National Institute of Aerospace

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

Zhi M. Chen
University of California at San Diego, La Jolla, USA

Ronald Krueger
National Institute of Aerospace, Hampton, VA, USA

Martin Rinker
Rolls-Royce Deutschland Ltd & Co KG, Dahlewitz, Germany

The Aerospace Corporation, El Segundo, CA, June 25, 2015

Work was funded by NASA Langley Research Center under contract number NNL09AA00A

OVERVIEW

National Institute of Aerospace

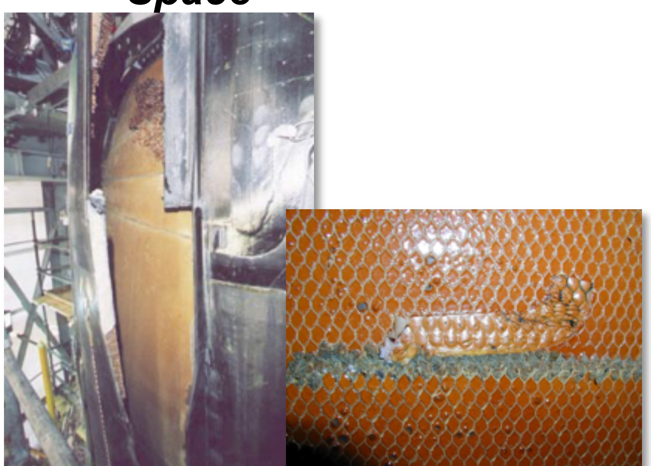
- **Background**
- **Objective**
- **Detailed Problem Description**
- **Analysis Methodology**
  - Fracture Mechanics Approach
  - Finite Element Modelling
- **Initial Model Verification and Validation**
- **Analysis Results**
  - Analysis of a Flat Panel Under Internal Pressure, In-Plane and Combined Loading
  - Analysis of a Curved Panel
- **Summary**
- **Concluding Remarks**

BACKGROUND

NATIONAL INSTITUTE OF AEROSPACE

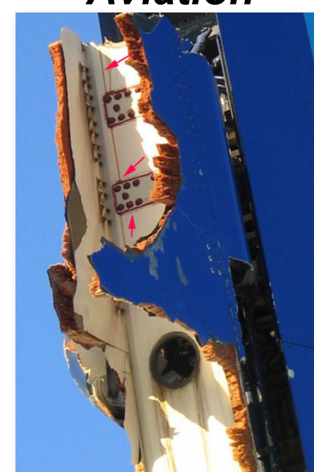
- **Problem**
  - **In-service component failures associated with disbonding in unvented honeycomb core sandwich**
  - **Degradation due to disbonding affects operational safety**
  - **Failures may discourage use of composites in ‘future’ vehicles**
  - **Methods for assessing propensity of sandwich 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



Marine

Aviation



OBJECTIVE

NATIONAL INSTITUTE OF AEROSPACE

- Identify, describe and address the phenomenon associated with face sheet/core disbonding
- Increase the knowledge on the subject and the awareness of consequences
- Develop a methodology to assess face sheet/core disbonding in honeycomb sandwich components similar to delamination in composite laminates
  - Develop standard test methods for characterizing face sheet/core disbonding in sandwich components
  - Develop a fracture mechanics based methodology to assess face sheet/core disbonding in sandwich components
  - Develop models and analysis tools for face sheet/core disbonding in sandwich components subjected to ground-air-ground cycles and/or in-plane loading
  - Evaluate the developed test methods and analysis tools using honeycomb sandwich panel tests

DETAILED PROBLEM DESCRIPTION

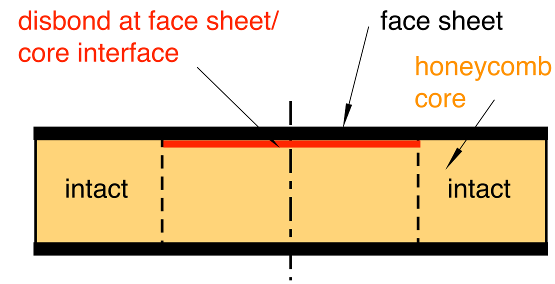
NATIONAL INSTITUTE OF AEROSPACE

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

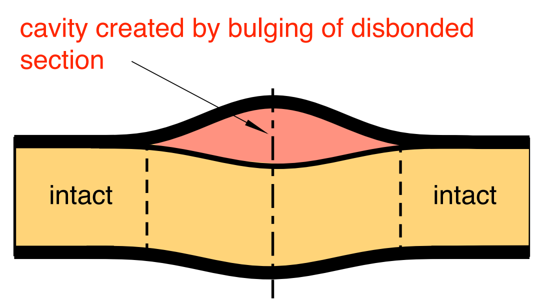
$$p\,V = n\,R\,T$$

- **Initial disbonds between face sheets 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**



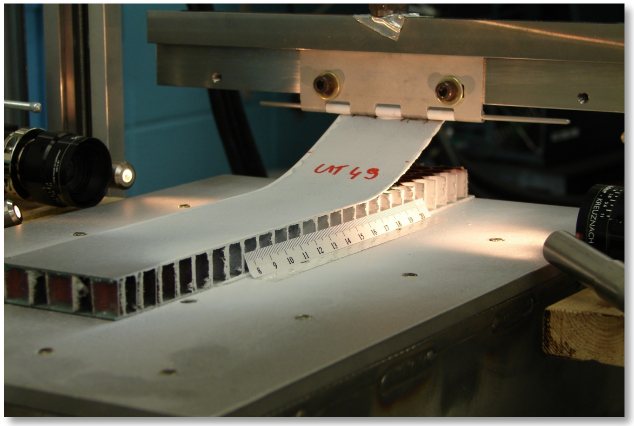
- **Deformed configuration at cruising altitude**

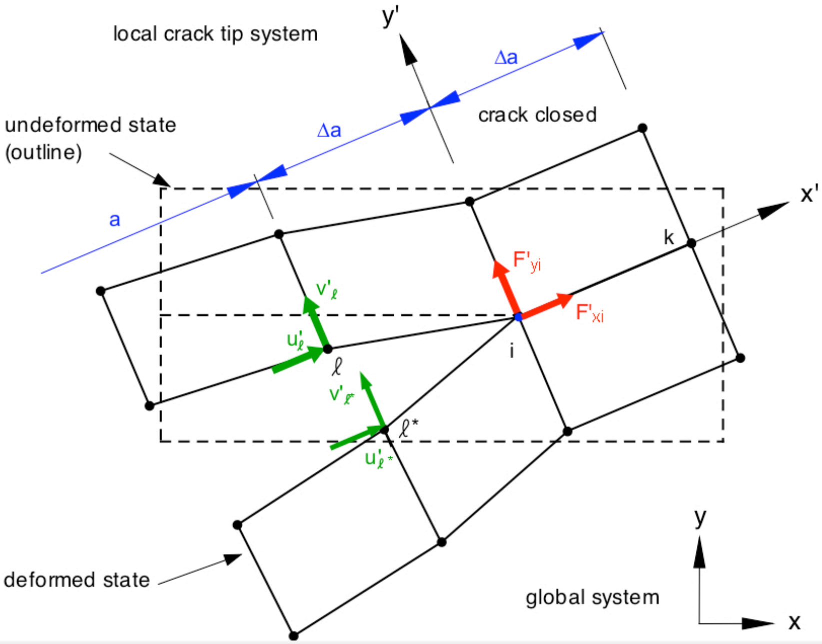


ANALYSIS METHODOLOGY
Fracture Mechanics Approach

NATIONAL INSTITUTE OF AEROSPACE

- **Two steps are required to identify, describe and address face sheet/ core disbonding**
  - **Test standard development in ASTM committee D30 (WK 47682)**
    - Characterize the properties of the face sheet/core interface[14]
    - Measure fracture toughness G_c
  - **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
- **Propagation is predicted to occur once the computed value exceeds the measured fracture toughness**



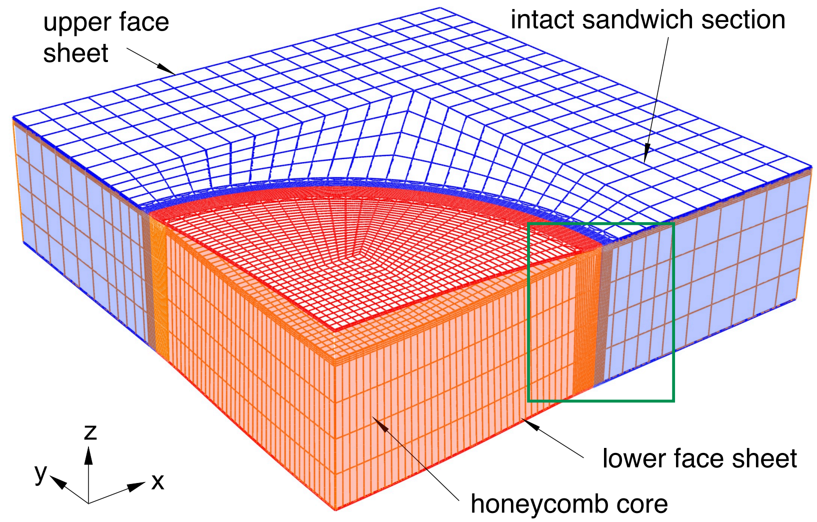


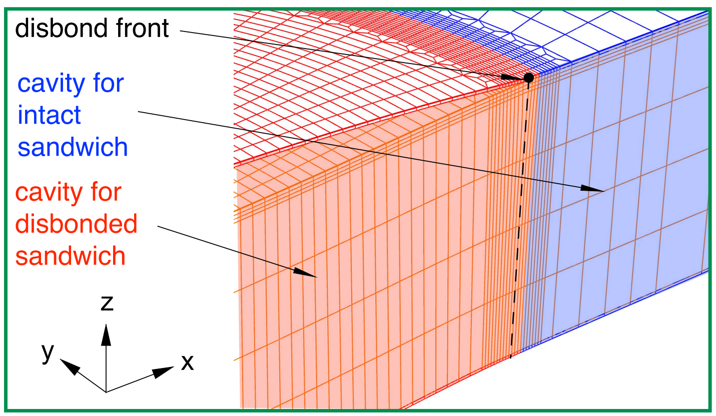
[14] reference to publication cited in conference proceedings

ANALYSIS METHODOLOGY
Finite Element Modelling – 1/4

National Institute of Aerospace

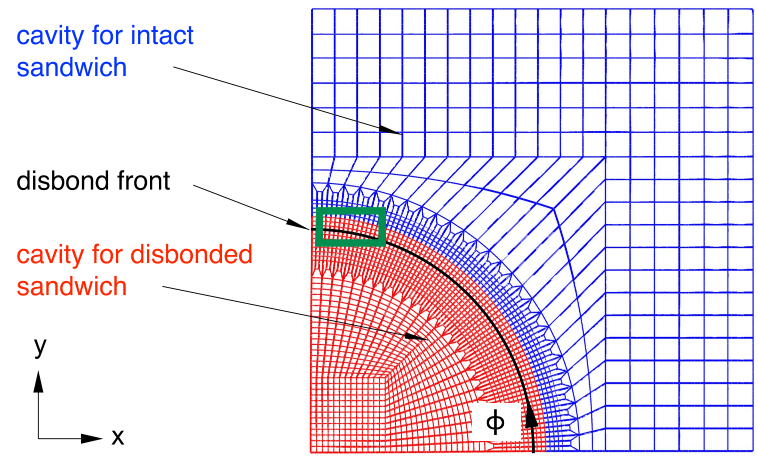
- **A quarter section of a flat panel was modelled**
  - Circular disbond radius: 152.4 mm (6”)
  - Square section modelled: 304.8 mm (12”)
  - Abaqus/Standard® was used (C3D20)
    - Boundary conditions applied at symmetry planes
    - Surface contact used between top face sheet and core in the disbonded section
- **Sandwich properties based on previous results**
  - Thin face sheet: 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
    - Modelled as an orthotropic, homogeneous continuum

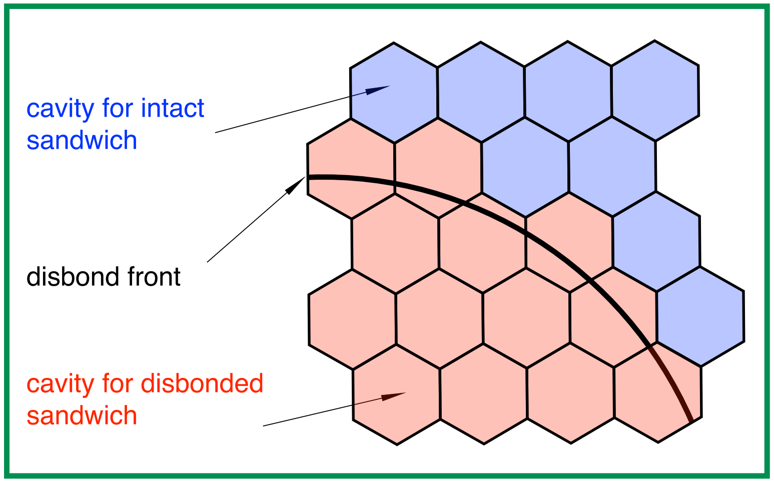




ANALYSIS METHODOLOGY
Finite Element Modelling – 2/4

- **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

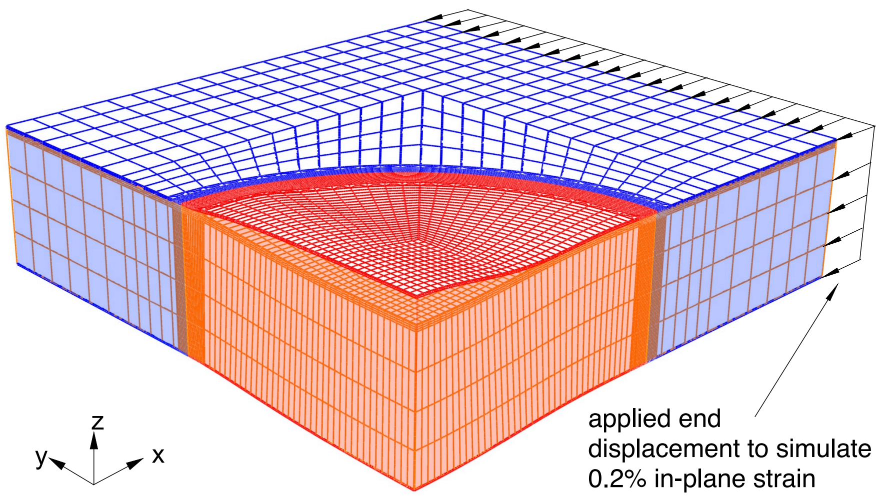


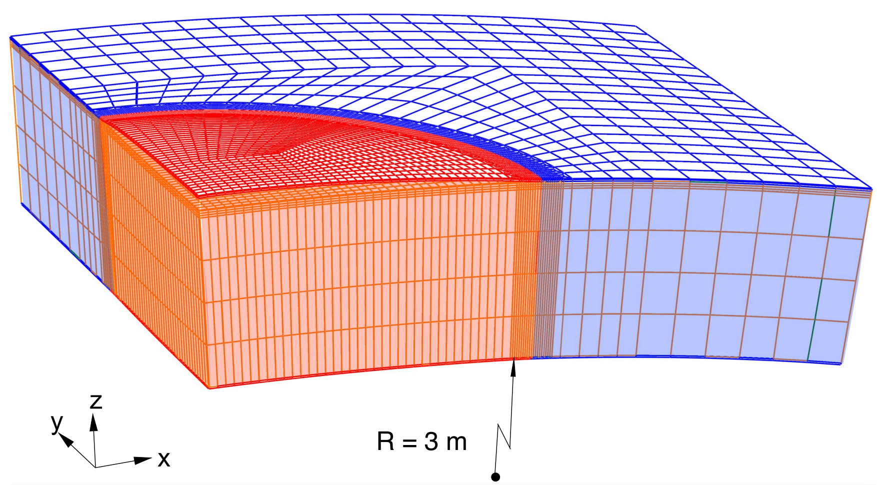


ANALYSIS METHODOLOGY
Finite Element Modelling – 3/4

NATIONAL INSTITUTE OF AEROSPACE

- **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 condition
- **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



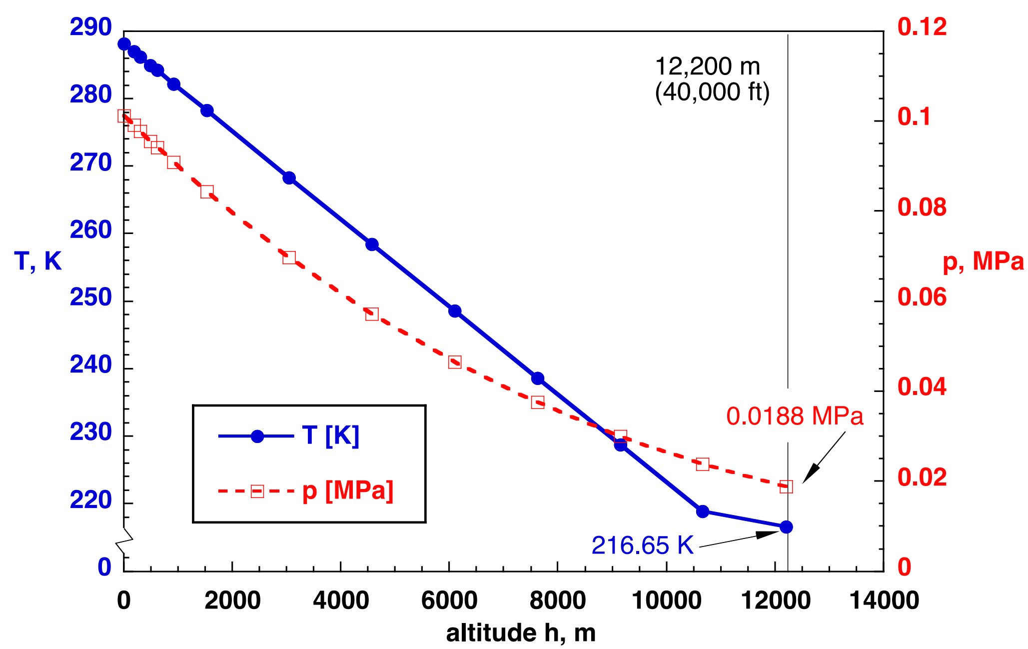


ANALYSIS METHODOLOGY
Finite Element Modelling – 4/4

NATIONAL INSTITUTE OF AEROSPACE

- **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
  - Combination of GAG and 0.2% (2000 με) strain

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



ANALYSIS RESULTS

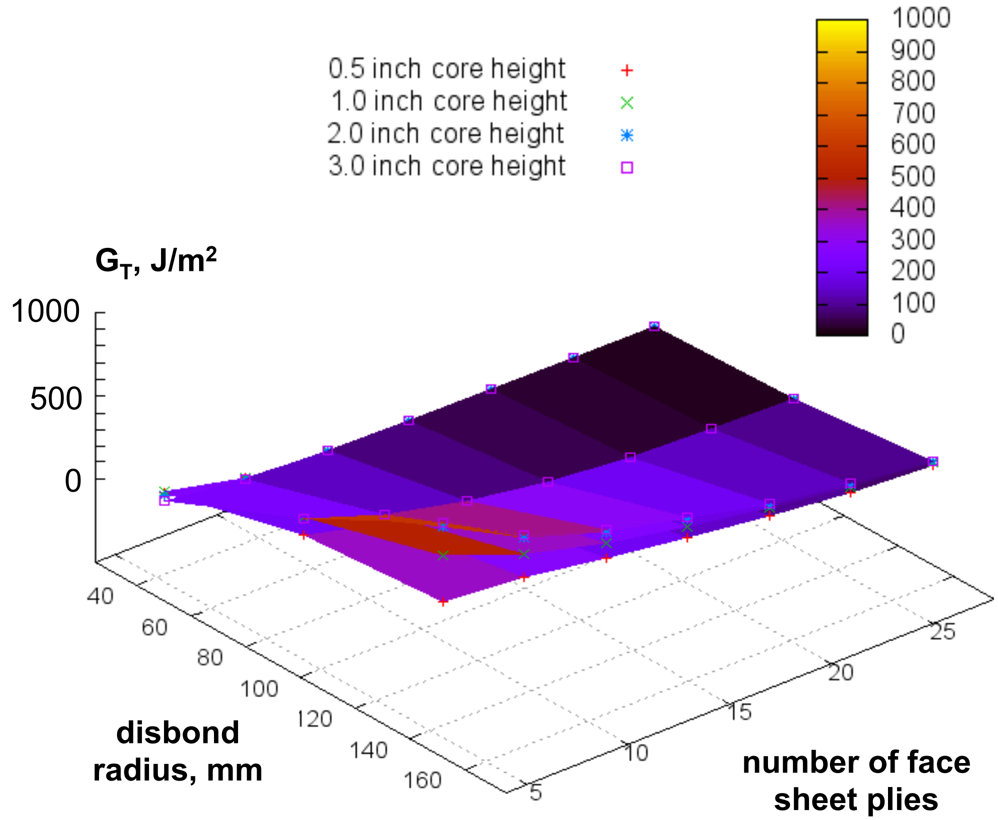
Flat panel under internal pressure loading – 1/3

NATIONAL INSTITUTE OF AEROSPACE

- **Initial study[6]**
  - Variation of
    - Face sheet thickness, number of plies
    - Disbond radius
    - Core density: 29 kg/m³, 48 kg/m³, 80 kg/m³ (1.8 lb/ft³, 3.0 lb/ft³, 5.0 lb/ft³)
    - 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 face sheets result in maximum G_T
- **Current study**
  - Dimensions based on results from initial study

- **Averaged G_T along crack front**

3.275 mm (1/8") cell size, 48 kg/m³ (3.0 lb/ft³) core density



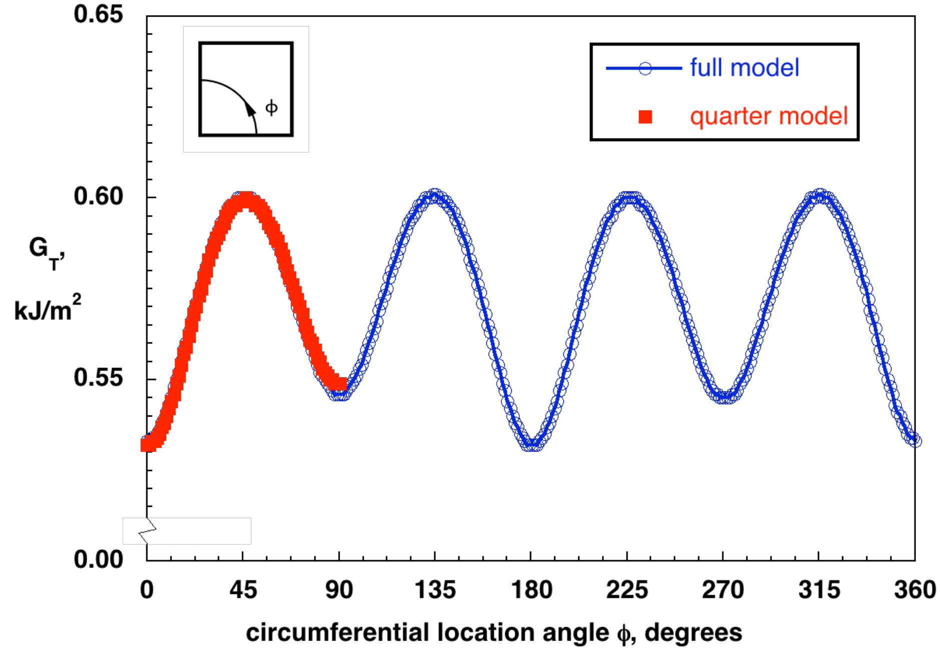
ANALYSIS RESULTS

Flat panel under internal pressure loading – 2/3

NATIONAL INSTITUTE OF AEROSPACE

- **Conditions**
  - 12,192 m altitude (40,000 ft)
    - External pressure p=0.0188 MPa
    - External temperature T= 216.65 K
- **Verification for using a FE model of a quarter section of the panel**
  - Analysis using a full model of the panel with circular disbond
  - Analysis using a model of a quarter panel with boundary conditions
  - 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**



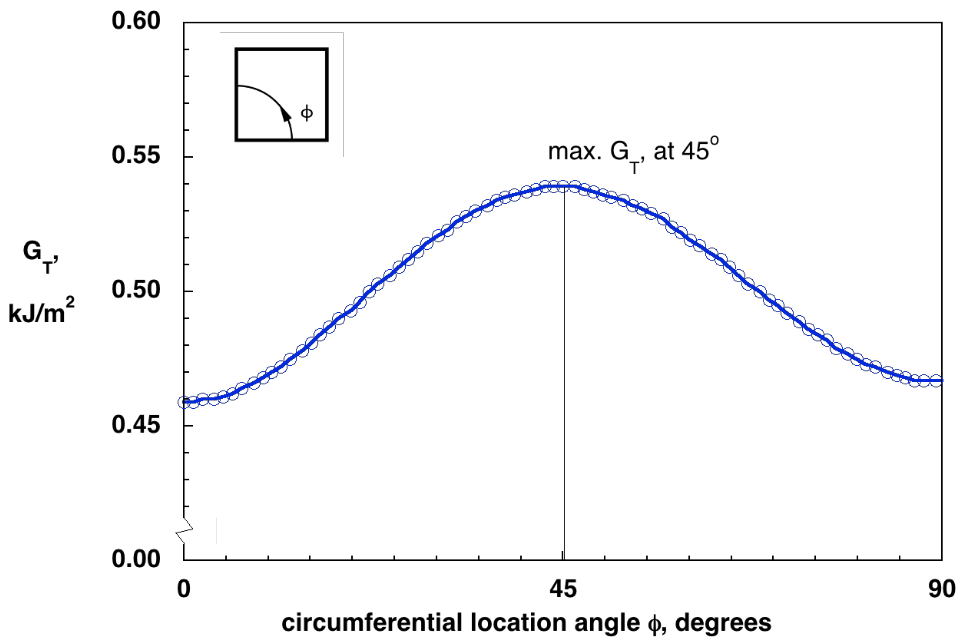
ANALYSIS RESULTS

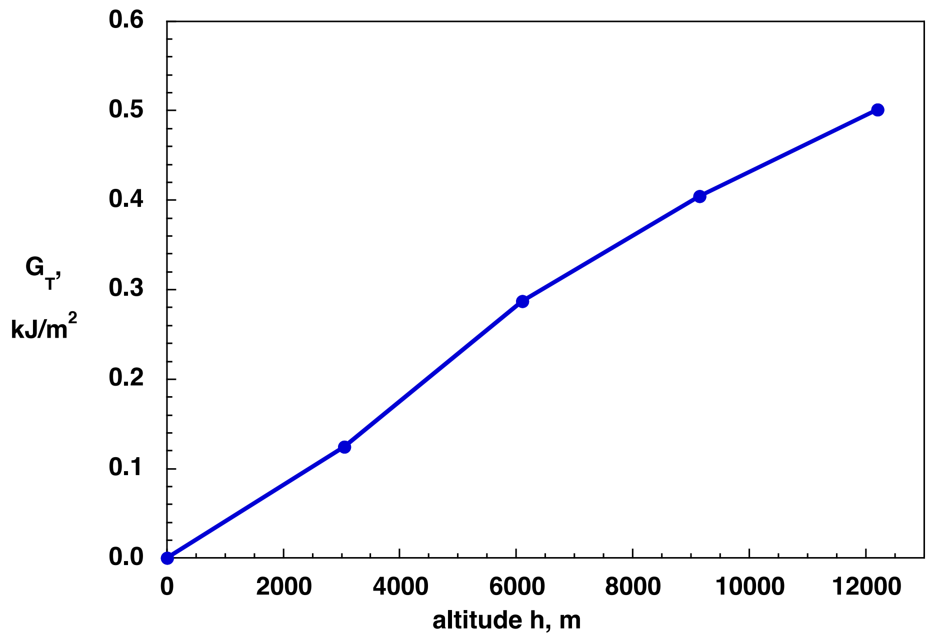
Flat panel under internal pressure loading – 3/3

NATIONAL INSTITUTE OF AEROSPACE

- **Conditions**
  - 12,192 m altitude (40,000 ft)
    - External pressure p=0.0188 MPa
    - External temperature T= 216.65 K
- **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





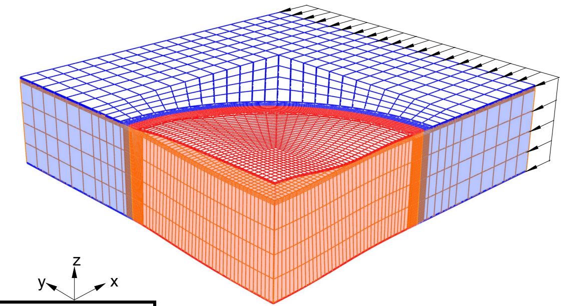
ANALYSIS RESULTS

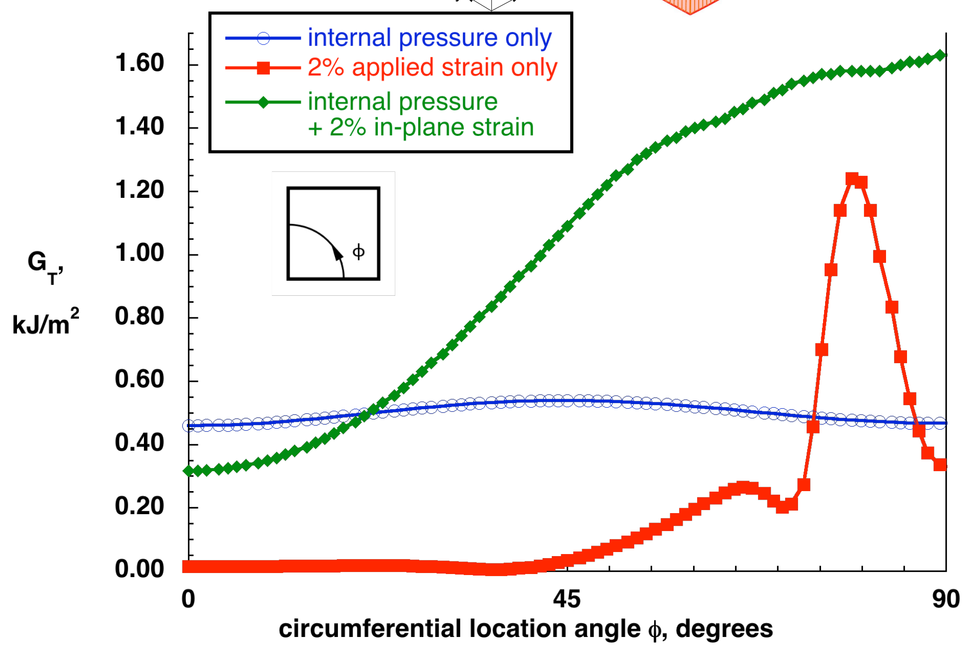
Flat panel under in-plane and combined loading

NATIONAL INSTITUTE OF AEROSPACE

- **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
  - In-plane strain aggravates the condition
  - Due to non-linearity superposition of the results is not possible

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



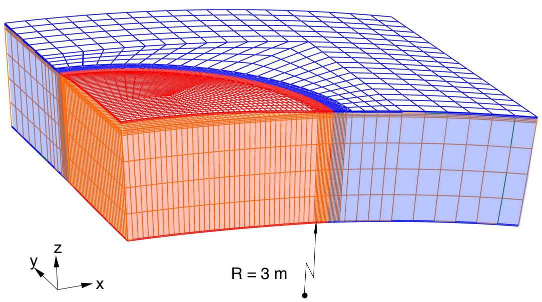


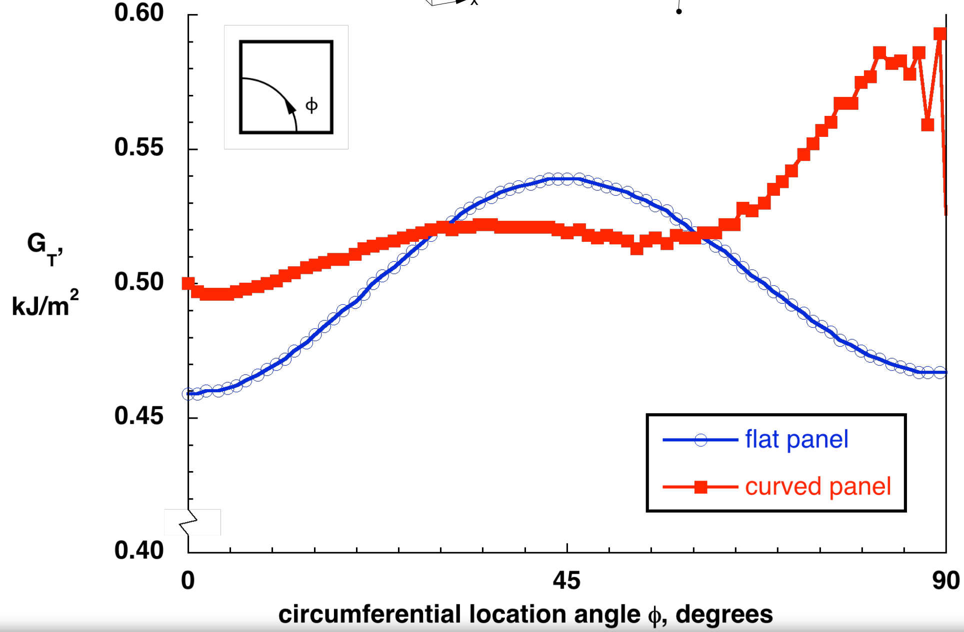
ANALYSIS RESULTS
Analysis of a curved panel

National Institute of Aerospace

- **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 further aggravate the condition
  - Additional analyses with different radii and more refined mesh should be preformed before a definite statement is made

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





SUMMARY

NATIONAL INSTITUTE OF AEROSPACE

- A sandwich panel containing a circular disbond at the face sheet/core interface was studied.
- A fracture mechanics approach was used.
- The pressure-deformation coupling was a focus of the analysis.
- Special fluid-filled cavities were used to model the entrapped air.
- Sandwich panels with large disbonds, thin face sheets, and thick cores are most critical.
- Computed averaged energy release rate values increased almost linearly with increasing altitude.
- The presence of the in-plane compressive strain aggravated the condition along the crack front.
- Due to the non-linearity of the problem, the results for combined load cases cannot simply be obtained by superposition of the individual load cases.
- For a curved panel with 3 m radius, the computed energy release rate values were higher than the values computed for a flat panel.

CONCLUDING REMARKS

NATIONAL INSTITUTE OF AEROSPACE

- Overall, the finite element analysis with fluid cavities appears to perform well and is capable of capturing the pressure-deformation coupling in the disbonded section of the panel.
- Based on the current preliminary results, however, it is recommended that additional validation studies be performed to compare.
  - The computed local deformation field of the disbonded face sheet with far field measurements
  - The computed pressure inside the cavity with measured values.
- Additionally, analyses of curved panels with different radii should be performed before a definite statement about the effect of panel curvature on the crack tip loading is made.
- Methods development will continue within the Disbond/Delamination Task Group in CMH-17

ACKNOWLEDGEMENTS

National Institute of Aerospace

The analyses were performed at the Durability, Damage Tolerance and Reliability Branch at NASA Langley Research Center, Hampton, Virginia, USA while Zhi Chen was a participant in the Langley Aerospace Research Student Scholars (LARSS) program. Ronald Krueger (NIA) was supported under contract NNL09AA00A and Martin Rinker was a visiting scientist at the National Institute of Aerospace (NIA).

NATIONAL INSTITUTE OF AEROSPACE

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

Zhi M. Chen
University of California at San Diego, La Jolla, USA

Ronald Krueger
National Institute of Aerospace, Hampton, VA, USA

Martin Rinker
Rolls-Royce Deutschland Ltd & Co KG, Dahlewitz, Germany

The Aerospace Corporation, El Segundo, CA, June 25, 2015

Work was funded by NASA Langley Research Center under contract number NNL09AA00A

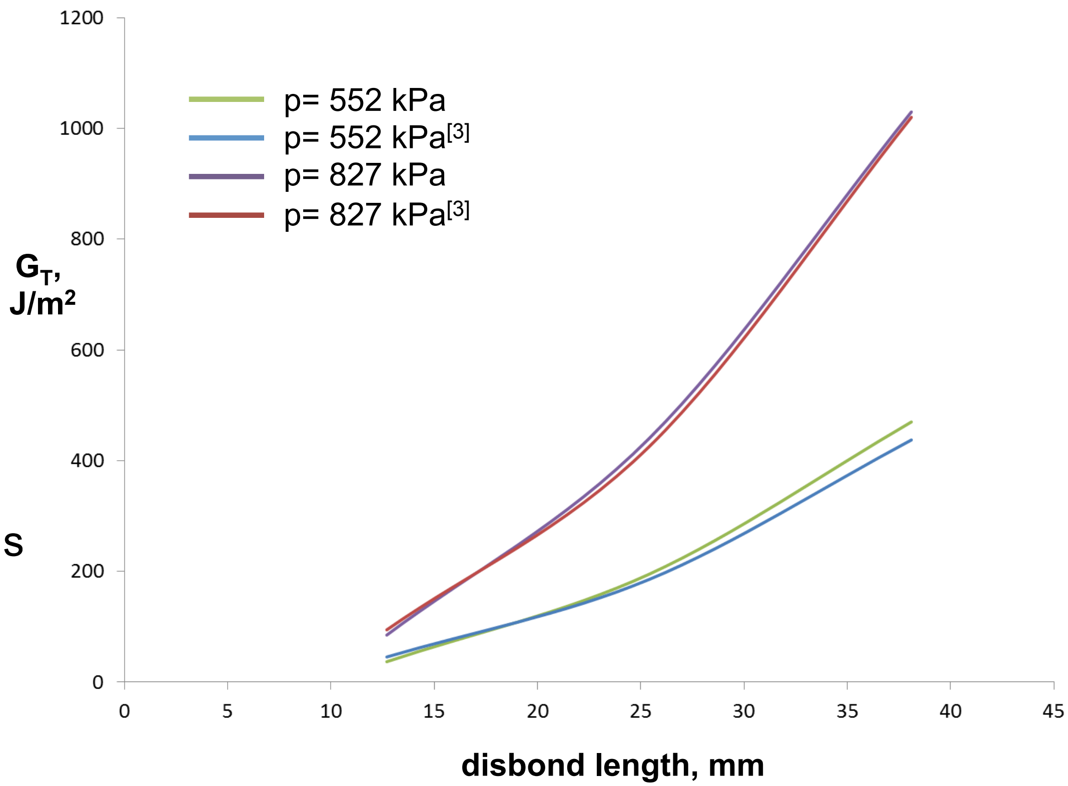
BACKUP SLIDES

National Institute of Aerospace

INITIAL MODEL VERIFICATION AND VALIDATION – 1/2

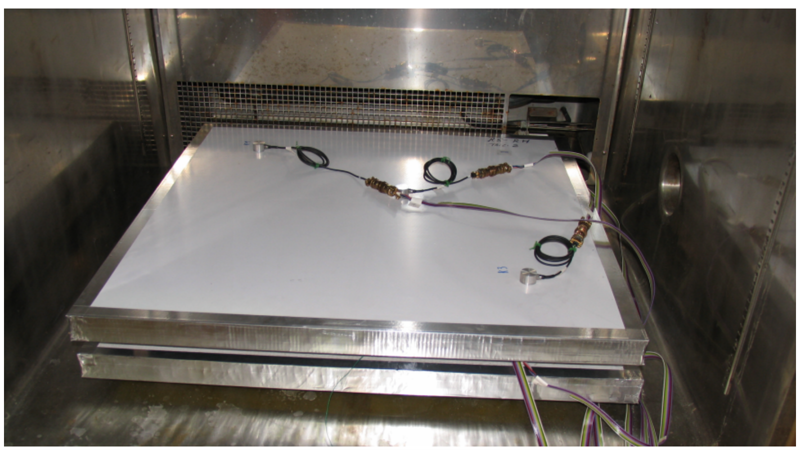
NATIONAL INSTITUTE OF AEROSPACE

- **X-33 cryogenic fuel tank**
  - NASA sandwich disbond investigation[3]
    - Square delamination
    - Panel pressurized by a compressor
    - Defined load, no pressure-deformation coupling
    - Calculations were performed using surface loads
  - Current analysis approach[6]
    - Same dimensions as NASA publication
    - Pressure application with Abaqus fluid elements
    - VCCT calculation using post-processing routine
  - Result comparison
    - Good correlation between G_T values calculated using different models



INITIAL MODEL VERIFICATION AND VALIDATION – 2/2

- **Sandwich panel with disbond**
  - Airbus test in vacuum chamber[4]
    - 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



  - Current analysis approach
    - Same dimensions as Airbus panel
    - Pressure pressure-deformation coupling solved with Abaqus fluid elements
  - Result comparison
    - Pressure-deformation coupling is correctly solved via Abaqus Fluid Cavity Simulation
    - 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