The Catastrophic Failure of Pressurized Graphite/Epoxy Cylinders Initiated by Slits at Various Angles

S.G. Chang* and J.W. Mar†
Massachusetts Institute of Technology, Cambridge, Massachusetts

Graphite/epoxy cylinders with single slits were tested at angles of 0, 22.5, 45, and 67.5 deg to the longitudinal axis. The cylinders were fabricated from four plies of graphite/epoxy cloth and were fitted with end caps. Slits of varying lengths were cut through the wall at different angles to the longitudinal axis. The slits were sealed with patches constructed of thin aluminum strips that were slightly longer than the slit. Using the motion of an "equivalent" cylinder to extend the Mar-Lin relationship of a flat sheet to the cylinder, a simple method was developed to predict the fracture pressure of those cylinders exhibiting induced damage to the slits. A comparison of the predicted values with the experimental results shows that this method is reasonable.

Nomenclature

a	= half-slit length
h	= cylinder thickness
H_c	= composite fracture toughness in Mar-Lin equation
K	= curvature effect coefficient
K_1	= curvature effect coefficient of first equivalent cylinder
K_2	= curvature effect coefficient of second equivalent cylinder
p	= pressure
R	= cylinder radius
λ	= curvature parameter of cylinder
λ_1	= curvature parameter of first equivalent cylinder
λ_2	= curvature parameter of second equivalent cylinder
ρ_1	= radius of curvature of first equivalent cylinder
ρ_2	= radius of curvature of second equivalent cylinder
θ	= angle of slit to longitudinal axis
σ_f	= failure stress perpendicular to slit for cylinder
σ_{plate}	= failure stress for flawed plate

Introduction

THE rapid fracture of cylindrical shells is a major problem in engineering, not only for aerospace applications such as airplane fuselages and rocket motor cases, but also for nonaerospace structural applications such as fuel tanks and oxygen tanks used by scuba divers. Linear elastic fracture mechanics (which assumes the material is homogeneous and requires the notion of a "crack") has been used to study experimentally and analytically the failure of isotropic cylindrical shells fabricated of high-strength metal alloys.[1,2] These analyses have been extended to the case of homogeneous, specially orthotropic cylindrical shells.[2] Filamentary composite materials at the micromechanic level where fracture initiates are not homogeneous. Furthermore, the concept of a "crack" (which is central to the fracture mechanics of metals) is not directly transferable to a filamentary composite material. Nevertheless, certain of these ideas, suitably modified, are helpful in understanding the fracture sensitivity of filamentary composite shells containing slits.

The research described in this paper represents a continuation of work begun by Rogers,[3] who correlated his experimental work using linear elastic fracture mechanics, and extended by Graves,[4] who improved the correlation by incorporating the effects of curvature. Both of these investigators punctured the shell while it was under internal pressure with longitudinal "through-the-thickness" slits.

In the present investigation, experimental data have been obtained on the pressure required to cause the rapid fracture initiated at through-the-thickness slits oriented at angles to the axis of the cylinders. A theory using the idea of "equivalent" cylinders is proposed and is shown to provide a reasonable methodology for the prediction of rapid fracture.

Method of Testing

Previous investigators[3,4] have used knives to puncture the wall of the cylindrical shell with a slit of a given length while the cylinder was under internal pressure. If the first knife slit did not cause rapid fracture, the cylinder was made pressure tight by bonding a patch over the slit and a slit of a greater length was then cut with another knife.

For the experimental results obtained in the present investigation, we did not cut slits in the cylinder while it was under pressure. The slits were sealed with a combination of thin aluminum strips (0.4 mm thick) arranged into an overlapping pattern against the inner surface of the cylinder (Fig. 1). Two of the strips (which were 20 mm longer than the slits) were placed so that their adjacent edges coincided with the slit in the cylinder. A third strip was placed over the other two and this "patch" was sealed with sealant so that it became pressure tight. With the preslitted cylinder and the "patch," it became possible to monotonically increase the pressre until rapid fracture occurred.

A cylinder with a longitudinal precut 50.8 mm long slit and a "patch" was pressured tested to failure. The failure mode was the same as that observed by Graves.[4]

The advantages of the method used in this investigation are as follows:

1) The slit length and the fracture pressure are uniquely determined, whereas in previous methods the increments of the guillotine knives used meant that the slit length was not unique to the pressure at which rapid fracture occurred.

2) Testing time is reduced because repeated punctures of the same cylinder are not required.

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*Visiting Scholar, Department of Aeronautics and Astronautics, from Beijing Institute of Aeronautics and Astronautics, Beijing, China.

†Professor, Department of Aeronautics and Astronautics. Fellow AIAA.

3) Strain distributions in the vicinity of the slit can be easily measured prior to rapid fracture.

4) Other "flaws," such as holes or the interaction of two slits, can be more easily tested.

5) There are no kinetic effects such as that caused by the puncturing of the cylindrical wall with the guillotine.

Fabrication of the Test Specimens

The specimens were fabricated of Hercules A370-5H/3501-6 graphite/epoxy cloth prepreg purchased in widths of 1 m (39 in.). The stacking sequence oriented the two inner plies with their filaments at ±45 deg and the two outer plies with their filaments at 0 and 90 deg to the longitudinal axis of the cylinders. Fabrication was accomplished on a 12 in. diam aluminum mandrel that was covered with a single layer of nonporous Teflon upon which the four plies of cloth were wrapped. This stack was then sequentially wrapped with one layer of peel ply, one of porous Teflon, and five layers of paper bleeder; the entire assembly was then vaccum bagged. The autoclave cure was a two step process with the first step at 240°F for 1 h and the second stage at 350°F for 2 h. After removal from the mandrel, the cylindrical tube was postcured in an oven at 350°F for 8 h.

Slits were cut through the wall of the cylindrical shell using a jeweler's saw of 0.4 mm thickness. The patches were installed and then aluminum end caps were bonded onto the two ends of the shell. The end caps were 25.4 mm (1 in.) thick and had an o.d. of 330 mm (13 in.). A circular groove 12.7 mm (0.5 in.) deep and 3.175 mm (0.125 in.) wide was cut into the cap. The mean diameter of the groove is 306.5 mm (12.07 in.). Epoxy was used to bond the end caps to the cylinder.

Eight specimens were fabricated (see Table 1). One specimen had its slit oriented at 0 deg, five at 45 deg, one at 22.5 deg, and one at 67.5 deg. The slit lengths are tabulated in Table 1.

Test Procedures and Experimental Data

Testing took place in a large blast chamber that is capable of absorbing the energy from the explosion of 2 lb of TNT. Pressure was applied with nitrogen. Pressure in the cylinder was monotonically increased until catastrophic failure was initiated at the slits. The pressure was measured with a transducer and recorded with a plotter. The strains were measured with strain gages. Data acquisition was performed by a PDP-11 computer. Because the failure process was quite vio-

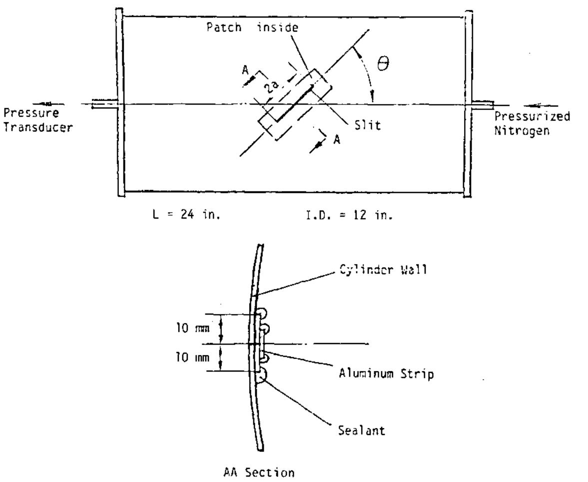

Fig. 1 Patch details.

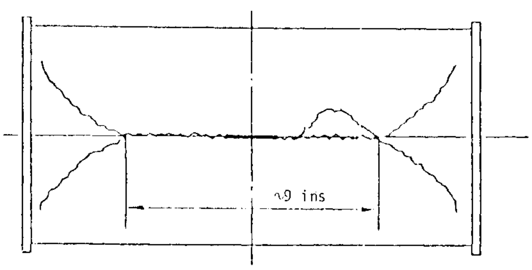

Fig. 2 Failure mode of tube 105.

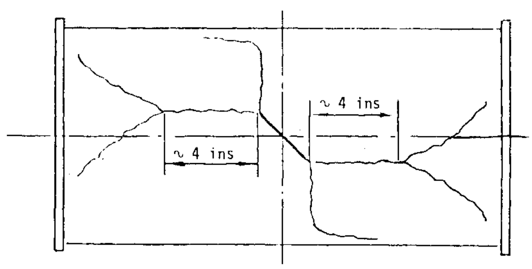

Fig. 3 Failure mode of tube 106.

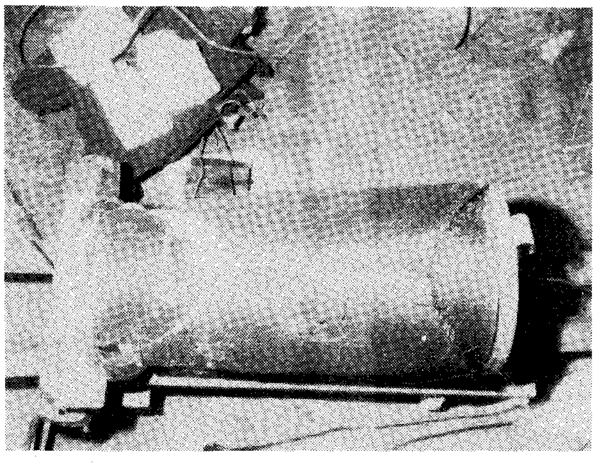

Fig. 4 Tube after failure.

Table 1 Data for tested cylinders

Cyl. No.	Tube No.	θ, deg	$2a$, mm	p_{fail}, MPa	p_{cal}, MPa	ϵ_{hoop}[a]
1	105	0	50.8	1.001	1.144	0.00177
2	111	22.5	76.2	0.841	0.821	0.00148
3	110	45	63.5	1.207	1.433	0.00213
4	109	45	69.85	1.055	1.283	0.00186
5	106	45	76.2	0.931	1.166	0.00164
6	107	45	82.55	0.896	1.061	0.00158
7	108	45	88.9	0.944	0.970	0.00167
8	112	67.5	101.6	1.650	1.438	0.00292

[a] ϵ_{hoop} is hoop strain calculated at failure pressure.

lent, an important part of the test procedures was in retrieving the pieces of the failed cylinders so that the fracture paths could be determined.

The pressures which caused catastrophic failure are shown in Table 1. Sketches of the paths of failure as determined by the postmortem assembly of the failed cylinders for two specimens are shown in Figs. 2 and 3. One photograph of the failure mode is shown in Fig. 4.

An Equivalent Cylinder Method to Correlate the Data

Graves[4] has shown that the fracture pressure of the cylinders can be correlated with the data obtained from unidirectionally loaded flat coupon specimens of the same layup. The flat coupon specimens are "flawed" with holes or slits and the fracture stresses are fitted to the Mar-Lin relationship

$$\sigma_{\text{plate}} = H_c (2a)^{-0.28}$$

where σ_{plate} is the far-field fracture stress as obtained from flat coupon specimens, H_c the composite fracture toughness (see Ref. 7 for a description of how H_c is determined), and $2a$ the hole diameter or slit length.

The hoop stresses at which rapid fracture of the pressurized cylinders with longitudinal slits inititates are given by the relations

$$\frac{\sigma_f}{\sigma_{\text{plate}}} = \frac{1}{(1+0.317\,\lambda^2)^{1/2}}$$

$$\lambda^2 = \frac{a^2[12(1-\nu^2)]^{1/2}}{Rh}$$

where σ_f is the hoop stress at rapid fracture, ν the Poisson's ratio, R the radius of the cylindrical shell, and h the wall thickness of the shell. For pressurized cylinders with circumferential slits, the relations are

$$\frac{\sigma_f}{\sigma_{\text{plate}}} = \frac{1}{K}$$

$$K = 1 + [(K_1 - 1) + (K_2 - 1)]$$

$$K_1 = (1 + 0.317\,\lambda_1^2)^{1/2}$$

$$K_2 = (1 + 0.05\,\lambda_2^2)^{1/2}$$

$$\lambda_1^2 = \frac{a^2[12(1-\nu^2)]^{1/2}}{\rho_1 h}$$

$$\lambda_2^2 = \frac{a^2[12(1-\nu^2)]^{1/2}}{\rho_2 h}$$

where ρ_1 is the local radius of curvature perpendicular the axis of the slit and ρ_2 the radius of curvature parallel to the slit.

In these formulas, the fracture stress σ_f is the component of stress perpendicular to the axis of the slit and is given by the

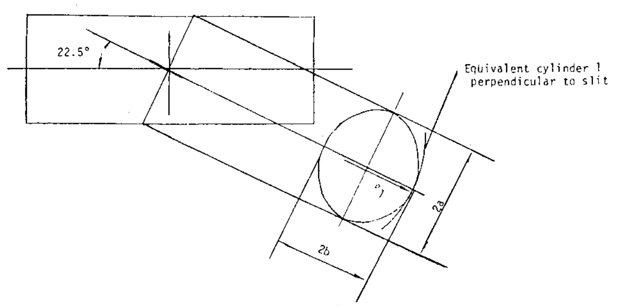

Fig. 5 Equivalent cylinder 1.

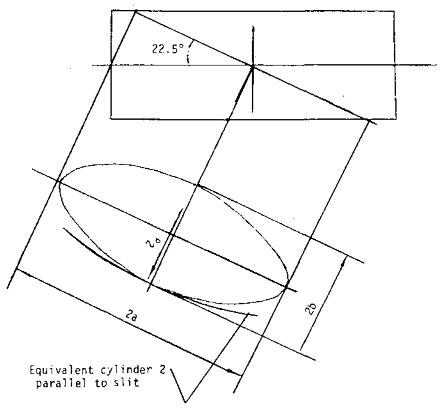

Fig. 6 Equivalent cylinder 2.

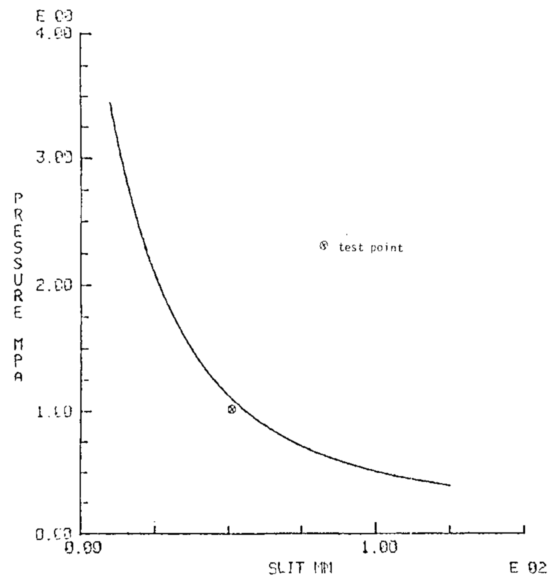

Fig. 7 Failure pressure to slit length at $\theta = 0$ deg.

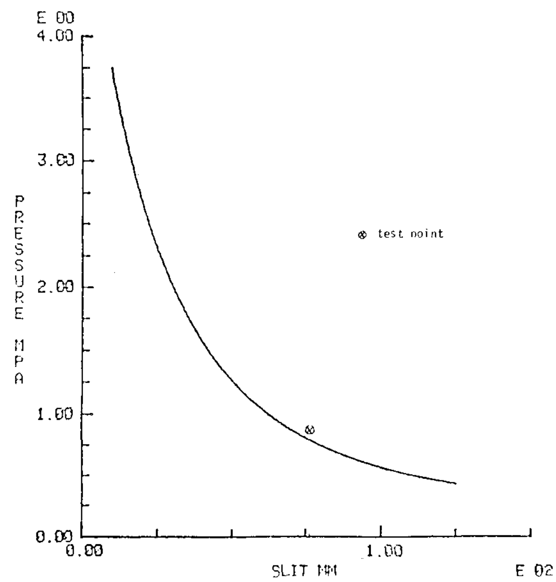

Fig. 8 Failure pressure to slit length at $\theta = 22.5$ deg.

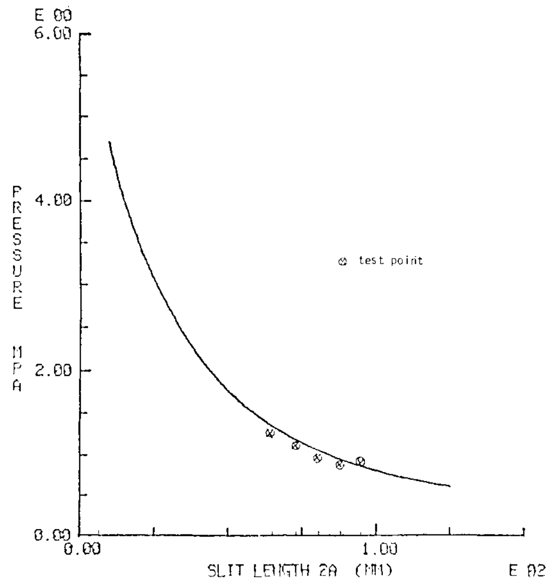

Fig. 9 Failure pressure to slit length at $\theta = 45$ deg.

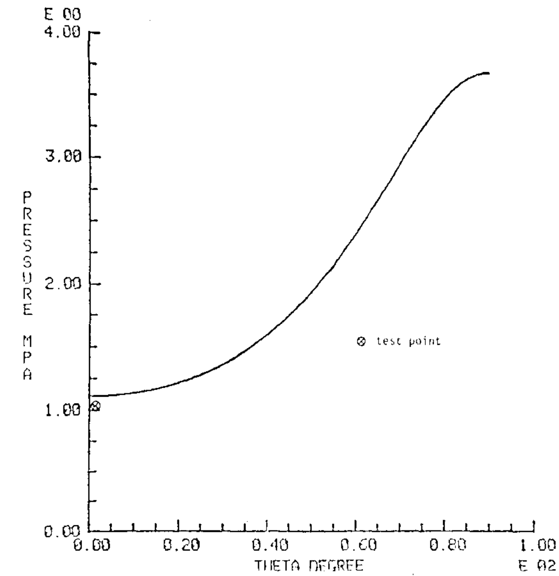

Fig. 11 Failure pressure to orientation at $2a = 50.8$ mm.

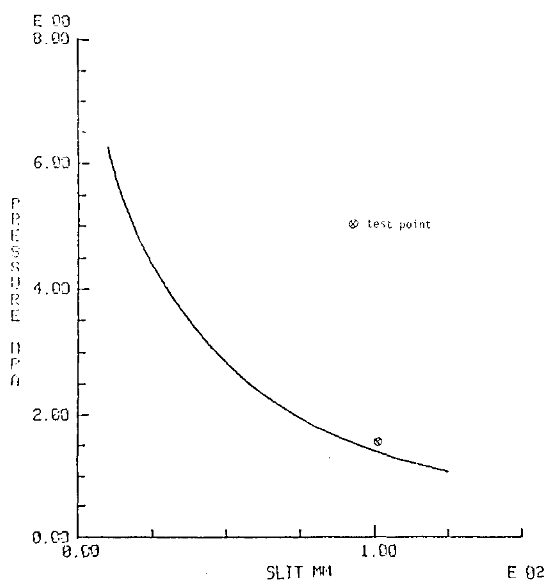

Fig. 10 Failure pressure to slit length at $\theta = 67.5$ deg.

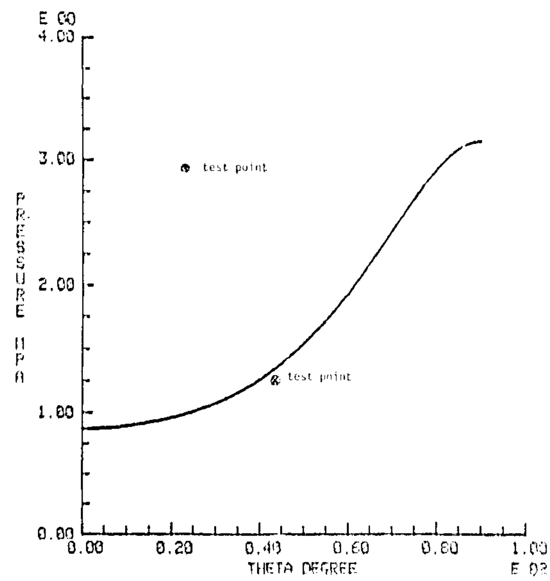

Fig. 12 Failure pressure to orientation at $2a = 63.5$ mm.

following expression in terms of the internal pressure:

$$\sigma_f = \frac{pR}{h} \; (0.5\sin^2\theta + \cos^2\theta)$$

where θ is the angle of the slit to the longitudinal axis and p the internal pressure.

It is seen from the above formulas that $(K_l - 1)$ represents the influence of the perpendicular curvature and $(K_2 - 1)$ the influence of the parallel curvature on the fracture stress.

For a cylindrical shell, the two radii of curvature are given by the relations

$$\rho_l = R/\sin^2$$

$$\rho_2 = R/\sin^2(\theta + \pi/2)$$

The pressure/slit length equation becomes

$$p = \frac{H_c(2a)^{-0.28}}{K} \; \frac{h}{(0.5\sin^2\theta + \cos^2\theta)R}$$

Two equivalent cylinders are shown in Figs. 5 and 6.

Discussion and Recommendations

The comparison of the theoretical calculations of the pressure to cause rapid fracture with the experimental pressure is shown in Table 1. The predictions for the burst pressures are below the experimental values for the slits oriented at 22.5 and 67.5 deg. For the other specimens, the predictions[5] are higher than the experimentally determined values. The values used in these calculations are for $H_c = 763$ MPa $\times$ mm$^{0.28}$, $\nu = 0.315$, and a nomial wall thickness of 1.4 mm.[4]

Curves of pressure vs slit length have been calculated for angular orientations of the slits at 0, 22.5, 45, and 67.5 deg. These are shown in Figs. 7-10 in which the experimental results are also shown. Curves of pressure vs angle have also been calculated for slit lengths of 50.8, 63.5, 76.2, 88.9 mm and are shown in Figs. 11-14.

Another way of depicting the experimental results theory is demonstrated in Fig. 15, which shows a curve of the slit length vs the slit orientation at which rapid fracture occurs for an internal pressure of 1 MPa. The experimental data have been adjusted by multiplying the lengths of the experimental slits by the ratio of the theoretical slit length for 1 MPa pressure to the theoretical slit length for the experimental pressure.

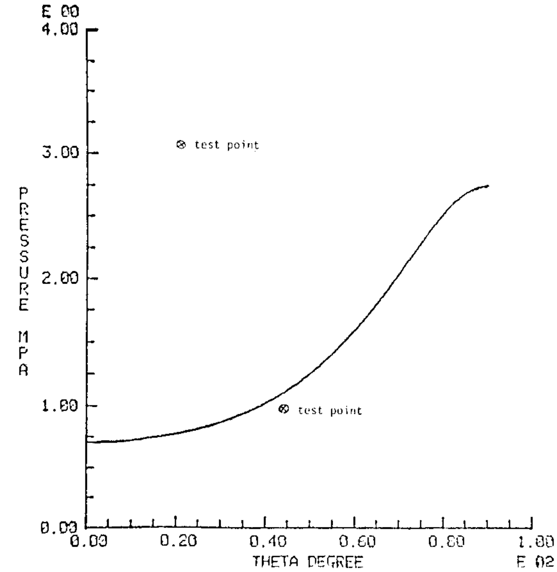

Fig. 13 Failure pressure to orientation at $2a = 76.2$ mm.

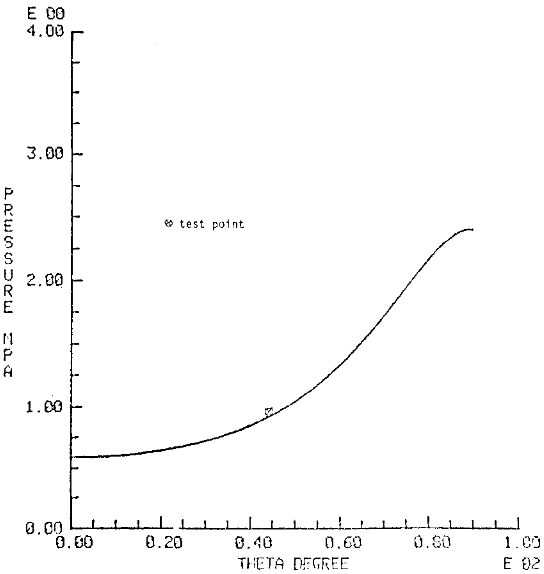

Fig. 14 Failure pressure to orientation at $2a = 88.9$ mm.

As can be seen, the methodology of the equivalent cylinders provides a reasonable correlation with the experiments.

It should be noted from Fig. 3 that the initial paths of the fractures run both longitudinally and circumferentially from both ends of the slits. The longitudinal fractures branch into two paths before the ends of the specimens, while the circumferential fractures make almost 90 deg turns to become longitudinal fractures. The disturbance in the membrane state of stress caused by the end caps extends about 2 in. from each end. Thus, the end caps have a negligible effect on the initiation of the branching. Of special note is the observation that

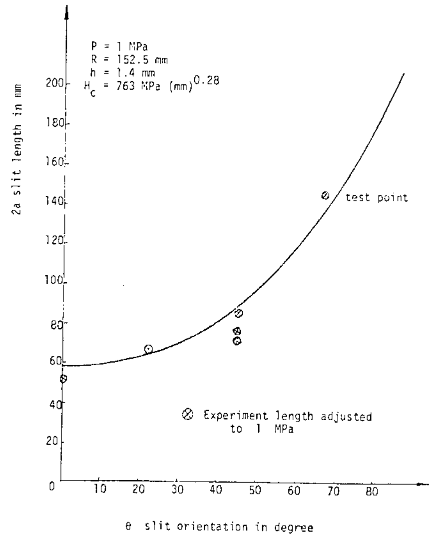

Fig. 15 Failure slit length to orientation.

the rapid fractures did not extend along the axis of these slits that were not longitudinally oriented.

The results of these experiments suggest many others, e.g., use of circular holes instead of slits, different layups such as those produced by filament winding, and the interaction of two slits.

This methodology has been applied to quasi-isotropic layups. Theoretical studies on the effect of the shell curvature on other layups would also be of interest.

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