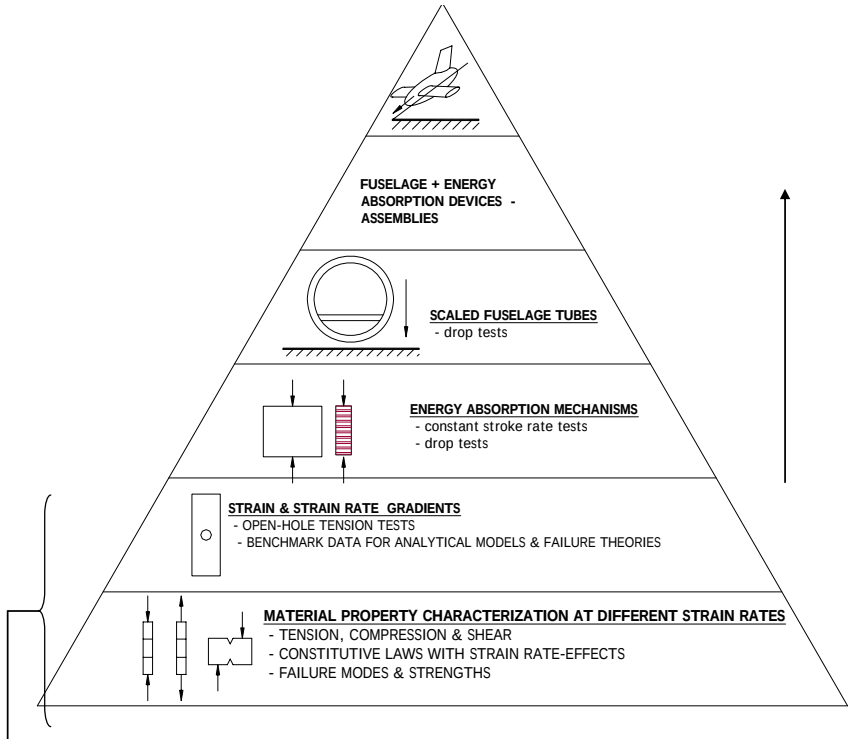
- **RESULTS**
  - Open-hole tensile strength observed to increase with test speed
  - Newport fiberglass material exhibited highest increase in open-hole strength
  - No significant change in failure modes



Current Phase

- INTERLAMINAR SHEAR
- PIN BEARING
- FLEXURE
  - Laminated and sandwich beams
  - 4-point flexure tests
- CYLINDRICAL FUSELAGE SECTIONS
  - Compression tests

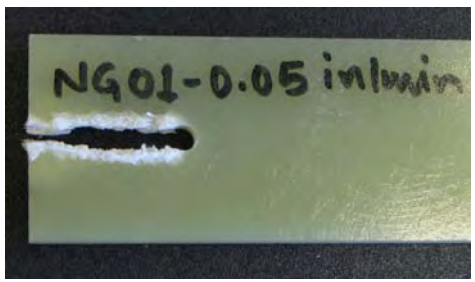


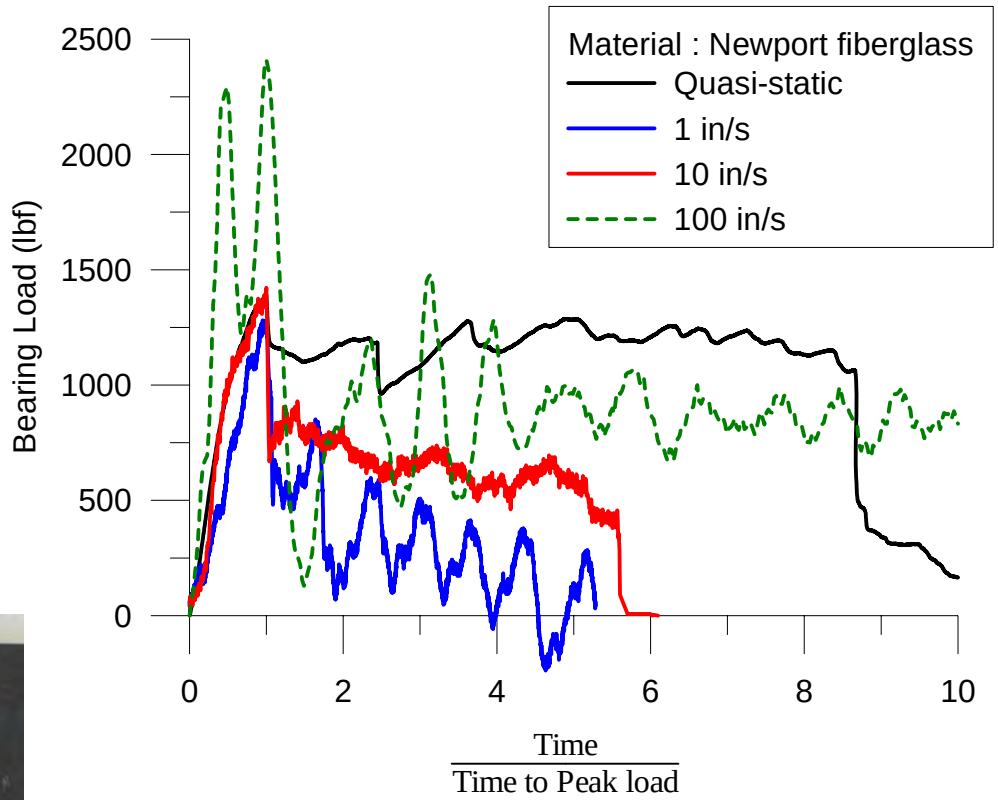


Pin-Bearing Response

- **Material Systems**
  - Newport NB321/7781 fiberglass
  - Newport NB321/3k70 PWCF
  - Toray T700G-12K-50C/3900-2 PWCF
- Laminate type
  - $[45/0/45/0/45]_s$
- **Pin diameter : 0.125 inches**
- **Test speeds : quasi-static, 1 ,10,100, and 250 in/S**

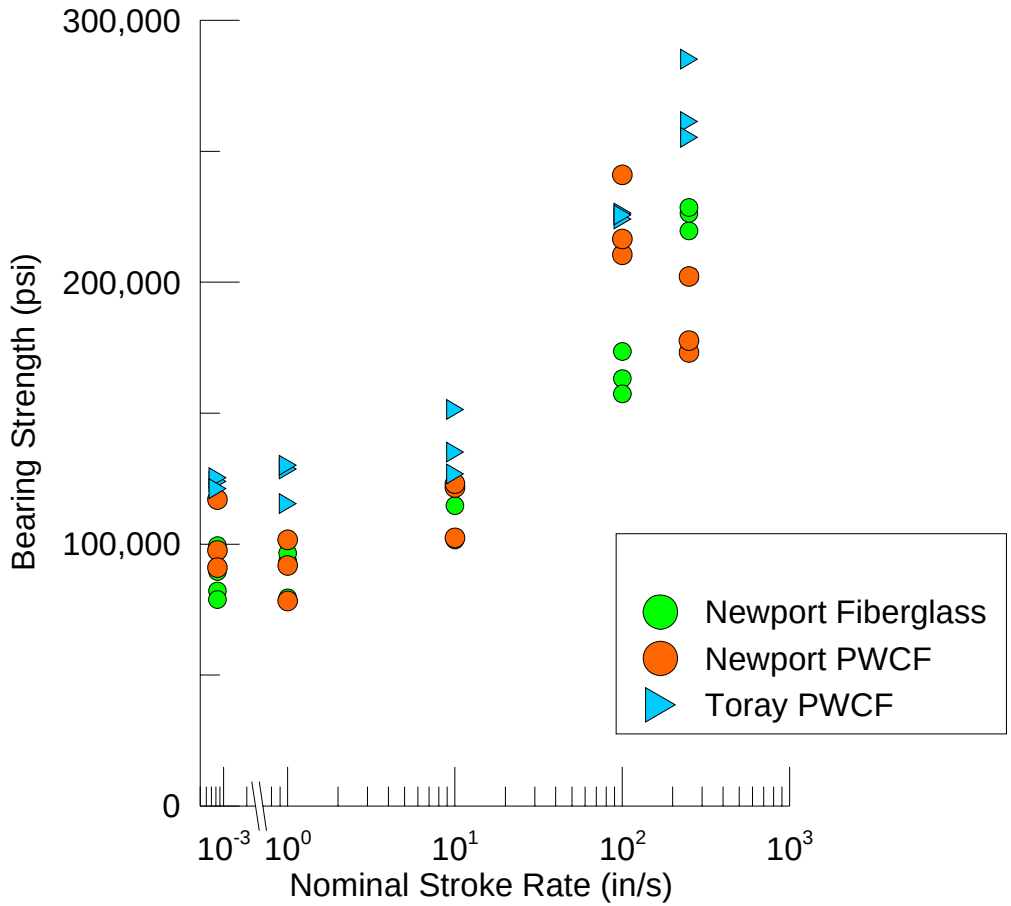
- **RESULTS**
  - **Sustained loading past initial failure, decreases at higher rates of loading**
  - **Failure mode**





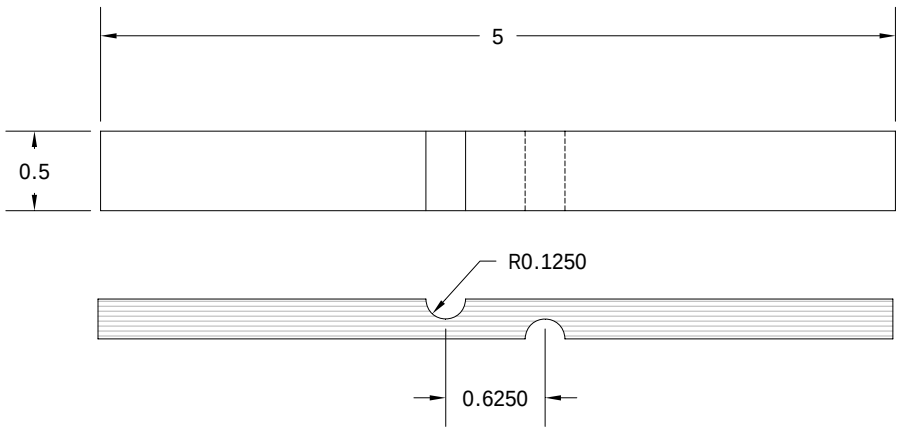
Pin-Bearing Response

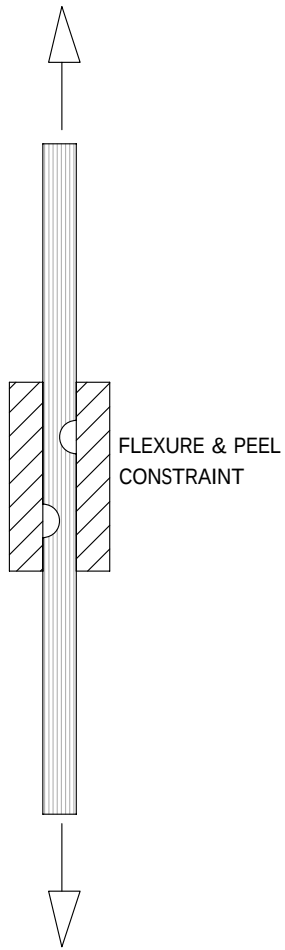
- **RESULTS**
  - **Bearing strengths based on peak recorded load**
    - **Hole deformation not measured**
  - Pin bearing strength increases with test speed



Interlaminar Shear

- **Specimen Geometry**
  - **Lap shear ~ Tensile loading**
- **Material Systems**
  - Newport NB321/7781 fiberglass
  - Newport NB321/3k70 PWCF
  - Toray T700G-12K-50C/3900-2 PWCF
- **STATUS**
  - **Testing under progress**



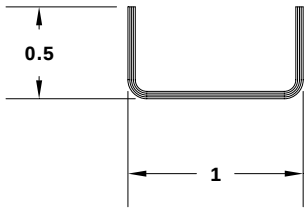


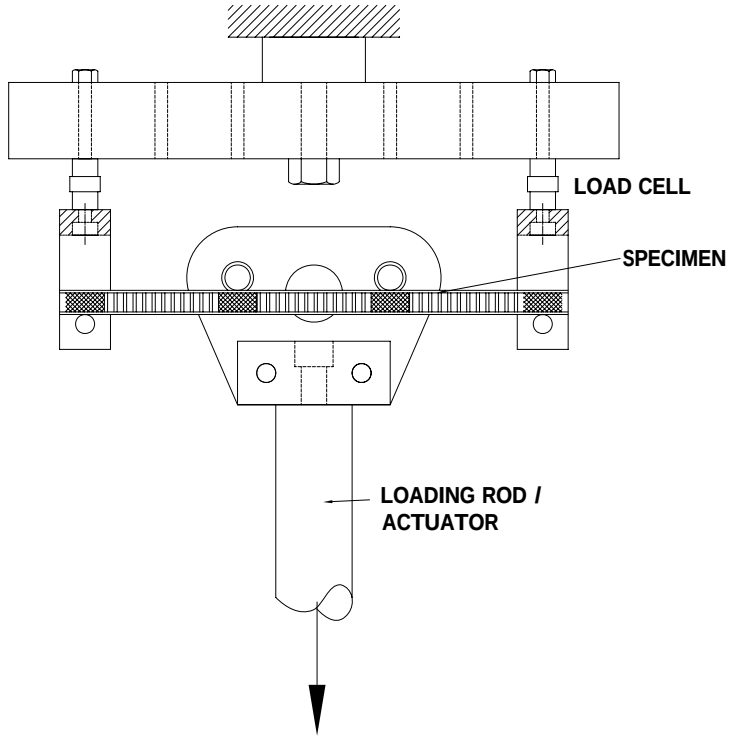
Flexure Tests

- **LAMINATED BEAMS**
  - **Material systems**
    - Newport NB321/7781 fiberglass
    - Newport NB321/3k70 PWCF
  - Layup sequence
    - [0/45/45/0]

- SANDWICH BEAMS
  - Material systems
    - Newport NB321/7781 fiberglass
    - Newport NB321/3k70 PWCF
  - Layup sequence
    - $[0/45/0/45/CORE]_S$

- STATUS : Testing under progress





A Look Forward

- Benefit to Aviation
  - Understanding of strain-rate effects on composite material properties. Material properties can be used in simulations involving high-strain rates
  - Off-axis, Open-hole, flexure and bearing data could be used as benchmarks for material models
  - Data can be used in dynamic applications
    - Eg. Impact analysis
- Future needs
  - Fracture toughness
  - Energy absorption devices
    - Tubes
    - Subfloor beams