FACE SHEET/CORE DISBONDING IN SANDWICH COMPOSITE COMPONENTS: *A ROAD MAP TO STANDARDIZATION*

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Overview

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- Background
- Road map
- Detailed problem description
- Fracture mechanics approach
- Development of a test method for fracture toughness testing
  - Coupon test standard development
  - Single Cantilever Beam (SCB) specimen
  - International test round robin
- Finite element modeling
  - Analysis of a panel with circular disbond subjected to internal pressure
  - Analysis development
- Closing remarks

BACKGROUND

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- **Problem**
  - **In-service component failures associated with disbonding in unvented honeycomb core sandwich**
  - **Degradation due to disbonding affects operational safety**
  - **Failures may discourage use of composites in 'future' vehicles**
  - **Methods for assessing propensity of sandwich structures to disbonding not fully matured, accepted and documented**
  - **Methods development is currently being discussed within the Disbond/Delamination Task Group in CMH-17**

Space (X-33)

Detail of flaw

Marine

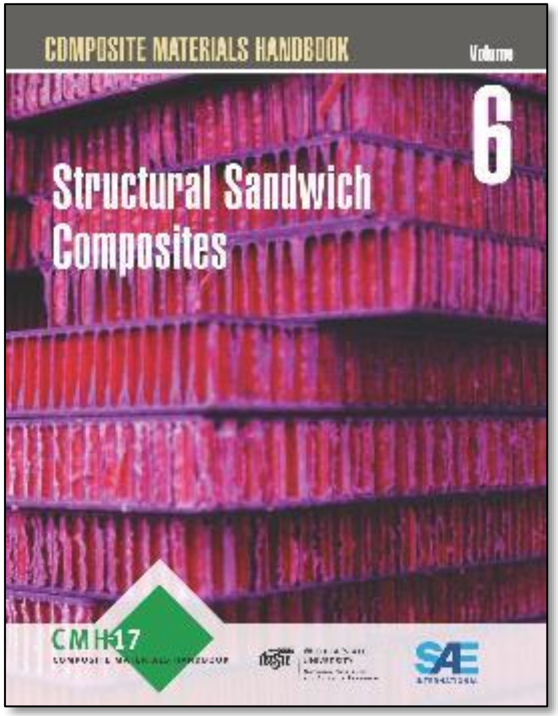
Fracture test*

Aviation*

*Focus of this presentation

ROAD MAP

- **Methods development within the Disbond/Delamination Task Group in Composite Materials Handbook CMH-17**
- **Current FAA initiative on Continuous Operational Safety (COS)**
- **Objective**
  - Develop a methodology for damage tolerance assessment of sandwich structure
  - Formalize research performed for X-33 and A-310 failures
- **Approach**
  - Coupon test standard development
  - Analysis development
  - Panel testing for analysis validation
  - Publication
    - ASTM D30 fracture toughness standards
    - CMH-17 Vol. 6 best practices, guidelines and case studies



*Focus of this presentation

GROUND-AIR-GROUND CYCLE

Detailed Problem Description

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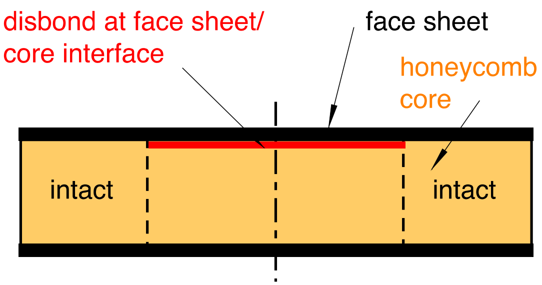
- **Pressure difference between the inside and outside of unvented sandwich structures**
  - Caused by alternating ambient pressure and temperature changes
  - Results in significant deformations and core volume increase
  - Volume increase results in pressure decrease based on the ideal gas law

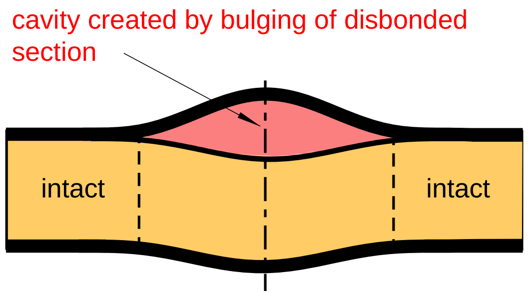
$$p\,V = n\,R\,T$$

- **Initial disbonds between face sheets and core increase the peeling effect**
- **Peel force causes damage propagation at every flight cycle**
- **Beyond critical damage size rapid propagation occurred, demonstrated by test**

- **Initial configuration at ground elevation**



- **Deformed configuration at cruising altitude**



Fracture Mechanics Approach

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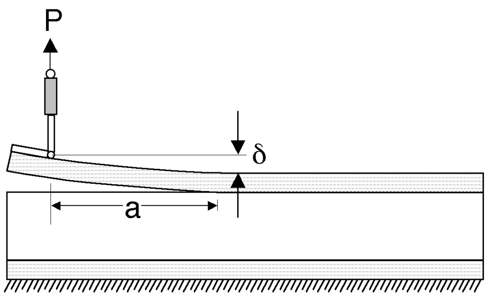
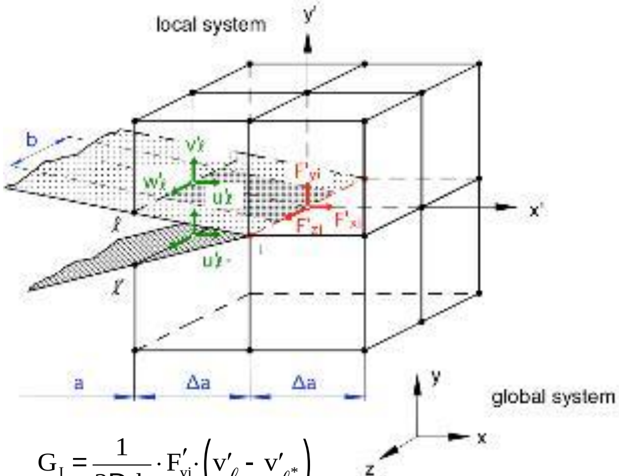
- **Coupon test standard development**
  - Characterize properties of facesheet/core interface
  - Measure fracture toughness G_c
  - Single cantilever beam (SCB) type configuration was identified as the most appropriate test
- **Analysis development**
  - Compute the energy release rate along the disbond front
  - Use the Virtual Crack Closure Technique (VCCT) based on the results obtained from a finite element analysis
    - Provides mode separation
    - Transformation of nodal forces and displacement into deformed system for non-linear analysis
    - Computation along an arbitrarily shaped delamination path is possible
- **Propagation is predicted to occur once the computed value exceeds the measured fracture toughness**

- **SCB test schematic**



- **VCCT**



$$G_I = \frac{1}{2Dab} \cdot F'_{yi} \cdot \left(v'_\ell - v'_{\ell^*}\right)$$

$$G_{II} = \frac{1}{2Dab} \cdot F'_{xi} \cdot \left(u'_\ell - u'_{\ell^*}\right)$$

$$G_{III} = \frac{1}{2Dab} \cdot F'_{zi} \cdot \left(w'_\ell - w'_{\ell^*}\right)$$

COUPON TEST STANDARD DEVELOPMENT - 1 OF 2

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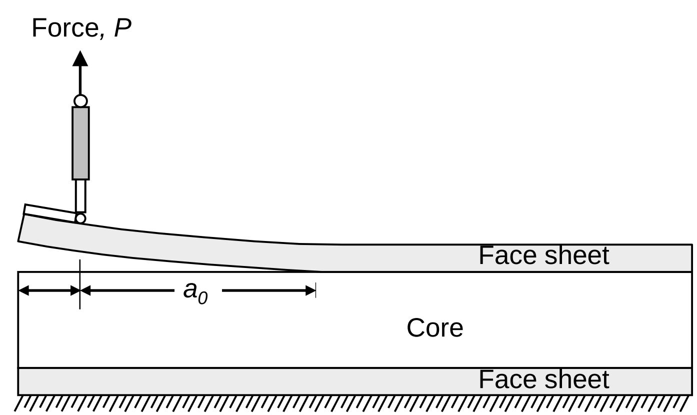
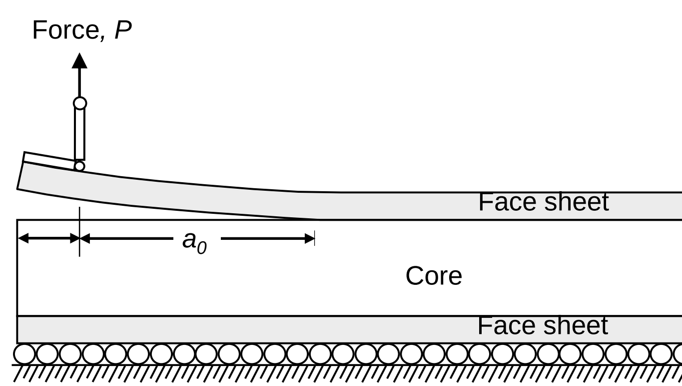
- **Test standard development in ASTM committee D30 (WK 47682)**
- **Characterize properties of face sheet/core interface**
- **Mode-I disbond driving force assumed most critical for fracture control**
- **Measure fracture toughness G_c**
- **Single cantilever beam (SCB) type configuration was identified as the most appropriate test**
  - **Starter crack**
    - Teflon
    - Saw cut
  - **Simple loading fixture**
    - Loading offset fixture
    - Translatable carriage fixture
  - **Loading at disbond front independent of disbond length**
  - **Disbonding along or near the face sheet/core interface (no kinking into the core)**
  - **Disbond toughness can be calculated by using a compliance calibration procedure for data reduction**

Loading offset fixture

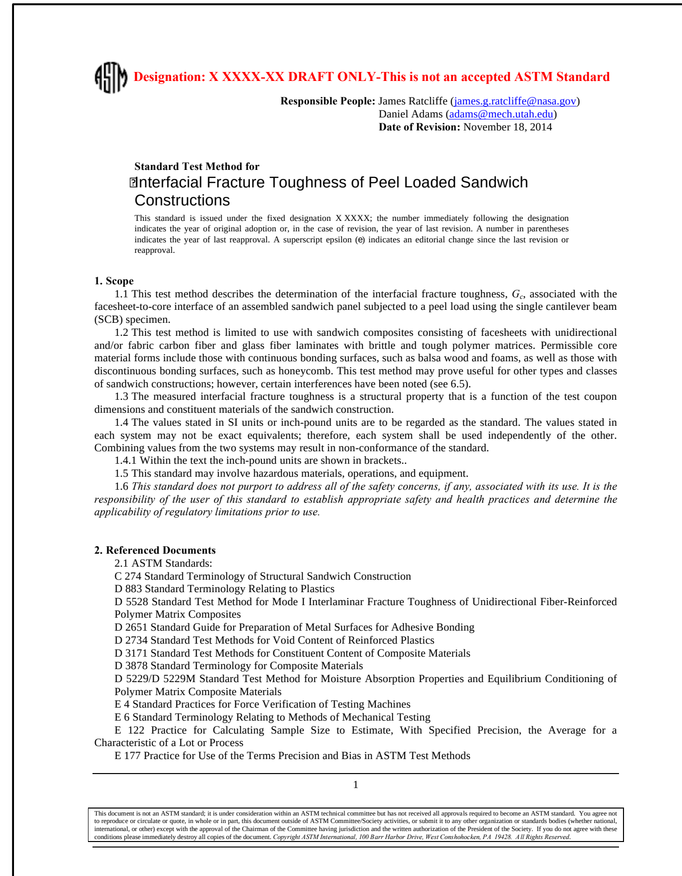


Translatable carriage fixture



COUPON TEST STANDARD DEVELOPMENT - 2 OF 2

- **ASTM Committee D30 (WK 47682)**
- **Standardized test method for peel-dominated interfacial fracture toughness of sandwich constructions (draft)***
  - Main partners University of Utah and NASA Langley
  - ASTM draft¶ includes procedure to determine the SCB specimen dimensions (specimen length, face sheet thickness, initial disbond length)
  - Current round robin activity involves seven research laboratories in the US and Europe



Designation: X XXXX-XX DRAFT ONLY-This is not an accepted ASTM Standard

Responsible People: James Ratcliffe (james.g.ratcliffe@nasa.gov)
Daniel Adams (adams@mech.utah.edu)
Date of Revision: November 18, 2014

Standard Test Method for
Interfacial Fracture Toughness of Peel Loaded Sandwich Constructions

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method describes the determination of the interfacial fracture toughness, G_c, associated with the facesheet-to-core interface of an assembled sandwich panel subjected to a peel load using the single cantilever beam (SCB) specimen.

1.2 This test method is limited to use with sandwich composites consisting of facesheets with unidirectional and/or fabric carbon fiber and glass fiber laminates with brittle and tough polymer matrices. Permissible core material forms include those with continuous bonding surfaces, such as balsa wood and foams, as well as those with discontinuous bonding surfaces, such as honeycomb. This test method may prove useful for other types and classes of sandwich constructions; however, certain interferences have been noted (see 6.5).

1.3 The measured interfacial fracture toughness is a structural property that is a function of the test coupon dimensions and constituent materials of the sandwich construction.

1.4 The values stated in SI units or inch-pound units are to be regarded as the standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance of the standard.

1.4.1 Within the text the inch-pound units are shown in brackets..

1.5 This standard may involve hazardous materials, operations, and equipment.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:
C 274 Standard Terminology of Structural Sandwich Construction
D 883 Standard Terminology Relating to Plastics
D 5528 Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites
D 2651 Standard Guide for Preparation of Metal Surfaces for Adhesive Bonding
D 2734 Standard Test Methods for Void Content of Reinforced Plastics
D 3171 Standard Test Methods for Constituent Content of Composite Materials
D 3878 Standard Terminology for Composite Materials
D 5229/D 5229M Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials
E 4 Standard Practices for Force Verification of Testing Machines
E 6 Standard Terminology Relating to Methods of Mechanical Testing
E 122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process
E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

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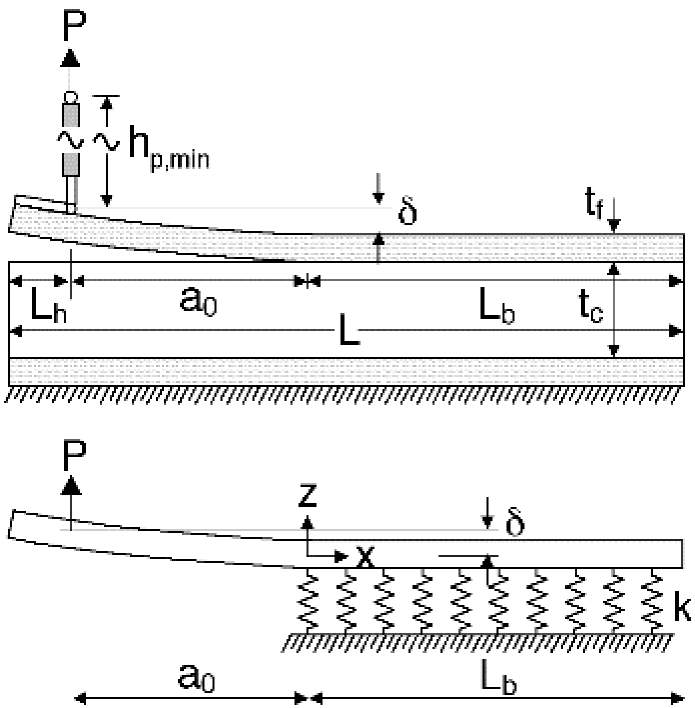
*D. Adams and B. Kuramoto, "Development and Evaluation of Fracture Mechanics Test Methods for Sandwich Composites," *JAMS 2012 Technical Review*, 2012.
*M. Rinker, J. Ratcliffe, D. Adams, and R. Krueger, "Characterizing Facesheet/Core Disbonding in Honeycomb," NASA/CR-2013-217959, 2013.

SINGLE CANTILEVER BEAM (SCB) TEST SPECIMEN

- **Beam sandwich laminate with pre-implanted starter disbond (Teflon, saw cut)**
- **Specimen dimensions sized to match known compliance solution and ensure proper specimen behavior***
- **Test configured to yield mode-I dominated disbond driving force**



SCB Specimen Parameter	Limitation
Intact portion of specimen	$L_b \ge L_{b,min} = 2.7\left[\frac{t_c t_f^3 E_f}{3E_c}\right]^{\frac{1}{4}}$
Initial disbond length (bending dominant deformation)	$a_0 \ge a_{min}^{bending} \approx \sqrt{\frac{30E_f t_f^2}{G_{xz,f}}} - 0.59L_{b,min}$ $a_0 \ge a_{min}^{compliance} = L_{b,min}$
Final disbond length	$a_{max} \ge a_0 + a_{prop}$
Face sheet thickness for small deformations	$t_f \ge t_f^{small\,disp} = \left[\frac{a_{max}}{\left(\frac{3a_{max}^2 E_f}{200G_c}\right)^{\frac{1}{4}} - \left(\frac{t_c E_f}{3E_c}\right)^{\frac{1}{4}}}\right]^{\frac{4}{3}}$
Face sheet thickness to prevent flexural failure of face sheet	$t_f \ge t_f^{strength} \approx \frac{6E_f G_c a_{max}^2}{\sigma_c^2}\left[a_{max} + \left(\frac{t_c (t_f^{small\,disp})^3 E_f}{3E_c}\right)^{\frac{1}{4}}\right]^{-2}$
Specimen length	$L \ge L_{min} = L_{hinge} + a_{max} + L_{b,min}$
Load application offset to ensure vertical load application	$h_p \ge h_{p,min} \approx 1.06a_{max}$

*J. G. Ratcliffe and J. R. Reeder, "Sizing a single cantilever beam specimen for characterizing facesheet-core debonding in sandwich structure," *Journal of Composite Materials,* vol. 45, pp. 2669-2684, 2011.

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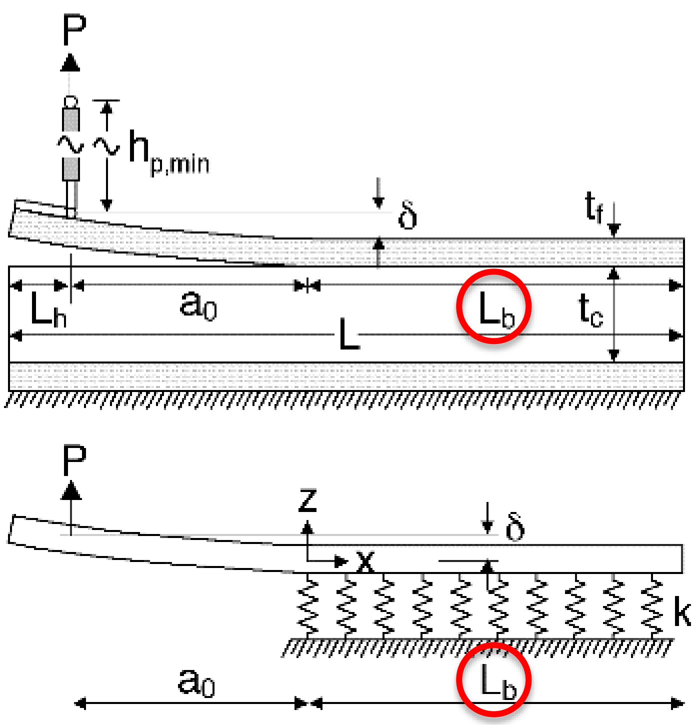

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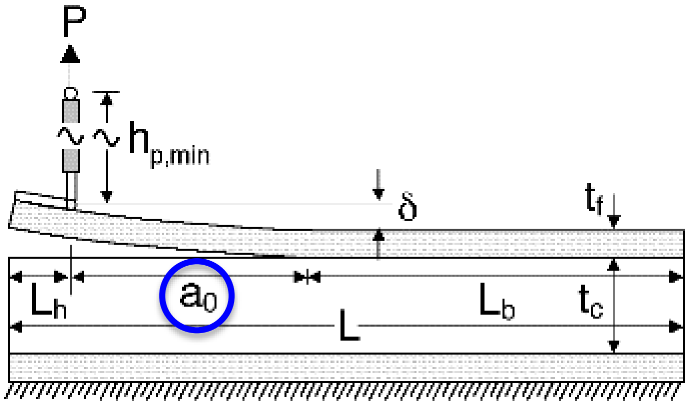

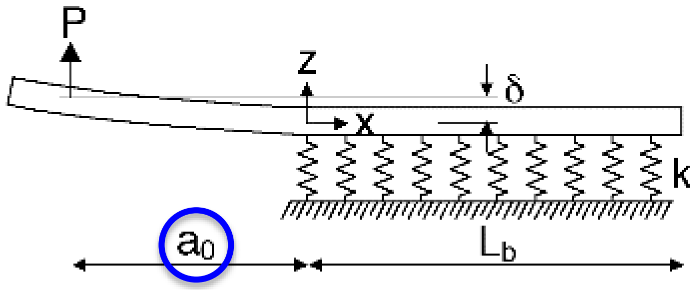

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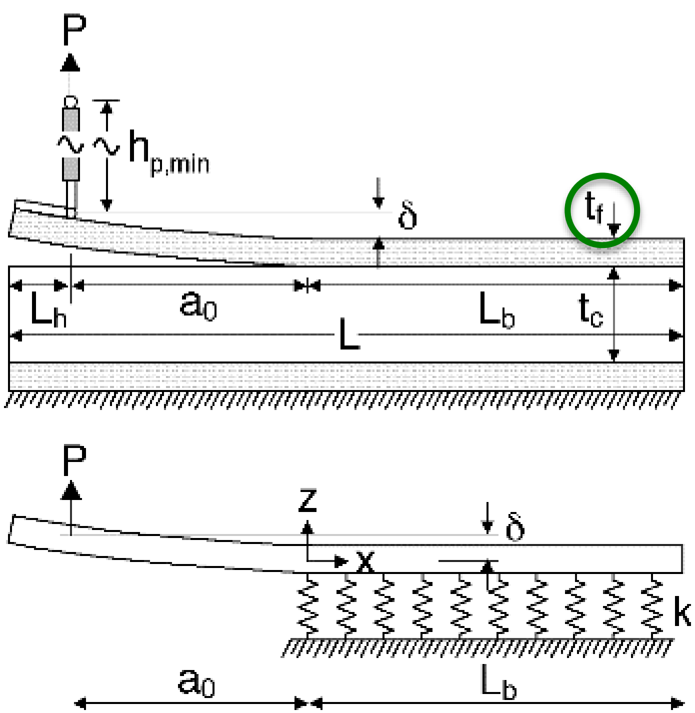

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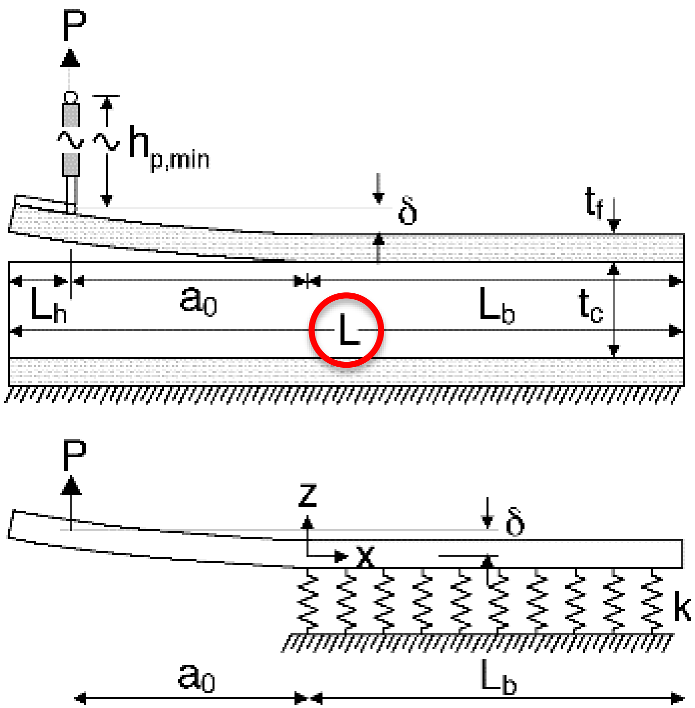

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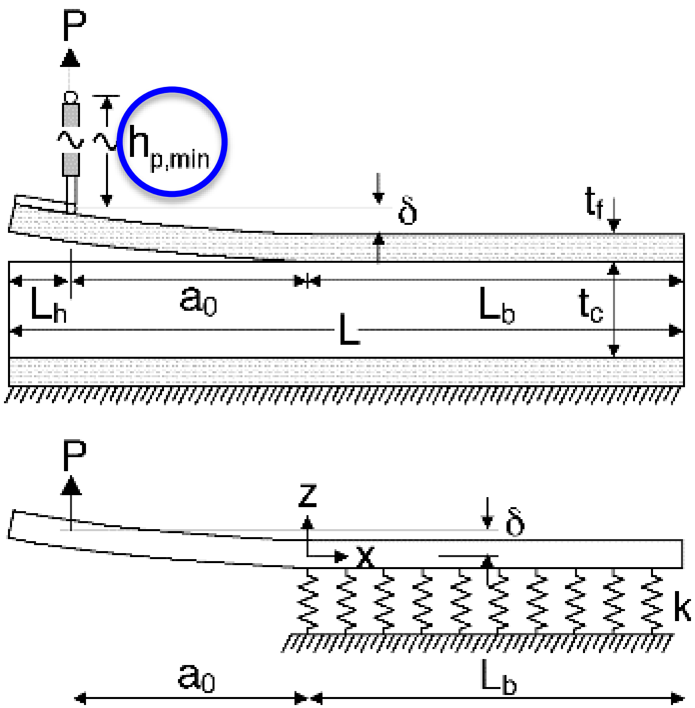

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INTERFACIAL FRACTURE TOUGHNESS TEST PROCEDURE

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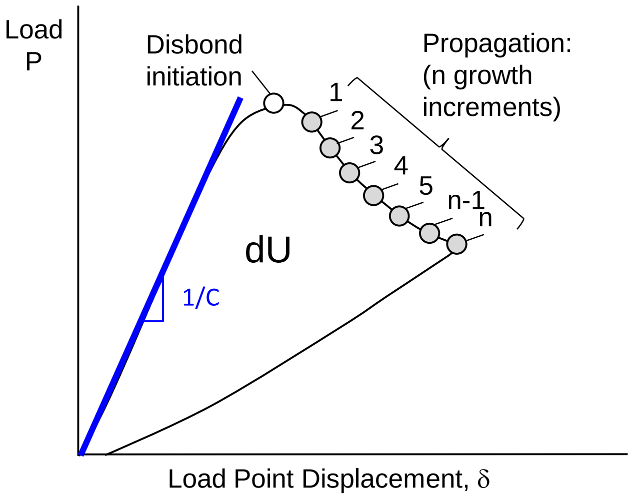
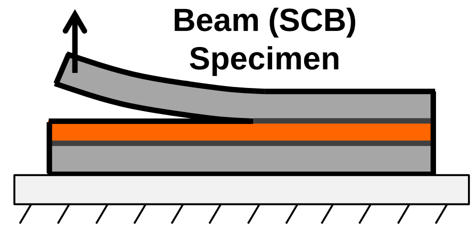
1. **Load specimen (stroke control) and unload after required amount of disbonding**
2. **Record load/displacement response**
3. **Document changes in specimen compliance with disbond growth**
4. **Compute interfacial fracture toughness, G_c (initiation and propagation values)**

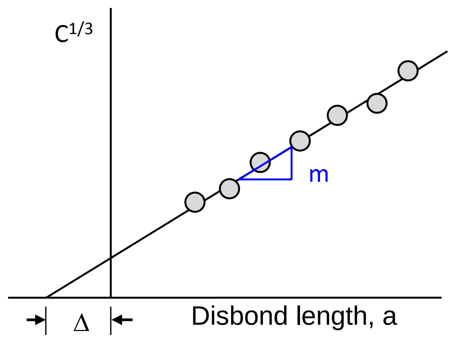


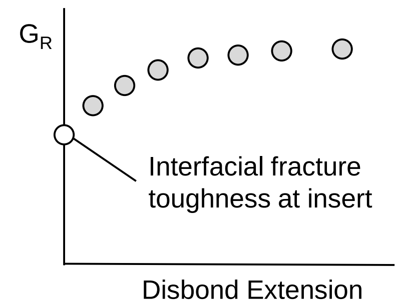
Single Cantilever Beam (SCB) Specimen



$$C = \frac{\delta}{P}, \quad C(a) = m^3 (a + \Delta)^3$$

$$G_C = \frac{P_C^2}{2b}\frac{dC}{da}$$





SCB TEST APPARATUS
Overview

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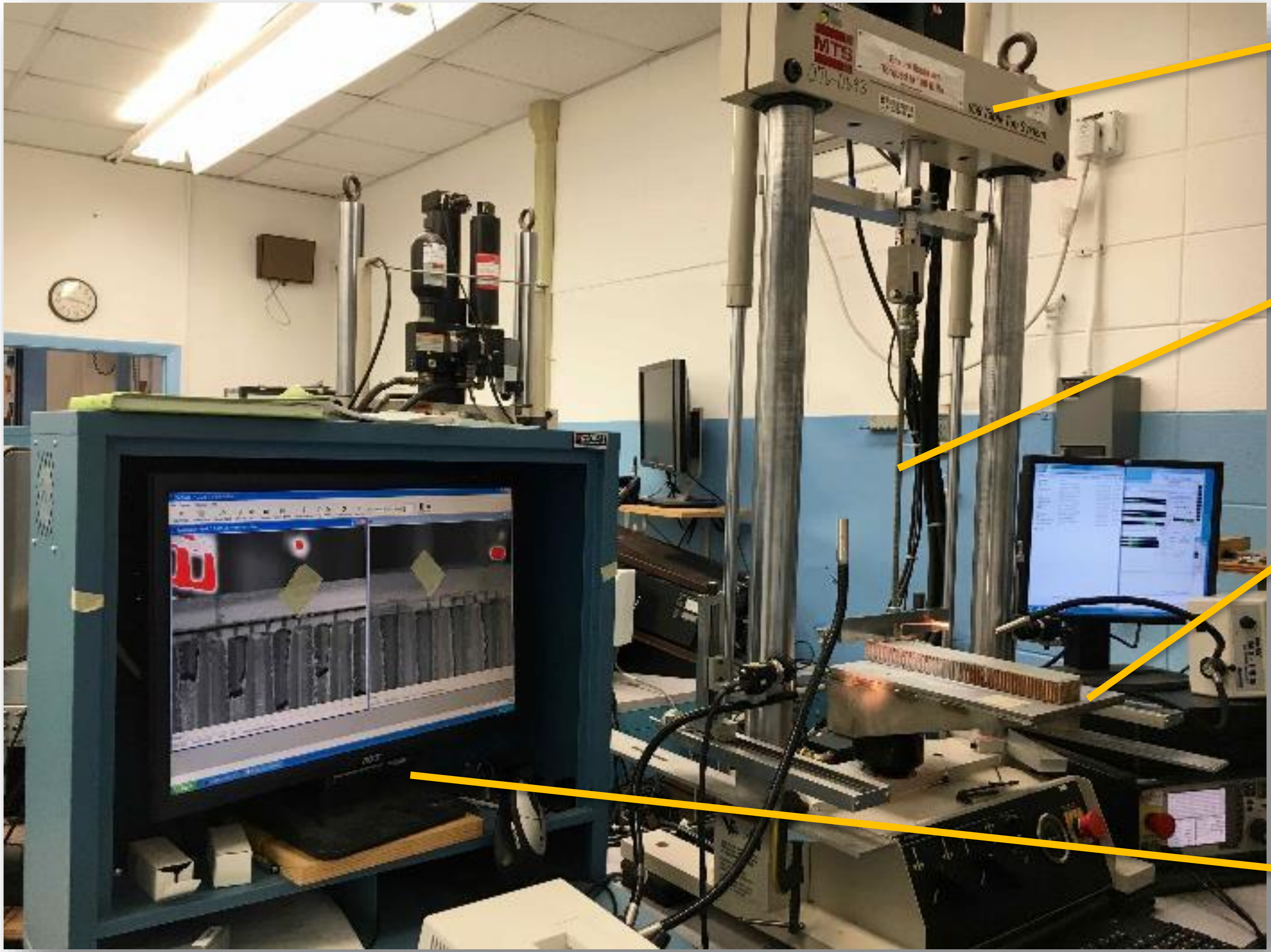


Load frame

Test fixture

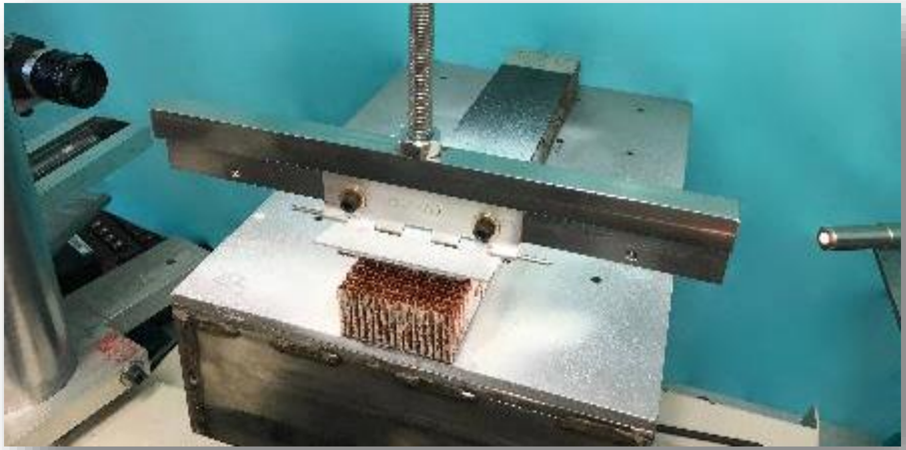
SCB Specimen

Disbond Tracking station

SCB TEST APPARATUS
Detailed Views

- **Offest test fixture**

- **Base plate**



- **Closeup of baseline test**

SCB TEST ROUND ROBIN
Test configuration

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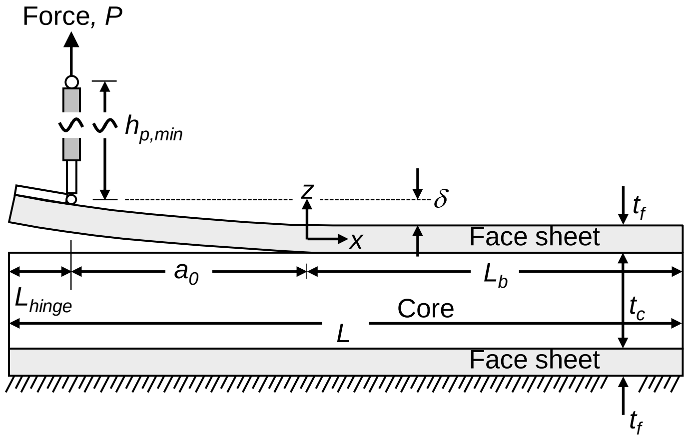
SCB specimen*

Baseline Specimen parameters	
a_0	12.7 mm (0.5”)
width, b	50.8 mm (2.0”)
$h_{p,min}$	500 mm (20”)
L	305 mm (12”)
L_{hinge}	25.4 mm (1.0”)
t_c	25.4 mm (1.0”)
t_f	0.772 mm (0.0304”)
Face sheet	T650/5320 PW Layup (4 plies): $[45/0]_s$ 0-dir along specimen length
Core	HRH-10: Cell size = 3.2 mm (0.125”) Density = 3lb/ft^3 (48kg/m^3)

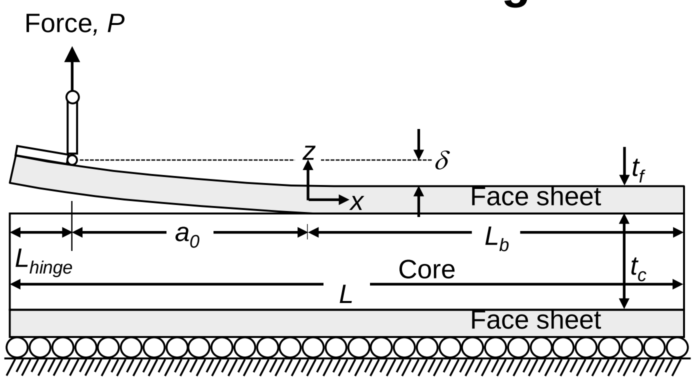
*manufactured at NIAR, Wichita State University, Kansas, USA

Two loading fixture types considered to force a peel dominated behavior

Loading offset fixture



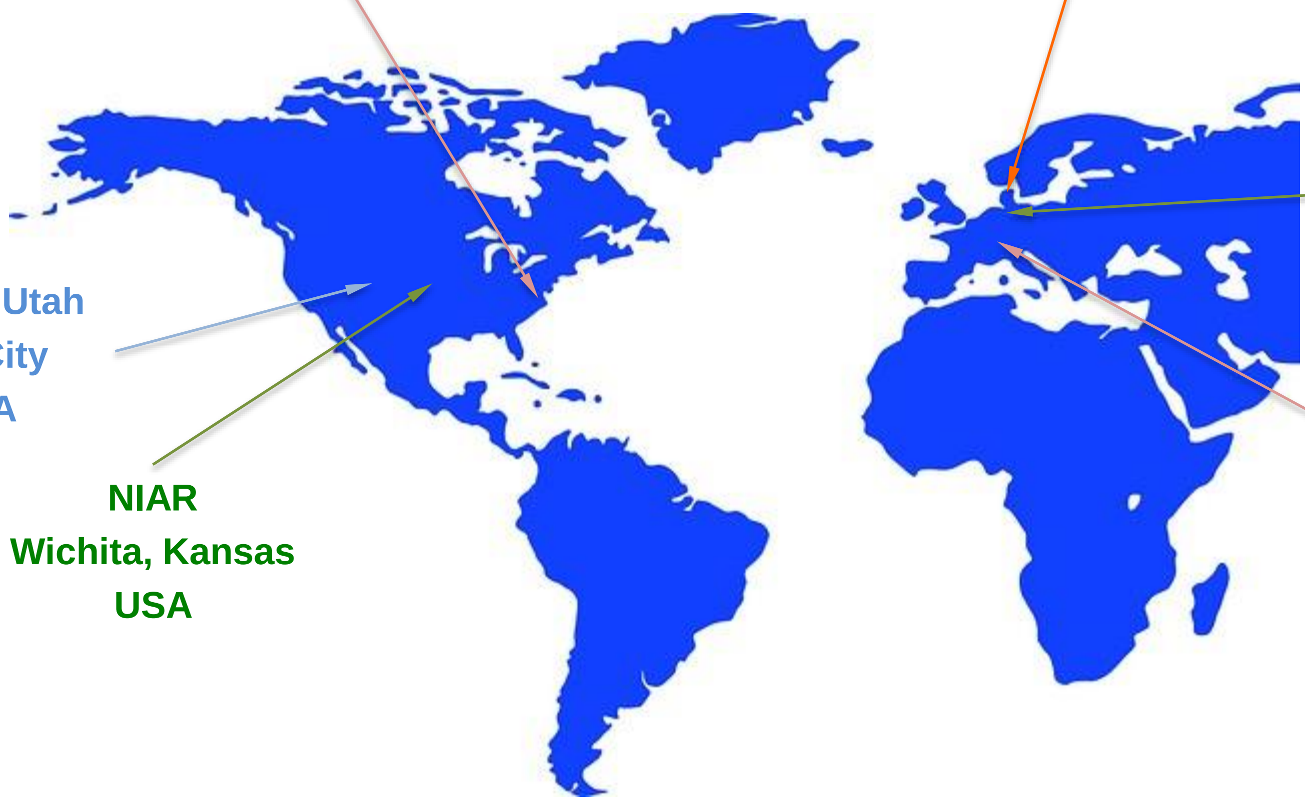
Translatable carriage fixture



SCB TEST ROUND ROBIN

International Partners

National Institute of Aerospace



NASA Langley,
Hampton, Virginia, USA

DTU, Copenhagen, Denmark

Airbus, Hamburg
FhG, Halle
Germany

University of Utah
Salt Lake City
Utah, USA

DuPont, Geneva
Switzerland

NIAR
Wichita, Kansas
USA

SCB TEST ROUND ROBIN

Test Matrix

Lab #	Test protocol	Number of Specimens		Additional Studies						
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed loading (mm/min)	Test Speed unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

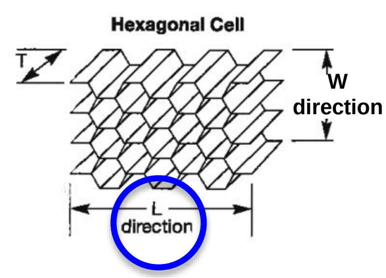
Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

Dimensional Nomenclature

T = Thickness, or cell depth

L = Ribbon direction

W = Long direction, or direction perpendicular to the ribbon



SCB TEST ROUND ROBIN

Test Matrix

NATIONAL INSTITUTE OF AEROSPACE

Lab #	Test protocol	Number of Specimens: Baseline	Number of Specimens: Additional	Additional Studies: L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed: loading (mm/min)	Test Speed: unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

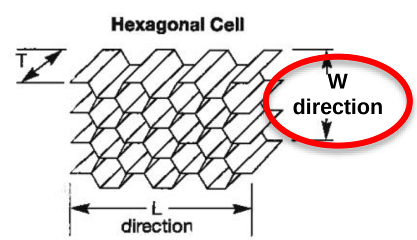
Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

Dimensional Nomenclature

T = Thickness, or cell depth

L = Ribbon direction

W = Long direction, or direction perpendicular to the ribbon



SCB TEST ROUND ROBIN

Test Matrix

Lab #	Test protocol	Number of Specimens		Additional Studies						
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed loading (mm/min)	Test Speed unloading (mm/min)
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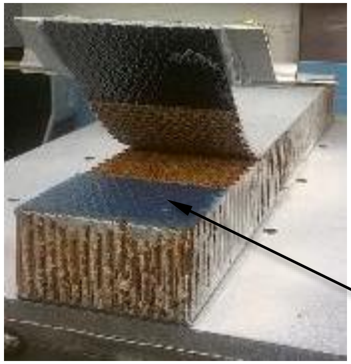
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm



Teflon or saw cut

SCB TEST ROUND ROBIN

Test Matrix

NATIONAL INSTITUTE OF AEROSPACE

Lab #	Test protocol	Number of Specimens		Additional Studies						
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed loading (mm/min)	Test Speed unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

Thin face sheet tested without doubler

Thin face sheet tested with doubler

- **Reduces face sheet damage**
- **Creates unwanted core facture due to shear component**

SCB TEST ROUND ROBIN

Test Matrix

Lab #	Test protocol	Number of Specimens		Additional Studies					Test Speed	
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	loading (mm/min)	unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

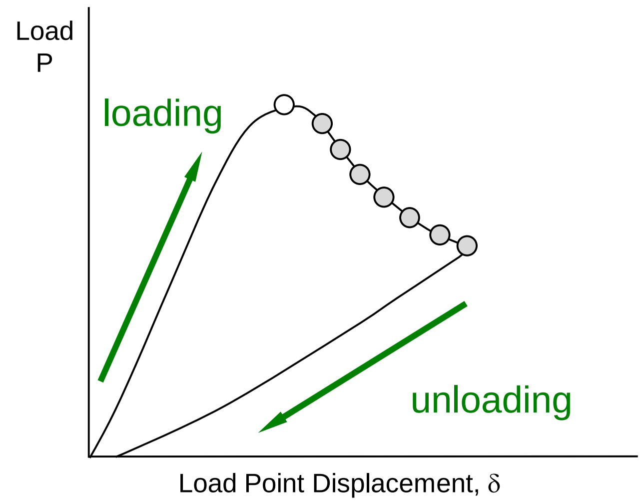
Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

SCB TEST ROUND ROBIN
Test Matrix

National Institute of Aerospace

Lab #	Test protocol	Number of Specimens		Additional Studies					Test Speed	
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	loading (mm/min)	unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm



SCB TEST ROUND ROBIN

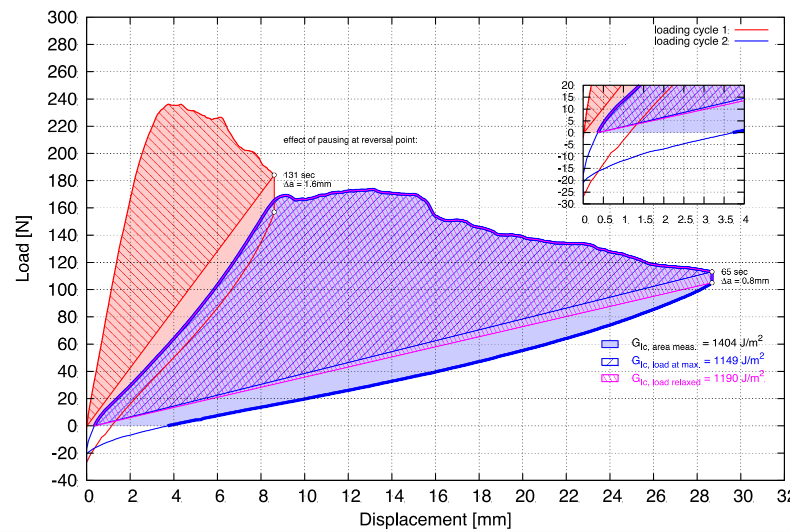
Test Matrix

National Institute of Aerospace

Lab #	Test protocol	Number of Specimens: Baseline	Number of Specimens: Additional	Additional Studies: L/W	Additional Studies: Starter Crack	Additional Studies: Doubler	Additional Studies: Fixture	Additional Studies: Unloading	Test Speed: loading (mm/min)	Test Speed: unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

Will unloading to 0 mm create damage?



FE MODEL OF A PANEL WITH DISBOND – 1 of 4

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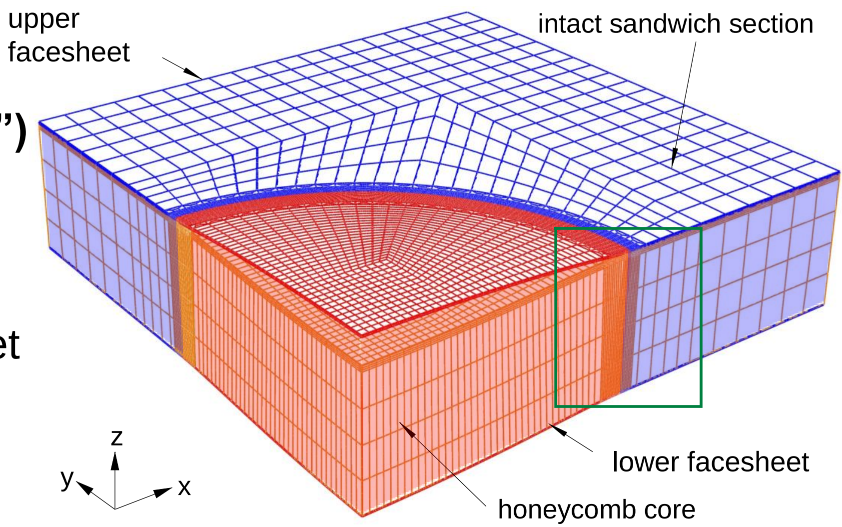
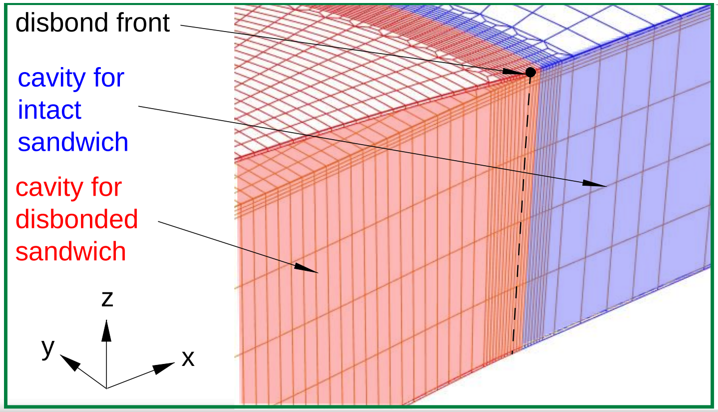
- **A quarter section of a flat panel was modeled**
  - **Circular disbond radius: 152.4 mm (6”)**
  - **Square section side dimension: 304.8 mm (12”)**
  - **Abaqus/Standard® was used (C3D20 element)**
    - Boundary conditions applied at symmetry planes
    - Surface contact used between top facesheet and core in the disbonded section
- **Sandwich properties**
  - **Thin facesheet: 0.772 mm (0.03”)**
    - CYCOM 5320PW plain weave fabric
    - [45/0/90/-45] quasi-isotropic layup
  - **Thick core: 76.5 mm (3.0”)**
    - Hexcel HRH-10® honeycomb
    - NOMEX® paper with 48 kg/m³ (3.0 lb/ft³) density and 3.175 mm (1/8”) cell size
    - Modeled as an orthotropic, homogeneous continuum

3D model of a disbonded flat panel



Detail near disbond front

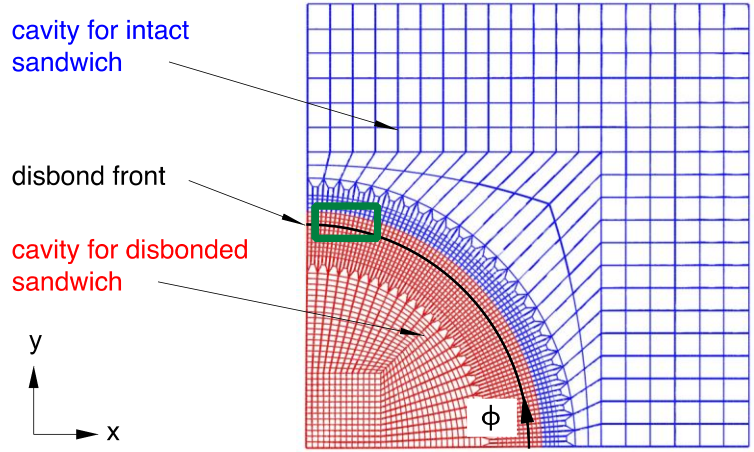


FE MODEL OF A PANEL WITH DISBOND – 2 of 4

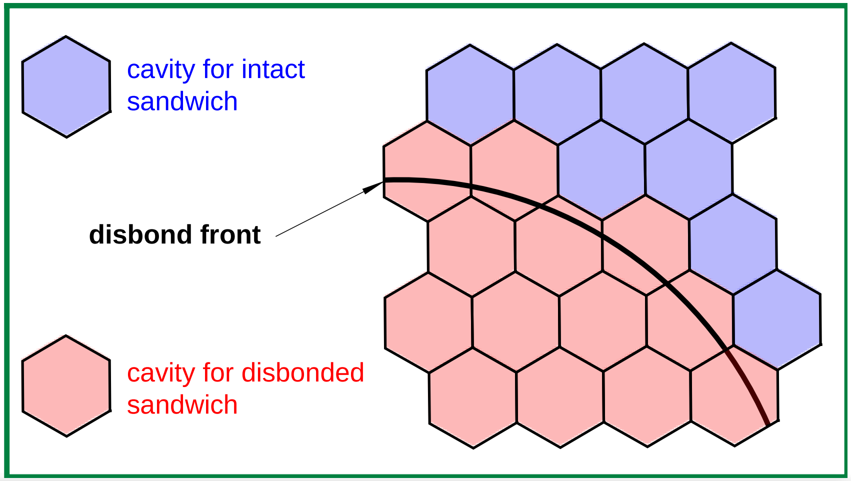
NATIONAL INSTITUTE OF AEROSPACE

- **Pressure deformation coupling was simulated using fluid-filled cavities**
  - **Abaqus/Standard® feature enabled the definition of fluid-filled cavities enclosed by structural elements**
  - **The ideal gas law is solved within each increment until equilibrium is found**
  - **The volume of the fluid cavities was assumed to be equal to that of the entire sandwich core**
  - **Two separate cavities were defined**
    - One cavity was used to simulate the intact part
    - The other cavity included only the disbonded section
    - The disbonded cavity extended by one cell size, 3.175 mm (1/8"), ahead of the disbond front

Top view on disbonded flat panel



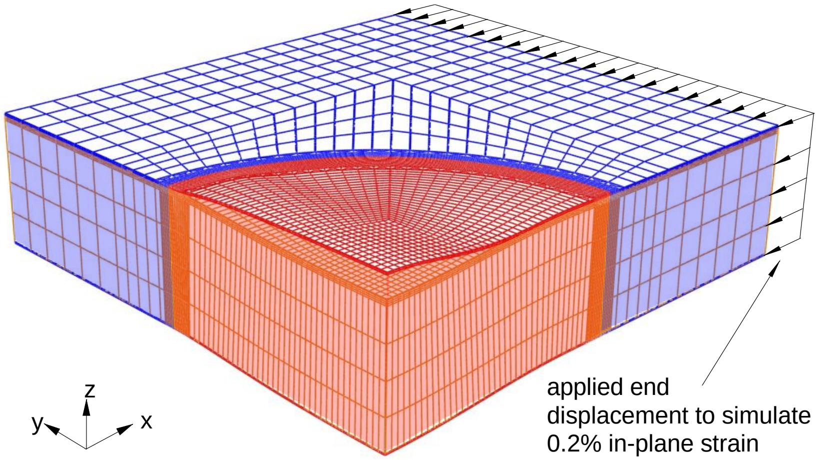
Detail near disbond front



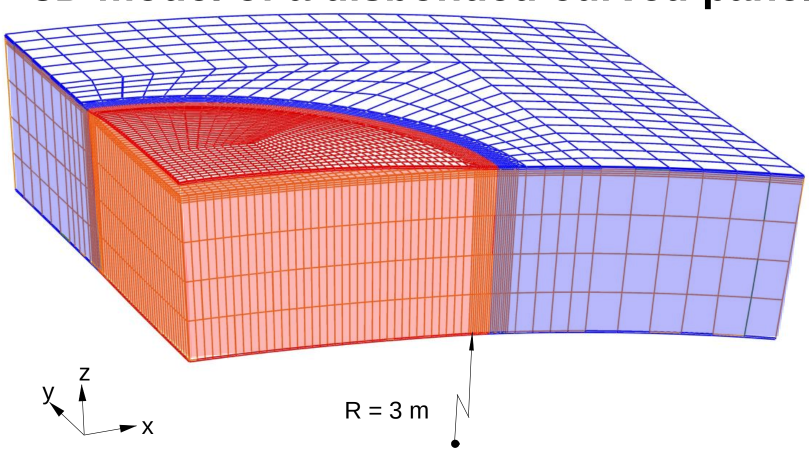
FE MODEL OF A PANEL WITH DISBOND – 3 of 4

- **Model of a flat panel with in-plane loading**
  - **Study the effect of in-plane service load on a flat control surface**
  - **In-plane displacement applied to the model to simulate a 0.2% (2000 με) strain condition during a flight maneuver**
  - **A compressive strain condition was chosen since it was believed that it would aggravate the tendency to disbond**
- **Model of a curved panel**
  - **Honeycomb sandwich constructions may be used for cylindrical fuselage structures**
  - **A 3 m radius (wide body airliner) was chosen for this study**

3D model of a disbonded flat panel



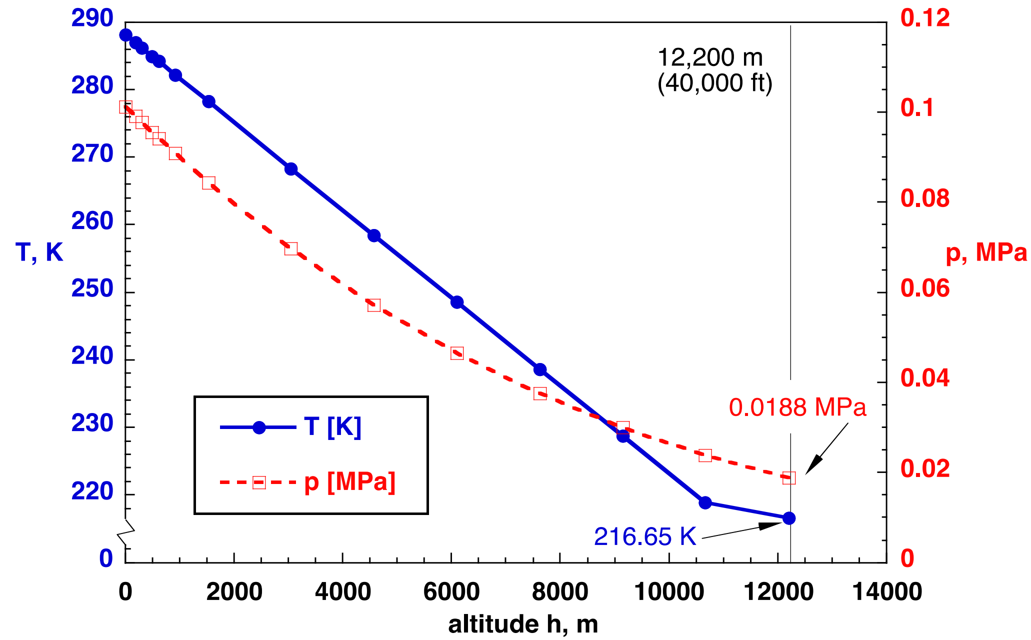
3D model of a disbonded curved panel



FE MODEL OF A PANEL WITH DISBOND – 4 of 4

- Internal pressurization of the disbond
  - Commercial jetliner ascent scenario was considered from 0 to 12,192 m (0 to 40,000 ft)
  - The pressure and temperature values were taken from the International Standard Atmosphere ISO 2533
  - The temperature in the core was defined to be equal to the ambient temperature
  - Pressure and volume inside the cavities were calculated during the analysis
- Additional load conditions
  - 0.2% (2000 με) strain condition only
  - 0.2% (2000 με) strain condition plus GAG cycle

Decrease of temperature and pressure with increasing altitude

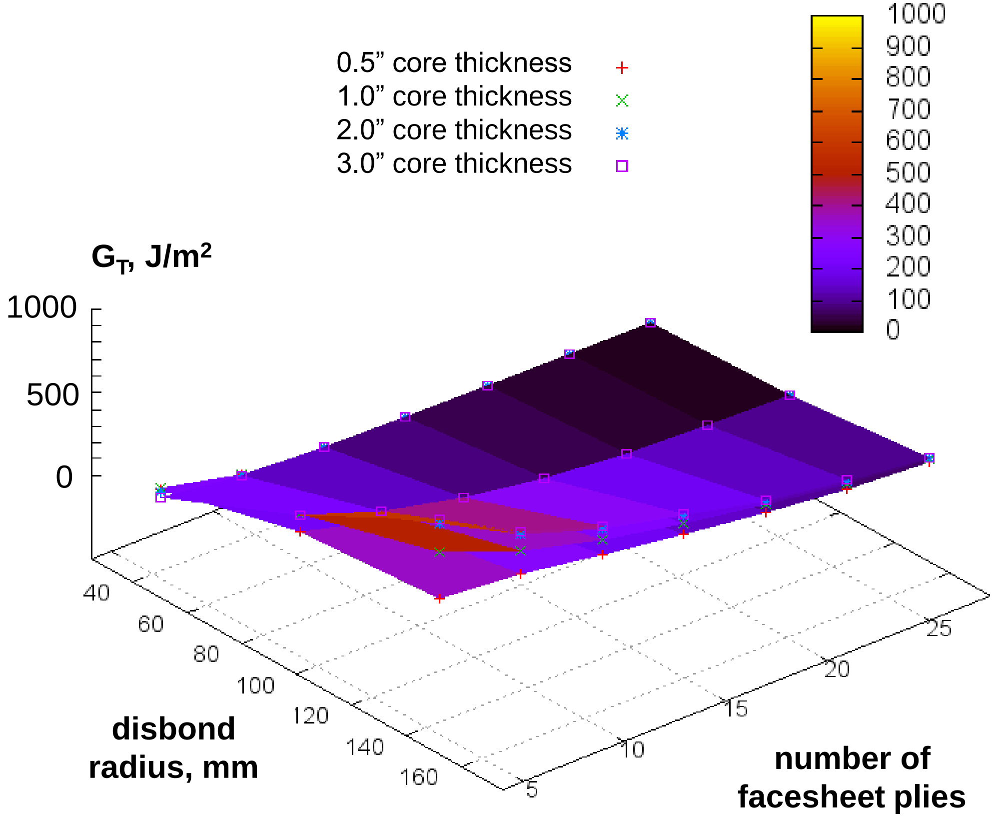


FLAT PANEL SUBJECTED TO INTERNAL PRESSURE LOADING – 1 of 2

- **Parametric study**
  - **Variation of**
    - Facesheet thickness, number of plies
    - Disbond radius: 50.8 – 762 mm (2.0” – 30.0”)
    - Core density: 29 kg/m^3, 48 kg/m^3, 80 kg/m^3 (1.8 - 5.0 lb/ft^3)
    - Core thickness: 12.5 mm, 25.4 mm, 50.8 mm, 76.5 mm (0.5” - 3.0”)
  - **Results**
    - Variation of core density does not have a significant effect on computed G_T
    - Large disbond radius and thin facesheets result in maximum G_T
- **Following studies**
  - Dimensions based on results from parametric study

Averaged G_T along crack front

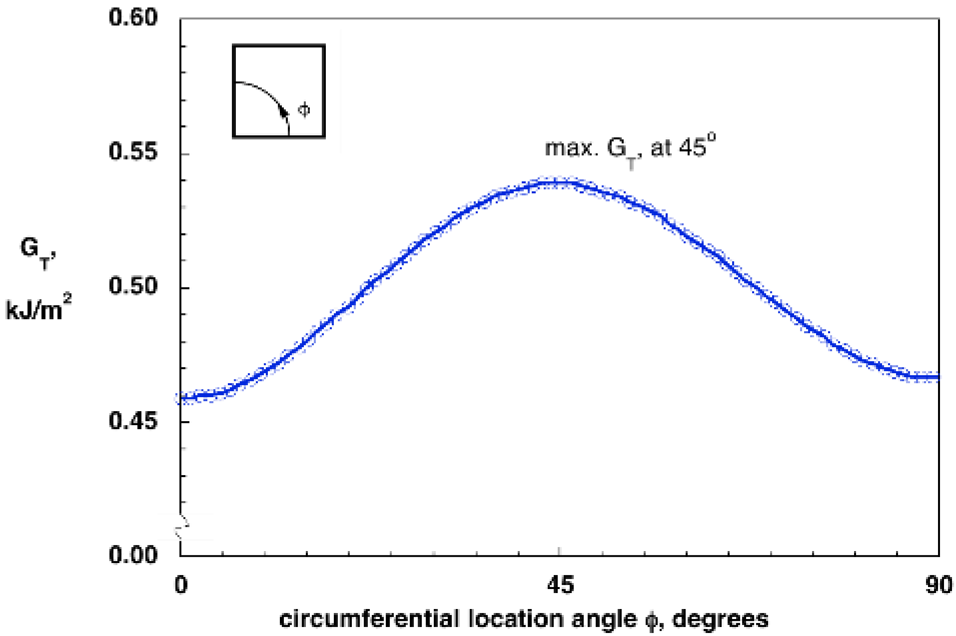
3.275 mm (1/8”) cell size, 48 kg/m^3 (3.0 lb/ft^3) core density



FLAT PANEL SUBJECTED TO INTERNAL PRESSURE LOADING – 2 of 2

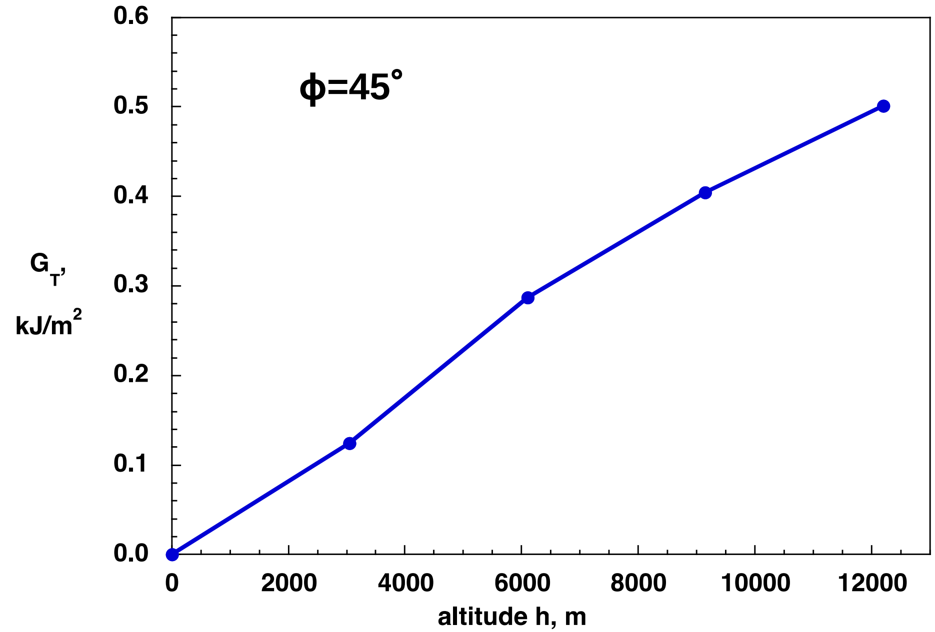
- **Conditions**
  - **12,192 m altitude (40,000 ft)**
    - p=0.0188 MPa (2.73 lbs/in^2)
    - T= 216.65 K (-69.7° F, -56.5° C)
- **Result**
  - **Max G_T observed at ϕ=45°**

Energy release rate along the disbond front



- **Conditions**
  - **0 m - 12,192 m altitude**
  - **Sea level to cruising altitude**
- **Results for max G_T at ϕ=45°**
  - **G_T increases monotonically with increasing altitude**

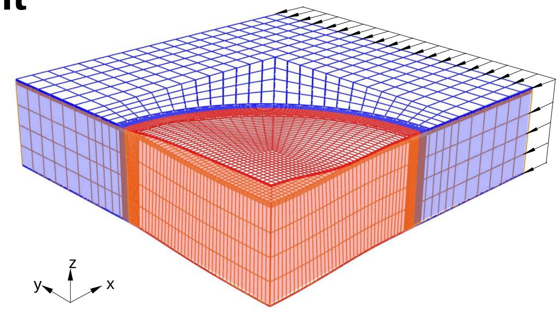
Energy release rate dependence on altitude

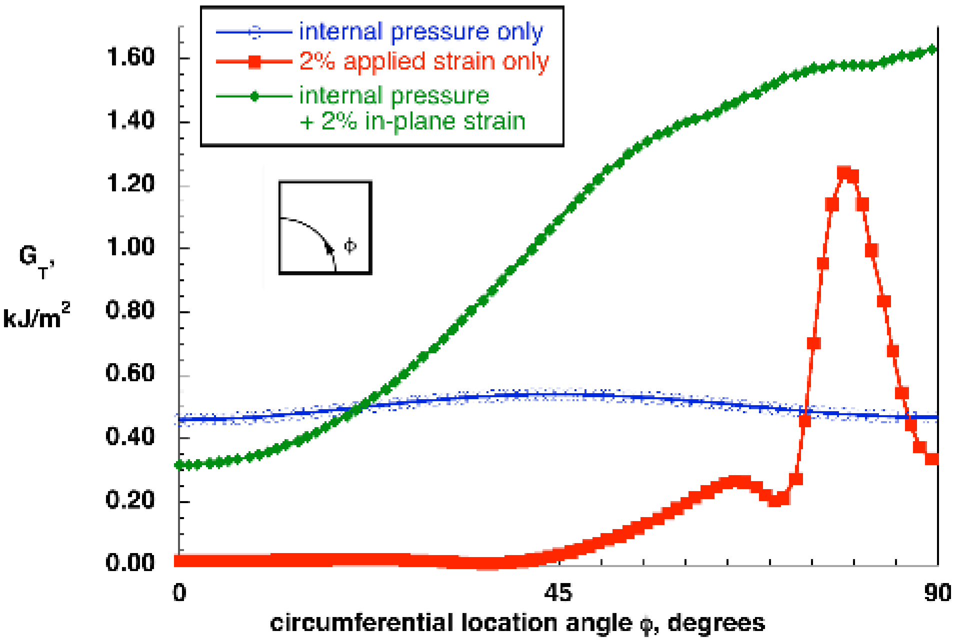


FLAT PANEL SUBJECTED TO IN-PLANE AND COMBINED LOADING

- **Conditions**
  - **12,192 m altitude (40,000 ft)**
    - External pressure p=0.0188 MPa
    - External temperature T= 216.65 K
  - **0.2% (2000 με) applied in-plane strain to simulate service loads on a flat control surface**
  - **Combined internal pressure + 0.2% (2000 με) in-plane strain**
- **Results**
  - **Out-of-plane deformation of the disbonded section changes**
  - **Leads to a change in the G_T distribution**
  - **Addition of in-plane strain leads to an increase in G_T**
  - **Due to non-linearity superposition of the results is not possible**

Distribution of energy release rate along the disbond front





ANALYSIS OF A CURVED PANEL

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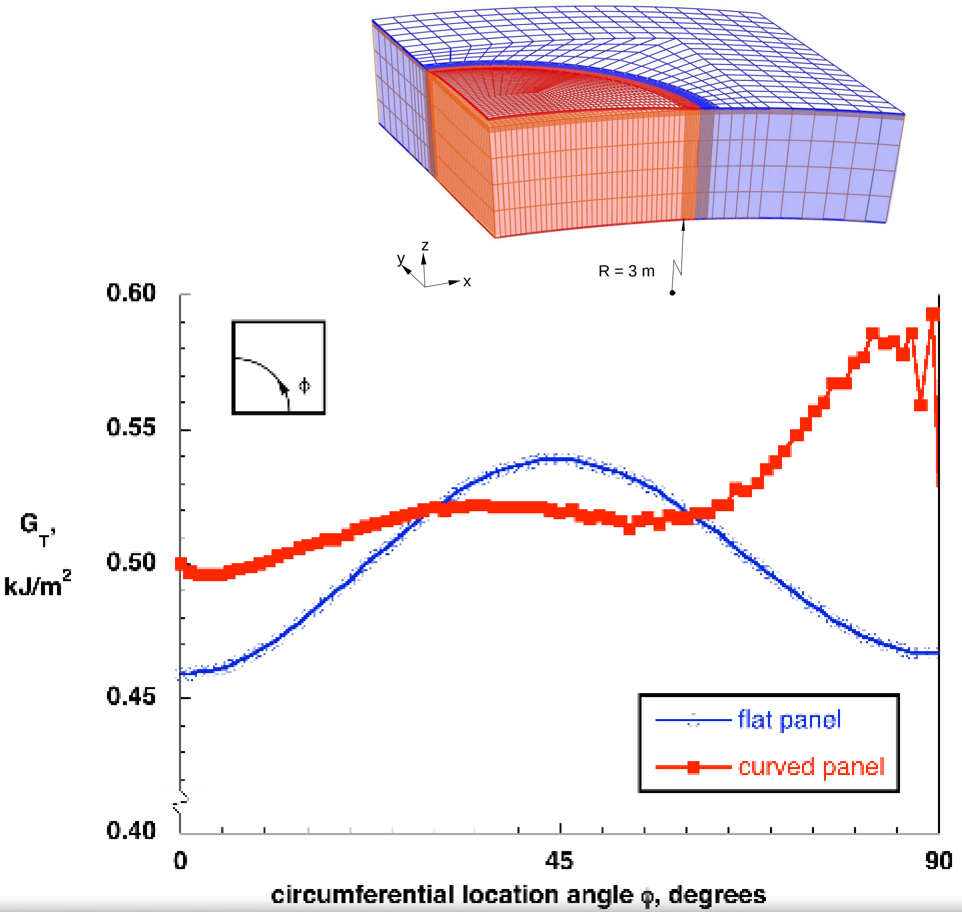
- **Conditions**
  - **12,192 m altitude (40,000 ft)**
    - External pressure p=0.0188 MPa
    - External temperature T= 216.65 K
  - **Flat panel**
  - **Curved panel with 3 m radius**
- **Results**
  - **Symmetry of the G_T distribution is lost for the curved panel**
  - **Locally and on average the computed G_T is higher than the result obtained from the flat panel**
  - **Result is unexpected**
  - **In-plane strain may lead to a further increase in computed G_T**
  - **Additional analyses with different radii and more refined mesh should be performed before a definite statement is made**

Distribution of energy release rate along the disbond front



ONGOING ANALYSIS DEVELOPMENT

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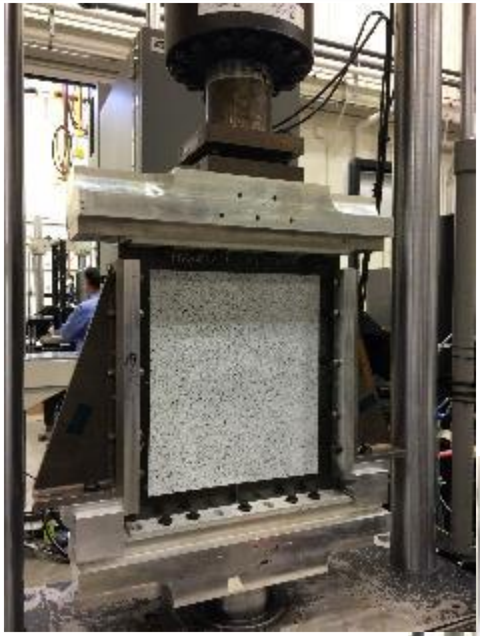
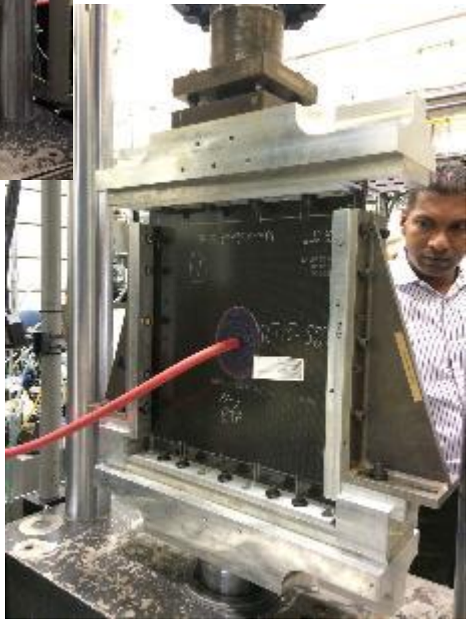
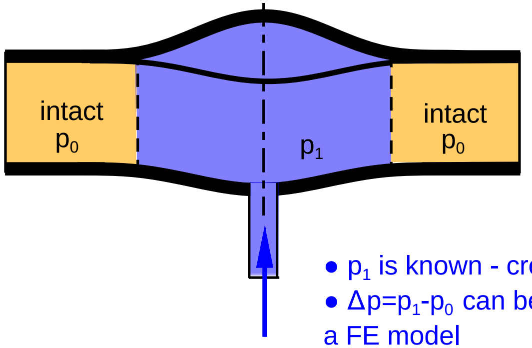
- **Current work**
  - Studying honeycomb core idealization used in modeling approach
  - Validating models by comparing to detailed results from panel testing
  - Studying effects of disbond location on convex and concave sides of curved panels
  - Analyzing disbond migration into the core
  - Studying fatigue and environmental effects





Pressurized panel test at NIAR (Wichita State)*

Schematic of a pressurized panel test



- p_1 is known - created by a compressor
- $\Delta p = p_1 - p_0$ can be directly used as input to a FE model

CLOSING REMARKS

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- Face sheet/core disbonding is a significant damage mode of sandwich composites
- A methodology similar to delamination modeling in composites is being developed to assess facesheet/core disbonding
- Mode-I disbond driving force assumed to be most critical
- Test method for measuring mode-I interfacial fracture toughness was developed into a draft ASTM test standard
- Round robin exercise composed of 7 international laboratories being conducted to evaluate draft standard
- Sandwich panel containing a circular disbond at the facesheet/core interface was studied using pressure-deformation coupling
- Large disbonds, thin facesheets, and thick cores are most critical
- Work ties in with activities in the broader community concerned with sandwich disbonding