COMPRESSION FAILURE OF COMPOSITE LAMINATES

R. B. Pipes
Center for Composite Materials
College of Engineering
University of Delaware
Newark, Delaware

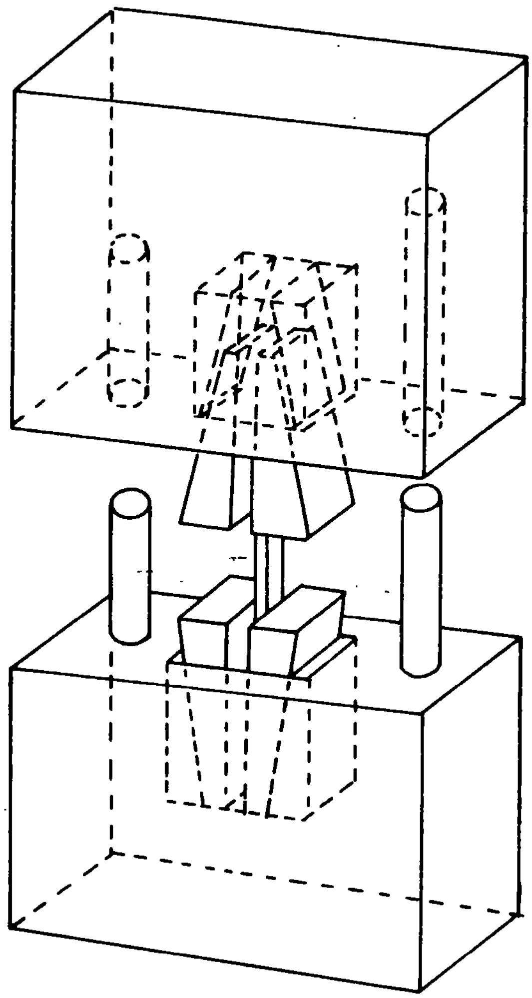
This presentation will attempt to characterize the compressive behavior of Hercules AS-1/3501-6 graphite-epoxy composite. This involves:

Studying the effect of varying specimen geometry on test results

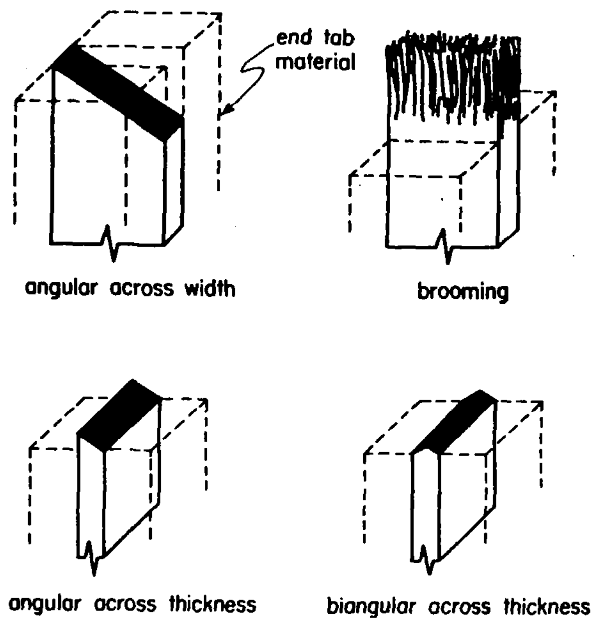
Determining end condition factors for IITRI fixture

Determining transition region between buckling and compressive failure

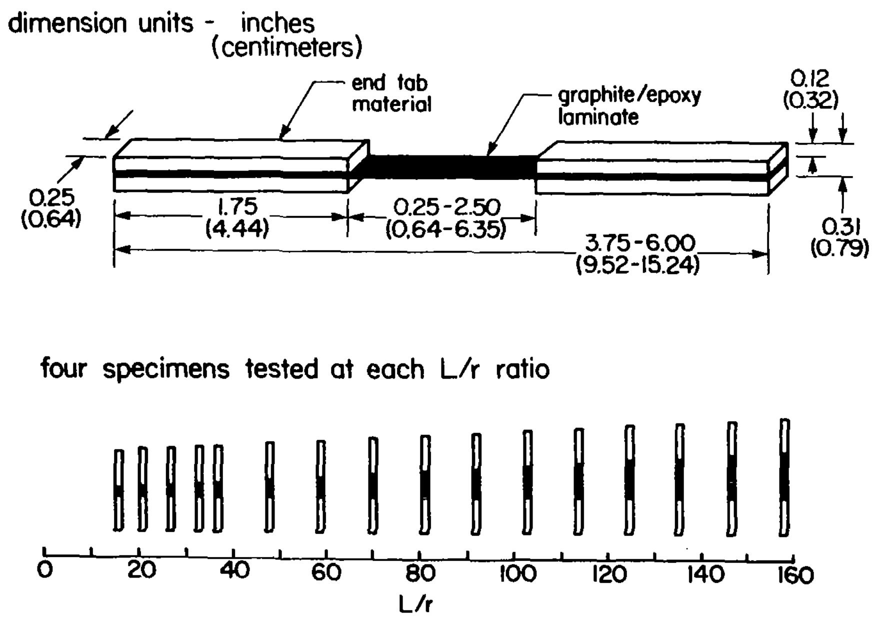
Defining failure modes and developing analytical models to describe and/or predict these modes



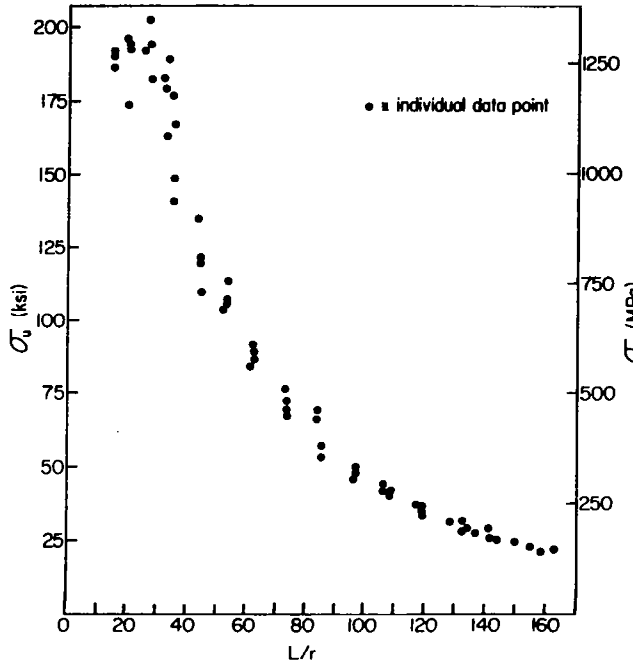
Modified IITRI compression fixture.



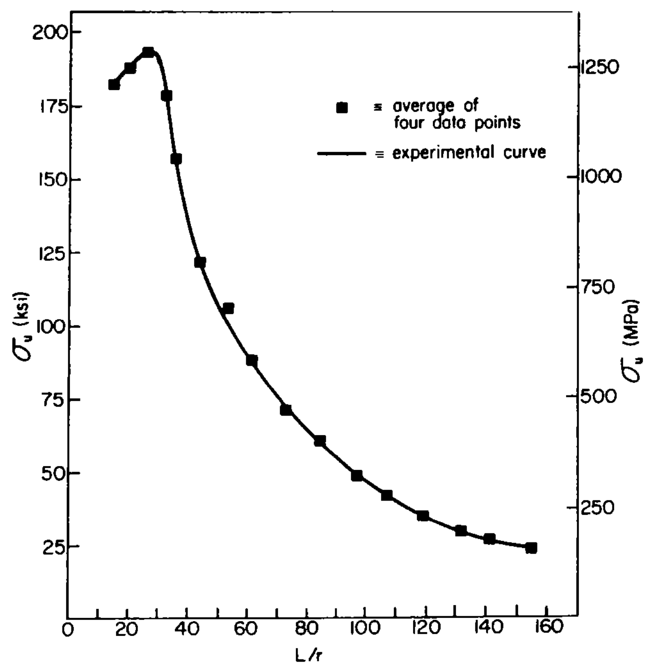
Failure modes



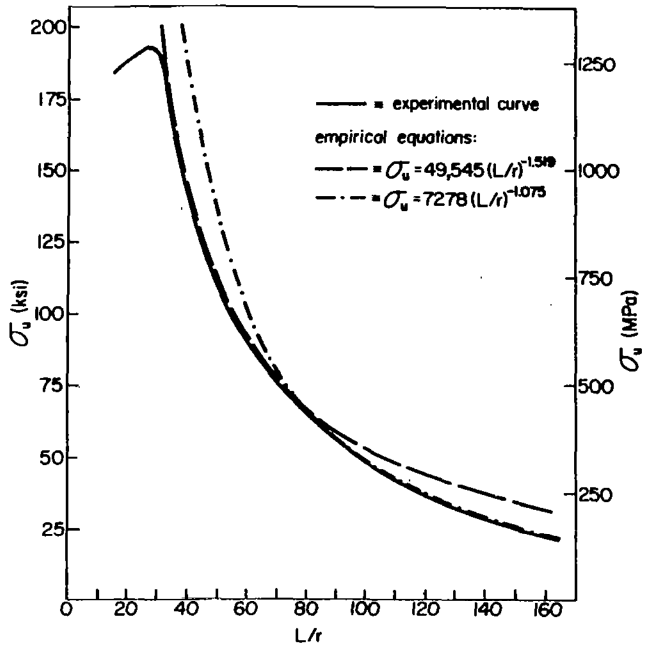
Test coupons



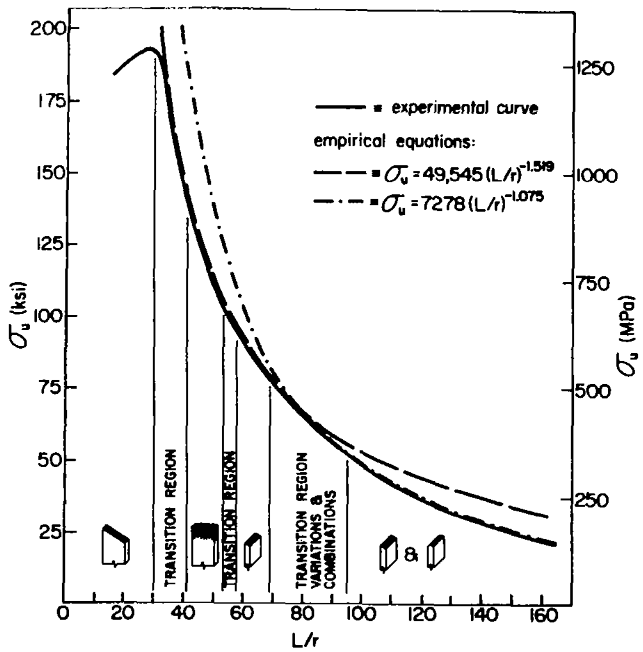
Ultimate stress (σ_u) versus
slenderness ratio (L/r)



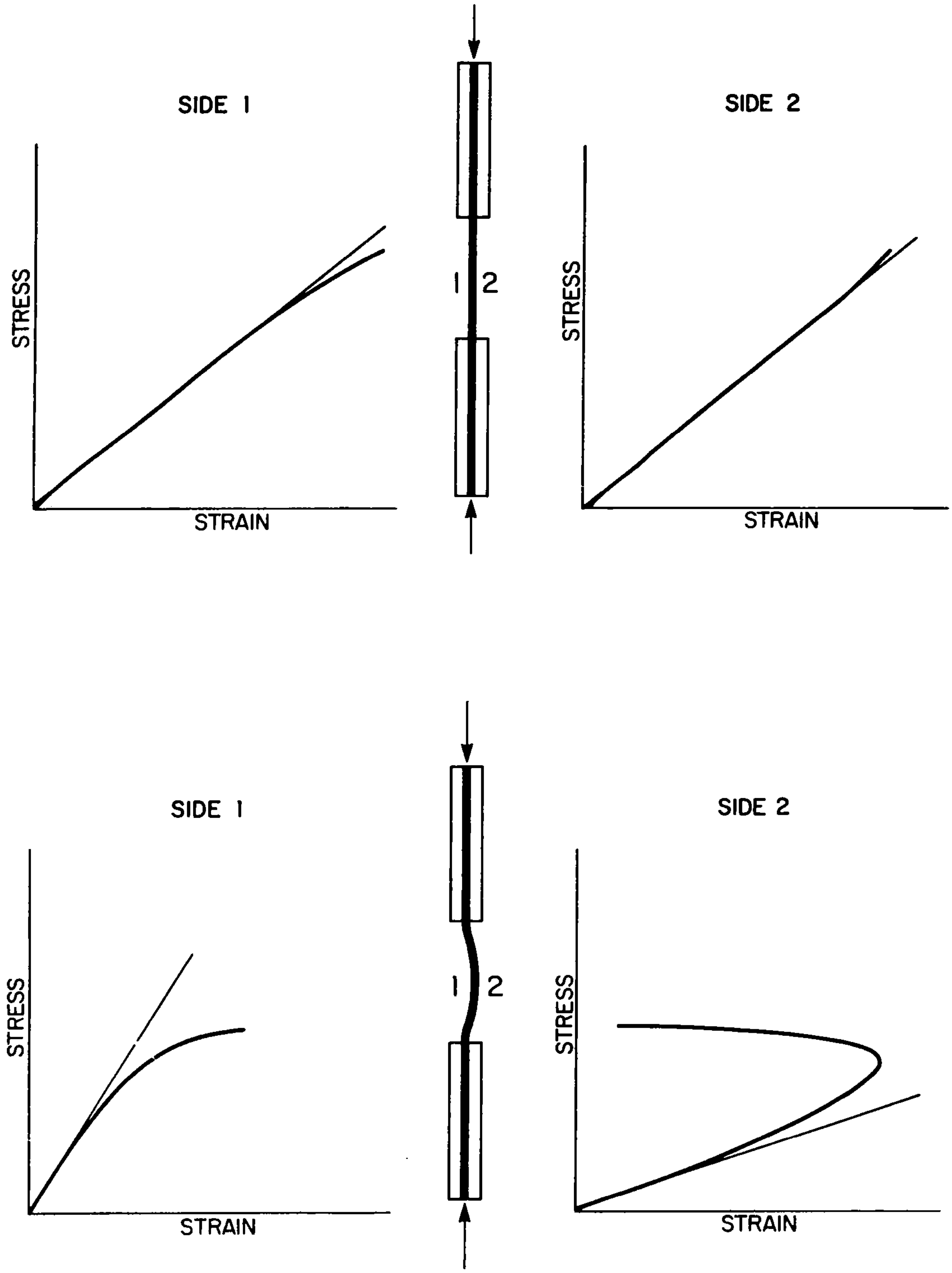
Ultimate stress (σ_u) versus
slenderness ratio (L/r)



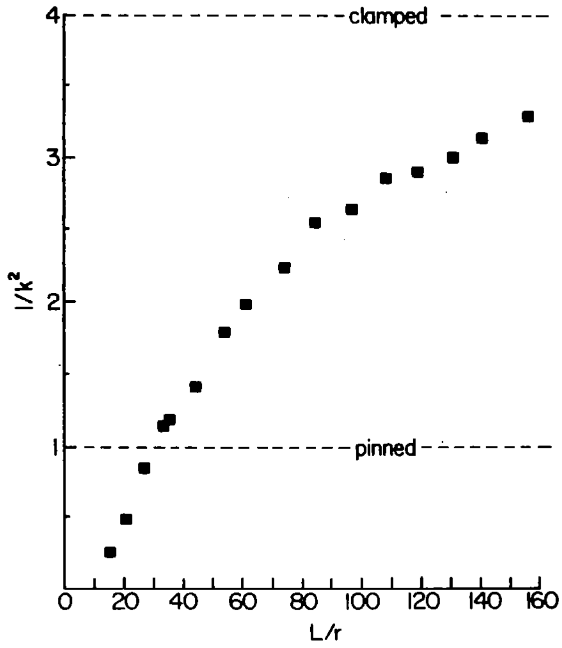
Ultimate stress (σ_u) versus slenderness ratio (L/r)



Ultimate stress (σ_u) versus slenderness ratio (L/r)



Strain gage output



End condition factor ($1/k^2$) 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

(R=0.1, frequency of 10 Hertz, ambient conditions)

Specimen	S-Level	Cycles
1	(Static)	--
2	(Static)	--
3	(Static)	--
4	0.50	1×10^6
5	0.50	1×10^6
6	0.50	1×10^6
7	0.60	1×10^6
8	0.60	1×10^6
9	0.60	1×10^6
10	0.60	5×10^6
11	0.60	5×10^6
12	0.60	5×10^6

Fatigue program

A: $[0_2/\pm45]_{5s}$ <=>

$[0/0/45/-45/0/0/45/-45/0/0/45/-45/0/0/45/-45/0/0/45/-45]_s$

B: $[0/45/0/-45]_{5s}$ <=>

$[0/45/0/-45/0/45/0/-45/0/45/0/-45/0/45/0/-45/0/45/0/-45]_s$

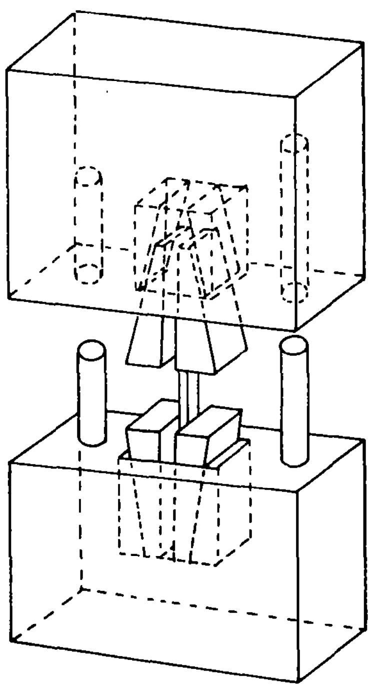
C: $[0/\pm45/90]_{5s}$ <=>

$[0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45/90]_s$

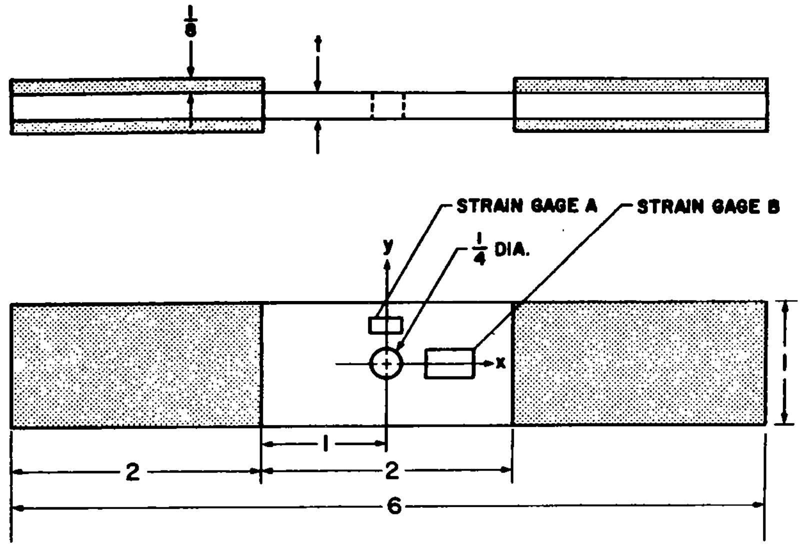
D: $[90/0/\pm45]_{5s}$ <=>

$[90/0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45/90/0/45/-45]_s$

Laminate configurations

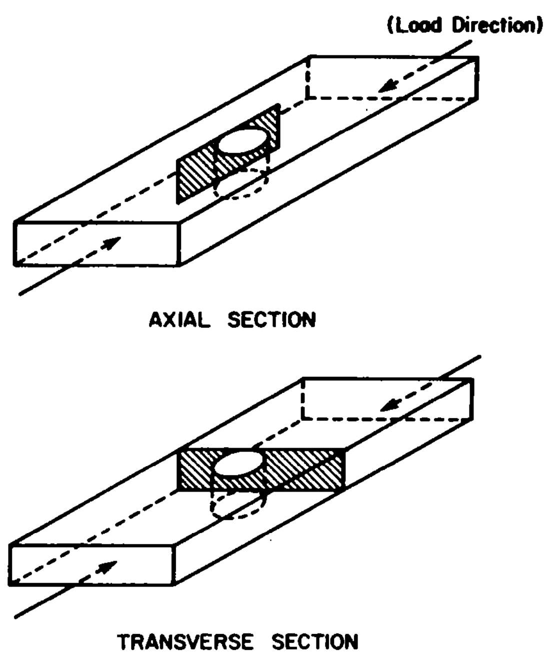


Modified IITRI compression fixture

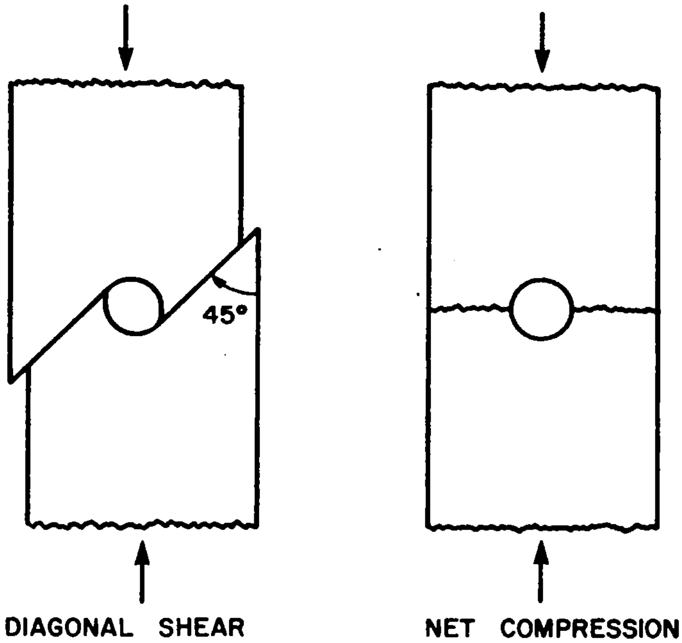


MICRO-MEASUREMENTS
STRAIN GAGE A: EA-06-125BZ-350
STRAIN GAGE B: EA-06-125AC-350

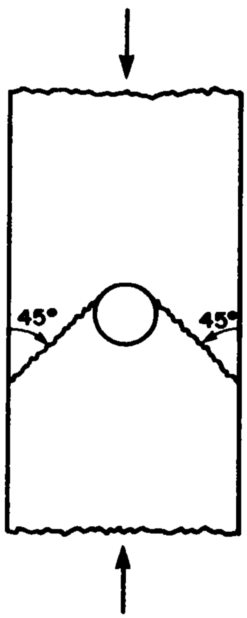
Notched fatigue specimen



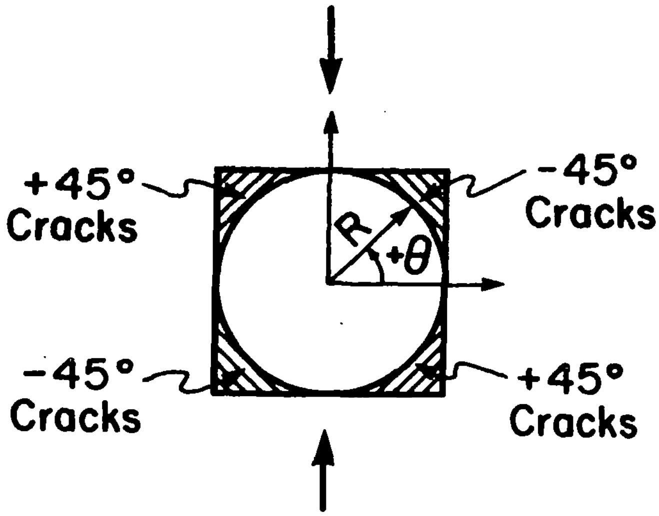
Micrograph section orientations



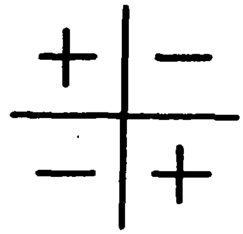
Notched compression failure modes



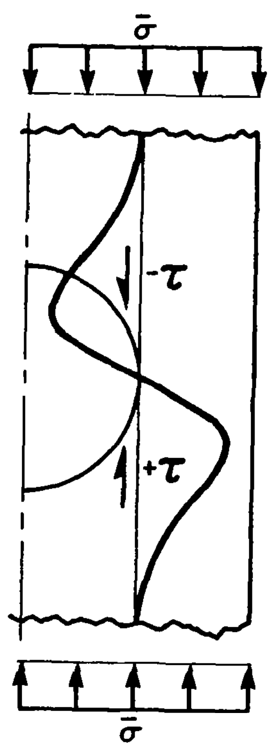
Dual shear compression failure mode



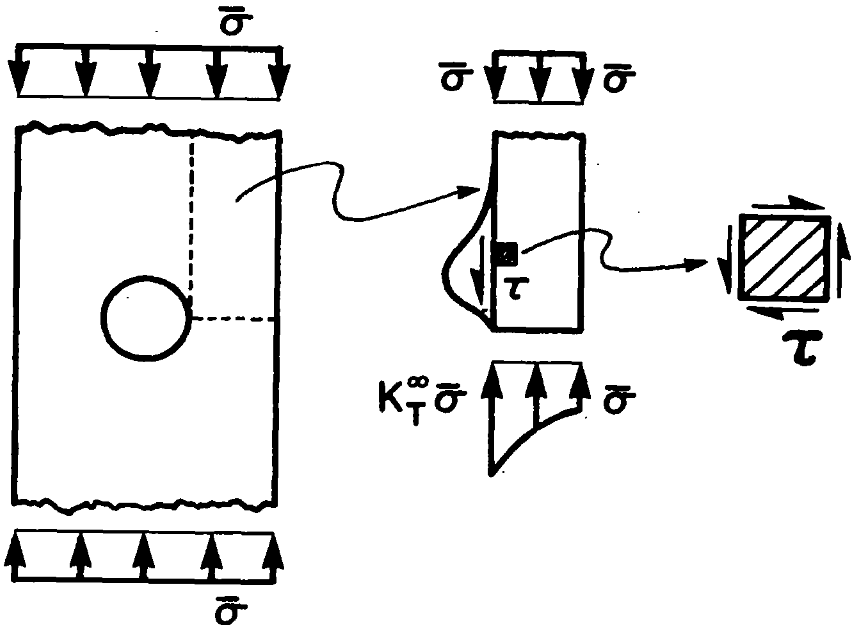
Fatigue crack pattern



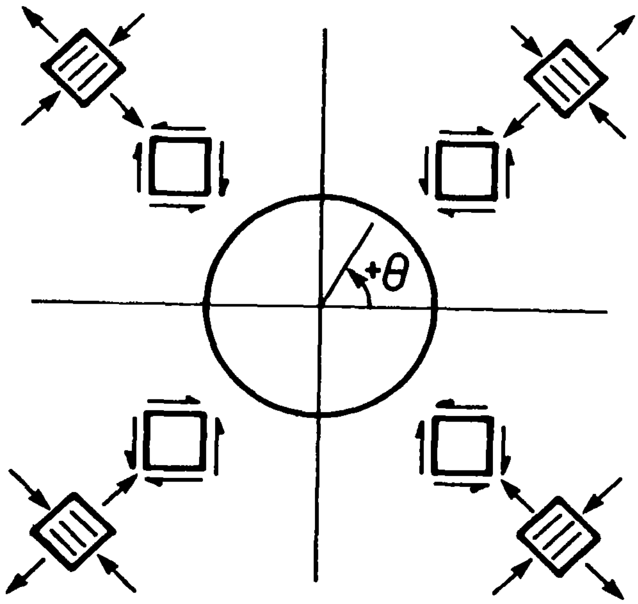
Cracked laminae by quadrant



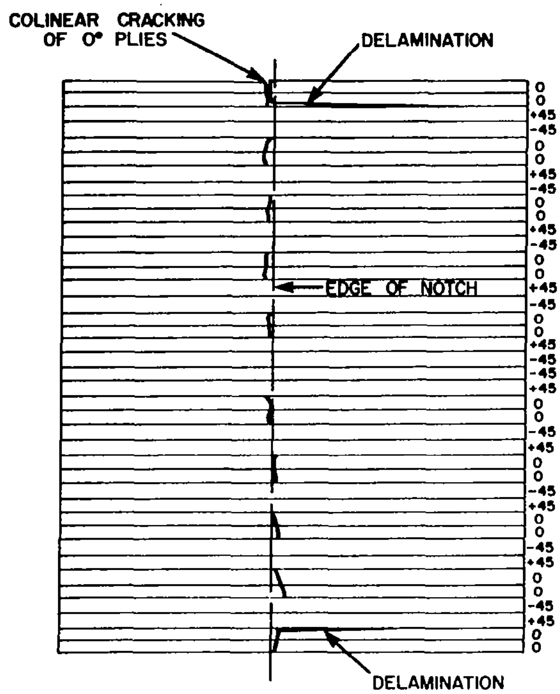
Antisymmetric distritution of shearing stress τ



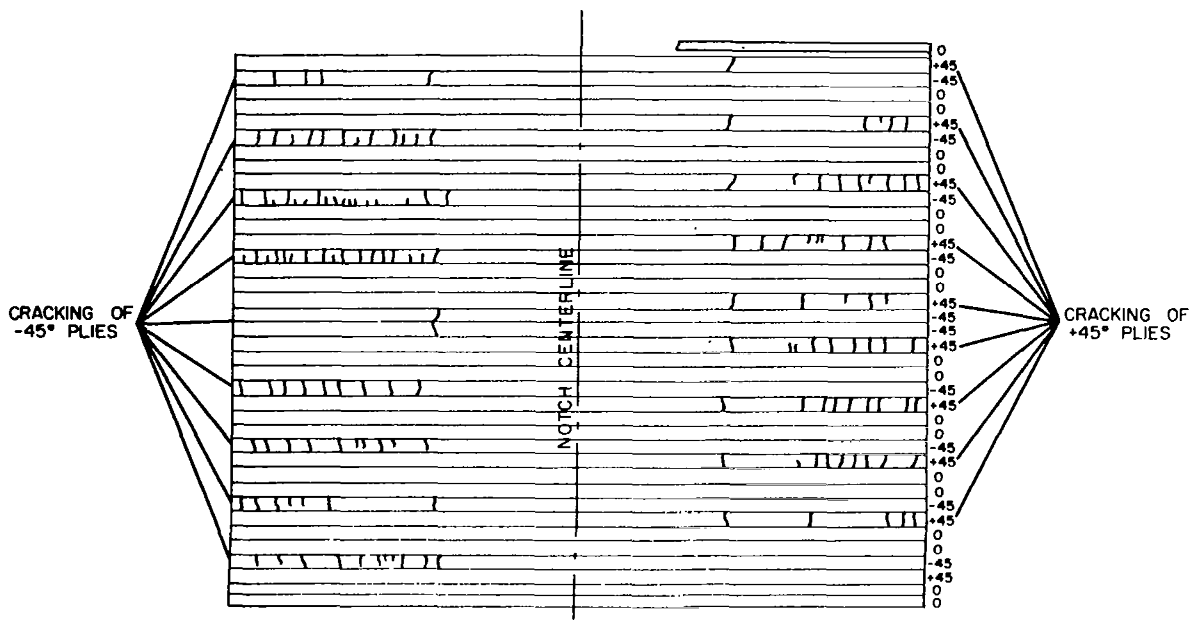
Direction of shearing stress τ



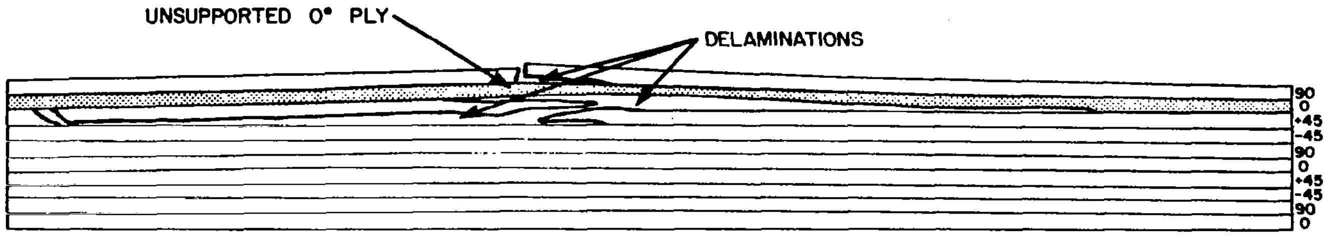
Shear-induced transverse tensile stresses



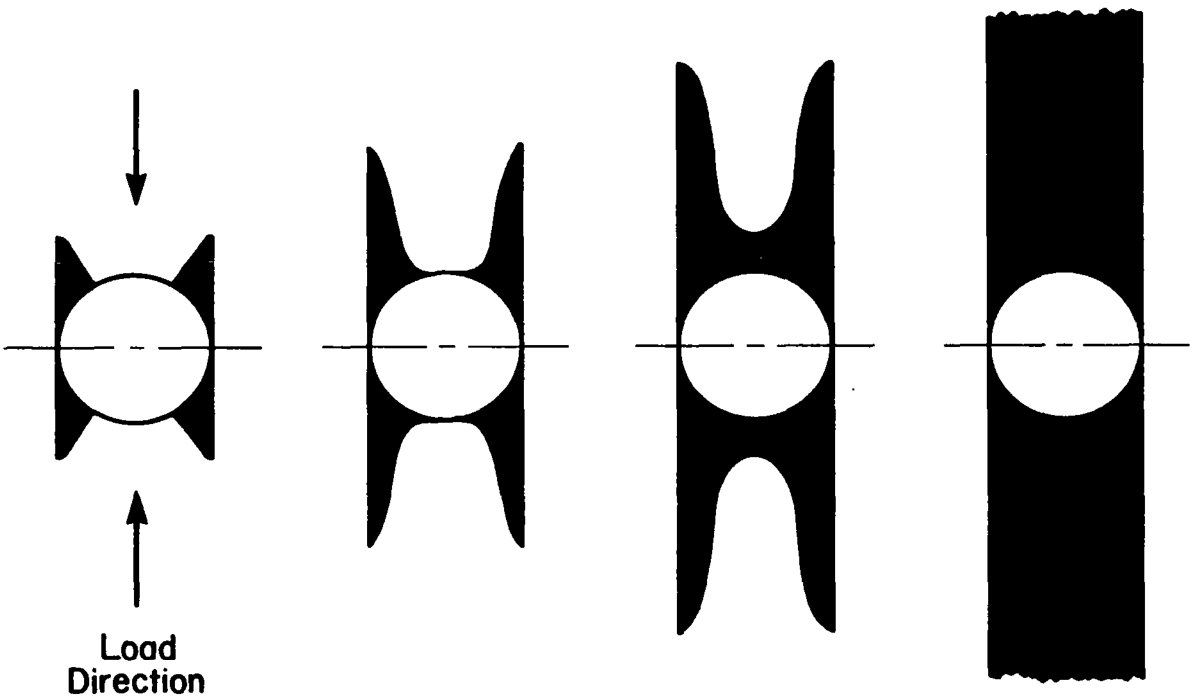
Laminate "A"; $[0_2/\pm45]_{5s}$; transverse section (50×)



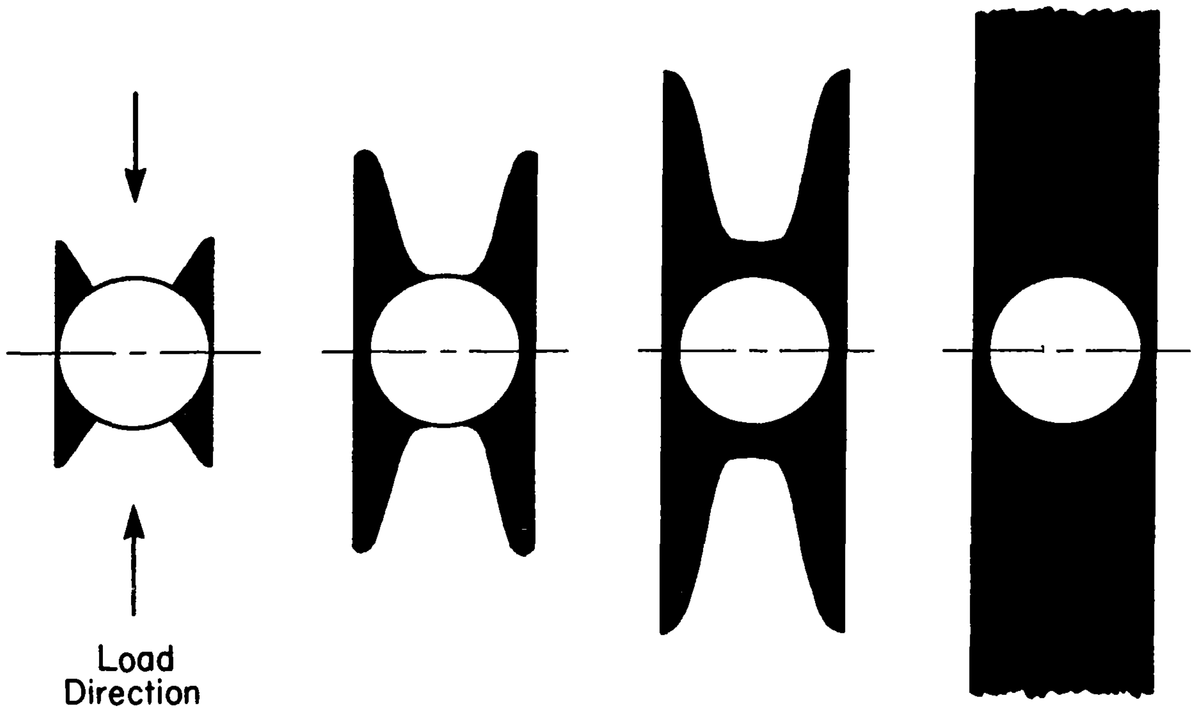
Laminate "A"; $[0_2/\pm45]_{5s}$; axial section (50×)



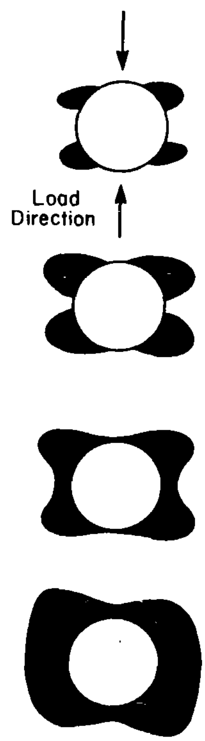
Laminate "D"; [90/0/±45]$_{5s}$; axial section (50×)



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 COMPRESSIVE 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 SEQUENCY) 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

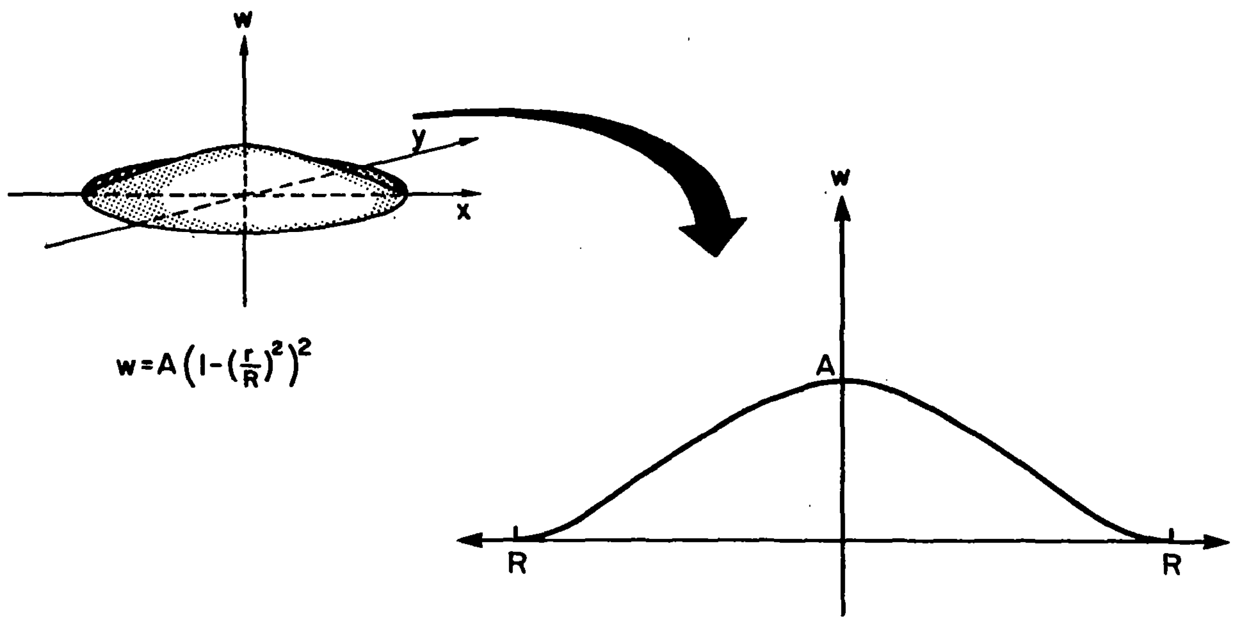
$$\frac{1}{2}\int_S \Big\{ D[(w_{xx} + w_{yy})^2 - 2(1-\nu)(w_{xx}w_{yy} - w_{xy}^2)] + [N_x w_x^2] \Big\} dS = \text{Constant}$$

INSERTING OUR ASSUMED DEFLECTION SHAPE

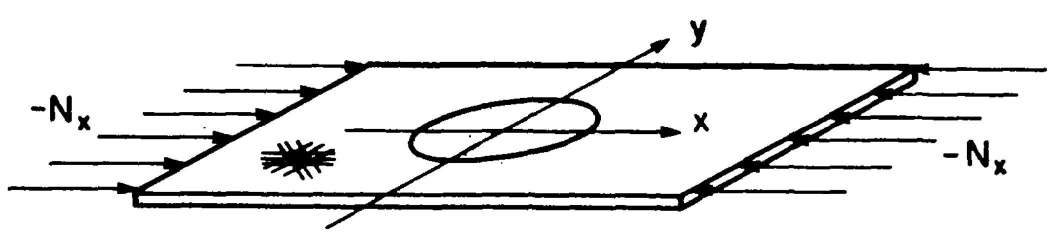
$$w(r) = A\left[1 - \left(\frac{r}{R}\right)^2\right]^2$$

PERFORMING THE INTEGRATION AND THE VARIATION YIELDS THE BUCKLING CONDITION FOR THE ISOTROPIC CASE

$$N_{x_{crit}} = \frac{-32D}{R^2}$$



Approximate buckling strength for Rayleigh-Ritz approximation



Disbond load geometry

INSERTING THE DEFLECTION SHAPE AND PERFORMING THE INTEGRATION YIELDS

$$N_{x_{crit}} = \frac{-24}{R^2}\left(\frac{D^*_{11}+D^*_{22}}{2} + \frac{D^*_{12}+2D^*_{66}}{3}\right)$$

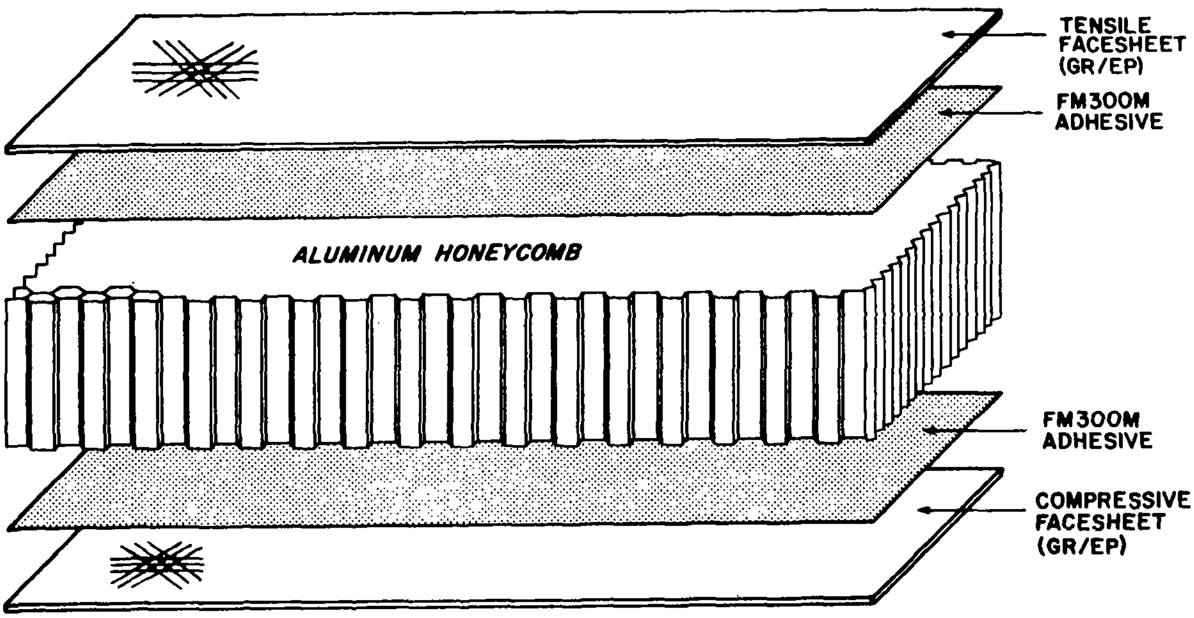
BY COMPARING ELEMENTS OF THE BENDING STIFFNESS MATRIX WE SEE THAT FOR AN ISOTROPIC MATERIAL

$$D_{12} = \nu D$$

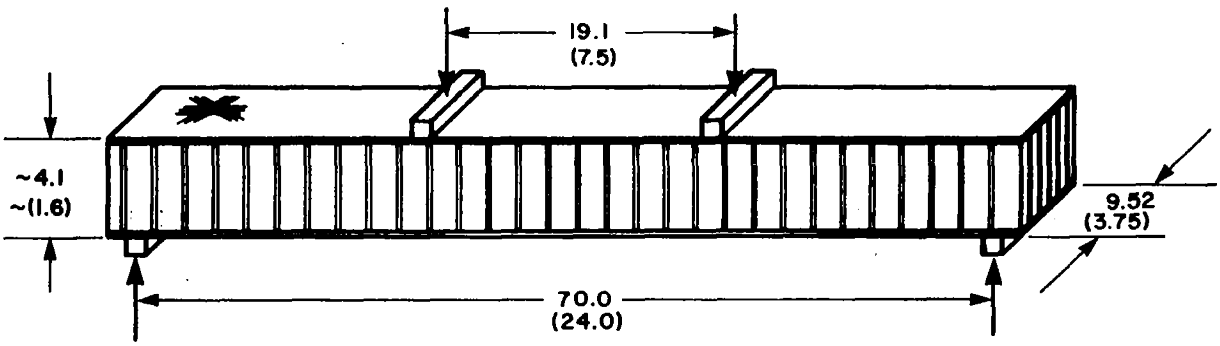
$$D_{11} = D_{22} = D \qquad D_{66} = \frac{(1-\nu)}{2} D$$

INSERTING THESE INTO THE ORTHOTROPIC RESULT PRODUCES THE ISOTROPIC CASE.

$$N_{x_{crit}} = \frac{-24}{R^2}\left(\frac{D+D}{2} + \frac{\nu D + 2(1-\nu)/2D}{3}\right) = \frac{-32D}{R^2}$$



Sandwich construction



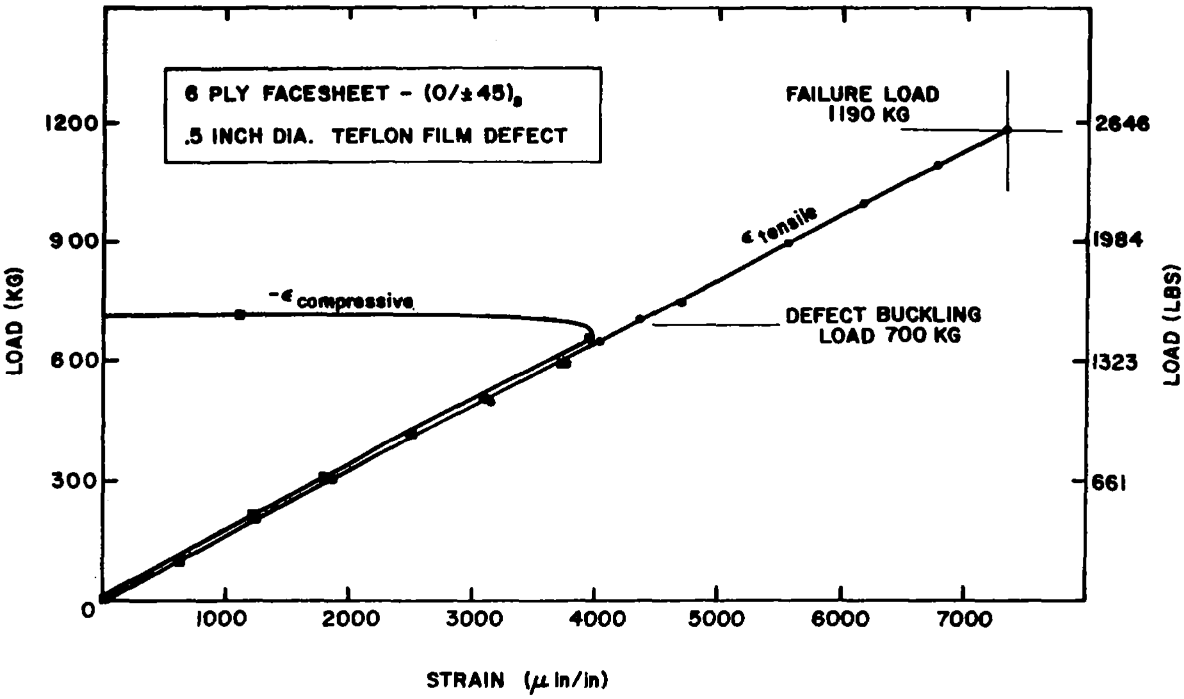
NOTES: 1. LOADING PADS ARE 1.905cm (.75 in) WIDE ALUMINUM
2. ACTUAL HEIGHT IS DETERMINED BY FACE THICKNESS
3. OVERALL BEAM LENGTH (PLUS OVERHANG) IS 66.0 cm (26.0 in)

Sample geometry

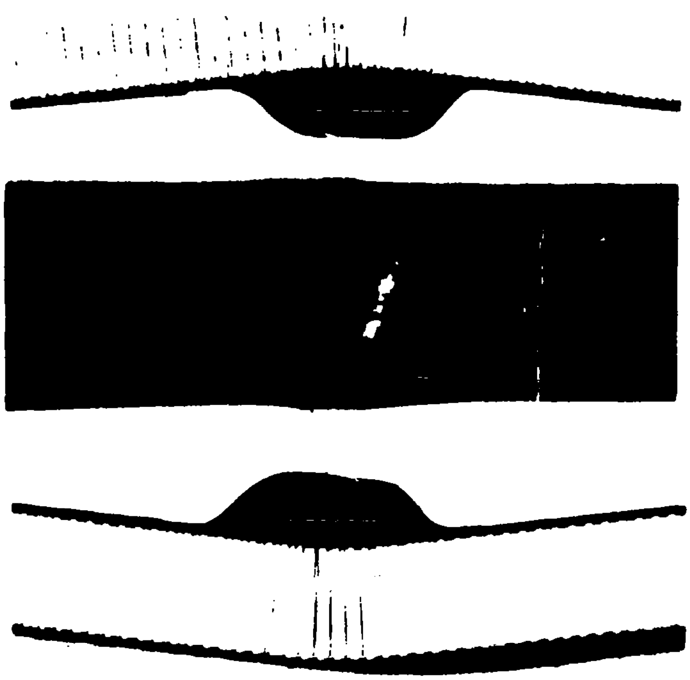
	Teflon Film Defect			Kapton Bag Defect			No Defect
	2.0 in. Dia.	1.0 in. Dia.	0.5 in. Dia.	2.0 in. Dia.	1.0 in. Dia.	0.5 in. Dia.	
$[0/\pm45]_{2s}$ (12 ply)	F_{12}-1-1* F_{12}-1-2	F_{12}-2-1 F_{12}-2-2	F_{12}-3-1 F_{12}-3-2	F_{12}-6-1 F_{12}-6-2	F_{12}-5-1 F_{12}-5-2	F_{12}-4-1 F_{12}-4-2	F_{12}-0-1 F_{12}-0-2 F_{12}-0-3
$[\pm45]_{2s}$ (8 ply)	F_8-3-1 F_8-3-2	F_8-2-1 F_8-2-2	F_8-1-1 F_8-1-2	F_8-6-1 F_8-6-2	F_8-5-1 F_8-5-2	F_8-4-1 F_8-4-2	F_8-0-1 F_8-0-2 F_8-0-3
$[0/\pm45]_s$ (6 ply)	F_6-3-1 F_6-3-2	F_6-2-1 F_6-2-2	F_6-1-1 F_6-1-2	--	--	--	F_6-0-4 F_6-0-5 F_6-0-6
$[90/\pm45]_s$ (6 ply)	--	--	--	F_6-6-1 F_6-6-2	F_6-5-1 F_6-5-2	F_6-4-1 F_6-4-2	F_6-0-1 F_6-0-2 F_6-0-3

*Specimen Identification Number

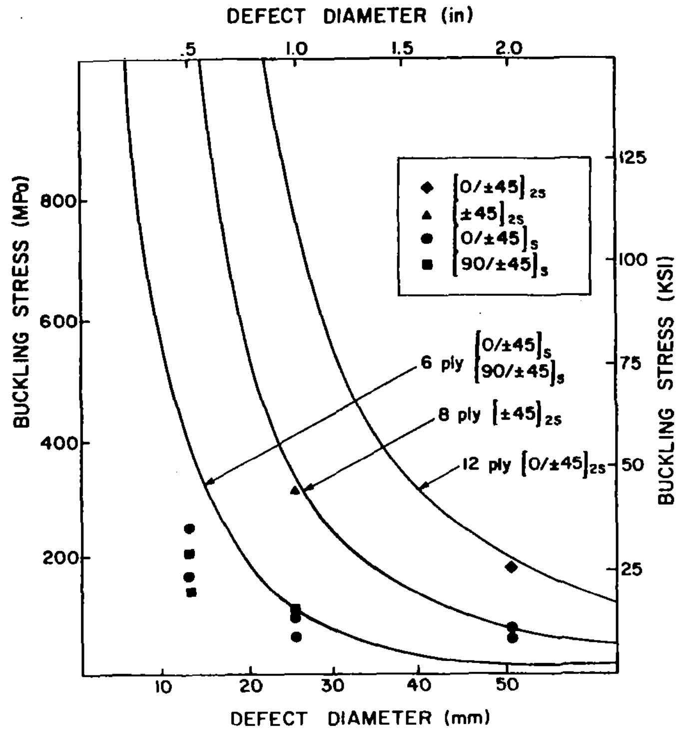
Experimental test program



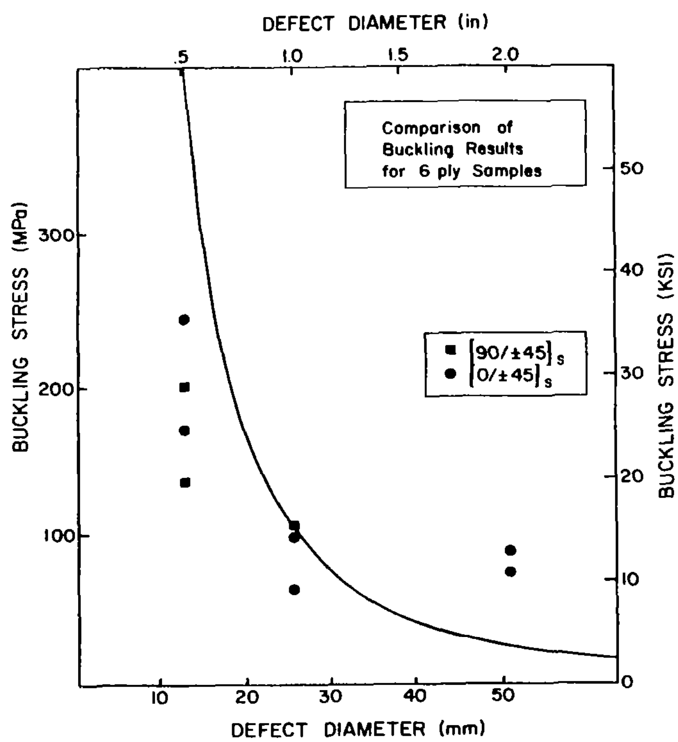
Load/strain data for sample F_6-1-2



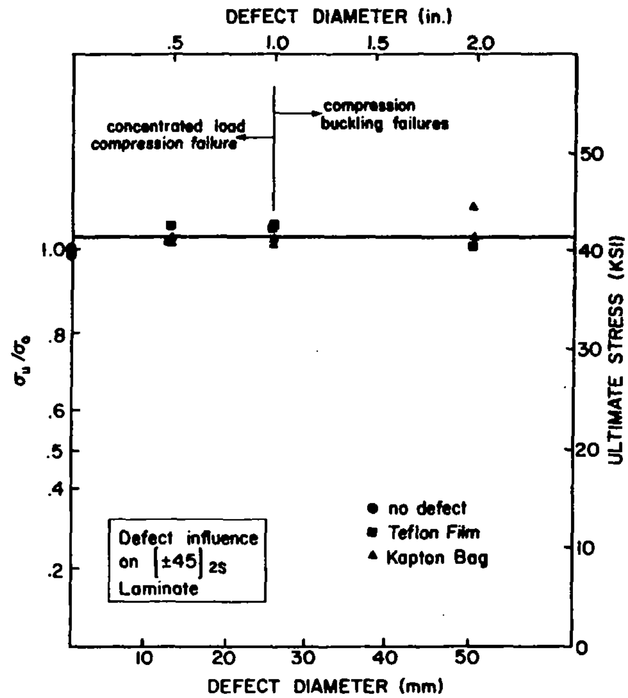
Failure of a sandwich beam composite with a 1.5-in. circular defect located at the near surface



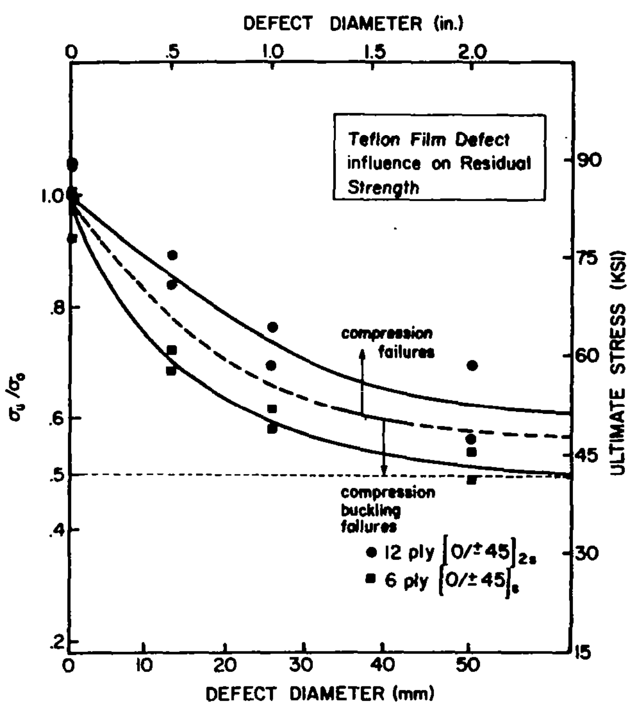
Buckling stress versus defect diameter
for all laminates



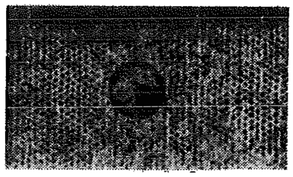
Buckling results for 6-ply laminates



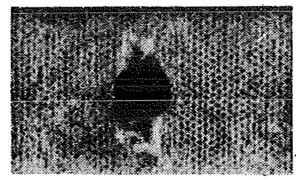
Influence of Kapton bag and Teflon film defects on residual strength of the $[\pm 45]_{2s}$ laminate



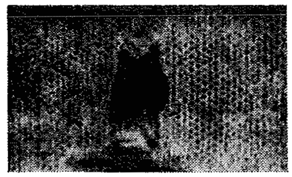
Effect of laminate thickness on residual strength of the $[0/\pm 45]_{ns}$ laminate



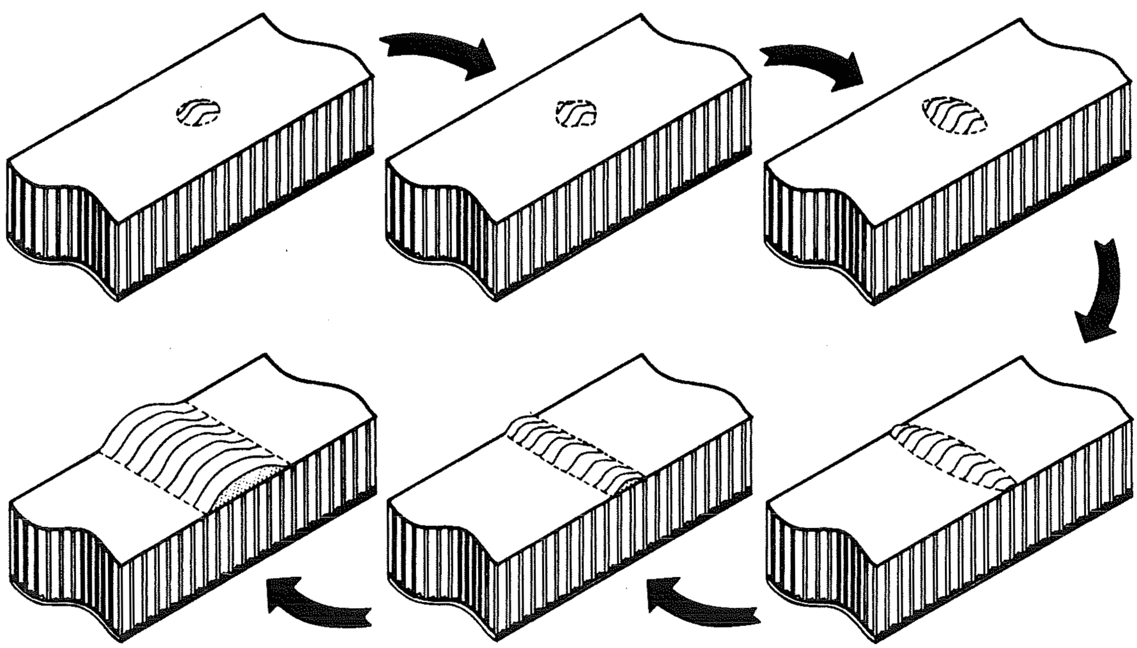
1.0-in. circular near-surface delamination prior to testing



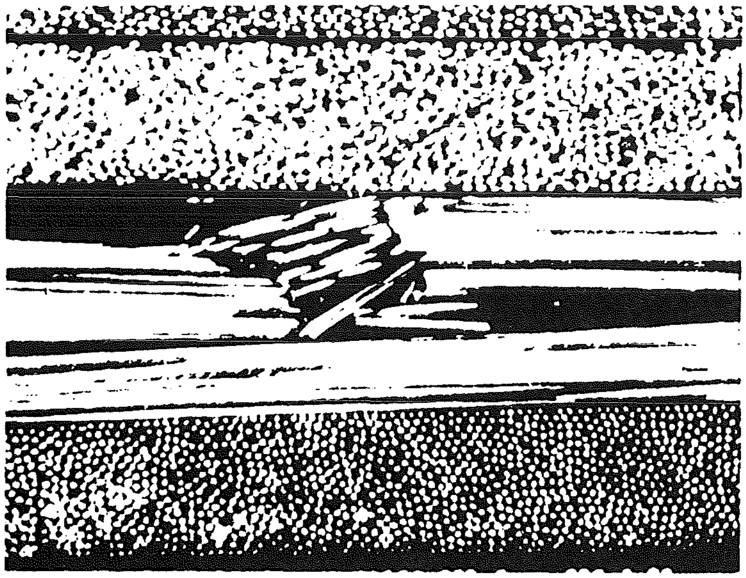
1.0-in. circular near-surface delamination after buckling



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