COMPRESSION FAILURE OF
COMPOSITE LAMINATES

R. B. Pipes
Center for Composite Materials
College of Engineering
University of Delaware
Newark, Delaware
This presentation will attempt to characterize the compressive behavior of Hercules AS-1/3501-6 graphite-epoxy composite. This involves:

- Studying the effect of varying specimen geometry on test results
- Determining end condition factors for IITRI fixture
- Determining transition region between buckling and compressive failure
- Defining failure modes and developing analytical models to describe and/or predict these modes

Modified IITRI compression fixture.
Failure modes

dimension units - inches (centimeters)

four specimens tested at each L/r ratio

Test coupons
Ultimate stress ($\sigma_u$) versus slenderness ratio ($L/r$)
Ultimate stress ($\sigma_u$) versus slenderness ratio ($L/r$)

---

Ultimate stress ($\sigma_u$) versus slenderness ratio ($L/r$)

---

269
Strain gage output
End condition factor \((l/k^2)\) versus slenderness ratio \((L/r)\)

Maximum compressive strength occurred at \(25 < L/r < 30\)

End condition factor increased as \(L/r\) increased

Failure modes change with varying \(L/r\)

Conclusions
Induce fatigue damage in the vicinity of a circular hole in a composite laminate through compressive loading

Observe and characterize the nature and extent of damage

Determine the influence of induced damage upon residual compressive failure

Objectives

<table>
<thead>
<tr>
<th>Specimen</th>
<th>S-Level</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(Static)</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>(Static)</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>(Static)</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>0.50</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>5</td>
<td>0.50</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>6</td>
<td>0.50</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>7</td>
<td>0.60</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>8</td>
<td>0.60</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>9</td>
<td>0.60</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>10</td>
<td>0.60</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td>11</td>
<td>0.60</td>
<td>$5 \times 10^6$</td>
</tr>
<tr>
<td>12</td>
<td>0.60</td>
<td>$5 \times 10^6$</td>
</tr>
</tbody>
</table>

Fatigue program
A: \([0_2/\pm45]_5s \leftrightarrow [0/0/45/-45/0/0/45/-45/0/0/45/-45/0/0/45/-45]_s\)

B: \([0/45/0/-45]_5s \leftrightarrow [0/45/0/-45/0/45/0/-45/0/45/0/-45/0/45/0/-45]_s\)

C: \([0/\pm45/90]_5s \leftrightarrow [0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45/90]_s\)

D: \([90/0/\pm45]_5s \leftrightarrow [90/0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45]_s\)

Laminate configurations

Modified IITRI compression fixture
Notched fatigue specimen

Micrograph section orientations
DIAGONAL SHEAR

NET COMPRESSION

Notched compression failure modes

Dual shear compression failure mode
Fatigue crack pattern

Cracked laminae by quadrant

Antisymmetric distribution of shearing stress \( \tau \)
Direction of shearing stress $\tau$

Shear-induced transverse tensile stresses
Laminate "A"; \([0_2/\pm 45]_{5}\); transverse section (50x)

Laminate "A"; \([0_2/\pm 45]_{5}\); axial section (50x)
Laminate "D"; \([90/0/\pm45]_5\); axial section (50×)

Near-surface delamination growth - laminate "A"
Near-surface delamination growth - laminate "C"

Near-surface delamination growth - laminate "D"
Two modes of compressive failure observed:

- Diagonal shear - predominant mode in fiber-dominated laminates
- Net compression - predominant mode in quasi-isotropic laminates

Both failure modes are characterized by local instability of individual lamina or small lamina subgroupings.

Mode of failure is related to the nature of the specimen delamination and the fatigue-induced cracking.

Angle plies crack in transverse tension during fatigue cycling with the cracked layers determined by quadrant location about the hole.

Primary direction of near-surface delamination progression is dependent upon the fiber direction of the laminate surface ply.

Laminate stacking sequence affects the nature of cracking as well as the predominant failure mode.

Failure mechanisms are not significantly different for the two resin systems.

Conclusions

- DEVELOPMENT OF AN EXPRESSION FOR THE BUCKLING OF THE DEBONDED REGION ABOVE AN IMPLANTED FLAW.

- VERIFICATION OF THE BUCKLING ANALYSIS THROUGH THE USE OF EXPERIMENTAL TESTING.

- DEVELOPMENT OF AN UNDERSTANDING, THROUGH EXPERIMENTAL TESTING, OF THE INFLUENCE OF IMPLANTED FLAWS ON THE COMRESSIVE PERFORMANCE OF SEVERAL GRAPHITE/EPOXY LAMINATES.

Objectives
• Debond defects may allow for premature compressive failure of laminates.

• Instability analysis must treat asymmetric laminates and consider transverse shear deformations.

• Boundary geometry influences buckling load more than laminate asymmetry.

• Laminate geometry (fiber orientation and stacking sequence) strongly influences defect criticality.

• Defect instability precedes interlaminar crack propagation and ultimate failure.

• Simplified buckling analyses model instability initiation.

• Strength losses of 50 percent were observed.

Debond defect studies.

For an isotropic material

\[ D = \frac{Eh^3}{12(1-\nu^2)} \]

The potential energy for a plate with a single in-plane load is

\[ \frac{1}{2} \int_{S} \left[ D \left( (w_{xx} + w_{yy})^2 - 2(1-\nu)(w_{xx}w_{yy} - w_{xy}^2) \right) + [N_{xx}w_{x}^2] \right] dS = \text{Constant} \]

Inserting our assumed deflection shape

\[ w(x) = A \left[ 1 - \left( \frac{x}{R} \right)^2 \right]^2 \]

Performing the integration and the variation yields the buckling condition for the isotropic case

\[ N_{x_{\text{crit}}} = -\frac{32D}{R^2} \]
Approximate buckling strength for Rayleigh-Ritz approximation

Disbond load geometry
INSERTING THE DEFLECTION SHAPE AND PERFORMING THE INTEGRATION YIELDS

\[ N_{x_{\text{crit}}} = -\frac{24}{R^2} \left( \frac{D_{11}^* + D_{22}^*}{2} + \frac{D_{12}^* + 2D_{66}^*}{3} \right) \]

BY COMPARING ELEMENTS OF THE BENDING STIFFNESS MATRIX WE SEE THAT FOR AN ISOTROPIC MATERIAL

\[ D_{12} = \nu D \]

\[ D_{11} = D_{22} = D \]

\[ D_{66} = \frac{(1-\nu)}{2} D \]

INSERTING THESE INTO THE ORTHOTROPIC RESULT PRODUCE THE ISOTROPIC CASE.

\[ N_{x_{\text{crit}}} = -\frac{24}{R^2} \left( \frac{D + D}{2} + \frac{\nu D + 2(1-\nu)/2D}{3} \right) = -\frac{32D}{R^2} \]
NOTES: 1. LOADING PADS ARE 1.905 cm (.75 in) WIDE ALUMINUM 2. ACTUAL HEIGHT IS DETERMINED BY FACE THICKNESS 3. OVERALL BEAM LENGTH (PLUS OVERHANG) IS 66.0 cm (26.0 in)

Sample geometry

<table>
<thead>
<tr>
<th>Teflon Film Defect</th>
<th>Kapton Bag Defect</th>
<th>No Defect</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 in. Dia.</td>
<td>1.0 in. Dia.</td>
<td>0.5 in. Dia.</td>
</tr>
<tr>
<td>[0/±45]_{2s} (12 ply)</td>
<td>F_{12}-1-1*</td>
<td>F_{12}-2-1</td>
</tr>
<tr>
<td></td>
<td>F_{12}-1-2</td>
<td>F_{12}-2-2</td>
</tr>
<tr>
<td>[±45]_{2s} (8 ply)</td>
<td>F_{8}-3-1</td>
<td>F_{8}-2-1</td>
</tr>
<tr>
<td></td>
<td>F_{8}-3-2</td>
<td>F_{8}-2-2</td>
</tr>
<tr>
<td>[0/±45]_{s} (6 ply)</td>
<td>F_{6}-3-1</td>
<td>F_{6}-2-1</td>
</tr>
<tr>
<td></td>
<td>F_{6}-3-2</td>
<td>F_{6}-2-2</td>
</tr>
<tr>
<td>[90/±45]_{s} (6 ply)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

*Specimen Identification Number

Experimental test program
Load/strain data for sample F_6-1-2

Failure of a sandwich beam composite with a 1.5-in. circular defect located at the near surface
Buckling stress versus defect diameter for all laminates

Buckling results for 6-ply laminates
Influence of Kapton bag and Teflon film defects on residual strength of the \([\pm45]_{2S}\) laminate.

Effect of laminate thickness on residual strength of the \([0/\pm45]_nS\) laminate.
1.0-in. circular near-surface delamination prior to testing

1.0-in. circular near-surface delamination after buckling

1.0-in. circular near-surface delamination after 2000-kg applied load

Disbond propagation sequence
Load compressive failure in graphite/epoxy (200×)

- Study various defect configurations to evaluate the sensitivity of the laminate to defect materials and construction.

- Extend the work to defects located at other positions throughout the laminate thickness.

- Conduct testing designed to produce buckling in an effort to verify the buckling result.

- Produce a solution to the two-dimensional fracture problem which stems from the buckled geometry.

Recommendations for future work
LAMINATE RESIDUAL STRENGTH IS A FUNCTION OF FAILURE MODE FOR THE HIGH STRENGTH CONFIGURATIONS BUT NO INFLUENCE ON STRENGTH WAS SEEN FOR THE LOW STRENGTH LAMINATES.

CERTAIN LAMINATES FAIL BY A CHARACTERISTIC MECHANISM AND THIS MECHANISM MAY BE INDEPENDANT OF THE PRESENCE OF DELAMINATION FLAWS.

IMPLANTED FLAW CONSTRUCTION CAN HAVE A SUBSTANTIAL INFLUENCE ON COMPRESSIVE PERFORMANCE. THIS HIGHLIGHTS THE NECESSITY OF SELECTING AN APPROPRIATE DEFECT CONSTRUCTION WHEN MODELING A DELAMINATION.

THE OCCURRENCE OF BUCKLING PLAYS AN IMPORTANT ROLE IN THE FAILURE PROCESS BECAUSE DELAMINATION GROWTH OCCURS WITH THE ONSET OF DEFECT INSTABILITY.

THE BUCKLING ANALYSIS IS USEFUL IN PREDICTING THE DEFECT BUCKLING LOAD FOR THE THICKER LAMINATES BUT THE ACCURACY OF THE APPROXIMATION IS LOST FOR THE THIN 6 PLY RESULTS.

Summary
COMMENT

The fact that it is difficult to measure compressive strength in composites does not mean that there is no such property. Even if it were impossible to measure it, we would have to define it in order to deal with structures subjected to combined states of stress. It can be defined macroscopically as a structural failure of the particular lamina or laminate.

I. M. Daniel
Illinois Institute of Technology