CRASHWORTHINESS OF COMPOSITE FUSELAGE STRUCTURES -Material Dynamic Properties

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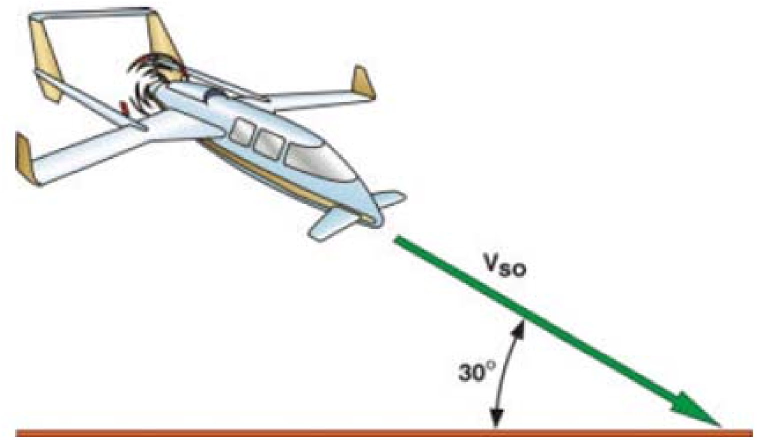
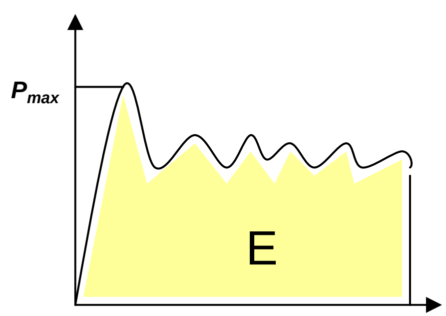
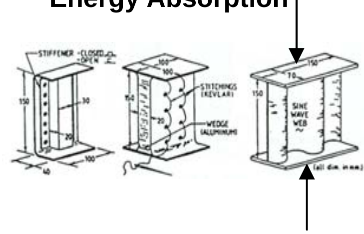
Background

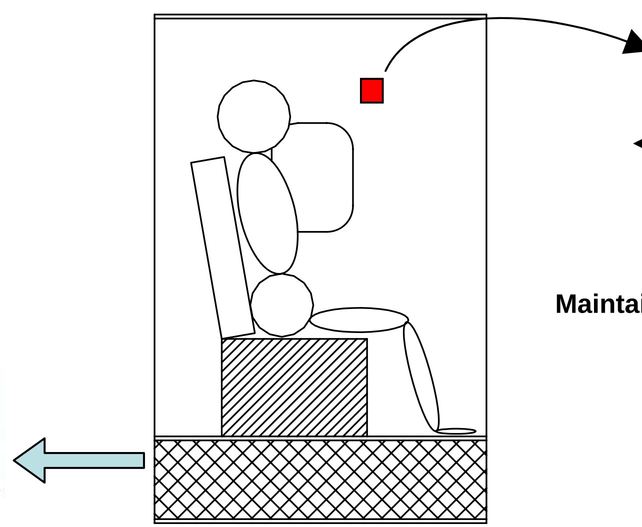
- Crashworthiness
  - Maintain survivable volume
  - Alleviate occupant loads
- Energy Absorption
  - Metals – Plastic deformation
  - Composites – controlled failure modes
- Factors affecting energy absorption
  - Geometry (?)
  - **Strain rate (?)**

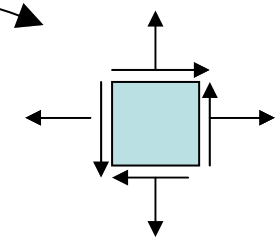




Energy Absorption



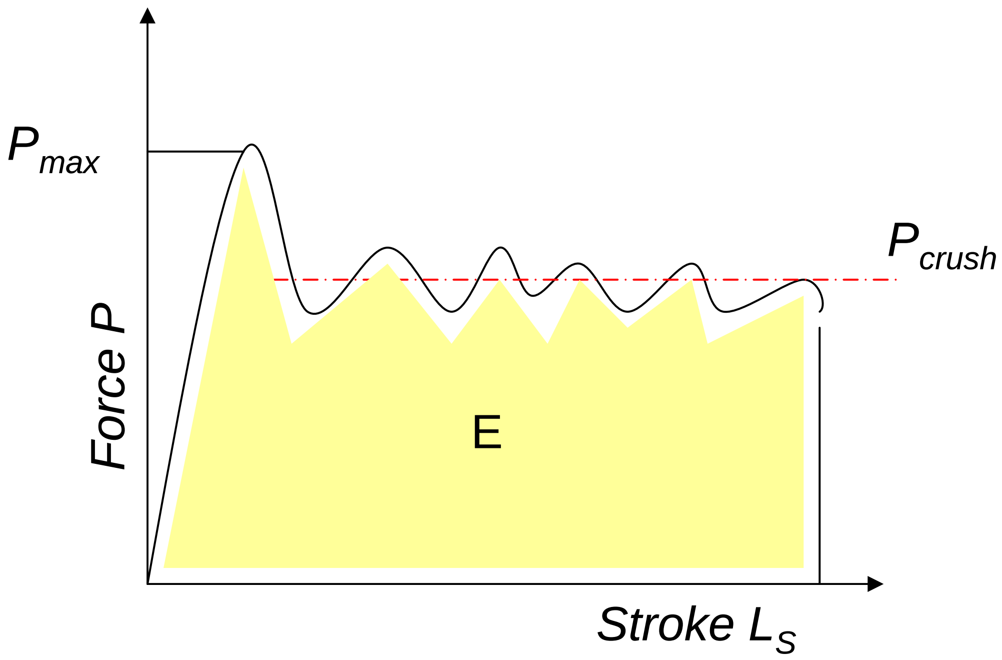




Maintain survivable volume

Energy Absorption in Composites

- Maximize energy dissipated due to formation of surfaces
  - Matrix cracks, delaminations, fiber-matrix interface failure, fiber fractures
  - Maximize the damage volume {multiple locations of damage}
- Minimize reduction /loss of load path
  - Provision for sustained stability

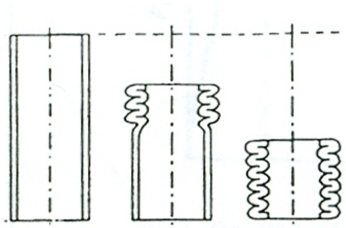


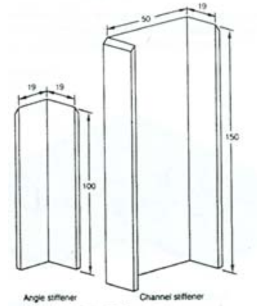
Maximization bounded by *"stability"* of the transmitting structure/device and availability of crush space

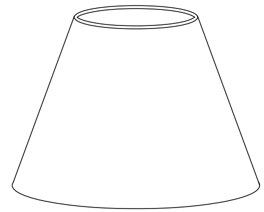
Maximization bounded by *"safe loads"* that can be transmitted

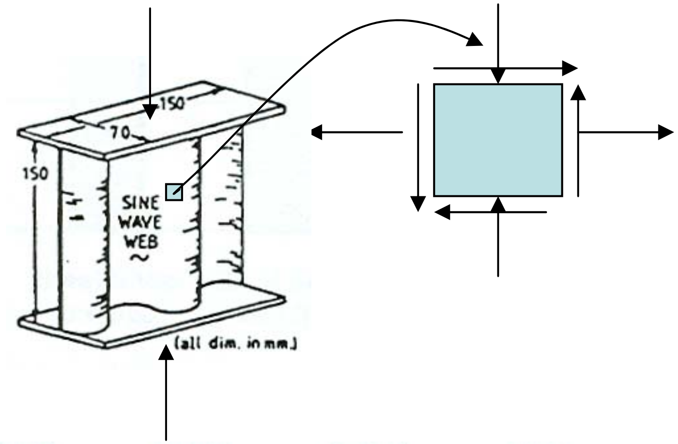
$$E = \int_0^{L_S} P d\delta$$

Energy Absorption Devices









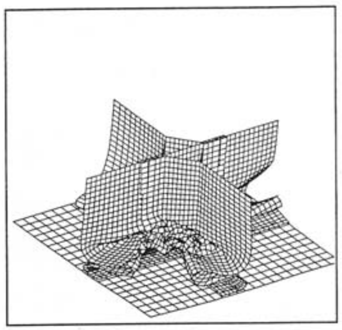


Figure 11. Finite elelment simulation of HTP-cruciform under impact at 10 m/s.

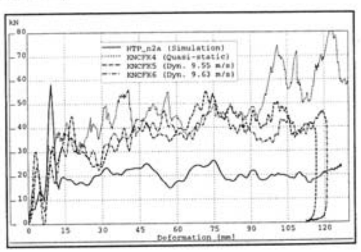
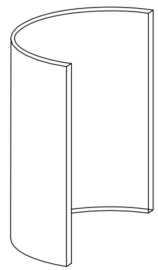
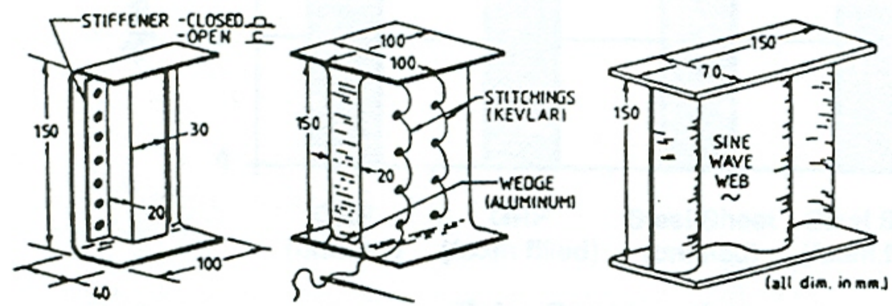


Figure 12. Load-deflection response of HTP-cruciforms under impact-comparison of finite element simulation and test data.





-Rate effects are evident (+ or -) but in terms of stroke rate

-Strain rates not reported /measured (?)

-Strain rate not proportional to stroke rate due to complexity of localized deformation & Strain gradients

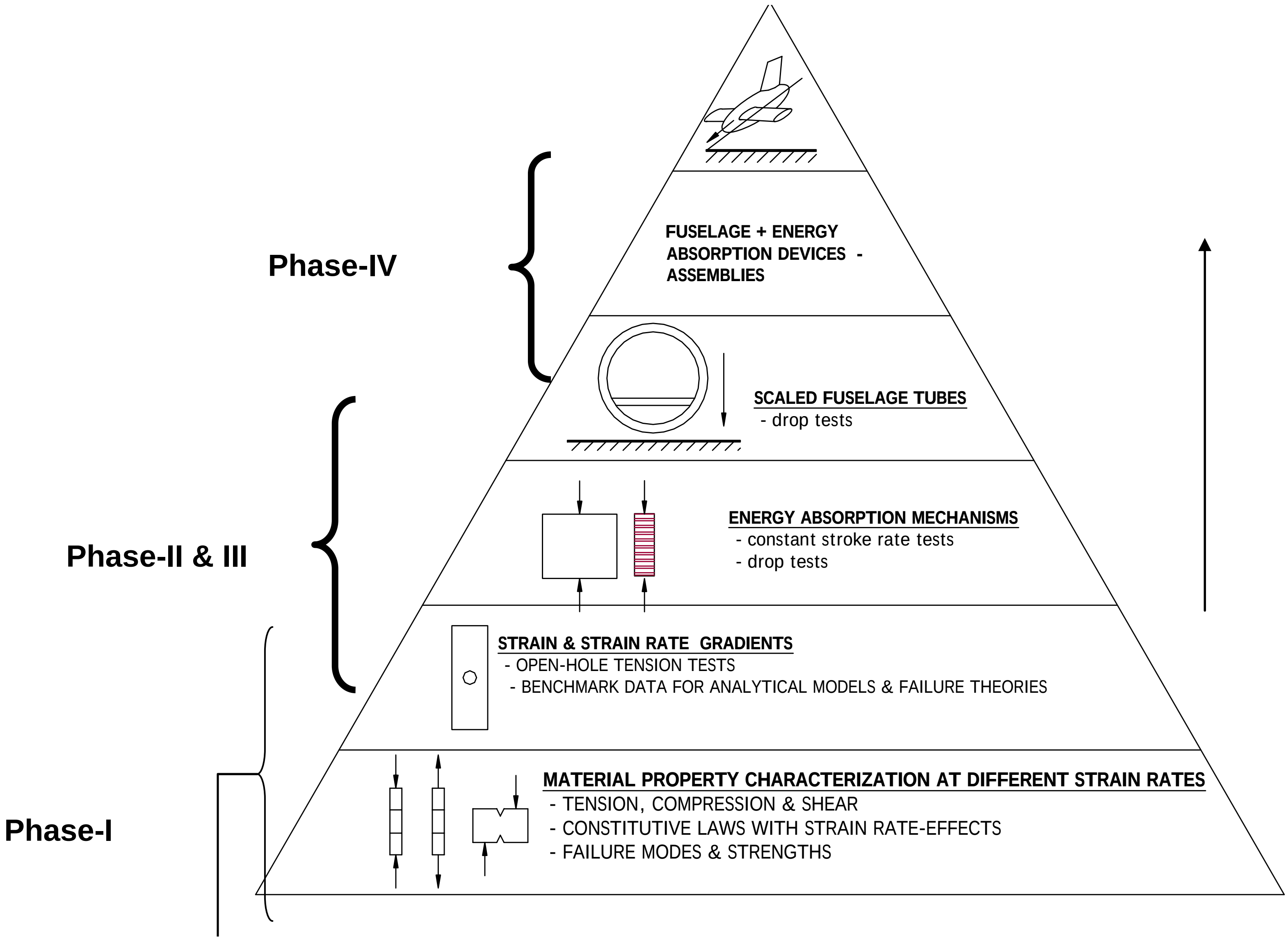
Hull D (1991) Comp. Sci Tech, 40.

Bannerman & Kindervater (1984) in Structural Impact and Crashworthiness

Bolukbasi & Laananen (1995) Composites, 26.

Carruthers, Kettle & Robinson (1998) Appl Mech Rev, 51.

APPROACH


Phase-IV
Phase-II & III
Phase-I
FUSELAGE + ENERGY ABSORPTION DEVICES - ASSEMBLIES
SCALED FUSELAGE TUBES
- drop tests
ENERGY ABSORPTION MECHANISMS
- constant stroke rate tests
- drop tests
STRAIN & STRAIN RATE GRADIENTS
- OPEN-HOLE TENSION TESTS
- BENCHMARK DATA FOR ANALYTICAL MODELS & FAILURE THEORIES
MATERIAL PROPERTY CHARACTERIZATION AT DIFFERENT STRAIN RATES
- TENSION, COMPRESSION & SHEAR
- CONSTITUTIVE LAWS WITH STRAIN RATE-EFFECTS
- FAILURE MODES & STRENGTHS

Tasks..

- Phase-I
  - 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)
    - $[0°/90°]_{ns}$

- PHASE-II
  - Open- Hole Tension
  - Pin Bearing
  - Interlaminar Shear
  - Flexure
  - Scaled Fuselage sections

- PHASE-III

- Fracture Toughness

- PHASE-IV

- EA device

Material Systems

- Material systems selected by FAA/industry participants
  - State of Kansas (NIAR.INDUSTRY.STATE) funding
    - Boeing, Spirit Aerosystems, Hawker BeechCraft (Raytheon), Cessna
  - FAA personnel involved
    - Allan Abramowitz, Curtis Davies, J. Zvanya
  - Wide range of materials

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

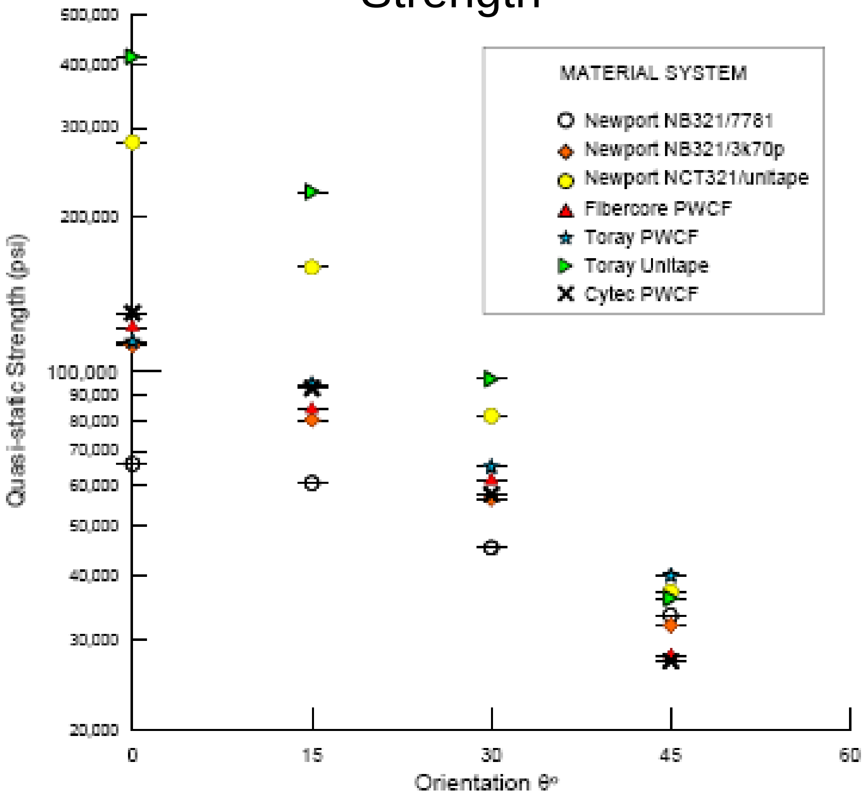
  - Toray T800S/3900-2B[P2352W-19] BMS8-276 Rev-H- Unitape*
  - Toray T700G-12K-50C/3900-2 Plain Weave Carbon Fabric*

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

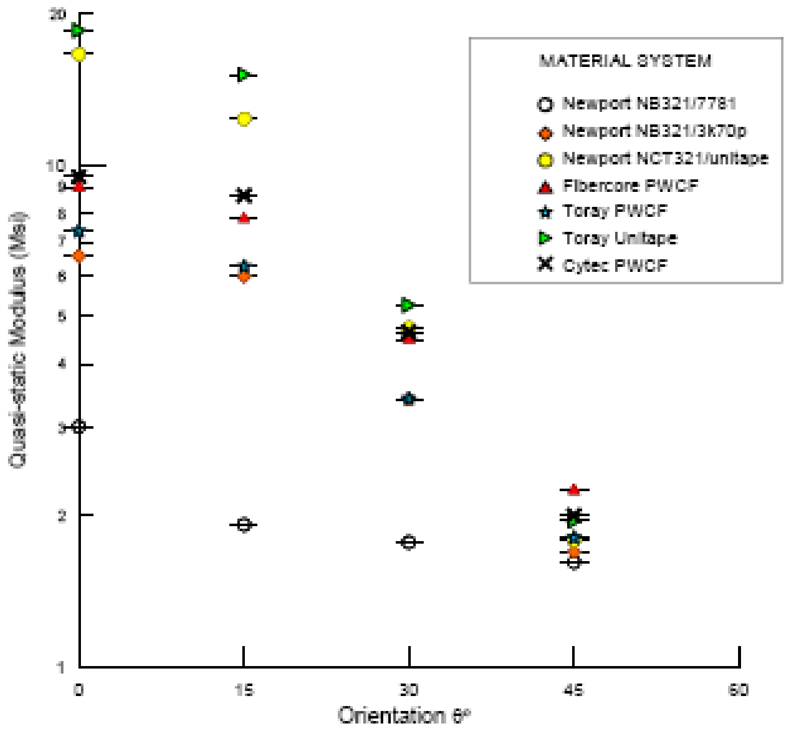
- Material systems for phase-II and beyond limited to Newport & Toray systems

Tensile Properties … Quasi-Static Loading

Strength



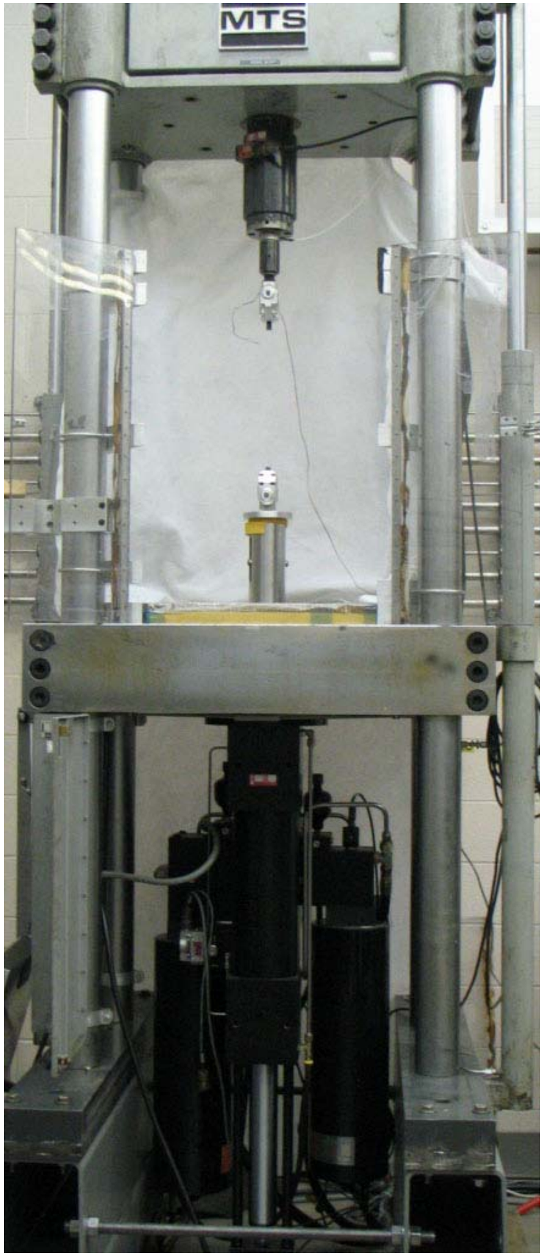
Modulus



TEST APPARATUS

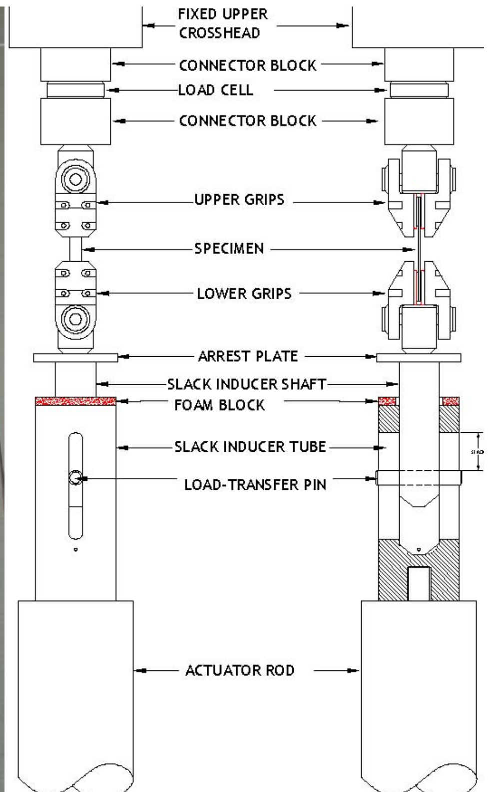
- TENSION MODE TESING
    - Tension, shear and flexure tests

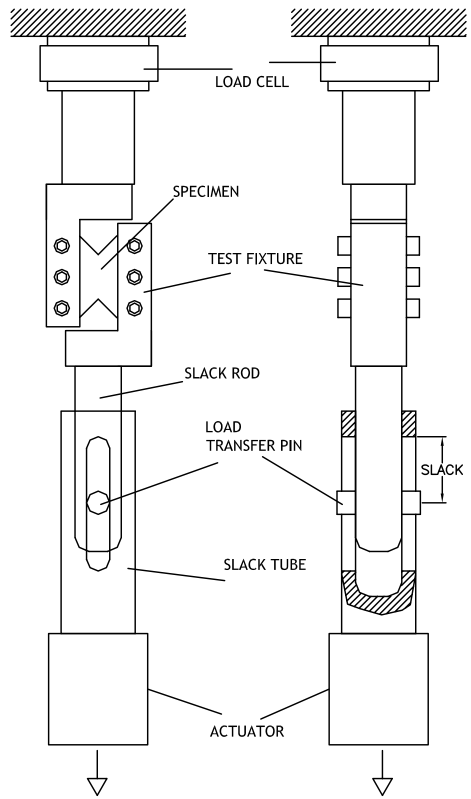
- MTS High Stroke Rate System (MTS-HSRS)
    - Stroke rate ~ 500 in/sec
    - +/- 7 inches stroke
    - Load capacity
        - 5 kips @ rated speed
        - 9 kips maximum
    - Load measurement
        - Piezoelectric load cells
            - +/- 0.5kip, +/- 1kip, +/- 10kips
    - National Instruments PCI 6110 DAQ
        - 4 Channels
        - 5 MHz (simultaneous sampling)
        - 12 bits resolution
    - Test control
        - MTS MultipurposeTestware computer program



TEST APPARATUS

- TENSION MODE TESING
  - Tension, shear and flexure tests



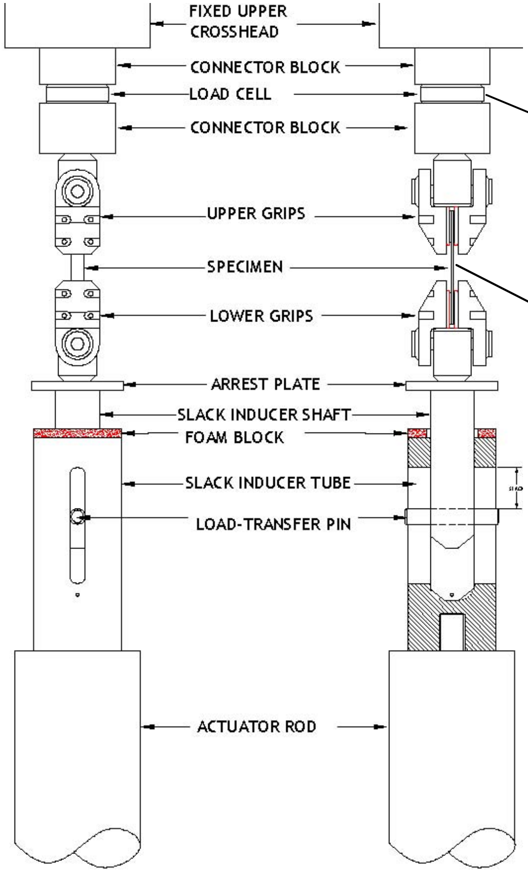


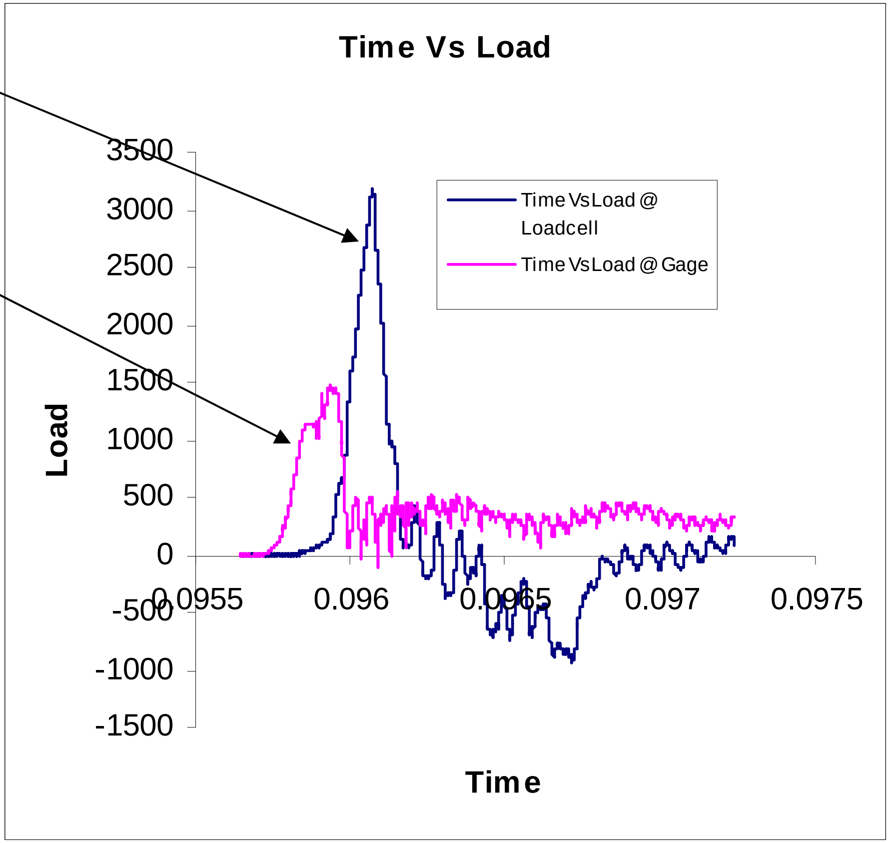
- SLACK INDUCER MECHANISM
  - –Allows actuator acceleration to desired speed prior to loading the specimen
- LOW-MASS GRIPS
  - –mechanical wedge grips
  - –2.4 lbs
  - –15 kip capacity

Davis, E.A., Trans. ASME, 60, 1938
Elam, C.F., Proc. Roy. Soc. Lond., A, 165, 1938
ManJoine, M.J., Trans. ASME, 66, 1944 A-21
Milkowitz, J., Trans.ASME, 69, 1947 A-21
Morrison, J.L., Engineer, Lond., 158, 1934

TENSION TEST APPARATUS

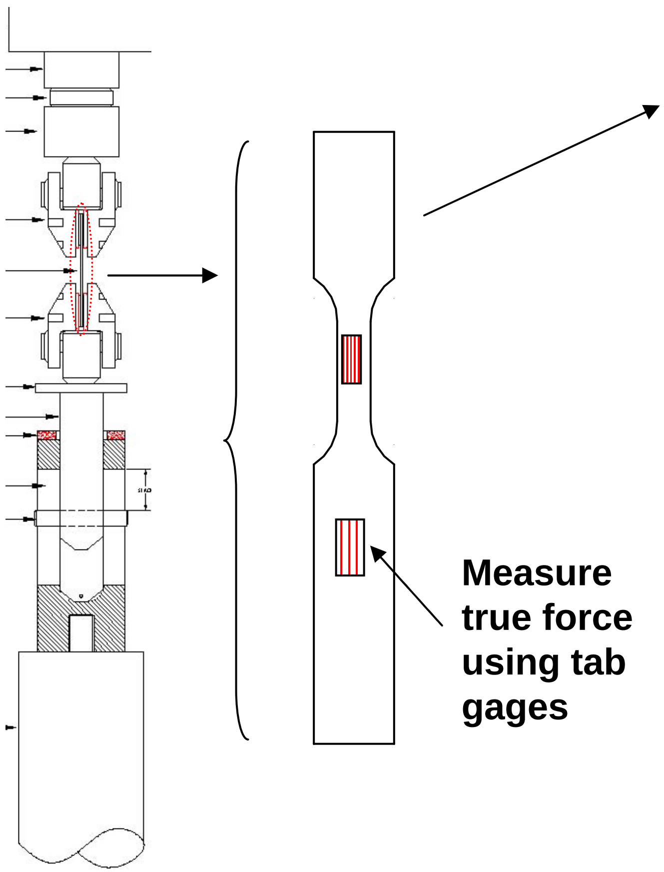
- Signal Modulation

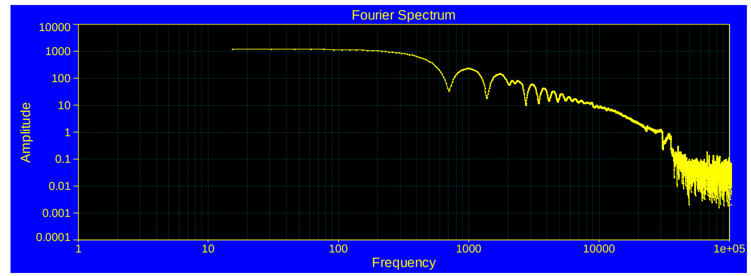


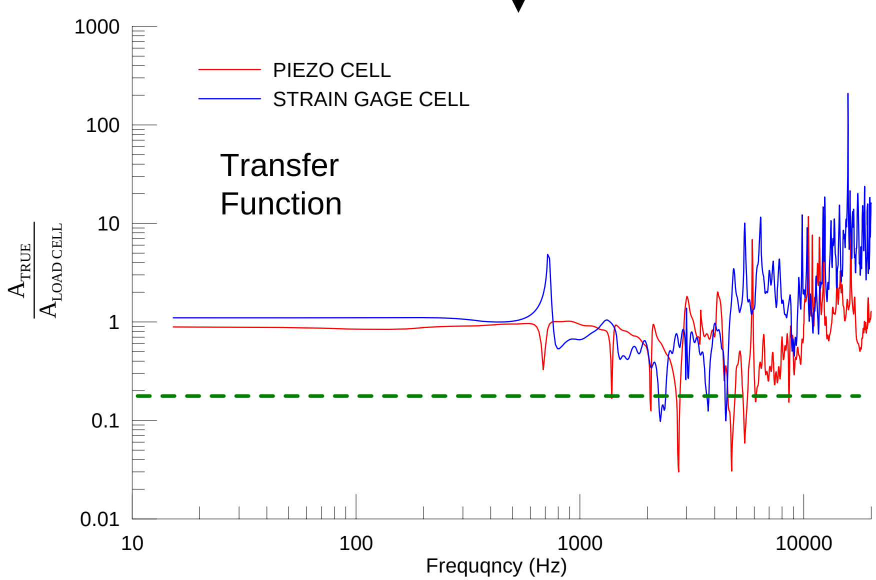


Tension testing – Signal Modulation

- Correction using Experimentally determined Transfer Function



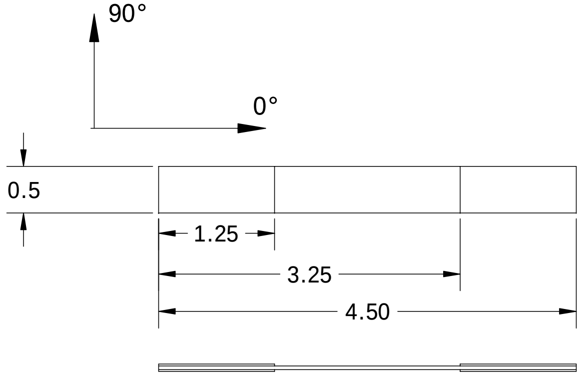


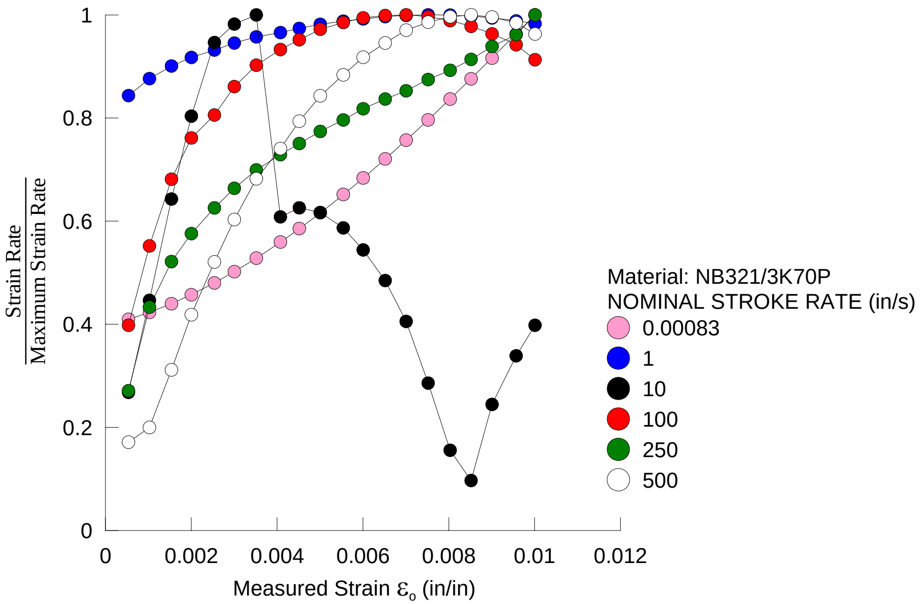


L.D. Mitchell, " Signal Processing and the FFT Analyzer – A Survey," IJMA, Jan. 1986

Tension Testing

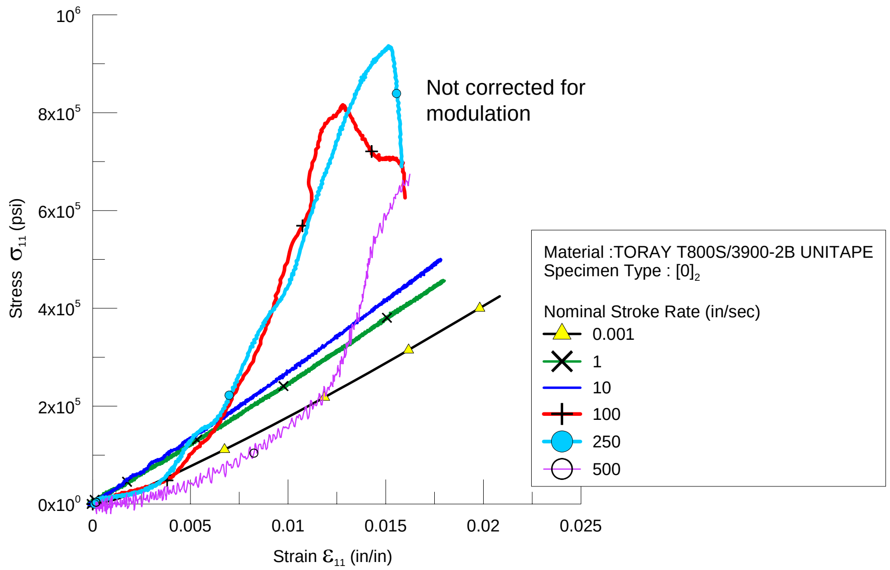
- SPECIMEN GEOMETRY
  - 2 inch gage length
  - 0.5 inch width
  - Thickness limited by loading capacity of the testing machine
- TEST RATES
  - 1×10^{-4} in/s (quasi-static)
  - 1, 10 , 100, 250 and 500 in/s
  - 3 specimens each
- CONSTANT STROKE RATE TESTS
  - Based on actuator displacement
  - Strain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

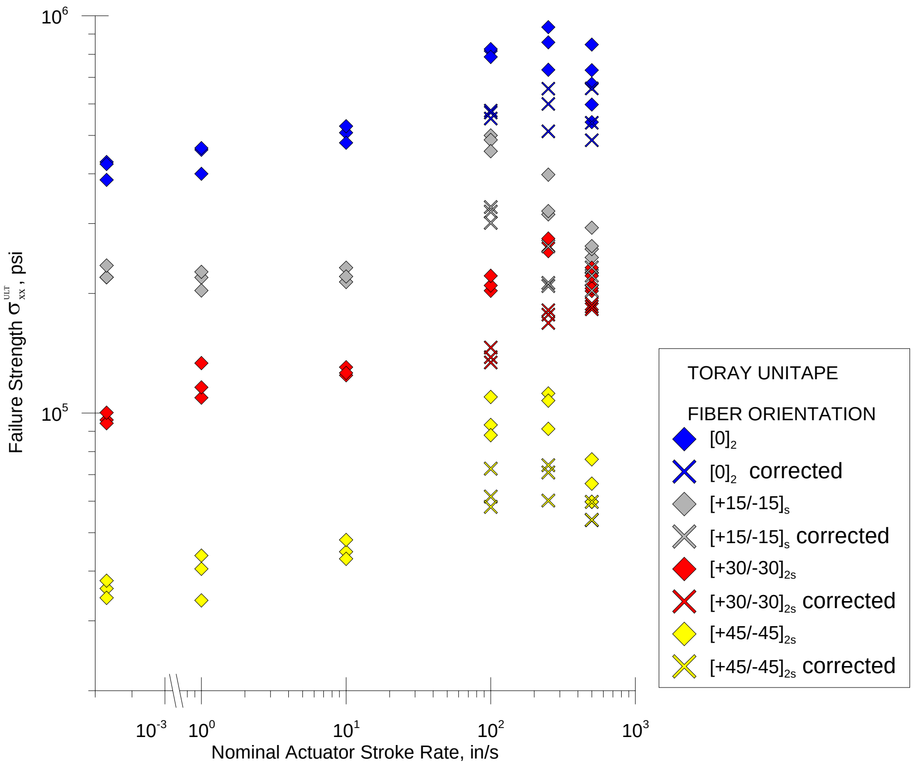




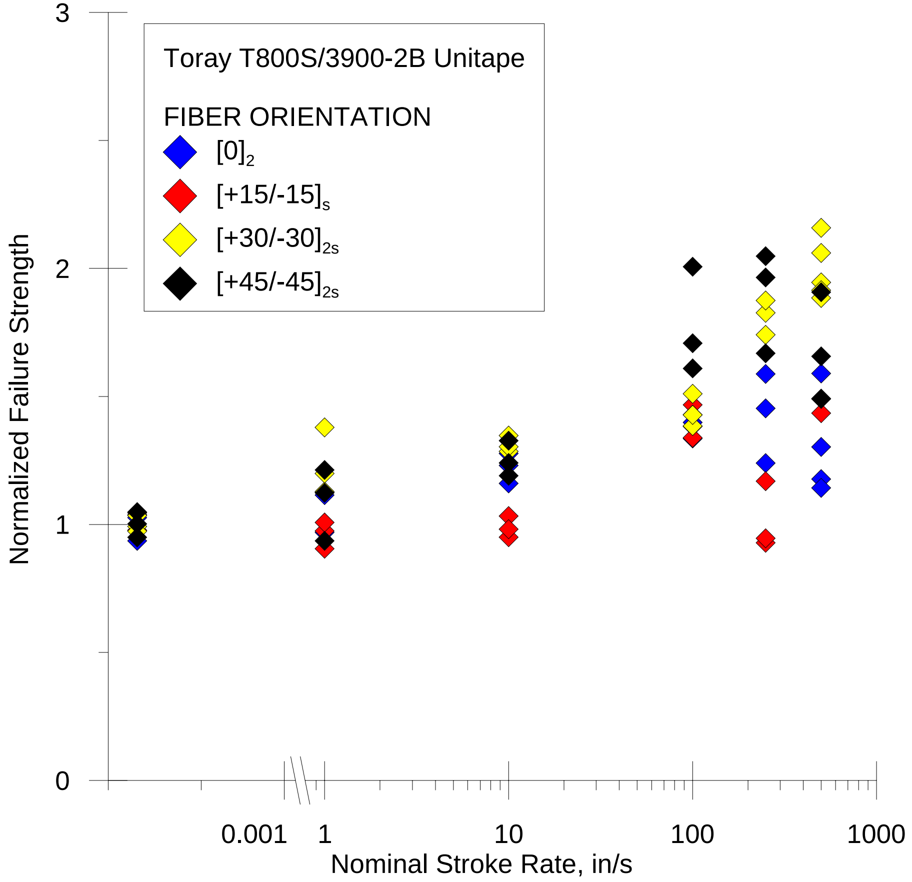
Tension testing – Results

- Maximum strain rate achieved ~ 250/s
- Tensile Strengths
  - –Tension strength was observed to increase with stroke (strain) rate for all material systems & orientations
  - –Magnitude of strength increase was dependent on fiber orientation and material system
  - –Newport NB321/7781 fiberglass material exhibited highest strength increase amongst the materials tested

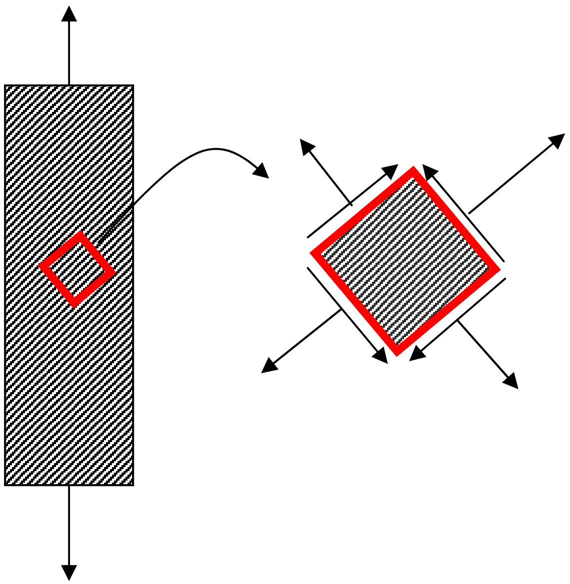




Effects of Combined State of Stress

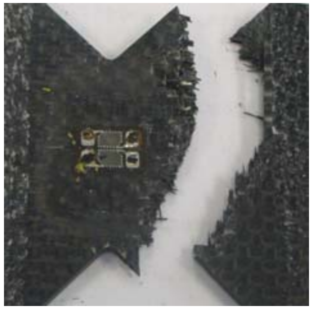


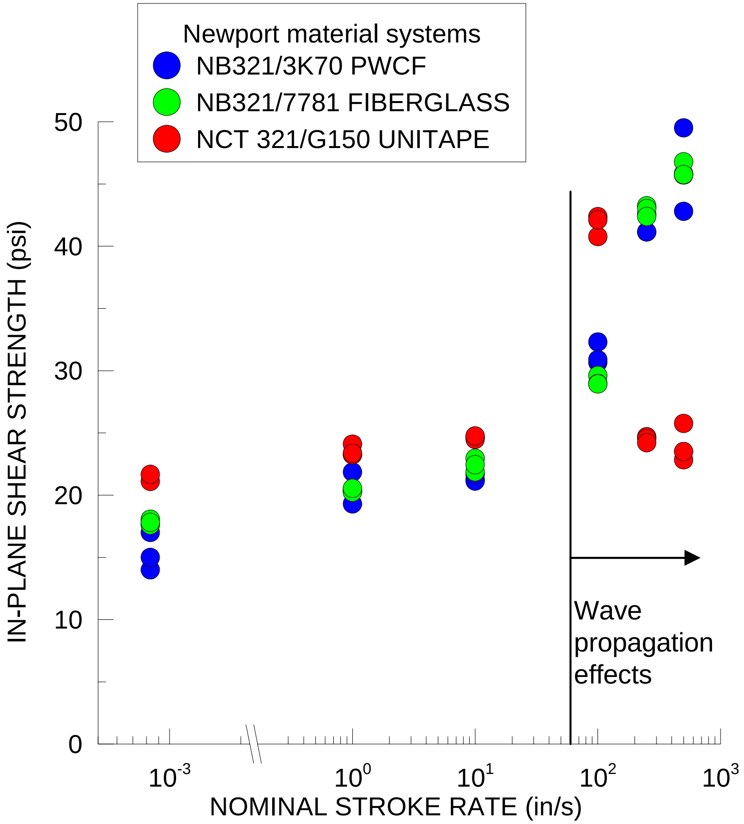
• Strength increase higher for off-axis specimens



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**

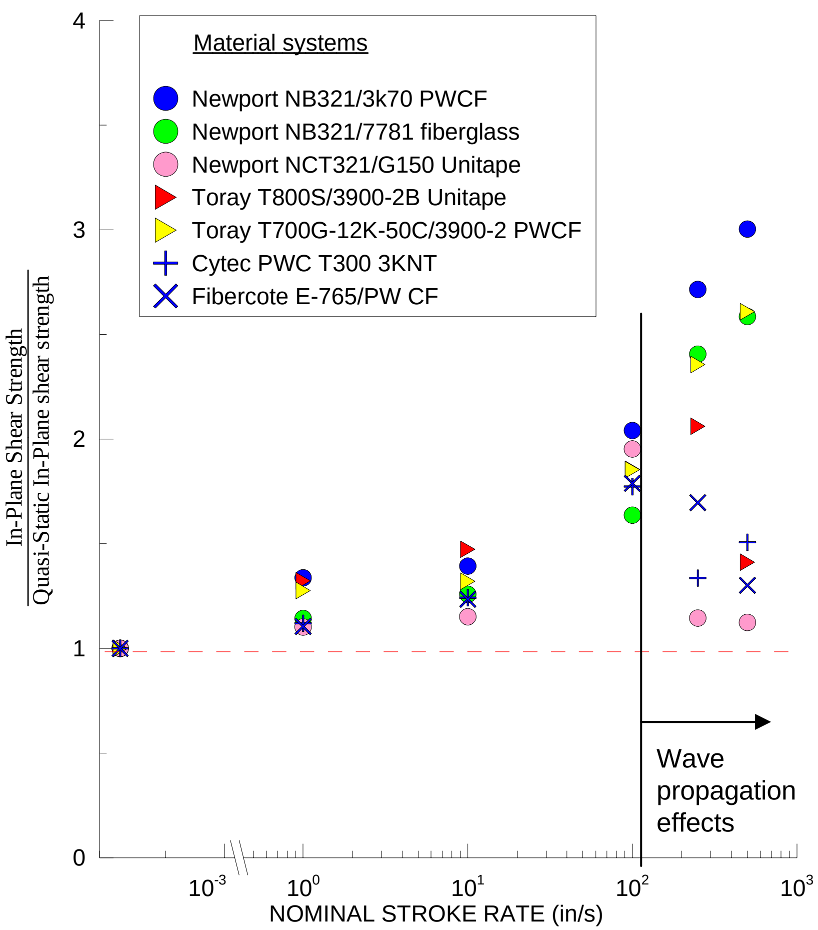




K.S.Raju, S. Dandayudhapani and C.K. Thorbole, AIAA-2006-2258

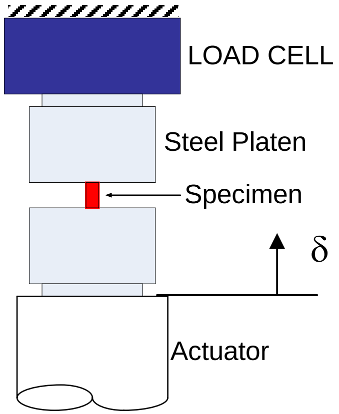
IN-PLANE SHEAR STRENGTH

- **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)**

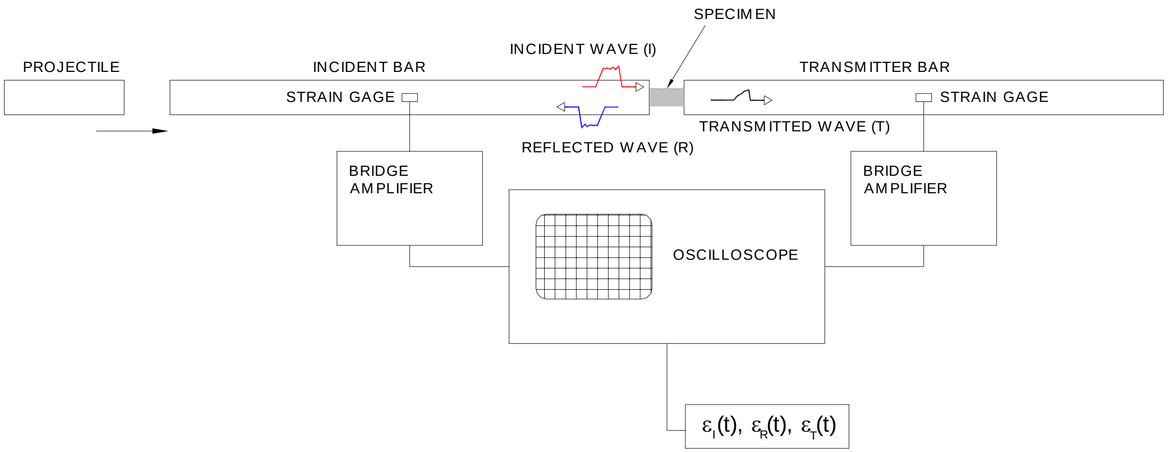


COMPRESSION TEST APPARATUS

- COMPRESSION MODE TESTING
  - Split- Hopkinson Pressure Bar (SHPB)
    - Compressive strength
  - MTS servo hydraulic testing machine
    - Compression at slow to medium rates



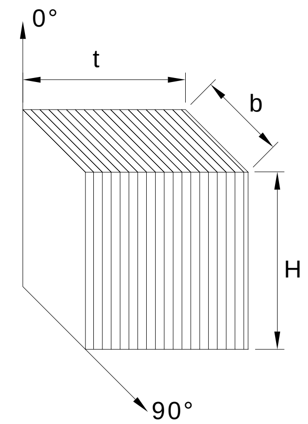
- SHPB SPECIFICATIONS
  - Bar diameter : 1.00 inch
  - Bar Material : Vascomax 350
  - Bar lengths
    - Incident bar : 48”
    - Transmitter bar : 36”
  - Barrell length : 48 inches
  - Projectiles : 1”, 2”, 4”, 6” & 12”
    - Pneumatically driven (100 psi)
    - Velocities ~ 2000 in/s
  - PULSE SHAPING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



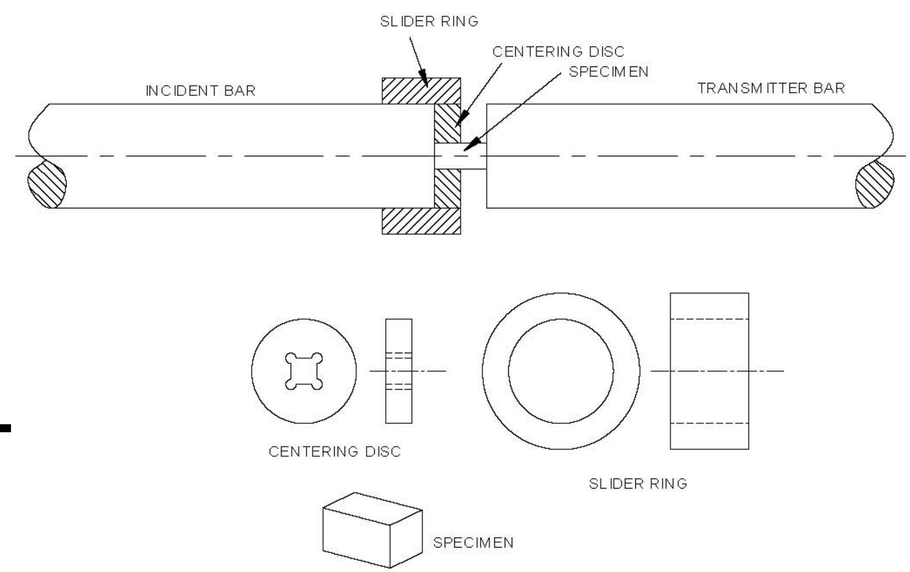
P.S.Follansee, Metals Handbook, vol.8, American Society for Metals, 1985
K.F. Graff, Wave Motion in Elastic Solids, Dover Pub., Inc.1991

SPLIT-HOPKINSON PRESSURE BAR APPARATUS (SHPB)

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

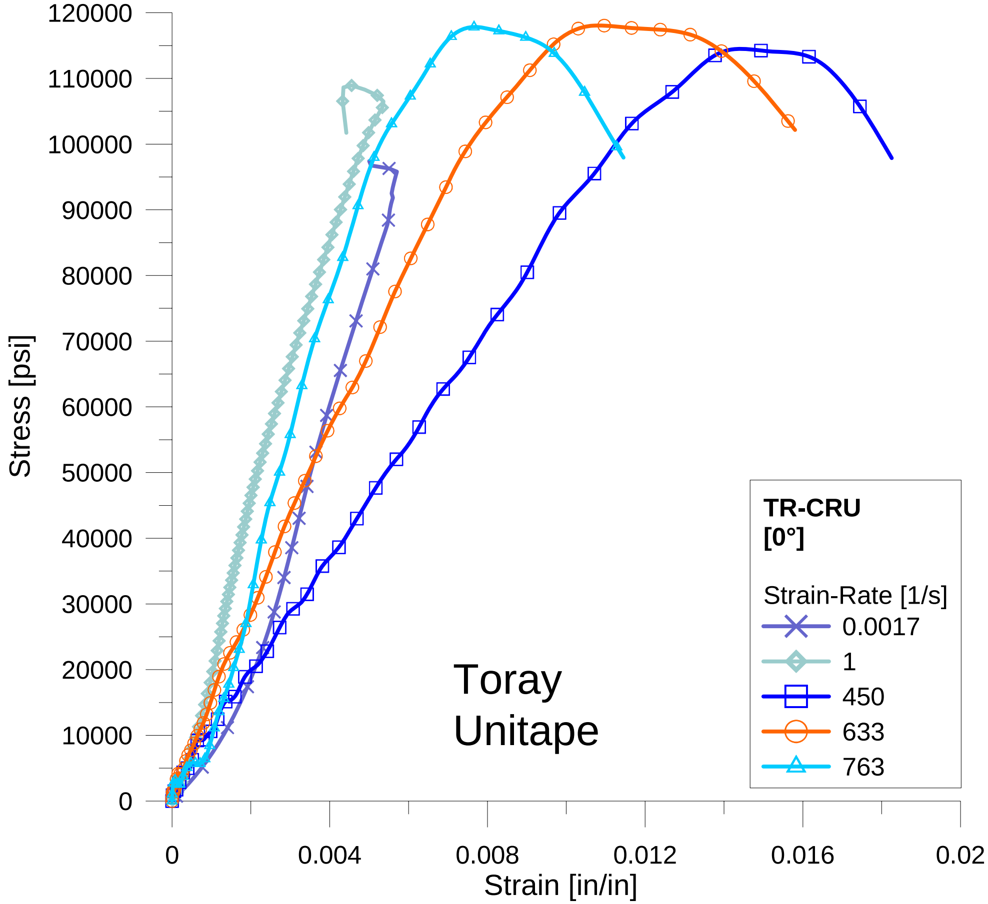


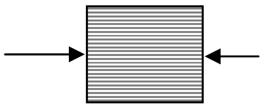
- SPECIMEN ALIGNMENT
  - Centering disc & slider ring



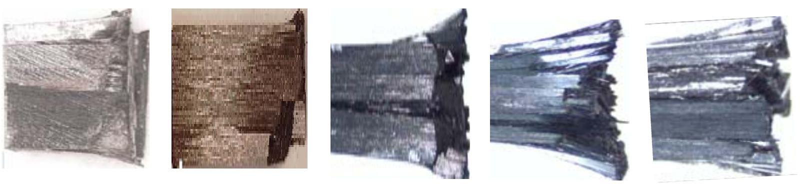
Ref: E. Woldesenbet & J.R. Vinson, AIAA Journal, Vol.37, Sept. 1999.

Compression Testing…Results



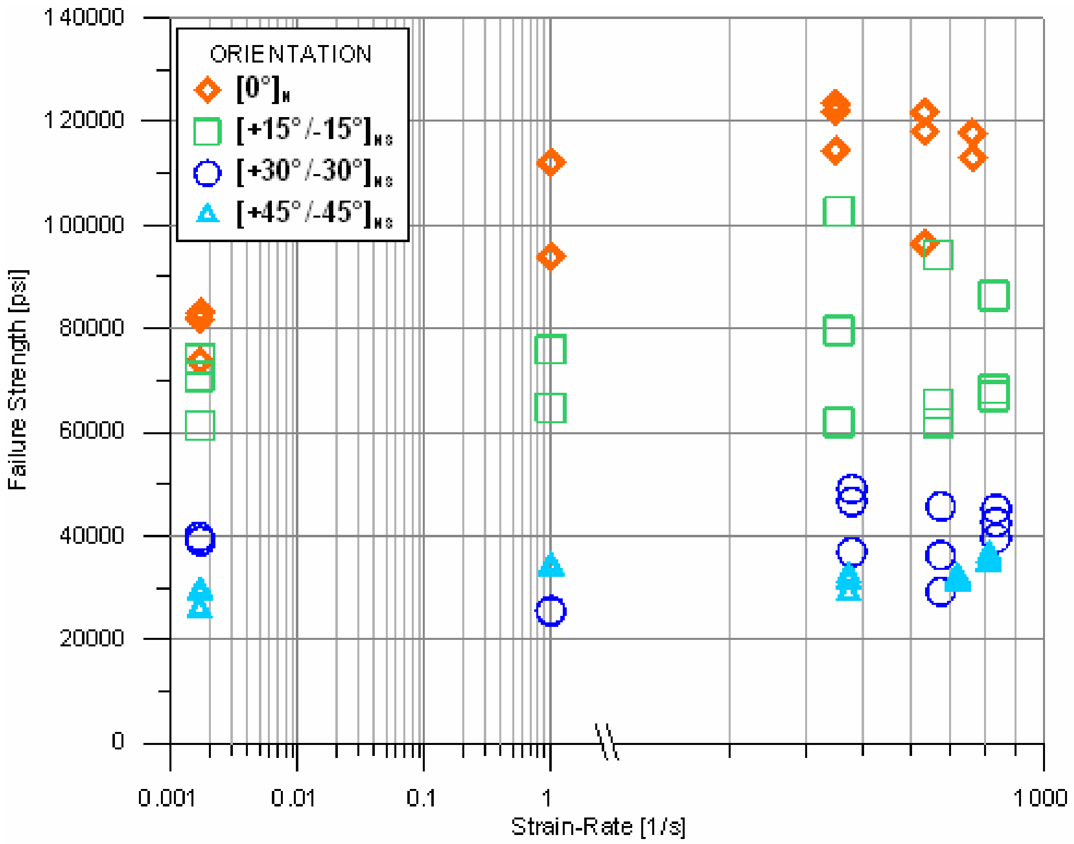


Failure modes



0.0017 s^{-1} **1 s^{-1}** **450 s^{-1}** **633 s^{-1}** **763 s^{-1}**

Compression Testing…Results

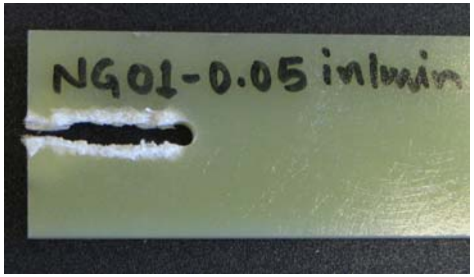


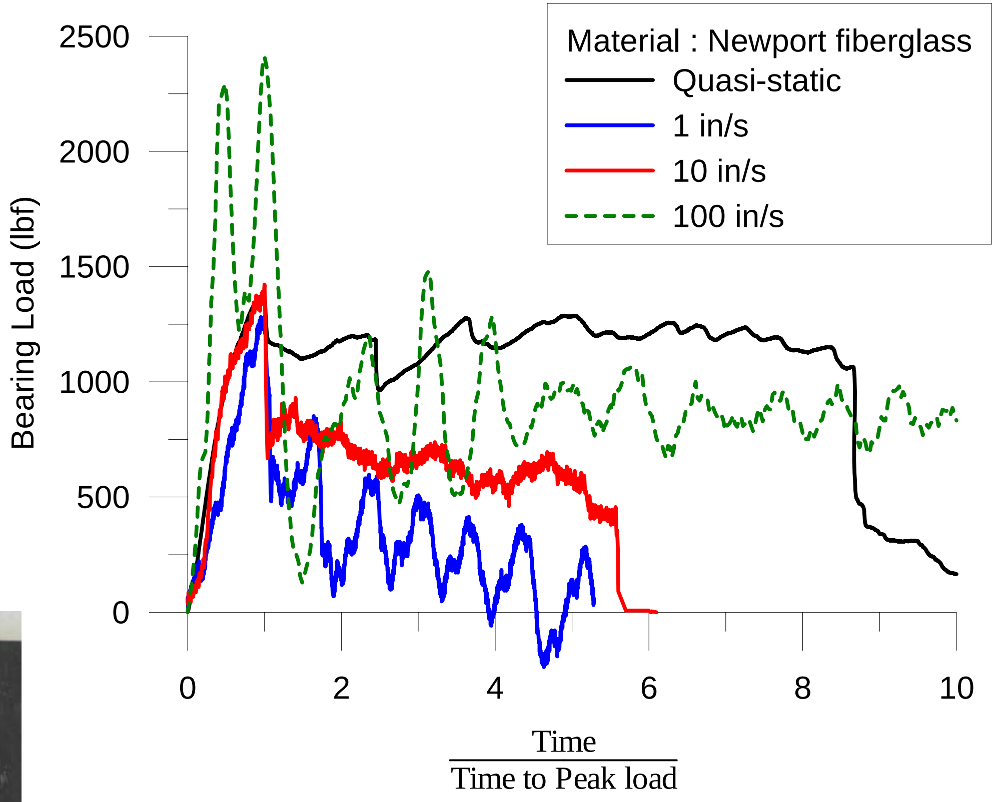
Toray Unitape

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**

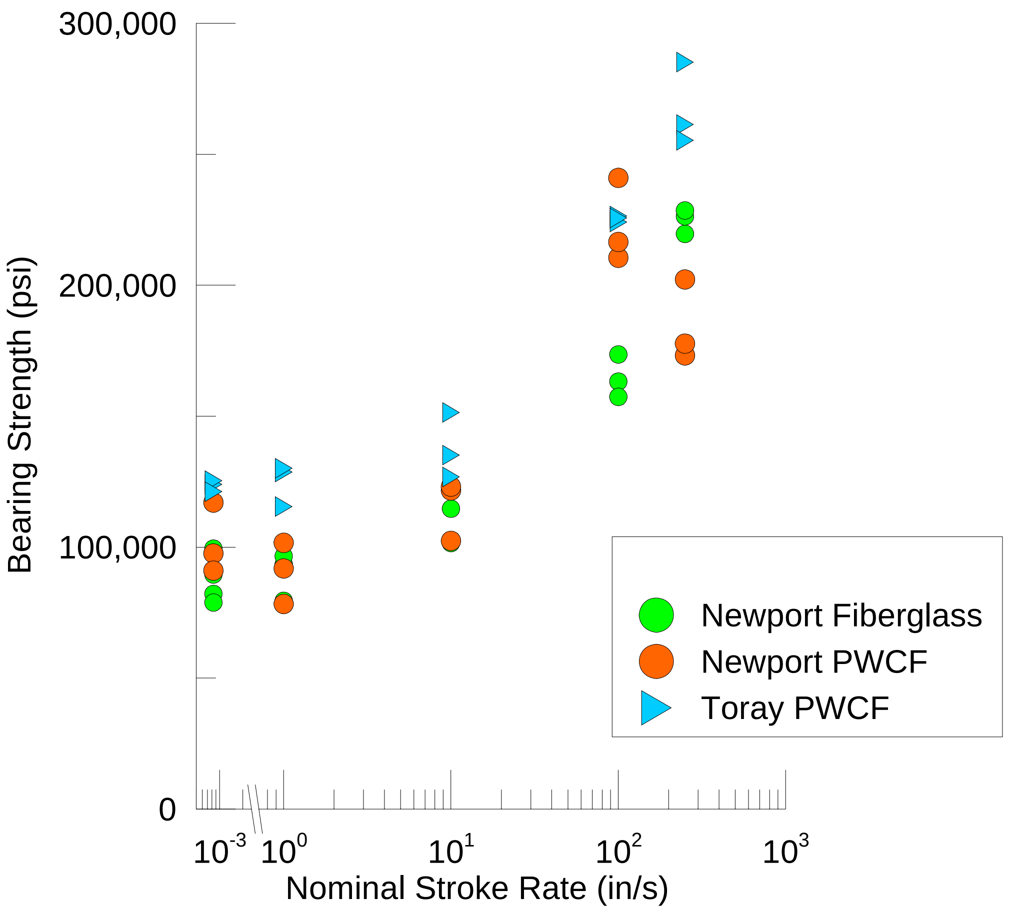
- **RESULTS**
  - **Sustained loading past initial failure, decreases at higher rates of loading**
  - **Failure mode**





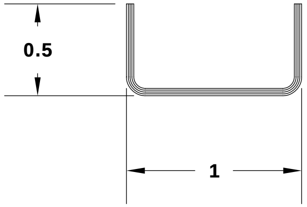
PIN-BEARING RESPONSE

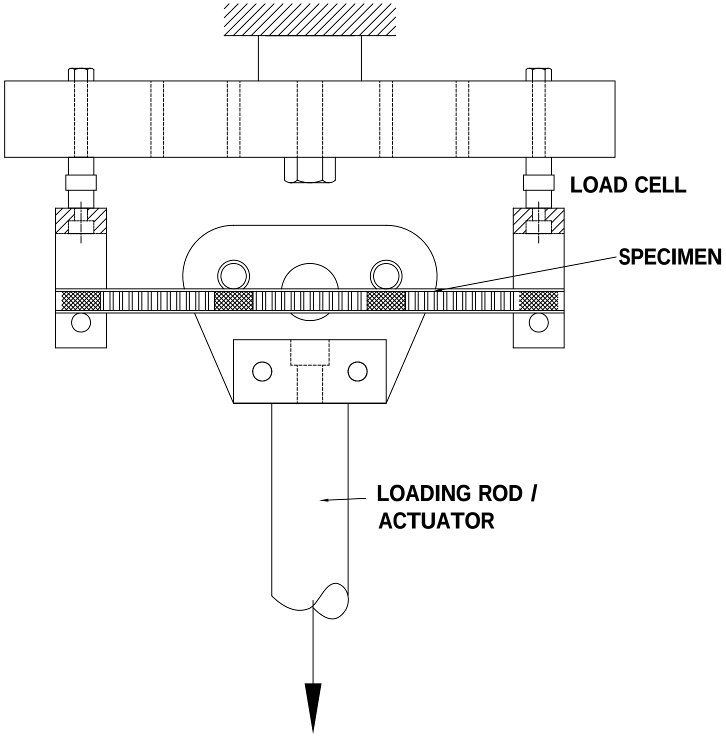
- **RESULTS**
  - **Bearing strengths based on peak recorded load**
    - **Hole deformation not measured**
  - Pin bearing strength increases with test speed



FLEXURE TESTS

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



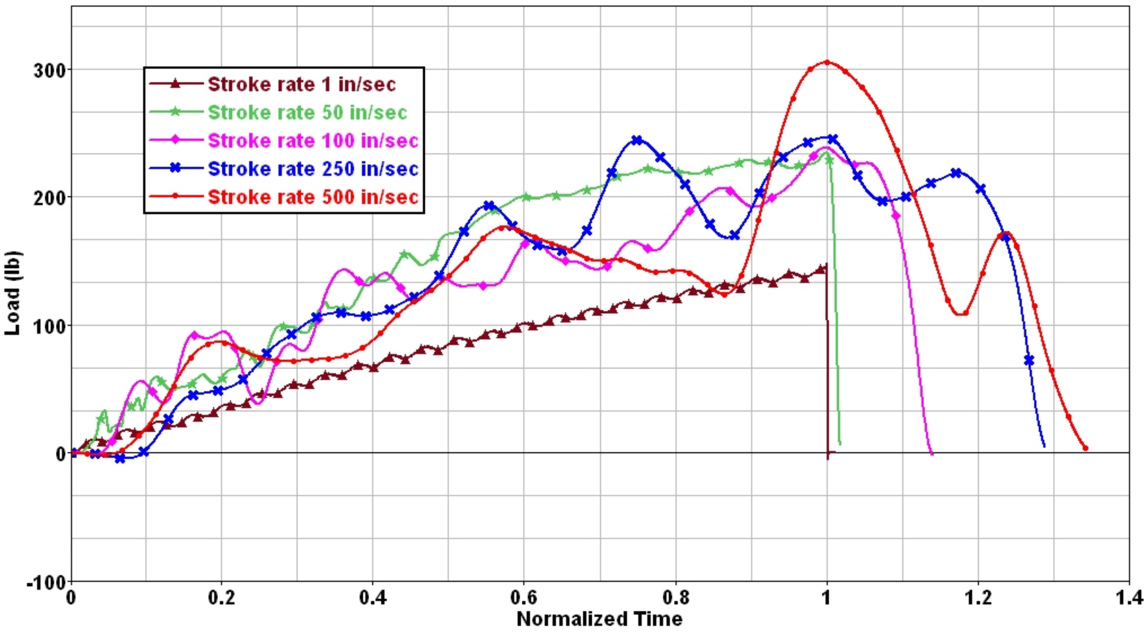


- SANDWICH BEAMS
  - Material systems
    - Newport NB321/7781 fiberglass
    - Newport NB321/3k70 PWCF
  - Layup sequence
    - $[0/45/0/45/CORE]_S$

- STATUS : Testing completed

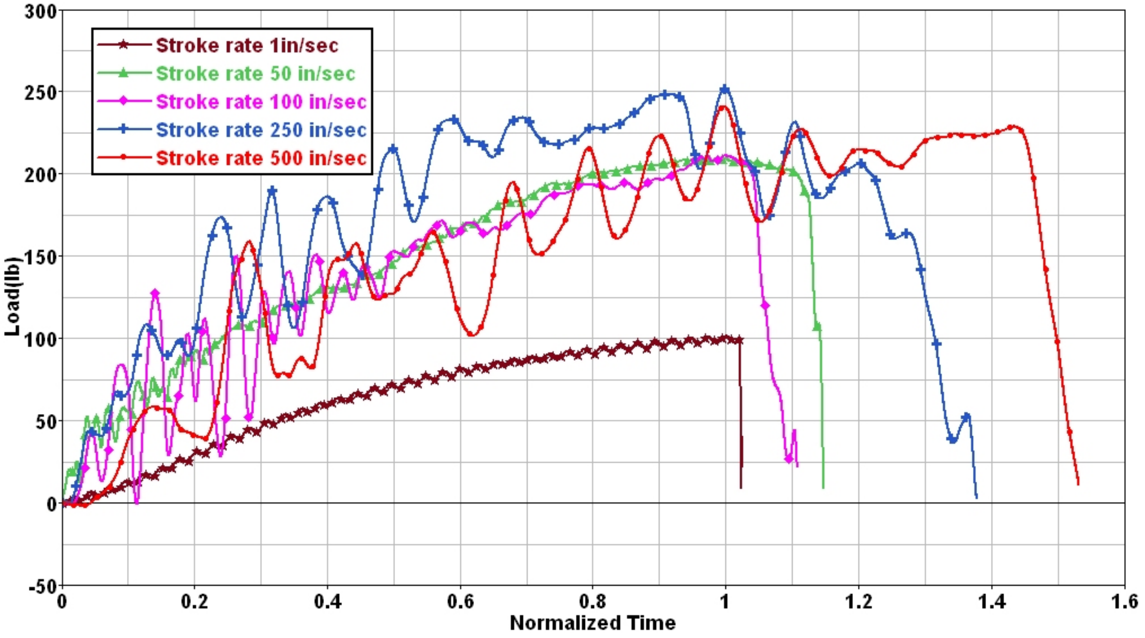
FLEXURE TESTS – Sample results

Peak bending load Vs Normalized time for **Carbon fiber beam specimens at various strokes rates.**



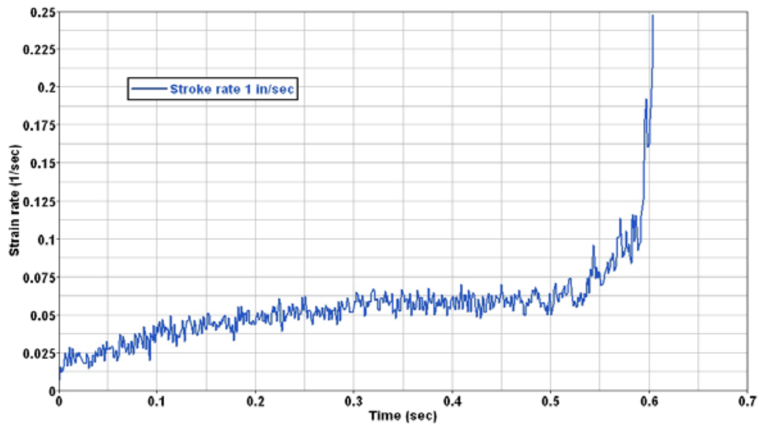
FLEXURE TESTS – Sample Results

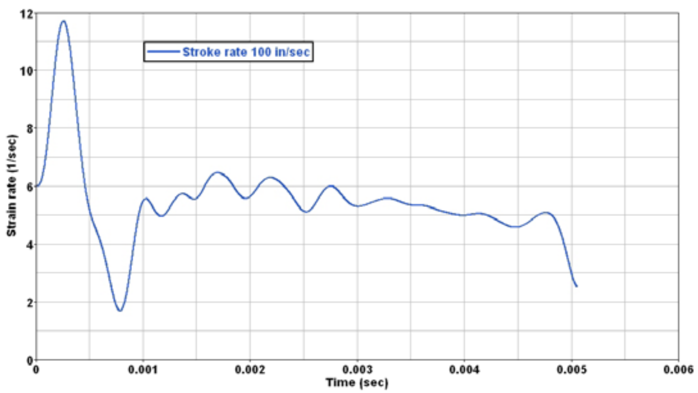
Peak bending load Vs Normalized time for **fiberglass beam specimens at various strokes rates.**

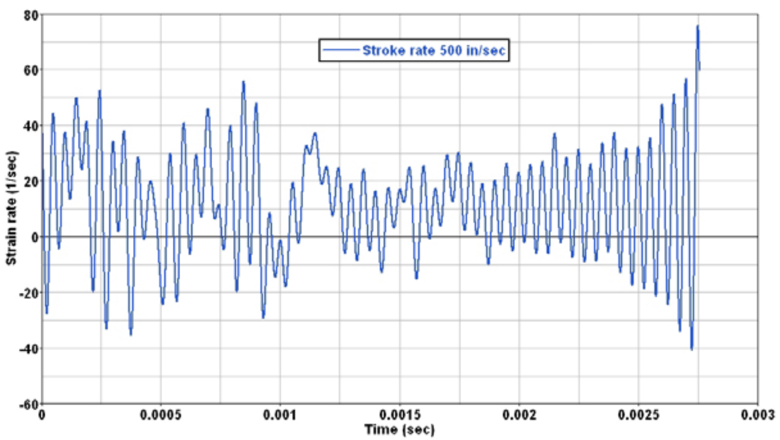


FLEXURE TESTS - RESULTS

Typical strain rates achieved in the gage section of the beams

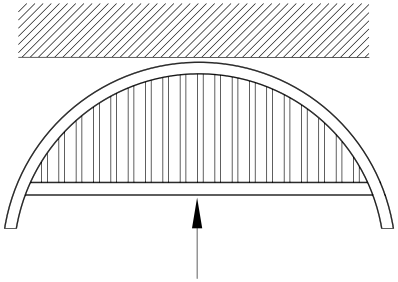


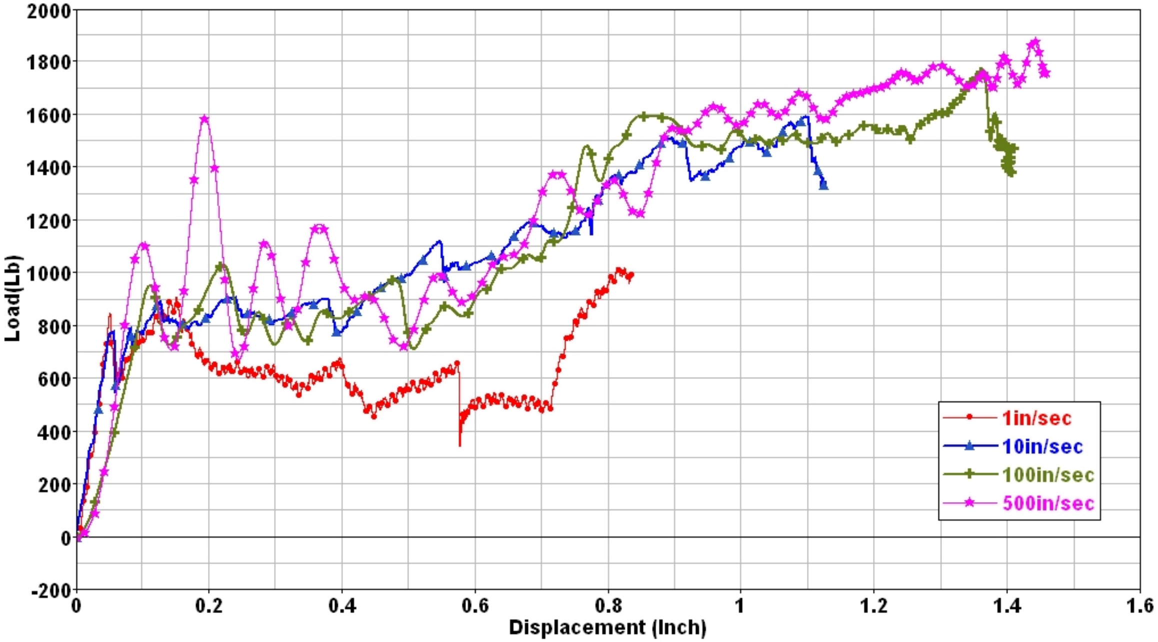


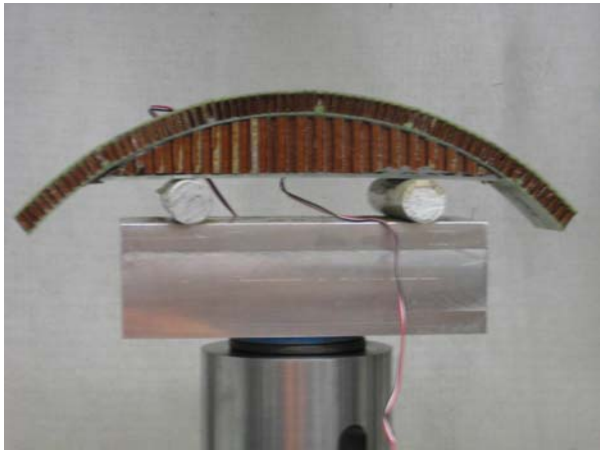


Maximum strain rate achieved in the test region ~ 100 s^{-1}

SCALED FUSELAGE SECTION TESTS







Work in Progress

- Rate effects on delamination fracture toughness
  - nearing completion
- Rate effects on behavior of corrugated webs under compression
  - Failure modes
  - Energy absorption
- Signal modulation corrections for test data
- Tensile characterization using SHPB (rates ~ 10^3 1/s)