CRASHWORTHINESS OF COMPOSITE FUSELAGE STRUCTURES – MATERIAL DYNAMIC PROPERTIES

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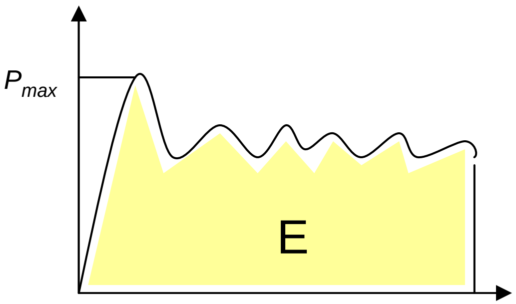
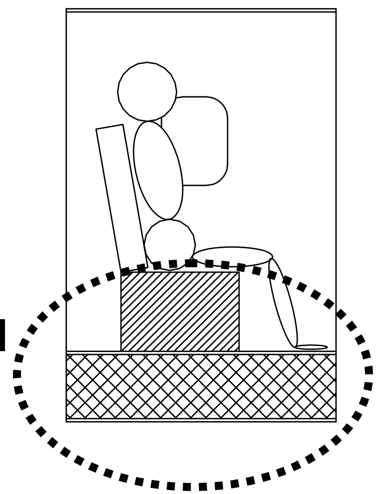
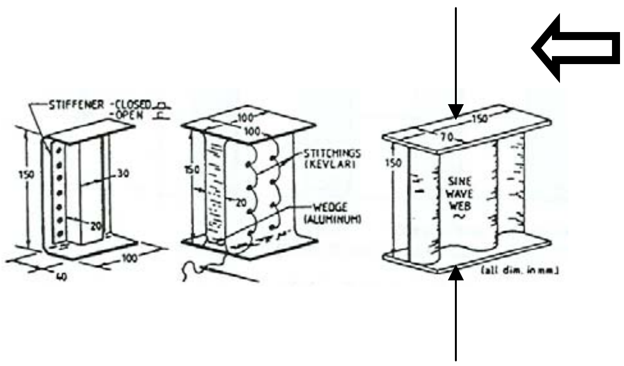
Motivation and Key Issues



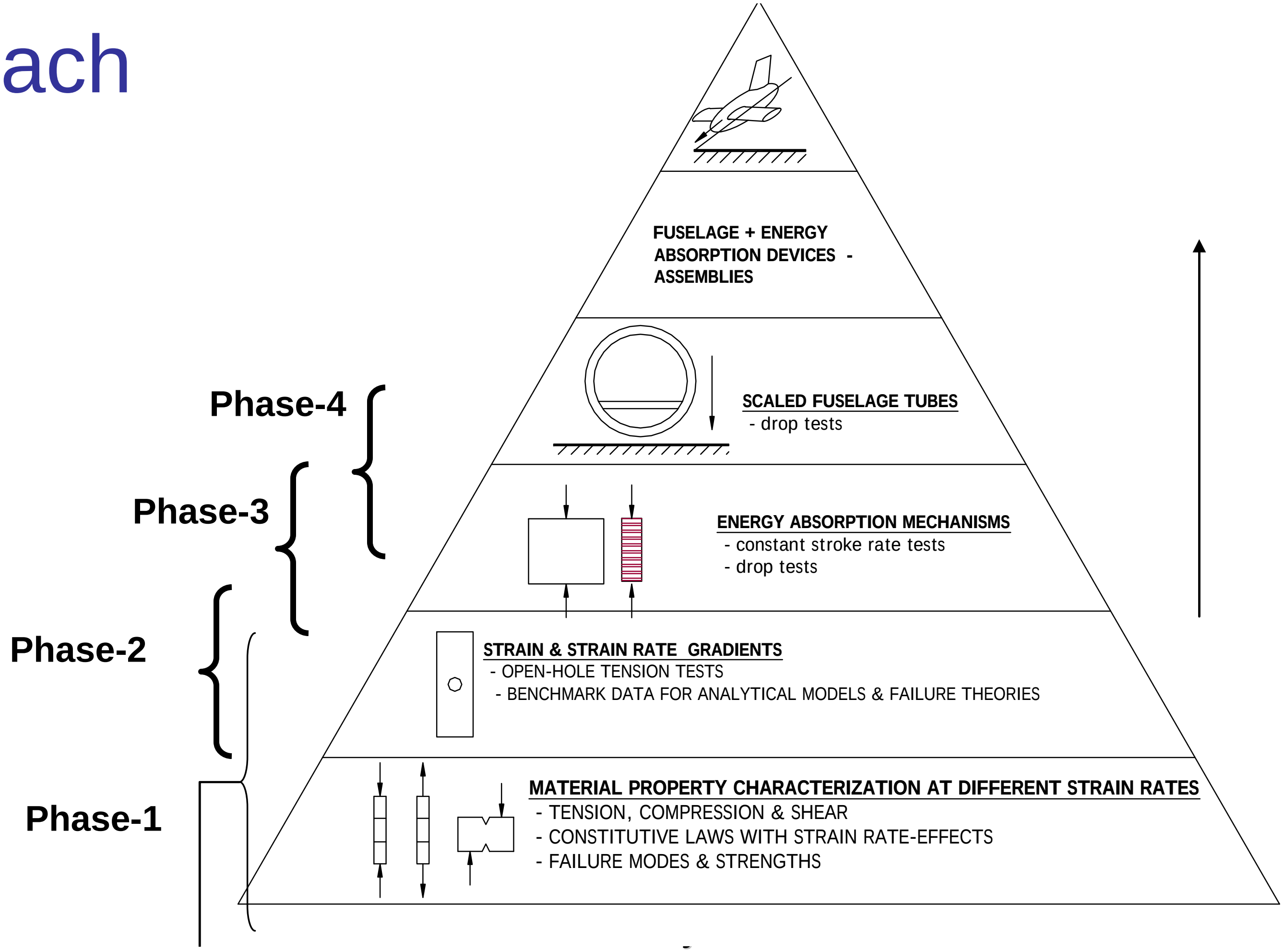




- Crashworthiness
  - maintain survivable volume
  - dissipate kinetic energy → alleviate occupant loads
- Energy absorption
  - Composite structures /energy absorption (EA) devices
    - Controlled failure modes
    - Maximize damage volume
    - Provision for sustained stability
  - Influencing factors
    - EA device geometry
    - Material
    - Rate sensitivity (?)

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-4
Phase-3
Phase-2
Phase-1
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

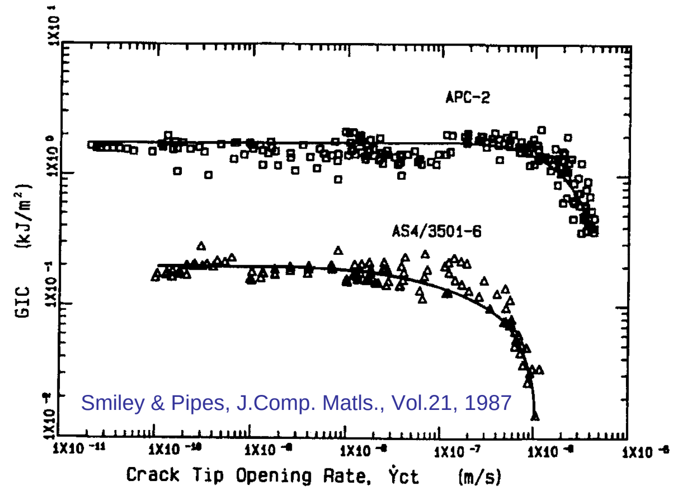
- Objective(s)
  - Literature Review
  - Material property characterization at different strain rates (10^{-4} s^{-1} to 10^{3} s^{-1})
    - Phase-1 : Tension, Compression & Shear
      - » Development of test apparatus & fixtures for high strain rate testing
      - » Split Hopkinson Pressure Bar (SHPB) Apparatus
    - Phase-2 : Open Hole Tension, Interlaminar Shear, Pin Bearing
    - Phase-3 : Fracture Toughness (mode I & II)
    - Phase-4 : Characterization of EA device (in progress)

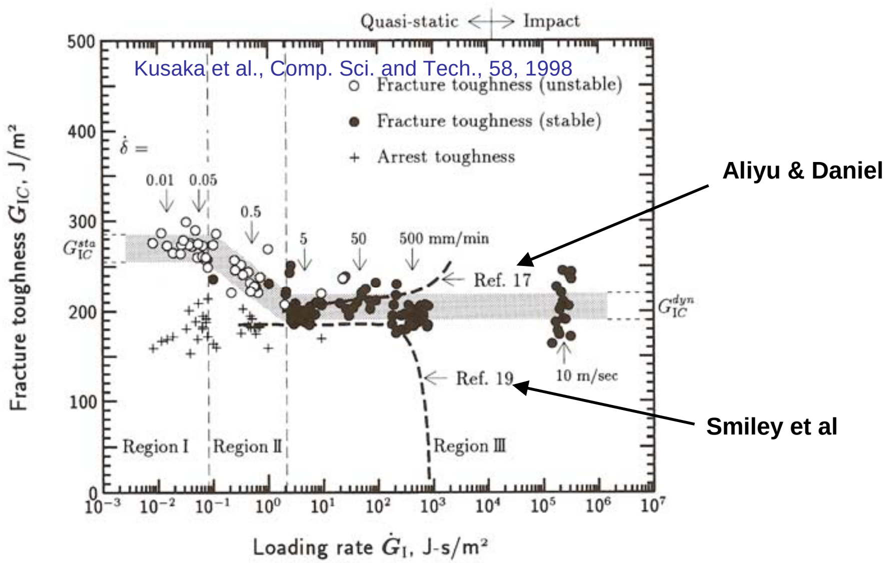
FAA Sponsored Project Information

- Principal Investigators & Researchers
  - K.S. Raju
  - H. Lankarani, P. Sriram
  - J.F. Acosta, C.K. Thorbole, A. Deshpande, V. Mariyanna, N. Pratap
- FAA Technical Monitor
  - Alan Abramowitz
- Other FAA Personnel Involved
  - Curtis Davis, J. Zvanya
- Industry Participation
  - Spirit Aerosystems
  - Raytheon

Rate effects on Toughness …Past work

- Smiley et al.,
  - AS4/3501-6, APC-2 PEEK ; Mode-I
- Kasuka et al.,
  - Toray T300/2500; Mode-I
- Aliyu & Daniel
  - AS4/3501-6 ; Mode-I
- Cantwell et al.,
  - AS4/PEEK, IM6/PEEK, T300 fabric/toughened epoxy, T300 uni/epoxy ; Mode-II
- Béguelin et al.,
  - IM6/PEEK; Mode-I
- Fracasso et al.,
  - Unitape carbon/PEEK; Modes I &II
- Compston et al.,
  - E-glass/vinyl ester (411-45, 8084, 9EXL, 8X33, 8S22) ; Mode-II





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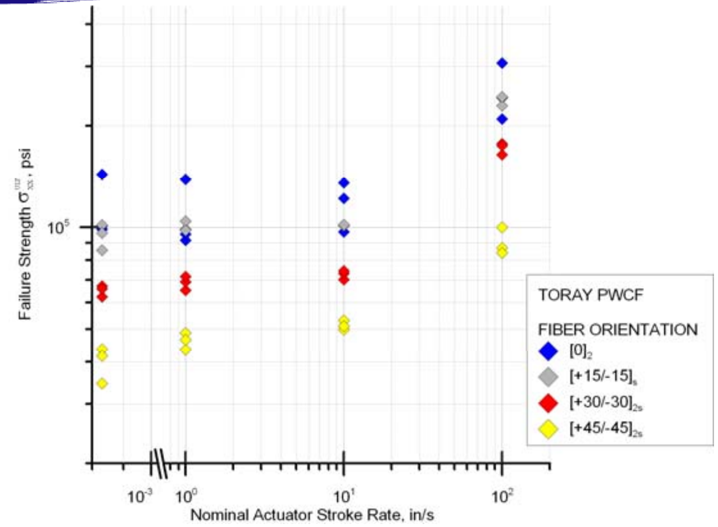
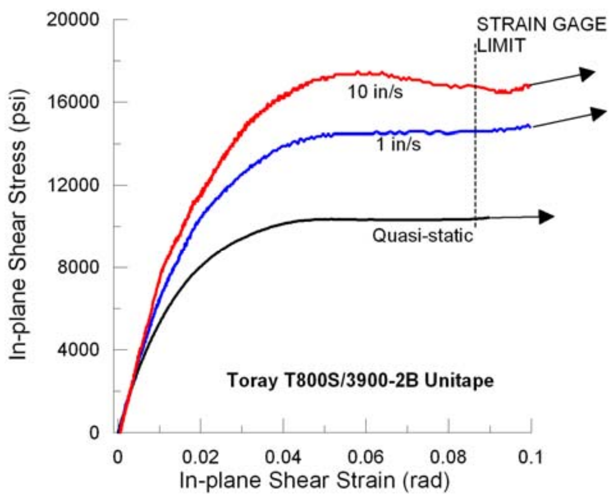
Material Systems

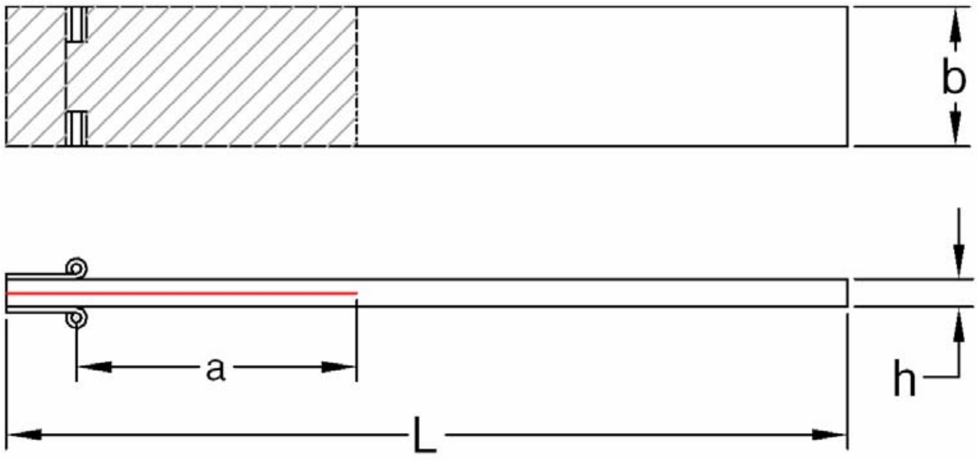
- TORAY systems
  - T800S/3900-2B[P2352W-19] BMS8-276 Rev-H- Unitape
  - T700G-12K-50C/3900-2 Plain Weave Carbon Fabric (PWCF)
- NEWPORT systems
  - NB321/3k70 Plain Weave Carbon Fabric (PWCF)
  - NB321/7781 Fiberglass





Experimental details..

- Mode-I Fracture Toughness tests
  - Double Cantilever Beam (DCB) specimen
    - ASTM D5528



L = 6 inches

b = 1inch

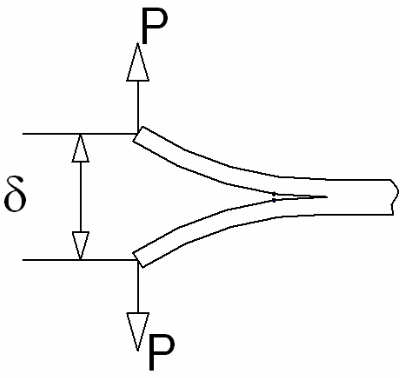
a = 1.5 - 2 inches

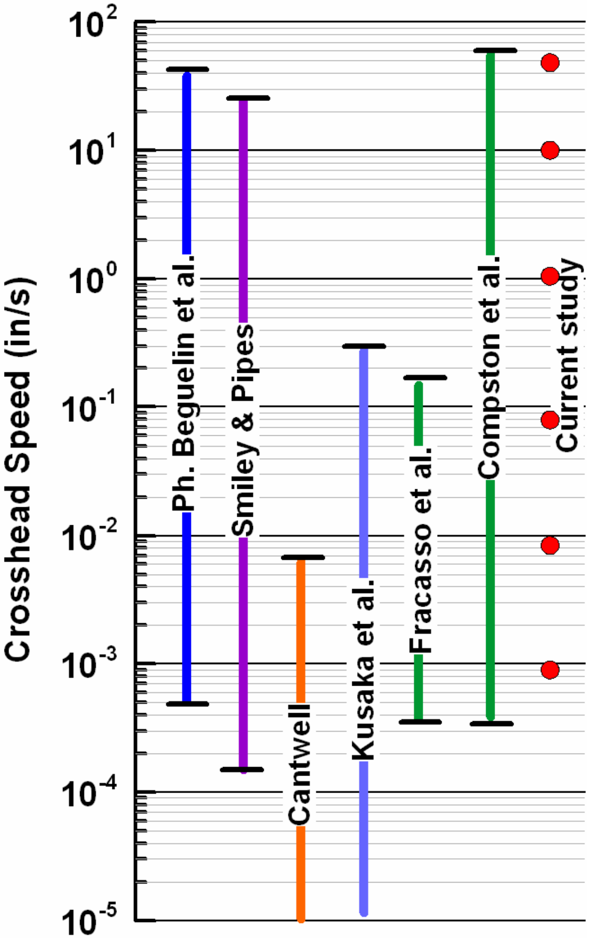
0.0003” thick Kapton film insert

Experimental Details

- Test Speeds & Apparatus
  - Slow rate tests (10^{-3}, 10^{-2} & 10^{-1} in/s)
    - MTS Electromechanical testing machine
  - Medium rate tests (1, 10 & 50 in/s)
    - MTS High Rate servo system

Crosshead (actuator) displacement)

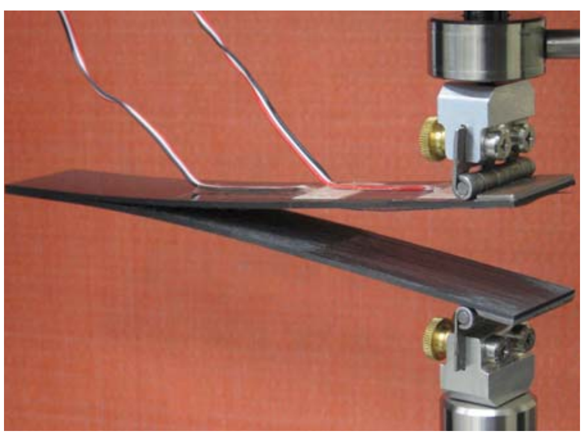


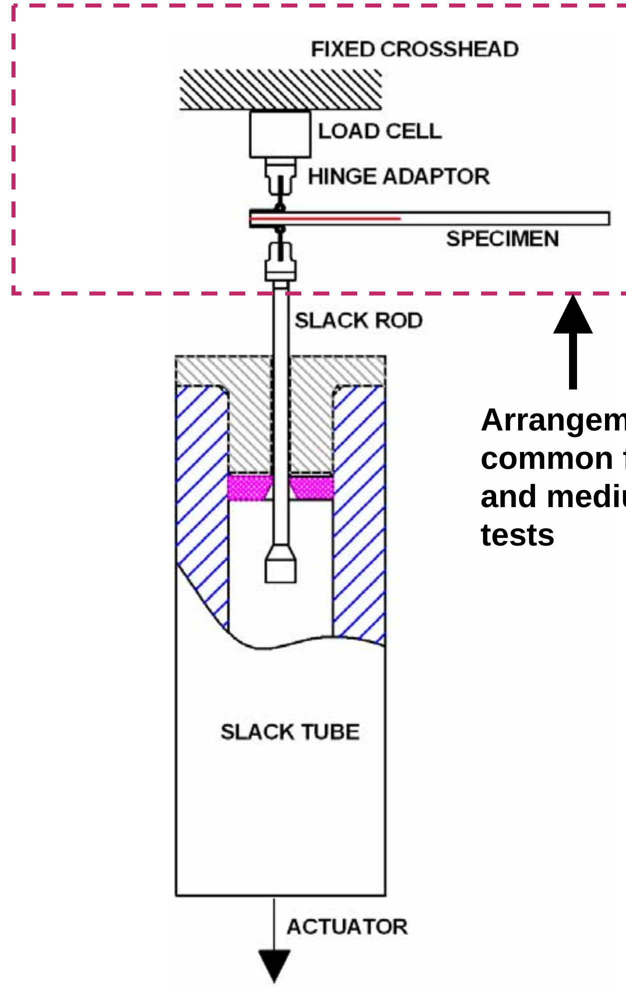


Smiley & Pipes, J.Comp. Matls., Vol.21, 1987
Ph. Beguelin et al., J. Phys. III, 1, 1991
Cantwell, J. Comp. matls., Vol.31, No.14, 1997
Kusaka et al., Comp. Sci. and Tech., 58, 1998
Compston et al., Comp. Sci and Tech., 61, 2001
Fracasso et al., Comp. Sci. and Tech., 61, 2001

Experimental Details

- Load cell
  - Honeywell Sensotec model M31 strain gage based load cell
    - ±100 lbs
    - 10 kHz ringing frequency
- Slack mechanism
  - Low mass





Arrangement common for slow and medium rate tests

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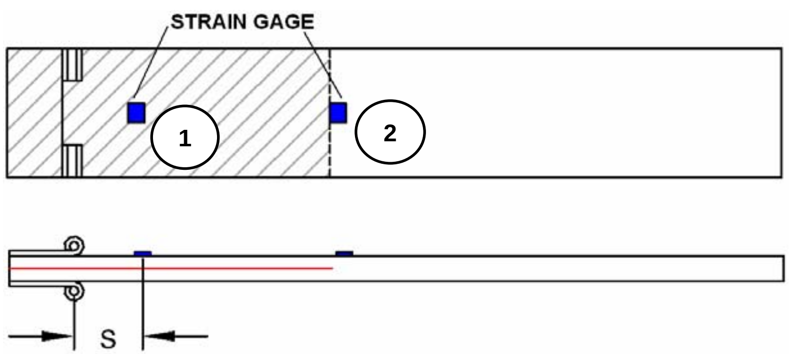
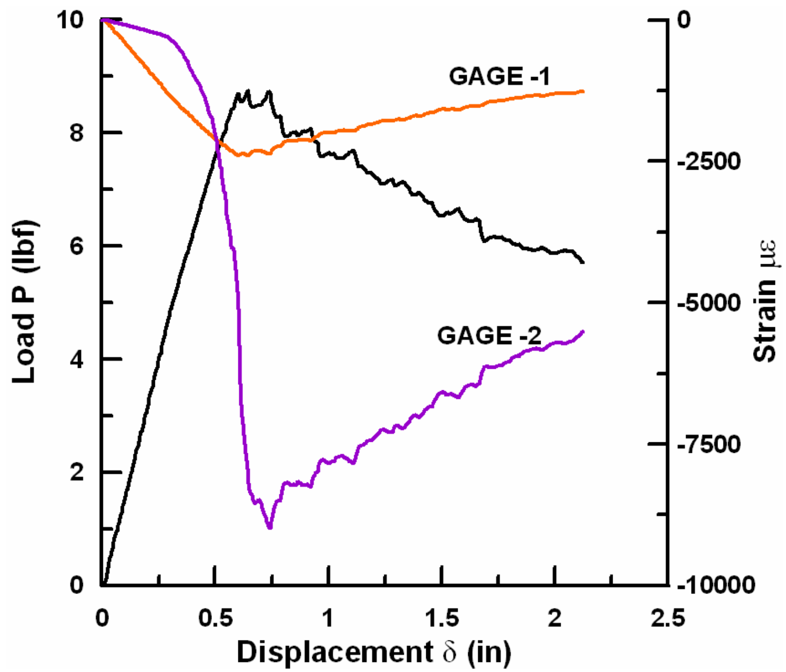
Experimental Details

- Additional instrumentation
  - Strain gages
    - Estimation of crack length
    - Crack initiation/propagation (at speeds that do not facilitate visual observation) – (Ref. Aliyu & Daniel)

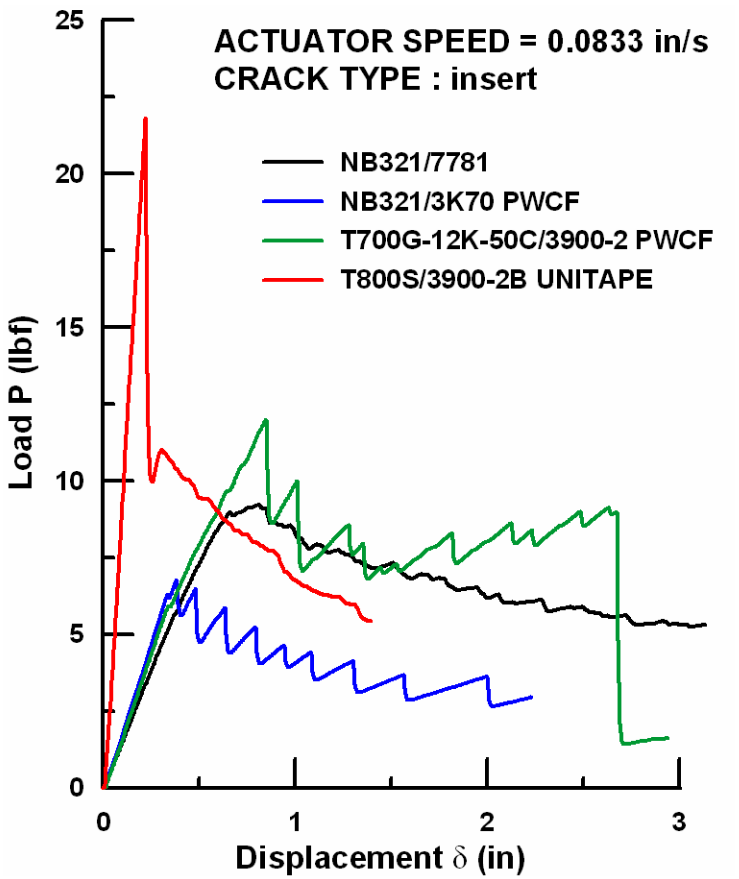




$$a \approx \left(\frac{3\delta s h}{16\varepsilon_1} \right) \text{based on Euler - Bernoulli beam theory}$$

Results..

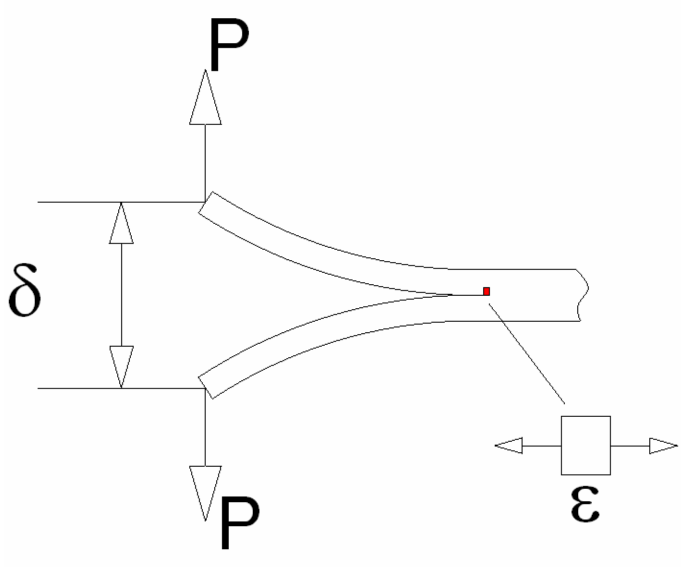
- Comparison at slow speed
  - NB321/7781 exhibits a ductile-stable* behavior while NB321/3k70 exhibits brittle-unstable behavior*
  - Both Toray materials exhibited brittle unstable behavior. Crack propagation in unitape material was observed to be ductile stable while the PWCF was brittle-unstable during propagation
    - Unitape material with precrack exhibits ductile-stable behavior



* Smiley & Pipes, J.Comp. Matls., Vol.21, 1987

Results..

- Presentation of Toughness data



$\dot{\delta}$ ~ Crosshead (actuator) displacement rate (Cantwell)

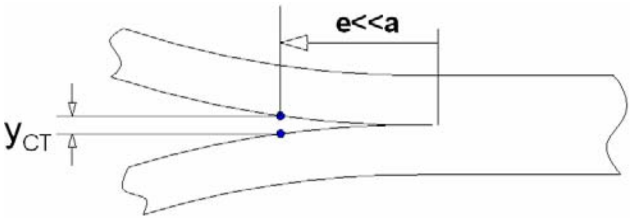
$\dot{\varepsilon}$ ~ Reference strain rate (Mall)

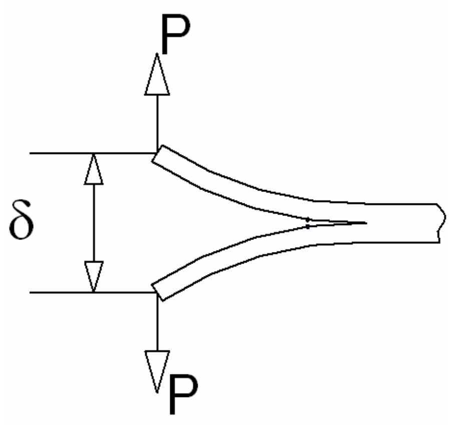
$$\dot{\varepsilon} = \frac{3h\dot{\delta}}{4a^2} \text{ (based on Euler - Bernoulli theory)}$$

$\dot{a}$ ~ Crack propagation velocity (high speed)

Results..

- Presentation of Toughness data





$\dot{y}_{CT}$ ~ Crack tip opening rate (Smiley & Pipes)

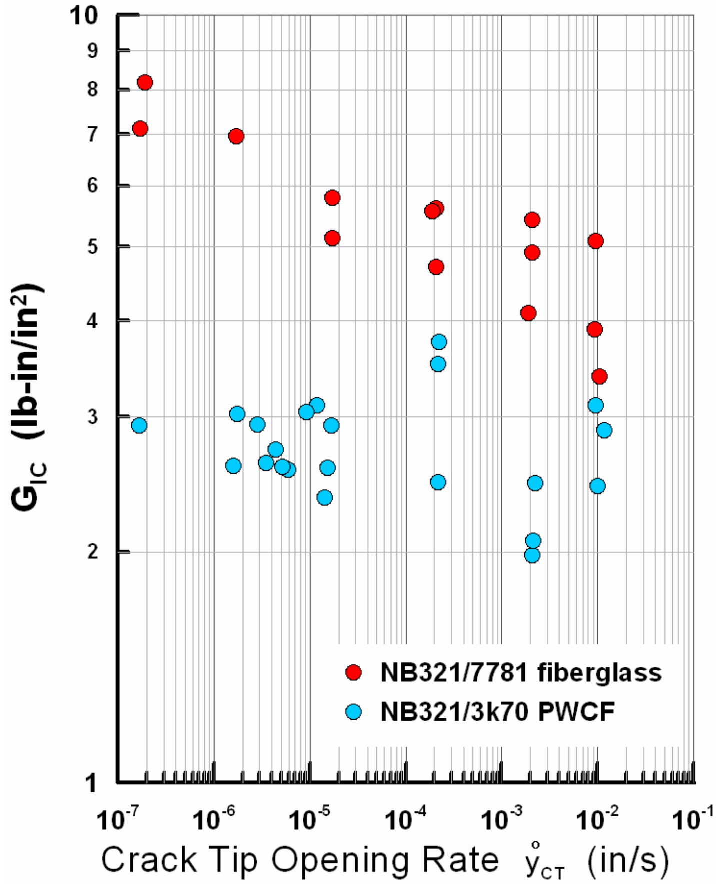
$e \approx 2t_{PLY}$

$$\dot{y}_{CT} = \frac{3\dot{\delta}\ e^2}{2a^2}$$

based on Euler - Bernoulli beam theory

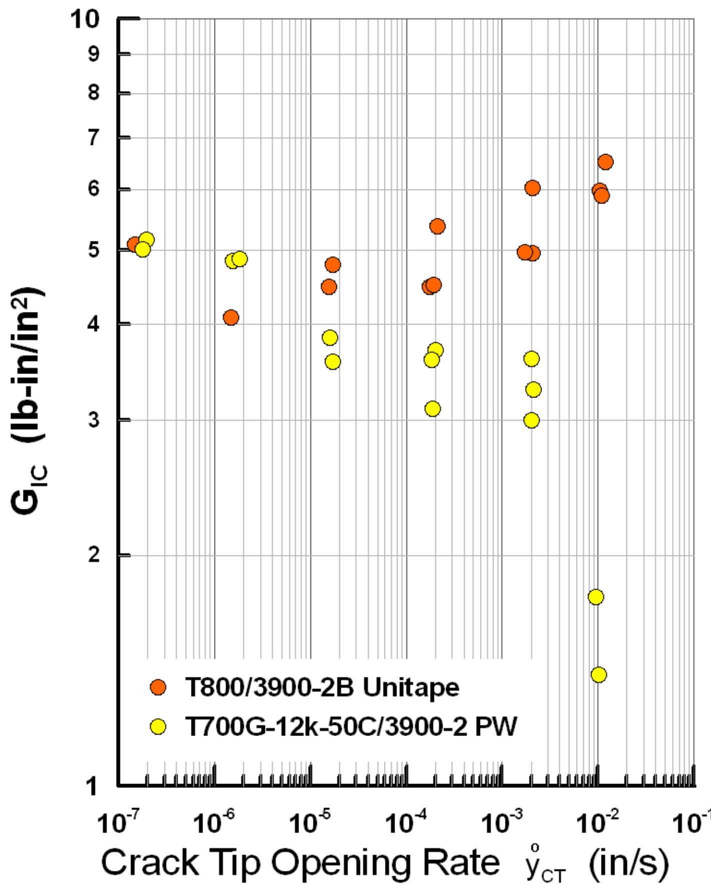
Results..NB321 systems

- Mode-I fracture toughness for Newport systems
  - Based on maximum load (PWCF) and deviation from non-linearity (7781) per ASTM D5528 (modified beam theory used)
  - At test speeds of 10 and 50 in/s, strain gage data was used to determine loads corresponding to fracture
  - Crack tip opening rate determined at a distance of $e=2t_{PLY}$ from the crack tip
- 7781 system exhibited a gradual decrease in G_{IC} with rate, similar to observations of Béguelin et al.
- 3k70P did not exhibit a strong trend
  - Data scatter (additional tests)



Results..Toray systems

- Mode-I fracture toughness for Toray systems
  - Based on maximum load and modified beam theory per ASTM D5528
  - At test speeds of 10 and 50 in/s, strain gage data was used to determine loads corresponding to fracture
  - Crack tip opening rate determined at a distance of $e=2t_{PLY}$ from the crack tip
- T700G-12k-50C system exhibits a gradual decrease in G_{IC} and a sharp decrease at a rate of 10^{-2} similar to observations of Smiley & Pipes.
- T800/3900-2B exhibits an increasing trend (Aliyu & Daniel)



In Progress

- Mode-I fracture toughness
  - propagation data (using strain gages)
  - specimens pre-cracked at 0.00083 in/s
  - Examination of fracture surfaces
- Mode-II fracture toughness
  - End Notch Flexure (ENF) configuration
  - Testing/data reduction nearing completion
- Rate sensitivity of EA device
  - Corrugated beam
  - Testing under progress

A Look Forward

- Benefit to Aviation
  - Rate sensitive test data for candidate material systems (6)
    - Rate sensitivity due to geometric or material effects ?
    - Can be utilized for applications involving dynamic loading
    - Design/Modeling of EA devices

A Look Forward

- Future needs
  - Material characterization conducted on scaled down specimen (short gage lengths and thin) to facilitate higher strain rates and lower failure loads (machine limitation). The uniformity of stress/strain over the gage region is questionable and failure modes & strengths may not be realistic.
  - Scaling studies over a limited strain rate range are required to leverage the use of existing test data for modeling purposes
    - Tensile and compressive behavior