# FACESHEET/CORE DISBOND GROWTH IN HONEYCOMB SANDWICH PANELS SUBJECTED TO GROUND-AIR-GROUND PRESSURIZATION AND IN-PLANE LOADING

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# Overview



- **Background**
- **Road Map**
- **Detailed problem description**
- **Fracture mechanics approach**
  - Development of a test method for fracture toughness testing
  - Finite element modeling
- **Finite element analysis of a panel with circular disbond**
  - Model benchmarking
  - Analysis of a flat panel under internal pressure, in-plane and combined loading
  - Analysis of a curved panel
- **Summary**

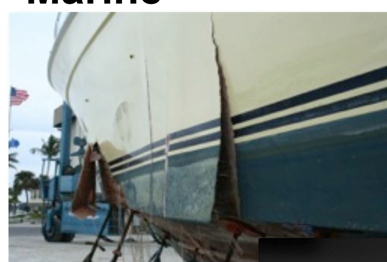
# Background

- **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)**

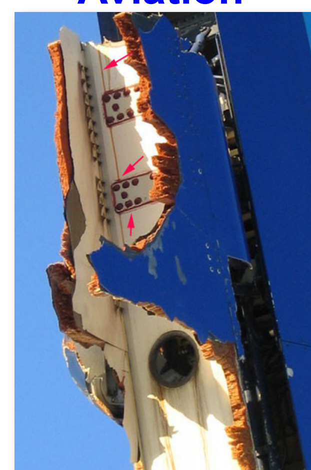
**Detail of flaw**

**Marine**



**Fracture test***

**Aviation***



*Focus of this presentation

# Road Map

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- **Ongoing CMH-17/ASTM D30 activity initiated 2012**
- **Current FAA initiative on Continuous Operational Safety (COS)**
- **Objective**
  - **Develop a fracture mechanics based methodology for damage tolerance assessment of sandwich structure**
  - **Assessment of facesheet/core disbonding in sandwich components similar to delamination in composite laminates**
- **Approach**
  - **Coupon test standard development**
    - Test method for peel-dominated (mode I) interfacial fracture toughness*
    - Test method for mode II and mixed-mode interfacial fracture toughness
  - **Analysis development**
    - Develop analysis tool for facesheet/core disbonding in sandwich structure*
    - Develop models to simulate the ground-air-ground cycle load case*
  - **Panel testing for analysis validation**
  - **Sandwich disbond methodology development**
  - **Publication**
    - ASTM D30 fracture toughness standards
    - CMH-17 Vol. 6 best practices, guidelines and case studies

*Focus of this presentation

# Detailed Problem Description

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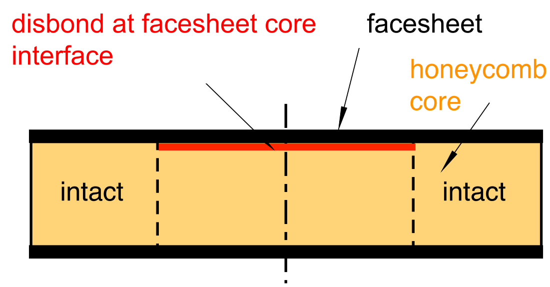
- **Pressure difference between inside and outside of unvented sandwich structures**
  - Caused by alternating changes in ambient pressure and temperature
  - Results in significant deformations and core volume increase
  - Volume increase results in pressure decrease based on the ideal gas law

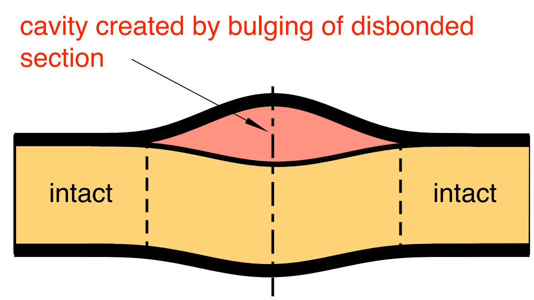
$$p\,V = n\,R\,T$$

- **Initial disbonds between facesheets and core**
  - increase the peeling effect and
  - decrease the structural reliability significantly
- **For an accurate structural analysis, a coupled pressure-deformation problem needs to be solved**

- **Initial configuration at ground elevation**




- **Deformed configuration at cruising altitude**



# Fracture Mechanics Approach – 1 of 2

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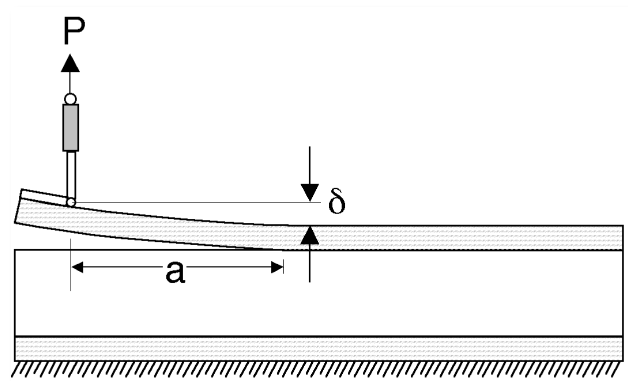
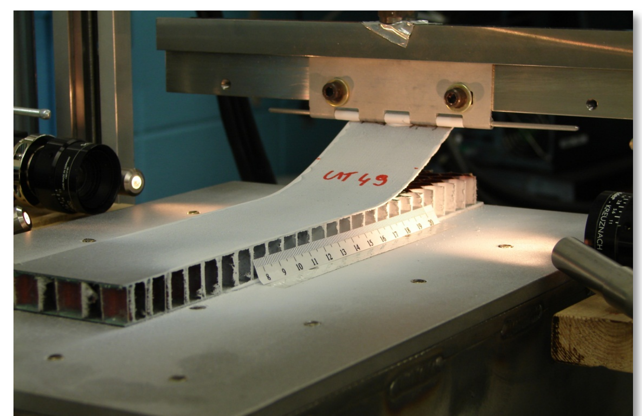
- **Test standard development in ASTM committee D30 (WK 47682)**
  - **Characterize properties of facesheet/core interface**
  - **Measure fracture toughness $G_c$**
  - **Single cantilever beam (SCB) type configuration was identified as the most appropriate test**
    - Simple loading fixture
    - Disbond front loading is independent of disbond length
    - Disbonding occurs along or near the facesheet/core interface (no kinking into the core)
    - Disbond toughness can be calculated by using a compliance calibration procedure for data reduction
  - **Standardized test method for peel-dominated interfacial fracture toughness of sandwich constructions (draft)**
    - Draft includes procedure to determine the SCB specimen dimensions (specimen length, facesheet thickness, initial disbond length)
    - Current round robin activity involves seven research laboratories in the US and Europe

**SCB test schematic**




**Honeycomb sandwich test**



# Fracture Mechanics Approach – 2 of 2

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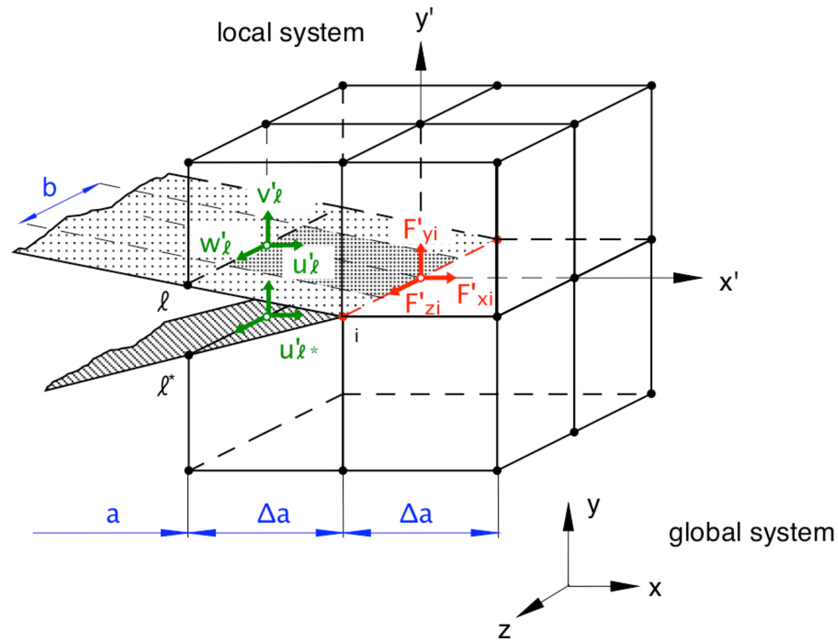
- **Analysis development**
  - **Compute the energy release rate along the disbond front**
  - **Use the Virtual Crack Closure Technique (VCCT) based on the results obtained from a finite element analysis**
    - Provides mode separation
    - Transformation of nodal forces and displacement into deformed 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**

**Schematic of 3D elements at crack tip**




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

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

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

# FE Model of a Panel With Disbond – 1 of 4

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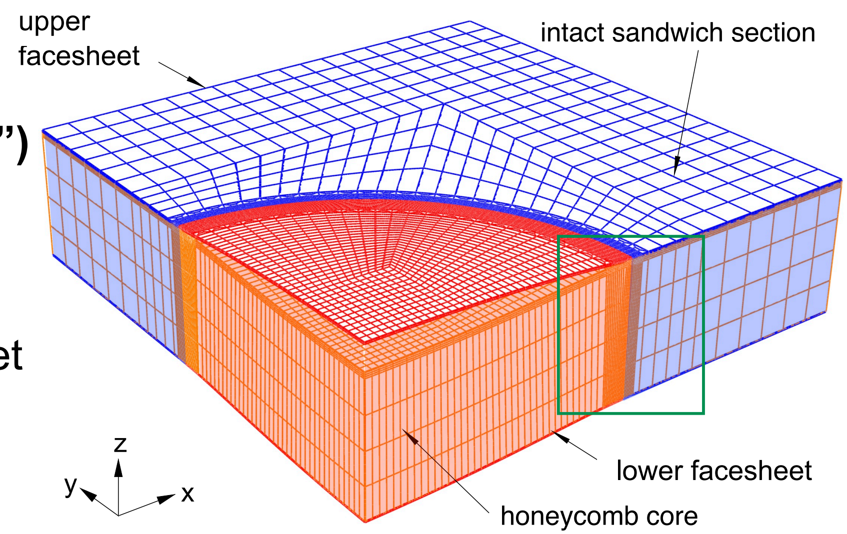
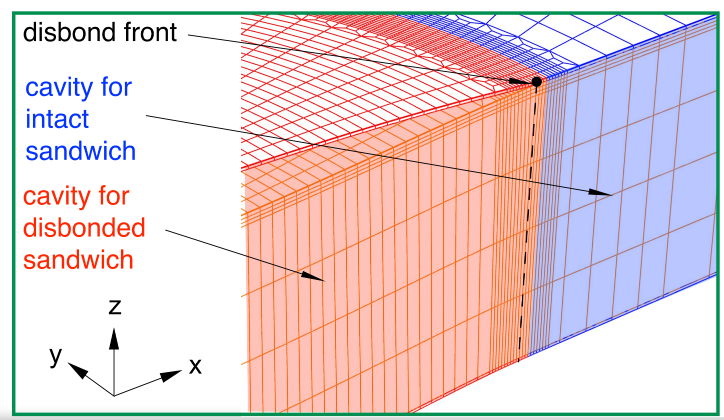
- **A quarter section of a flat panel was modeled**
  - **Circular disbond radius: 152.4 mm (6”)**
  - **Square section side dimension: 304.8 mm (12”)**
  - **Abaqus/Standard® was used (C3D20 element)**
    - Boundary conditions applied at symmetry planes
    - Surface contact used between top facesheet 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/m$^3$ (3.0 lb/ft$^3$) 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

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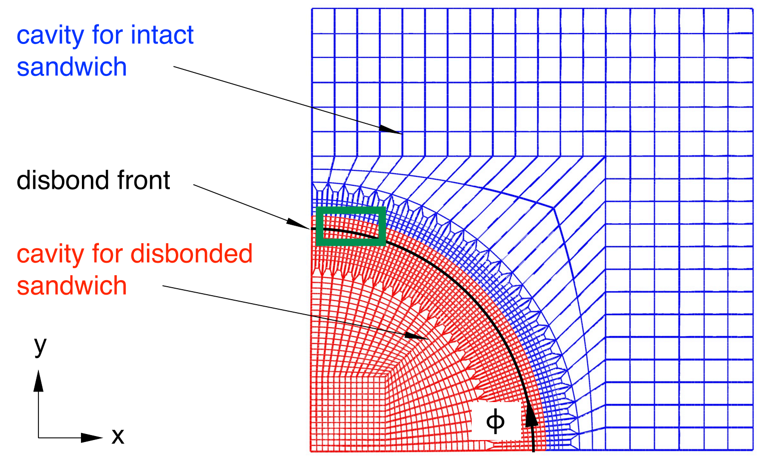
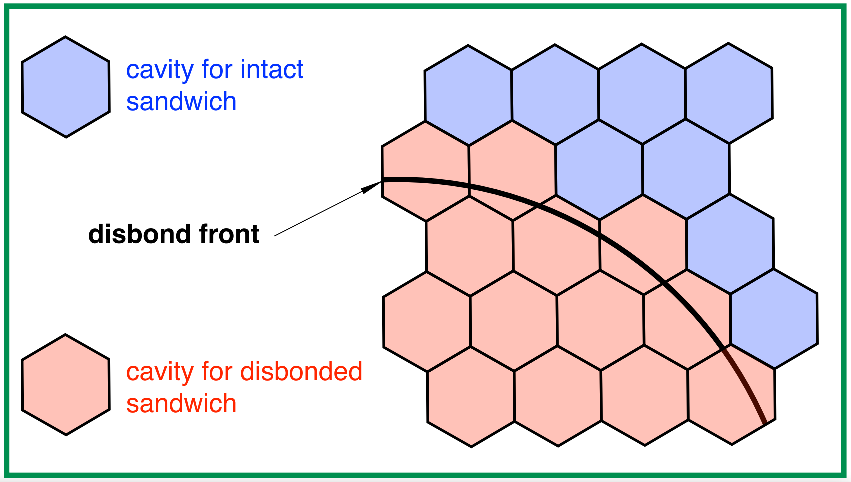
- **Pressure deformation coupling was simulated using fluid-filled cavities**
  - **Abaqus/Standard® feature enabled the definition of fluid-filled cavities enclosed by structural elements**
  - **The ideal gas law is solved within each increment until equilibrium is found**
  - **The volume of the fluid 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

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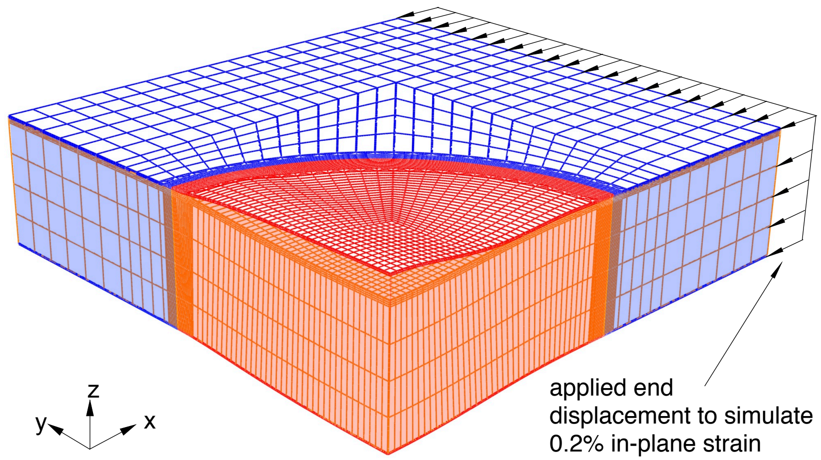
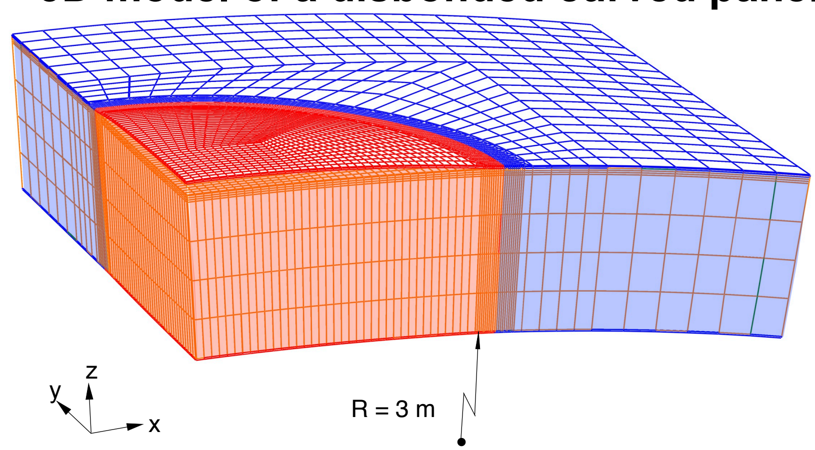
- **Model of a flat panel with in-plane loading**
  - Study the effect of in-plane service load on a flat control surface
  - In-plane displacement applied to the model to simulate a 0.2% (2000 με) strain condition during a flight maneuver
  - A compressive strain condition was chosen since it was believed 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**



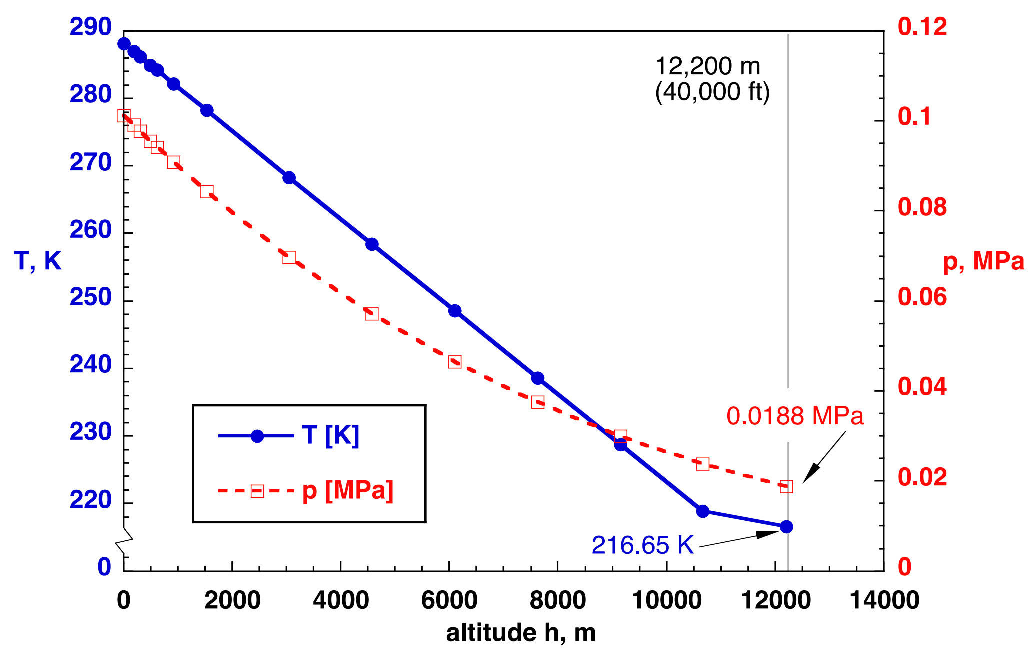

**3D model of a disbonded curved panel**



# FE Model of a Panel With Disbond – 4 of 4

- **Internal pressurization of the disbond**
  - Commercial jetliner ascent scenario was considered from 0 to 12192 m (0 to 40000 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

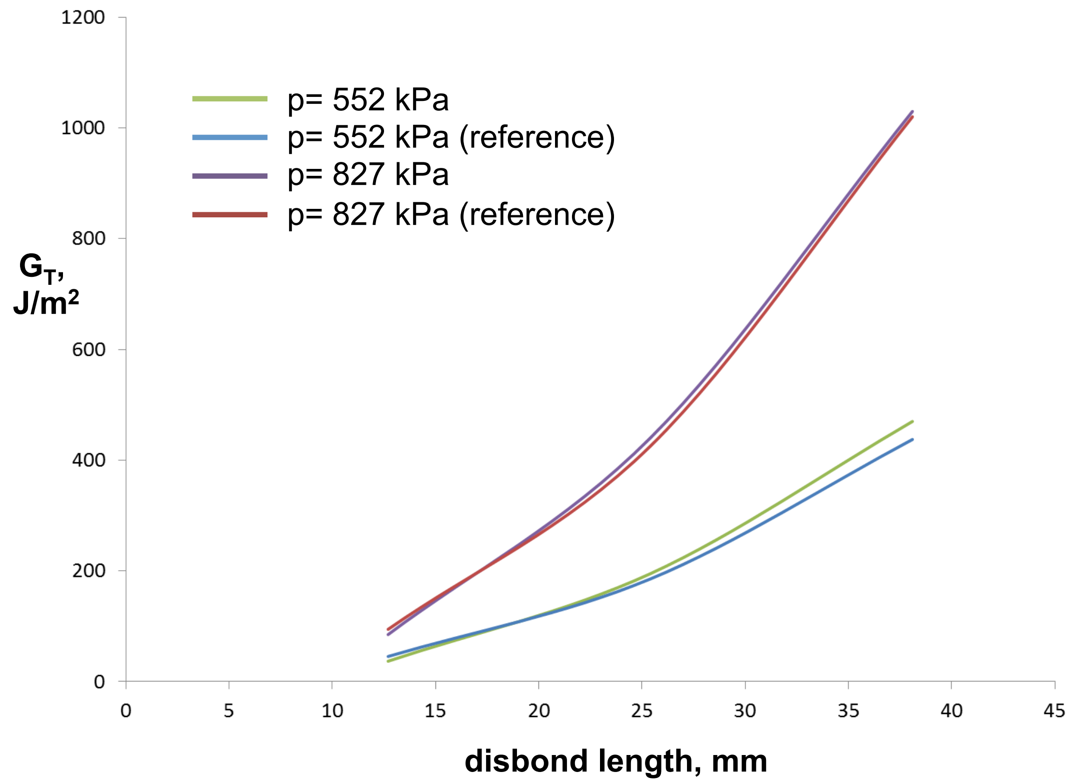
**Decrease of temperature and pressure with increasing altitude**



# Model Benchmarking – 1 of 3

- **X-33 cryogenic fuel tank**
  - **NASA sandwich disbond investigation**
    - Square delamination
    - Panel pressurized by a compressor
    - Defined load, no pressure-deformation coupling
    - Calculations were performed using surface loads
  - **Current analysis approach**
    - Same dimensions as NASA investigation
    - Pressure load case modeled with Abaqus fluid elements
    - VCCT calculation using post-processing routine
  - **Result comparison**
    - Good correlation between $G_T$ values calculated using different models

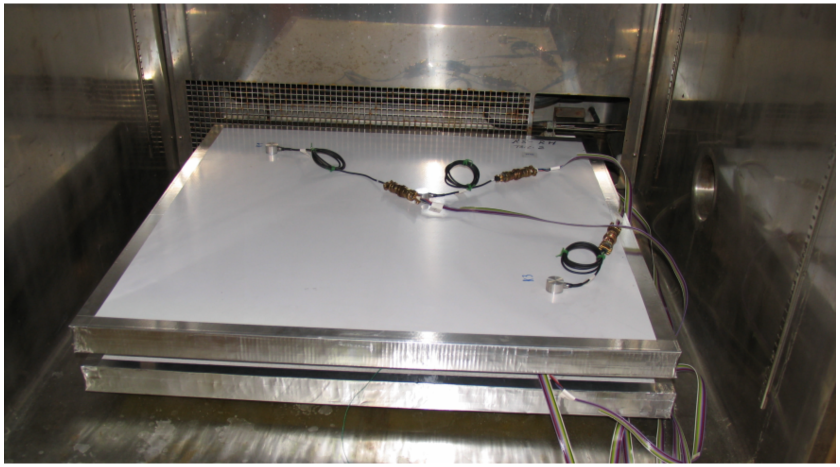
**Energy release rate dependence on disbond length**



# Model Benchmarking – 2 of 3

- **Sandwich panel with disbond**
  - Panel with 350 mm disbond
  - Pressure-deformation coupling needs to be considered
  - Pressure in disbonded core section was measured during test
  - FE analysis was performed calculating pressure-deformation coupling iteratively

**Airbus test panel in vacuum chamber**

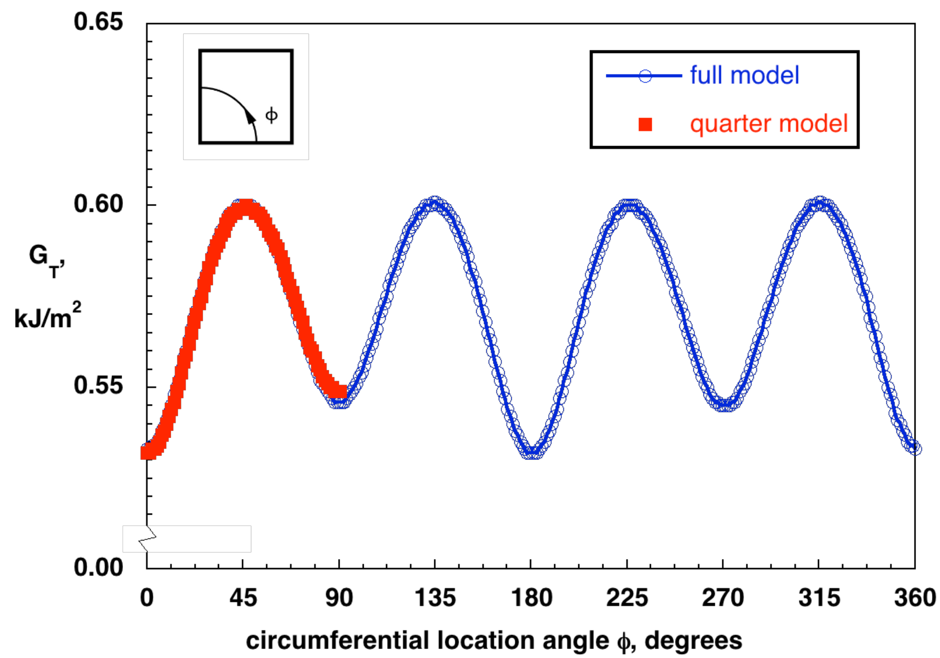


  - **Current analysis approach**
    - Same dimensions as Airbus panel
    - Pressure-deformation coupling solved using Abaqus Fluid Cavity Simulation
  - **Result comparison**
    - Good correlation for pressure-deformation coupling using different models
    - Pressure in core:
      - Airbus test: 0.0582 MPa
      - Airbus analysis: 0.0577 MPa
      - Current analysis: 0.0571 Mpa
- **Additional validation studies should be performed to compare test results and analysis**
  - **Compare deformation field**
  - **Compare pressure inside the cavity**

# Model Benchmarking – 3 of 3

- **Conditions**
  - **12,192 m altitude (40,000 ft)**
    - External pressure p=0.0188 MPa (2.73 lbs/in$^2$)
    - External temperature T= 216.65 K (-69.7°F, -56.5°C)
- **Verification for using a FE model of a quarter section of the panel**
  - **Excellent agreement of computed $G_T$ along the front for the currently used quasi-isotropic layup**
  - ***Deviation, however, for other layups that violate the symmetry conditions of the model***

**Distribution of energy release rate along the disbond front**



# Flat Panel Subjected to Internal Pressure Loading – 1 of 2

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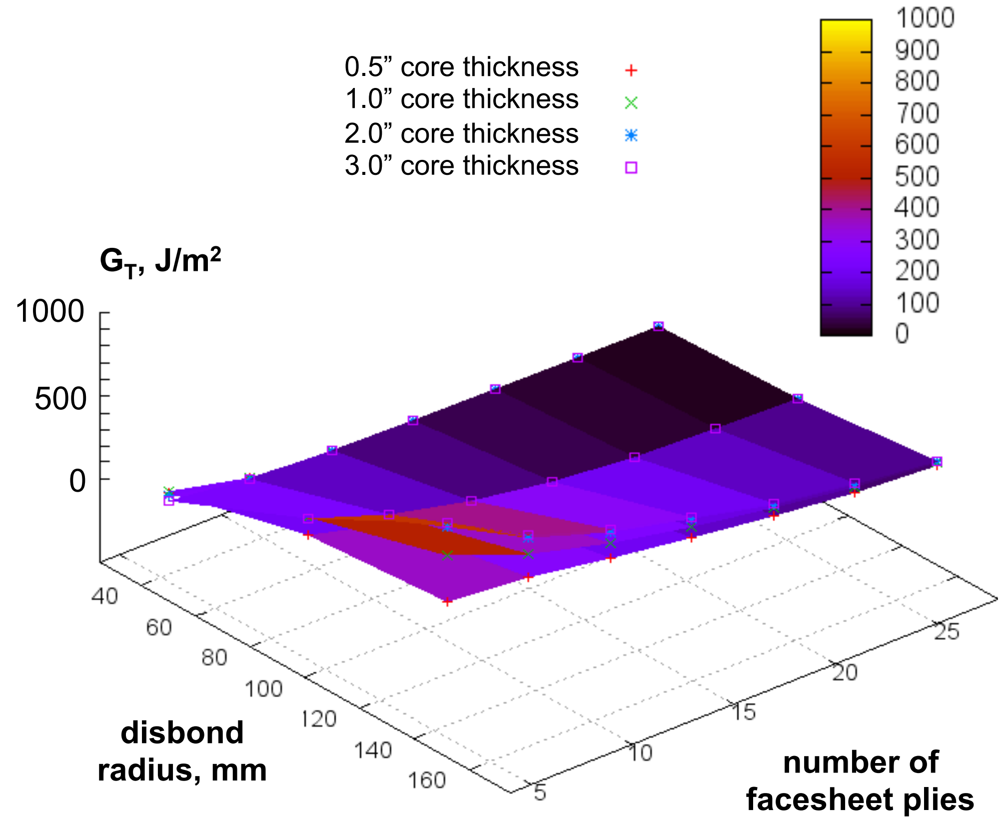
- **Parametric study**
  - **Variation of**
    - Facesheet thickness, number of plies
    - Disbond radius: 50.8 – 762 mm (2.0" – 30.0")
    - Core density: 29 kg/m$^3$, 48 kg/m$^3$, 80 kg/m$^3$ (1.8 - 5.0 lb/ft$^3$)
    - Core thickness: 12.5 mm, 25.4 mm, 50.8 mm, 76.5 mm (0.5" - 3.0")
  - **Results**
    - 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*

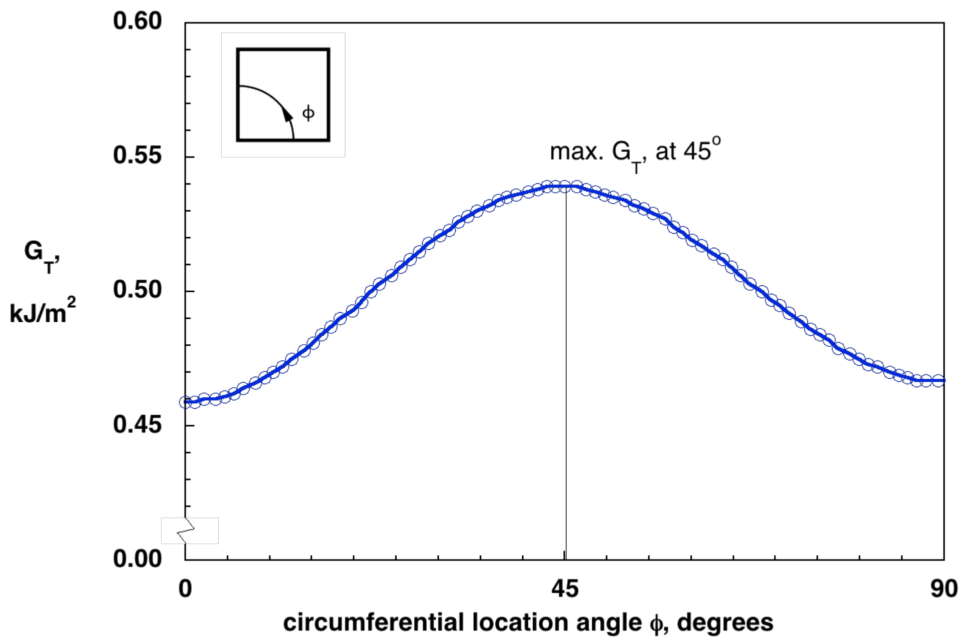


# Flat Panel Subjected to Internal Pressure Loading – 2 of 2

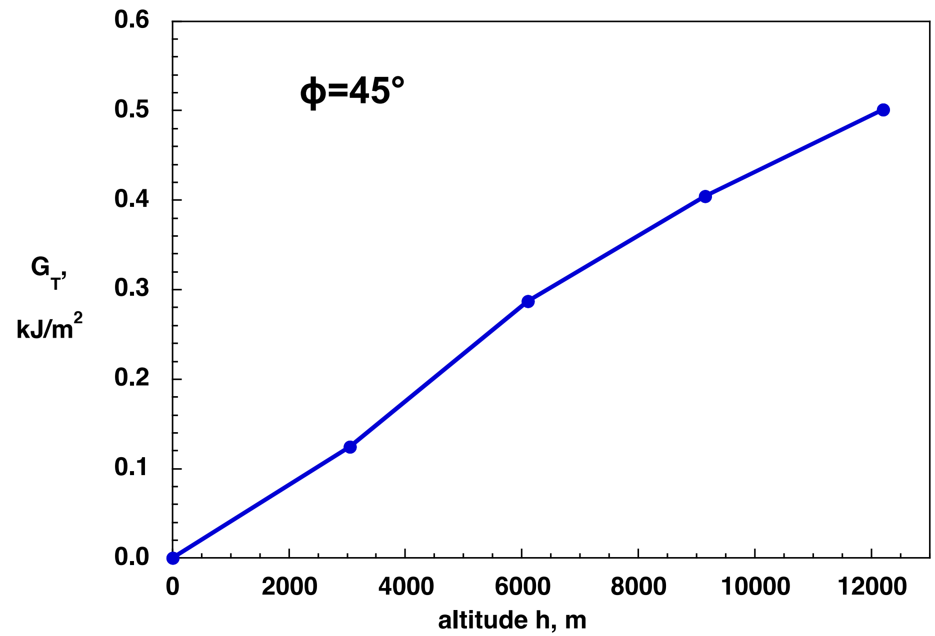
- **Conditions**
  - **12,192 m altitude (40,000 ft)**
    - p=0.0188 MPa (2.73 lbs/in²)
    - T= 216.65 K (-69.7°F, -56.5°C)
- **Result**
  - **Max $G_T$ observed at ϕ=45°**

- **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 along the disbond front**



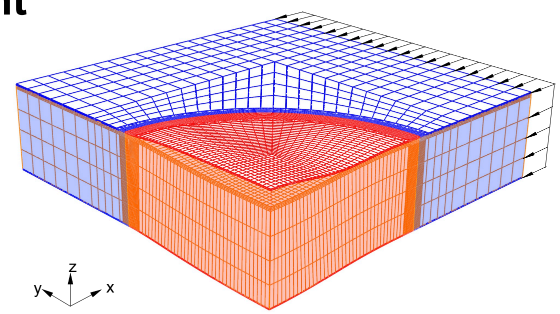

**Energy release rate dependence on altitude**

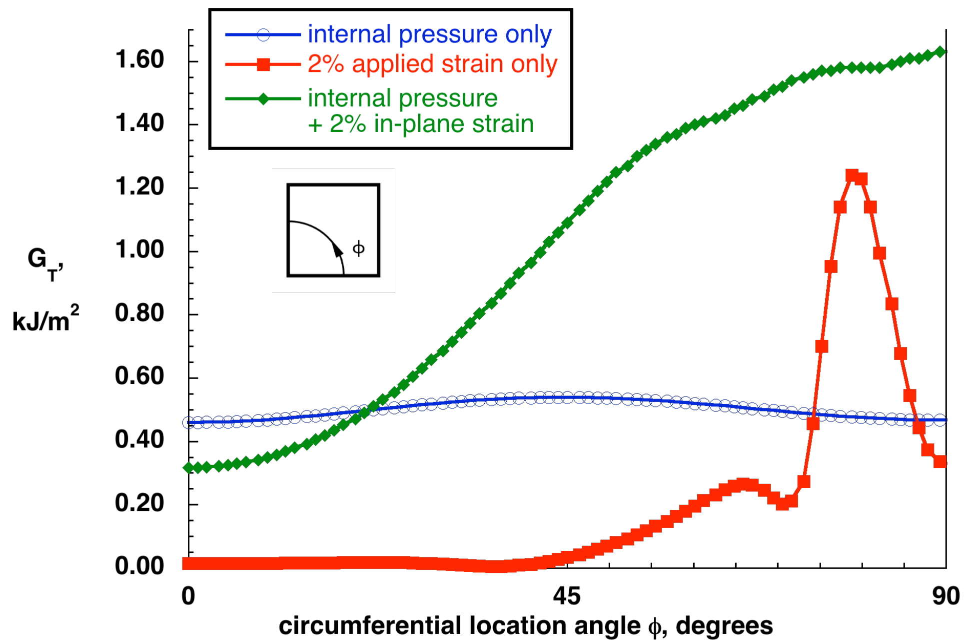


# Flat Panel Subjected to In-Plane and Combined Loading

- **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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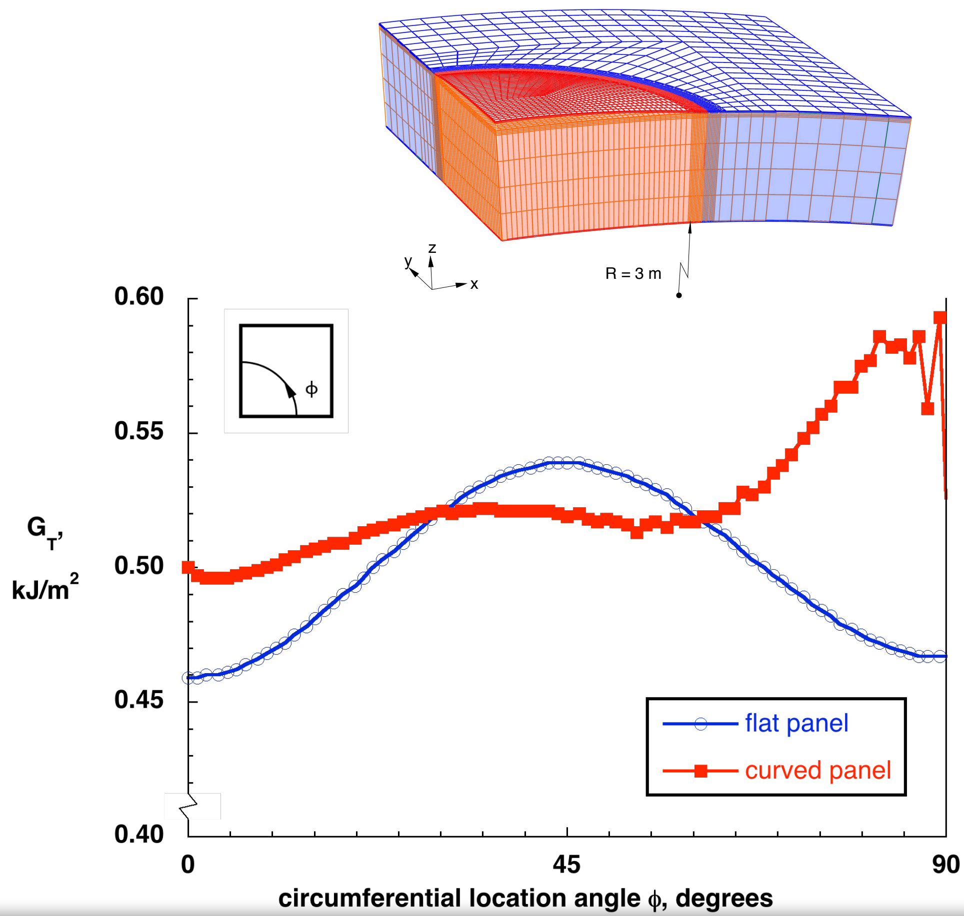
- **Conditions**
  - **12,192 m altitude (40,000 ft)**
    - External pressure p=0.0188 MPa
    - External temperature T= 216.65 K
  - **Flat panel**
  - **Curved panel with 3 m radius**
- **Results**
  - **Symmetry of the $G_T$ distribution is lost for the curved panel**
  - **Locally and on average 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**



# Summary



- A methodology similar to delamination modeling in composites was developed to assess facesheet/core disbonding in honeycomb sandwich components.
- A 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.
- Computed averaged $G_T$ values increased almost linearly with increasing altitude.
- In-plane compressive strains increased $G_T$ along the crack front.
- Due to non-linearity of the problem, results for combined load cases cannot be obtained simply by superposition of individual load cases.
- Computed $G_T$ values were higher for a curved panel than for a flat panel.