Fracture of Composites: A Soon-To-Be Old Guy's Perspective

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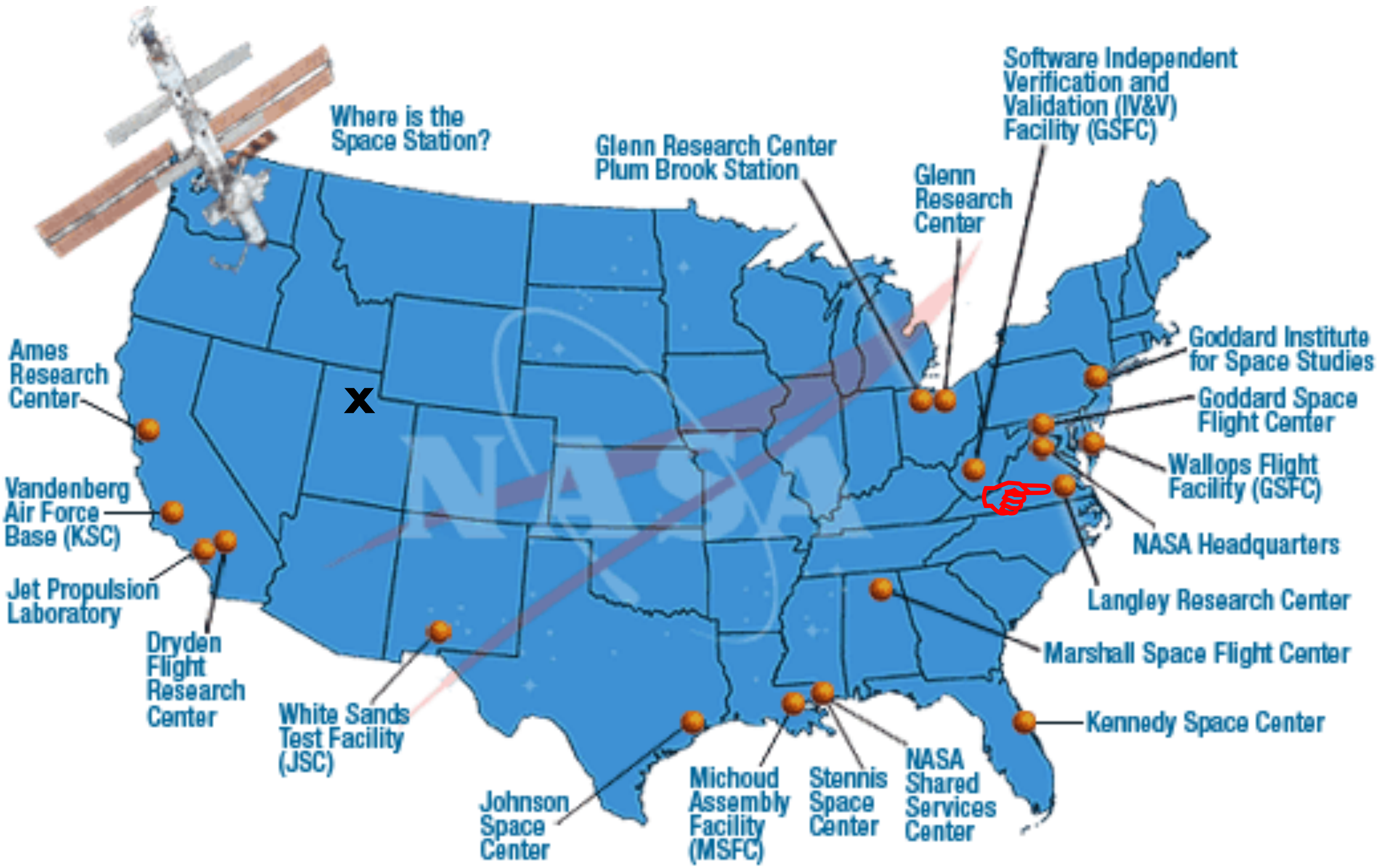
National Aeronautics and Space Administration

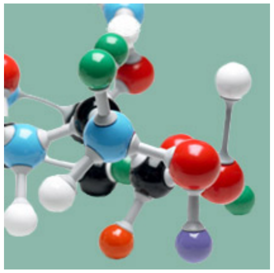


NASA Missions

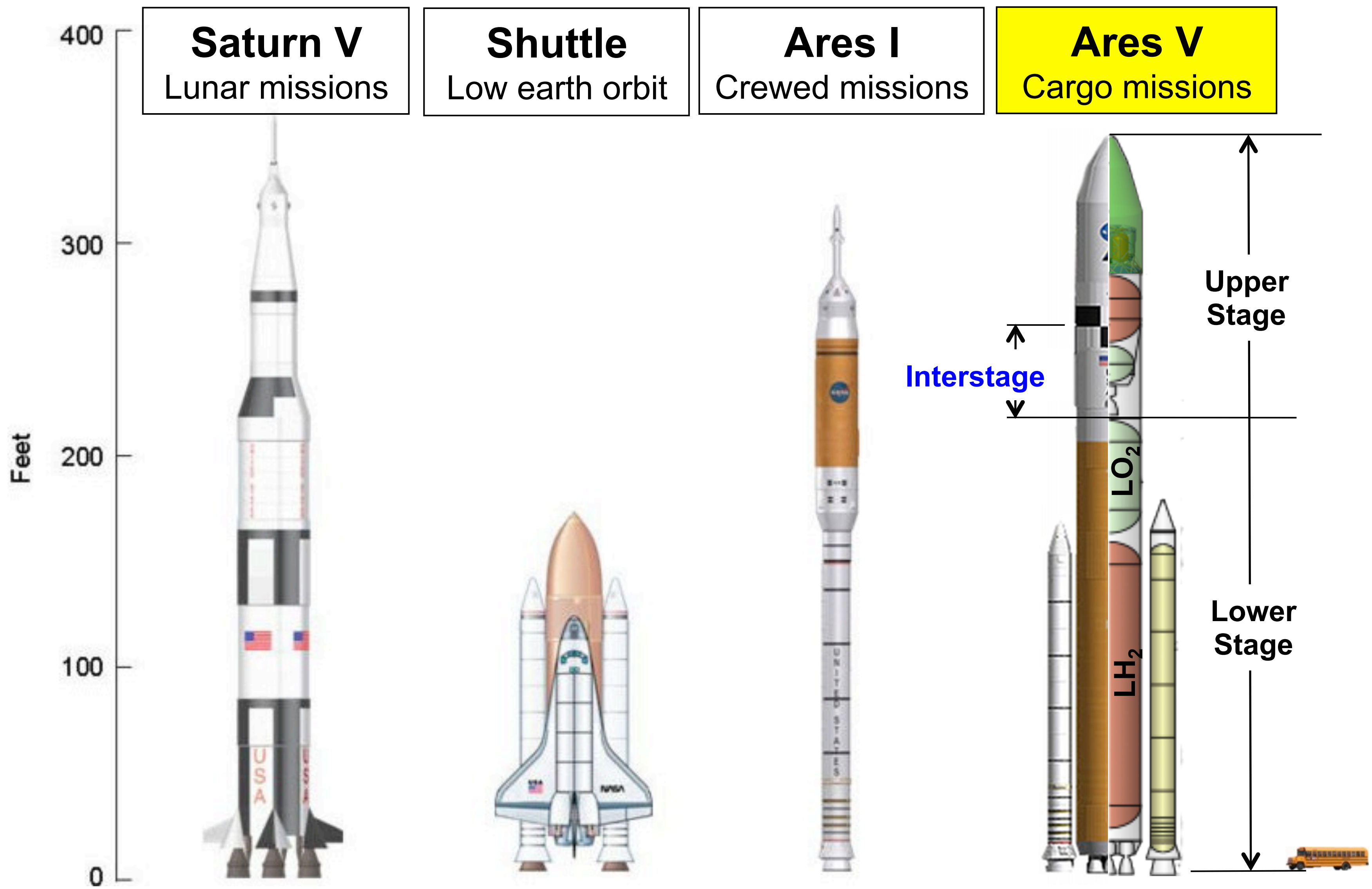
NATIONAL TRANSPORTATION SAFETY BOARD

Federal Aviation Administration

CMH17
COMPOSITE MATERIALS HANDBOOK

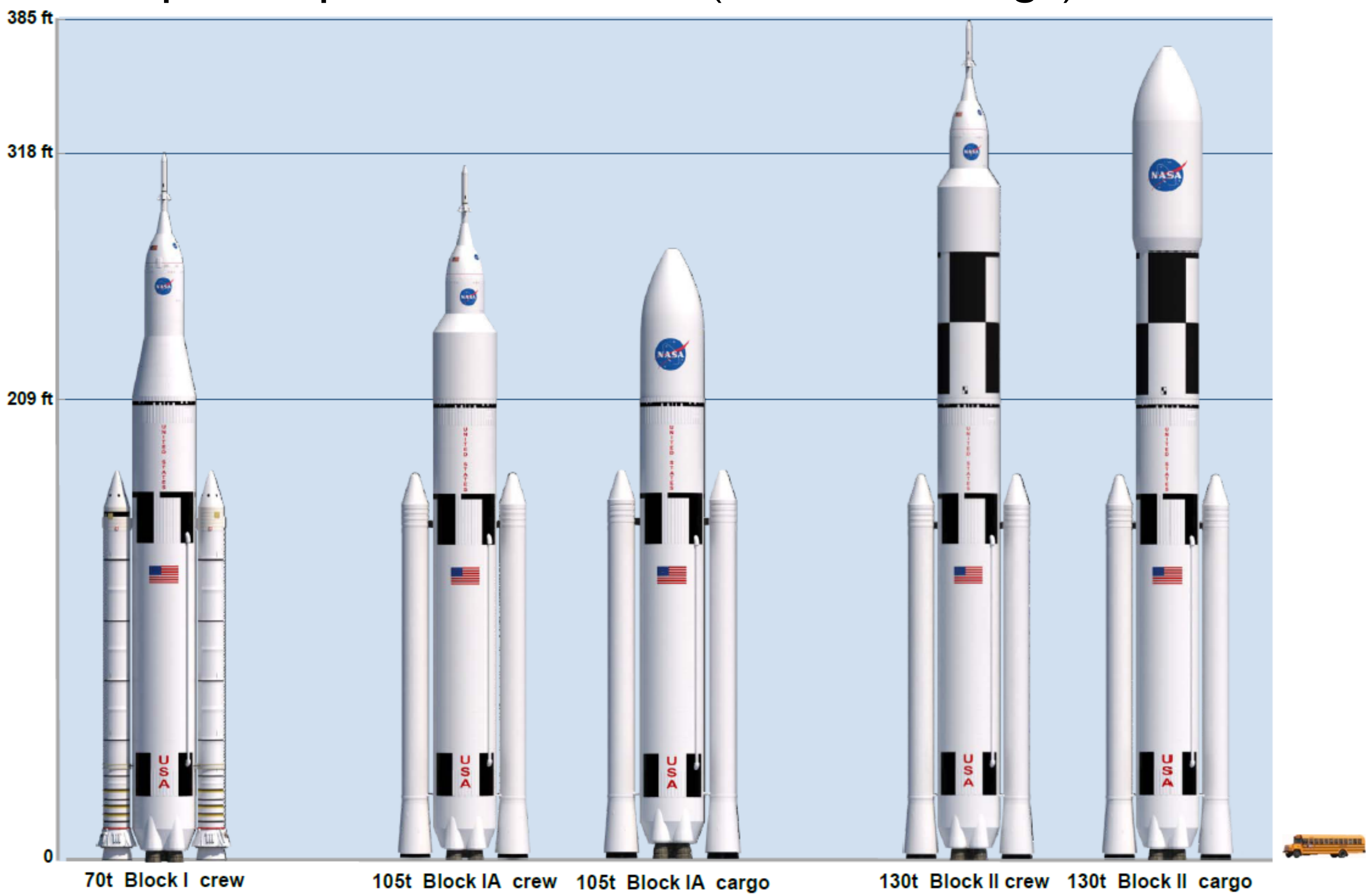


Launch Vehicle Systems: Apollo - Constellation



Launch Vehicle System: Space Launch System

Space Exploration Missions (Crew and Cargo)



1. NASA Missions
2. **NASA Langley Research Center**
3. Why Do We Worry About Fracture in Composites?
4. Examples of Failure of Composite Structure
5. How is Fracture Dealt With in Design and Certification?
6. Summary Thoughts

Langley Research Center (LaRC)

Langley Research Center (LaRC)

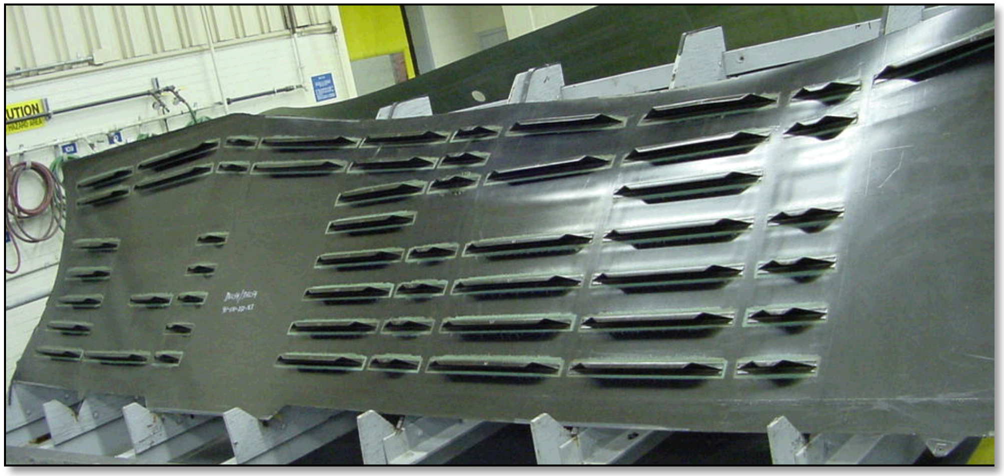
Research Directorate (RD) consists of 26 branches

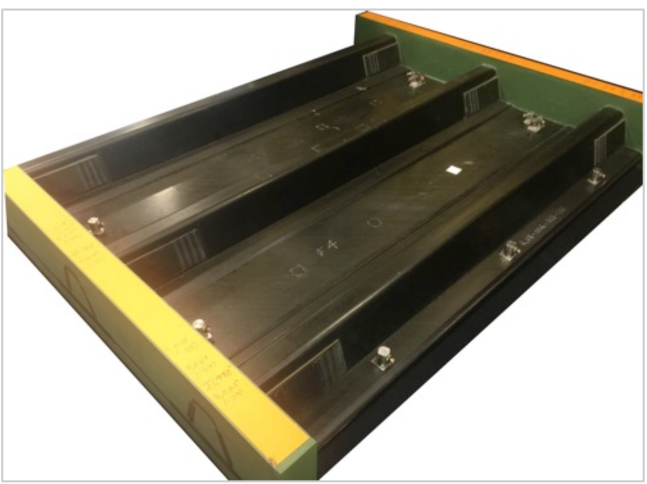
Configuration Aerodynamics Branch	Aeroelasticity Branch	Flight Dynamics Branch	Structure Experiments Branch
Computational Aerosciences Branch	Durability, Damage Tolerance and Reliability Branch	Crew Systems and Aviation Operations Branch	Subsonic/Transonic Testing Branch
Flow Physics and Controls Branch	Structural Mechanics and Concepts Branch	Electromagnetics and Sensors Branch	Supersonic/Hypersonic Testing Branch
Advanced Sensing and Optical Measurement Branch	Nondestructive Evaluation Sciences Branch	Safety-Critical Avionics Systems Branch	Structures Testing Branch
Aerothermodynamics Branch	Aeroacoustics Branch	Structural Acoustics Branch	Technologies Application Branch
Hypersonic Airbreathing Propulsion Branch	Dynamic Systems and Controls Branch	Structural Dynamics Branch	Revolutionary Aviation Technologies Branch
Advanced materials and Processing Branch	Applied Technologies and Testing Branch	Materials Experiments Branch	

Why Do We Worry About Fracture in Composites?

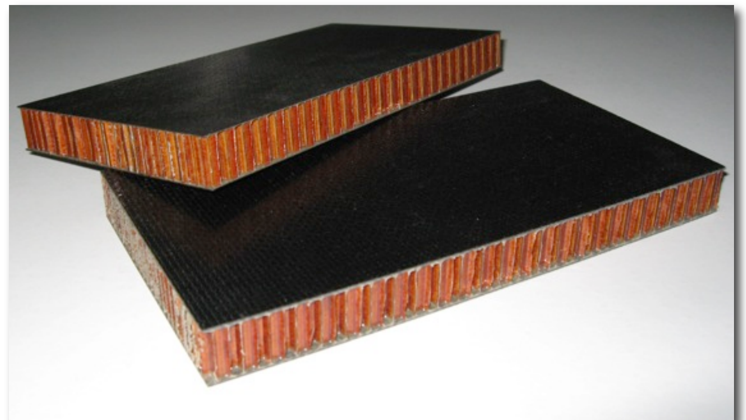
Fiber-Reinforced Polymeric Composite Laminates

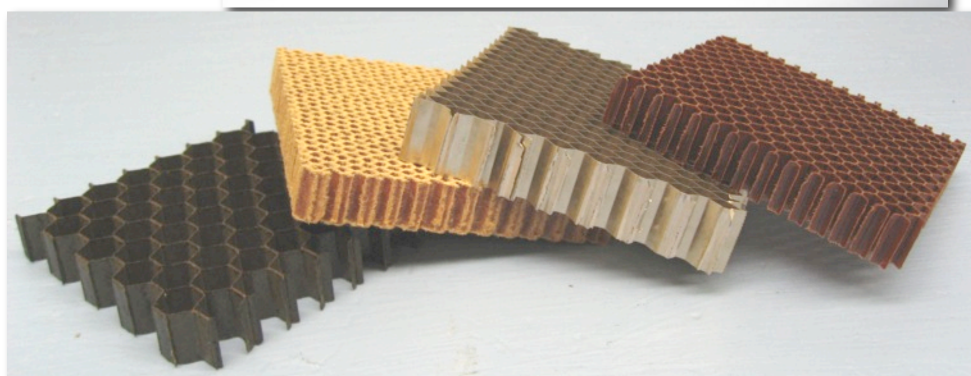
Integrally stiffened panels





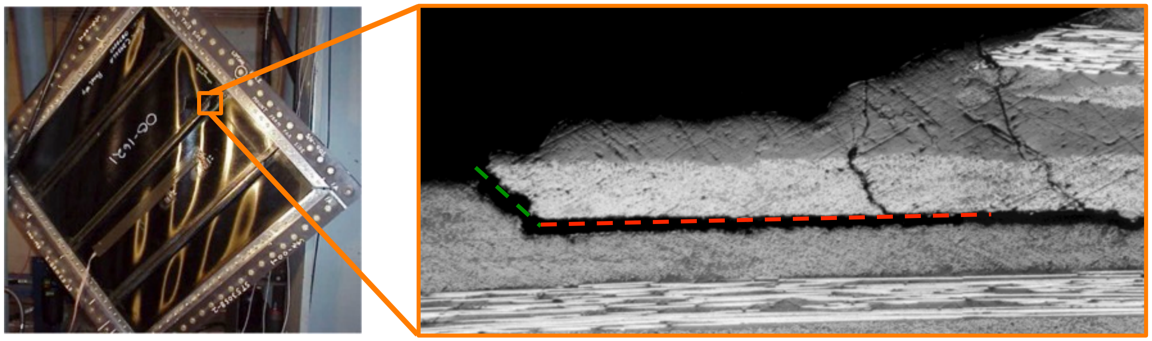
Sandwich structure





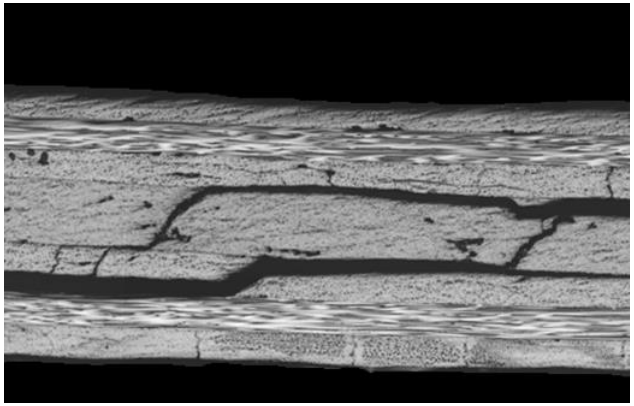
Why Do We Worry About Fracture in Composites?

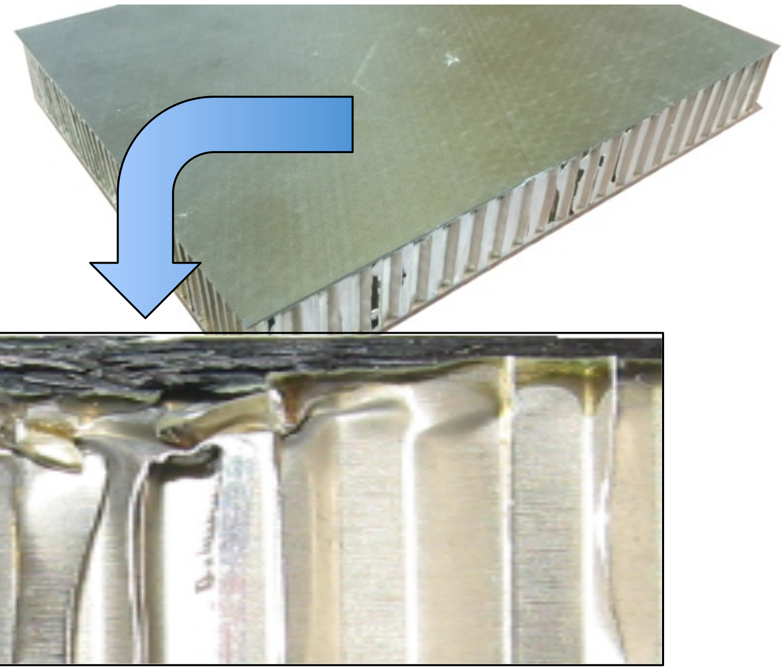
#1 Fracture occurs in many forms..

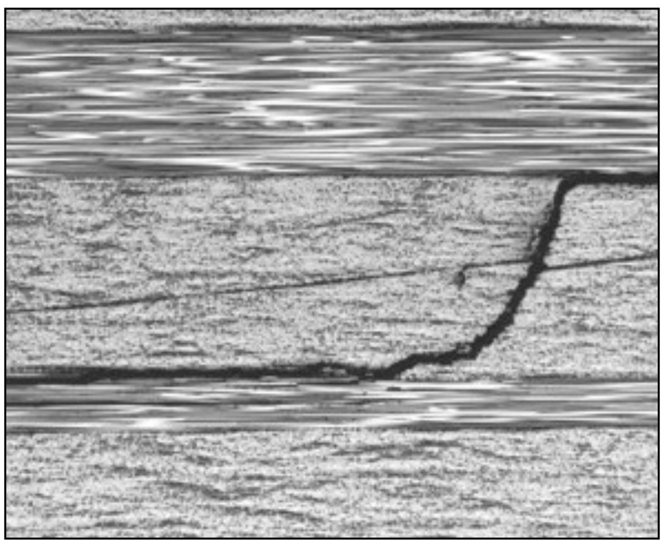


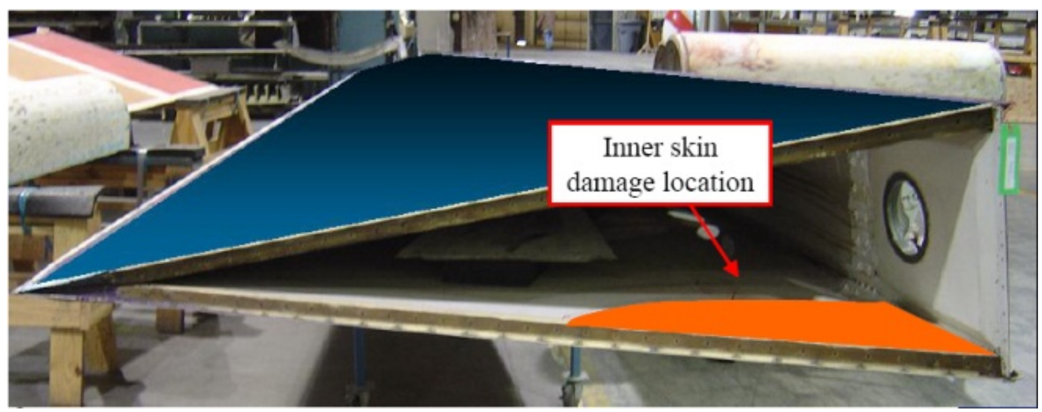
Why Do We Worry About Fracture in Composites?

#2 You can’t always see it!









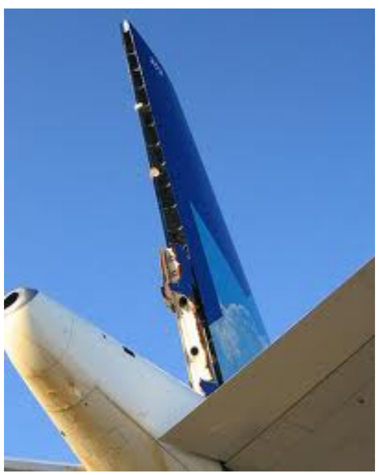
1. Rudder Failure

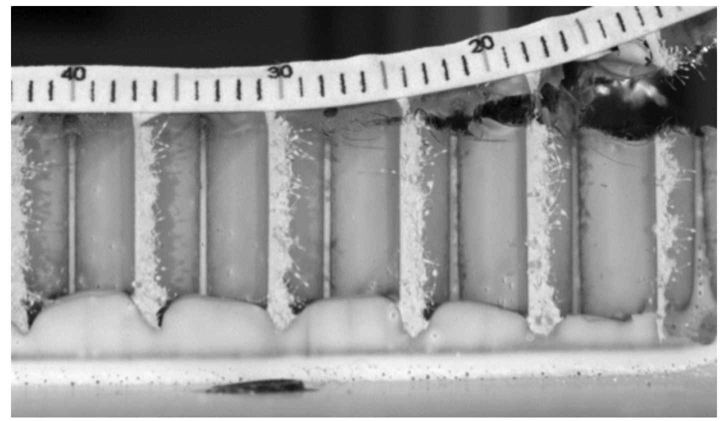
Pressure difference between inside and outside of honeycomb sandwich structures caused by alternating ambient pressure is a major cause of face sheet peeling loads

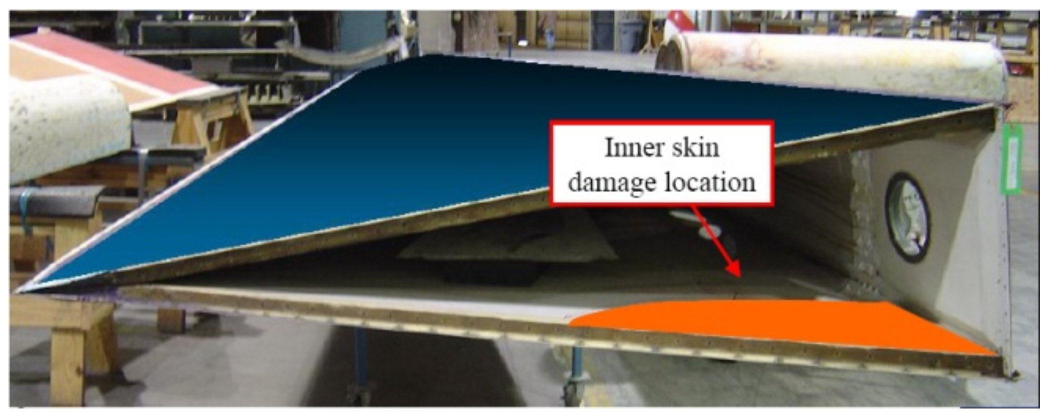
Initial disbonds between face sheets and core increase the peeling effect and can decrease the structural reliability significantly

FAA-sponsored CMH-17 debond/delamination task group to study the problem

Air-Transit flight 961 (Airbus A310-300):
- Rudder failure due to face sheet disbonding caused by pressure difference and initial disbond



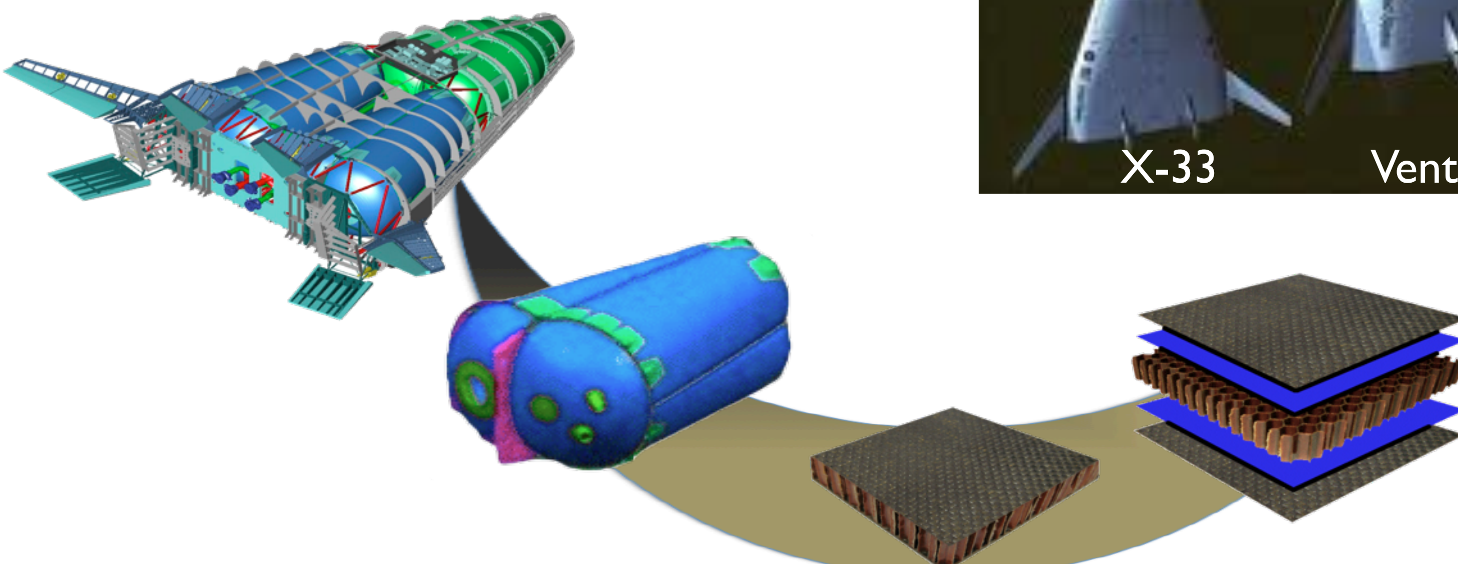




Hilgers R: Substantiation of Damage Growth within Sandwich Structures, In: FAA Workshop for Composite Damage Tolerance & Maintenance, Tokyo, 2009

2. X33 Tank Failure

LOX tank (sandwich structure) failed due cryo pumping

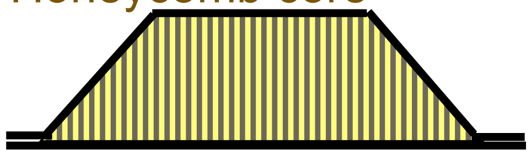


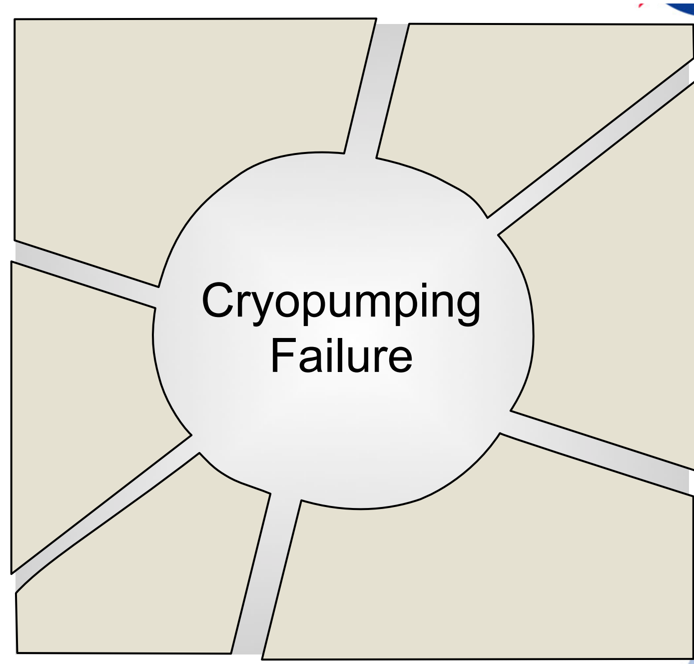
Tank Failure Via Cryopumping

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)**

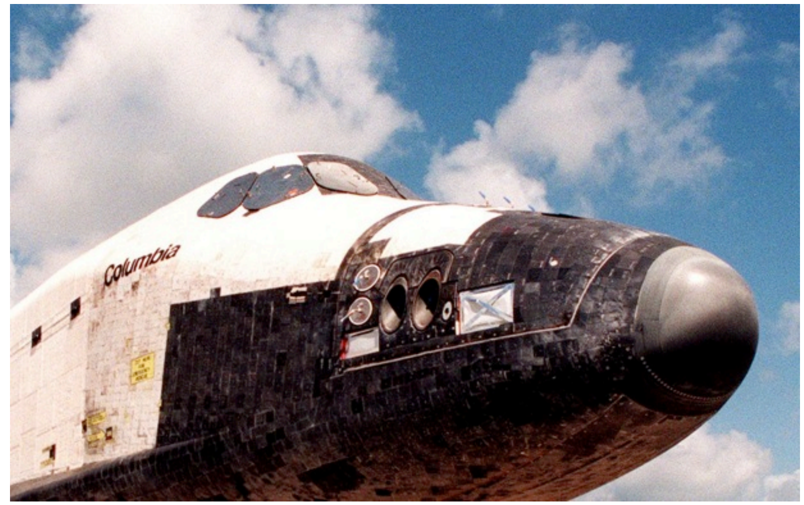
- **Warm up**

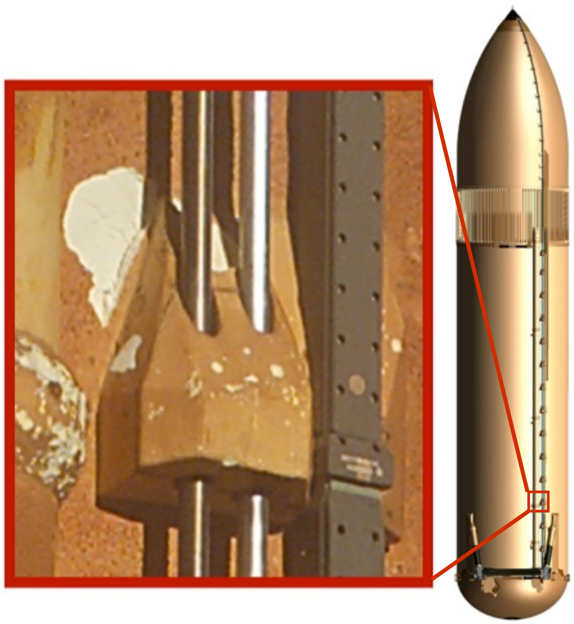
After tank drain

3. Columbia Orbiter Re-entry Incident

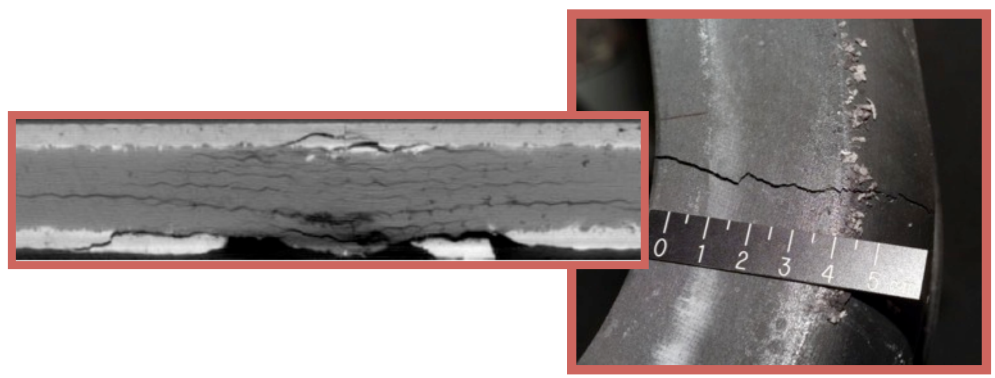
ORBITER WING LEADING EDGE (WLE) DAMAGE TOLERANCE ASSESSMENT

On February 3, 2003, Space Shuttle Columbia crashed killing its seven member crew. Insulating foam was separated from the external tank , which caused damage that resulted in the loss of the Orbiter.





Potential damage scenarios include through-crack, front-side coating loss, backside damage



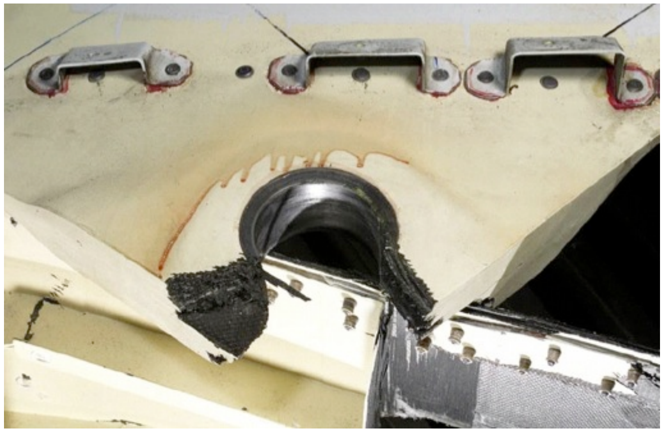
4. AA Flight 587 Accident

The Accident

On November 12, 2001, American Airlines Flight 587 crashed shortly after takeoff, killing 260 people on board and 5 on the ground

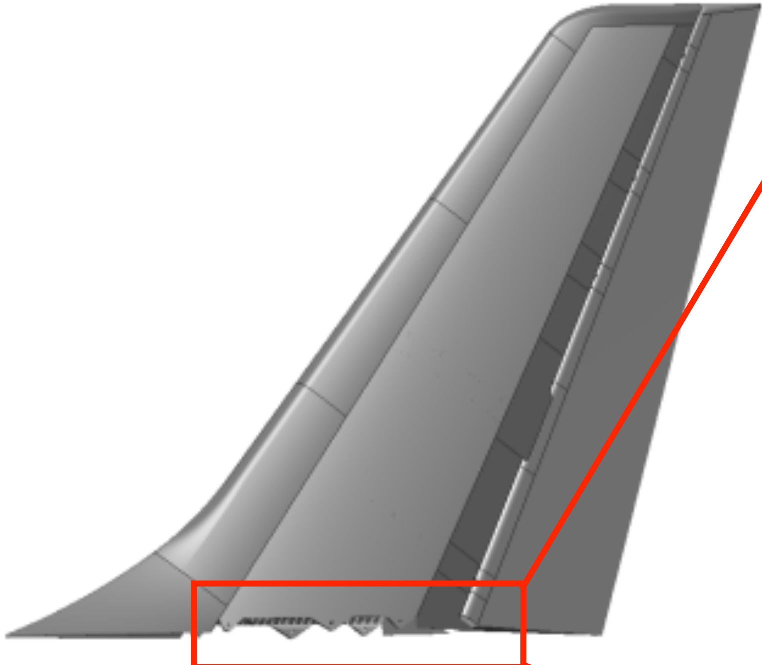
The probable cause of this accident was the in-flight separation of the vertical stabilizer as a result of the loads beyond ultimate design

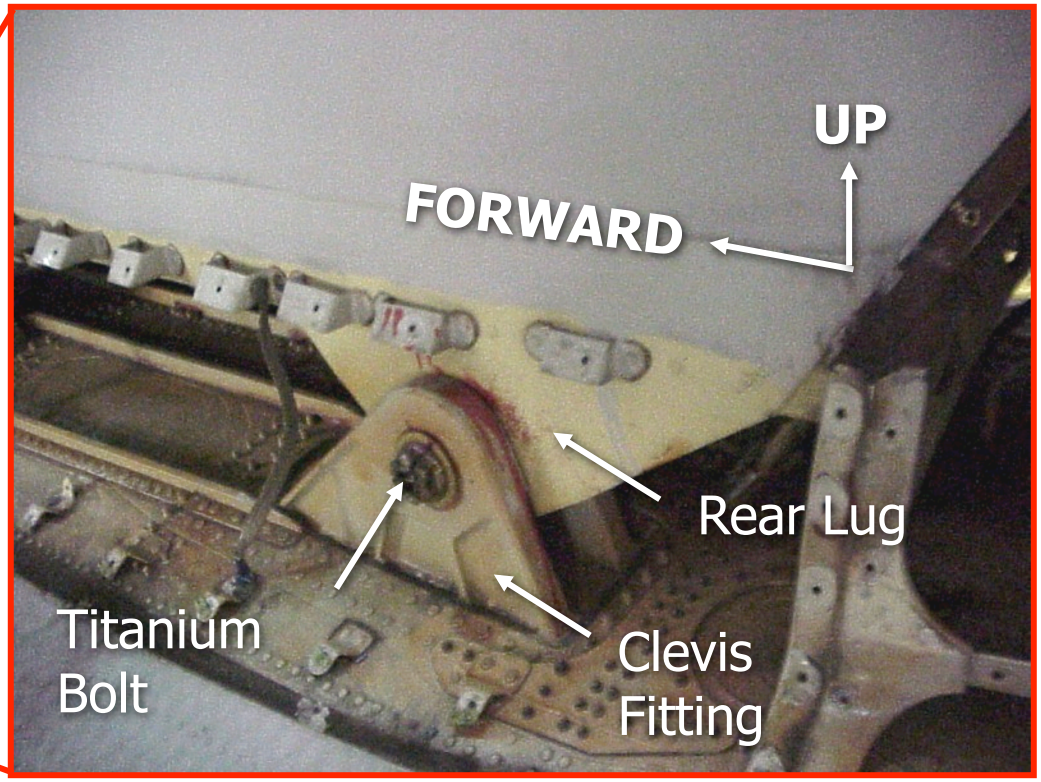
Recovery of Vertical Tail



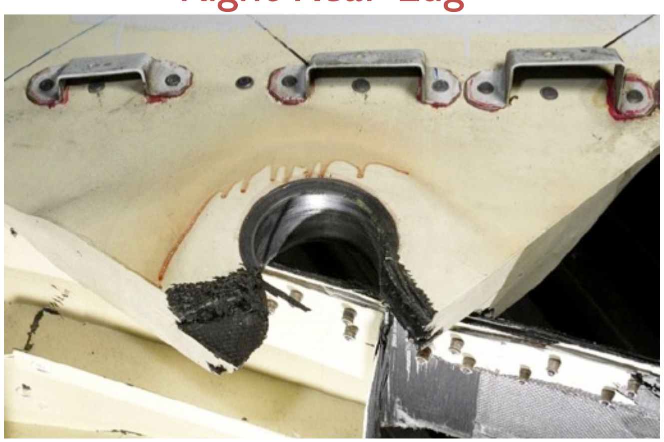
Right Rear Lug

Lug Failure





Right Rear Lug



- Complex 200 ply laminate
- Numerous plies in form of tape and fabric
- Numerous curvilinear ply drops

5. Gulf Helicopter AW139 Tail Boom Failure

The Accident

On 25th August, 2009 a Gulf Helicopter AW139 experienced a tail boom failure during a pre-flight taxi manouver

"The most probable root cause of this accident was determined in a tail boom strength degradation caused by **hidden Nomex internal damages** of the RH panel corners areas induced by the previous tail strike event…." Aircraft Accident Investigation Final Report

AW139 with failed tail boom

Close-up view of tail rotor

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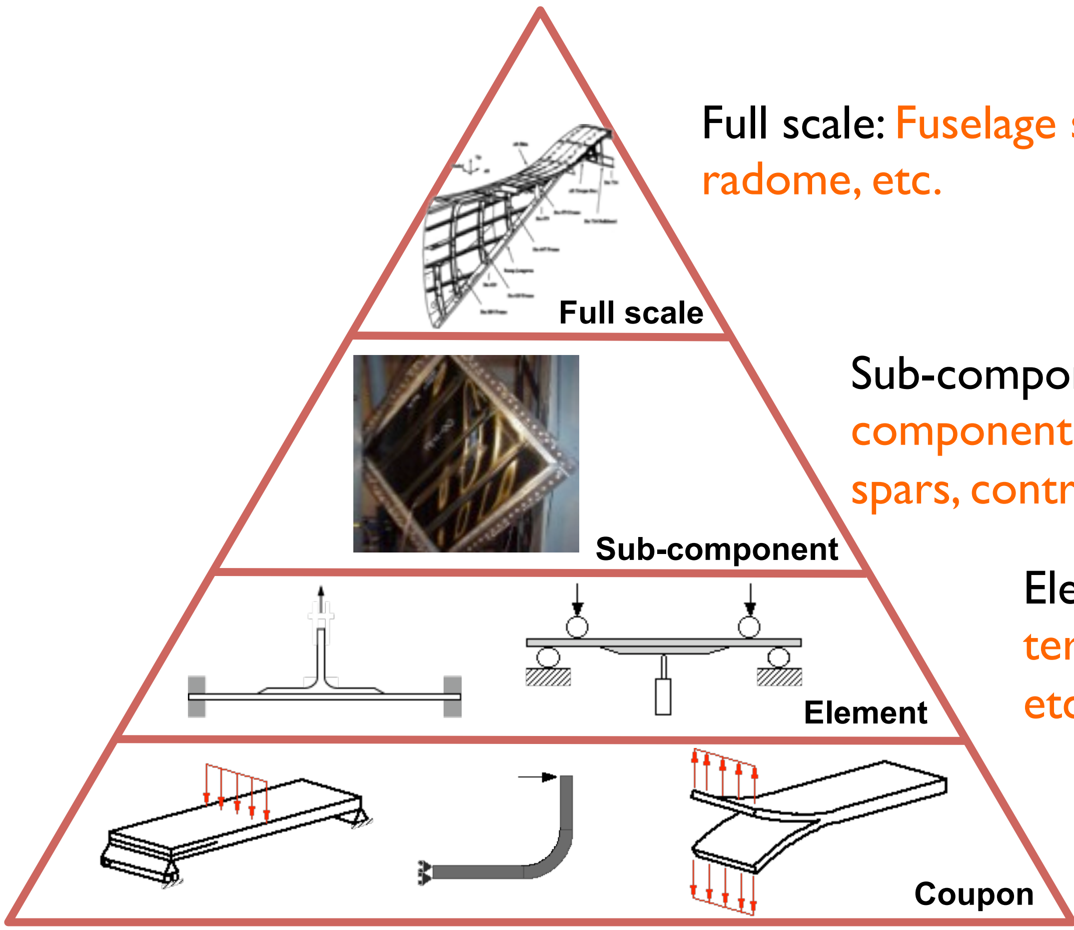
Building Block Approach: Design and Certification



Full scale: Fuselage section, tail boom, radome, etc.

Sub-component: Full-featured structural components (integrally stiffened panels, rotor spars, control surfaces, etc.)

Element: Key structural features (ply terminations, holes, bondlines, joints, etc.)

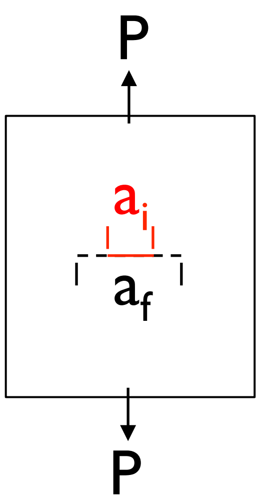
Coupon: Material characterization (strength, **fracture toughness**, creep, etc.)

Basic Principles of Fracture in Composites

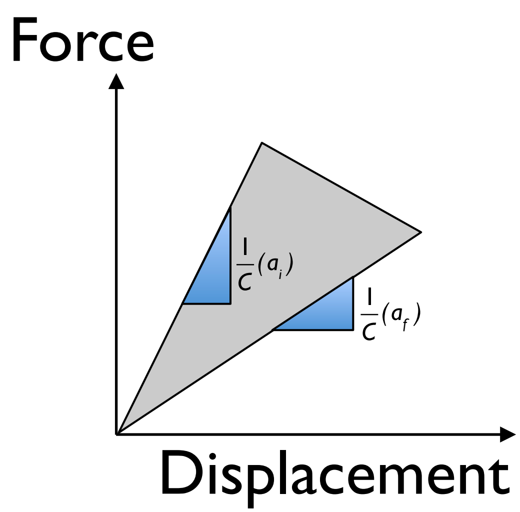
- A.A. Griffith: Application of classical elasticity concepts leads to infinite crack-tip stresses (due to infinitesimally small area of crack tip).

- Most things inherently contain cracks (e.g., buildings, roads, rocks, people..)
  - So, we should immediately fall apart according to classical elasticity…

- Griffith's alternative was to therefore use an energy-based principle:
  Consider a cracked body whose crack undergoes an extension; The resulting decrease in <u>strain energy, U,</u> must equal the increase in surface energy, S, due to the crack extension:



$$\frac{dU}{da} = \frac{dS}{da} = G_c$$

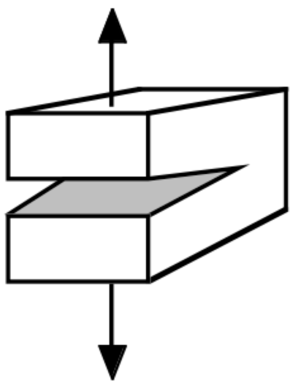


$$G_c = \frac{P^2}{2b}\frac{dC}{da}$$

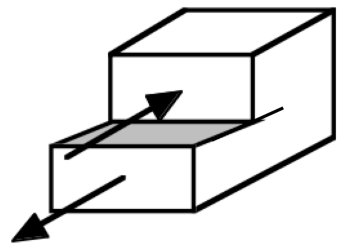
Modes of Fracture

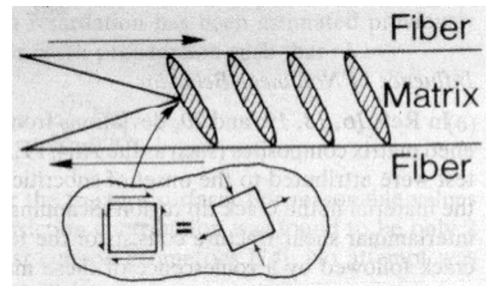
- Irwin pointed out the three possible modes of fracture…

Mode I: Loading normal to crack plane

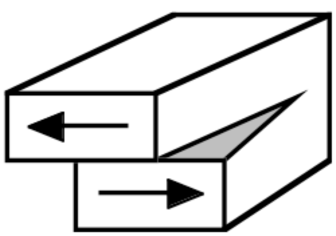


Mode II: Loading along crack plane and perpendicular to crack front

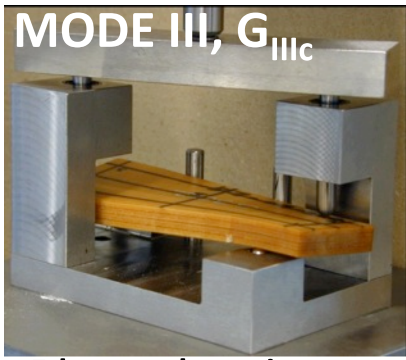




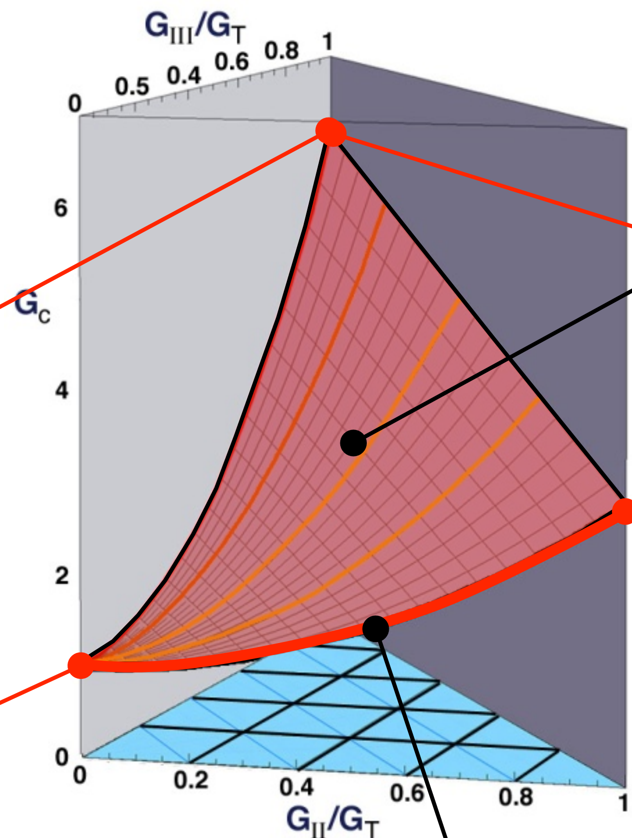
Mode III: Loading along crack plane and parallel to crack front

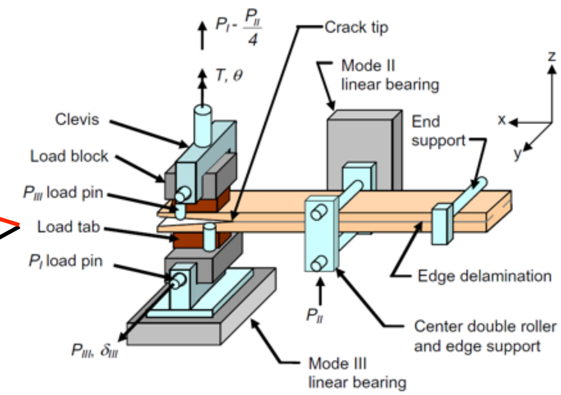


Characterizing Fracture Using Test Coupons

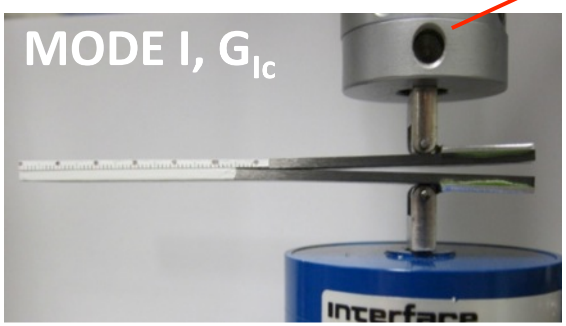


Edge-crack torsion test
(Lee, 1993)

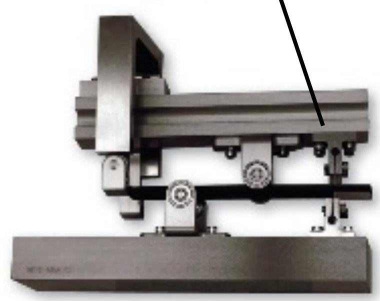




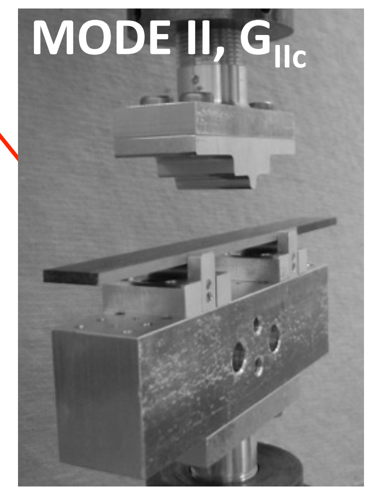
Shear-torsion-bending test
(Davidson, 2011)



Double cantilever beam test
(Russell, 1982)



Mixed-mode bending test
(Reeder, 1990)



End-notched flexure test
(Street, 1983)

Computational Analysis – Virtual Crack Closure Technique

Irwin's contention: Energy required to extend a crack by a small amount is equivalent to the work done Needed to close the crack to its original length.

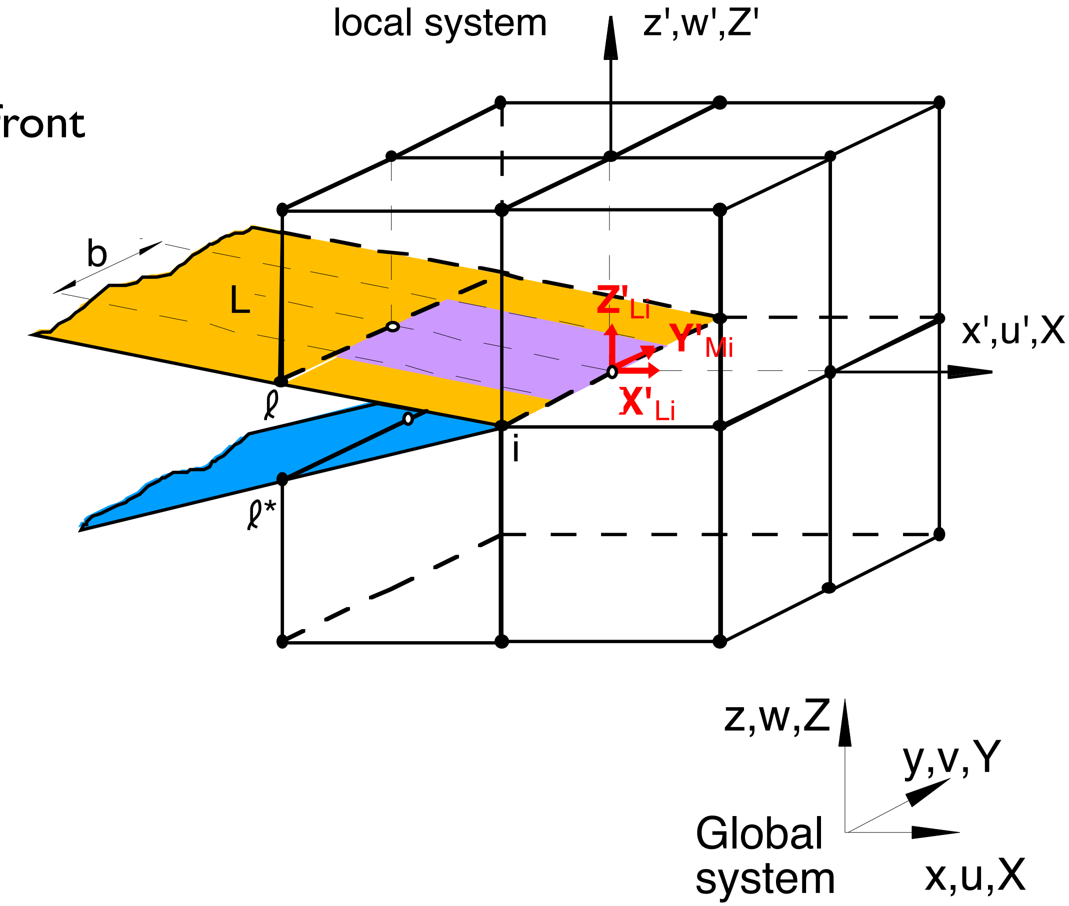
- Two and three-dimensional analysis
- Nonlinear analysis
- Arbitrarily shaped delamination front
- No initiation

$$G_{\mathrm{I}} = \frac{1}{2\Delta ab} \cdot Z'_{\mathrm{Li}} \cdot \left(w'_{\mathrm{L}\ell} - w'_{\mathrm{L}\ell^*}\right)$$

$$G_{\mathrm{II}} = \frac{1}{2\Delta ab} \cdot X'_{\mathrm{Li}} \cdot \left(u'_{\mathrm{L}\ell} - u'_{\mathrm{L}\ell^*}\right)$$

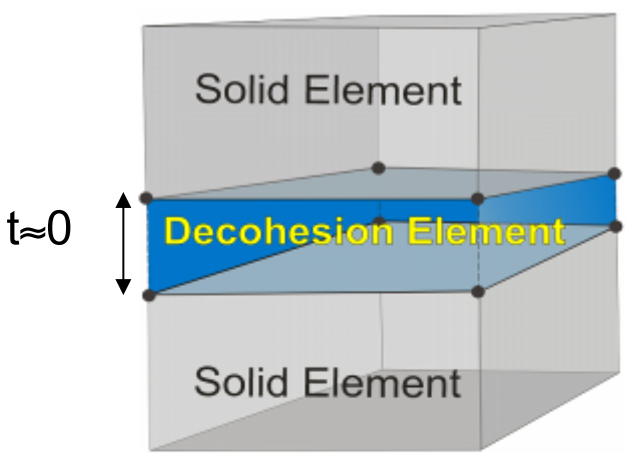
$$G_{\mathrm{III}} = \frac{1}{2\Delta ab} \cdot Y'_{\mathrm{Li}} \cdot \left(v'_{\mathrm{L}\ell} - v'_{\mathrm{L}\ell^*}\right)$$

$$G_T = G_I + G_{II} + G_{III}$$

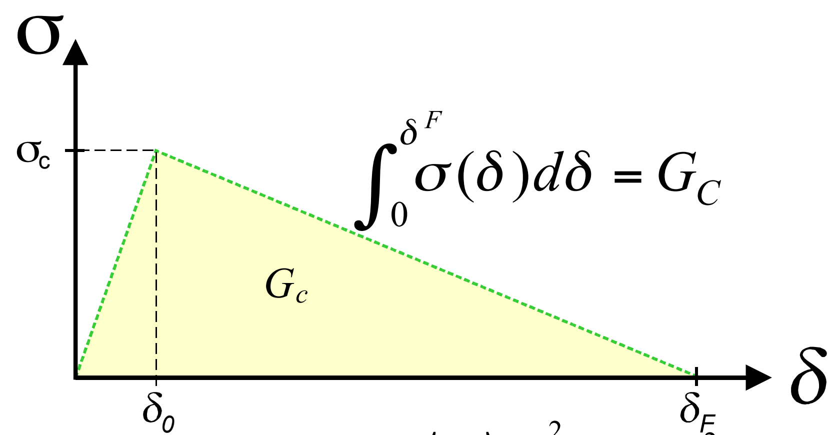


Computational Analysis – Cohesive Zone Method

- Two and three-dimensional analysis
- Nonlinear analysis
- Arbitrarily shaped delamination front
- Initiation possible

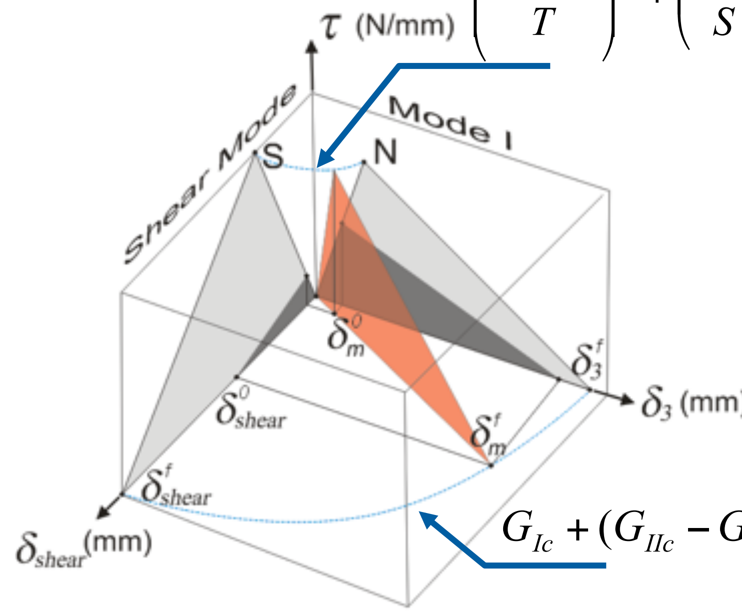


Bilinear Traction-Displacement Law



Mixed-Mode Fracture

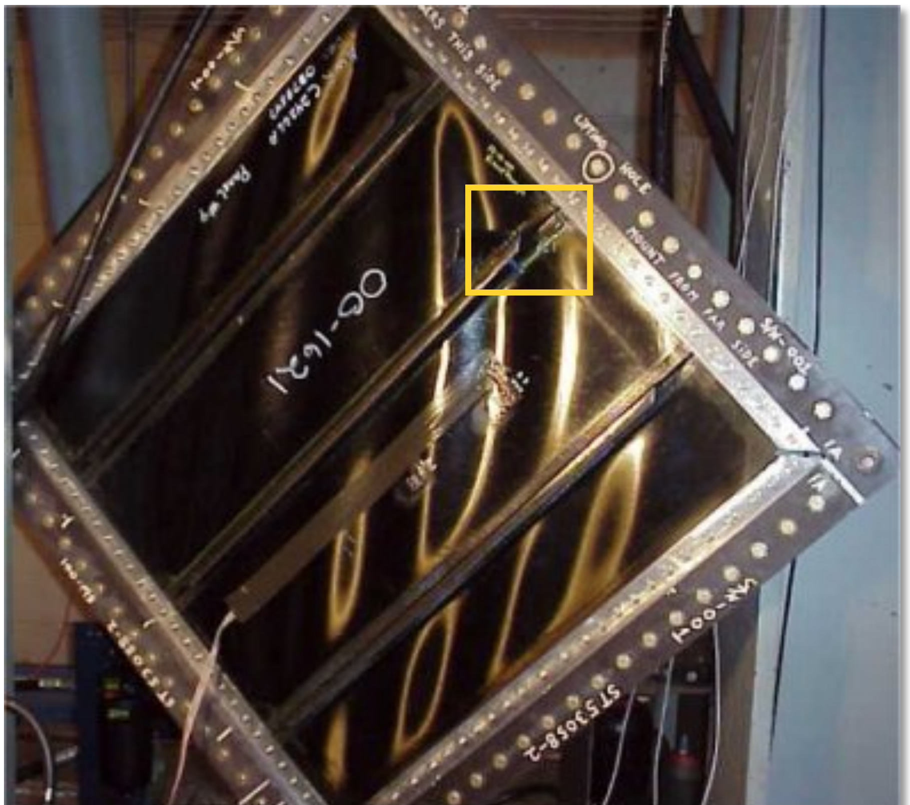
$$\left(\frac{\langle \sigma_z \rangle_+}{T}\right)^2 + \left(\frac{\tau_{xz}}{S}\right)^2 + \left(\frac{\tau_{yz}}{S}\right)^2 = 1$$



$$G_{Ic} + (G_{IIc} - G_{Ic})\left(\frac{G_{II}}{G_I + G_{II}}\right)^{\eta}$$

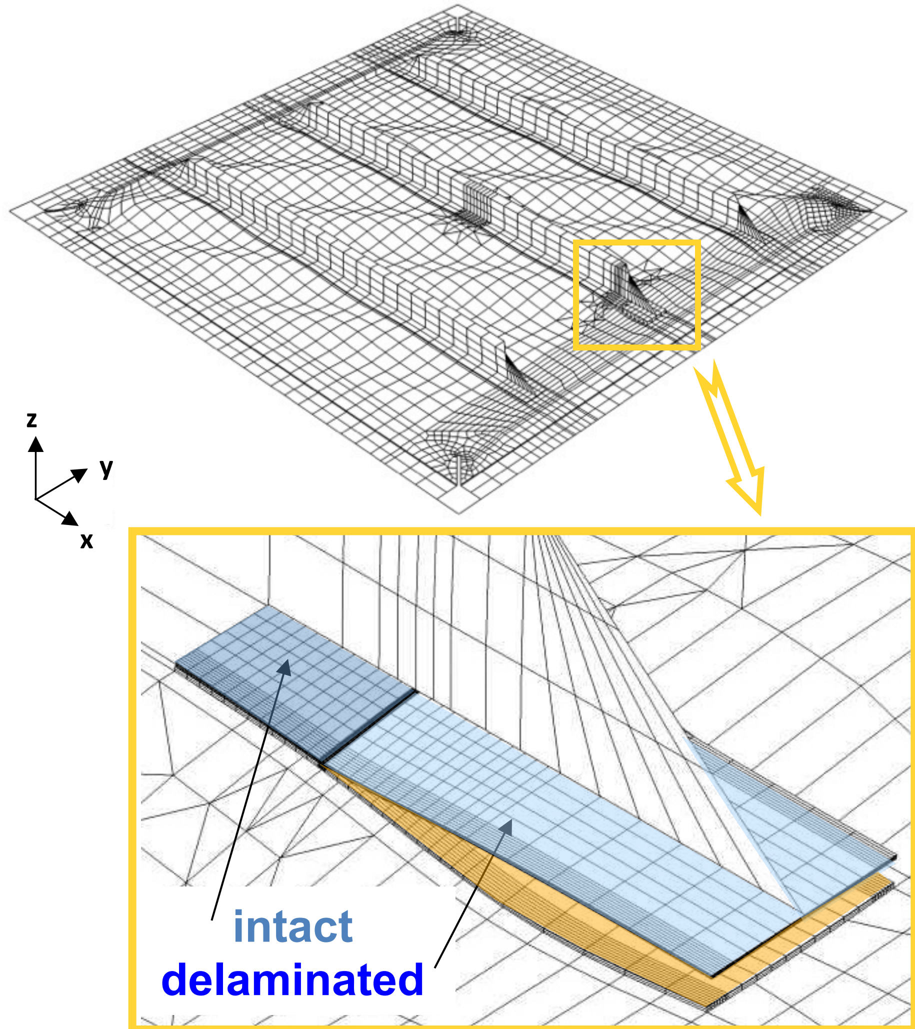
Computational Simulation of a Structural Element

- Element section Test (building block)



Application of VCCT to finite element analysis to predict crack growth

- Global Shell and Local 3D Model



Fracture Mechanics To Streamline the Building Block?

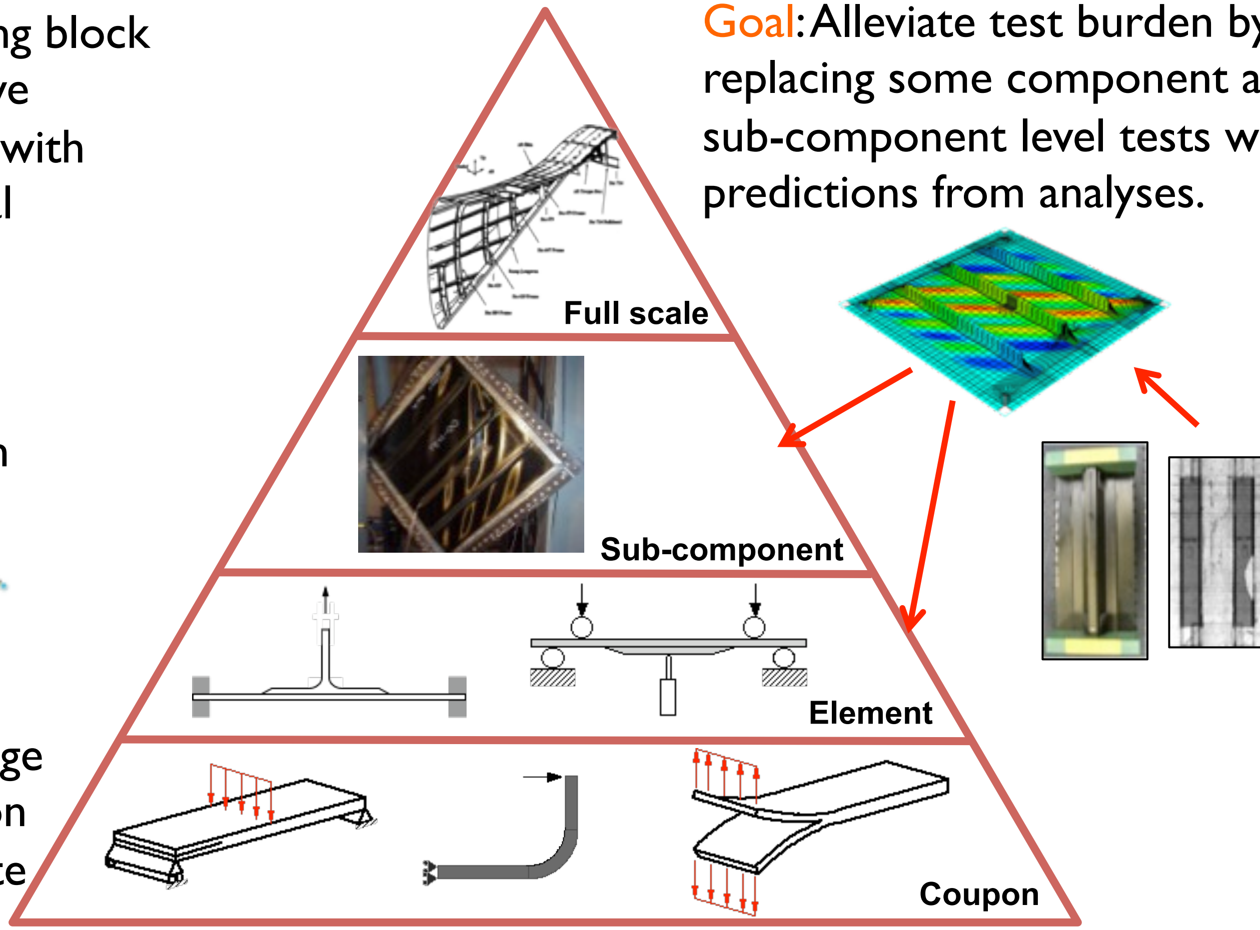
Motivation: Current building block approach requires extensive testing. Reduction of tests with analyses requires additional understanding of:

- Damage initiation
- Damage propagation
- Failure mode interaction

New Approach:

- Failure criteria for damage initiation and propagation
- Analysis tools to simulate failure process
- <u>Validation tests</u>
- Coupon tests

Goal: Alleviate test burden by replacing some component and sub-component level tests with predictions from analyses.



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Summary Thoughts

Why Care About Fracture In Composite Laminates?

- Many different types
- Things aren't necessarily what they appear to be
- Initiation and growth difficult to detect
- Knowledge can affect design/certification philosophies

What Remains To Be Accomplished?

- Inspection Methodologies / Visualization Technologies
- Prediction of Fracture Initiation
- Robust/general computational methods