A series of experiments was conducted to study the influence of test temperature on the compression strength of typical graphite cloth and tape epoxy laminates containing 2.54-cm holes. Buckling was prevented. This resulted in the desired material failure by delamination initiated at the hole edge. For these cloth laminates, the clear influence of layup and temperature were demonstrated. The tape laminates with different resin and fibers exhibited no measurable sensitivity to temperature but a dependence on layup. Strength data from the tests were correlated with the Average Stress Failure Criterion. Consistent trends were demonstrated. The residual strength ratios of two laminate types were similar. Strain gage data, particularly on and adjacent to the hole edge, gave evidence of nonlinear behavior, particularly in these cloth laminates, well below failure. Modelling this type of highly localized anisotropic nonlinear response appears to present considerable difficulty. This puts a premium on simple macroscopic failure models such as the Average Stress Criterion.
Nomenclature

\( a_0 \)  Characteristic Length of the Average Stress Failure Criterion

\( E \)  Youngs Modulus

\( G \)  Shear Modulus

\( K \)  Stress Concentration Factor

\( R \)  Hole Radius

\( RSR \)  Residual Strength Ratio \((\frac{\sigma_{\infty}^u}{\sigma_o})\)

\( RT \)  Room Temperature

\( T_g \)  Glass Transition Temperature

\( \sigma \)  Direct Stress

\( \frac{R}{R + a_0} \)

Subscripts

\( c \)  Compression

\( N \)  Notched Material

\( O \)  Unnotched Material

\( 1 \)  Loading Direction

\( 2 \)  Normal to Loading Direction

Superscripts

\( cu \)  Compression Ultimate

\( \infty \)  Infinite Width Laminate

INTRODUCTION

Stress distributions around holes and cutouts in structures always have been a challenging problem in structural integrity. In addition to the classical failure criteria based on unnotched material behavior, the fracture mechanics behavior must be understood to avoid excessively conservative design practice. When using filamentary reinforced materials, at least two further complications arise. First, the material anisotropy and its influence on stress distribution must be considered. It is well known (see [1], [2], and [3]) that the classical lamination theory is invalid within roughly one laminate thickness of free edges. These edge stresses depend on ply material properties, stacking sequence, plus fine details of micromechanical behavior. Second, the transverse or through-thickness tension strength can be an order of magnitude less than the inplane strength. This causes delamination failures, which markedly increase the difficulty of formulating failure criteria.

Much of the work on the structural response of filamentary composites has been devoted to situations where the applied loading is uniaxial tension. Analyses have been based on homogenous, orthotropic plate theory [4], [5], and [6], boundary layer solutions [7], and
finite element analyses such as [8]. These contributions, with their diverse assumptions and solution methods, have explained many aspects of the local stress distributions around holes. Linear elastic fracture mechanics approaches by Waddoups et al. [9], and a series of papers by Nuismer, Whitney, and their associates [10], [11], and [12] have shed considerable light on the effects of hole size and have produced failure criteria for notched composites. Broad studies covering many aspects of the overall problem and data useful for designers are available in references such as [13]. Biaxial tension testing and correlating studies are presented by Daniel [14].

Much less has been published on the behavior of composites containing holes, when the applied loading is compressive. As expected—and demonstrated by Knauss, Starnes, and Hennke [15]—some geometries tend to fail by buckling; in others, the material failure starts at the hole edge. These lead to delaminations which propagate rapidly in a direction normal to the loading. Nuismer and Labor [16] studied laminates with countersunk holes containing both loaded and unloaded fasteners, subjected to compression loading. They confirmed the test data correlates quite well with the behavior predicted on the basis of the average stress criterion. This allows the ratio of notched-to-unnotched compression strength to be determined. In [17], Starnes points out that anomalies can arise in defining the notched-to-unnotched strength ratio when the holes induce a failure mode significantly different from that occurring in the basic or unnotched material.

All these contributions have two common characteristics; they are restricted to unidirectional tape laminates, tested at room temperature. Graphite cloth prepregged by epoxy resins now is being used widely in several flight vehicles; however, apparently there are no generally available publications describing their behavior when the laminates have holes in them and compression loading is applied. To produce some data on this subject, a project was undertaken to address a few specific questions. The work is an extension of [18] for cloth and tape laminates containing holes and subjected to tension loading at temperatures up to 450° K.

The objective is to study the material failure mode initiating at the edge of 2.54-cm-diameter circular holes in a series of both cloth and tape laminates. This was accomplished by attempting to preclude overall buckling of the panels. Three different layups were tested for each material type. It is important to note that because of differences in fiber, resin, and stacking sequence used in the tape and cloth laminates, direct comparisons between their behavior should be made with care.

Test Specimens

The cloth laminates were made from the Fiberite HMF330C/34 prepreg consisting of T300 fibers woven into 8 Harness Satin weave with 24 tows in the warp direction and 23 in the fill direction. The resin is a 450° K cure epoxy. All laminates were autoclave processed with two hours at 450° K terminating the cure cycle. All cloth laminates were 8-ply layups having a thickness of roughly 0.265 cm. To give 0%, 25%, and 50% of 45 plies, the three layups chosen were \([0/45]_{4s}, [0/45/02]_{1s}\) and \([0/45]_{2s}\). These laminates were cut into panels 12.7 cm wide and 25.4 cm long; their ends were tabbed with smooth epox glass-epoxy. Three replicates were made for each of the three test temperatures. The 2.54-cm-diameter central holes were drilled by a carbide tipped boring head to give a very smooth finish. This hole size was chosen to be above where the well known "hole size" effect [11] influences strength of holed laminates. The panel width was selected as five times the hole diameter to minimize the edge effect on hole stresses yet allow a test fixture to be designed to preclude buckling, at least of the thicker cloth panels. The ends were very carefully machined to be flat and parallel. Prior to testing, but after machining and tabbing, the test specimens were subjected to ultrasonic C-scan inspection. This confirmed their high quality. Samples of panels from each layup had their Glass Transition Temperature (Tg) measured. It was found to be close to 430° K. This was the reason for selecting this value as the highest test temperature. To provide unnotched material strength data, the data base for these production materials was used.

The tape specimens were made from the Hercules AS fibers with their 3501-6 resin. Their platform dimensions and holes were the same as the cloth panels. However, as they were to provide data for a different application, the following three 16-ply layups were fabricated, all had 50% of ±45 deg plies and the stacking sequences were respectively \([±45/02\]
±45/02]₀, [±45/02/±45/90]₂, and [±45/02/±45/0/90]₂. Their thicknesses were roughly 0.203 cm. The Tg of this material was well above the maximum intended test temperature of 394°K.

Test Setup

The test fixture, designed to prevent buckling, is illustrated in Fig. 1. The two circular section vertical members were slotted to receive roughly 1 cm of the panel. This provided restraint of the rotation and lateral displacement of the panels vertical edges. The loading heads contained tight tolerance holes into which these members fitted. The lighter colored loading blocks were slotted to receive the tabbed panel. Each panel was carefully skimmed with 0.00254-cm steel shims; hence, the gaps between the panel and its fixture was always less than this. The two pairs of horizontal bars each contain three steel bolts with hemispherical nylon tips. By tightening each of the six pairs of bolts, lateral displacement is locally prevented.

For high temperature testing, a box of insulating material was constructed to enclose the panel and much of the test fixture. It is shown, prior to assembly for a test, in Fig. 1. Heating was provided by a pair of hot air guns, one ducting air to each side of the panel. To ensure uniform panel heating, the hot air was forced through screens attached within each half of the box. Careful thermal calibrations were conducted to ensure uniform temperatures throughout the critical sections of the panel figure. Within 5 cm of the hole edges, the test temperature was within 5°K of nominal. Slow heating rates were used and temperatures held steady for 15 min prior to commencing the loading sequence. Loading rates were very slow; strain measurements were taken on at least fifteen load steps up to failure.

This fixture was entirely successful in preventing buckling of all the cloth panels. However, the thinner tape panels tended to buckle between the horizontal bars and the loading blocks. To combat the situation, two more pairs of horizontal bars and their adjustable bolts were added and buckling prevented for most panels. The details are discussed later.

Most of the strain gage installations are visible in Fig. 1. The gage length of all gages on the panel surfaces was 0.3175 cm, but the "thru thickness" gage on the hole surface had a gage length of 0.1524 cm. The gages across the minimum section were to provide the strain gradient induced by the hole. The centerline of the gage closest to the hole was 0.1778 cm from the hole edge, so it does not record strain at the hole edge. The four gages adjacent to the tabs gave values of the far field stress. The two back-to-back pairs were intended to give indications of bending or incipient buckling.

TEST RESULTS FOR THE CLOTH

The overall results are summarized in Fig. 2. It is of interest to study the influence of layup and temperature on the Residual Strength Ratio (RSR). It is defined as the gross failure stress for the notched (holed) laminate, corrected for finite edge effects, divided by the unnotched material strength. For these panels, the edge effect correction is [11] 4.6%.

Figure 2 indicates that the strength of the panels with holes in them is much less dependent upon the layup than unnotched material. The reason for this is that every single failure was multiple delaminations, starting at the hole edge. This is consistent with the results of tape laminates reported in [15] and [17]. In other words, the failures resulted from predominantly tension failures of the resin, which would not be expected to be particularly sensitive to the fiber directions. A typical example is shown in Fig. 3. However, note that the panel with no 45 deg plies is clearly more sensitive to temperature than the others. It is also clear from both this figure and Table 1 that the quasi-isotropic layup retains the greatest RSR at all temperatures. The room temperature RSR of just less than 0.5 for the quasi-isotropic panels is very similar to the value obtained in [15] for 48-ply, and in [17] for 96-ply tape laminates.

It is of particular interest to correlate these results with the average stress failure criterion, extracting the parameter a0 and comparing this cloth data with the tape data of [16], [15], and [17], as well as the tension data of [18]. The average stress failure

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FIGURE 1. TEST FIXTURE DESIGNED TO PREVENT BUCKLING, WITH "HOT BOX" DISASSEMBLED.

FIGURE 2. COMPRESSION STRENGTH OF UNNOTCHED MATERIAL AND 12.7 CM WIDE SPECIMENS WITH 2.54 CM HOLES IN HMF330C/34 GRAPHITE CLOTH EPOXY LAMINATES.
FIGURE 3. TYPICAL DELAMINATION FAILURE AT HOLE EDGE INDUCED BY LAMINATE COMpressive LOADING.

FIGURE 4. RESIDUAL COMPRESSIVE STRENGTH RATIOS FOR HMF330C/34 CLOTH LAMINATES WITH 2.54 CM CIRCULAR HOLES.
criterion can be summarized as giving the RSR as a function of \( a_o \) and the laminate elastic constants as (see [11])

\[
\text{RSR} = \frac{\sigma_N^\infty}{\sigma_o} = \frac{2 (1 - \xi_2)}{\left\{ 2 - \xi_2^2 - \xi_2^4 + (K_c^\infty - 3)(\xi_2^6 - \xi_2^4) \right\}}
\]

where \( \xi_2 = R/(R + a_o) \) and

\[
K_c^\infty = 1 + \frac{2}{E_{11}} \left( \frac{1}{E_{22}} - \nu_{12} \right) + \frac{E_{11}}{G_{12}}
\]

Test data have demonstrated that while the strengths are strong functions of the temperature, the moduli are invariant with temperature to within the accuracy of routine production testing utilized to establish the data base. Thus, the stress concentration factor and RSR are predicted to be independent of temperature. Using the material properties gives \( K_c^\infty \) of 4.37, 3.48, and 3.02 for the \([0]_{4s}, [0/45/0]_s\), and \([0/45]_2s\) layups, respectively. Using these in (1) allows the computation of RSR versus \( a_o \) for our 2.54-cm hole. The results are plotted in Fig. 4, with the experimental results of Table 1 super-imposed to provide the \( a_o \) values for each lay-up-temperature combination.

Room temperature results demonstrate a steadily increasing value of \( a_o \) as the layup approaches quasi-isotropy. A similar situation arises for the 394°K results. At 427°K, a different situation arises with the \([0/45/0]_s\) laminates exhibiting the largest value of \( a_o \). Looking upon decreasing \( a_o \) as indicating progressively more brittle behavior, all three layups show a steady increase in brittleness as the test temperature rises. In fact, the \([0]_{4s}\) panels are very close to the condition of brittle behavior. Note that this trend of increasing brittleness with temperature and degree of orthotropy is similar to the tension data reported for these layups with 2.54-cm holes [18]. The major difference is that the values of \( a_o \) for compression are very roughly 40% greater than for tension. In neither case is the RSR precisely independent of material, but assuming it to be may be entirely satisfactory for many engineering or design analyses.

**STRAIN GAGE DATA**

To confirm the quality of strain data, the average for field strain adjacent to the tabs at failure was divided by the unnotched material failure strain and compared to the RSR in Table 1. These two measure of relative strength did not differ by more than 8% for any lay-up-temperature combination. Also note that the failure strains of this material are very nearly independent of the three layups used. They are 0.86% at RT, 0.72% at 394°K, and 0.66% at 430°K. The average far field strains at failure are obtained by multiplying these strains by the ratios of Table 1.

<table>
<thead>
<tr>
<th>Layup</th>
<th>Temp. °K</th>
<th>( K_c^\infty )</th>
<th>( \sigma_N (\text{MN/m}^2) )</th>
<th>( \sigma_o (\text{MN/m}^2) )</th>
<th>( \sigma_N^\infty/\sigma_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>([0]_{4s})</td>
<td>296</td>
<td>4.37</td>
<td>186.6</td>
<td>516.8</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>394</td>
<td>4.37</td>
<td>138.1</td>
<td>465.3</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>430</td>
<td>3.48</td>
<td>102.2</td>
<td>427.2</td>
<td>0.25</td>
</tr>
<tr>
<td>([0/45/0]_s)</td>
<td>296</td>
<td>3.48</td>
<td>186.9</td>
<td>454.7</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>394</td>
<td>3.48</td>
<td>154.3</td>
<td>413.4</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>430</td>
<td>3.48</td>
<td>127.5</td>
<td>372.0</td>
<td>0.36</td>
</tr>
<tr>
<td>([0/45]_2s)</td>
<td>296</td>
<td>3.02</td>
<td>173.5</td>
<td>385.8</td>
<td>0.47</td>
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<td></td>
<td>394</td>
<td>3.02</td>
<td>145.2</td>
<td>358.3</td>
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<td></td>
<td>430</td>
<td>3.02</td>
<td>116.0</td>
<td>330.7</td>
<td>0.36</td>
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</tbody>
</table>

Table 1: Strength Data for HMF300C/34 Cloth Laminates with 2.54 cm Hole
Despite excellent agreement in failure load between the three replicates for each test condition, the strain gages at and close to the hole often differ significantly as the failure load was approached. The strain gage responses at these locations are also of considerable interest as indicators of when non-linear behavior first becomes apparent. Let us focus attention on the quasi-isotropic layups and, in particular, the gages at the hole edge on the laminate surface and the through-thickness gage adjacent to it. Strain response for the other two layups exhibited similar trends.

In Fig. 5, we see clear evidence of nonlinear behavior at roughly half the failure stress. It is also clear that, as expected, the maximum edge strain exceeds the unnotched failure value of roughly 0.8% by a large margin. As all the hole specimens failed by delamination, it is natural to look for a consistent through-thickness strain at failure. None is evident.

For the 394°K tests in Fig. 5b, note that the edge strain does not exceed the unnotched failure value of about 0.72%. Also note that the maximum through-thickness strains measured now exceed those on the edge in magnitude, and their average is roughly double their RT value.

As at 394°K, the 430°K data of Fig. 5c show that the maximum edge strains do not reach the average unnotched material failure values of 0.65%.

The fact that the planar strains at the edge of the holes do not reach the failure levels of the unnotched material at the higher temperatures might cause concern about the application of the average or point stress failure criteria. One obvious concern is whether the strain gages are measuring the composite strain. The relevant checks were conducted, and good agreement was found between the gages and predictions. A plausible resolution of this question can be expressed as follows: in determining compression strength of laminates with and without holes, it is natural to measure inplane strains which are close to average fiber strains. However, the failure is very strongly influenced by the resin-dominated interlaminar shear and tension strength, which are not quantified by these gages. Thus, we have a situation where the reported strains are an imperfect measure of those contributing most significantly to the failure mode. Data in Fig. 5 and [11] suggest the two stress failure criteria retain their credibility and are a reminder that the inplane compressive strain can sometimes be an inadequate measure of failure. This tends to further substantiate what was pointed out by Starnes [17] who noted that care must be taken to use appropriate normalizing data when applying methodology such as the average stress failure criterion.

TEST RESULTS - TAPE LAMINATES

Test results for these holed laminates also exhibited encouragingly little scatter with no test point more than 8% different from the average of the three replicates. The only testing problem which arose was that three of the [±45/02 ±45/02] g laminates buckled. After the two RT tests failed in this manner, the test fixture was modified by adding two pairs of horizontal bars with their pins restricting lateral motion. The buckling gross stresses were 221.0 and 243.8 MN/m² while the material failure occurred at 225.1 MN/m². Table 2 shows the averages of the three replicates.

Note that all three tape laminate layups had 50% of ±45-deg plies and varied less markedly from quasi-isotropic than the cloth laminates tested. Also note there is little difference in notched or unnotched laminate strength between 296 and 394°K. In fact, in two of the three layups, slightly higher strength was evident at the higher test temperature. This insensitivity of the basic material properties over this temperature range has been noted elsewhere [19].

Evaluation of \( a_0 \)

Using (1) and (2), it is simple to produce curves of RSR versus \( a_0 \) for the three tape laminates and to superimpose the experimental results from Table 2. This is accomplished...
FIGURE 5. STRAIN GAGE RESPONSE AT THE EDGE OF 25.4 MM HOLES IN THE QUASI-ISOTROPIC HMF330C/34 CLOTH LAMINATES (a) R.T., (b) 394°K and (c) 427°K.
Table 2: Strength Data for AS/3501-6 Tape Laminates with 2.54 cm Holes

In Fig. 6 which shows \( a_0 \) varying slightly as a function of layup. The variation of \( a_0 \) is between about 0.25 cm for the most orthotropic laminates and reaches a maximum of about 0.40 cm for the quasi-isotropic laminate. Experiments by Nuismer and Labor [16] using the very similar AS/3501-5 material with small (0.48-cm) holes containing loaded and unloaded countersunk rivets resulted in a selection for \( a_0 \) of 0.62 cm. Thus, the larger nong countersunk holes seem to suggest a value for \( a_0 \) of 50% to 65% of the value obtained for the smaller countersunk holes. In making this comparison, note that the specimens of [16] were moisture conditioned to approximately 1.8% moisture content by weight. The panels tested in this program were tested after five months in the ambient environment of about 60% Relative Humidity, and thus contained about 0.4 \( \pm 0.05 \) moisture content by weight. Increasing moisture content tends to make the resin more ductile, which may explain at least part of the difference between the two sets of experiments.

**STRAIN DISTRIBUTIONS**

As this material is so insensitive to temperature between 296°C and 394°C, the strains for both temperatures are presented in Fig. 7. As with the cloth laminates, attention is focused on the gages at the edge of the hole and the "through thickness" gage. It is obvious from Fig. 7 that the panels which buckled showed a characteristically different strain history, and thus will not be discussed further. Overall comparisons between Figs. 5 and 7 show three obvious differences between the strain response at the hole of these cloth and tape laminates. Tape laminates exhibit rather more linear behavior, their through-thickness strains are markedly lower, and the material relative insensitivity to temperature is again in evidence. It is also pertinent to note that regardless of the layup, all unnotched AS/3501 laminates tested at typical ambient moisture levels have average failure strains in excess of 1.2%. Yet none of the edge gages reached this value, and failure was always by delamination, as discussed previously. As examples, the quasi-isotropic laminates tested in [20] had average failure strains of 1.3%, while the edge gages of our quasi-isotropic laminates had strains at failure below 1.1%. The 62.5% 0 deg plies, 25% \( \pm 45 \) deg plies, and 12.5% 90 deg plies laminates of [20] had \( \varepsilon_{\text{th}} \) 1.3% while our 50% 0 deg plies, 50% \( \pm 45 \) deg plies had strains at failure less than 0.7%. Even allowing for the extrapolation between the gage center and hole edge, the maximum strain did not reach the \( \varepsilon_{\text{th}} \) of the unnotched material. Thus, as pointed out in [17], again we have a failure mode in the notched specimens which is different from that of the basic material.

**EXAMINATION OF FAILURE SURFACES**

An item of considerable interest is the type and degree of damage induced by the failure. To evaluate the degree of delamination, one specimen from each trio of replicates was immersed in opaque fluid diiodobutane and x-rayed. Figure 8 portrays the results. They indicate a multi-ply delamination over a width of the same order as the hole across the critically loaded section normal to the loading. The decrease in delamination occurring less than 1 cm from the edges is caused by the clamping action of the test fixture side rails. At
FIGURE 6. RESIDUAL COMPRESSION STRENGTH RATIOS FOR AS/3501-6 TAPE LAMINATES WITH 2.54 CM CIRCULAR HOLES.

FIGURE 7. STRAIN GAGE RESPONSE AT THE EDGE OF 25.4 MM HOLES IN QUASI-ISOTROPIC AS/3501-6 TAPE LAMINATES AT 297 AND 394°K.
FIGURE 8. X-RAY PICTURES OF DIB SOAKED SPECIMENS INDICATING EXTENT OF DELAMINATIONS.
CONCLUSIONS

There are, of course, the inherent differences between the two materials — namely, the AS/3501-6 tape is modern, stronger, stiffer material, less influenced by temperature, at least between RT and 250° F. The HMF330C/34 has other virtues [21] and has been in mass production use since 1974. The material failures were always multiple delaminations. Each material was laid up into quasi-isotropic laminates which can be compared directly, plus two other layups. Comparing Tables 1 and 2, note that the quasi-isotropic strengths at RT were 385.8 MN/m² and 551.2 MN/m² for the HMF330C/34 and AS/3501-6, respectively; a 43% strength advantage for the latter. However, the RSR ($a_N/a_0$) and hence, $a_0$ values were very similar with the details summarized in Tables 1 and 2. They also confirm that $a_0$ is larger for compression than tension. This demonstration that higher strength composites are no more notch sensitive than their weaker brethren has often been reported in other works, but usually in reference to tension behavior. In both sets of tests, the quasi-isotropic layups had the highest RSR ratios. In general, the less quasi-isotropic the layup, the lower the RSR and $a_0$. In the AS/3501, there was no clear difference in notch sensitivity between RT and 394° K tests. However, the HMF330C/34 demonstrated slightly increased notch sensitivity as the test temperature was raised.

Except for the HMF330C/34 laminates at R.T., none of the strain gages mounted at the hole edge on the laminate surface recorded strains as high as the unnotched failure levels. This can be explained by noting that the compression failures are strongly influenced by the interlaminar strength and questions arise, as shown by Starnes [17], as to the relevant normalizing strength. In other words, the surface strain is not an infallible measure of compression strength. Hence, the fact that such strains at a hole edge do not reach the unnotched material failure strains at failure need not invalidate the average or point stress failure criteria.

In all cases, the strain gages on and adjacent to the hole edge showed distinctly nonlinear behavior well before failure. These departures from linearity were more pronounced in these cloth laminates than those made from the tape. In spite of all the material failures being delaminations, the thru thickness strain at failure varied quite widely, and no such strain failure criterion is immediately apparent. The variation in strains measured close to the hole between nominally identical specimens and test conditions is markedly greater then failure loads, RSR, or similar overall measures of strength. This local nonlinear behavior may be considered a severe test of any linear failure criterion, but the x-ray pictures of the delaminations show the damage zone to have a width of the same order of magnitude as the hole diameter. However, no quantitative information has been extracted from them.

REFERENCES


