Integrated Design and Analysis Overview

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3rd Gen Airframe/TPS:

Integrated Design and Analysis

- **PMC Damage Tolerance & Repair**
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- **Safe Structures Design Technologies**
  - **POC:**
    - Dr. Damodar R. Ambur, NASA LaRC
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PMC Damage Tolerance and Repair
Goals & Objectives

- Develop methodology for assessing the effects of manufacturing defects
- Develop damage tolerance criteria and damage tolerance database for RLV cryogenic tank structures
  - impact
  - pressure leakage
  - cryogenic permeation
  - validated damage prediction tools
- Develop repair technology

PMC Damage Tolerance and Repair
Current Program Status

- Initiated in FY1999 as Bantam Damage Tolerance Program
- Continued as PMC Damage Tolerance Program during FY2000 with reduced funding level
- Needs continuation to address technology issues that will limit composites application to cryogenic tank structures

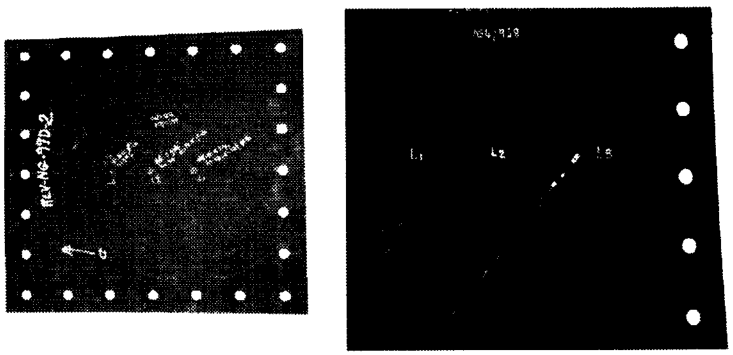
PMC Damage Tolerance and Repair
Current Technical Status

- **FY1999:**
  - Established damage tolerance requirements (impact, pressure leakage, cryogenic permeation)
  - Fabricated and impact tested flat and curved thin-skin panels made of different material forms
  - Conducted impact damage tolerance tests for damage resistance and barely visible damage (BVID); developed a 0.05 in. dent depth BVID criterion
  - Developed analytical methods to predict the impact response and damage resistance for curved, thin laminated composites
- **FY2000:**
  - Assessed existing repair methods for stiffened-skin and sandwich constructions
  - Developed analysis methods for optimally sizing bolted and bonded anisotropic patch repairs
  - Completed compression-after-impact strength tests on three material forms
  - Developed analytical models and methods to assess the critical size of delaminations for combined loading conditions
  - Assessed mixed-mode fracture toughness for IM7/977-2 and AS4/PEEK material systems at cryogenic temperatures
  - Conducting pressure leakage threshold tests

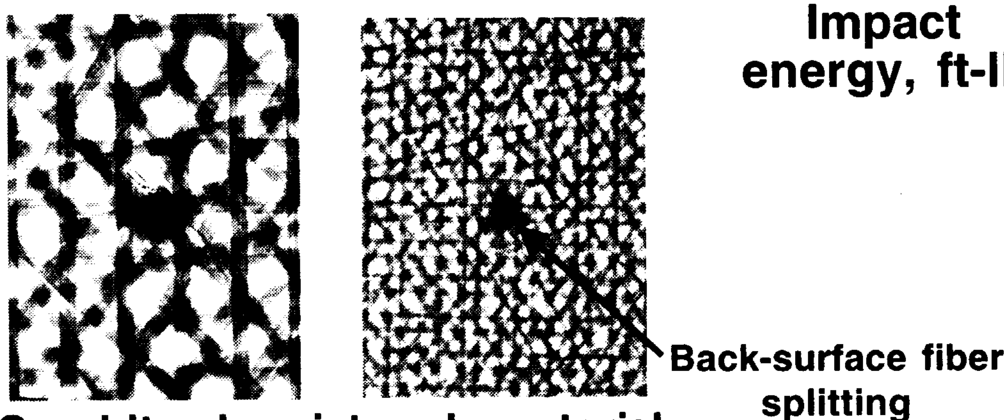
PMC Damage Tolerance and Repair

ENERGY THRESHOLDS FOR BARELY VISIBLE IMPACT DAMAGE OF CURVED THIN LAMINATES MADE OF DIFFERENT MATERIAL FORMS

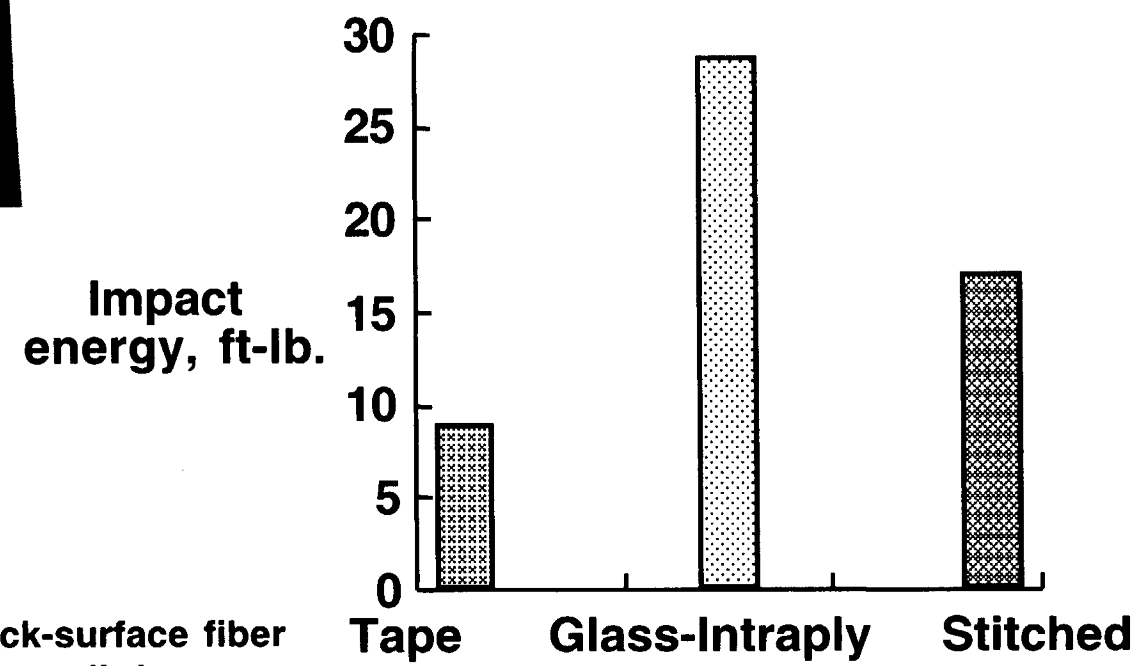
Criterion: 0.05-in. dent depth



Pre-impregnated tape material



Graphite-glass intra-ply material



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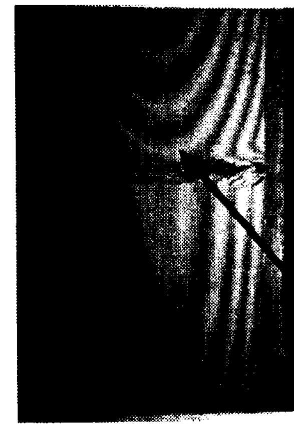
PMC Damage Tolerance and Repair

TYPICAL COMPRESSION RESPONSE AND FAILURE OF 16-PLY-THICK CURVED PLATES LOADED IN COMPRESSION

Displacement con

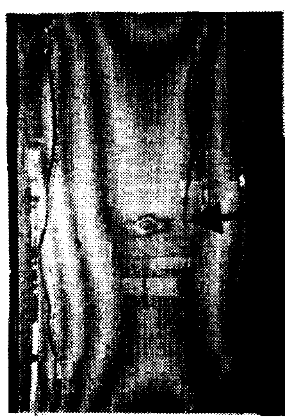
Failed specimen



Undamaged

Failure location

Impact damaged



Impact damage location

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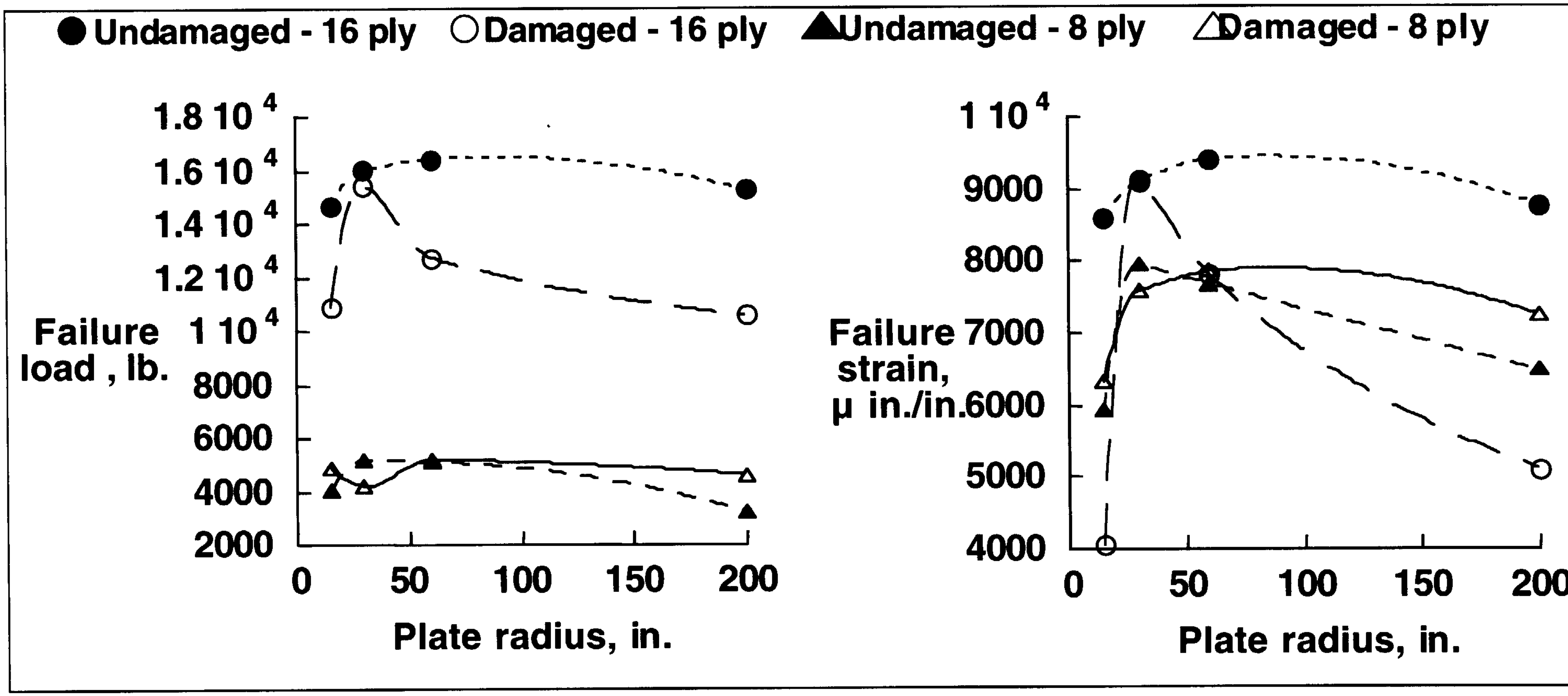
PMC Damage Tolerance and Repair

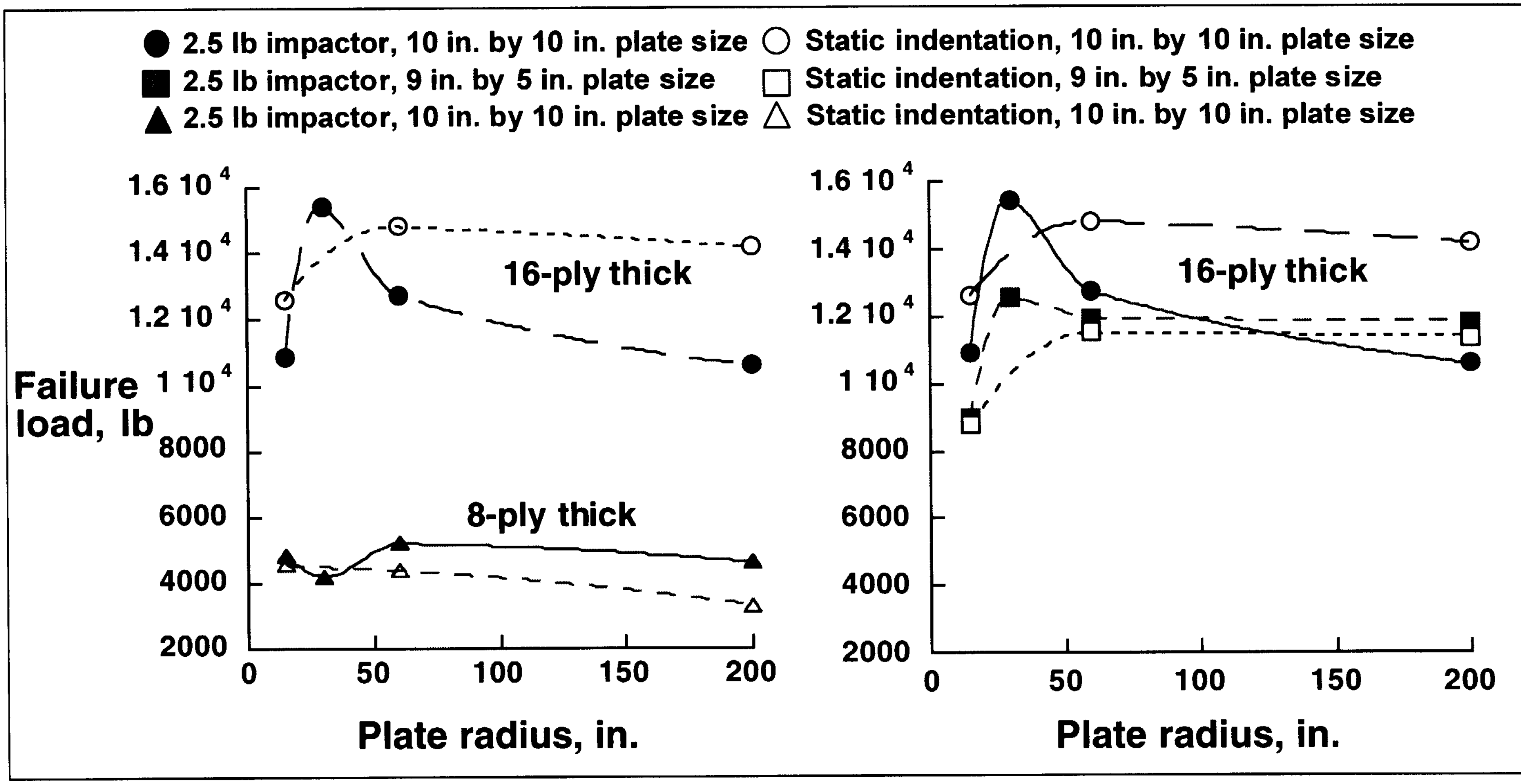
COMPARISON OF COMPRESSION-AFTER-IMPACT STRENGTH RESULTS FOR CURVED THIN PLATES

AS4-3502 Prepreg Tape Material



PMC Damage Tolerance and Repair

COMPARISON OF RESIDUAL STRENGTH RESULTS FOR PLATES SUBJECTED TO DROPPED-WEIGHT IMPACT AND STATIC INDENTATION DAMAGE



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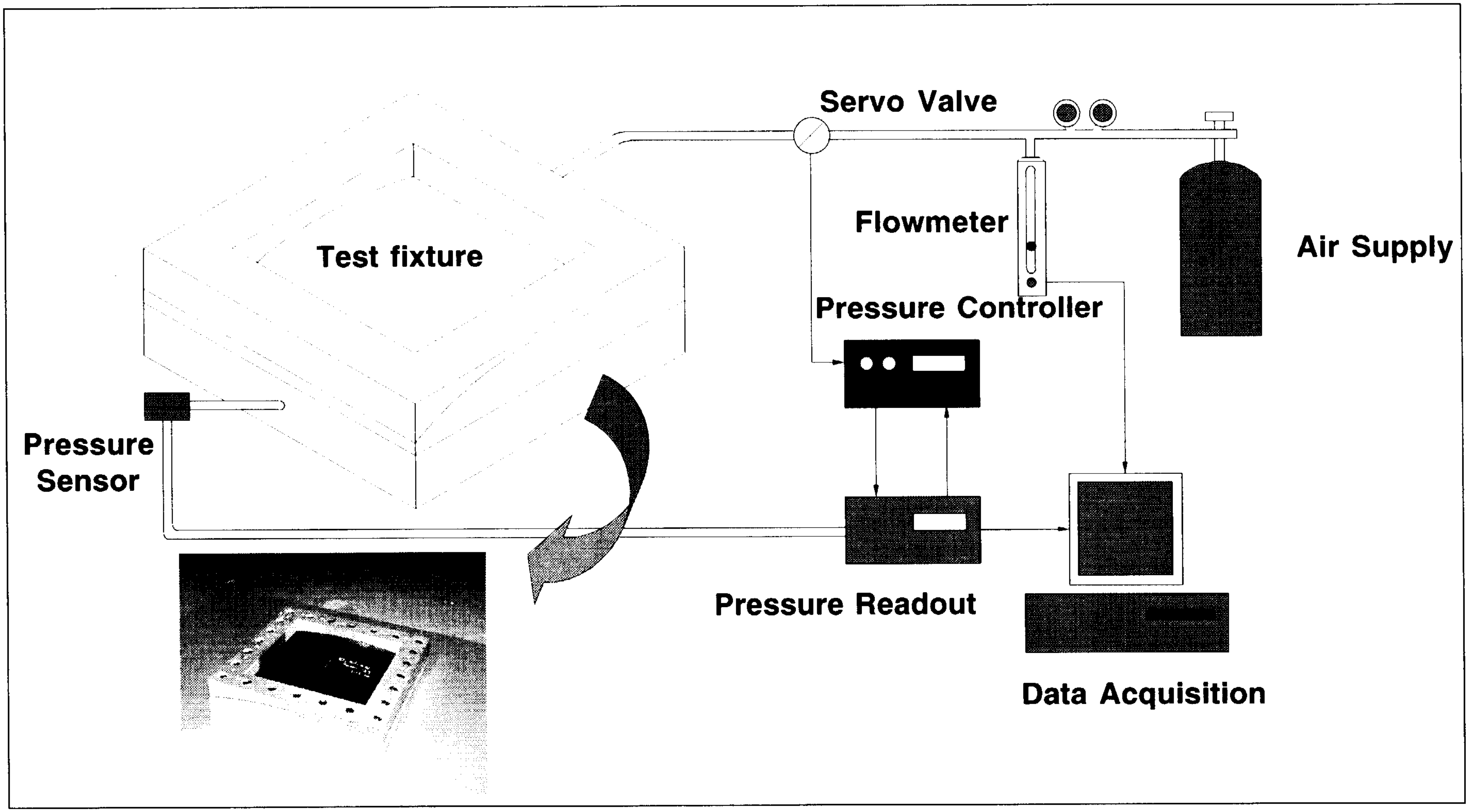
PMC Damage Tolerance and Repair

SCHEMATIC DIAGRAM OF TEST SET-UP FOR PRESSURE LEAKAGE TESTS



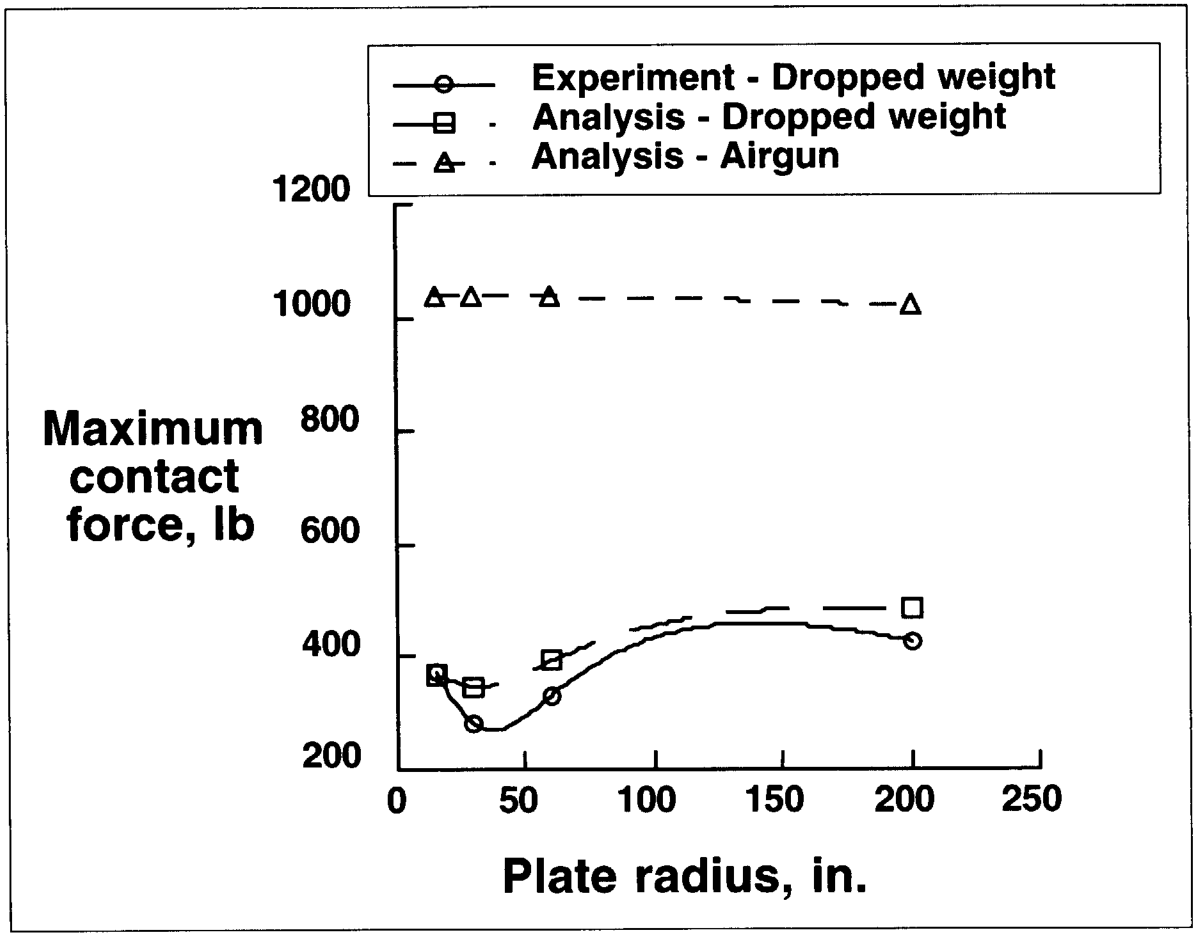
PMC Damage Tolerance and Repair

SUMMARY OF ANALYTICAL EFFORTS

- **Impact response of thin curved laminates**
- **Finite element analysis to assess critical manufacturing defect size for combined mechanical and thermal loaded structures**
- **Methods for optimizing bonded and bolted repairs**

PMC Damage Tolerance and Repair

DEVELOPED NONLINEAR ANALYSIS METHOD FOR ACCURATELY DETERMINING IMPACT RESPONSE AND DAMAGE INITIATION

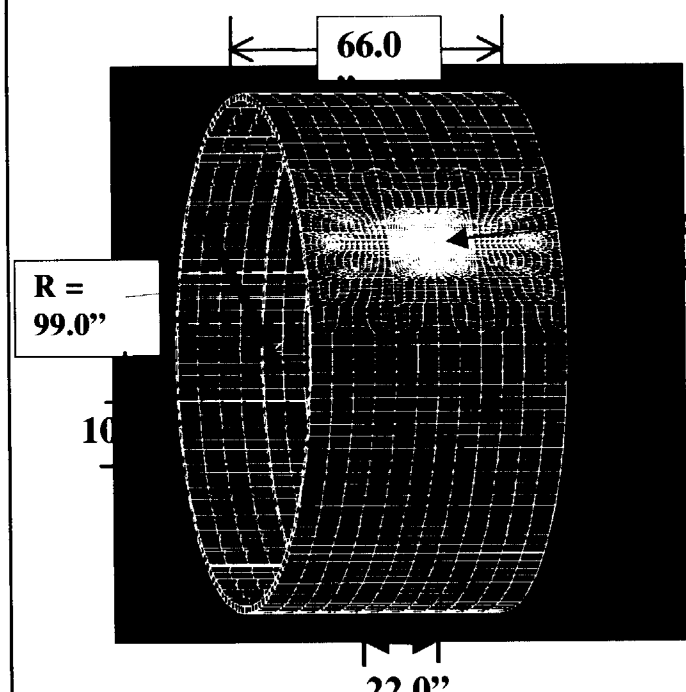


PMC Damage Tolerance and Repair

DELAMINATION GROWTH STUDIES

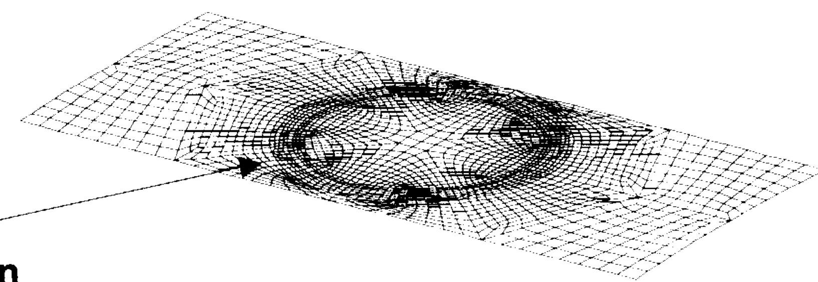
Modeling and Analysis Approach

Global model



- **Number of elements: 10,664**
- **Dof: 64,314**

Local model



- **Number of elements: 7,784**
- **Dof: 46,548**

Virtual crack closure technique to determine strain energy release rates.

Parametric studies with combined mechanical, thermal and internal pressure loading conditions.

- **Critical delamination size and location.**
- **Stiffened skin and sandwich constructions.**

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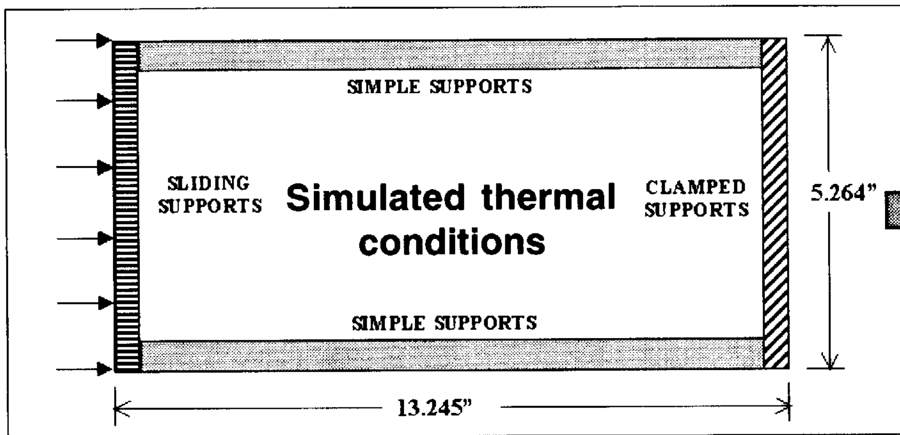
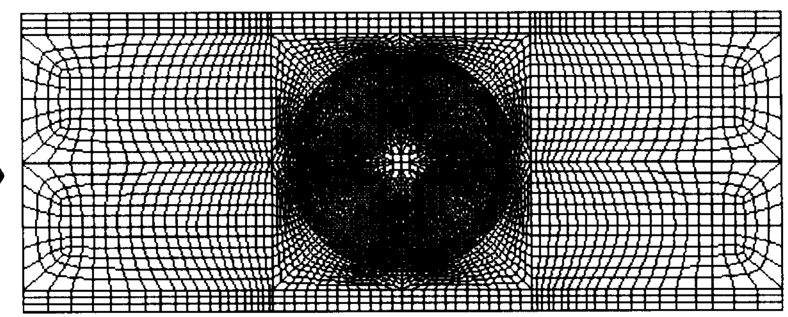
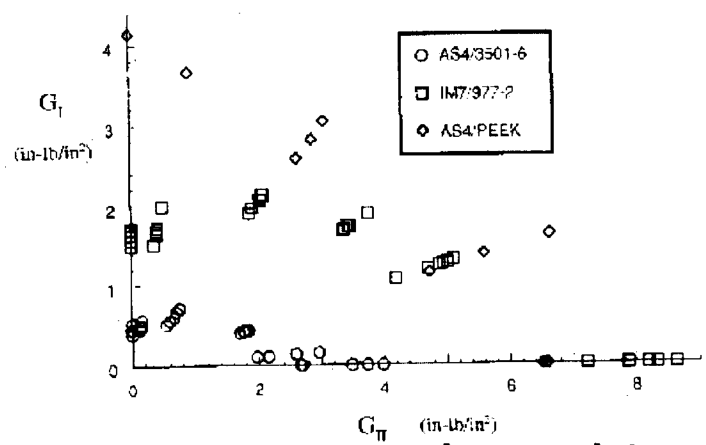
APPROACH FOR DELAMINATION GROWTH VERIFICATION TESTING



Test configuration



Finite element model



Fracture toughness data

Experimental verification of the critical size and location of delaminations

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NEAR-TERM PLANS

- Conduct pressure leakage tests on laminates made from different material forms
- Complete compression-after-impact strength tests on laminates made from different material forms
- Complete delaminated panel compression tests at cryogenic temperatures to verify criticality of the effects of defects

- PMC Damage Tolerance & Repair
  - POC - Dr. Damodar R. Ambur/Dr. Tom S. Gates, NASA LaRC
- Safe Structures Design Technologies
  - POC - Dr. Damodar R. Ambur, NASA LaRC

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Integrated Design and Analysis

Safe Structures Design Technologies

Goals and Objectives

- Develop validated second generation nonlinear progressive failure analysis method for composite structures subjected to combined mechanical loads
- Develop non-deterministic analysis and design methods that bound manufacturing uncertainties
- Conduct sensitivity analyses for manufacturing uncertainties
- Develop and demonstrate 3rd. generation progressive failure analysis method that includes combined mechanical and thermal load effects and delaminations
- Develop design and analysis relationships between structural weight and reliability for composite structures subjected to combined mechanical and thermal loads
- Develop hybrid deterministic and non-deterministic analysis and design methods that account for uncertainties at the material, structures, and mission levels
- Conduct hierarchical sensitivity analyses and identify design trends for multiple length scales subjected to combined loads

Safe Structures Design Technologies

- Current Program Status
  - Initiated in FY2000
  - Efforts continue under the 3rd Generation RLV Program
- Current Technical Status
  - Developed analytical methods and algorithms for using the current damage progression methods to predict the response of nonlinearly deformed structures
  - Conducted progressive damage verification tests on a compression-loaded composite cylinder
  - Conducting progressive damage verification tests on a composite panel subjected to nonlinear deformation with in-plane shear loading
  - Initiated tools development for predicting delamination initiation and growth

Safe Structures Design Technologies

MECHANICS TECHNOLOGY FOR PROGRESSIVE FAILURE ANALYSIS

- Embed progressive failure criteria and material degradation models with robust nonlinear structural mechanics solver STAGS
- Provide progressive damage capability coupled with large displacement, large rotation deformation states for laminated composite structures
- Provide traditional and state variable damage models
  - Maximum strain with ply discounting
  - Crack density based criteria for failure and degradation
  - User interfaces include ABAQUS/UMAT
- Incorporate artificial damping feature to mitigate non-convergence problems in re-establishing equilibrium
- Establish consistency between first and second variations for the energy functional
- Enhance visual depiction of progressive damage simulation
- *Increased design robustness through evaluation of extreme loading conditions and understanding possible composite structures failure scenarios*

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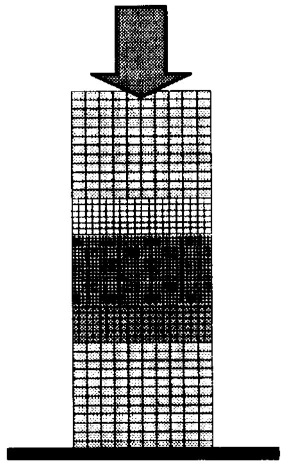
COMPRESSION-LOADED POSTBUCKLING COMPOSITE PANEL

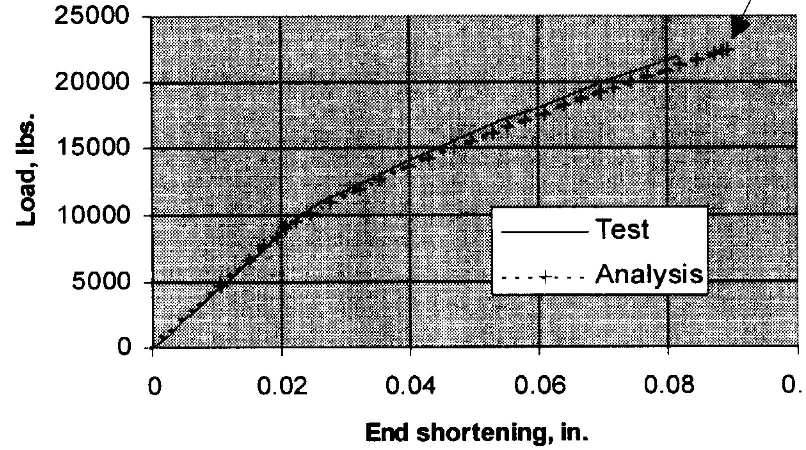


24-ply Graphite-epoxy orthotropic laminate

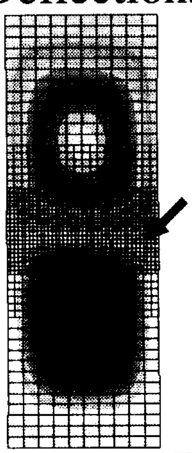
Starnes & Rouse, AIAA Paper 81-0543

Failure load =21,910 lbs
End shortening at failure = 0.0818 in.

Massive failures occur after this last solution

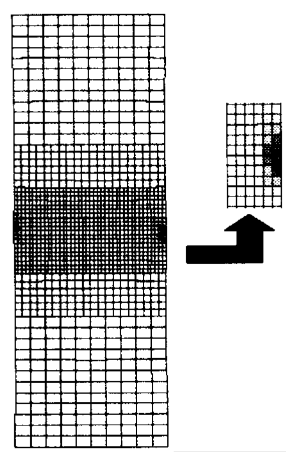


Out-of-plane Deflections



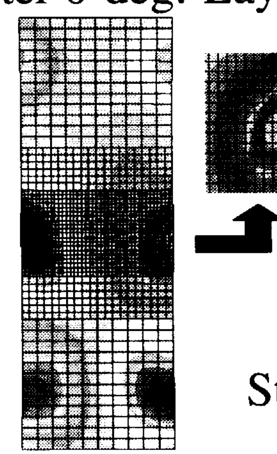
Node Line in Buckle Pattern

Percent Failed Plies



Close-up of Failed Region

Inplane Shear Stress in Outer 0-deg. Layer



Close-up Showing Stress Relief

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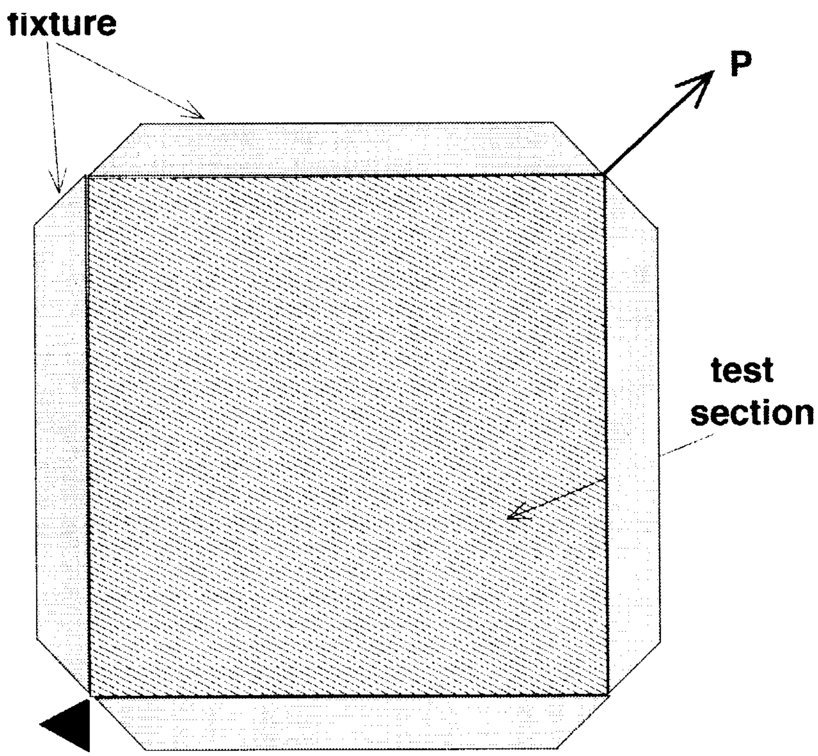
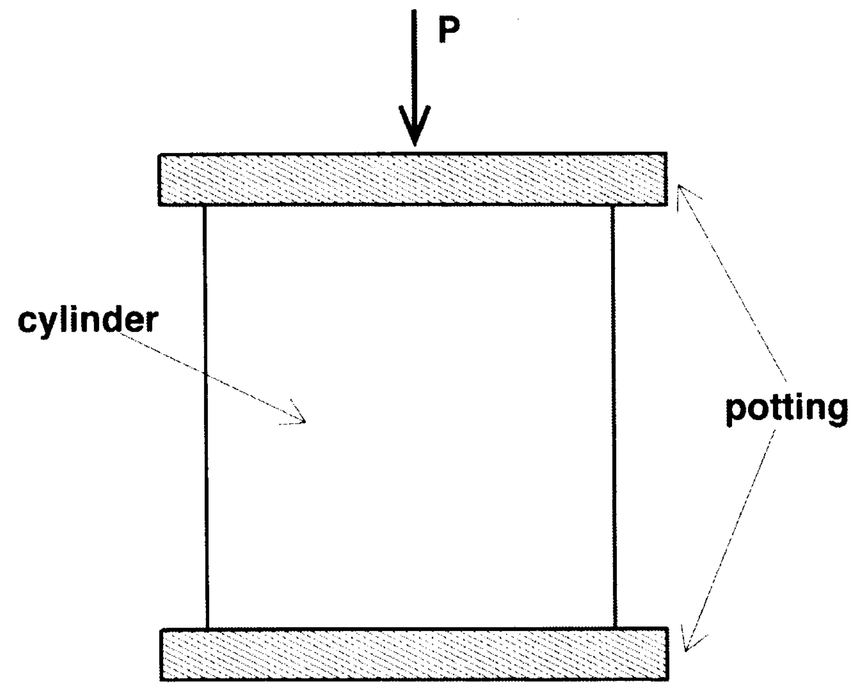
CORRELATION OF PROGRESSIVE FAILURE ANALYSIS RESULTS
FOR PANELS AND SHELLS

Stiffened and Unstiffened Panels
Loaded in a Picture Frame



Cylinders in Axial Compression



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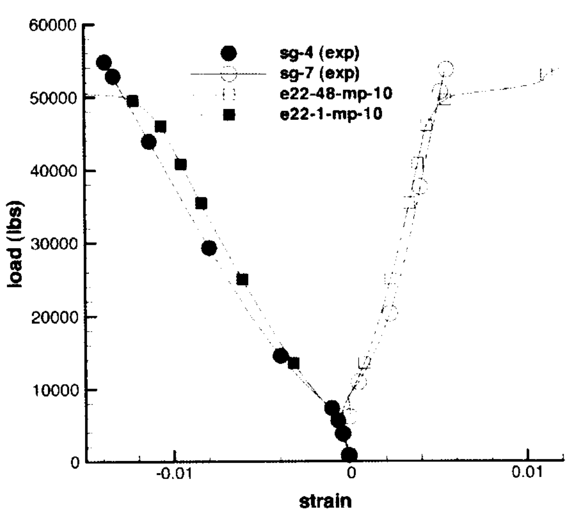
UNSTIFFENED PANEL LOADED IN PICTURE FRAME SHEAR

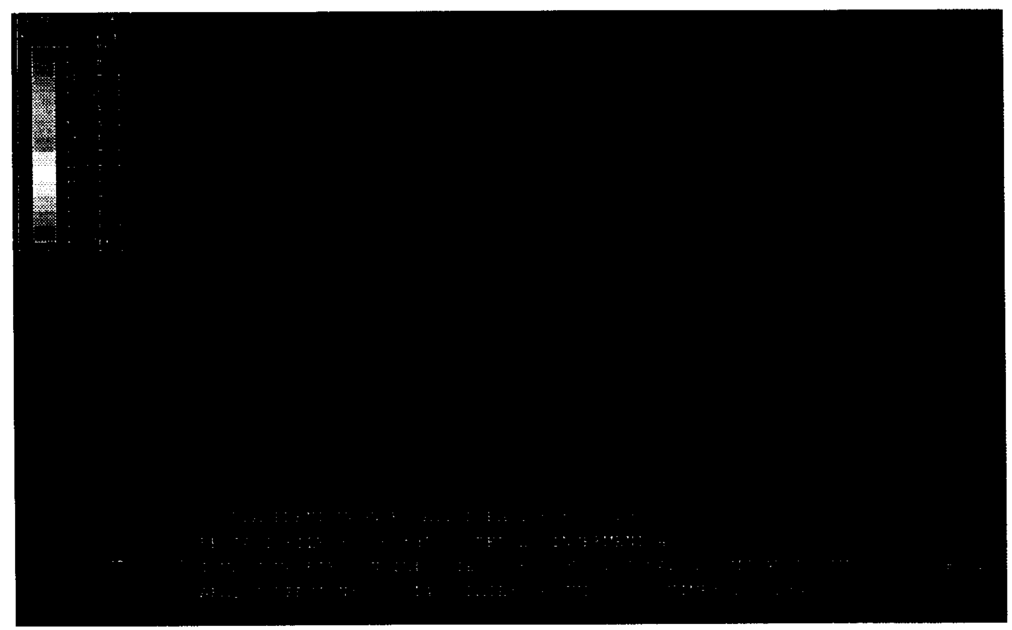
- Panel size: 12-in. by 12-in.; Thickness: 0.0896-in.
- Stacking sequence is $[\pm 45/0/90]_{2s}$
- E_{11} = 18.5 Msi, E_{22} = 1.67 Msi, G_{12} = 0.87 Msi, G_{13} = 0.87 Msi, G_{23} = 0.258 Msi, μ_{12} = 0.3
- X_T = 0.233 Msi, X_C = 0.21 Msi, Y_T = 0.0147 Msi, Y_C = 0.0287 Msi, SC = 0.02975 Msi

Failure Load:
54,807 lbs - Test
54,447 lbs - Analysis

Strain Normal to Fiber Direction on Top and Bottom Surfaces at Center of Test-Section



Map of Matrix Failure Region



3rd Gen Airframe/TPS:

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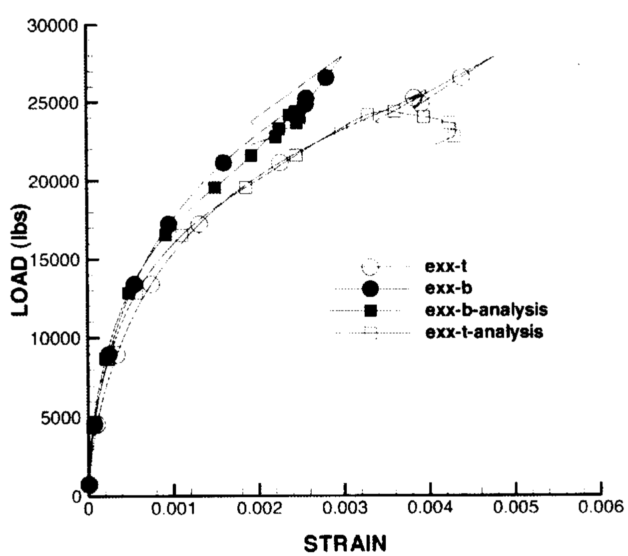
BEAD-STIFFENED PANEL LOADED IN PICTURE FRAME SHEAR

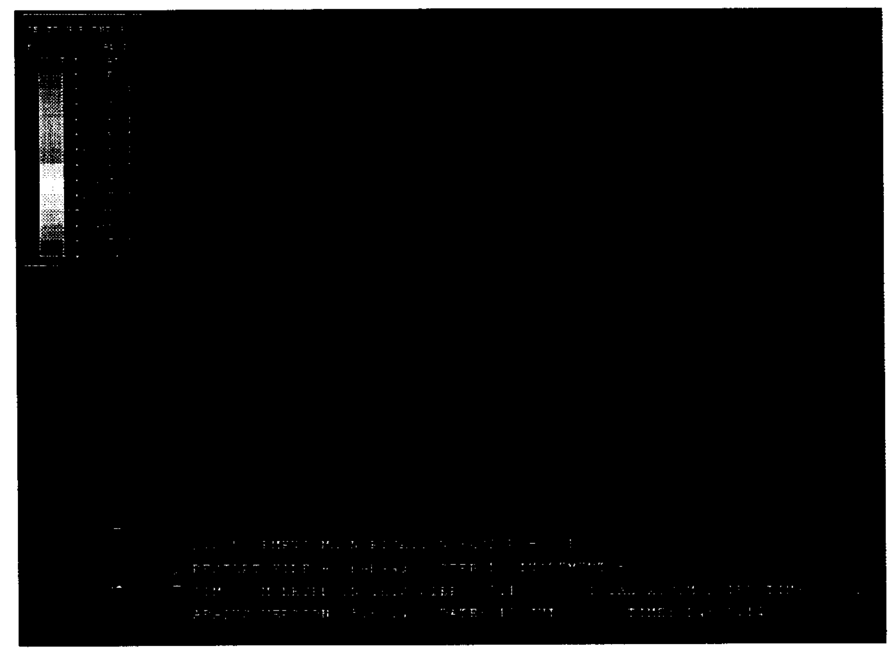
- Panel size: 12-in. by 12-in.; Thickness: 0.08-in.
- Stacking sequence is $[\pm 45/\pm 45/0/\pm 45/90]_s$
- E_{11} = 18.0 Msi, E_{22} = 1.50 Msi, G_{12} = 0.82 Msi, G_{13} = 0.82 Msi, G_{23} = 0.82 Msi, μ_{12} = 0.3
- X_T = 0.30 Msi, X_C = 0.20 Msi, Y_T = 0.013 Msi, Y_C = 0.031 Msi, SC = 0.027 Msi

Failure Load:
27,936.9 lbs -Test
26,995.9 lbs -Analysis

Axial Strain on the Top and Bottom Surfaces at Center of Panel



Map of Matrix Failure Region



3rd Gen Airframe/TPS:

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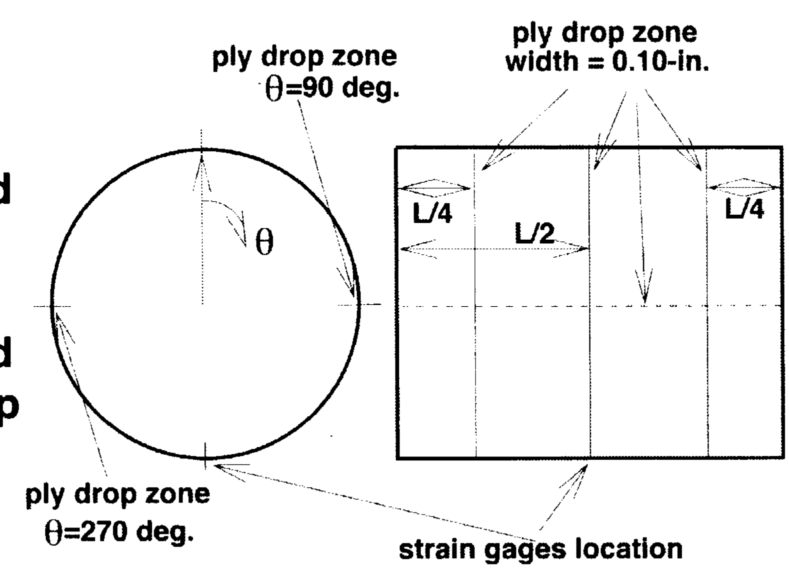
EFFECTS OF MANUFACTURING UNCERTAINTIES ON COMPOSITE CYLINDER AXIALCOMPRESSION RESPONSE

- Cylinder is 16.0-in. long; 16.0-in. diameter
- Laminate is $[\pm 45/0/90]_{2s}$ and 0.08-in. thick
- E_{11} = 19.0 Msi, E_{22} = 1.450 Msi, G_{12} = 0.814 Msi, G_{13} = 0.814 Msi, G_{23} = 0.55 Msi, μ_{12} = 0.3
- X_T = 0.156 Msi, X_C = 0.156 Msi, Y_T = 0.00725 Msi, Y_C = 0.0145 Msi, SC = 0.010826 Msi
- Two models were considered:
  - Model 1:
    - Measured geometric imperfection modeled
    - 7,560 elements; 4-noded
  - Model 2:
    - Measured geometric imperfection modeled
    - Laminate imperfection modeled as ply drop
    - 10,692 elements; 4-noded



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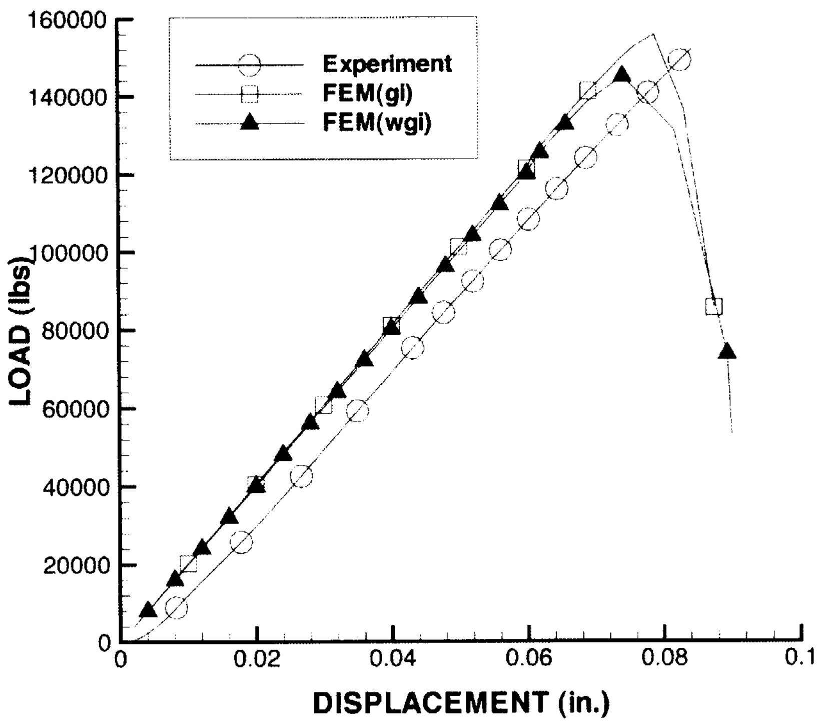
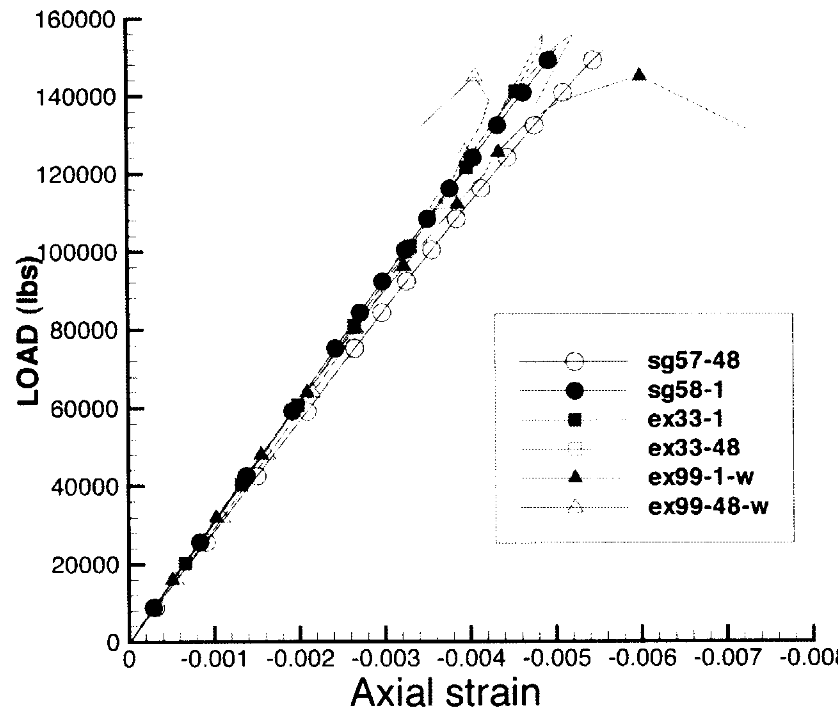
EFFECT OF MANUFACTURING UNCERTAINTIES ON
COMPOSITE CYLINDER AXIAL COMPRESSION RESPONSE (Contd.)

Load Vs. End-shortening Results



Load Vs. Axial Strain Results



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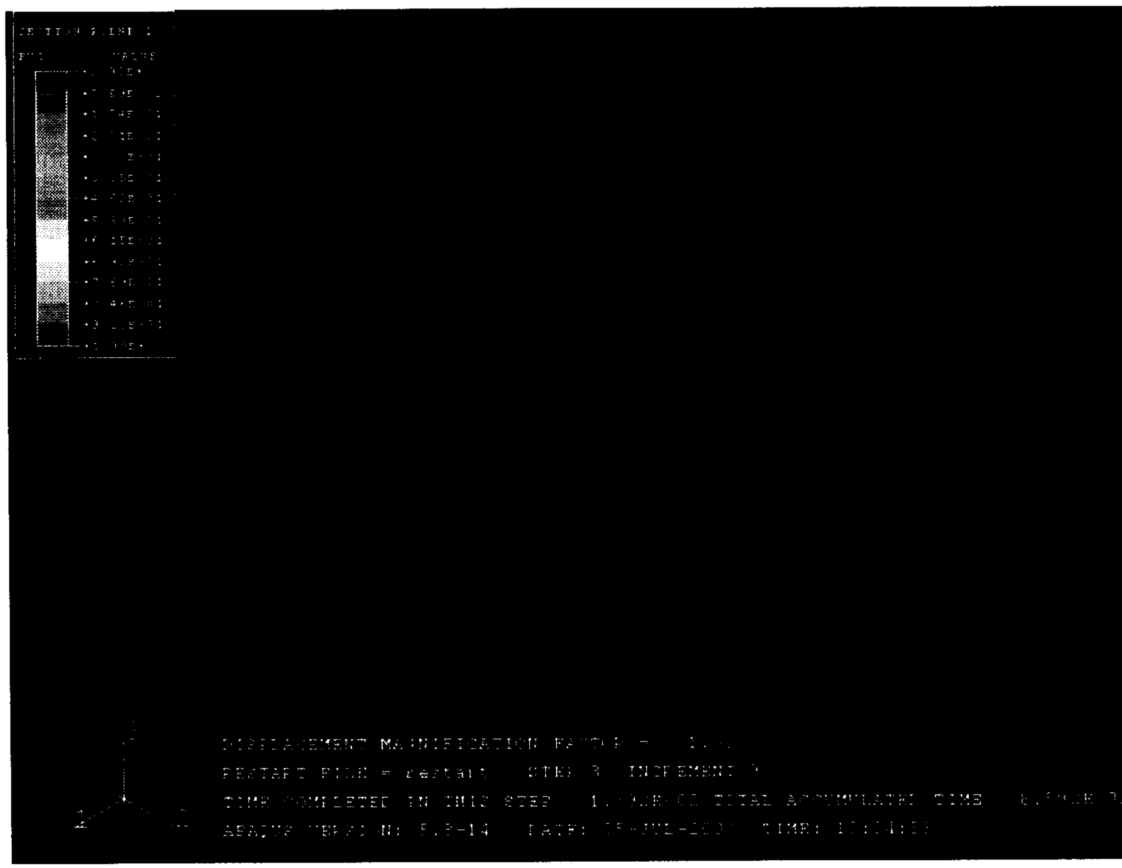
EFFECT OF MANUFACTURING UNCERTAINTIES ON COMPOSITE CYLINDER AXIAL COMPRESSION RESPONSE (Contd.)

Map of Failure Region for Model 1



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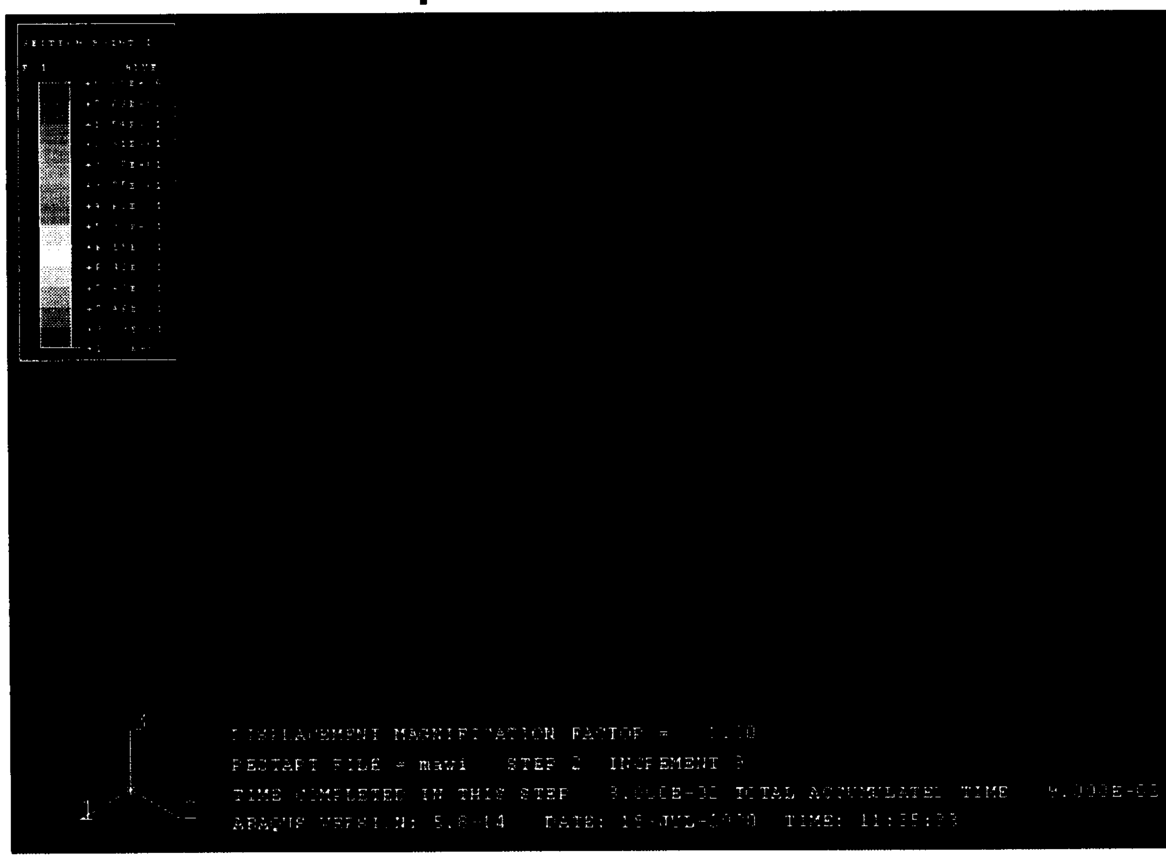
EFFECT OF MANUFACTURING UNCERTAINTIES ON COMPOSITE CYLINDER AXIAL COMPRESSION RESPONSE (Concluded)

Map of Failure Region for Model 2

Failure modes and damage region results obtained using Model 2 compare well with experimental results



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NEAR-TERM PLANS

- Conduct inplane shear tests on stiffened and unstiffened panels
- Correlate analytical and experimental results
- Continue efforts to validate the decohesion element for simulating the delamination failure mode
- Incorporate decohesion element into STAGS finite element analysis code