



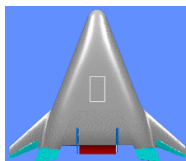
Failure Analysis of the X-33 Liquid Hydrogen Composite Tank

**E.H. Glaessgen
NASA Langley Research Center
Hampton, Virginia**

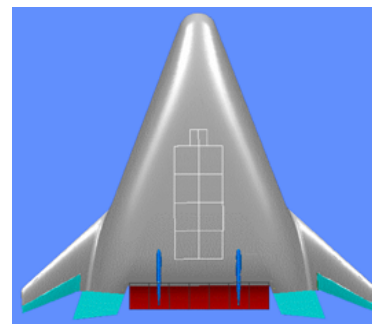
**The Symposium for Ed Rybicki
The University of Tulsa
Tulsa, OK**

July 11-12, 2012

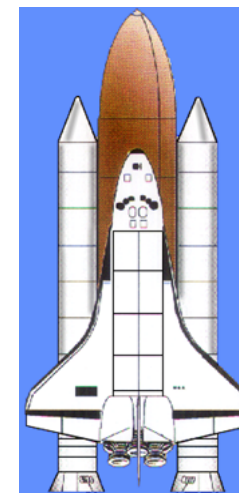
Vehicle Comparison



X-33



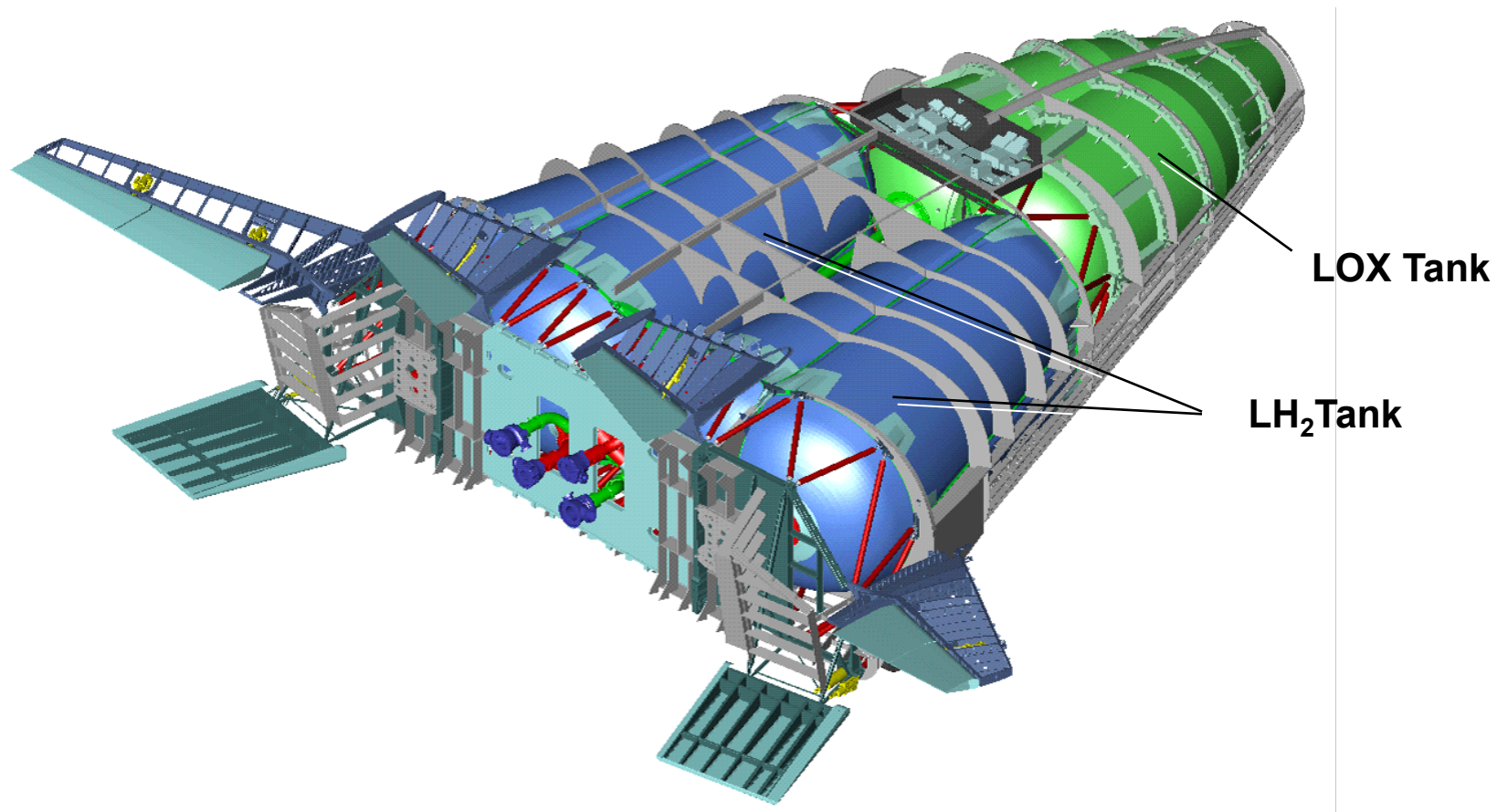
SSTO/RLV Target



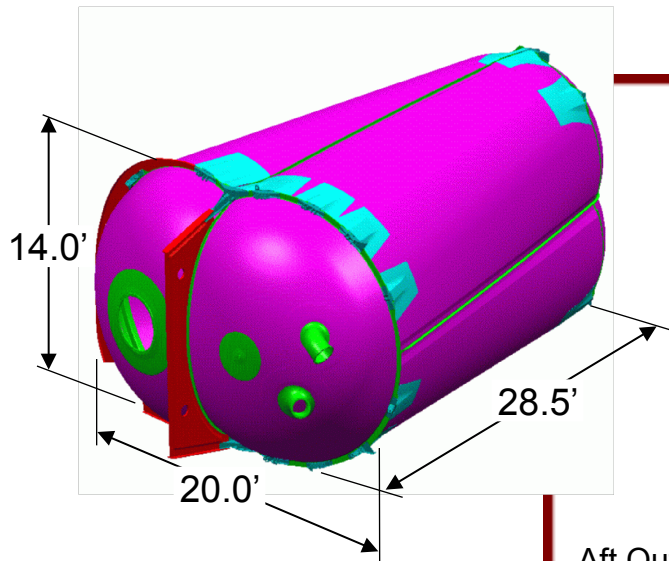
SHUTTLE

WEIGHT	285K LB	2.6M LB	4.5M LB
LENGTH	69 FT	140 FT	184 FT
PAYLOAD	N/A	55,000+ LB	51,000 LB
(100 NM) /			
28.58°)	N/A	15 x 45 FT	15 x 60 FT
BAY SIZE	2 XRS2200	8 RS2200	3 SSME
PROPULSION	AEROSPIKES	AEROSPIKES	+ 2 SOLIDS

X-33 Vehicle and Liquid Hydrogen Composite Tank



X-33 Vehicle and Liquid Hydrogen Composite Tank



LH₂ Tank Assembly

Aft Domes
IM7/977-2 Gr/Ep
Invar Flanges

Lobe Skin Assembly
IM7/977-2 Gr/Ep
Korex Core

Aft Outer Bulkhead
IM7/977-2 Gr/Ep

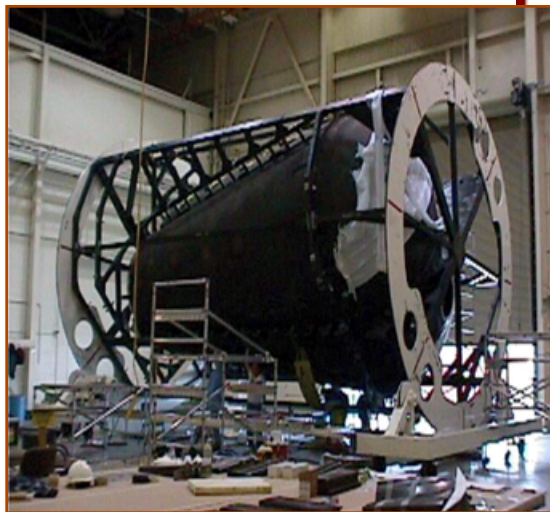
Sumps
IM7/977-2 Gr/Ep
Invar Flanges

Manhole Ring
Invar Flange

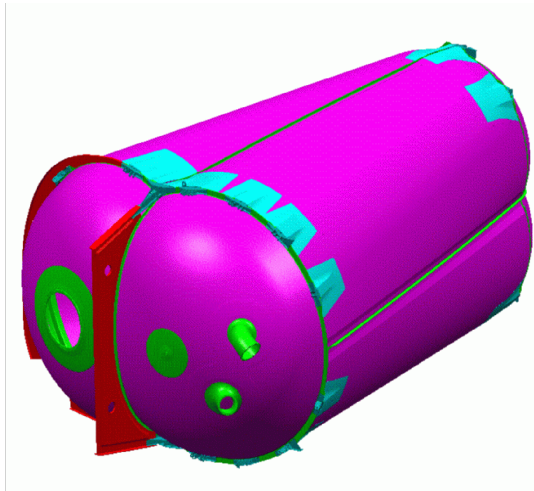
Invar-to-Composite
Bond Joint*

Hold Down Bulkhead
IM7/977-2 Facesheets
AMS 3711 Core

*Margin based on 85%
of mean test data.

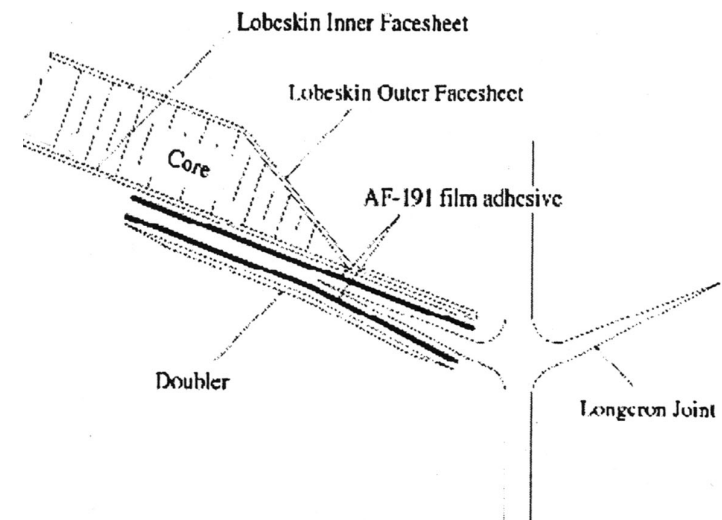
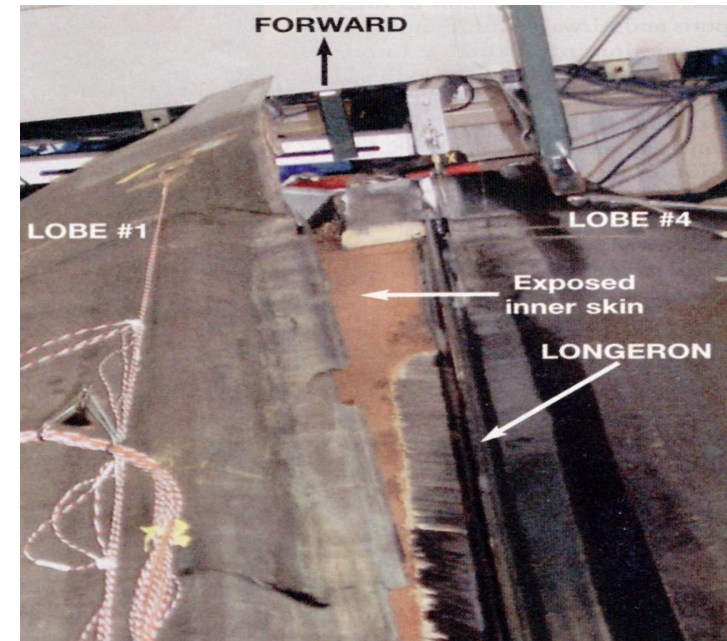
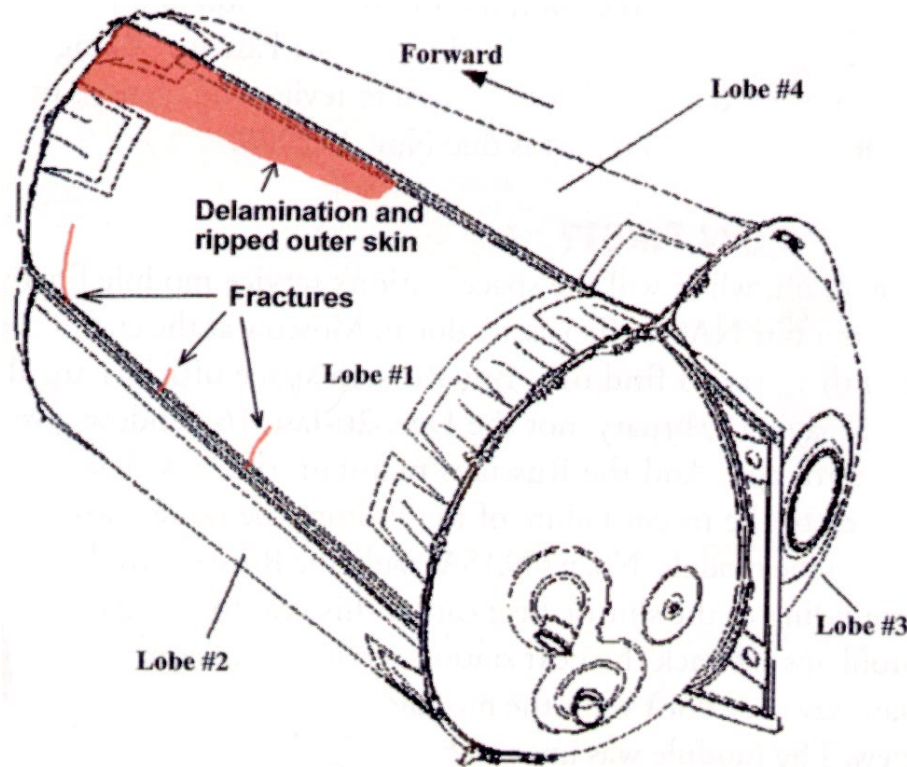


X-33 Sequence of Events



10:54:05	LH2 Transfer Initiated	Pressure Proof Test
12:25:51	LH2 Transfer Completed	
12:29:26	Tank Pressure Cycle Initiated	
13:58:48	Tank Pressure at 57 psia	
15:00:36	Tank Pressure Cycle Completed (Tank Pressure at 17 psia)	
15:31:16	Applied Loads Initiated	Mechanical Loads
15:40:44	Applied Loads Terminated	
16:05:20	Applied Loads Initiated	
16:08:50	Tank Pressure at 20 psia	
16:40:16	Applied Loads Terminated	Tank Drain
16:50:18	Tank Drain Initiated	
18:00:32	Tank Drain Completed (Tank Pressure at 20 psia)	
18:24:59	Lobe 1 Failure (Tank Pressure at 17 psia)	Failure
18:27:33	Tank Vented	
18:42:35	Tank Helium Purge Initiated	

X-33 Composite Liquid Hydrogen Tank Failure



The lobes are sandwich construction:

- Inner face sheet: $[45/90_3/-45/0_3/-45/90_3/45]_T$
- Outer face sheet: $[65/0/-65/90/-65/0/65]_T$
- Face sheets material: IM7/977-2
- Core material: Korex 3/16 - 3.0 (1.5 in. thick)
- Adhesive: AF-191

Hypothesized Sequence of Events Leading to Failure

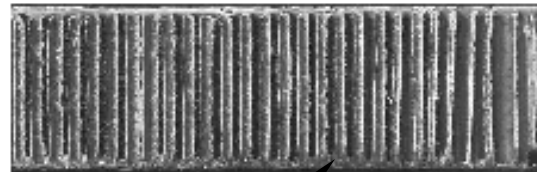
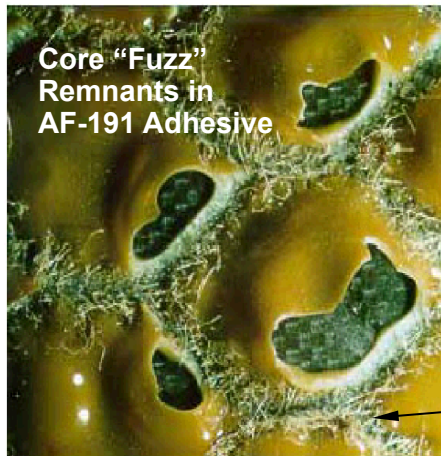


- LH2 transfer ($T = -423^{\circ}\text{F}$) and tank pressurization precipitated microcracking of inner facesheet
- LH2 permeated sandwich core through inner facesheet and gaseous N₂ & H₂ on tank outer surface cryopumped into core
- Tank temperature increase (after drain) and tank pressure decrease after pressure cycle allowed microcracks to close trapping LH₂, H₂ and N₂ in the core
- Tank temperature increase caused LH₂ to change state to gaseous H₂ causing increase in pressure within core
- Internal pressure drove starter crack (F.O.D.) causing debonding of facesheet at a weak interface

Causes of the X-33 Composite Tank Failure



Weak Core-Face Sheet Bond

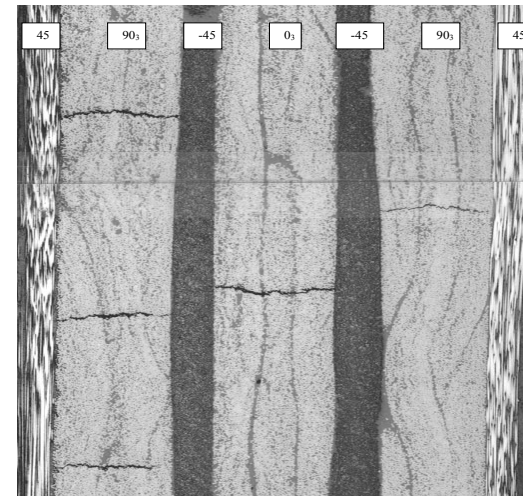
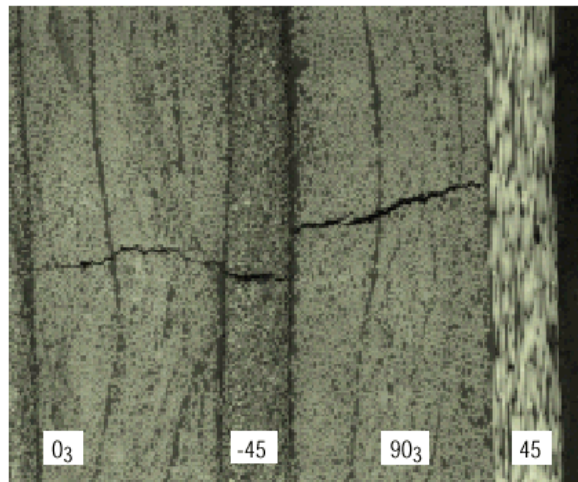


Inner Face Sheet
To Core Weak
Bond Due To Mfg
Snafu

Teflon Tape in Core



Inner Skin Microcracking (sectioned at 45 deg)



Summary of the Analysis & Testing

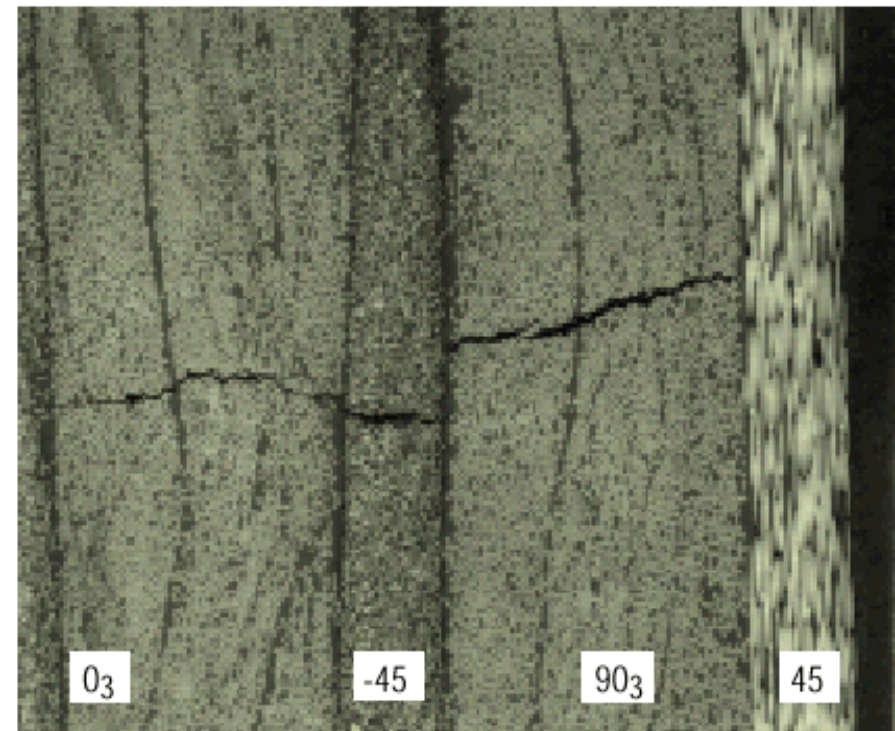
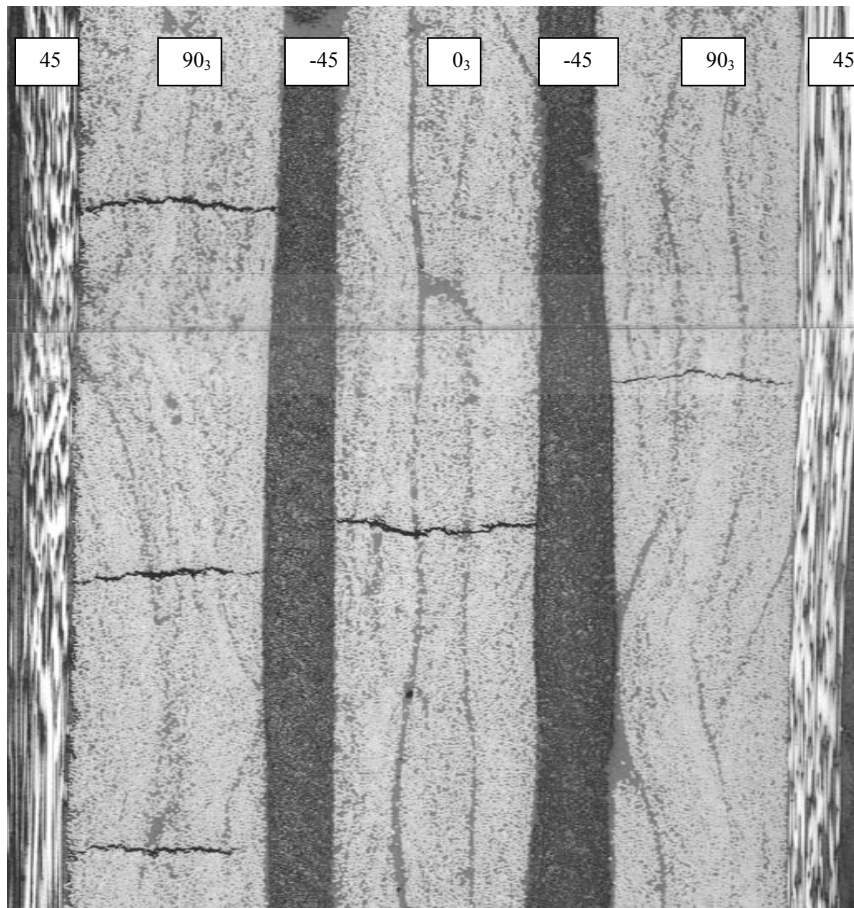


- **Matrix microcrack analysis**
- **Fracture model development**
- **Measurement of fracture toughness (critical energy release rate)**
- **Model correlation and experimental verification test results**
- **Analysis of foreign object debris (F.O.D.)**

Matrix Microcracking



Sections taken at 45 degrees to the 0 degree fiber direction



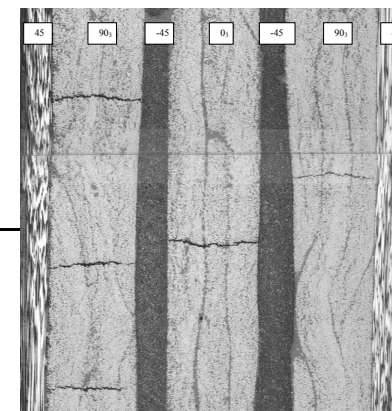
Graphite/epoxy, IM7/977-2, $[45/90_3/-45/0_3/-45/90_3/45]_T$



Matrix Microcrack Analysis

Ply Level Transverse Stresses:

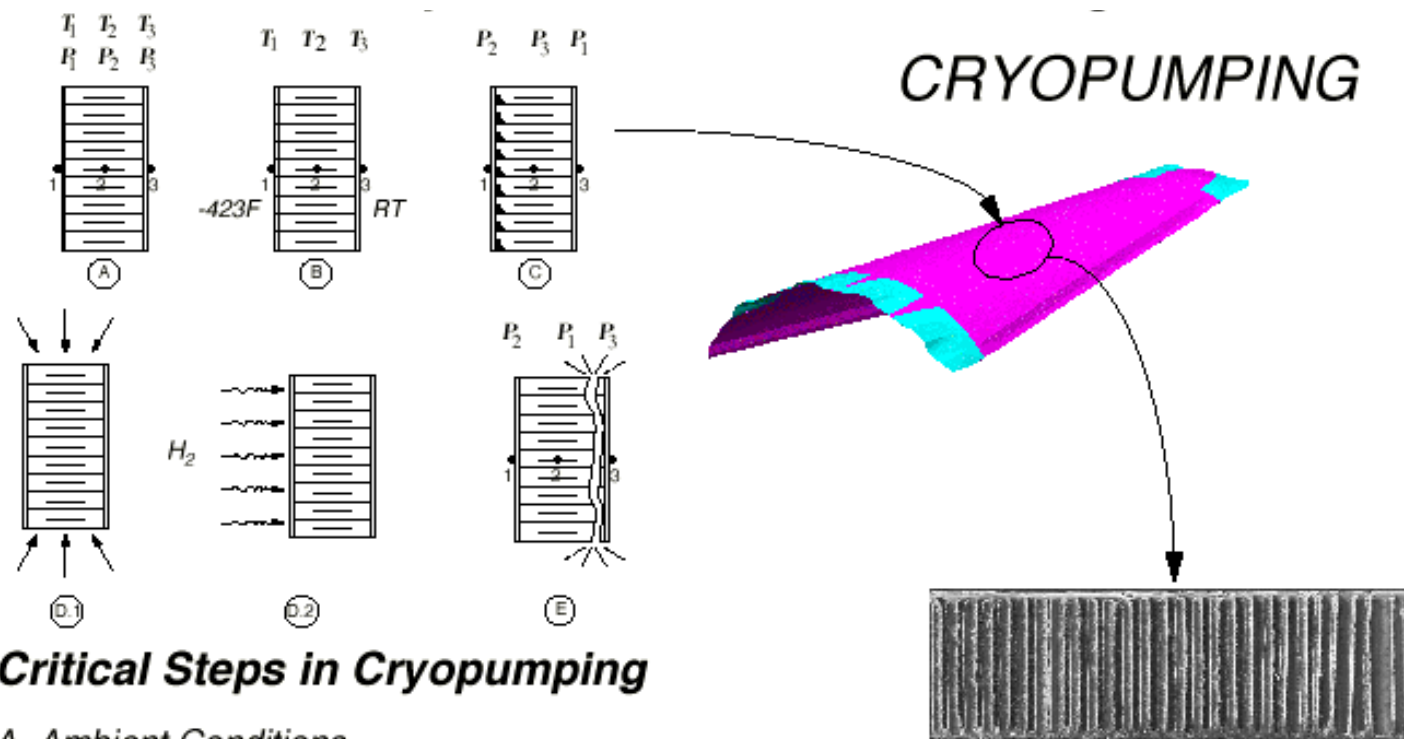
Laminate / Material System	Thermal Stress -ksi-	Pressure 0.20 / 0.13 %ε -ksi-	Total Stress -ksi-
X-33 inner skin, IM7 / 977-2, ΔT=-743F			
90 plies	10.1	4.2	14.3
0 plies	10.8	5.0	16.3
45 plies	10.5	4.6	15.1
X-33 outer skin, IM7 / 977-2, ΔT=-470F			
90 plies	6.4	4.2	10.6
0 plies	6.8	5.0	11.8
45 plies	6.5	4.3	10.8



Transverse Strength and Modulus:

Material System	Laboratory	90 Tensile Strength	E ₂₂ Modulus
IM7 / 977-2	Fiberite	12.4 ksi	1.20 msi
	NASA	10.4 ksi	1.33 msi
	LMSW	5.7 ksi (-423F)	1.94 msi (-423F)
	Rockwell	9.3 ksi (-423F)	2.0 msi (-423F)

Cryopumping



Critical Steps in Cryopumping

- A. Ambient Conditions
- B. Hydrogen Fill & Hold
- C. Condensation of Air in Cells, Vacuum in Core Results
- D.1. Possible Air Ingress at Open Edges
- D.2. Hydrogen Permeates through Facesheet
- E. Upon Heating, Core Pressure Exceeds Critical Value

This data was generated by the Lockheed Martin Skunk Works under NASA Cooperative Agreement No. NCC6-115, dated July 1, 1996.

LOCKHEED MARTIN

AlliedSignal
AEROSPACE

ROHR

BOEING
Rockwell International

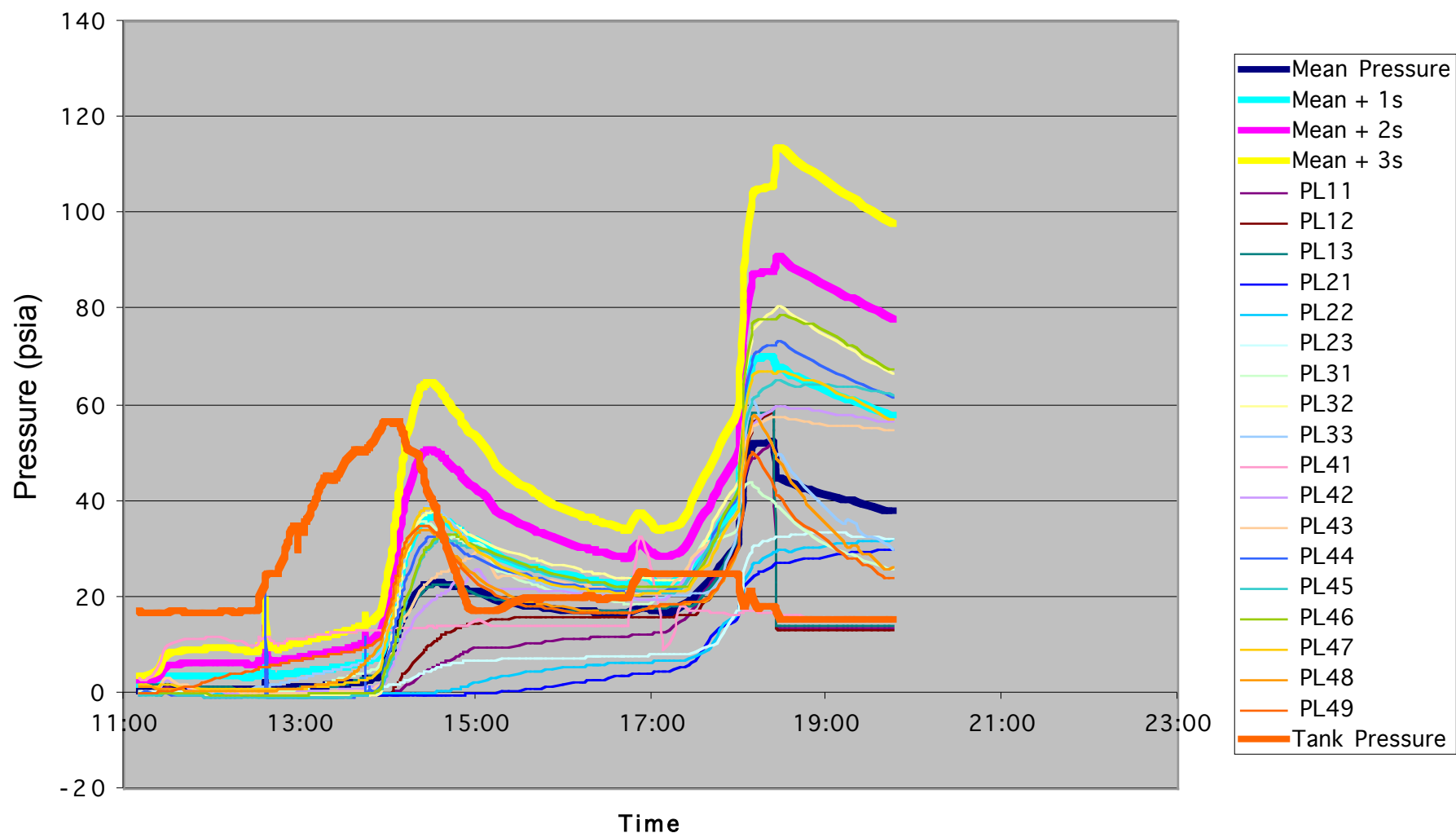
Sverdrup

X-33 CDR, Day 4, Structural Analysis
Page 121

NASA

Rockwell

X-33 LH₂ Tank Mean Core Pressure vs Time



Summary of the Analysis & Testing



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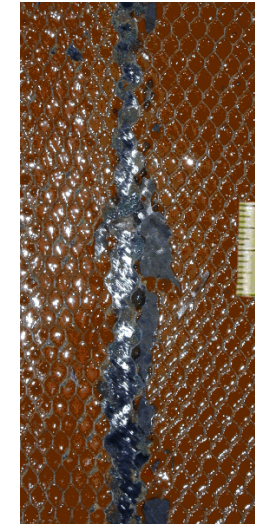
Foreign Object Debris



J-shaped debond



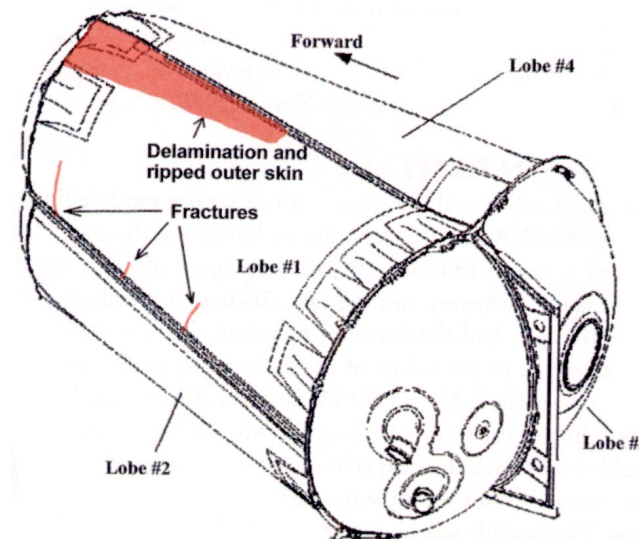
Pear-shaped debond



**Coalesced debonds
at core splice**



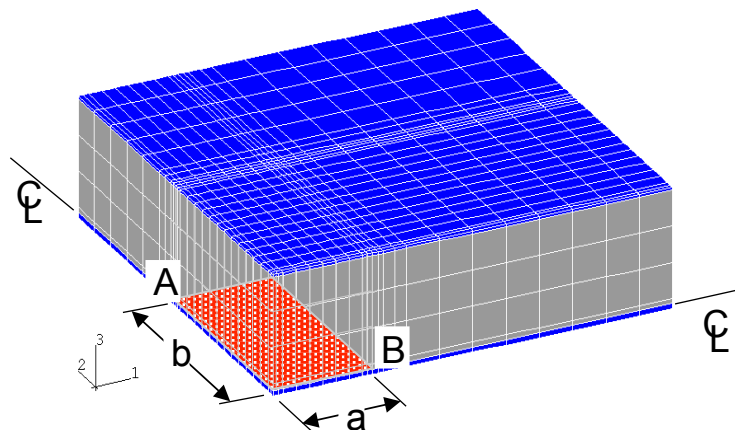
**0.050"x2.0" unbond between upper
and lower skin at lobe 1-lobe 4 longeron**



VCCT-Based Fracture Mechanics Analysis*



- Internal pressure load
- Homogenized core with equivalent properties using 20-noded hexahedra
- VCCT to calculate G -values at locations A and B
- E_{11}^b , E_{22}^b of facesheets and E_{33} , G_{13} , G_{23} of core were determined by correlation with compliance calibration of single cantilever beam tests



Sandwich modeled using 3-D solid elements with the core modeled as homogeneous material with equivalent stiffness

*Engineering Fracture Mechanics, 1977, Vol. 9, pp. 931-938. Pergamon Press. Printed in Great Britain

A FINITE ELEMENT CALCULATION OF STRESS INTENSITY FACTORS BY A MODIFIED CRACK CLOSURE INTEGRAL

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Applied Solid Mechanics Section, Battelle's Columbus Laboratories, Columbus, OH 43201, U.S.A.

Abstract—An efficient technique for evaluating stress intensity factors is presented. The method, based on the crack closure integral, can be used with a constant strain finite element stress analysis and a coarse grid. The technique also permits evaluation of both Mode I and Mode II stress intensity factors from the results of a single analysis. Example computations are performed for a double cantilever beam test specimen, a finite width strip with a central crack, and a pin loaded circular hole with radial cracks. Close agreement between numerical results given by this approach and reference solutions were found in all cases.

This method presented here falls into the category of indirect methods. Unlike other indirect methods, this method permits both K_I and K_{II} to be evaluated from a single analysis. The method does not require that stresses be calculated. Conventional constant strain elements have been used successfully and a coarse grid near the crack tip was found to be sufficient. The following contains a description of the method and the results for selected problems. Results are compared with reference solutions taken from the literature.

DESCRIPTION OF THE METHOD

Irwin's contention is that if a crack extends by a small amount Δc , the energy absorbed in the process is equal to the work required to close the crack to its original length[18]. Using a polar coordinate system with the origin at the extended crack tip, this statement in equation form is given by eqn (1). The physical interpretation of the integrals in eqns (4) and (5) is the amount of work required to close the crack and amount, Δc . In terms of the finite element representation, this is one-half the product of the forces at c and d required to close these nodes. In equation form, the expressions for $\mathcal{G}_I$ and $\mathcal{G}_{II}$ are

$$\mathcal{G}_I = \lim_{\Delta c \rightarrow 0} \frac{1}{2\Delta c} \bar{F}_c \cdot (v_c - v_d) \quad (8)$$

and

$$\mathcal{G}_{II} = \lim_{\Delta c \rightarrow 0} \frac{1}{2\Delta c} \bar{T}_c \cdot (u_c - u_d). \quad (9)$$

For computational purposes, a value of Δc is selected as shown in Fig. 1. The value of $\bar{F}_c$ and $\bar{T}_c$ are taken to be the y - and x -forces, respectively, that are required to hold nodes c and d together. When evaluating $\bar{F}_c$ and $\bar{T}_c$, it is convenient to maintain l_2 equal to Δc and Elements

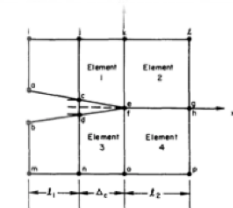


Fig. 1. Finite-element nodes near crack tip.

Summary of the Analysis & Testing

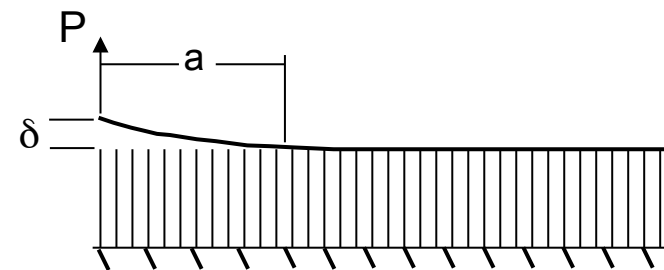
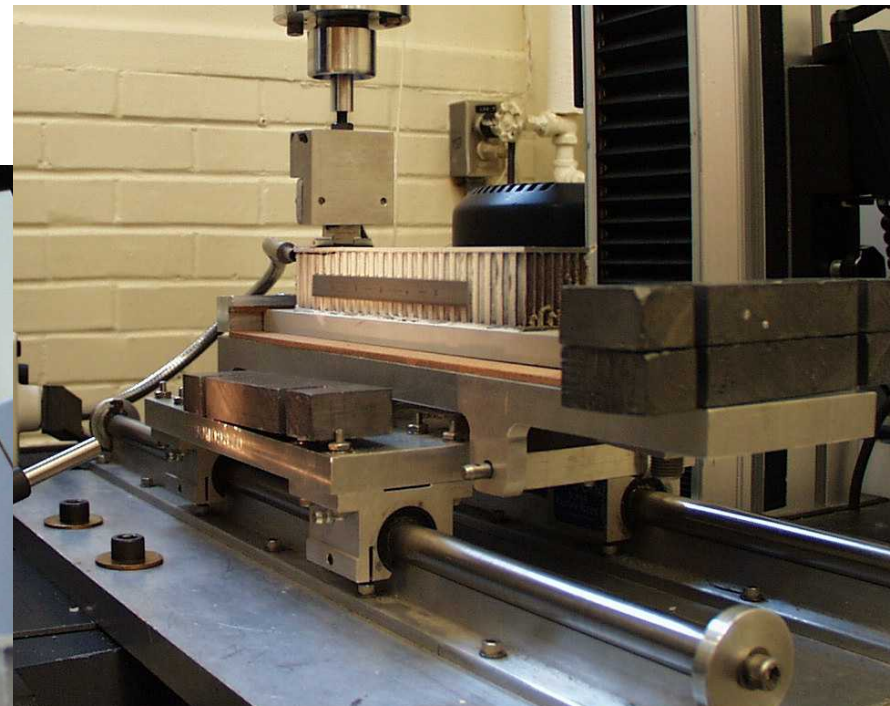
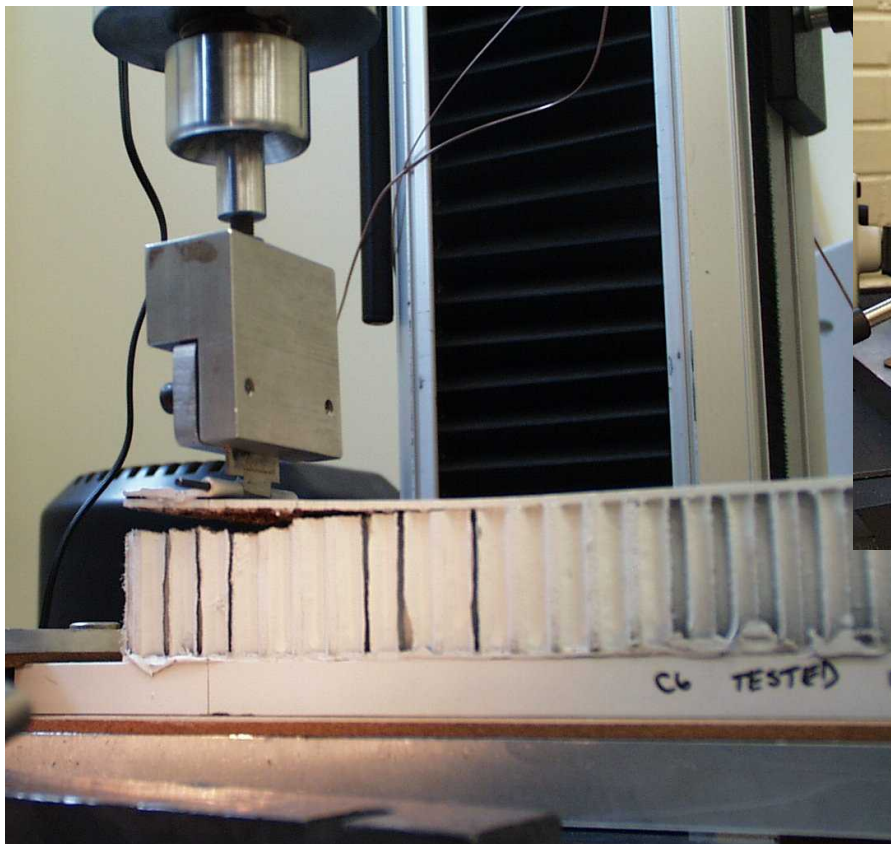


- Matrix microcrack analysis
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Fracture Toughness Test Results

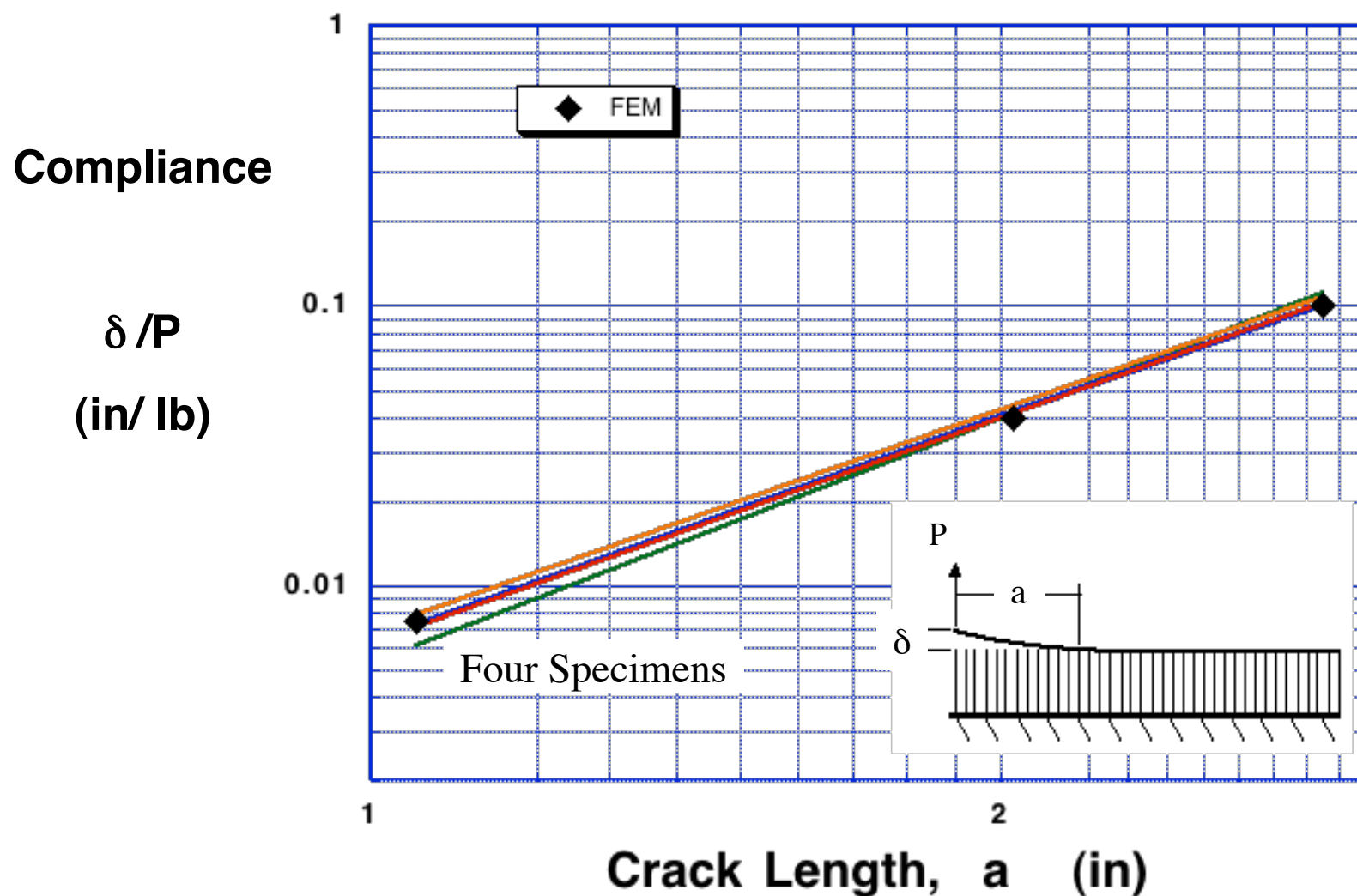


- Single cantilever beam test to characterize actual toughness of X-33 LH2 tank interface
- Fracture toughness (critical strain energy release rate) measured using the standard compliance calibration test method

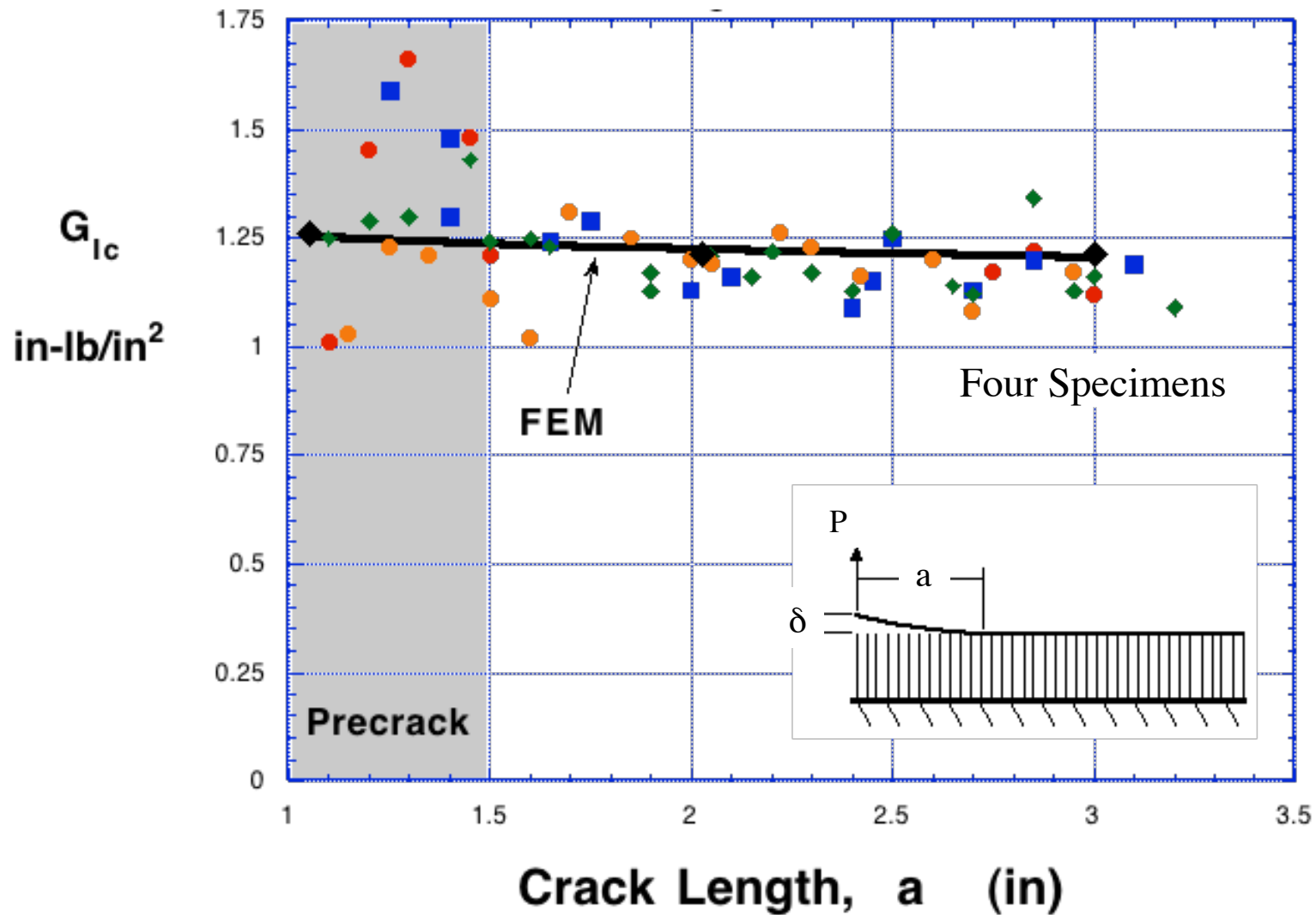




FEM Compliance Correlation



FEM Toughness Correlation



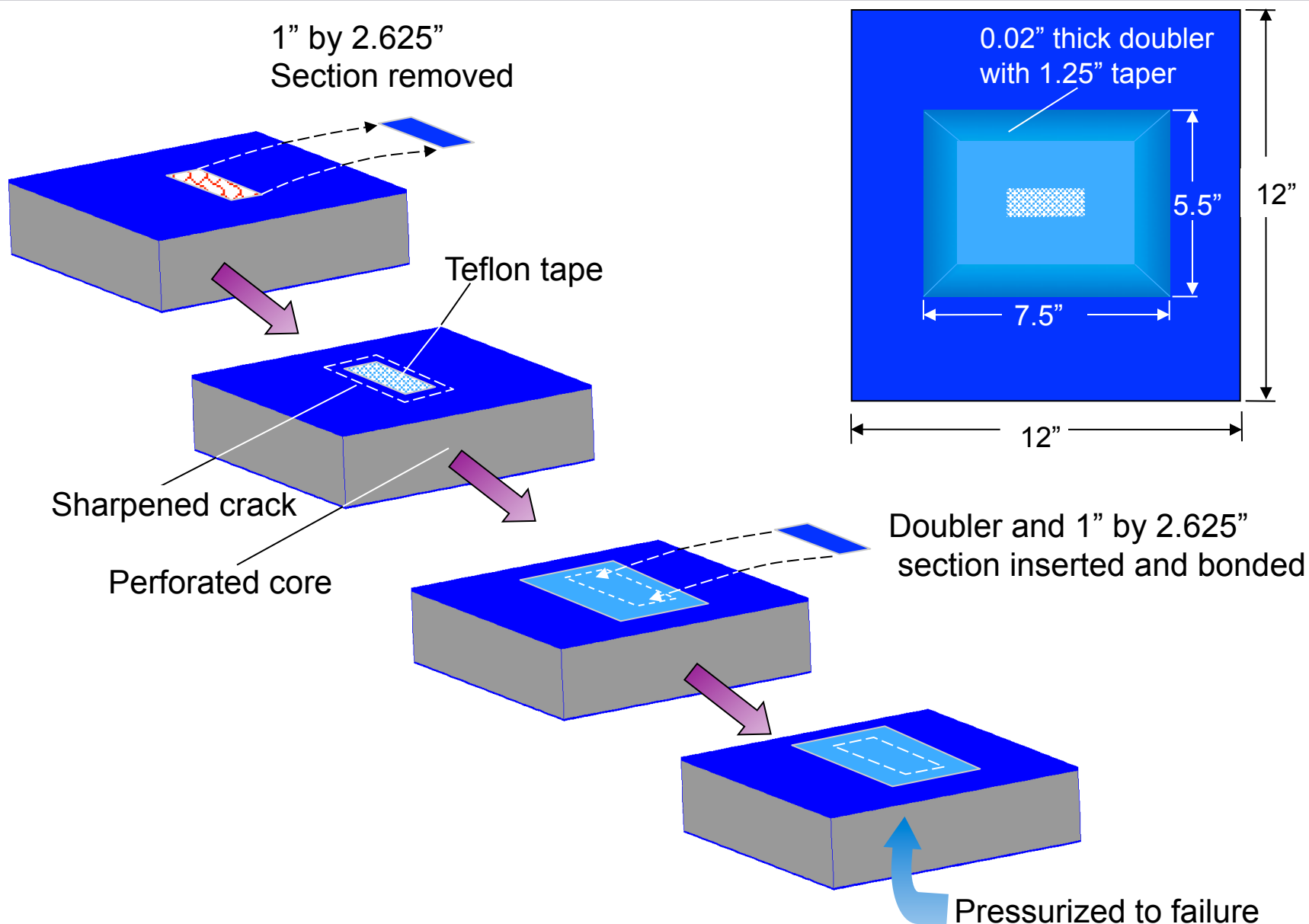
Summary of the Analysis & Testing



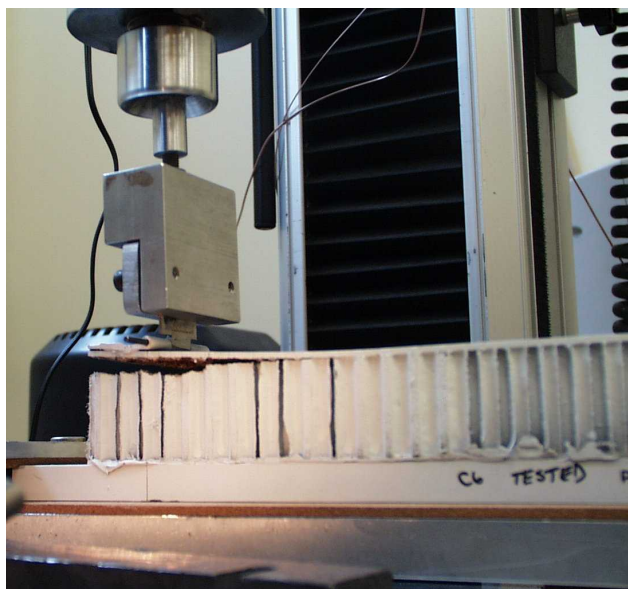
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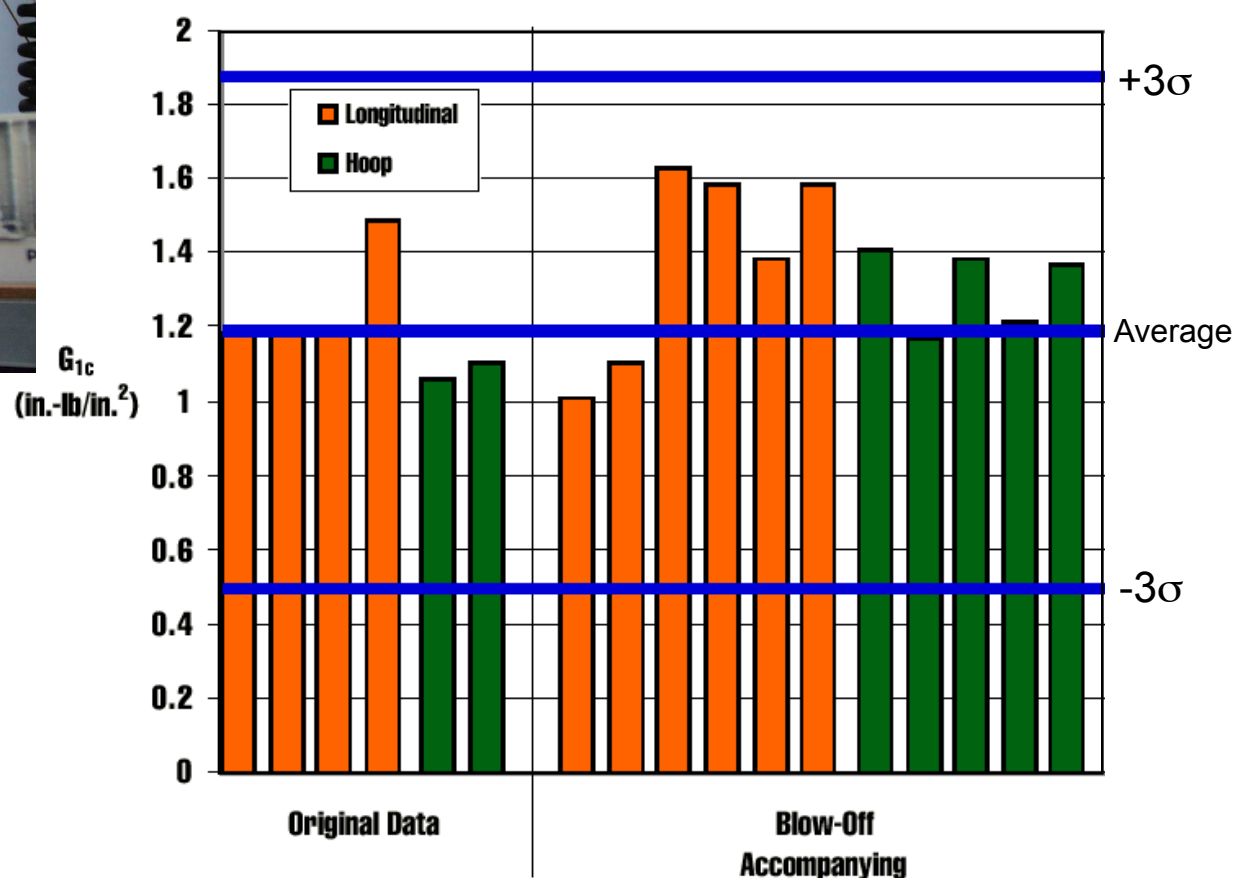
Blow-off Test Specimens



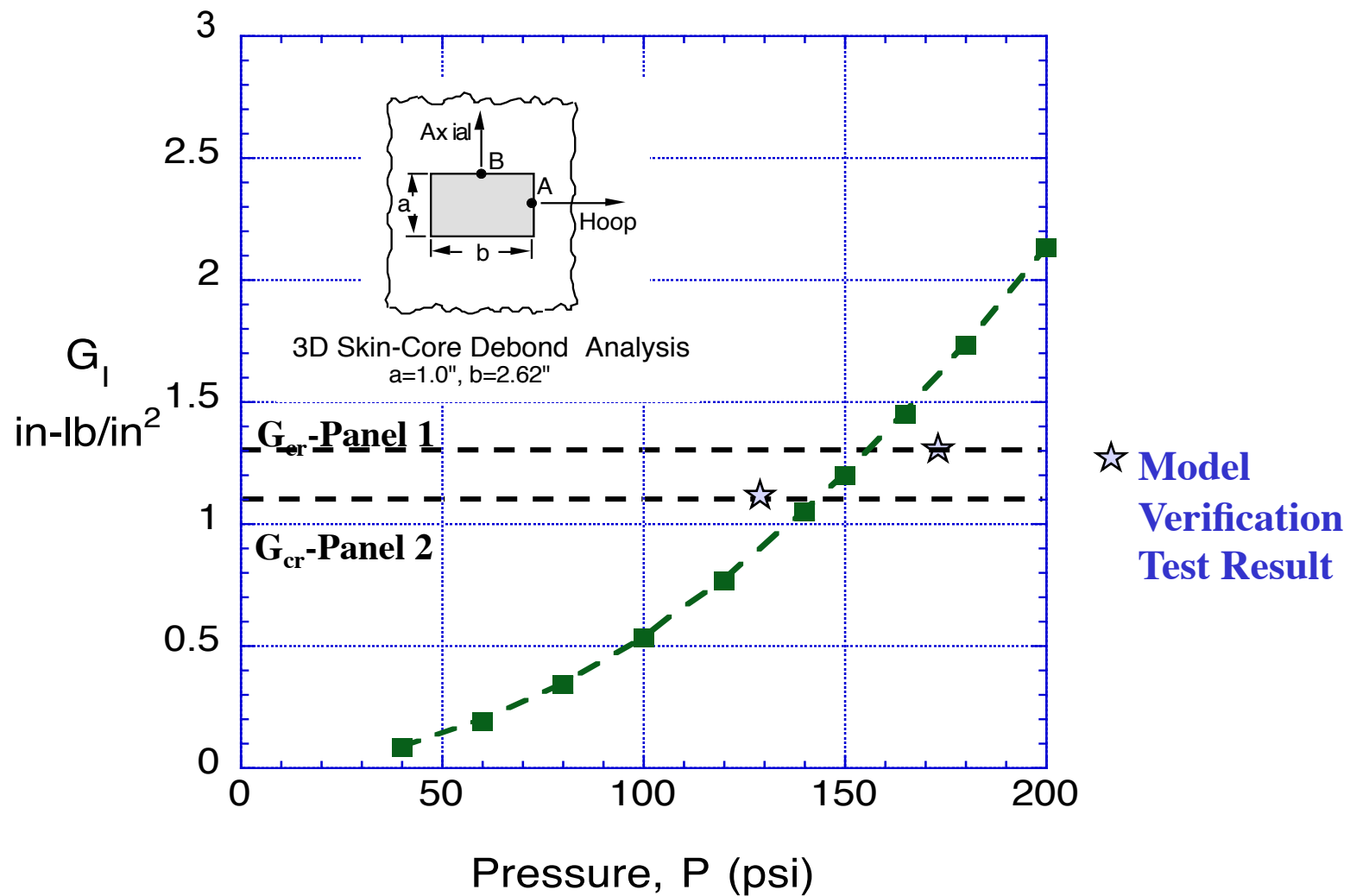
Fracture Toughness Test Results



Fracture toughness (critical strain energy release rate) measured using the standard compliance calibration test method



Comparison of Predicted Critical Pressure to Experimental Results from Panel Blow-off Tests

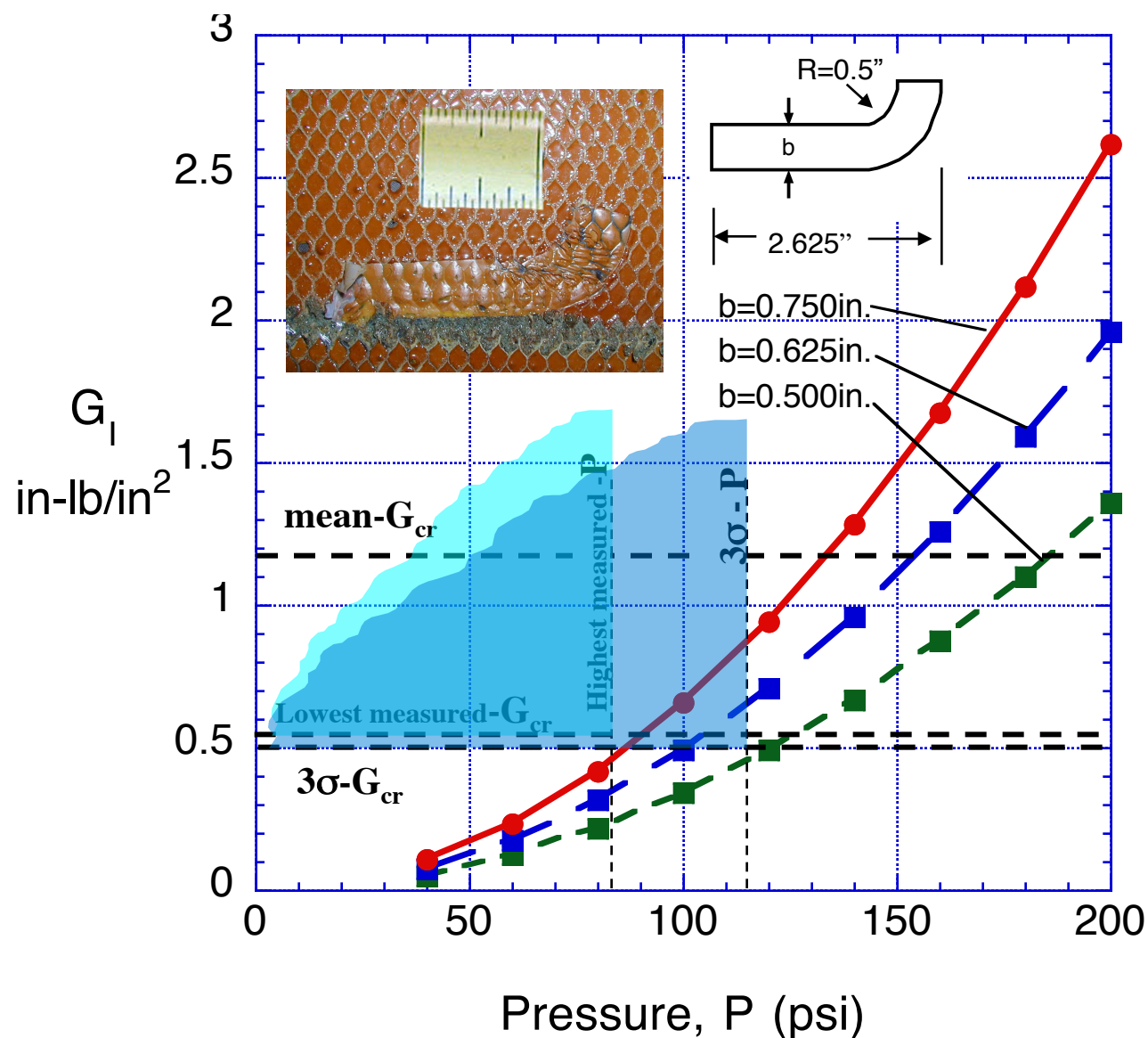


Summary of the Analysis & Testing



- **Matrix microcrack analysis**
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Strain Energy Release Rates for J-shaped Debond



Summary of X-33 LH2 Tank Failure



The X-33 LH 2 Tank Test Investigation Team determined that the most probable cause of the incident was a combination of factors:

- Microcracking of inner facesheet allowed hydrogen infiltration into core
- Nitrogen purge gas cryopumped through outer facesheet and other areas into core
- Presence of nitrogen and hydrogen in core produced higher than expected core pressures
- Core bondline strength (and toughness) lower than expected
- Presence of 0.5-in. wide by 2 5/8-in. long piece of PTFE tape at inner-facesheet-to-core bondline created critical debond area

Summary



- Matrix microcrack analysis and cryopumping mechanism explained presence of LH2 in core
- Fracture mechanics analysis consisted of
 - 3-D solid elements to model facesheets and core
 - VCCT-based fracture mechanics to compute G-values
 - Single cantilever beam test to characterize toughness
- Fracture mechanics model predicted blow-off test failure pressure well
- The fracture mechanics model explains the likelihood of the hypothesized failure scenario of the X-33 LH2 tank failure



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