JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

Crashworthiness of Composites – Material Dynamic Properties

2011 Technical Review

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Wichita State University

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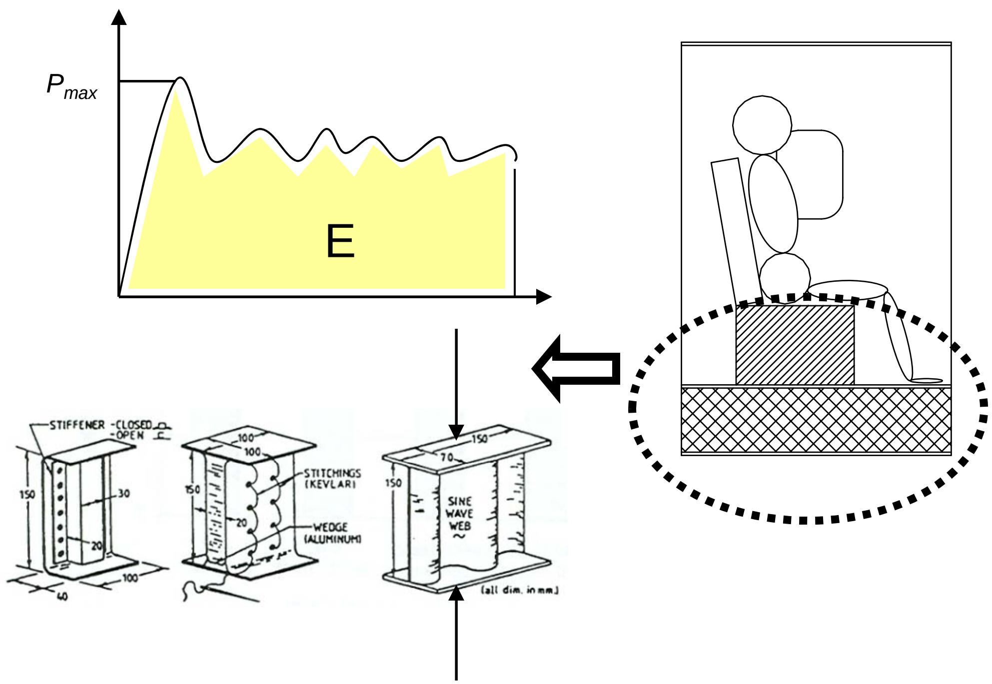
Crashworthiness of Composite Fuselage Structures – Material Dynamic Properties

- 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.

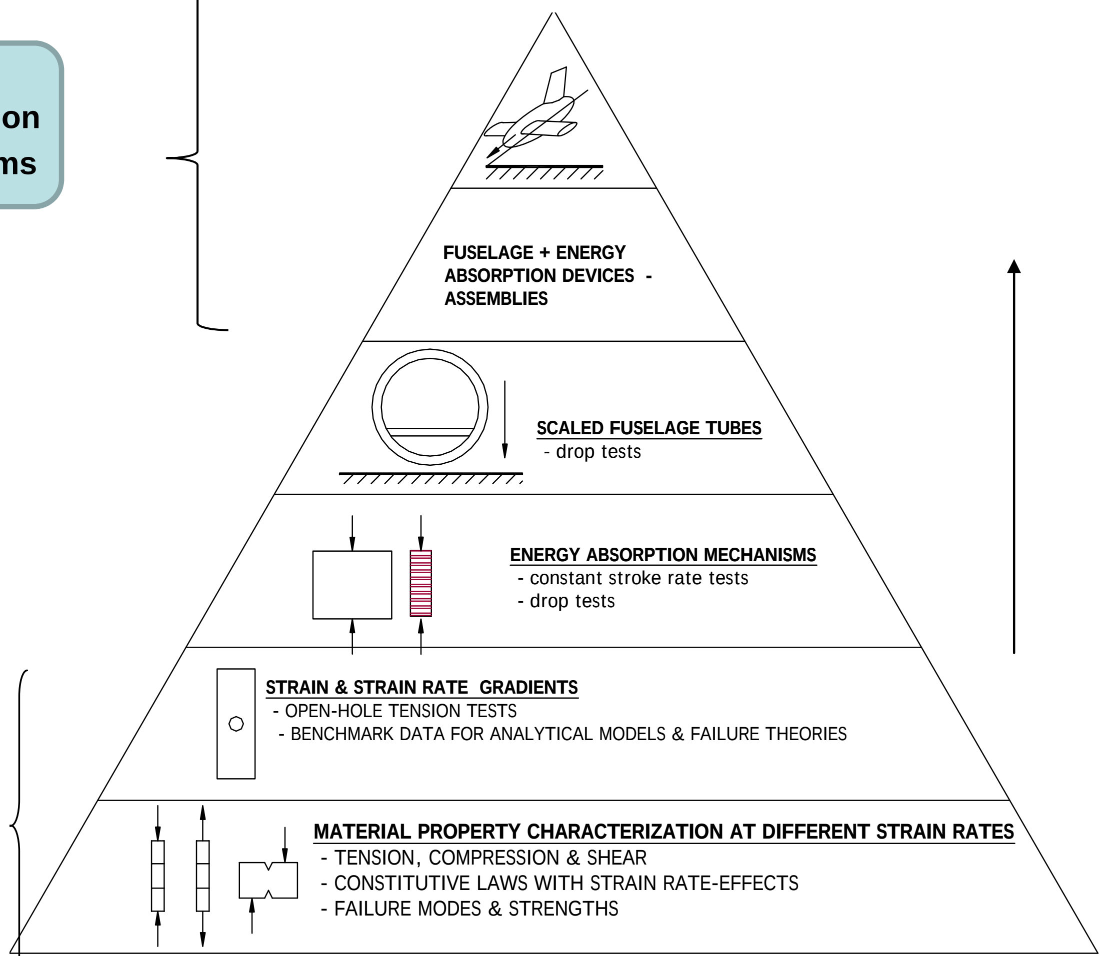
Approach

- CRASHWORTHINESS CERTIFICATION
  - specific to structural configuration
  - interactions between mechanisms

$/test

Application

- BENCHMARKING
  - Constitutive models
  - Failure theories
- LOCALIZED IMPACT PROBLEMS
  - Bird, hail, projectile impact
  - Damage Resistance
- CRASHWORTHINESS
  - Crush behavior
  - Structural integrity



Crashworthiness of Composites – Material Dynamic Properties

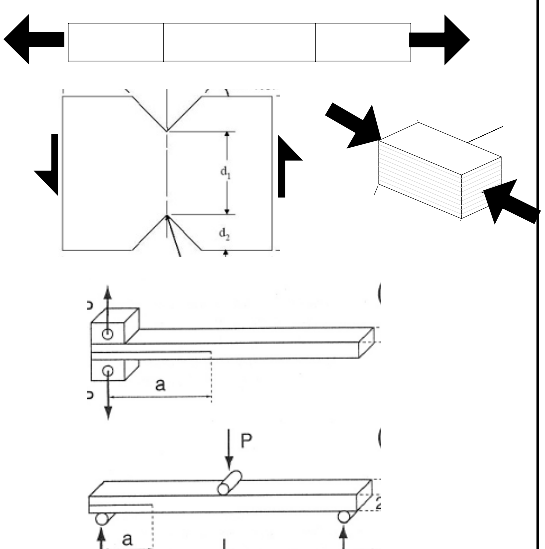
- Principal Investigators & Researchers
  - Suresh Keshavanarayana (PI)
  - Gerardo Olivares (PI)
  - J. Acosta, T. Siddiqui, K.Y. Tan
- FAA Technical Monitor
  - Allan Abramowitz
- Other FAA Personnel Involved
  - Curtis Davies
- Industry Participation
  - CMH17 Crashworthiness Working Group
  - NIS (State of Kansas)

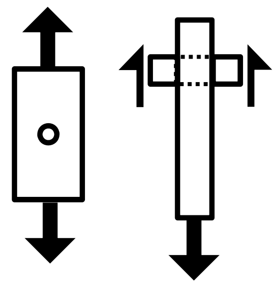
Program Overview…

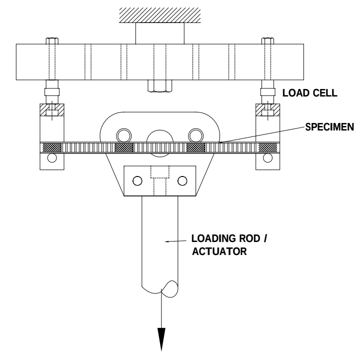
Material Characterization

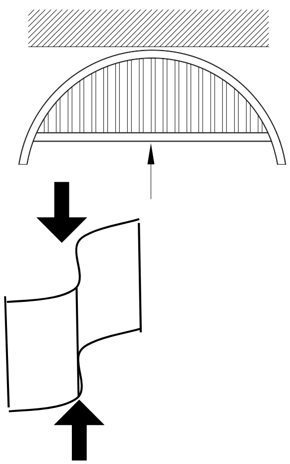
Coupons with Stress gradients

Element tests









Geometric Scaling Effects

CMH-17 material characterization

Round Robin exercise for dynamic tension testing

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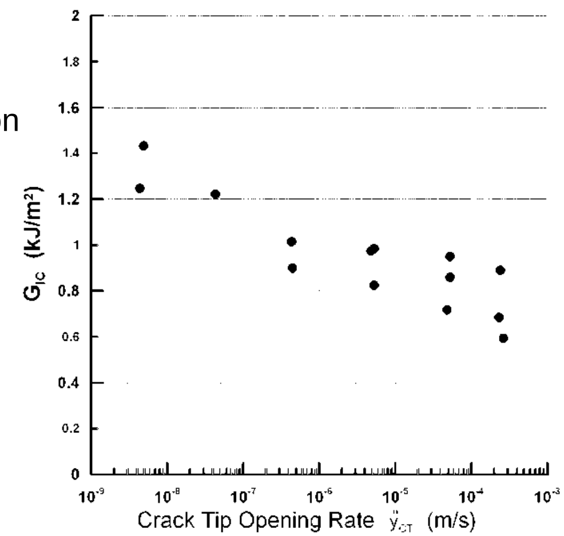
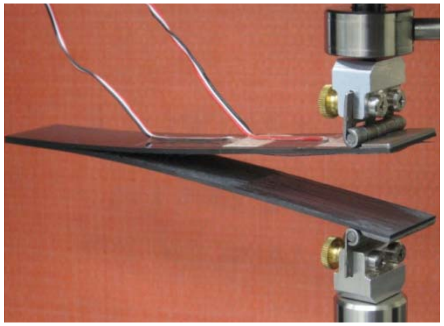
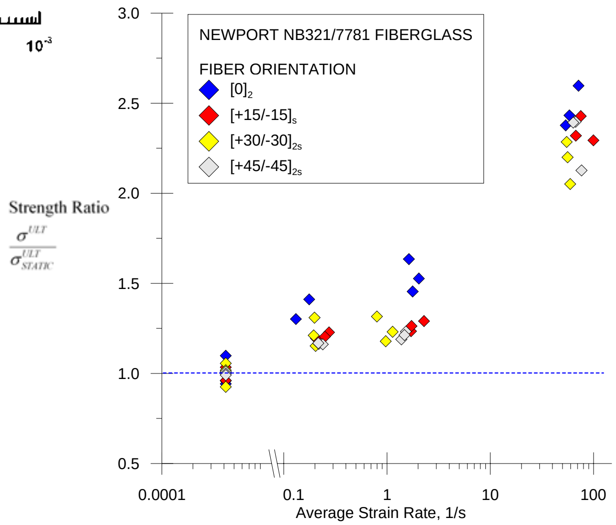
Background..Rate Sensitivity

- Material Systems
  - NEWPORT material systems
    - NB321/3k70 Plain Weave Carbon Fabric (PWCF)
    - NB321/7781 Fiberglass
  - TORAY material systems
    - T800S/3900-2B[P2352W-19] BMS8-276 Rev-H- Unitape
    - T700G-12K-50C/3900-2 Plain Weave Carbon Fabric (PWCF)
- Rate Sensitivity
  - Dependent on material
  - Dependent on loading type (tension, compression, shear)
  - Fracture toughness exhibits trend opposite to that of in-plane properties







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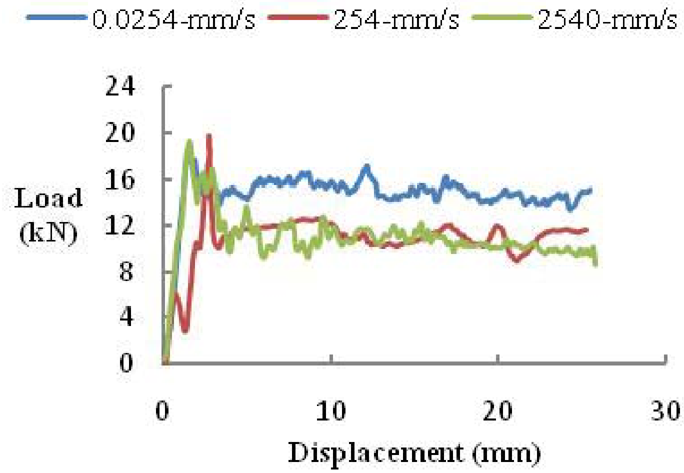
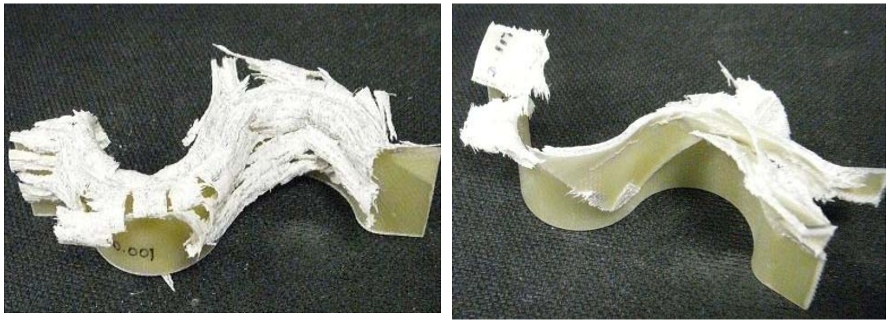
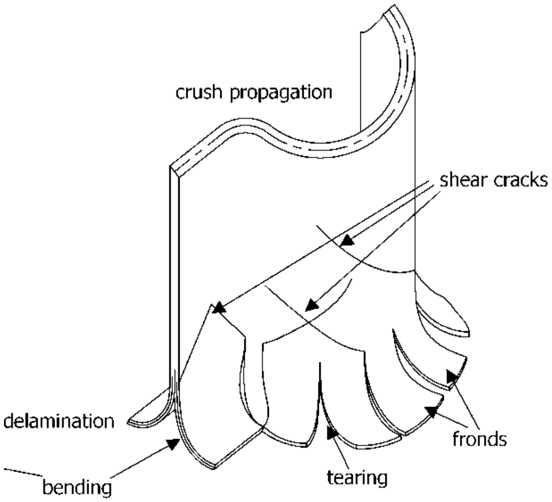
Background..rate sensitivity

- NB321/7781 material; $[0]_4$ & $[\pm 45]_4$
  - Crush loads decrease at higher speeds
  - Splaying mode accompanied by tearing of plies observed in $[0]_4$ specimens.
    - Delaminations
  - Shear cracking observed in $[\pm 45]_4$ specimens
    - Splaying mode /tearing not established
    - Separation of laminate fragments from specimen

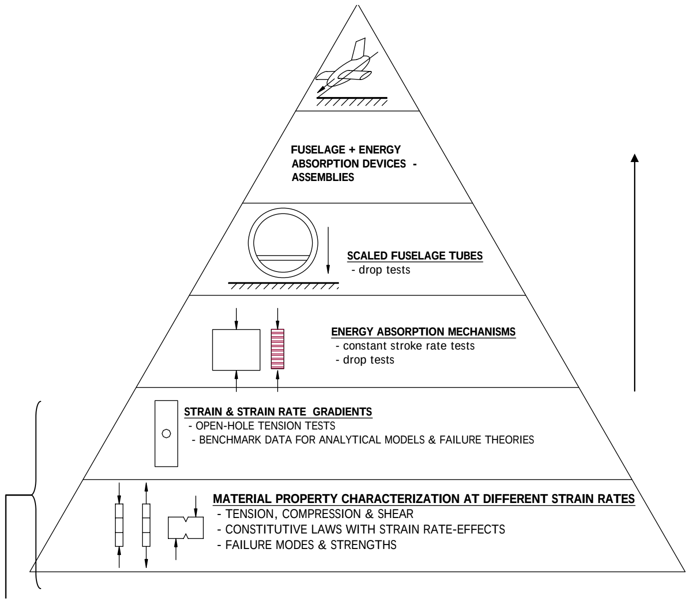






Recently Completed & Ongoing Work..

- Scaling Studies
  - Tension
    - Observed rate sensitivity in sub-scale coupons applicable at larger scales?*
- Characterization of CMH-17 material
  - Tension, Compression & Shear
- CMH-17 Round-Robin exercise for Dynamic tensile testing



*** K.E. Jackson et. al, J.Comp. Matls., Vol.26, 1992**
J.G. Carillo & Cantwell, Comp.Sci.Tech. Vol.67, 2007.

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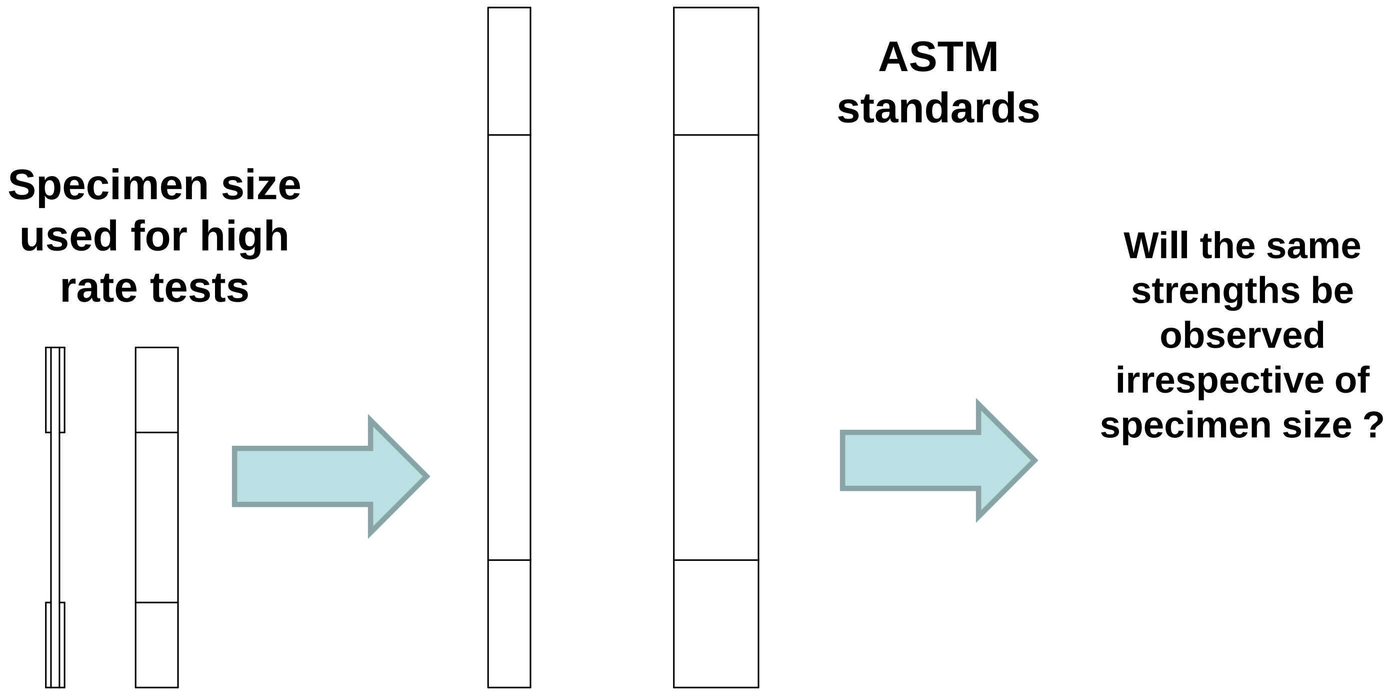
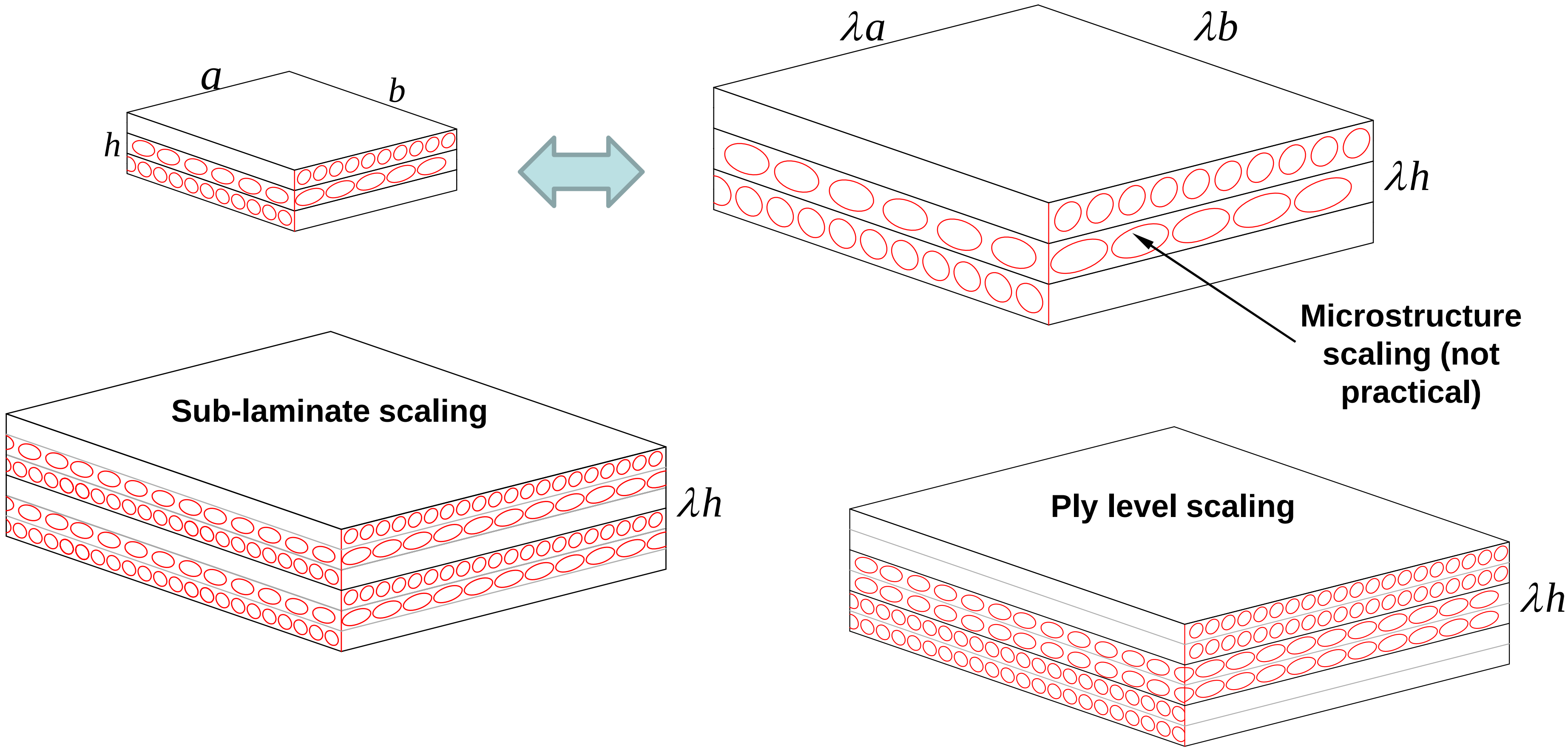
Scaling Issues..

- Specimen size
  - Reduced specimen size to maximize strain rates
  - Reduced specimens size to minimize failure loads to within testing machine capability

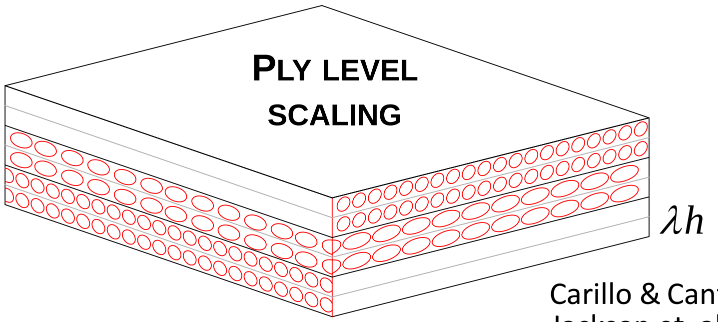


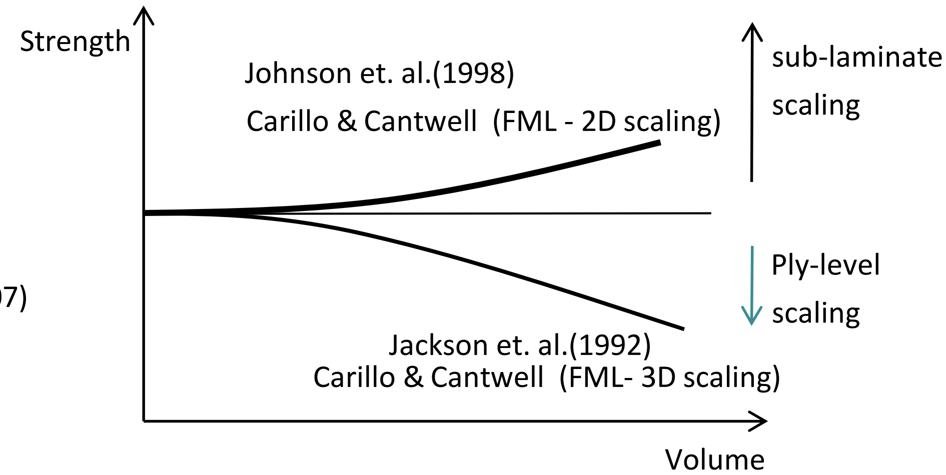
Geometric Scaling..

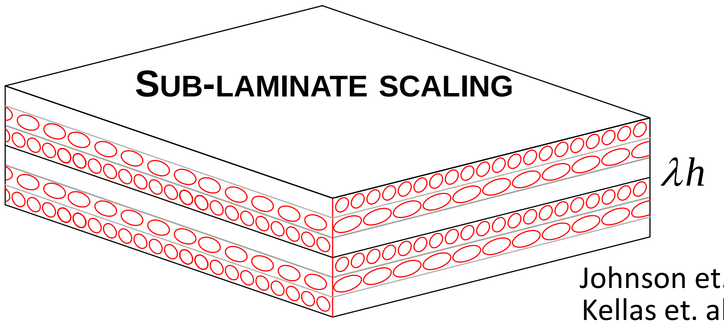


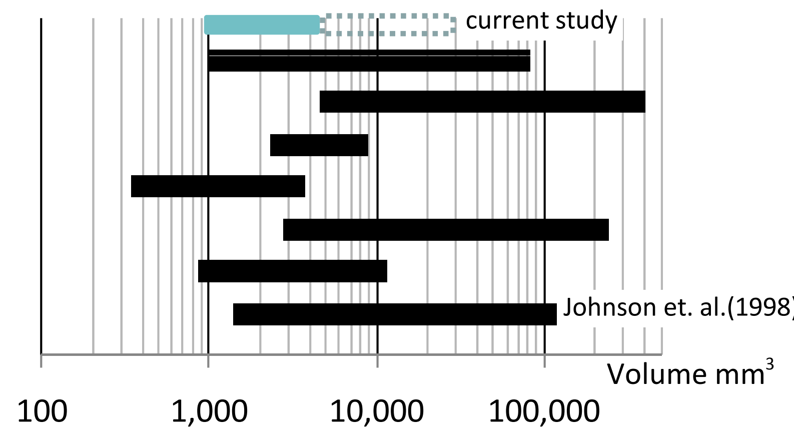
References:
Morton, (1988) AIAA J. Vol. 26, No.8
Wisnom (1999), Comp. Sc. Tech. Vol.59

Geometric Scaling..









References:
Wisnom (1999), Comp. Sc. Tech. Vol.59
Jackson,Kellas & Morton (1992), J. Comp. Mat. Vol.26
Kellas, Morton &Jackson (1993), ASTM STP 1156
Johnson, Morton , Kellas & Jackson (1998) AIAA J. Vol.36
Carillo & Cantwell (2007), Comp. Sc.Tech. Vol.67

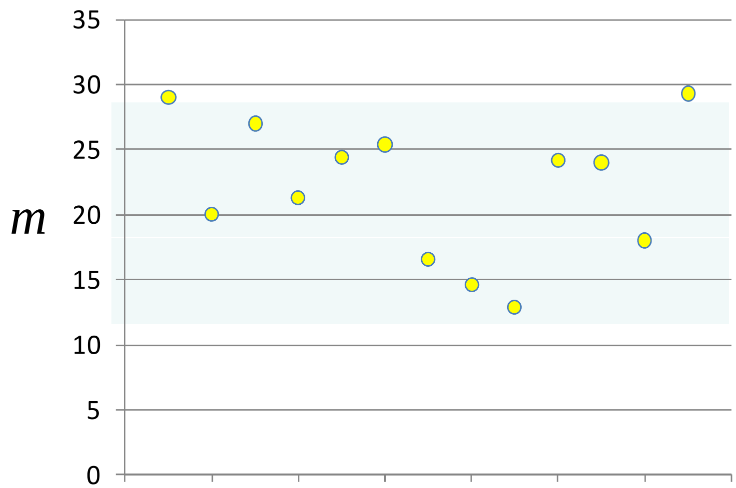
Weibull model

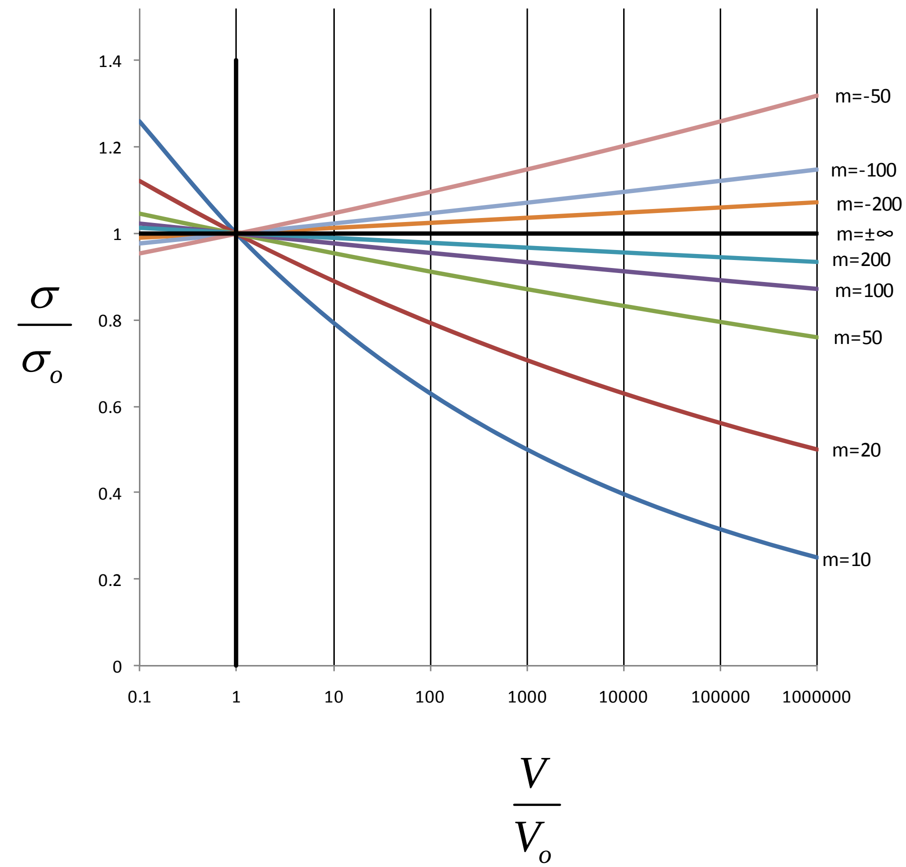
$$\frac{\sigma}{\sigma_o} = \left(\frac{V}{V_o}\right)^{-\frac{1}{m}}$$

σ_o ~ characteristic(reference) strength

V_o ~ characteristic(reference) Volume

m ~ Weibull modulus





References:

Weibull (1951), J. App. Mech., Vol.18

Jackson,Kellas & Morton (1992), J. Comp. Mat. Vol.26

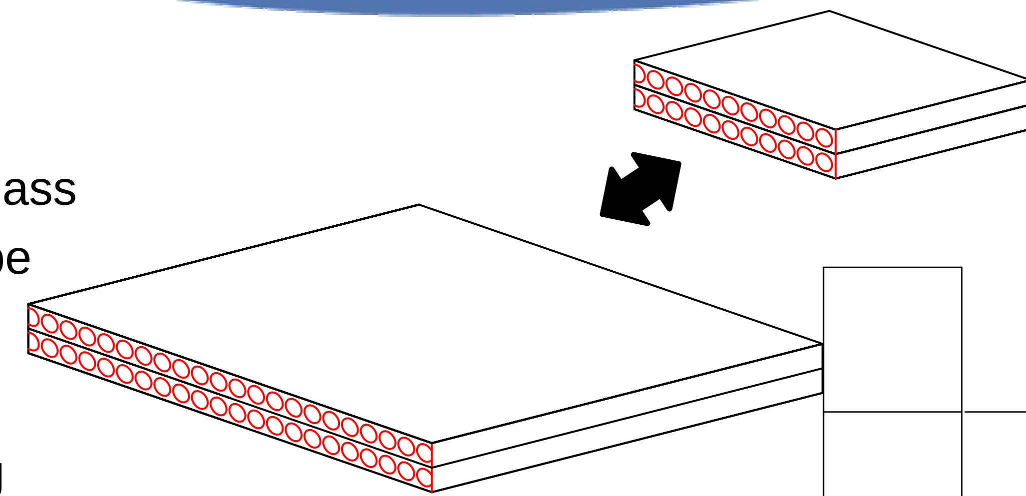
Wisnom (1999), Comp. Sc. Tech., Vol.59

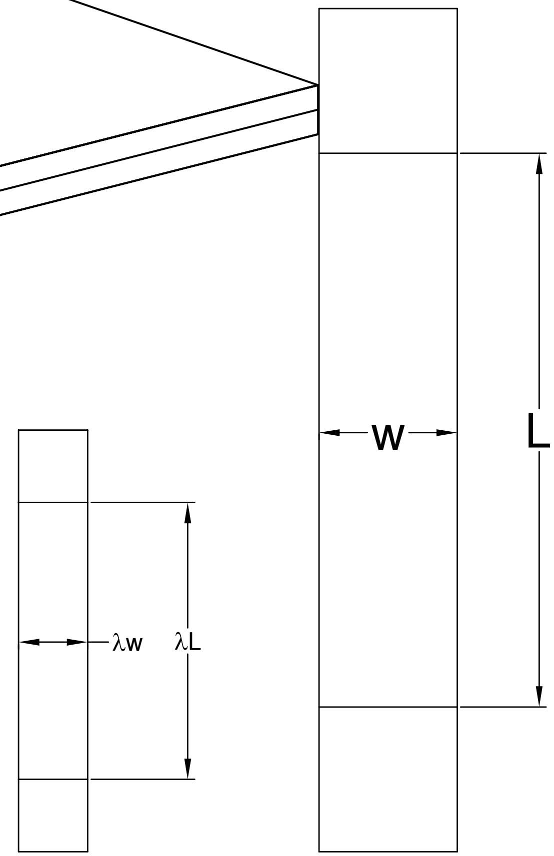
Objectives

- Investigate the geometric scaling effects on the tensile properties of composite materials at different strain rates
  - Are the scaling effects functions of strain rates?
  - Quantify effects in terms of Weibull modulus ‘m’

Scaling Experiments

- Material Systems
  - Newport NB321/7781 fiberglass
  - Toray T800/3900-2B Unitape
- Scaling type
  - Fabrics : 2D (planar) scaling
  - Unitape : 1D (length) scaling
    - Reduced loading capability





MATERIAL	STACKING SEQUENCE	SCALE λ	L (mm)	W (mm)
NB321/7781 fiberglass, T700G-12K-50C/3900-2 PWCF	$[0]_4$ $[+45/-45]_S$	1/4*	50.8	12.7
		1/2	101.6	25.4
		1	203.2	50.8
Toray T800S/3900-2B unitape	$[0]_4$	1/4*	50.8	12.7
		1/2	101.6	12.7
		1	203.2	12.7
	$[+45/-45]_S$	1/4*	50.8	12.7
		1/2	101.6	25.4
		1	203.2	50.8

*Specimen size used in phase-I

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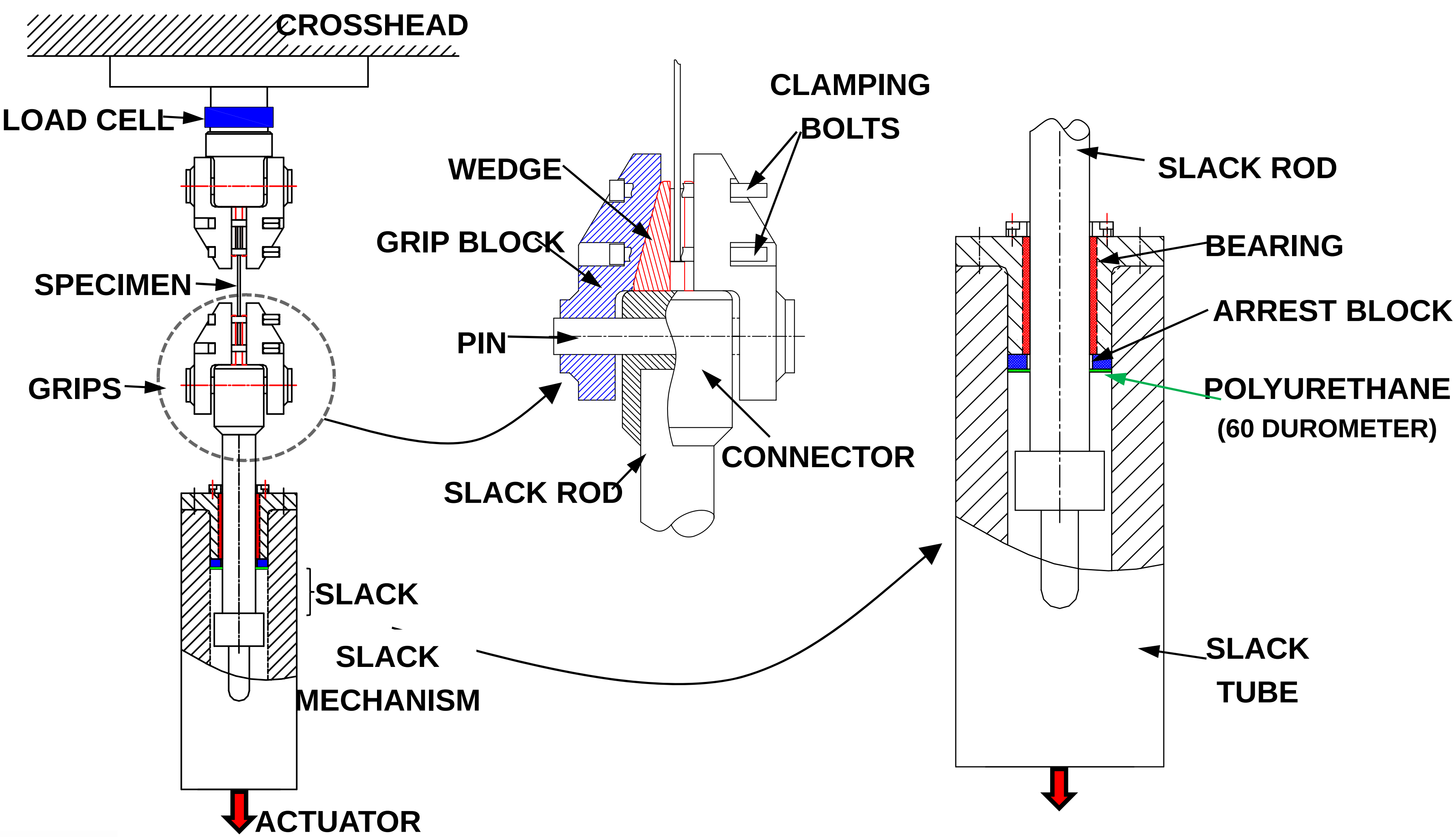
Tension Test Apparatus…



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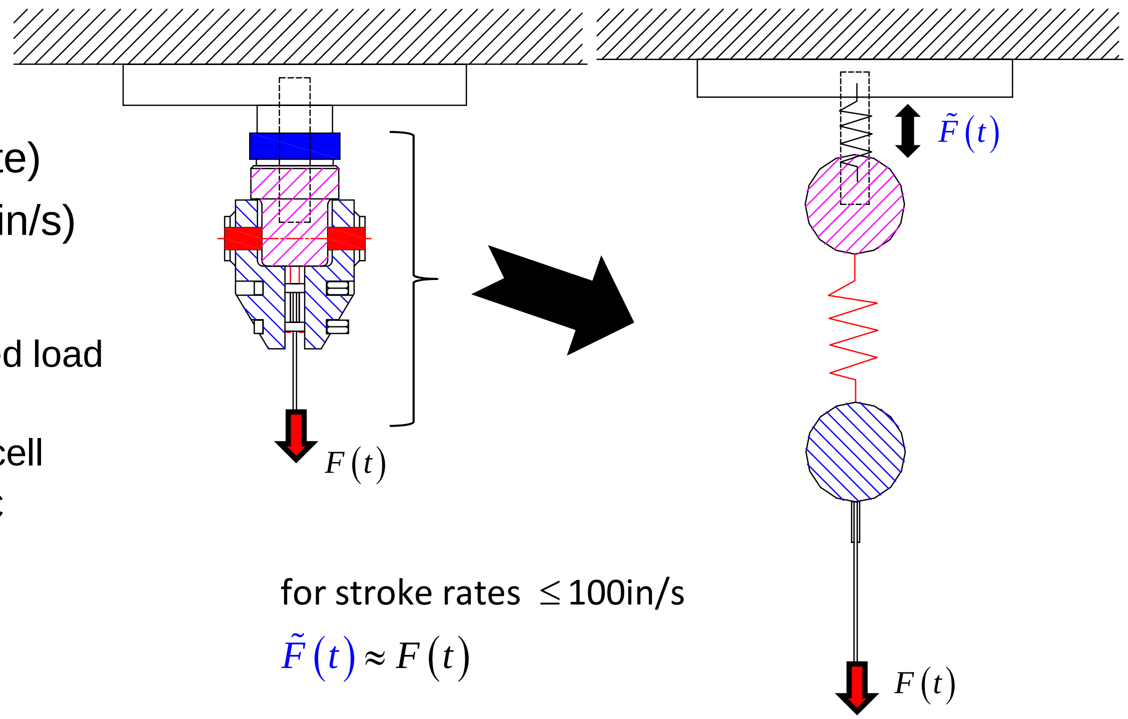
Tension Test…Instrumentation

- Load Frames
  - MTS electromechanical (slow rate)
  - MTS high rate (~ 0.5 in/s to 500in/s)
- Load measurement
  - Slow speed tests ~Strain gage based load cell (5 kip capacity)
  - Dynamic Tests ~Piezoelectric load cell
    - –PCB Piezotronics model 206C
    - –±10kip capacity
    - – ~40kHz upper frequency limit
- Strain measurement
  - Strain gage CEA-06-250UW-120
  - Vishay 2210 signal conditioner
    - Excitation voltage : 1V
    - DC to 50kHz (-0.5dB max)



for stroke rates $\leq$ 100in/s

$\tilde{F}(t) \approx F(t)$

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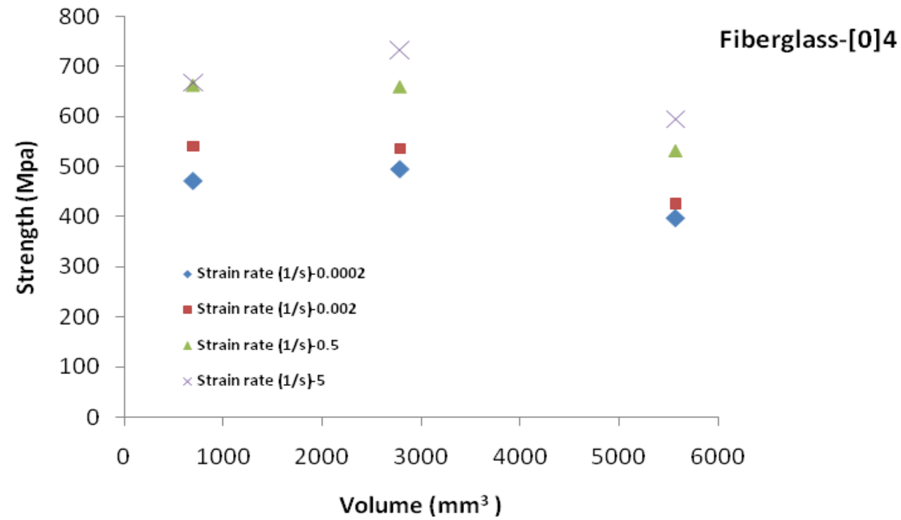
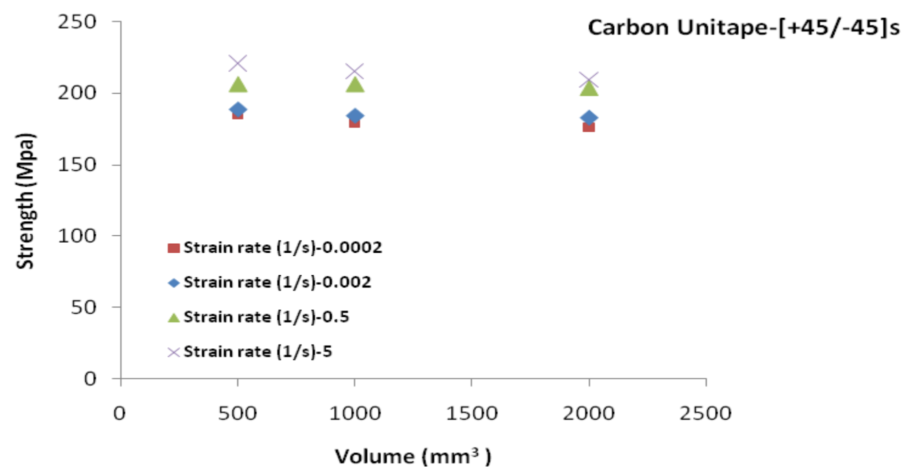
Test Results

- Sensitivity to strain rate observed at all volumes
- Scaling effects consistent with literature
  - Reduction in strength with increase in volume
  - No significant change in modulus
- Range of volumes investigated to date is limited.





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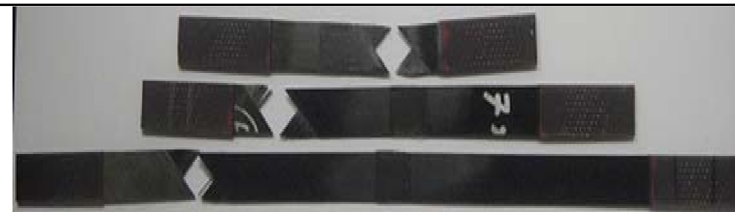
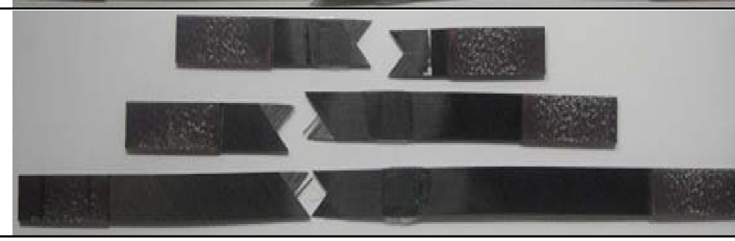
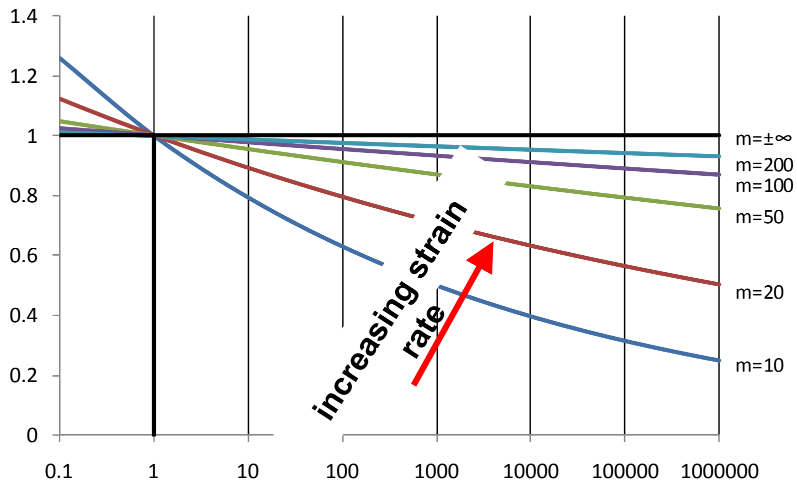
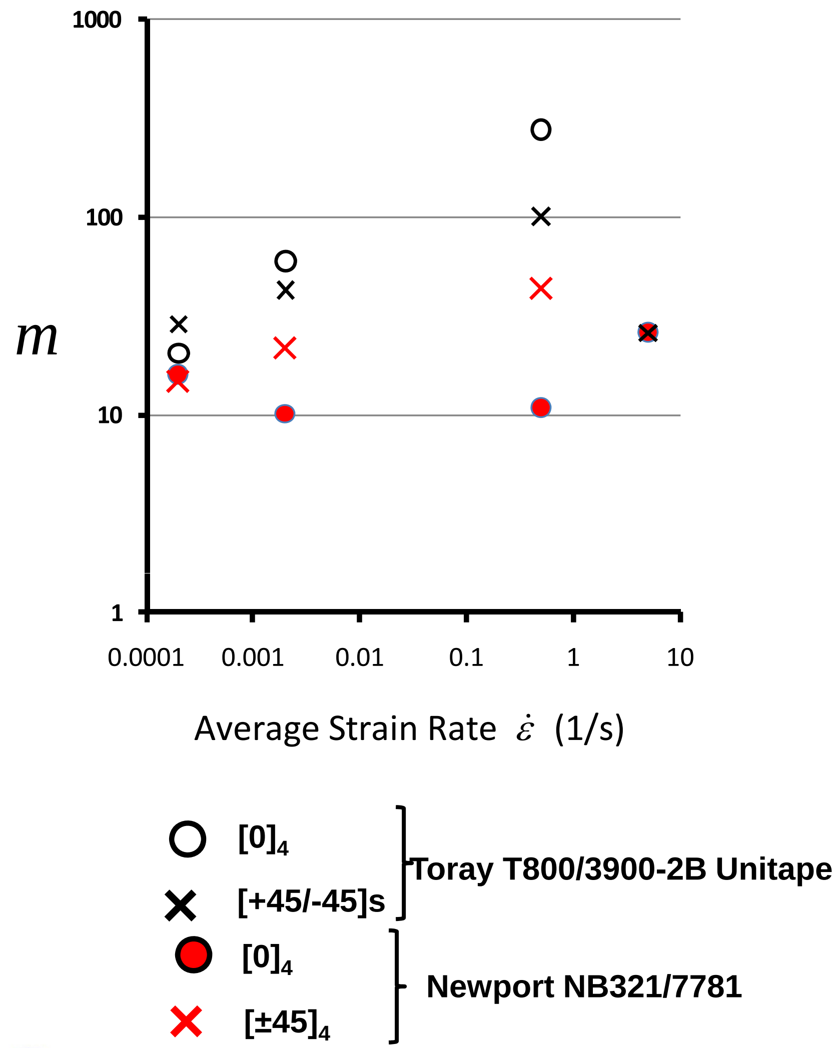
Failure modes..

Strain Rate (1/s)	$[0]_4$ specimens	$[+45/-45]_s$ Specimens
0.0002		
0.002		
0.5		

Test Results..Weibull Modulus

- Based on Weibull modulus, the scaling effects tend to diminish with increasing strain rates
  - Increase in 'm' dependent on material system and stacking sequence





Material Characterization..Round Robin

- Characterization of *in-plane* stress-strain behavior of Toray T700/2510 Plain weave carbon/epoxy (F6273C-07M) under dynamic rates of loading (P.I :G.Olivares)
  - Tension (current activity)
    - $[0]_n$, $[+/-45]_{ns}$
  - Compression
  - Shear
- Strain Rates
  - Quasi-static to ~$250s^{-1}$

Original plans included Newport NB321/7781 fiberglass/epoxy material. Due to budget & time constraints, this material will not be used.

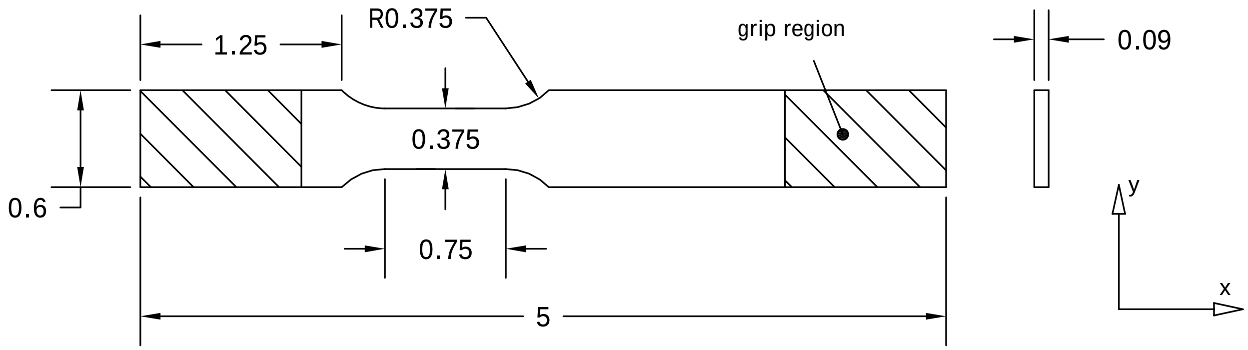
Participating Labs/Agencies (POCs)

- ■ Co-ordination, Reporting
- △ Specimen fab., fixturing, instrumentation (strain gage)
- ◔ Material
- ☆ Testing

- FAA/NIAR/WSU (A. Abramowitz, G. Olivares, K.S. Raju) ■ △ ☆ ◔
- Boeing (M.Rassaian, ?) ☆
- Ohio State University (A. Gilat) ☆
- DLR (Alastair Johnson) ☆
- University of Utah (Dan Adams) ☆
- Oakridge National Labs (M. Starbuck) ☆
- Toray America (Sam Tiam) ◔

Round Robin Activity

- Primary Objective
  - Characterize strain rate sensitivity of Toray T700/2510 Plain weave carbon/epoxy (F6273C-07M) material at strain rates ranging between 0.01 to 250 s^{-1}.
- Secondary Objective
  - evaluate the test methods/apparatus, specifically load measurement methods, employed by the participating laboratories.
    - Use extended tab 2024-T3 aluminum specimens



Nominal Quasi-Static Properties…

Property	Material		
	2024-T3 bare[1]	Toray[2]	Newport[3]
Thickness/ply thickness (in)	0.010 – 0.128	0.0084	0.009
Young's Modulii (Msi)	E=10.5	E_1=8.12 E_2=7.97	E_1=4.19
Shear Modulus (Msi)	G=4.0	G_{12}=0.58	G_{12}=0.61
Poisson's Ratio	ν=0.33	ν_{12}=0.042	ν_{12}=0.138
Tensile Strength (ksi)	F_{TU}=65 (L)*	F_{1t}=132 F_{2t}=112	F_t=63.5
Shear Strength (ksi)	F_{SU} = 40*	F_{12s}=22	F_{12s}=19

Used for tabs

Data Source

[1]MMPDS (* B-basis values)

[2]AGATE WP3.3-033051-134. Lamina properties (Oven cured)

[3]AGATE WP3.3-033051-097. Laminate properties (Oven cured)

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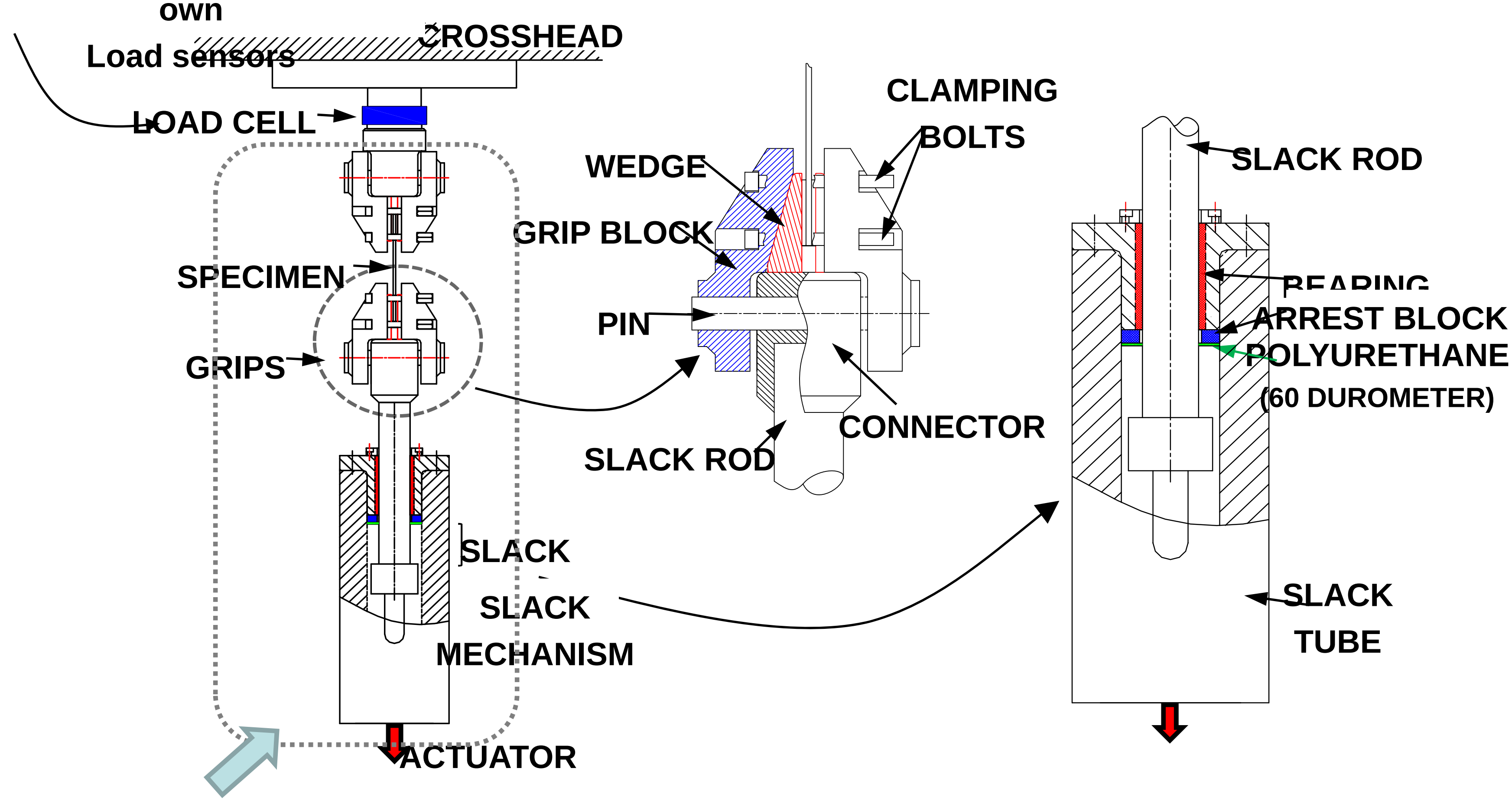
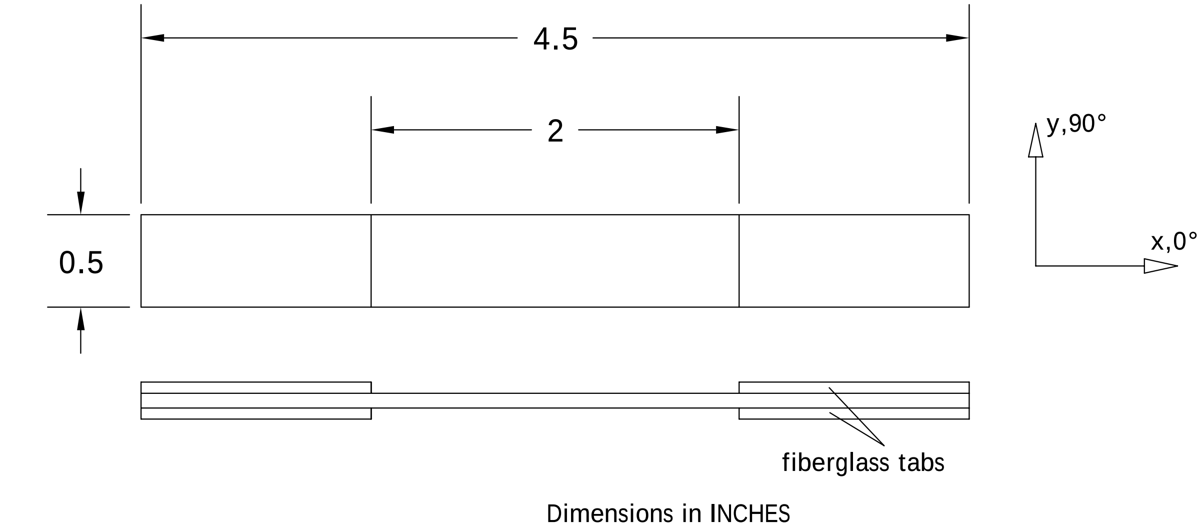
Tension Test Apparatus…

participating labs use their own Load sensors

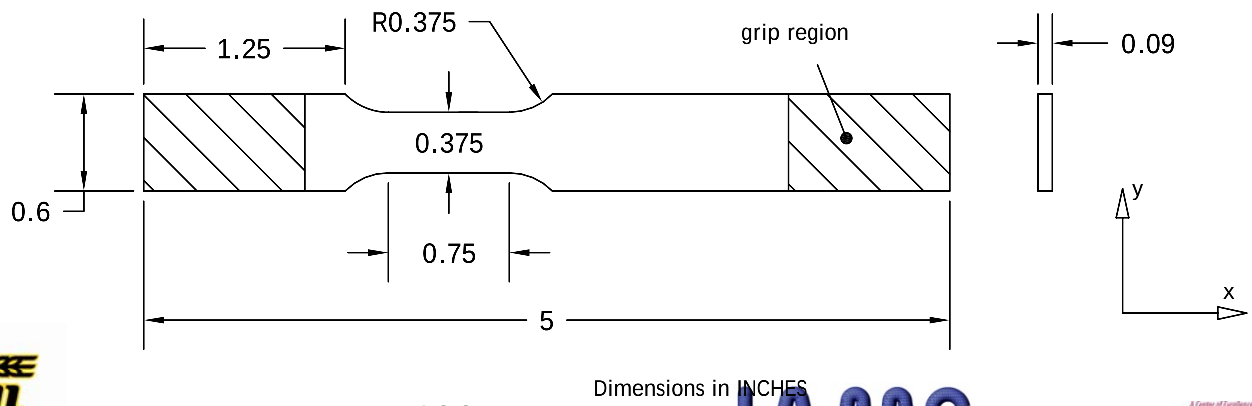


Will be provided to participating labs by WSU/NIAR

Test Specimen Geometries..



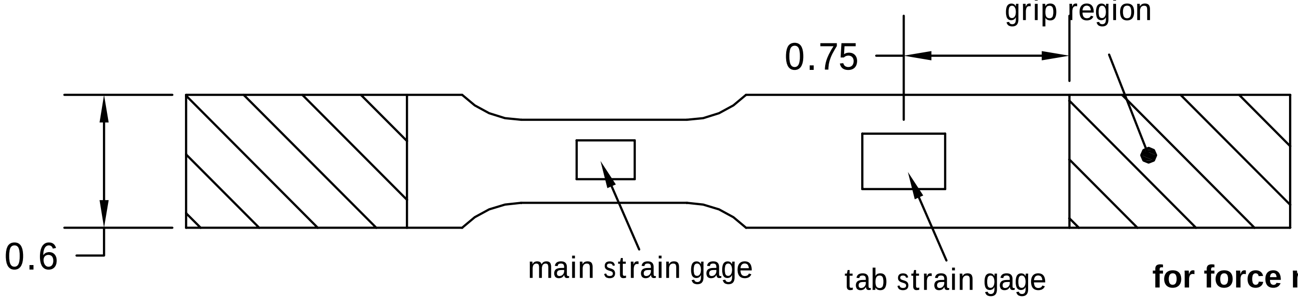
Composite specimens



Aluminum specimens

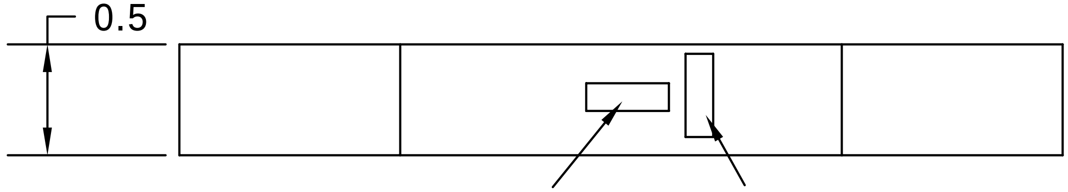
Will be provided to participating labs by WSU/NIAR

Instrumentation..



Aluminum specimens

for force measurement



Composite specimens

(for [+/-45]ns specimens only)

NOTE : Strain gages are not drawn to scale

Dimensions in INCHES

Instrumentation will be done by WSU/NIAR

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Test matrix…

Material System	Nominal Strain rate (1/s)			
	0.01	1	100	250
2024-T3 Aluminum	×3	×3	×3	×3
TORAY T700/2510 plain weave/epoxy (F6273C-07M)				
$[0]_4$	×3	×3	×3	×3
$[90]_4$ (TBD)	×3	×3	×3	×3
$[\pm45]_4$	×3	×3	×3	×3
NEWPORT NB321/7781 fiberglass/epoxy				
$[0]_4$	×3	×3	×3	×3
$[\pm45]_4$	×3	×3	×3	×3

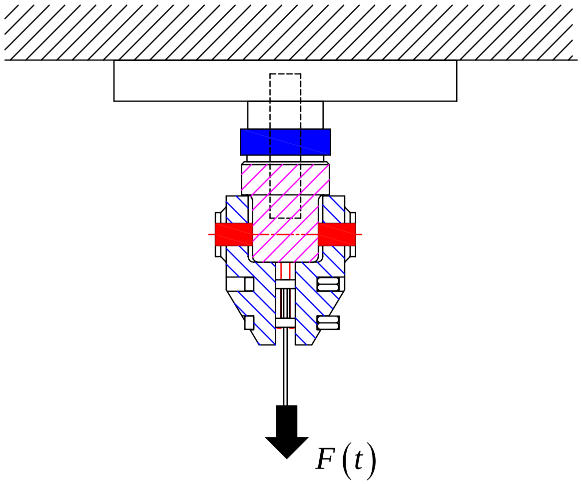
Total : 48 tests

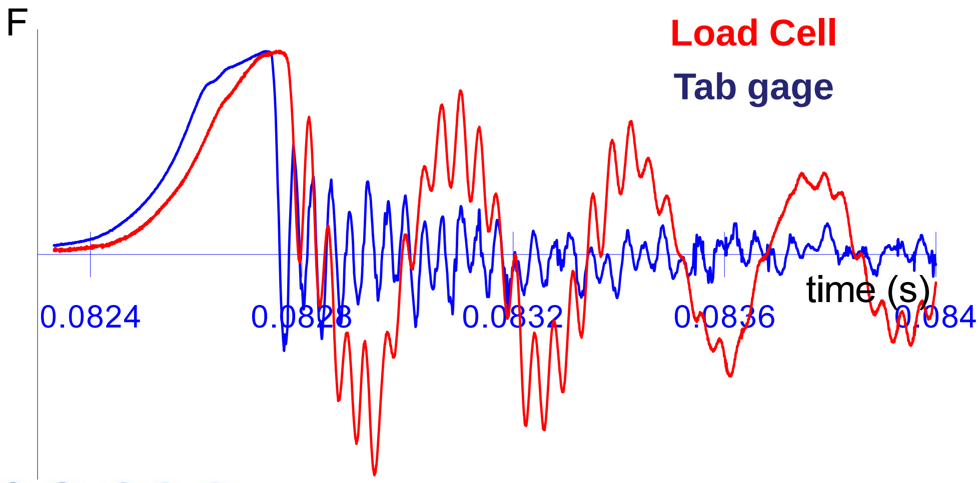
Status..

- Document (draft) describing the round-robin activity mailed to participants
  - Ohio State (A. Gilat) requested a different specimen geometry and attachments for use with SHPB apparatus
- Aluminum Specimens
  - Machining has been completed
  - Instrumentation under progress
- Fabrication of Test panels completed
  - C-scan of fabricated panels completed
  - Tabbing and specimen machining under progress
- Machining of test fixtures completed

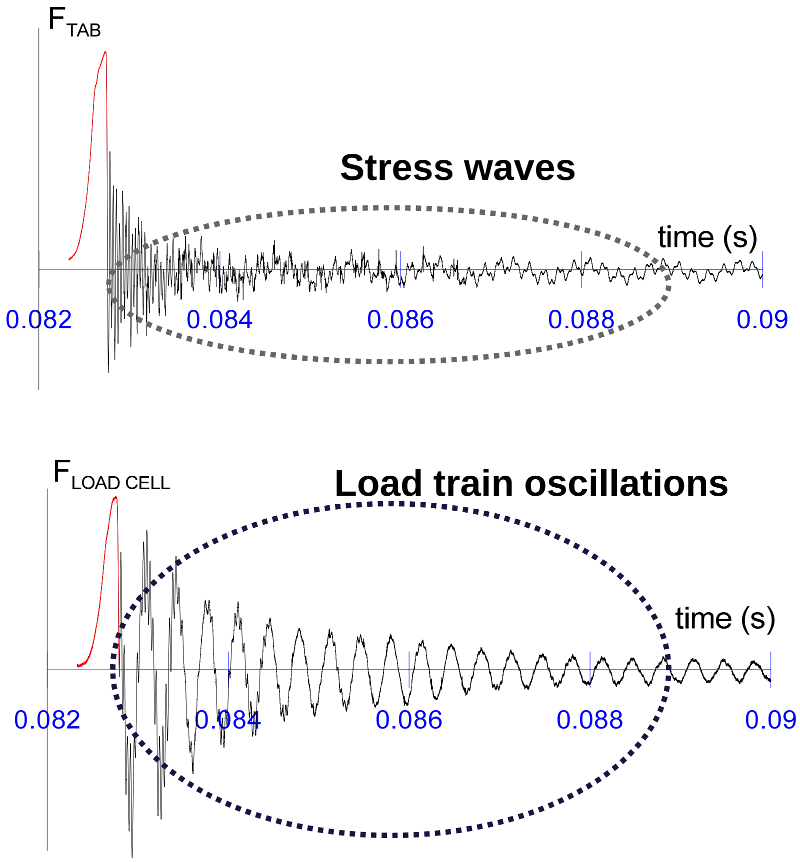
Preliminary Tests…

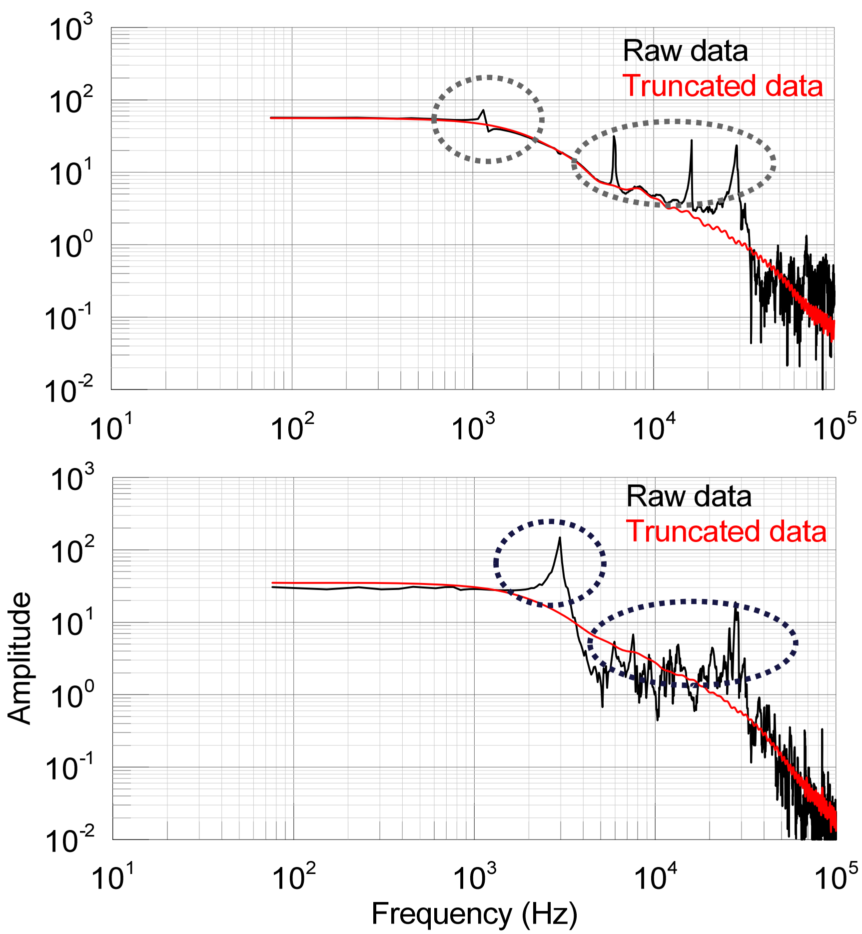
- Extended Tab Aluminum Specimen
- Load measurement
  - PCB Piezotronics model 206C
    - ±10kip capacity
  - ~40kHz upper frequency limit
- Strain measurement
  - Strain gage CEA-06-250UW-120
  - Vishay 2210 signal conditioner



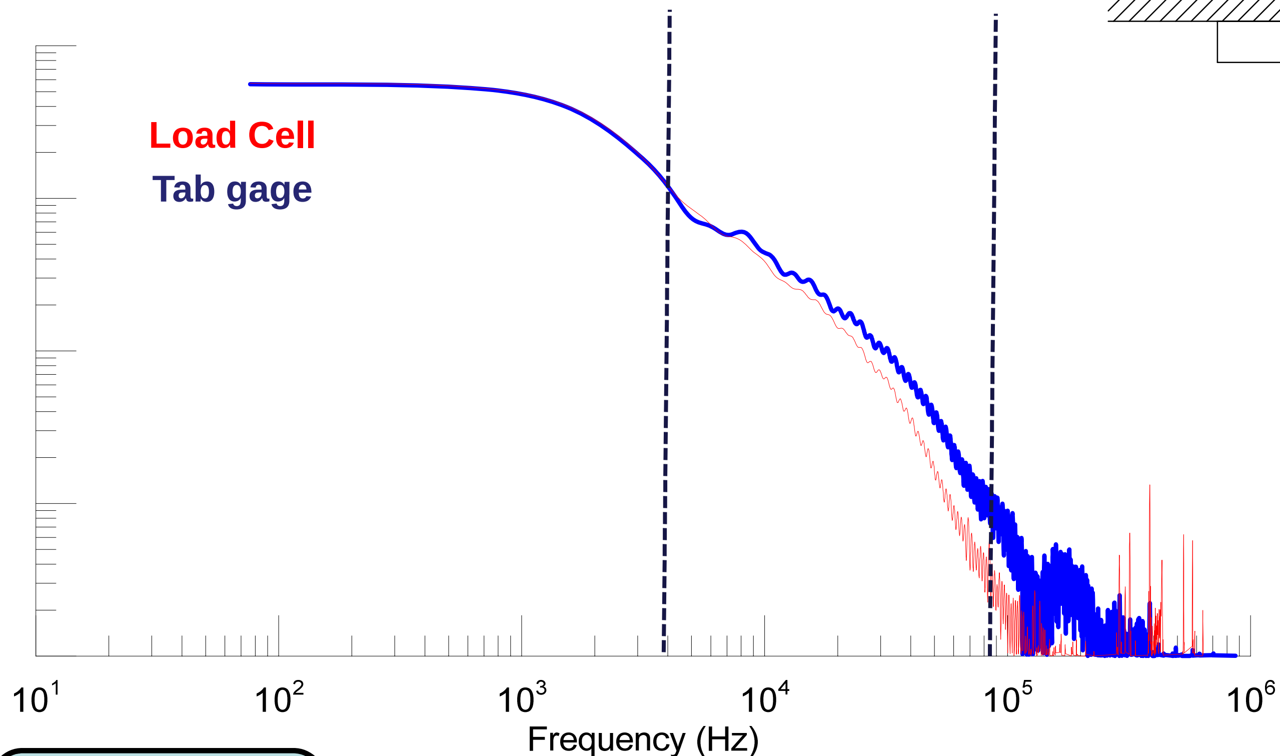


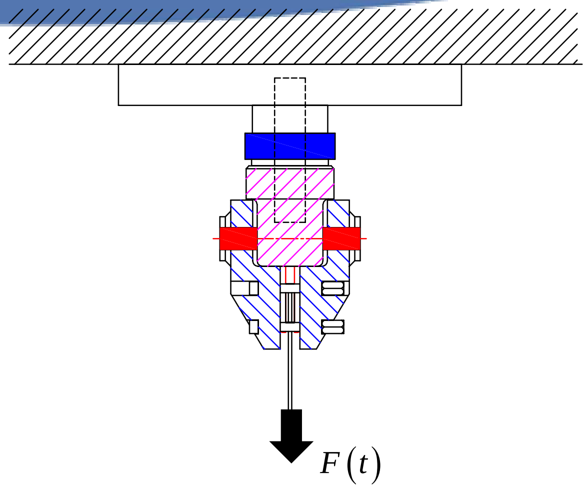
Load measurement..





Load Measurement..





Extended tab Aluminum Specimen → TRANSFER FUNCTION → Correct test data for Composite Specimens

Extended tab Aluminum Specimen → Simulations to improve test apparatus

Looking Forward

- Benefit to Aviation
  - Rate sensitive data for different material systems
  - Guidelines for conducting dynamic testing using servo machine
- Future needs
  - Round-Robin exercises for Compression, Shear
  - Evaluation of material models

End of Presentation.

Thank you.

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