Certification of Discontinuous Composite Material Forms for Aircraft Structures

Presented at the:
AMTAS Fall Meeting
November 5, 2009

The Joint Advanced Materials and Structures Center of Excellence

Cert of Discontinuous Composite Material Forms for Aircraft Structures

- Motivation
  - Discontinuous fiber composites (DFC) are being used in aircraft and automotive structures because (relative to continuous fiber composites):
    - ease of manufacturing complex parts
    - high delamination resistance
    - near quasi-isotropic in-plane stiffness and reasonable in-plane strengths
    - high out-of-plane strength-stiffness
    - low notch sensitivity

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- Key Issues
  - Rigorous structural analyses difficult:
    - rel high variability in all mechanical properties
    - lack of material allowables
    - lack of standard design or analysis methods

  - Consequently certification of DFC parts currently requires testing large numbers of parts ("point design")…issues:
    - Time-consuming
    - Expensive for all (material producer, part manufacturer, aircraft manufacturer, FAA)
    - Leads to suboptimal (e.g., overweight) parts

Cert of Discontinuous Composite Material Forms for Aircraft Structures

- Overall objective: Simplify certification of discontinuous fiber composite aircraft parts

Project Information

- Personnel Involved:

  University of Washington:
    Paolo Feraboli, Tyler Cleveland, Marissa Morgan (A&A Dept)
    Mark Tuttle, Paul Labossiere, Tim Briggs, Tory Shifman (ME Dept)
  Hexcel (principally):
    Bruno Boursier (Dublin, CA)
    Dave Barr (Kent, WA)
  Boeing (principally):
    Bill Avery (Seattle, WA)
  FAA (principally):
    Larry Ilcewicz (Renton, WA)

- FAA Technical Monitor:
    Curt Davies (Atlantic City, NJ)

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- Objective:
  - Simplify certification of DFC parts/structures
- Technical Approach:
  - Use HexMC as model material
  - 4-year study envisioned (began Aut '08)
  - Funding and specific technical tasks reviewed and (re)defined annually
  - All specific technical tasks defined with reference to the "building block philosophy" (CMH-17)

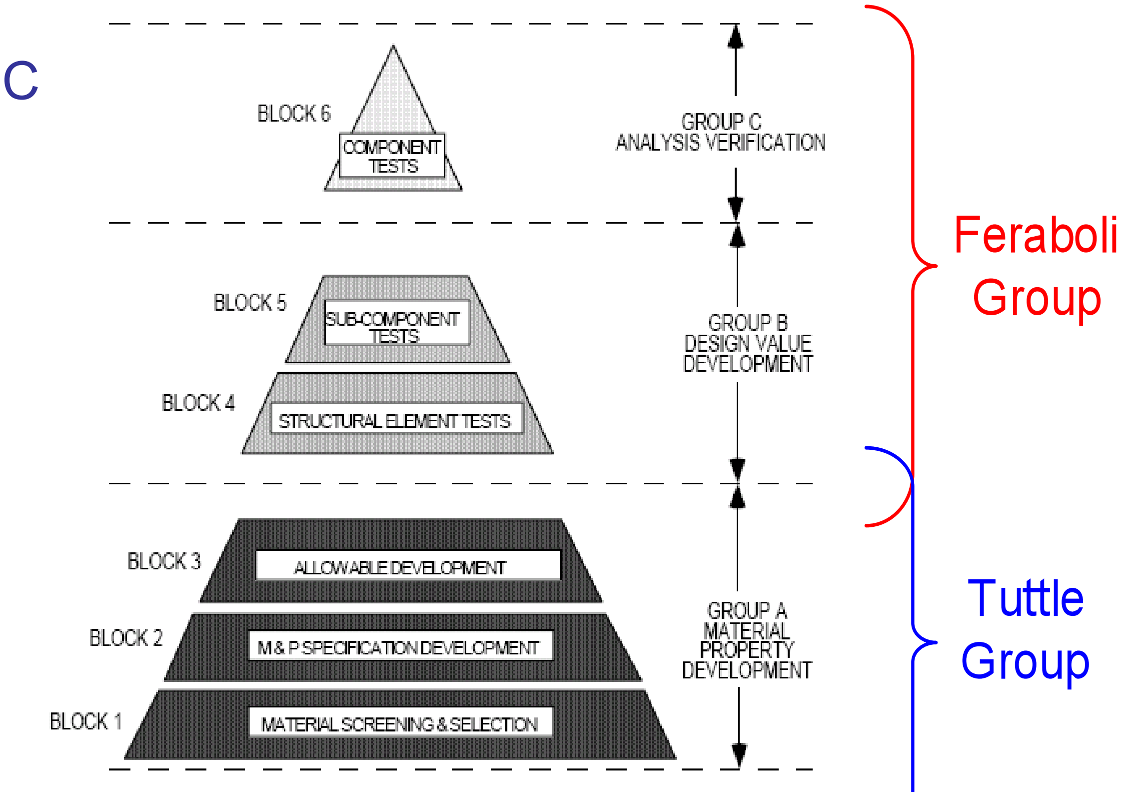

FIGURE 4.4.3.2 *Building block approach.*

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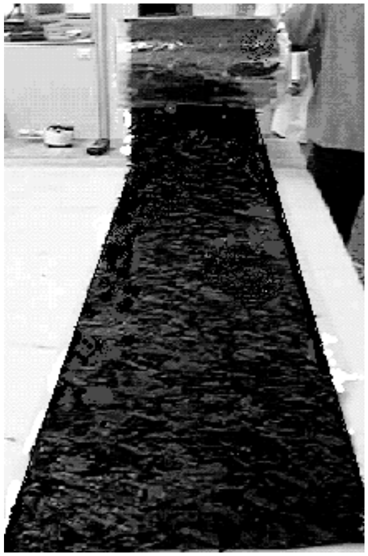
- HexMC® parts are produced using compression molding
- Industrial grade HexMC®:
  - Available from Hexcel in pre-preg form
- Aerospace grade HexMC®:
  - Exclusively provided by Hexcel as manufactured and finished parts



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…example aerospace grade HexMC® parts produced by Hexcel using compression molding

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- Technical Tasks (4-year):
  - Blocks 1,2,3 :
    - Hexcel: Generate allowables database: UNT, UNC, OHT, OHC, FHT, FHC, bearing, bearing/ by-pass, etc. Fabricate panels/etc needed for coupon-level UW studies
    - UW-Tuttle:
      - Evaluate and develop understanding of effects of ply drops/adds (ply drop rate, part thickness, and molding-related issues such as high- vs low-flow areas)
      - Evaluate and develop understanding of load redistribution and failure at or near part fastener locations
      - Evaluate and understand the effect of NDI indications on properties/performance

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- Technical Tasks (4-year):
  - Blocks 4,5,6 :
    - Hexcel: Fabricate specimens-subcomponents-components as needed
    - UW-Feraboli: Develop semi-empirical analysis methods to account for features in selected aircraft part (intercostal selected). Features being studied include:
      - Deep-web panel bending, tension and compression, with and without lightening holes.
      - Thickness transitions.
      - Large lightening holes.
      - Damage (BVID, saw cuts or other surface nicks and embedded defects in the most critical locations)

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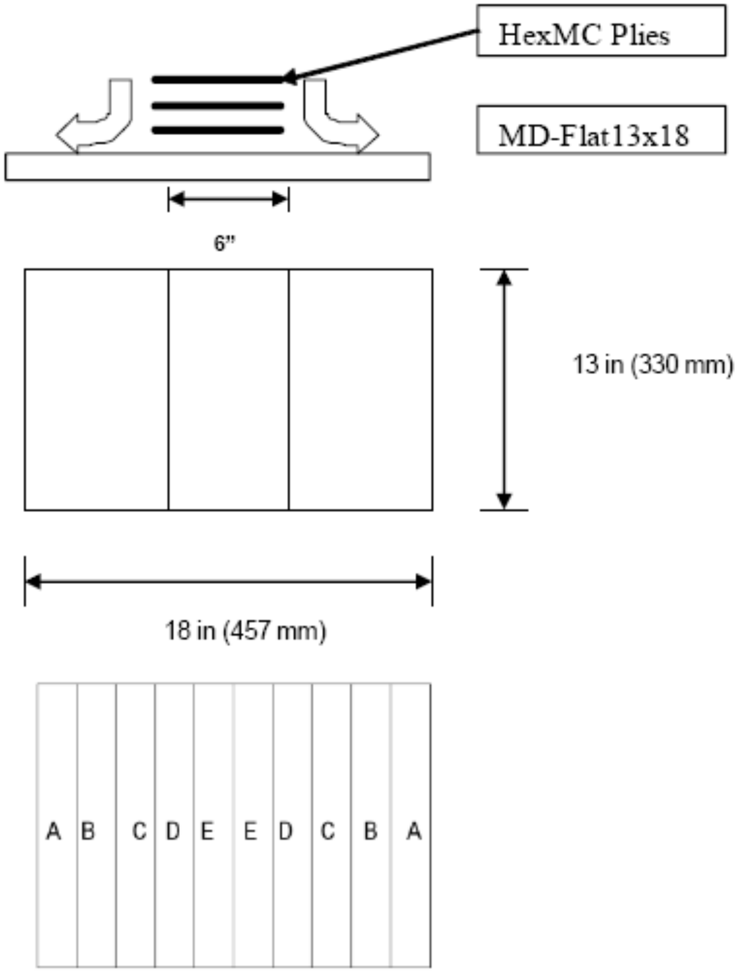
(A sampling of current activities & preliminary results):

- Characterizing structure in high-flow vs low-flow regions
- UNT & OHT versus UNC & OHC tests
- Beam flexural testing

High- and Low-Flow Panels

Panels fabricated by Hexcel:

- in-plane dimensions 13x18 in
- Target thicknesses:
  - 0.090 in (4 panels received)
  - 0.140 in (5 panels received)
  - 0.230 in (4 panels received)



High- and Low-Flow Panels

Surface Observations (0.14 in panel)

Extreme Flow Region
Small, Tightly Grouped, Curved/Swirling Fibers, Aligned Chips

Indistinct chip boundaries

Moderate Flow Regions
Medium, Intertwining Chips, Curved Fibers, Random Oriented Chips

Distinct chip boundaries

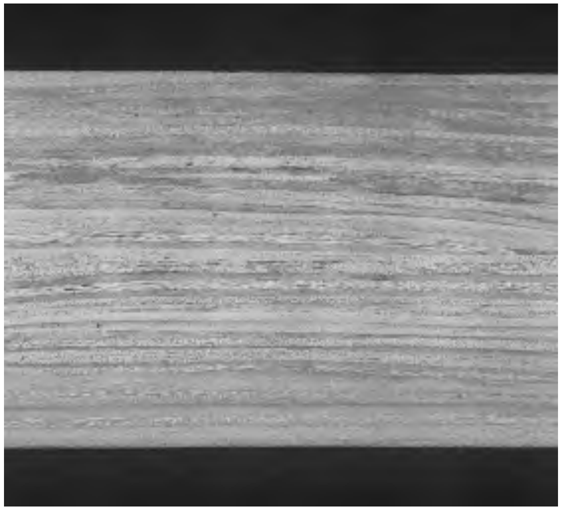
Low Flow Regions
Large, Layered, Straight Fibers, Random Oriented Chips

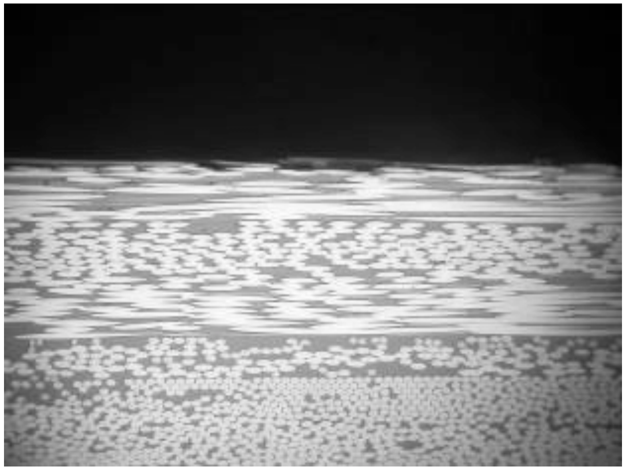
Distinct chip boundaries

Centerline of Plate (x=9)

Low-Flow Regions (near Center)

Well-defined laminar structure (0.14 panel)

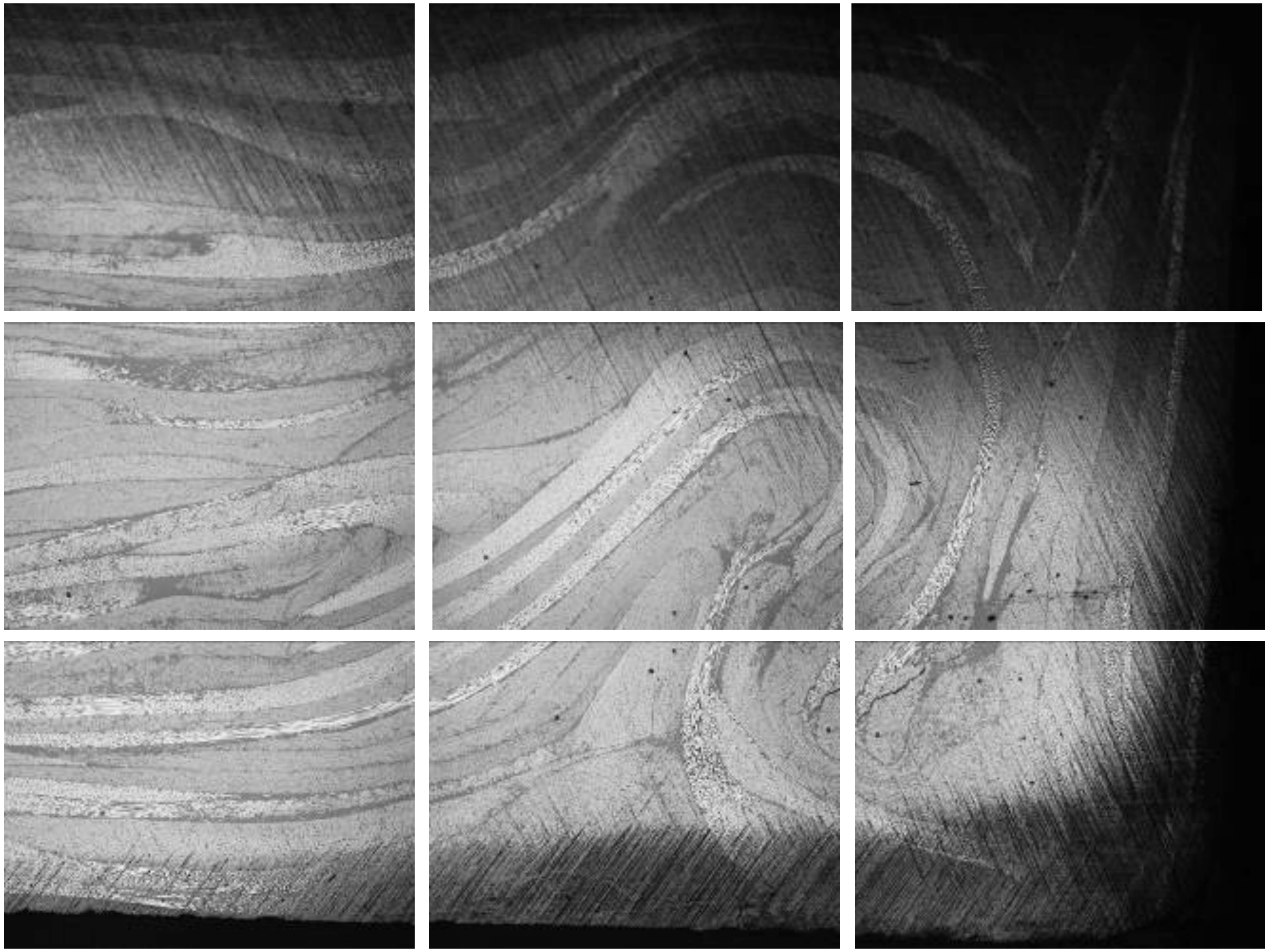




- Ply structure easily discernable
- Can deduce average fiber/matrix volume fractions
- Fiber aspect ratios reveal relative orientation

High Flow Region (near Edge)

Swirling chips; loss of lamination (0.14 in panel)

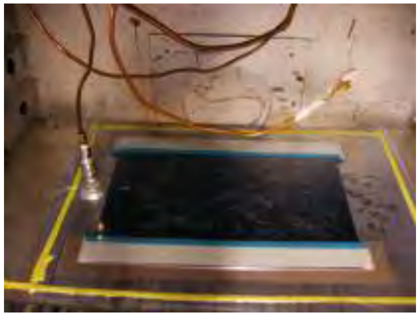


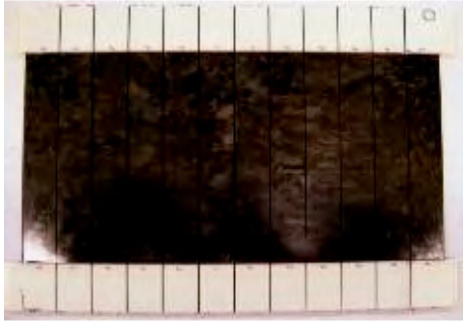
Tensile Tests

0.14 in panel

Specimens

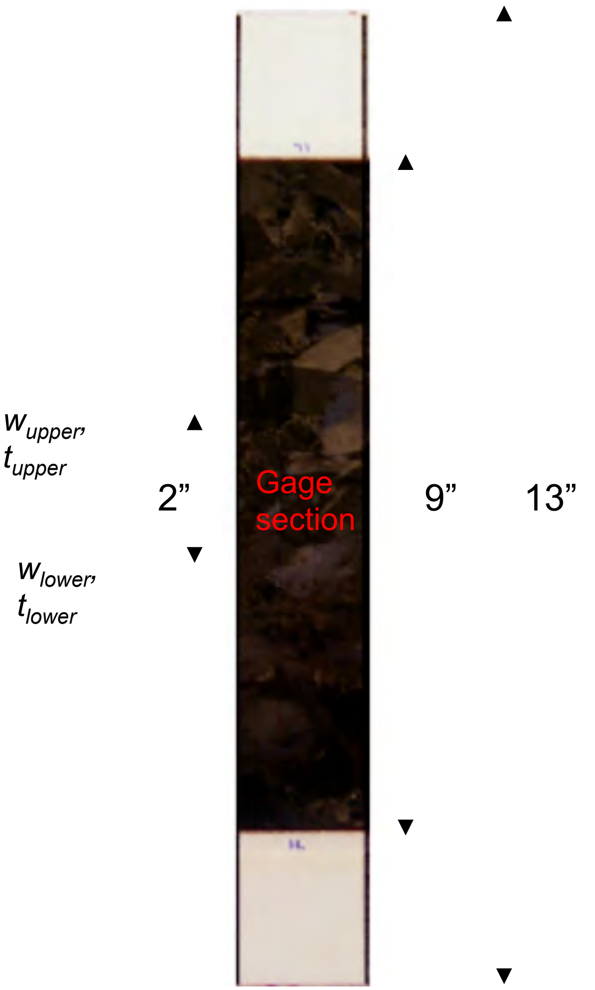
- 1.5'' Wide
- 2" Fiberglass Tabs w/ 6º bevel
- 13'' Length, 9'' gage length
- Machined w/water cooled diamond saw
- Full depth cut @3000 RPM, 6 in/min feed
- Surface finish:
  $R_a \approx 0.49$ (machined surface)
  $R_a \approx 0.73$ (as received)





Tensile Tests

0.14 in panel

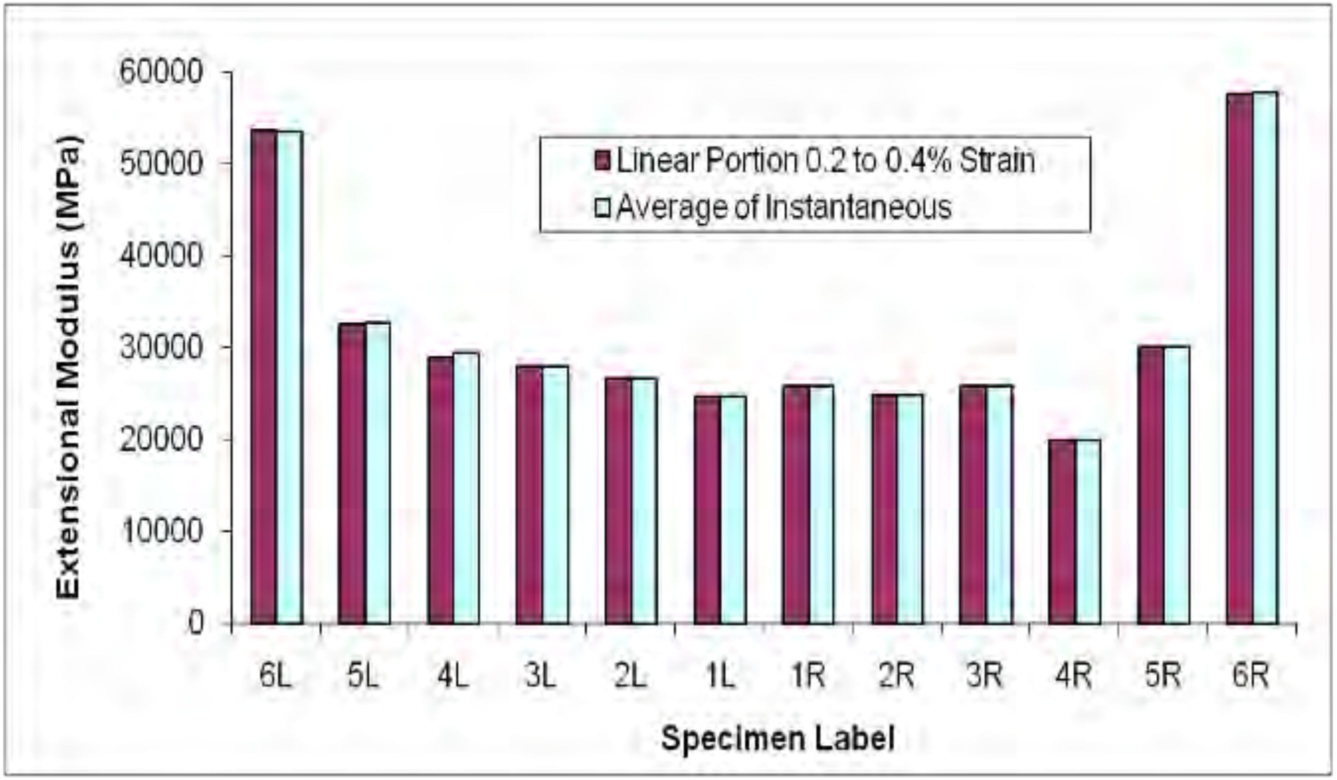


- Axial strains measured using 2” extensometer
- Axial stress defined using average X-sectional area:

$$A_{avg} = \frac{w_{upper}t_{upper} + w_{lower}t_{lower}}{2}$$

Tensile Modulus

0.14 in panel



- E_{ax} GPa (Msi):

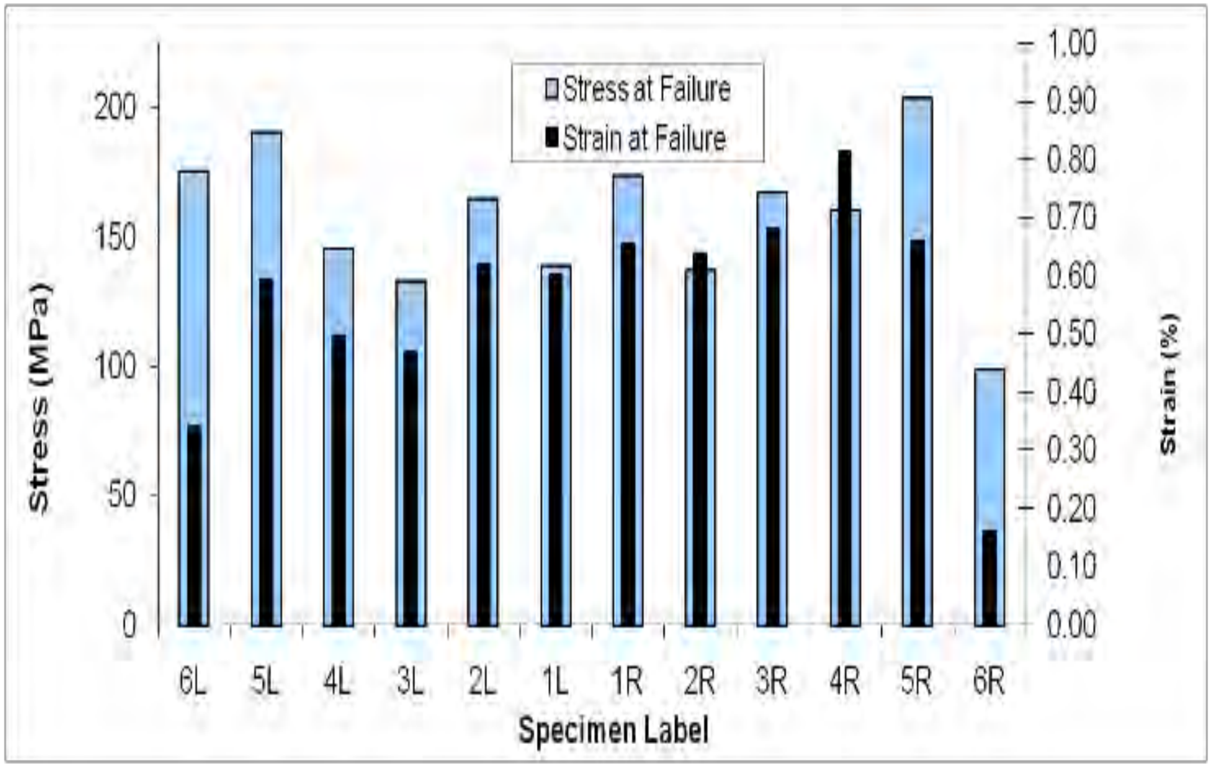
  Min: 19.9, (2.9)
  Max: 57.5, (8.3)
  (Max = 2.9 x Min)

- For specimens 4L→4R (only):

  E_{ax} = 25.6 ± 2.7 GPa
  (3.7 ± 0.4 Msi)

Tensile Strength

0.14 in panel



ε_{fail}, %

Min: 0.164

Max: 0.816

(Max = 5 x Min)

Specimens 4L→4R (only):

$\varepsilon_{fail} = 0.623 \pm 0.108\%$

σ_{fail}, MPa (ksi)

Min: 98.8 (14.3)

Max: 204 (29.6)

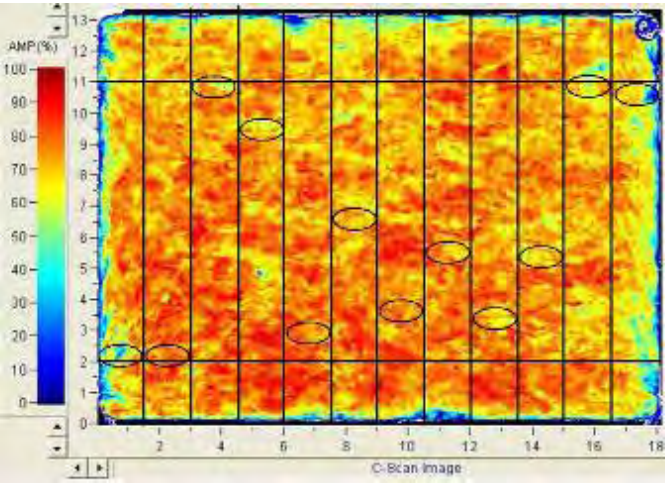
(Max = 2 x Min)

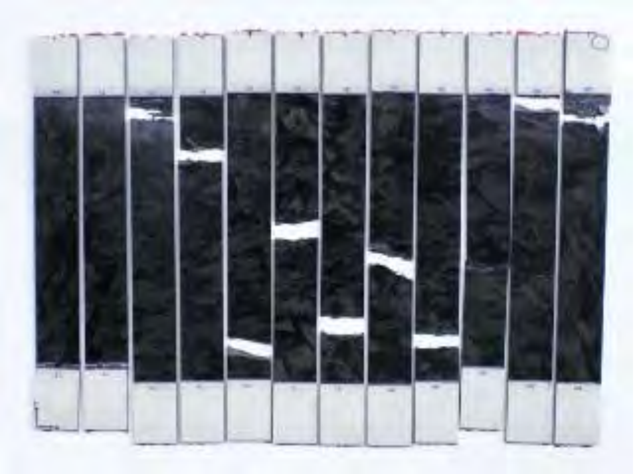
Specimens 4L→4R (only):

$\sigma_{fail} = 153 \pm 15.7$ MPa

(22.2 ± 2.3 ksi)

Fracture Locations





(Specimen fracture sites circled in C-scan)

Failure at tab location for outer specimens

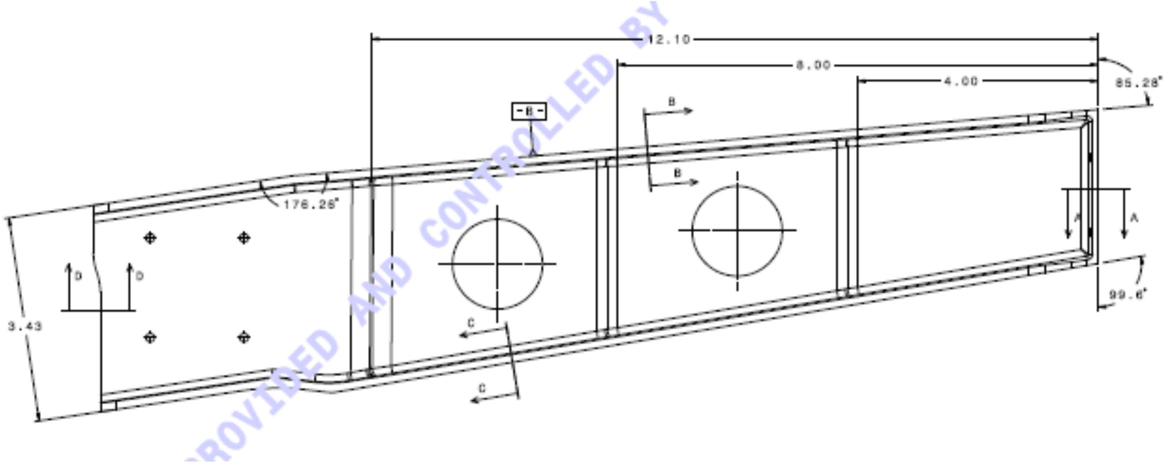
Internal gage failure for inner specimens

C-scan results inconclusive…

HexMC Intercostals

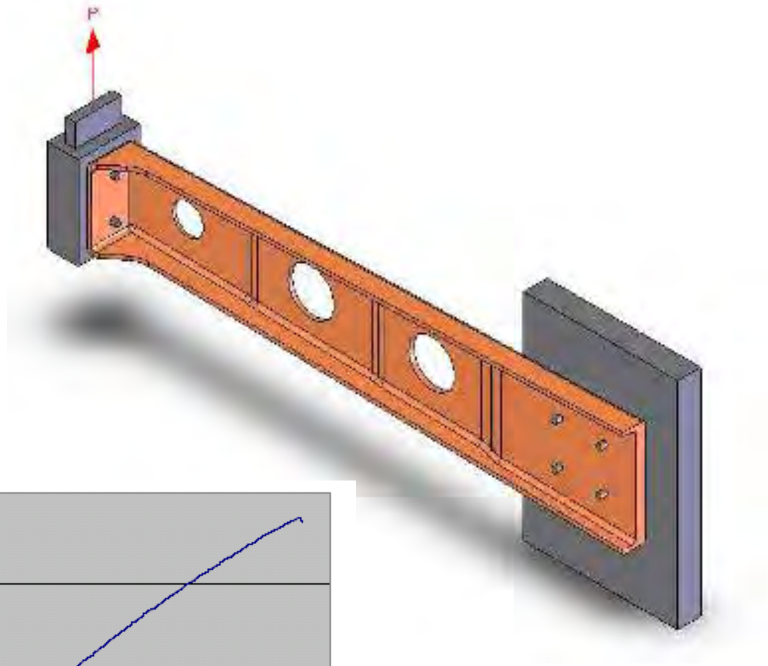
Being studied by Feraboli group

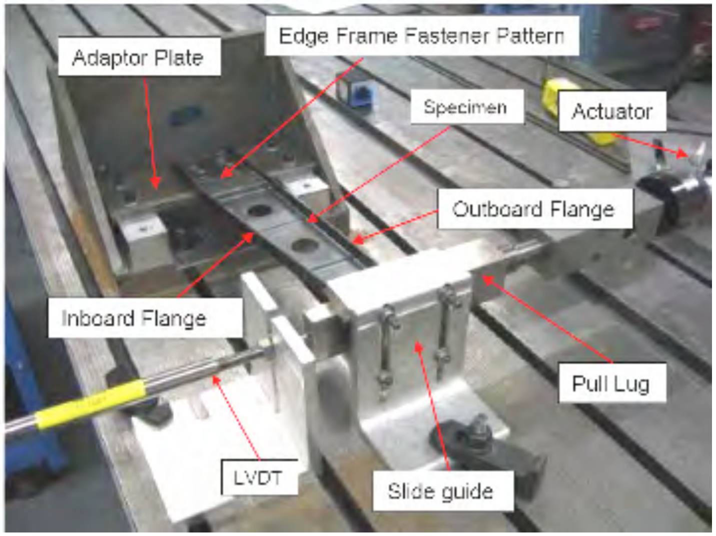
- Currently in production for 787
- Used to connect two circumferential frames
- C-channel beam of variable geometry
- Key geom. features:
  - Lightening holes
  - Fastener holes
  - Thickness transitions
  - Radii

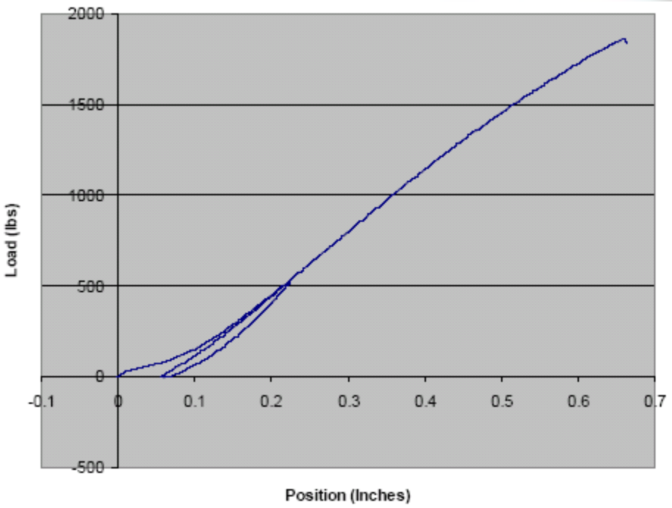


Intercostal

- Certification by point-testing
- Tested as a cantilever beam
  - Required to sustain a prescribed load

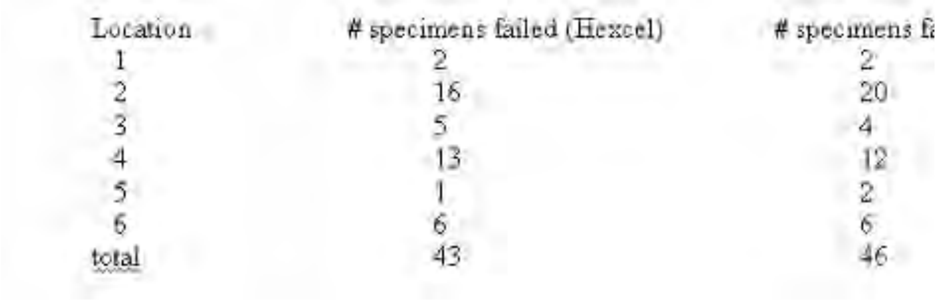






Intercostal

- Failure locations vary
  - Thickness transitions are most significant
- Difficult to predict failure location and load



Location	# specimens failed (Hexcel)	# specimens fa
1	2	2
2	16	20
3	5	4
4	13	12
5	1	2
6	6	6
total	43	46

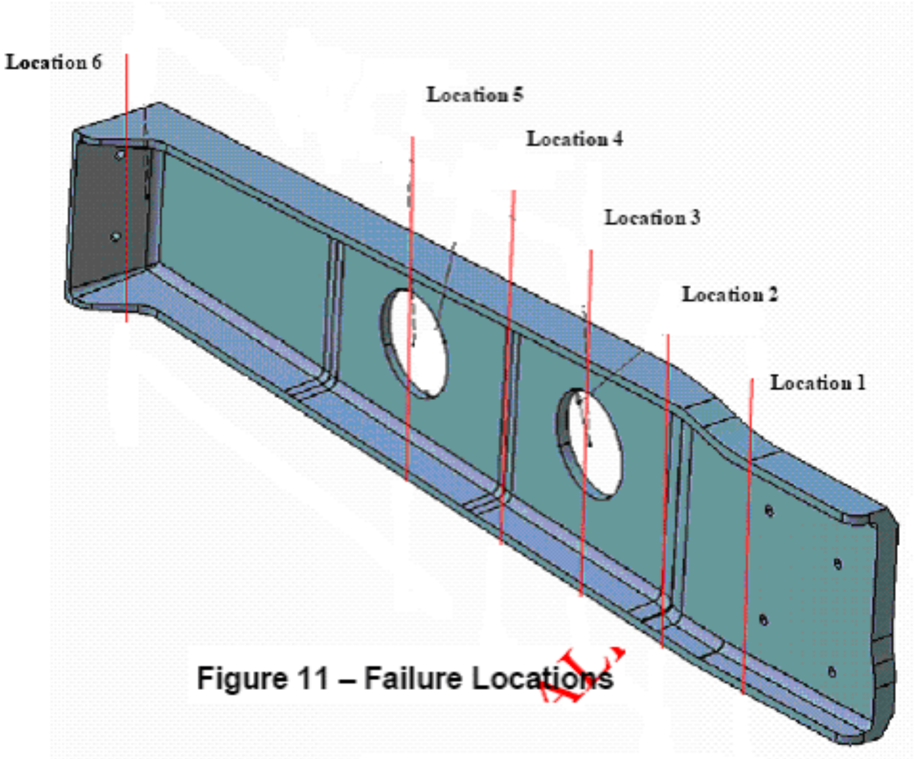
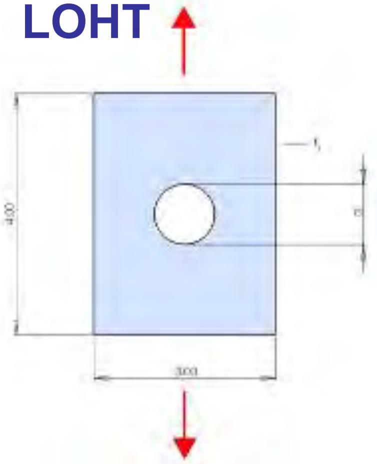


Figure 11 – Failure Locations

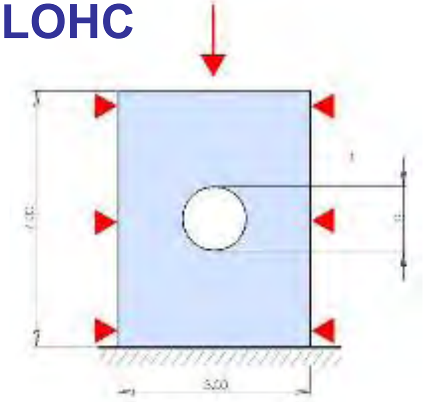
Intercostal

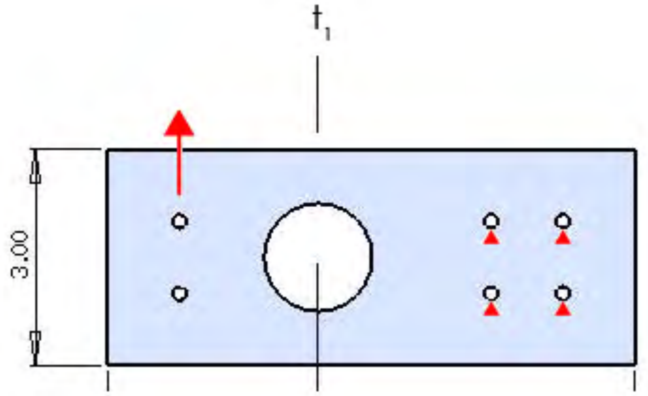
- Identify key geometric features
- Overall part behavior is a result of complex interaction between these features
- Isolate these features and their strength from the complex geometry
- Characterize failure modes and locations
- Simplify geometry of the intercostal to a cantilever beam

LOHT



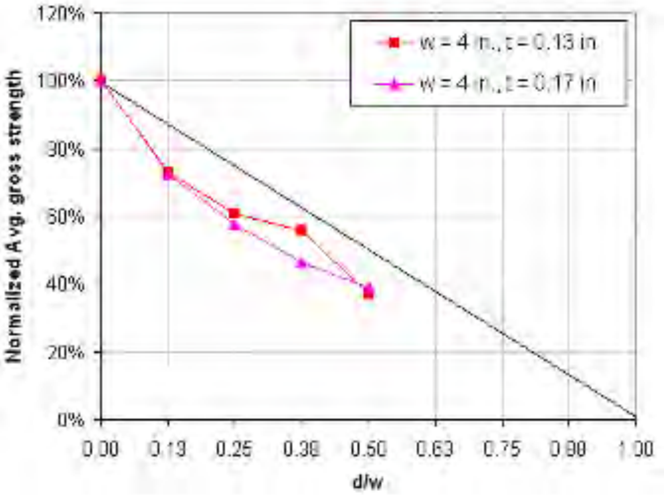
LOHC





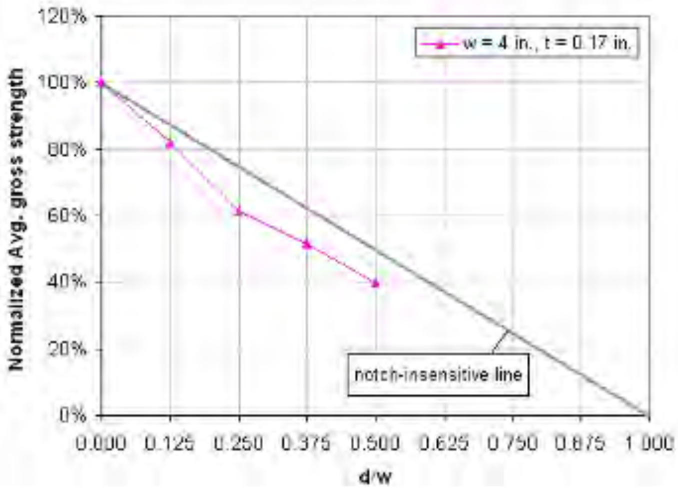
OHT Testing

- Straight-sided tensile specimens w/square end-tabs (4 in. x 6 in. specimens)
- Several thicknesses
- Several hole diameters
- Three replicate tests (60 tests total)



OHC Testing

- Boeing CAI Fixture (4 in. x 6 in. specimens)
- Several thicknesses
- Several hole diameters
- Three replicate tests (60 tests total)



Beam Flex Testing

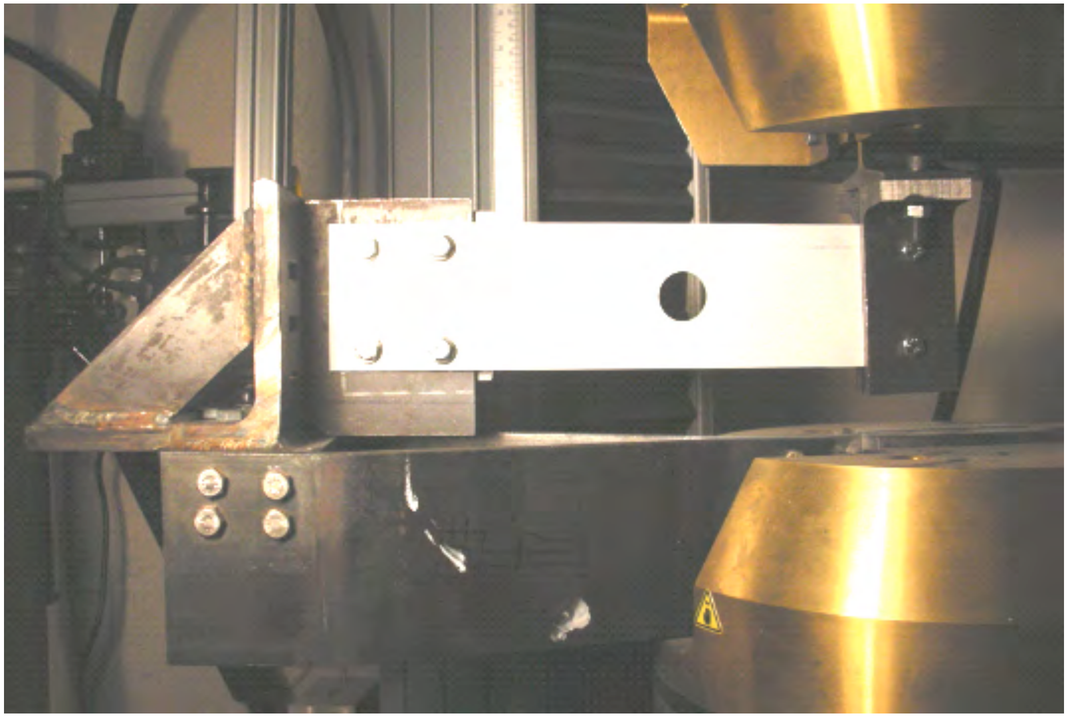
Coupon-level design values

- UNT = 47.5 ksi (12 in. x 1.5 in.)
- OHT = 40.9 ksi (12 in. x 1.5 in., D = 0.25 in.)
- FHT = 35.7 ksi (12 in. x 1.5 in., D = 0.25 in.)

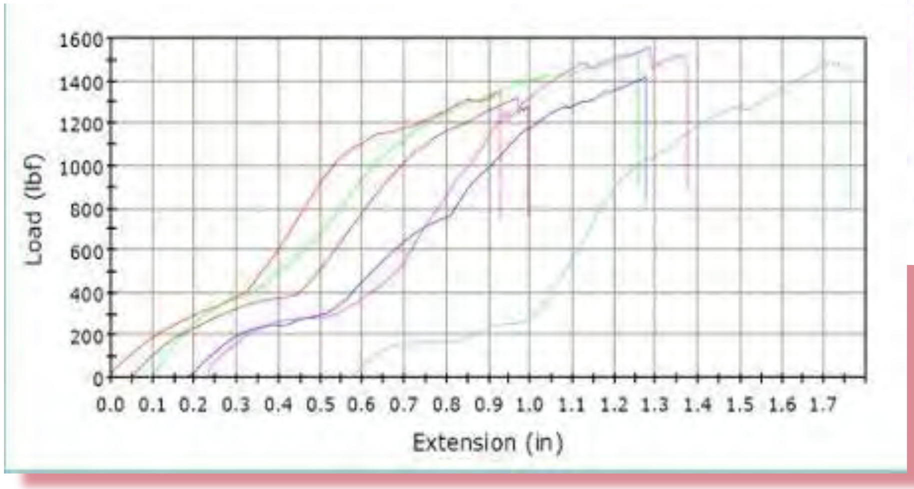
Element-level design values

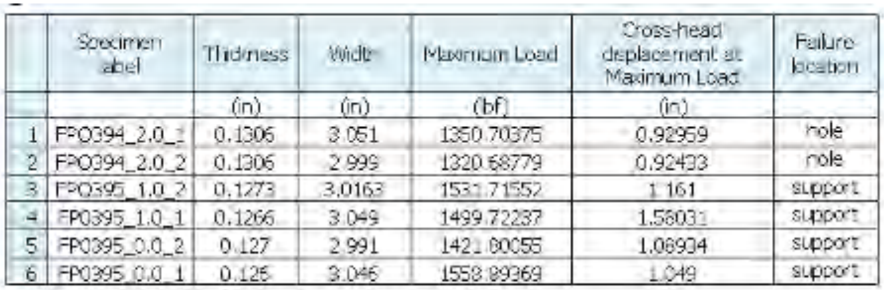
- LOHT1 = 32.5 ksi (6.5 in. x 4 in., D = 0.50 in.)
- LOHT2 = 25.8 ksi (6.5 in. x 4 in., D = 1.00 in.)
- LOHT3 = 20.2 ksi (6.5 in. x 4 in., D = 1.50 in.)
- LOHT4 = 17.5 ksi (6.5 in. x 4 in., D = 2.00 in.)
- LOHC1 = 36.2 ksi (6.5 in. x 4 in., D = 0.50 in.)
- LOHC2 = 27.4 ksi (6.5 in. x 4 in., D = 1.00 in.)
- LOHC3 = 22.6 ksi (6.5 in. x 4 in., D = 1.50 in.)
- LOHC4 = 17.5 ksi (6.5 in. x 4 in., D = 2.00 in.)

Beam Flex Testing



Beam Flex Results





	Specimen label	Thickness	Width	Maximum Load	Cross-head displacement at Maximum Load	Failure location
		(in)	(in)	(lbf)	(in)	
1	FP0394_2.0_1	0.1306	3.051	1350.70375	0.92959	hole
2	FP0394_2.0_2	0.1306	2.999	1320.68779	0.92433	hole
3	FP0395_1.0_2	0.1273	3.0163	1531.71552	1.161	support
4	FP0395_1.0_1	0.1266	3.049	1499.72237	1.58031	support
5	FP0395_0.0_2	0.127	2.991	1421.00055	1.08934	support
6	FP0395_0.0_1	0.125	3.046	1558.89369	1.049	support

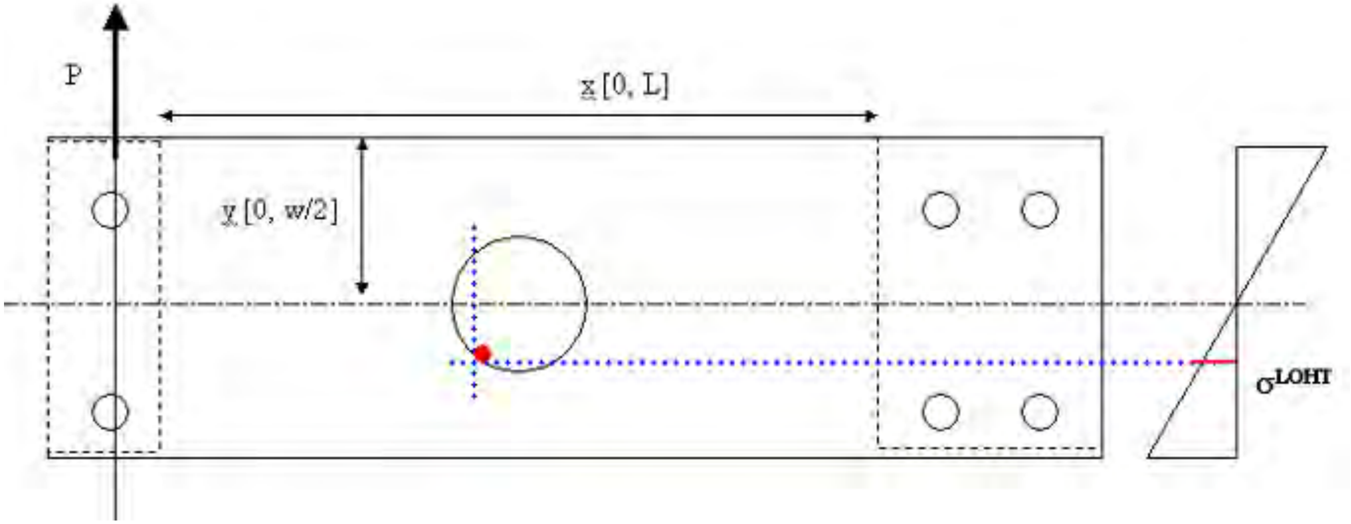
Table 1. Summary description of 0.13" thickness family

Analysis

Analysis approach

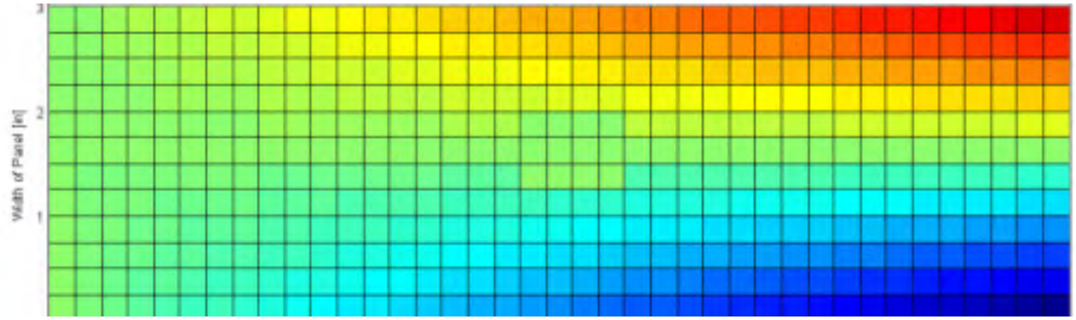
- Bending stress, where x = [0, 9.5] in. and y = [0, 1.5] in.

$$\sigma = \frac{M \cdot y}{I} = \frac{P \cdot x \cdot y}{\frac{t \cdot w^3}{12}}$$



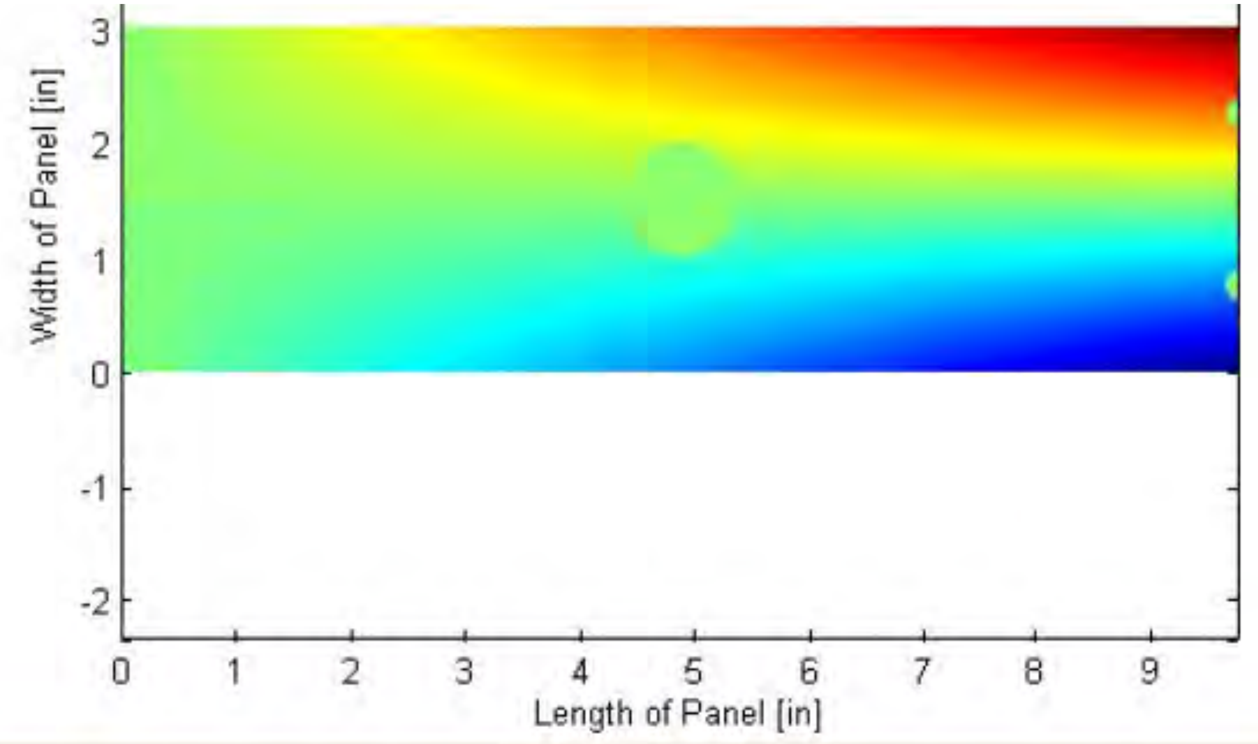
Analysis tool

- Closed form solution
- Developed in Matlab
- Solutions takes ~ 1 sec
- Currently developed to handle cantilever beam of constant width and thickness
- Fully parametric
    - hole diameter, “mesh” size, laminate thickness, applied load, etc.

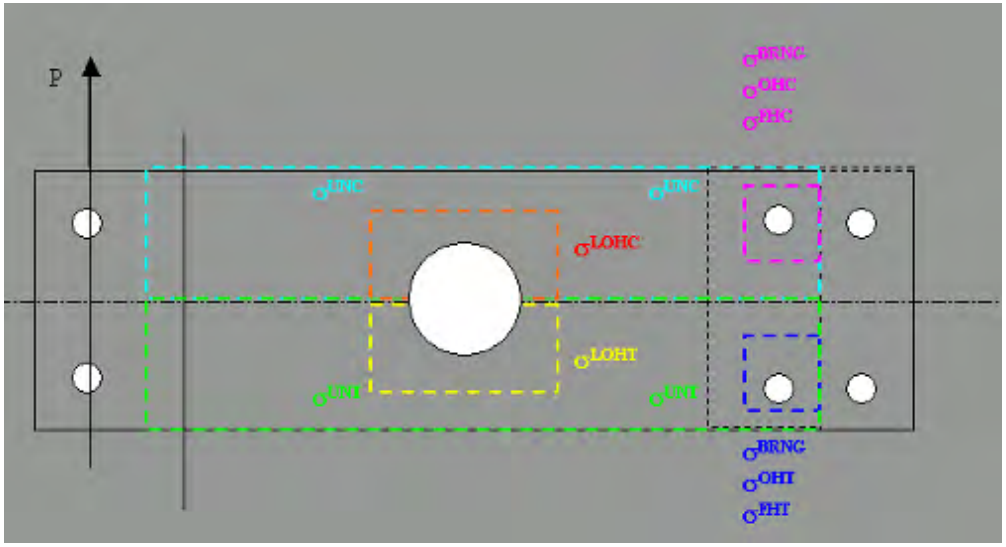


1. Nodal calculations for applied stress

- Bending (axial) stress is evaluated at each node
- Load applied is average of failure load measured during testing

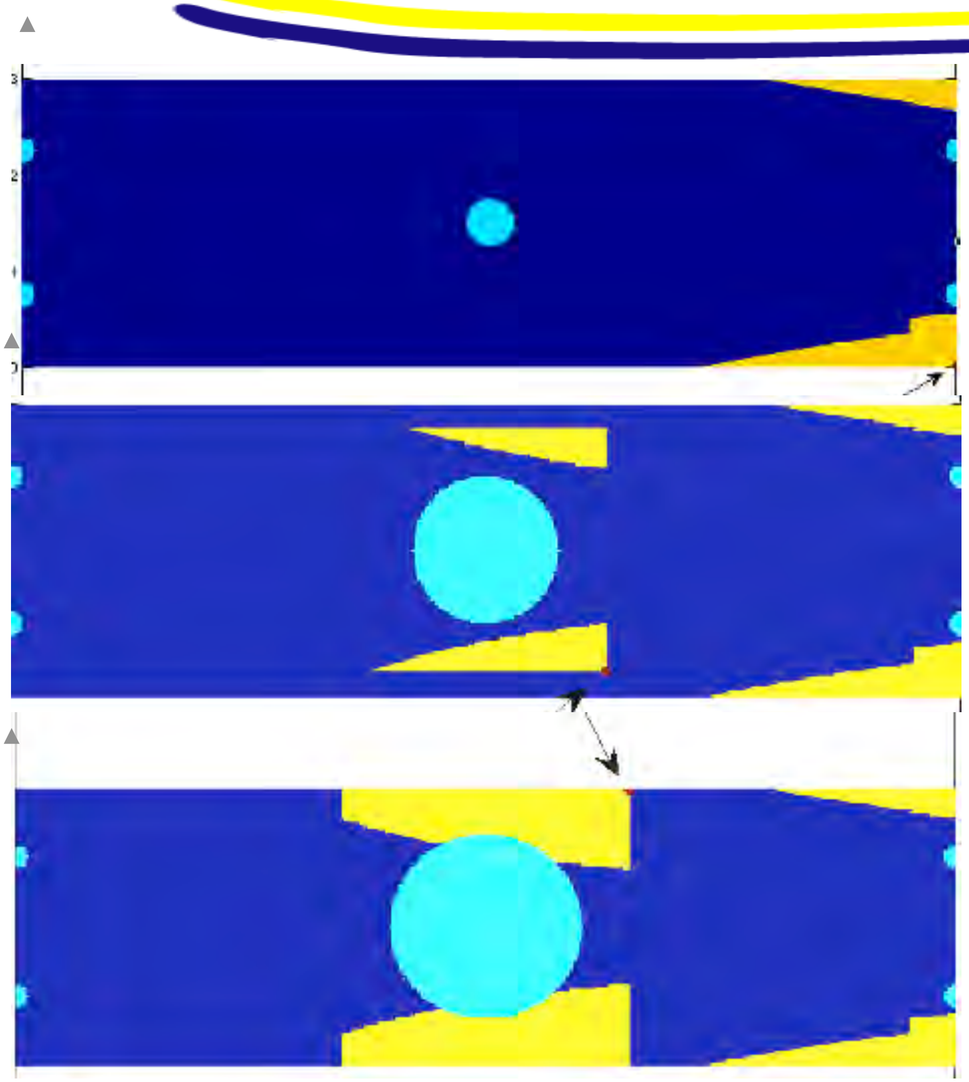


2. Assign regions of relevant allowables



3. MoS calculation and failure prediction

- Blue = positive MoS
- Yellow = negative MoS (failure)
- Single red dot = point of lowest MoS (most critical)



D = 0.5 in

Predicted failure at the root

D = 1.5 in

Predicted failure at the hole

D = 2.0 in

Predicted failure at the hole

Key Observations

LARGE OPEN HOLES

- Design values for LOHT and LOHC are significantly different from coupon-level UNT, OHT, UNC, OHC design values
- Failure occurs always at the hole
- Results show modest notch sensitivity but there is variation in data

BEAM FLEXURE

- Instability observed for constant-thickness specimens
- Failure load values show little sensitivity to size of lightning hole but are very sensitive to laminate thickness
- Failure location varies with hole size:
  - For small or no hole, failure occurs at the fastener holes or at the root
  - For large holes, it occurs near the hole

Future work

- Expand analysis method to include buckling
- Repeat process for thickness transition
  - LOHT, LOHC, Beam Flex
- Characterize strength of radii
  - Radius bend and pull-off
- Perform FEA analysis using simplified shell methodology proposed by Hexcel in conjunction with appropriate design values for MoS calculations
- Develop capability to predict failure load and location based on measured design values

Benefit to Aviation

FAA: Program objective supports safety regulations for design, production, and airworthiness certification of DFC parts

Industry: Program will contribute towards broader use of DFC structures at lower cost and lower weight

Academia: Represents an applied research project addressing an immediate need in industry and providing pertinent research & educational training for new aerospace engineers

QUESTIONS ?