National Aeronautics and
Space Administration

X33 Hydrogen Tank Failure

James Reeder
NASA Langley Research Center
Durability, Damage Tolerance
and Reliability Branch

- Many technical contributors to this work

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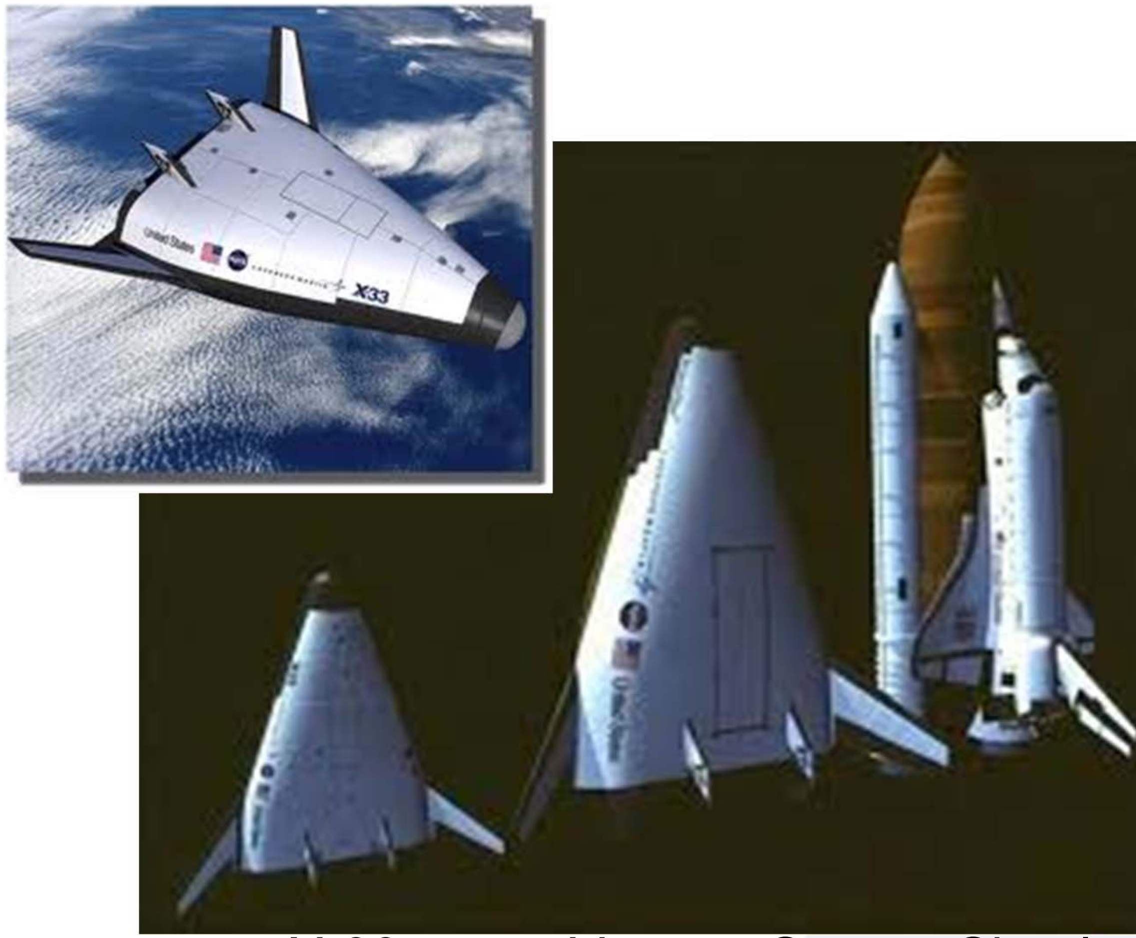
www.nasa.gov

Overview

- What was the X33 Program?
- How did the tank failure occur?
- What was found in the investigation?
- What was the effect?

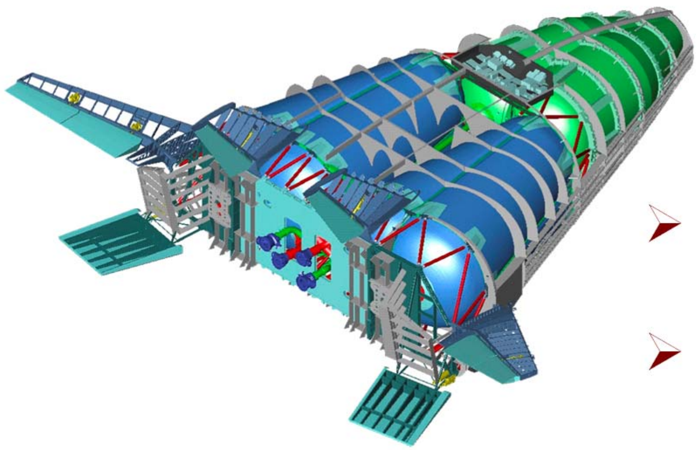
X33: Technology Demonstration Project

- 1995-2001
- Reusable Launch Vehicle Program
- Commercialization of Space
- Better Faster Cheaper



X-33 Venture Star Shuttle

X33 Key Facts

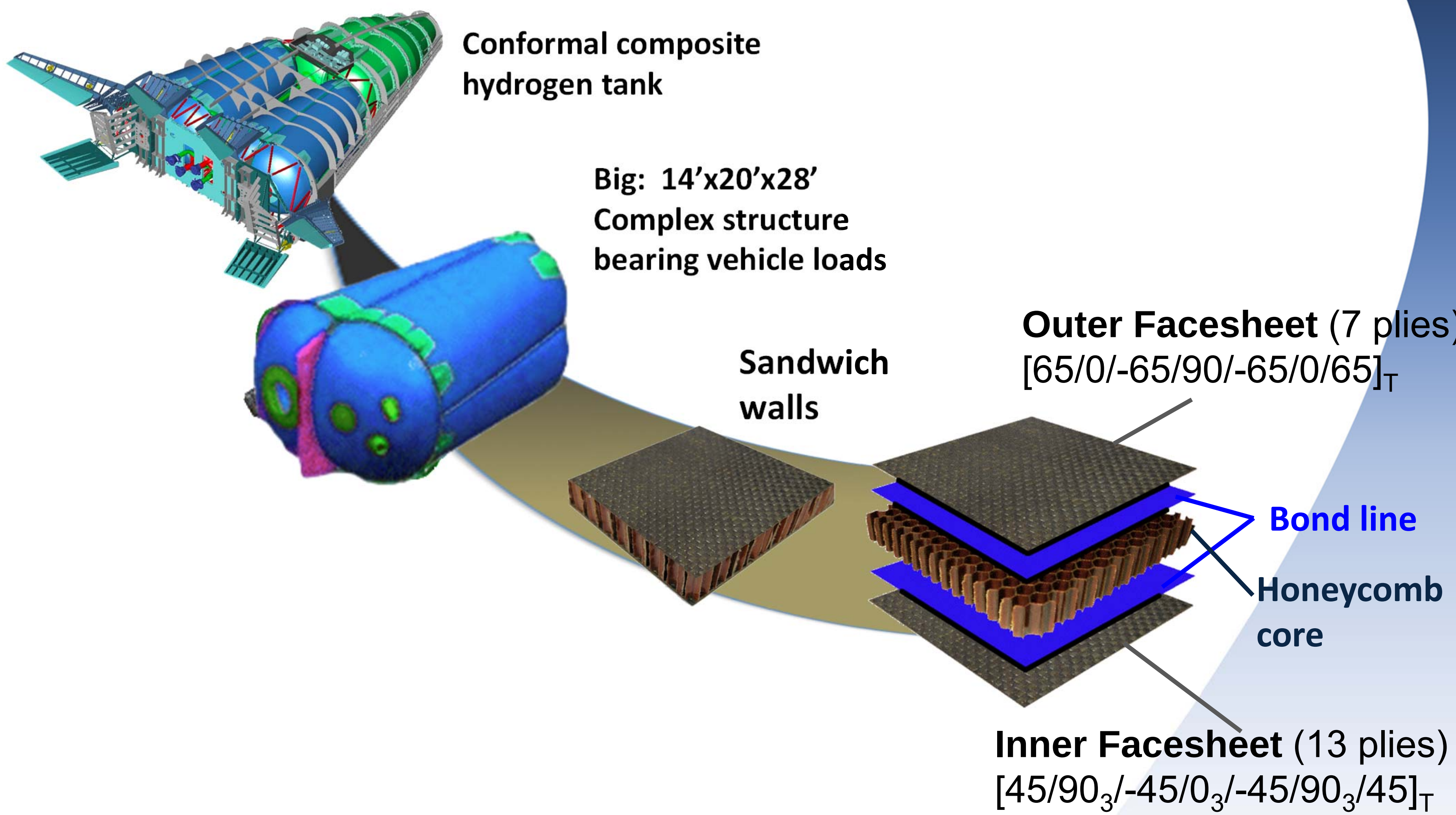


- **Technology demonstration program**
  - – Single stage to orbit vehicle
  - – Affordable access to low earth orbit
  - – Replacing shuttle

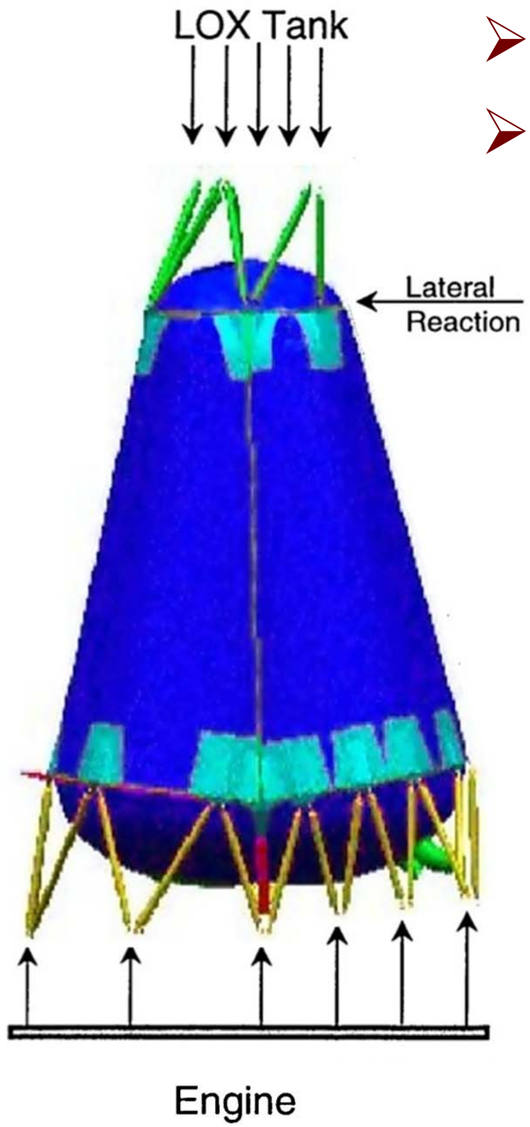
- **Competition among three companies (3/95)**

- **Lockheed Martin (LM) Skunk Works won (4/96)**
  ambitious plan to develop multiple technologies
  - Metallic Thermal Protection System
  - Aerospike Engine
  - Lifting Body Control
  - New Contracting Model
  - **Composite Cryotank**

Composite Liquid Hydrogen Tanks



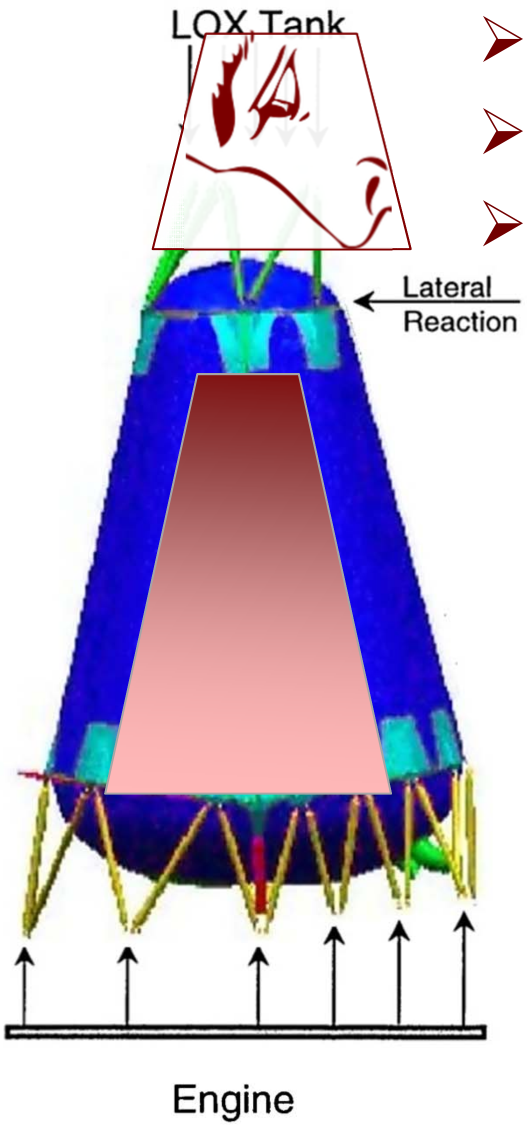
Liquid Hydrogen Tank Proto-Flight Test



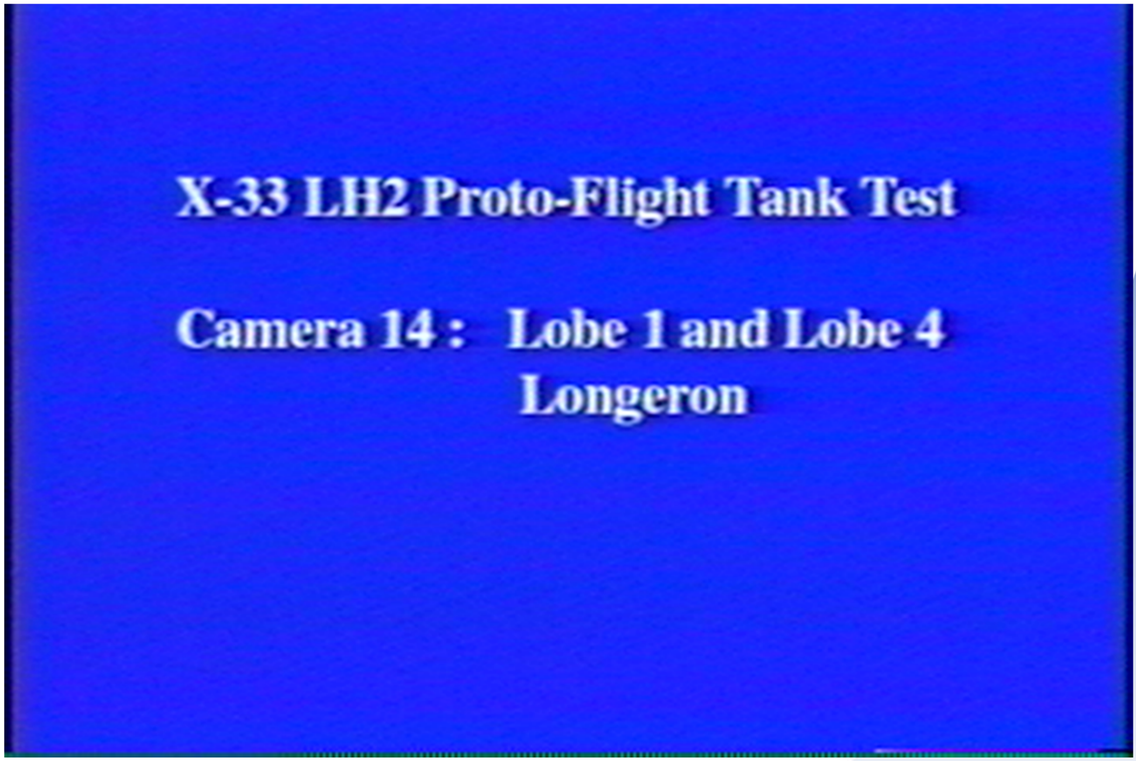
- **Conducted at Marshall Space Flight Center**
- **Loaded and Pressure**
  - Pressure with LN_2 32 psig 30% Full
  - Pressure with LH_2 42 psig 100% Full
  - Pressure & Load LH_2 42 psig 100% Full

    Many different load cases

Liquid Hydrogen Tank Proto-Flight Test

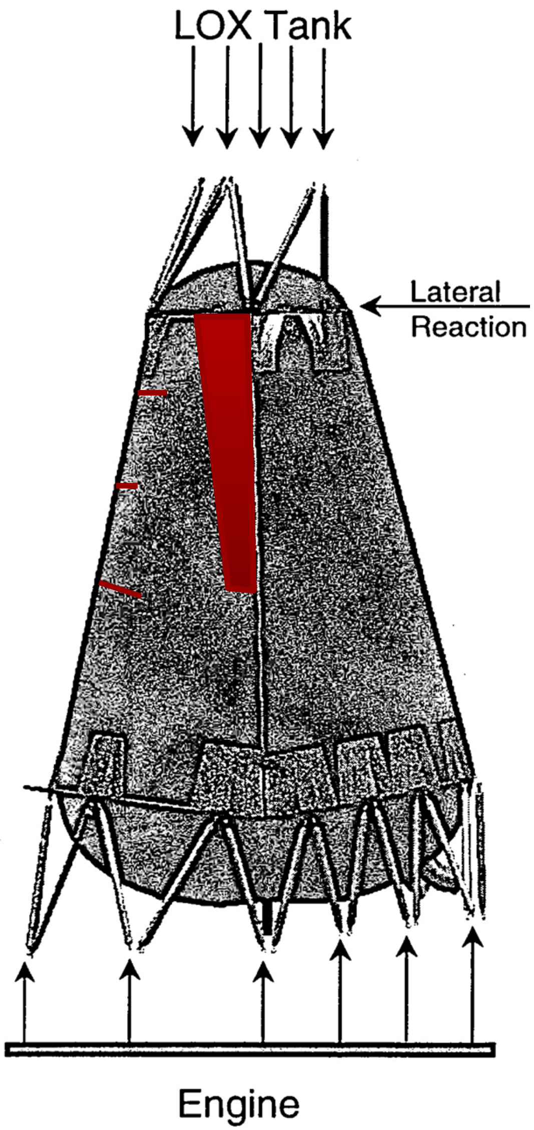


- Conducted at Marshall Space Flight Center
- Loaded and Pressure
- 15 minutes after test

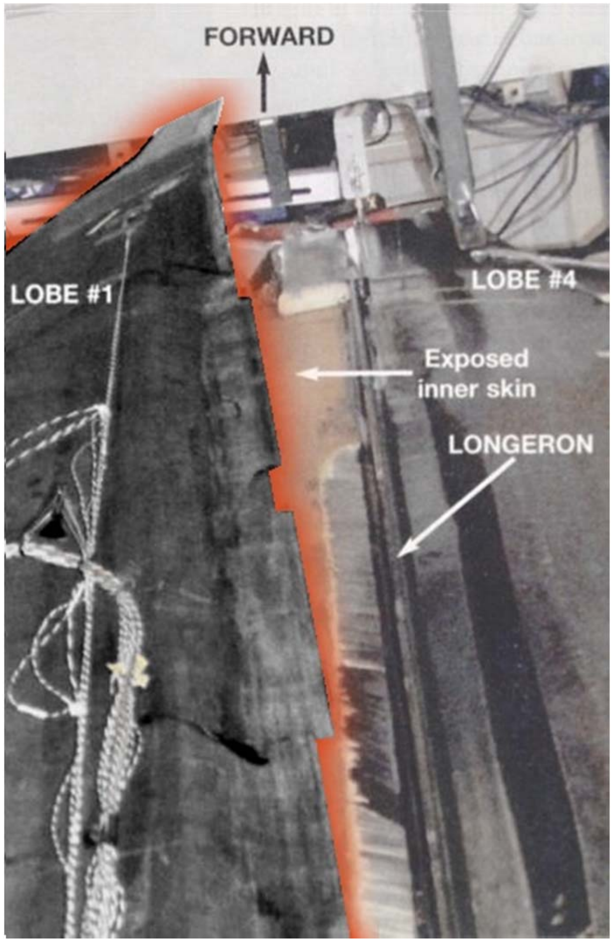


Liquid Hydrogen Tank Proto-Flight Test

What Happened?



- The tank outer skin and core of lobe 1 rapidly separated from the inner skin 15 minutes after the LH_2 drain, during tank warm-up.



- A clean bondline failure of the core from the inner skin.
- Several manufacturing defects were observed in the failed area.

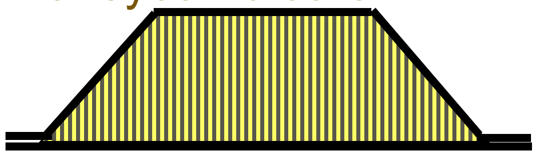
Teflon FOD next to splice

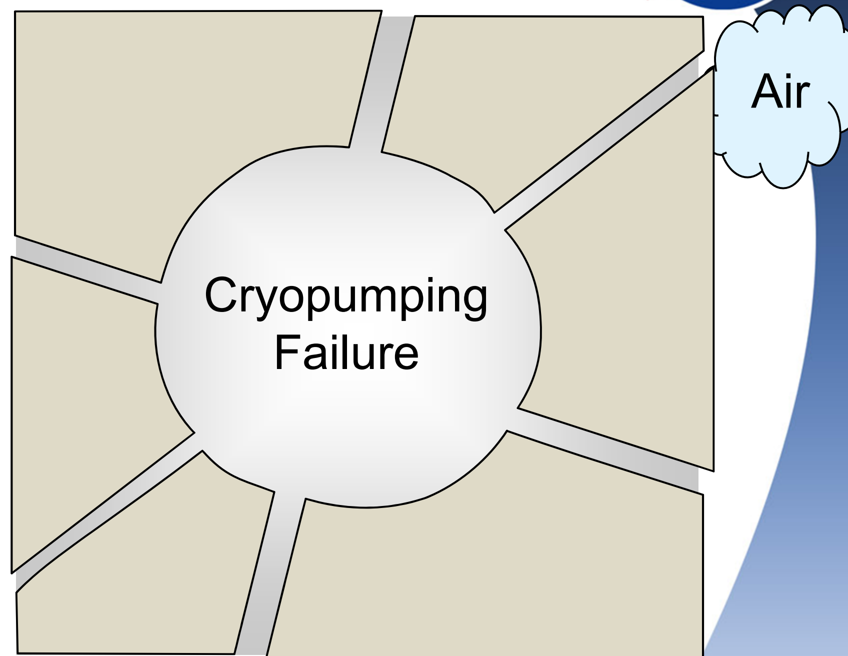
Cryopumping (The Mechanism)

4 Requirements

- **Void**

Honeycomb core





- **Cold** (really cold)

Liquid hydrogen (−423° F)

- **Leak path** (to atmosphere)

1. Close outs
2. Matrix cracking of outer facesheet
3. Matrix cracking of inner facesheet **(Cryoingestion)**

- **Warm up**

After tank drain

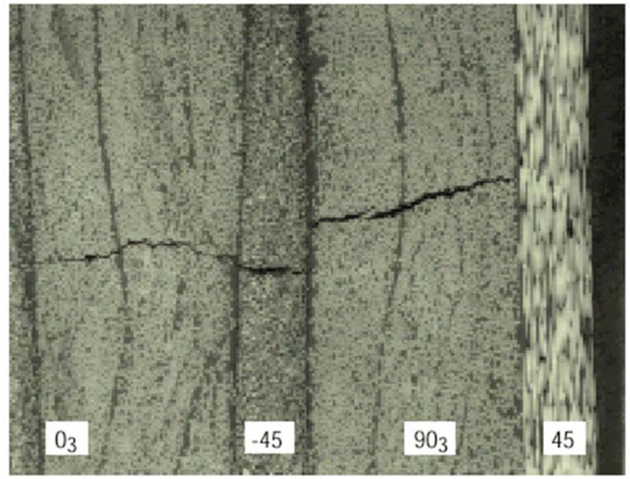
Matrix Cracking

Lamination Theory analysis

	Ply Stress (KSI)		
Ply	Thermal	Pressure	Total
Inner Skin	**-423°F (ΔT=-743°F)**	$[45/90_3/-45/0_3/-45/90_3/45]_T$	
90°	10.1	4.2	14.3
0°	10.8	5.0	16.3
45°	10.5	4.6	15.1
90° Strength @ -423°F 5.7-9.3			
Outer Skin	**-150°F (ΔT=-470°F)**	$[65/0/-65/90/-65/0/65]_T$	
90°	6.4	4.2	10.6
0°	6.8	5.0	11.8
65°	6.5	4.3	10.8
90° Strength @RT....................................... 10.4-12.4			

§ Charles E. Harris and James Reeder

Microscopy Inner Facesheet



§ Eric Stokes

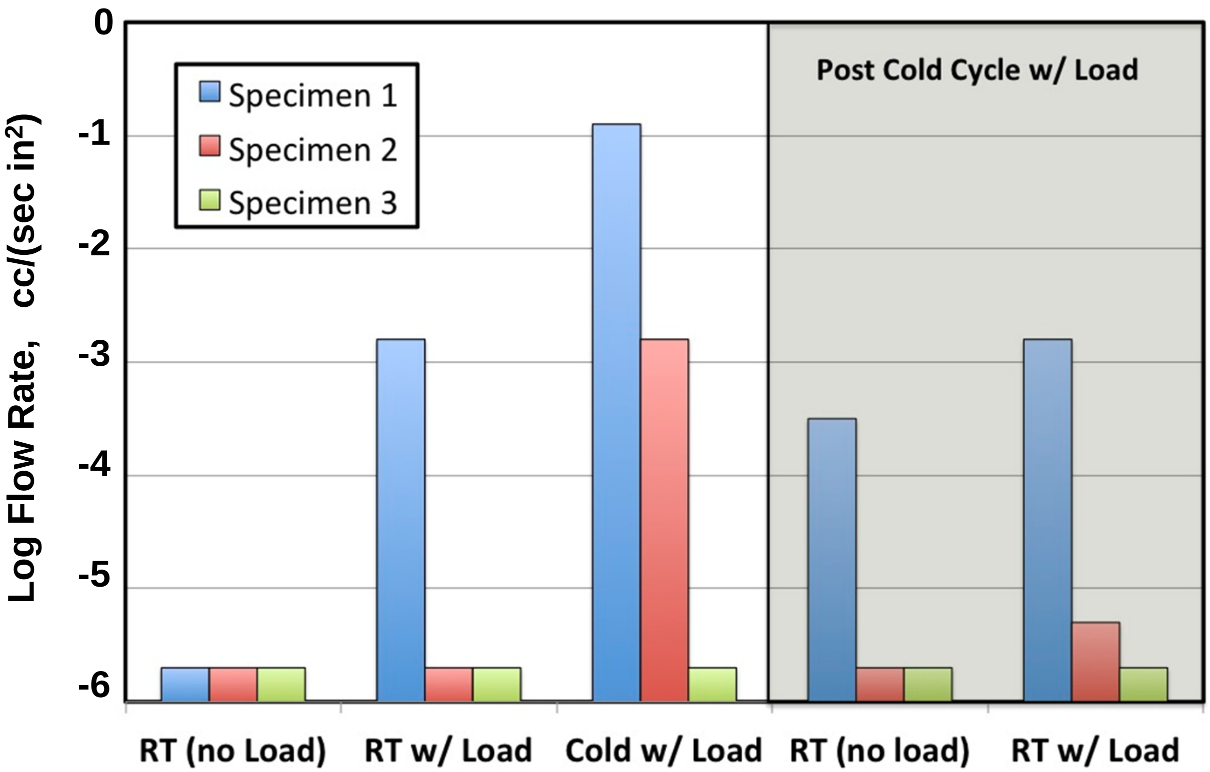
- No initial cracks
- Both Thermal and Mechanical load required for micro-cracks in all layers

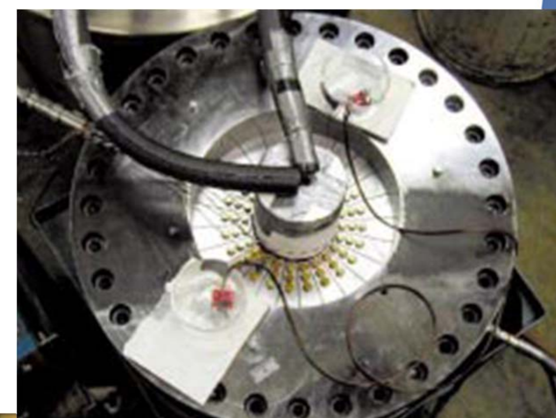
➢ **Inner facesheet micro-cracking should be wide spread**

➢ **Outer facesheet micro-cracking might be occasional**

Permeability Testing

- Permeability varied significantly from point to point
- Permeability slowed significantly without both mechanical and thermal strain on inner facesheet
- Outer facesheet low permeability

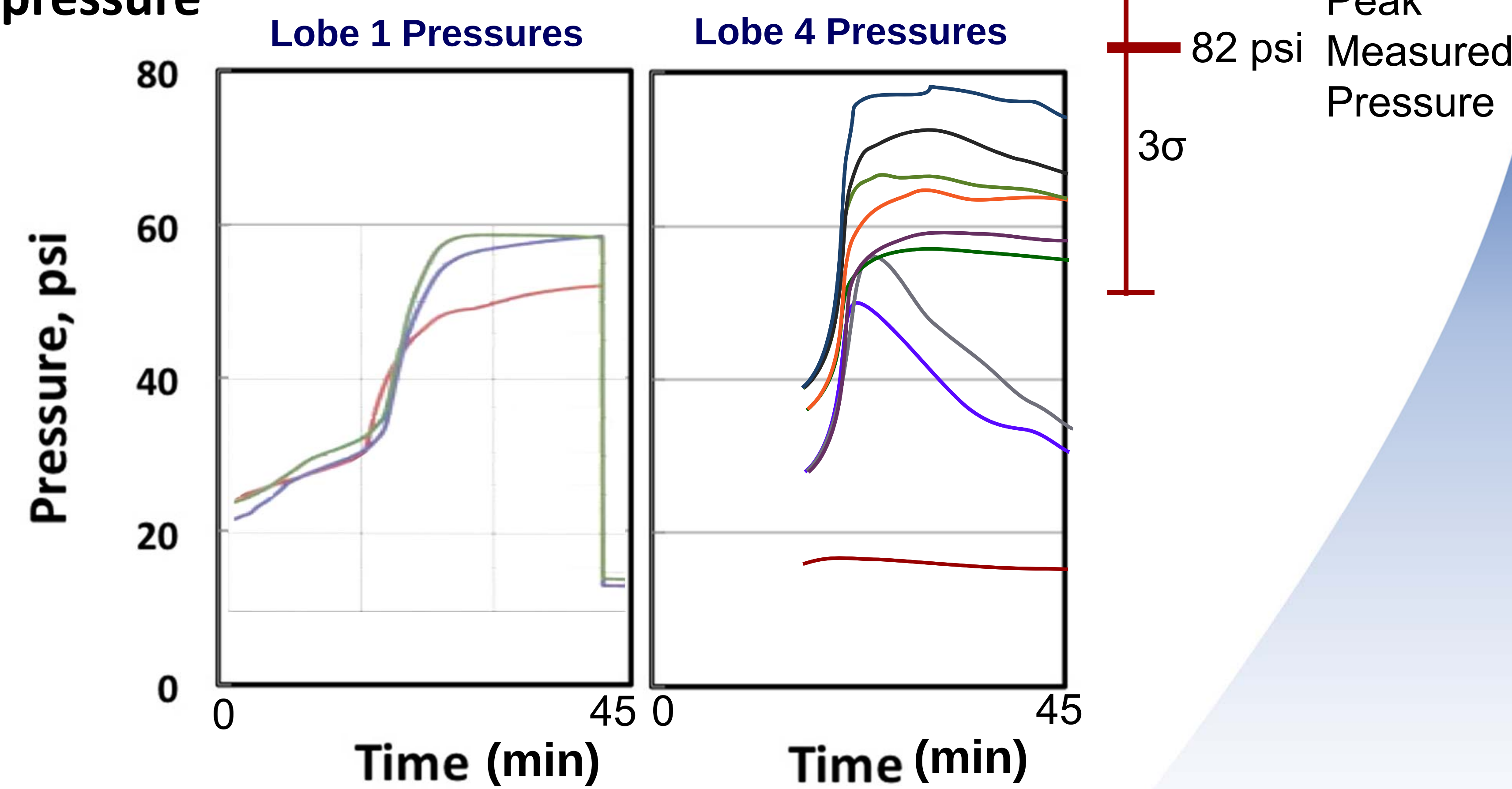




- Andrew Hodge, Anthony Day and Kevin Rivers

Core Internal Pressure

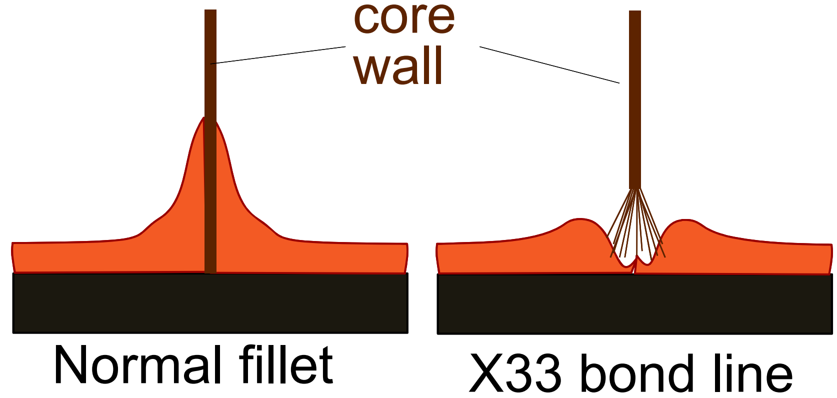
- **Significant variability in measured core pressures**
- **Evidence of rising core pressure with tank pressure**



Poor Bondline

Inner Bondline

Facesheet to core bond

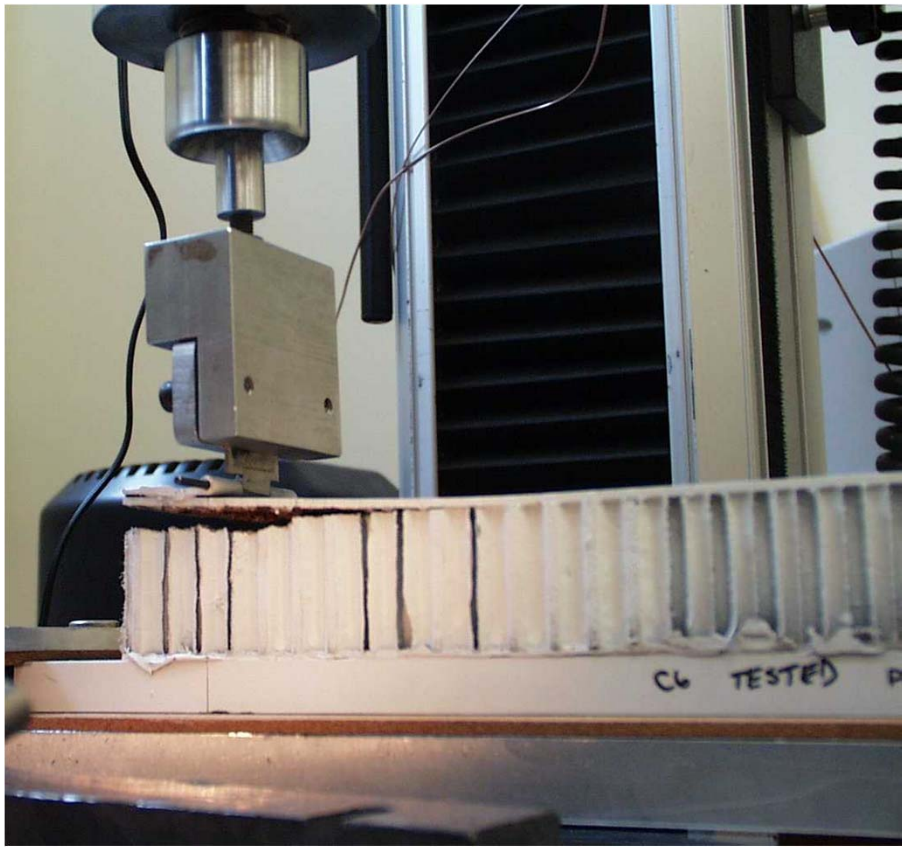


- **Poor prep of cut honeycomb**
- **Out time for adhesive**
  - AF-191 Adhesive
- **Cells communicated**
  - (perhaps not between core splice joints)

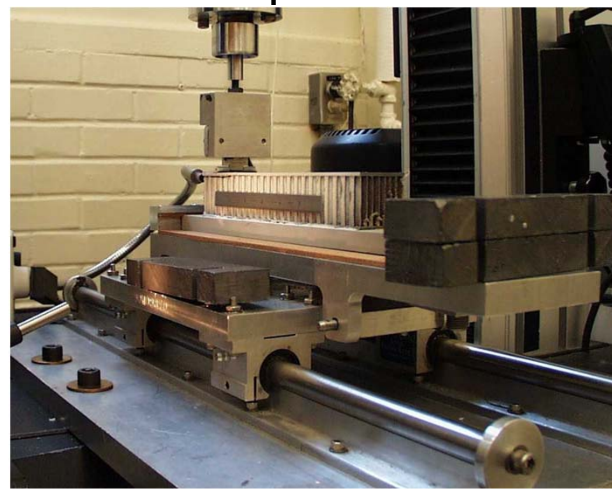
Removed outer facesheet and core
(showing core splices)

Bond Toughness Measurement

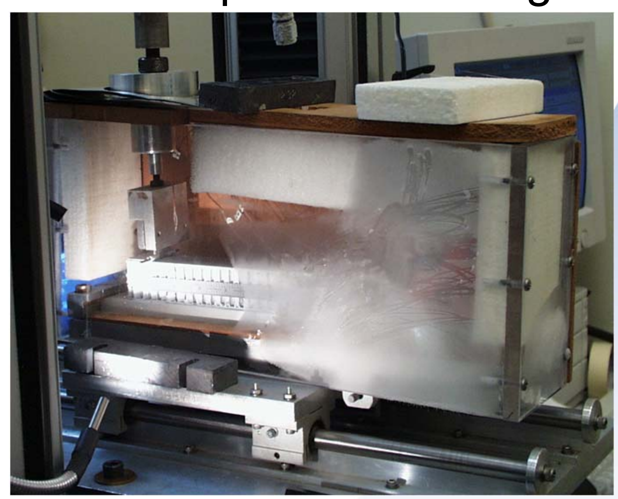
Single Cantilever Beam Test



Sled to keep force vertical



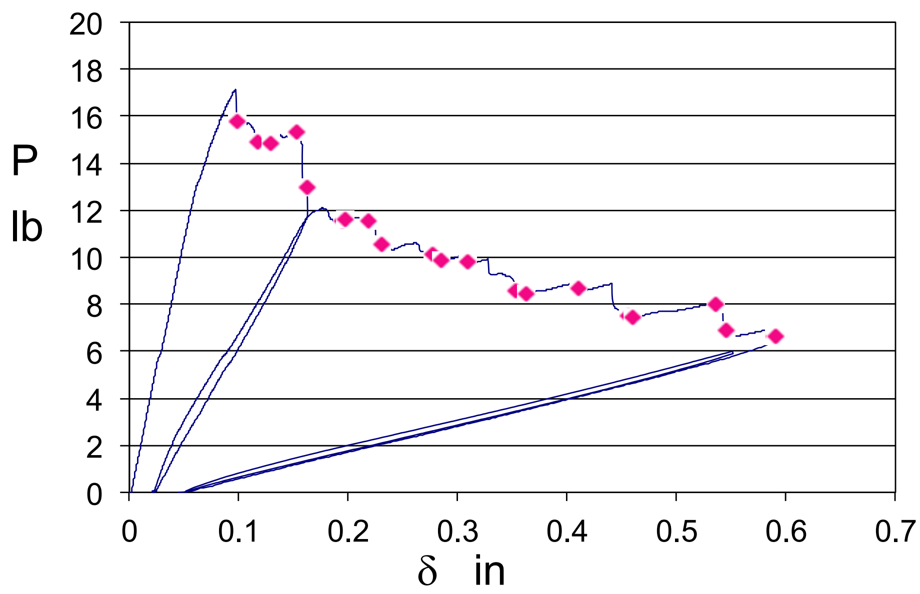
Cold temperature testing

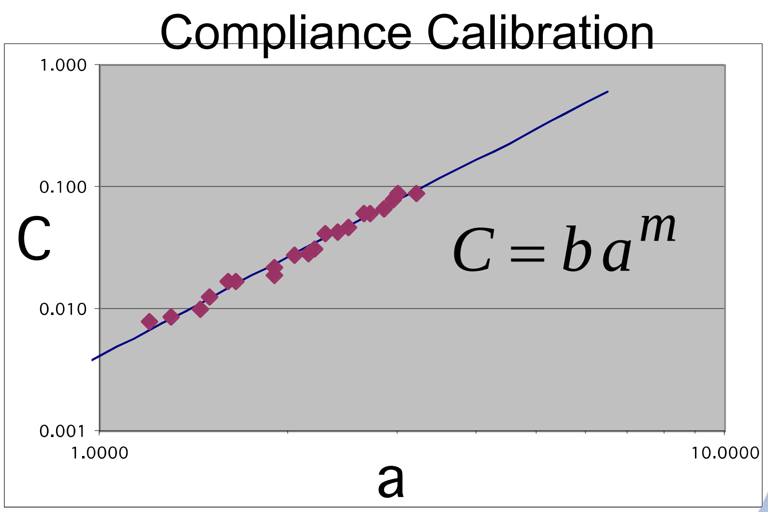


- Rich Fields at Lockheed Martin

Toughness Calculation

Load Displacement Data

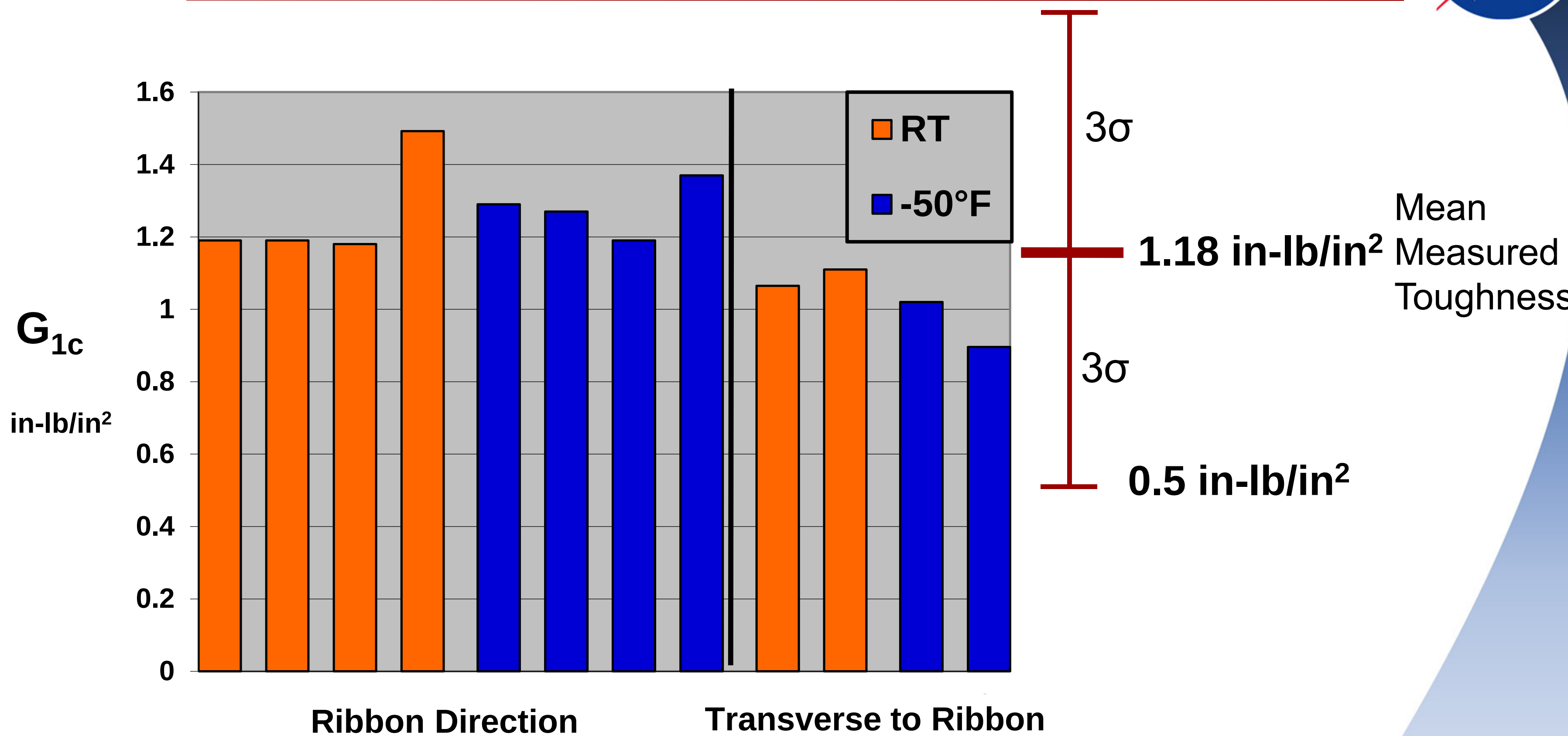


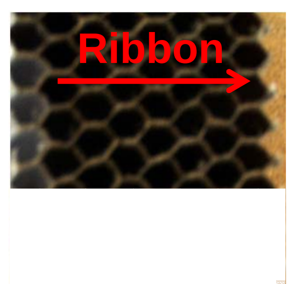


$$G_{Ic} = \frac{dU}{da} = \frac{P\,\delta}{2\,w\,C}\,\frac{dC}{da} = \frac{m\,P\,\delta}{2\,w\,a}$$

§ Alan Nettles and James Reeder

Toughness Results





§ Alan Nettles and James Reeder

Finite Element Fracture Modeling

Virtual Crack Closure Technique (VCCT)

- **Combine force and displacements**

$$G_I = -\frac{1}{2t\Delta l_e} F_{yi}\left(v_j - v_k\right)$$

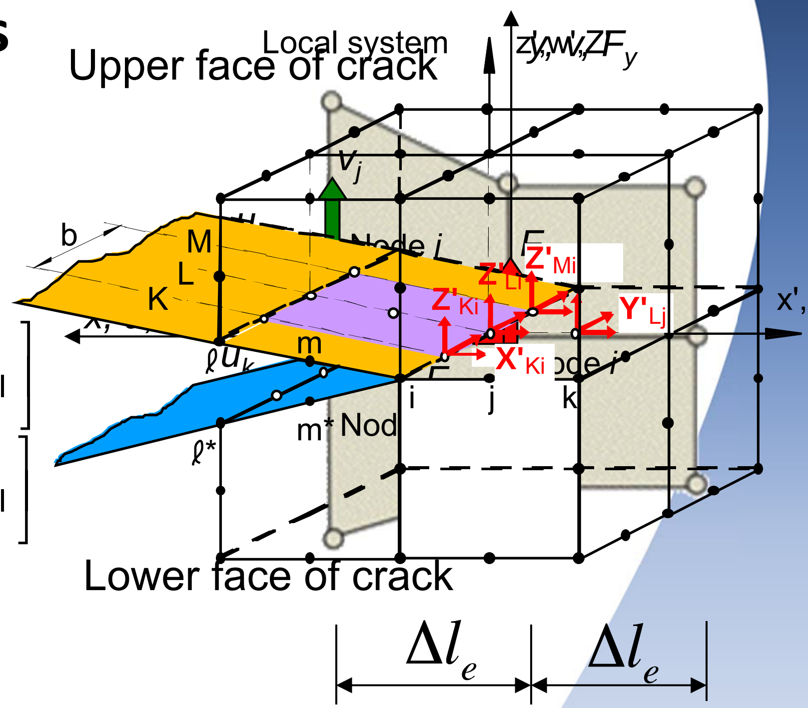
$$G_I = \frac{1}{2\Delta ab} \cdot \left[\frac{1}{2} Z'_{Ki} \cdot \Delta w'_{Kl} + Z'_{Li} \cdot \Delta w'_{Ll} + Z'_{Lj} \cdot w'_{Lm} + \frac{1}{2} Z'_{Mi} \cdot w'_{Ml}\right]$$

$$G_{II} = -\frac{1}{2t\Delta l_e} F_{xi}\left(u_j - u_k\right)$$

$$G_{II} = \frac{1}{2\Delta ab} \cdot \left[\frac{1}{2} X'_{Ki} \cdot \Delta u'_{Kl} + X'_{Li} \cdot \Delta u'_{Ll} + X'_{Lj} \cdot \Delta u'_{Lm} + \frac{1}{2} X'_{Mi} \cdot \Delta u'_{Ml}\right]$$

$$G_{III} = -\frac{1}{2t\Delta l_e} F_{zi}\left(w_j - w_k\right)$$

$$G_{III} = \frac{1}{2\Delta ab} \cdot \left[\frac{1}{2} Y'_{Ki} \cdot \Delta v'_{Kl} + Y'_{Li} \cdot \Delta v'_{Ll} + Y'_{Lj} \cdot \Delta v'_{Lm} + \frac{1}{2} Y'_{Mi} \cdot \Delta v'_{Ml}\right]$$



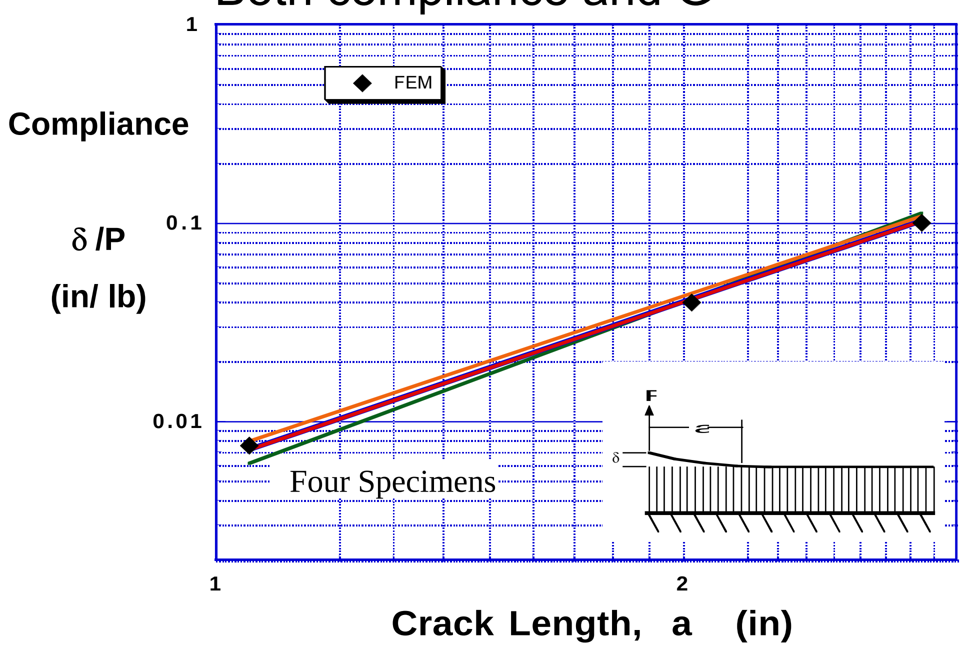
- **Uniform mesh around crack tip**

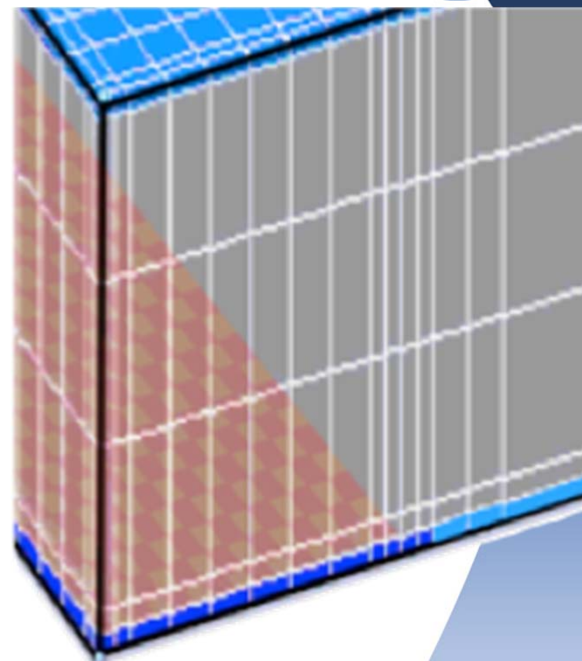
  While keep number of elements low

- **3D 20-noded quadratic brick elements**

Analysis Calibration

- How to model a facesheet with a single brick elements?
  - Effective Bending Modulus in debonded regions
  - Effective Tension Modulus in bonded regions
- How to model honeycomb core with solid brick element?
  - Shear properties adjusted
- Calibrated to single cantilever beam results
  - Both compliance and G





Inner Facesheet

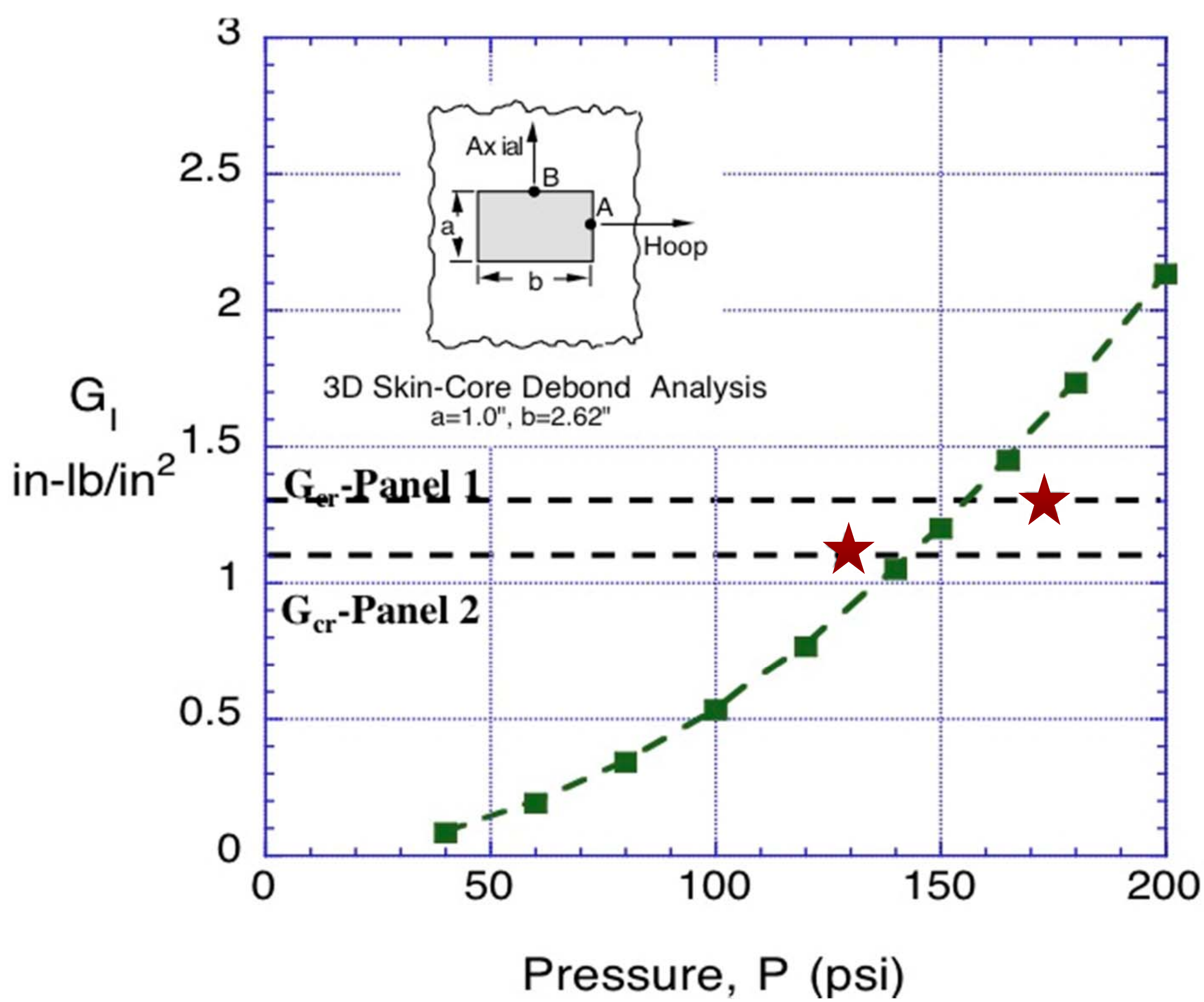
	Bending	Tension
E_{11}	2.8	7.09
E_{22}	11.3	11.4
G_{12}	1.93	2.11

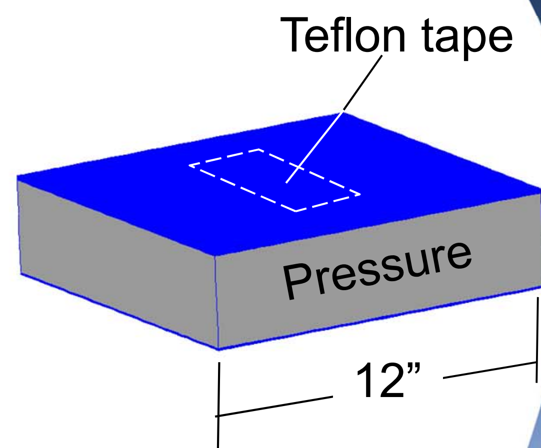
	Core
E_{11} & E_{22}	6E-04
E_{33}	0.02
G_{13}	0.018
G_{23}	0.002

Debond

Used to calibrate model

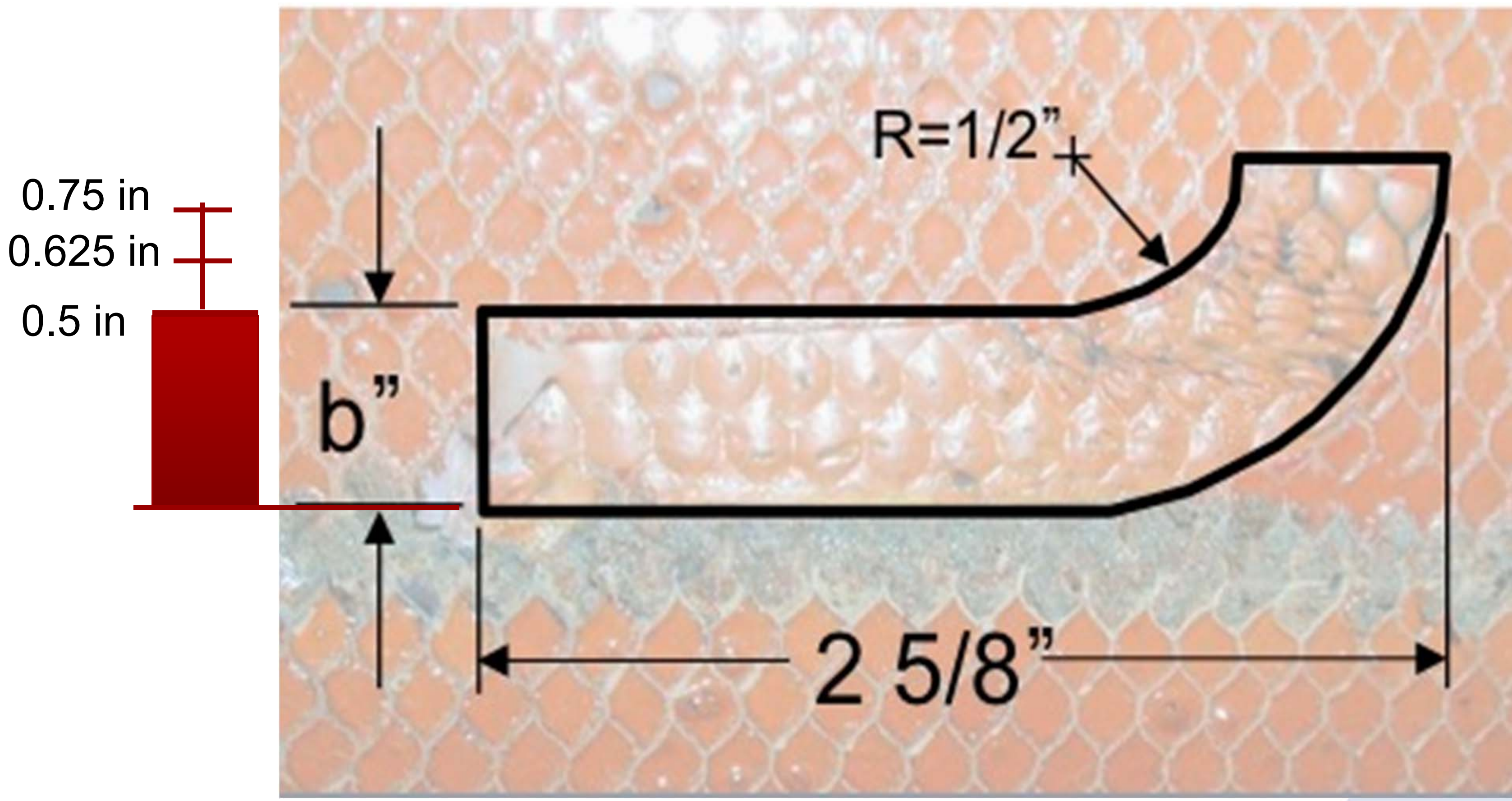
Model Validation with Test Panels



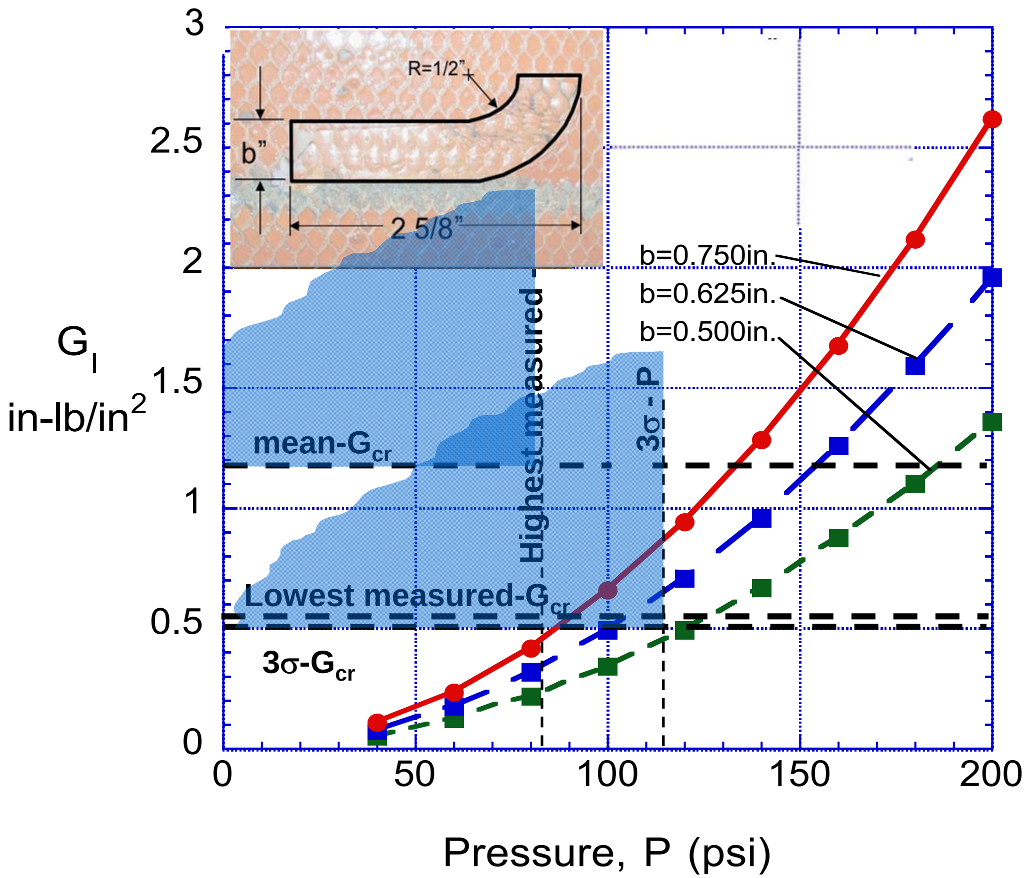


- **Two test Panels**

What Size Was the Flaw?



Analysis of J Defect



- **Nominal values do not explain failure**
- **Variability makes the failure plausible**

§ E.H. Glaessgen, D.W. Sleight, I.S. Raju, J.T. Wang

X-33 LH_2 Tank Investigation
Most Probable Cause

- **Microcracking of the inner skin allowed hydrogen infiltration into the core.**
- **The nitrogen purge gas was cryopumped through the outer skin and thrust buster areas into the core.**
- **The presence of nitrogen and hydrogen in the core produced higher than expected core pressures.**
- **Core bondline strength was lower than the original design allowable (a known condition prior to test).**
- **The presence of a 1/2-inch-wide by 3-inch-long piece of PTFE tape at the inner skin to core bondline created a critical disbond area. The same effect can be shown for the other manufacturing flaws of comparable size. These may have been critical flaws due to size, shape and location within the core.**
- **The most probable cause of the incident was a combination of the above factors.**

What Happened Next?

Project cancelled shortly after the very public structural failure

- Full scale composite hydrogen tank protoflight test
- Major issues with the Aerospike engines

Project had a path forward

- Either metal tank or fix composite tank (e.g. half thickness plies)

Economic driver for project had changed

- Cell phone tower proliferated minimizing the need for satellites required for satellite phones

Lessons Learned

- The design/development approach must integrate materials, structures and manufacturing technologies.
- The building-block development approach for design, manufacturing scaleup, and test of composite structures must be used.
- In-depth technical penetration at all levels of the design process must be accomplished. The importance of communication cannot be overstated. Communication is a two-way process. Technical information must be communicated clearly. There must be openness to receive the information properly.
- Failure modes must be addressed in depth, e.g., FMEA.
- Risk management must be a fundamental part of technology development. A risk management plan commensurate with the technical complexity must be used.
- In-depth reviews by experienced practitioners should be used the program to ensure that all issues are addressed. These reviews should be at the design levels as well as at the formal review level. Early expert reviews (at the design table) have the greatest effect on mission success.

References

- “Final Report of the X-33 Liquid Hydrogen Tank Test Investigation”, Marshall Space Flight Center, May 2000.
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- Ratcliffe, J. G.: ”Sizing Single Cantilever Beam Specimens for Characterizing Facesheet/Core Peel Debonding in Sandwich Structure”, NASA TP-2010-216169, 2010.

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Questions?