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Effects of Holes on Graphite Cloth Epoxy Laminates Tension Strength

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A series of tests was conducted on laminates made from a graphite cloth epoxy material and having circular machined holes. The tests showed room temperature behavior similar to holed tape laminates except that residual or notched-to-unnotched strength ratio of the cloth laminates were somewhat greater. Increasing temperature and degree of laminate orthotropy was demonstrated to increase the effective notch sensitivity to holes. Strain gages exhibited virtually linear response to failure except on or immediately adjacent to the hole edge, where significantly nonlinear response was evident well below the failure load. Highly localized anisotropic failures apparently are the cause of this behavior, suggesting it will be difficult to model analytically. Test results generally followed the trends predicted by the average stress failure criterion, but suggest the parameter a_0 is a function of both temperature and layup. X-ray pictures of the failed specimens show that internal damage is restricted to a small distance from the failure surface.

Nomenclature

a_0	= characteristic length for average stress failure criterion
d	= hole diameter
E	= Young's modulus
exp	= experimental
G	= shear modulus
K	= stress concentration factor
R	= hole radius
RH	= relative humidity
RSR	= residual strength ratio
R.T.	= room temperature
SCF	= stress concentration factor
Tg	= glass transition temperature
w	= test specimen width
ϵ	= direct strain
ξ_2	$= R/(R+a_0)$
σ	= direct stress
ν	= Poisson's ratio

Superscripts and Subscripts

N	= notched material
T	= tension
tu	= tension ultimate
0	= unnotched material
1	= direction of the uniaxial loading
2	= normal to uniaxial loading direction
∞	= infinite width laminate

Introduction

ANALYSES of stress concentrations and associated failure criteria around holes and cutouts in composite structures still require considerable effort. Several research and development efforts are supplementing the published contributions. This means the state of knowledge is increasing rapidly and has reached the point where designs can be created with confidence. However, much work must be done in the areas of crack propagation under fatigue loading. Accounting for delaminations and the wide range of material variables such as stacking sequence, fiber volume, moisture, etc., is a challenging problem.

Investigations are available into the effect of stress concentration factors[1,2] and stacking sequence.[3] Finite elements have been used frequently—some employing three-dimensional elements.[4] Wide-ranging studies such as those by Whiteside et al.[5] provide useful design data by covering these effects plus others such as hole roughness and reinforcing patterns. They present data for three fibers: glass, graphite, and boron in epoxy matrices.

Failure criteria are also of great concern and various methods have been employed to resolve the complex results. It also is well established that the failure stress in a notched composite, relative to the laminate unnotched strength, is a function of the hole or notch characteristic planform dimension. This "hole size" effect has been tackled by Waddoups et al.[6] They hypothesized a through-thickness crack and employed the methodology of linear elastic fracture mechanics. Reasonable agreement was obtained with the available experimental data for specimens loaded in tension. Two alternative methods, known as the average and point stress criteria, were proposed by Whitney and Nuismer.[7] Considerable support has been obtained since for the average stress failure criterion. It has been applied successfully to failure at holes under tension[8,9] compression[10] as well as bolted joints.[11] The point stress criterion has been utilized successfully by Garbo and Ogonowski.[12] As a result of experiments in which ply stacking sequence and hole size were varied, Karlak[13] produces evidence to suggest that the point stress characteristic length may depend on these two variables. This paper intends to study the behavior of flat graphite cloth epoxy laminates at temperatures up to 450 K (350°F). In doing this, the hole size effect is accounted for by using four hole sizes.

Test Specimens

The material used was the HMF330C/34 graphite cloth epoxy, for which a large data base has been established. In addition to assessing the importance of temperature, the influence of layup was evaluated. The material properties in warp and fill directions are within 8% of each other at all test temperatures. Hence varying the percentage of 0-deg (warp) and 90-deg (fill) plies is much less important in cloth than it is in tape laminates. Therefore the important layup variable becomes the percentage of 45-deg plies. To keep the program within the economic resources available, it was decided to keep to a single laminate thickness of eight plies or roughly 0.264 cm (0.104 in.). The three layups selected were $[0]_{4s}$, $[0/45/0_2]_s$, and $[0/45]_{2s}$. These were chosen to provide 0%,

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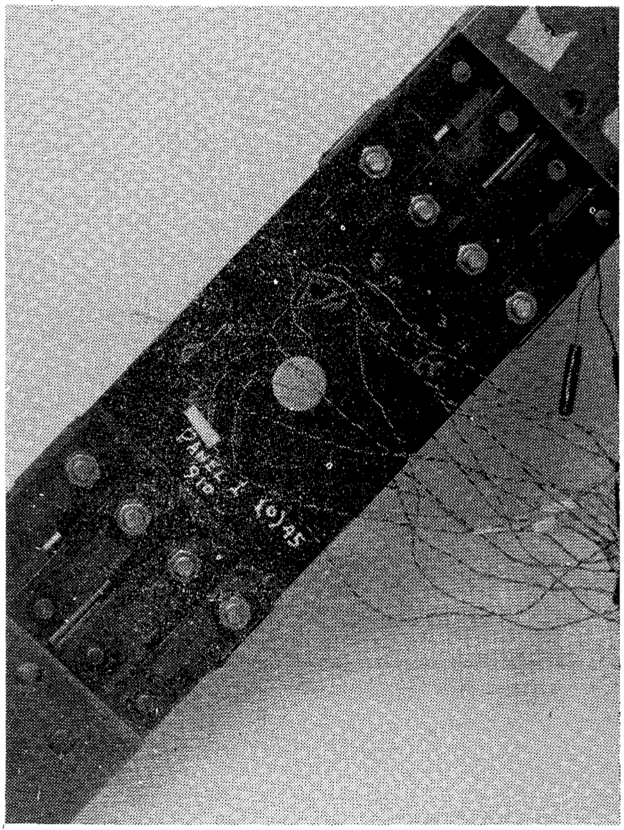

Fig. 1 Test configuration of the large panels with 2.54-cm (1 in.) diameter holes.

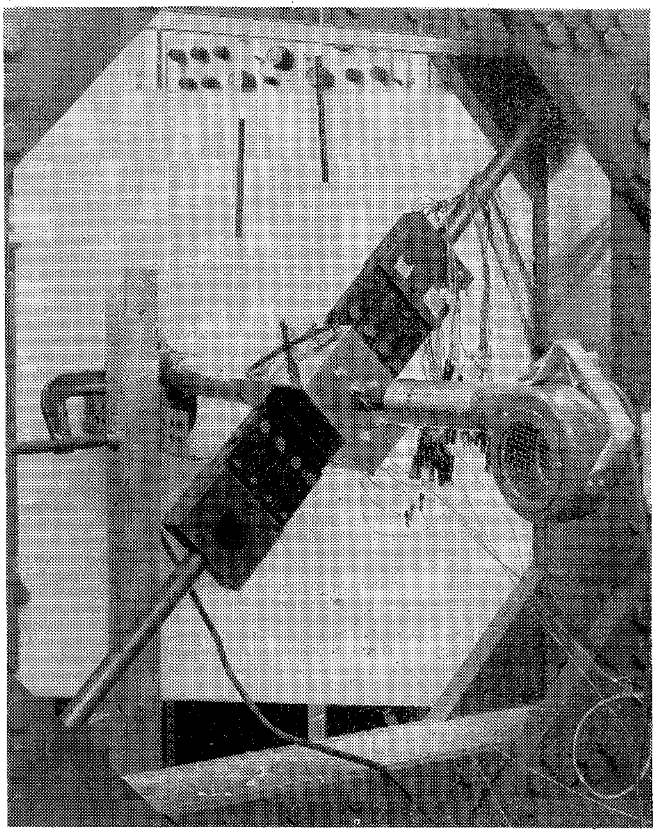

Fig. 2 Installation showing the "hot box" and air heaters for high temperature testing.

25%, and 50% of 45-deg plies, respectively. There were three replicates of every test.

The flat laminates were fabricated using the standard cure cycle for the material that is typical for the "450 K" (350°F) epoxy systems. It includes a hold at (455±5) K [(360±10)°F] for 2 h. Acid digestion techniques yielded a fiber volume of 62 ± 2% and a void content of less than 1%. For the 2.54-cm (1.0 in.) diameter holes, the 12.7-cm (5 in.) wide, 25.4-cm (10 in.) long panels were cut from the 61×61-cm (24×24 in.) panels. The holes were cut in the center as follows. A No. 4 carbide tip drill operating at 2200 rpm was used for the initial hole. This was followed by successive use of 1.27-cm (0.5 in.) and 1.91-cm (0.75 in.) diameter carbide tipped drill. A carbide tipped boring head operating at 1600 rpm and 0.0038 cm (0.0015 in.) per revolution feed provided the smooth finished surface. The three smaller holes were drilled at the center of 2.54-cm (1.0 in.) wide, 30.48-cm (12.0 in.) long, tabbed specimens. The laminates were supported on expendible fiberglass-epoxy sheets to preclude drill break-out damage. After drilling, each panel was subjected to "C" scan ultrasonic evaluation to assure no delaminations or other damage had been induced.

Instrumentation and Testing

After tabbing, the panels with 2.54-cm (1.0 in.) holes were strain gaged as indicated in Fig. 1. The uniaxial gages used on the surface and gage lengths of 0.318 cm (0.125 in.), as did those used in the rosette. The "through-thickness" gage on the hole edge to measure strains normal to the laminate plane had a gage length of 0.152 cm (0.06 in.). Micro Measurements CEA strain gages were bonded using M Bond 200 adhesive for room temperature tests and M Bond 610 adhesive for elevated temperature tests. In the latter, the bonding cure cycle was 2 h at 344 K (160°F) followed by 2-h postcure at 28 K (50°F) above test temperature.

The four gages close to the tabs, including one "back-to-back" pair, were obviously intended to measure the magnitude and uniformity of the applied strains. Those located between the hole center and the plate edge recorded the drop-off in strain from the hole edge. Note that the centerline of the gage closest to the hole is 0.178 cm (0.07 in.) away from it. To obtain an estimate of strain at the hole edge, the assumption was made that the gage reading represents the strain at its centerline and the strain gradient is constant to hole edge. Then, it is necessary to linearly extrapolate over this dimension to obtain the maximum strain.

After installation of each specimen and with the bolts untorqued, a 4535-kg (1000 lb) tension load was applied. This seated all the elements of the loading fixture prior to torquing the bolts. Because of concern about thermally induced degradation of bolt bearing strength in tabs, it was decided to exclude these areas from the "hot box." Air heaters were given preference over lamps to avoid the risk of localized hot spots and to ease temperature control. To insure symmetric heating, two air guns were mounted on opposite sides of the panel. The two box halves were held in position by crossed elastic bands, one pair of which is visible in Fig. 2. Their mating surface with the panel was a silicon rubber strip and was sealed with insulating wool to minimize heat losses and temperature gradients. Preliminary temperature surveys at the laminate faces were conducted at nominal temperatures of 394 K (250°F) and 450 K (350°F). Within 5 cm (2 in.) of the hole center, the laminate temperature was always within 5.6 K (10°F) of the nominal. All tests were conducted with the four thermocouples located as shown around the air heater nozzle in Fig. 2.

Keeping the total heating duration to a minimum, without inducing thermal gradients at critical locations, and minimizing changes in absorbed moisture were prime testing objectives. The procedure for heating the panels was derived as follows.

Prior to structural testing, spare composite specimens with 2.54 cm (1.0 in.) holes were utilized to conduct thermal tests to determine the required heating rates. These specimens had a hole, just large enough to contain a thermocouple, drilled radially inwards toward the hole center, in the laminate midplane at the minumum section. It terminated midway between the laminate side and the hole edge. The thermocouple was installed against the laminate at this location and entry of hot air into this hole was prevented by sealing the hole exit face with layers of glass tape. Temperatures recorded by this thermocouple were correlated with those of four others contacting the laminate surface. These four had no impact on structural integrity and were utilized on the structural tests. Thermal tests demonstrated that by setting the air entry temperature at the test value, the internal thermocouple reached the test temperature in less than 3 min. To assure thermal equilibrium in the critical area of the test panels, they were soaked for one more minute, prior to load application. The structural panels failed within 4 min of load initiation. The 2.54-cm (1.0 in.) wide specimens were heated in a very similar manner.

All specimens constituting the main body of this project were kept at ambient environmental conditions of roughly 45-50% humidity and a temperature of 297 ± 1 K (75 ± 2°F) for a maximum of two months between fabrication and test. This meant a relatively small moisture content, measured by weight gain of about 0.4% moisture. However, the specimens having 2.54-cm (1.0 in.) holes and tested at elevated temperatures would have contained less moisture, as the cure cycles described for strain gage bonding would have driven off moisture. As the time duration between gage bonding and testing was less than a week, little moisture could have been absorbed.

As the first step toward assessing the impact of moisture on notched tension strength, a supplemental series of tests was run. These specimens were 2.54 cm (1.0 in.) wide and had either 0.238-cm (3/32 in.) or 0.318-cm (1/8 in.) radius holes. They were moisture conditioned in a 60% RH atmosphere at 322 K (120°F) until weight measurements showed equilibrium had been reached at a weight gain of roughly 0.8%.

Despite the large data base on basic unnotched laminate properties, it was decided to conduct three tension tests on each layup at each of the three test temperatures. Instead of drilling the central hole, a single panel of each layup was cut into nine 1.27-cm (0.5 in.) wide tensile test specimens. Because of an anomaly in the 450 K (350°F) tests, additional 2.54-cm (1 in.) wide specimens were cut from other panels and tested. They are discussed in the following section.

The specimens containing the three smaller holes were tested in a much simpler manner without conventional strain gages. To ascertain the onset of nonlinear behavior, the strain adjacent to the hole was measured using the clip-on strain transducer shown in Fig. 3. It had a 1.27-cm (0.5 in.) gage length and was mounted 0.254 cm (0.1 in.) from the specimen's straight edge and symmetrically about the center of the hole.

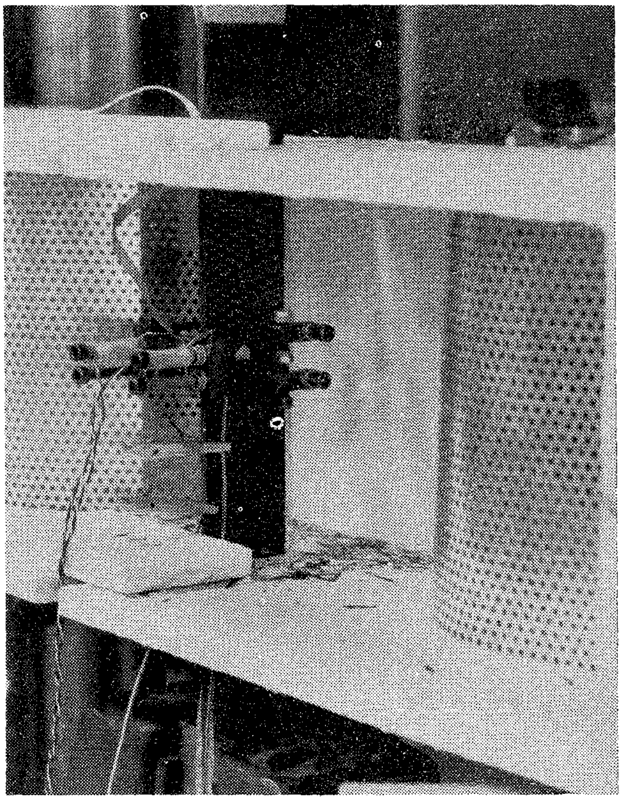

Fig. 3 Experimental setup for the small hole tests, showing the clip-on strain transducer.

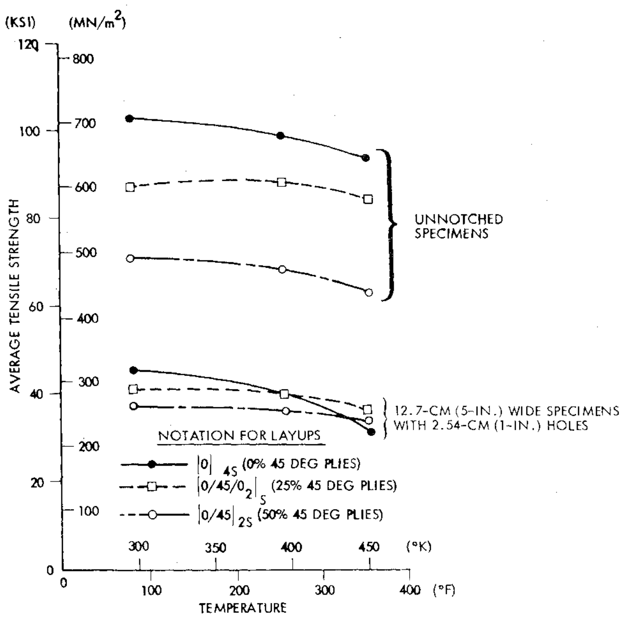

Fig. 4 Tension strength of unnotched material and 12.7-cm (5.0 in.) wide specimens with 2.54-cm (1.0 in.) holes in HMF330C/34 graphite cloth epoxy material.

Experimental Results—Unnotched Material

The data are presented in the upper part of Fig. 4. The R.T. values are approximately 10% higher than the previously derived large data base. At 394 K (250°F), the difference is about 3%; at 450 K (350°F), these values are roughly 8% lower than the data base—i.e., these panels show a greater-than-expected tension strength sensitivity to temperature. Another characteristic is that for all the tests at 450 K (350°F) on the $[0/45]_{2s}$ specimens, the failure mode consistently was delamination occurring at four or more ply interfaces. This was not expected. In all other cases, it was classical tension. To check the sensitivity of failure load at 450 K (350°F), 2.54-cm (1 in.) wide specimens were tested. No change in failure mode or failure stress range resulted. Note that the layup suffering delamination failure had the plies in different directions interspersed throughout the laminate thickness. Such stacking sequences normally minimize free edge effects. Here, the $[0/45/0_2]_s$ laminates did not suffer any edge-induced delamination failure at any temperature.

At this stage, it was decided to check *Tg* by cutting diagnostic samples from R.T. tension test samples. These twelve gave an average *Tg* of 427 K (310°F). Note that the tests of these and the notched specimens were conducted

Table 1 Experimentally determined stress concentration factors and residual strength ratios for the 2.54-cm (1.0 in.) hole tests, corrected for finite width

Layup	Temperature K	(°F)	K_T (exp)	σ_N/σ_0 (exp)	K_T (exp)	σ_N^∞/σ_0 (exp)
$[0]_{4s}$	296	(75)	2.30	0.44	2.19	0.46
	394	(250)	2.46	0.41	2.35	0.43
	450	(350)	3.06	0.33	2.92	0.34
$[0/45/0_2]_s$	296	(75)	2.14	0.47	2.04	0.49
	394	(250)	2.20	0.45	2.10	0.47
	450	(350)	2.12	0.47	2.05	0.49
$[0/45]_{2s}$	296	(75)	1.94	0.52	1.85	0.54
	394	(250)	1.93	0.52	1.85	0.54
	450	(350)	1.93	0.52	1.85	0.54

Table 2 Comparison of measured R.T. residual strength ratios for tape and cloth laminates with 2.54-cm (1 in.) holes (tape data from Ref. 8)

Material	Layup	σ_0 MPa	ksi	σ_N^∞/σ_0(exp)
T300/5208 tape	$[0/90]_{4s}$	637	92.4	0.57
HMF330C/34 cloth	$[0]_{4s}$	709	102.9	0.46
T300/5208 tape	$[0/\pm45/90]_{2s}$	494	71.7	0.45
HMF330C/34 cloth	$[0/45/02]_s$	594	86.2	0.49
HMF330C/34 cloth	$[0/45]_{2s}$	484	70.3	0.54

above the material Tg, and that the basic material (the $[0]_{4s}$ laminates) were stronger at R.T. and weaker at 450 K (350°F) than the data base. The following qualitative argument appears relevant. It seems reasonable to expect that a low Tg would accompany a plasticized and, hence, more ductile resin. Increased resin ductility will improve the transfer of load at broken fibers and, accordingly, improve R.T. strength. However, testing above Tg means the resin properties are likely to be reduced and degrade laminate strength.

Experimental Results—Laminates With 2.54-cm (1 in.) Diameter Holes

The lower part of Fig. 4 shows overall results depicting the average net tension stress at failure as functions of layup and temperature.

With these laminates containing holes, as with those having $[0/90]_{2s}$ tape layups,[8] the absence of 45-deg plies does not produce a precipitous loss in strength. In fact at R.T. the cloth laminate notched strength is greater than those layups with 45-deg plies. At higher temperatures, different behavior is apparent. The loss of strength as a function of temperature is far more pronounced in the absence of 45-deg plies. In fact, the $[0/45/0_2]_s$ and $[0/45]_{2s}$ laminates with holes are slightly less sensitive to temperature than the unnotched specimens. This is evident in Fig. 4. It is also interesting to compare the experimentally derived stress concentration factors by dividing σ_0 by the average failure stress of the holed laminate σ_N. Its inverse is the ratio notched-to-unnotched strength, σ_N/σ_0, also known as the residual strength ratio. Test results and their correction for finite width effects are included in Table 1.

This correction is discussed in the next section. Note, it produces just less than a 5% change in the parameters of interest in this case. Hence the qualitative discussion applies to both test data and those derived for infinite width panels.

It is worth noting that the test scatter of failure load among the three replicates of any test, unnotched or holed, was encouragingly small, with the coefficient of variation never exceeding 9%. Hence the average values of the experimentally derived quantities are considered to be a satisfactory measure of strength. They are used throughout except in the discussion involving strains measured on the hold edges, which are presented later in the paper in Fig. 6.

Table 1 shows that the residual strength ratio at failure does not go below 0.33, the value for isotropic materials. Anisotropic laminates can have much lower values of this ratio. This means much higher values than 3 for the stress concentration factor, as given elsewhere.[4,8,14]

It also indicates that σ_N/σ_0 decreases with temperature for the laminate without 45-deg plies. σ_N/σ_0 is independent of temperature for the $[0/45]_{2s}$ laminate with 50% of 45-deg plies. Those with 25% of 45-deg plies exhibit a slight drop in σ_N/σ_0 at 394 K (250°F) but a rise at 450 K (350°F), relative to R.T. value. Note that at all three test temperatures, the residual strength ratio rises as the percentage of 45-deg plies increases to the quasi-isotropic value of 50%. This is consistent with the predictions of elastic, homogeneous, plane stress theory.[2,14]

Comparison of R.T. Data With Tape Laminate Results

These R.T. experiments can be compared with the tests of 2.54-cm (1.0 in.) diameter holes in T300/5208 laminates.[8] In doing this, remember that our specimens had a nominal hole diameter to a width ratio of 0.2. For those discussed in Ref. 8, this ratio was 0.33. This parameter influences the stress concentration factor.[8,14] For circular holes in isotropic materials, the ratio of finite width to infinite width SCF is

$$\frac{K_T}{K_T^\infty} = \frac{2+(1-d/w)^3}{3\,(1-d/w)} \tag{1}$$

This ratio is 1.046 for our tests, but 1.145 for those of Ref. 8. To remove the complication of finite width and allow a direct comparison with the results of Refs. 8 and 13, our values of K_T in Table 1 must be reduced by 4.6% to obtain K_T^∞. Obviously, the residual strength ratios need to be increased by this amount. This provides the last two columns of Table 1. Using the relevant ones and the data from Ref. 8 allows Table 2 to be created.

Table 3 Material constants used in computing K_T^∞

Temperature K	Temperature (°F)	Layup	E_{11} GN/m^2	E_{11} MSI	E_{22} GN/m^2	E_{22} MSI	12	G_{12} GN/m^2	G_{12} MSI	K_T^∞
296	(75)	$[0]_{4s}$	76.5	11.1	71.7	10.4	0.09	6.9	1.00	4.60
296	(75)	$[0/45/0_2]_s$	67.5	9.8	63.4	9.2	0.20	12.4	1.80	3.67
296	(75)	$[0/45]_{2s}$	55.1	8.0	53.1	7.7	0.32	19.3	2.80	3.06
394	(250)	$[0]_{4s}$	72.0	10.5	66.8	9.7	0.09	6.8	0.98	4.55
394	(250)	$[0/45/0_2]_s$	63.4	9.2	60.6	8.8	0.20	12.7	1.85	3.57
394	(250)	$[0/45]_{2s}$	53.1	7.7	51.0	7.4	0.32	18.9	2.75	3.05
450	(350)	$[0]_{4s}$	74.4	10.8	70.3	10.2	0.09	6.5	0.95	4.64
450	(350)	$[0/45/0_2]_s$	64.8	9.4	62.0	9.0	0.20	12.4	1.80	3.62
450	(350)	$[0/45]_{2s}$	55.1	8.0	53.7	7.8	0.32	18.6	2.70	3.09

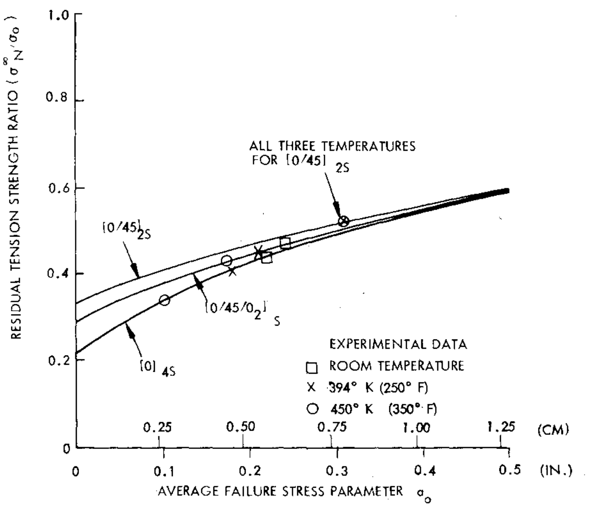

Fig. 5 Residual tension strength ratios for HMF330C/34 cloth laminates with 2.54-cm (1.0 in.) holes.

In the absence of 45-deg plies, the cloth has a roughly 10% greater unnotched strength but about 20% lower residual strength ratio. For the quasi-isotropic laminates, the unnotched strengths are very close together. However, the residual strength ratio of the cloth laminates is 20% greater than that for the tape. It also is noted that for the tape laminates, the residual strength ratio decreases in going from the $[0/90]_{4s}$ to the quasi-isotropic layup. As mentioned earlier, the cloth shows the opposite behavior with the residual strength ratio rising as the layup becomes progressively closer to quasi-isotropic. Reasons for this difference are not immediately apparent.

Derivation of Parameters for Average Stress Failure Criterion

This criterion for composite laminate failure is now know[7-9] sufficiently so that familiarity on the part of the reader is assumed. What follows is intended to extract the parameter a_0 defining the distance from the hole edge, over which the stress is average. The basic equation for the residual strength ratio is Eq. (8) of Ref. 8, to which the reader is referred for details. It is repeated here as

$$\frac{\sigma_N^\infty}{\sigma_0} = \frac{2(1-\xi_2)}{[2-\xi_2{}^2-\xi_2{}^4+(K_T^\infty-3)(\xi_2{}^6-\xi_2{}^8)]} \tag{2}$$

where $\xi_2 = R/(R+a_0)$. K_T^∞, the theoretical stress concentration factor for an infinite plate, is given as Eq. (3) in Ref. 8.

It is repeated here as

$$K_T^\infty = 1 + \sqrt{2(\sqrt{E_{11}/E_{22}} - \nu_{12}) + E_{11}/G_{12}} \tag{3}$$

For each set of material constants which are functions of layup and temperature, K_T^∞ is computed first. Then, Eq. (2) can be used to plot the residual strength ratio against parameter a_0 for constant hole size. To do this, the material elastic constants are required. Those for our cloth laminates, taken from the unpublished data base, are given in Table 3.

Figure 5 shows the residual strength ratio vs a_0 as functions of layup and temperature. Experimental results corrected for finite edge effects, as discussed previously, have been added. It is convenient to review the R.T. results first because there are tape data with which they can be compared.

The R.T. data cover the range of a_0 from 0.61 to 0.79 cm (0.24 to 0.31 in.) with an average of about 0.76 cm (0.30 in.). This is somewhat above the values of 0.38 cm (0.15 in.)[8] and 0.23 cm (0.09 in.)[9] quoted for tape laminates. A larger value of a_0 is indicative of a lower stress gradient; this suggests these cloth laminates may be more forgiving in the presence of circular holes than their tape counterparts. This difference in behavior deserves some attention. As stated in Ref. 9, "smaller values of a_0 cause the stress to be averaged nearer the notch, thereby causing the stress concentration to have a greater effect on failure predictions." It is probable that the effect of stress concentration is "smeared out by the presence of flaws that exist in abundance in low quality laminates." We suggest that larger values of a_0 may not necessarily be undesirable or indicate low quality laminates. It seems reasonable to consider the analogy to ductile behavior in metals. High unnotched static strength and sensitivity to notches often indicate brittleness. Such materials would have small a_0 values. Thus the larger a_0 value manifested by some laminates can be interpreted as greater effective ductility. Hart Smith, in his studies of composite bolted joints,[15] used this idea of localized composite nonlinear behavior, including local resin and fiber failures in regions of high stress concentration, being analogous to ductile behavior in metals. As each cloth ply is markedly less anisotropic than its tape counterpart, the interlaminar edge stresses may be less severe in holed laminates made from the former material. This conclusion was reached in a study devoted to delaminations in the edges of straight-sided laminates.[16] Care should be taken to avoid making unwarranted generalizations in this case. First, our discussion is based on cloth laminates tested for only one hole size. Tests for other hole sizes are discussed later in this paper. Second, a firm correlation between the two materials is not possible because, although T300 fibers were used in both cases, the resins and cure cycles used were not identical.

Other observations from Fig. 5 can be made. Parameter a_0 does not appear to be strictly a material property, but is a definite function of the layup. Larger values are associated with the more nearly quasi-isotropic layups, which are well known to have lower stress concentration factors. Table 1 gives this variation of K_T as functions of layup and temperature.

Discussion of the 450 K (350°F) test results poses a problem of relevance. Testing at a temperature well above Tg makes the results and the conclusions drawn from them of questionable usefulness. The low failure stresses of the unnotched material has a severe impact on the σ_N/σ_0 and, thus, the values of a_0. Nevertheless, the trends of these data points are consistent with those derived from tests at the other two temperatures. Parameter a_0 does not change with temperatures for the quasi-isotropic layup, but the more orthotropic the layup, the smaller it becomes.

In these discussions on determining a_0, remember that it is based on the assumption of linear elastic, homogeneous behavior up to failure. It is now pertinent to assess how well these assumptions were satisfied in the test series as well as to compare qualitatively the failure surfaces.

Evaluation of Strain Gage Data From Hole Edges

A vast majority of the strain gage data was linear right up to failure, which correlated well with the finite-element analysis, and test-to-test repeatability was excellent. In assessing failure modes, the most interesting data were from the two gages on the hole edge. These were the only two where significant nonlinear response was evident. One was on the laminate surface in the direction of loading where the axial strain is greatest, i.e., tangential to hole edge at the minimum section. The other was adjacent to it but measures through-thickness strain on the hole surface. In what follows, we will refer to them as the "edge" and "through-thickness" gages, respectively.

Those for the quasi-isotropic layup are shown in the strain versus stress plots of Fig. 6. The three different lines (——, – – – – –, and —— –) in each of Figs. 6a-c are for the three replicates of each test. Separate identification for each replicate in these figures is done to emphasize the significant lack of repeatability from test to test of the strains at the hole edge, regardless of temperature. At room temperature, the edge strains were linear out to about 80% of failure stress, but the through-thickness strains evidenced earlier nonlinear behavior. They suggest some localized nonlinearity when the strains away from the hole edge are at roughly half their values at laminate failure. Similar responses were recorded for all three layups. Thus this behavior is probably associated with highly localized fiber and resin damage, as delaminations are not expected, particularly when there is no angle change between the plies. For all layups, there was quite a variation in the behavior of these two gages' data for nominally identical specimens.

At 394 K (250°F) the noteworthy strain behavior is a decrease in through-thickness strain, as a function of stress, just prior to failure. From Fig. 6b, note that on one panel, a positive through-thickness strain was recorded just prior to failure. Quantitative explanation of this local behavior is not obvious. At the highest test temperature, the departure from linearity at the hold edge is even more extreme. The sudden change in slope of the surface hole edge gages at roughly 130.9 MN/m^2 (19 ksi) and their failure at about 1% strain indicate a significant nonlinear redistribution of strain. At even lower loads, the through-thickness strains are indicated linear response throughout, so the nonlinear behavior is restricted to areas close to the hole. Note that in all cases, the failure strain of the unnotched material ϵ^{tu} is exceeded at the hole edge.

Post-test Examination of Failure Surfaces

In all cases, the failures were through the thickness across the minimum section. To assess the propagation of failure into the laminates, the specimen which failed at the highest load among the three tested at each layup-temperature combination was soaked in diiodobutane and x-rayed. Typical results are exhibited as Fig. 7. Failure surfaces were highly localized, as evidenced by the minimal interlaminar propagation of failure. Compare these figures with those

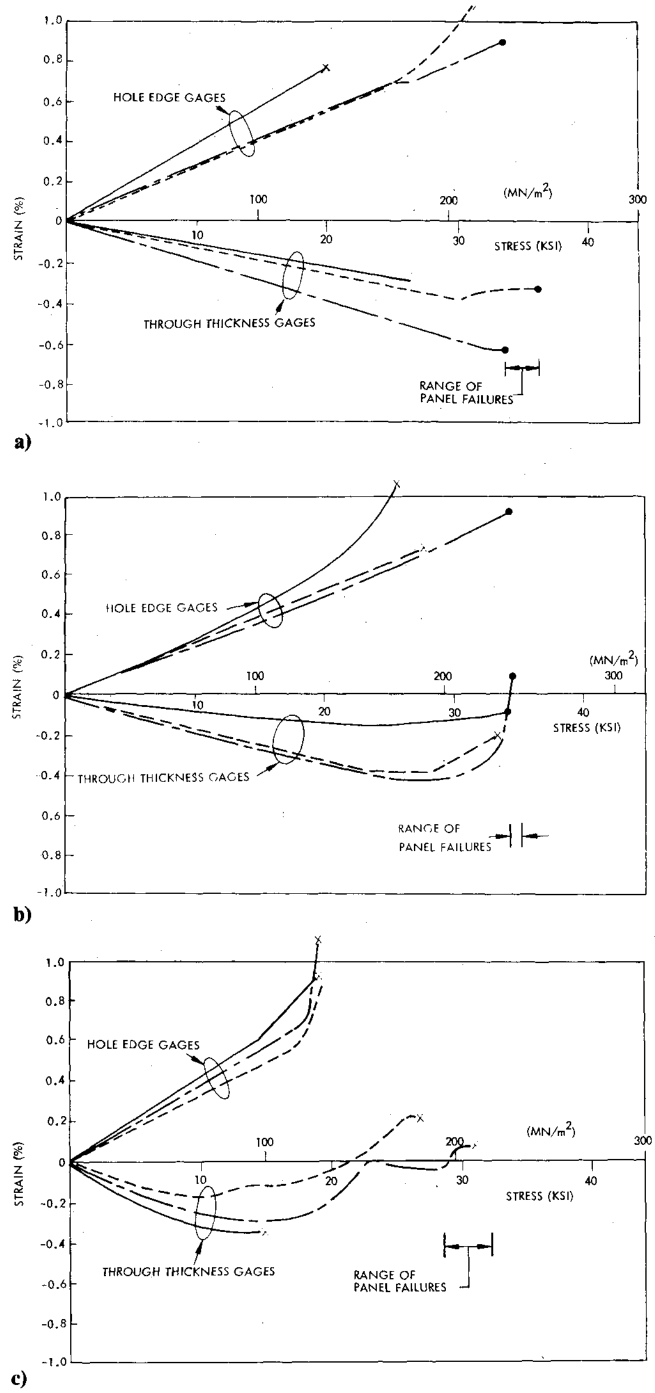

Fig. 6a) Hole edge and through-thickness strains on $[0/45]_{2s}$ quasi-isotropic panels with 2.54-cm (1 in.) holes at room temperature. b) Hole edge and through-thickness strains on $[0/45]_{2s}$ quasi-isotropic panels with 2.54-cm (1 in.) holes at 394 K (250°F). c) Hole edge and through-thickness strains on $[0/45]_{2s}$ quasi-isotropic panels with 2.54-cm (1 in.) holes. Each of the three lines (——, – – –, ——) represents a different replicate.

depicting failure of tape laminates, such as Figs. 7 and 8 of Ref. 8, and note that holed tape laminates often involve delaminations which propagate much further away from the holes with the various plies failing at widely dispersed locations. There is no evidence in Fig. 7 to indicate significant delaminations except very locally at the hole edge. In some cases, the distance normal to the cracked surface that delamination is evident, is greater away from the hole edge than at it. Although the through-thickness strain data at 450 K (350°F) of Fig. 6c show a tension value well below failure, the damage at the hole edge does not appear significantly different from that at room temperature when these gages indicated compression. Further attempts are continuing to extract quantitative data from x-rays of this type of failure.

Influence of Hole Size

Correcting the test data for finite edge effects by means of Eq. (1) allows the results for all hole sizes to be displayed in the conventional form. This is done in Fig. 8, which also shows the average stress failure criterion prediction for isotropic laminates using three values of a_0. They were obtained using K_T of Table 3 in Eq. (2). From this figure, a number of interesting trends can be discerned. For the three smaller hole sizes, the experimental data for the quasi-isotropic laminates suggest values of somewhat above 0.254 cm (0.1 in.) rather than 0.762 cm (0.3 in.) found in the 1.27-cm (0.5 in.) radius holes. This shows close agreement with the previous discussed tape laminates.[8] The laminates without 45-deg plies show similar trends but indicate smaller values of a_0, in agreement with the predictions of the criterion. The fact that the quasi-isotropic laminates with 1.27-cm (0.5 in.) radius holes have a higher RSR than those with 0.635-cm (0.25 in.) holes is consistent with some data on tape laminates.[8] The RSR reduction induced at the higher test temperatures is evident for both layups but is less severe for the quasi-isotropic ones.[12]

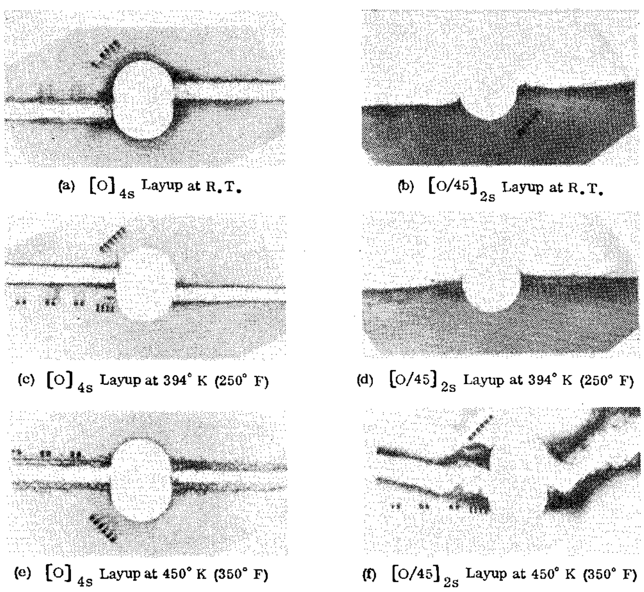

Fig. 7 X-ray photographs of failed specimens with 2.50-cm (1.0 in.) holes.

Garbo and Ogonowski[12] have found good agreement with the point-stress failure criterion using $d_0 = 0.51$ cm (0.02 in.) and their test data on the effect of small holes on certain tape laminates. Attempts to correlate our test results with this criterion were less successful. Using $d_0 = 0.127$ cm (0.05 in.) gave good agreement for the quasi-isotropic laminates having the two smaller holes. However, with this value for d_0, the lack of agreement for the larger holes and anomalies concerning the behavior of orthotropic laminates were quite marked.

Though the results for the 450 K (350°F) tests may be considered outside the mainstream of this type of investigation because of their being well above the material Tg, the effect of layup on RSR nevertheless is worth noting.

It shows the decrease in RSR is markedly greater for the layup with no 45-deg plies than it is for the quasi-isotropic laminates. In fact, their degradation at this temperature is not particularly serious because it indicates reasonable agreement with the average stress criterion, with a_0 close to 0.25 cm (0.1 in.). This clear difference in response to temperature caused by layup seems to deserve further investigation.

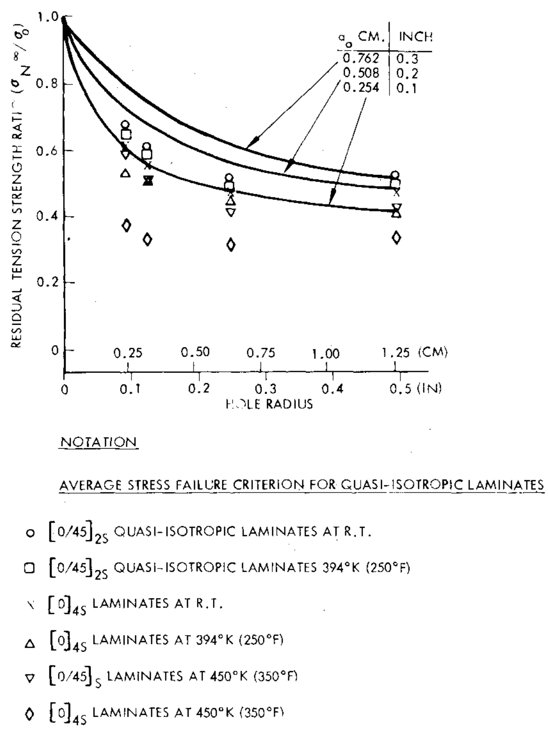

Fig. 8 Residual strength ratio as a function of hole size for $[0/45]_{2s}$ and $[0]_{4s}$ HMF330C/34 cloth laminates at R.T. and 394 K (250°F).

Table 4 Effect of moisture on notched strength

Hole radius, cm	(in.)	Layup	Temperature K	(°F)	Nett stress, σ_N, 60% RH	(ksi)	MPa, ksi Ambient	(ksi)	Ratio to R.T. ambient 60% RH	Ambient
0.238	(3/32)	$[0]_{4s}$	297	(75)	481.0	(69.81)	515.3	(74.79)	0.93	1.00
0.238	(3/32)	$[0]_{4s}$	394	(250)	328.3	(47.64)	422.1	(61.26)	0.64	0.82
0.238	(3/32)	$[0]_{4s}$	450	(350)	315.4	(45.77)	285.8	(41.48)	0.61	0.55
0.238	(3/32)	$[0/45]_{2s}$	297	(75)	388.6	(56.40)	392.1	(56.91)	0.99	1.00
0.238	(3/32)	$[0/45]_{2s}$	394	(250)	340.1	(49.36)	366.7	(53.22)	0.87	0.94
0.238	(3/32)	$[0/45]_{2s}$	450	(350)	297.6	(43.20)	303.3	(44.02)	0.76	0.77
0.318	(1/8)	$[0]_{4s}$	297	(75)	495.9	(71.98)	492.2	(71.43)	1.00	1.00
0.318	(1/8)	$[0]_{4s}$	394	(250)	338.6	(49.14)	419.9	(60.94)	0.69	0.85
0.318	(1/8)	$[0]_{4s}$	450	(350)	314.7	(45.68)	271.9	(39.46)	0.64	0.55
0.318	(1/8)	$[0/45]_{2s}$	297	(75)	364.9	(52.96)	369.9	(53.69)	0.99	1.00
0.318	(1/8)	$[0/45]_{2s}$	394	(250)	333.9	(48.46)	357.2	(51.85)	0.90	0.96
0.318	(1/8)	$[0/45]_{2s}$	450	(350)	283.0	(41.07)	272.2	(39.51)	0.76	0.74

The clip-on gages showed virtually linear response at room temperature. However, clearly nonlinear behavior was evident in the 1.27 mm (0.5 in.) diam hole tests at the higher test temperatures. Its onset occurred at roughly 90% for failure load at 394 K (250°F) and at approximately two-thirds of the failure load at 450 K (350°F). This supports the strain data obtained in the 2.54-cm (1 in.) hole tests in showing clearly nonlinear response at some reasonably large fraction of the hole diameter. This might arouse questions concerning the applicability of failure criteria based on the assumption of linear behavior; however, this does not appear to be the case. In particular, the average stress criterion retains considerable usefulness even though the parameter a_0 appears to be a function of both layup and temperature.

Effect of Moisture

The supplemental tests, intended as a first step in assessing the impact of absorbed moisture, are summarized in Table 4. It does not appear to be particularly significant, but the following observations can be made. At room temperature the effects of moisture are indeed small, as expected. At 394 K (250°F) the drop-off in strength of the $[0]_{4s}$ layups is greater than for the isotropic laminates, for both hole sizes. However, at the highest test temperature, a slight increase in strength due to moisture is indicated for the specimens without 45-deg plies. In making these observations, it is worth noting that the quasi-isotropic laminates show little influence of moisture on notched strength at any of the test temperatures. It should be remembered that the small sample size of the replicates is bound to produce variations in the sample mean relative to the values that would be obtained from a much larger sample size.

Conclusions

Room temperature, uniaxial tests on quasi-isotropic laminates made from a single graphite cloth epoxy and having circular holes exhibited behavior which generally followed that of existing data[8] on holed tape laminates. Residual strength ratio (RSR) as a function of hole size was very similar—the cloth laminates had somewhat higher values. As the test temperature was increased, the RSR decreased, suggesting decreasing effective ductility. In this regard, the layup also was shown to be important. As the percentage of 45-deg plies was reduced from the quasi-isotropic value of 50% to zero, the RSR decreased. This was demonstrated at all three test temperatures and is the opposite trend reported for certain tape laminates. Correlation of the data with the average stress failure criterion shows its parameter a_0 is a function of both layup and temperature for this material. Increasing both orthotropy of the laminates and test temperature decreased a_0. Test data were in closer agreement with the average stress criterion than the point stress criterion.

Strain gages on and adjacent to the edge of the 2.54-cm (1 in.) diameter holes exhibited highly nonlinear response at well below failure loads. The higher the test temperature, the smaller was the fraction of failure load at which this was first evident. No explanation for this highly localized, complex response is immediately obvious. Because of the markedly anisotropic behavior induced by resin and fiber failures in the critical region, analytic modeling, such as by finite-element methods, may be difficult. This puts a premium, at least for applications studies, on relatively simple phenomenological explanations of residual strength, such as the average stress failure criterion.

Those tests devoted to assessing the influence of moisture on the strength of specimens with small holes suggest it is small.

Acknowledgments

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