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PREDICTION OF FRACTURE STRENGTH FOR NOTCHED LAMINATE SUBJECTED TO COMPRESSION LOADING

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Abstract

Two previously developed failure criteria (the average stress failure criterion and the point stress failure criterion), which are used to predict the uniaxial compressive strength of a laminated composite containing through-the-thickness material discontinuities (notches), are subjected to further experimental scrutinization. This paper contains predictions, using the two failure criteria, for compressive fracture strength in open hole laminates. This is accomplished by obtaining experimental data on the carbon/epoxy material system, in conjunction with unnotched multidirectional laminates and open hole multidirectional laminates. The composite material used in this paper is a carbon/epoxy unidirectional (UD) tape prepreg (Cycom G40-800/5276-1) cured at a 350°F (177°C). The operating temperature is -60°F ~ +200°F (-55°C~+95°C). A total of 84 compression tests were conducted on specimens from 6 distinct laminates that were laid up by standard angle layers (0°, +45°, -45° and 90°). The ASTM-D-6484D standard was used for the test method. Results are presented for the fracture compressive strengths of several carbon/epoxy laminates containing a circular hole. The point stress failure criterion was more reasonable than the average stress failure criterion to predict the observed strengths in all cases considered.

1 Introduction

Originally introduced to explain the hole effect in laminated composites without resorting to inherent flaws and fracture mechanic concepts, the average stress failure criterion [1] and point stress failure criterion [1] were found to result in remarkably good quantitative strength predictions for composites containing cutout [2].

This paper describes the compressive fracture strength predicted using two failure criteria for open hole laminates. This is accomplished by obtaining experimental data on the carbon/epoxy material system, in conjunction with unnotched UD laminates and open hole UD laminates. The 0.25 inch diameter hole is located in the center of the specimen.

The composite material used in this paper is a carbon/epoxy UD tape prepreg (Cycom G40-800/5276-1) cured at 350°F (177°C). Forty-two (42) compression tests for unnotched laminate and open hole laminate were conducted on specimens from six (6) distinct laminates respectively. The laminates were laid up by standard angle layers (0°, +45°, -45° and 90°). The ASTM-D-6484D standard was used for test method.

In the present paper, the application of the average stress criterion and the point stress criterion as failure criteria is considered for compressive loading cases.

2 Material and Test Method

2.1 Material

The material system, supplied by the Cytec Company in Cycom G40-800/5276-1 UD tape prepreg, was investigated. The mechanical properties of cured lamina are shown in Table 1.

Laminates for the unnotched compressive test (UNC) and the open hole compressive test (OHC) were chosen to span the range of practical structural applications.

The layup range is validated by uniaxial unnotched and notched tests, as in Fig. 1.

Table 1. Mechanical properties of cured lamina material.

Property		Unit	@ 70°/AMB
Lamina thickness	t	inch	0.00741
Density	ρ	lb/in3	0.057
Elastic modulus	E1*	msi	21.18
	E2	msi	1.31
	G12	msi	0.49
Poisson's ratio	v12	-	0.33

* E_1 is the average of tension and compression moduli

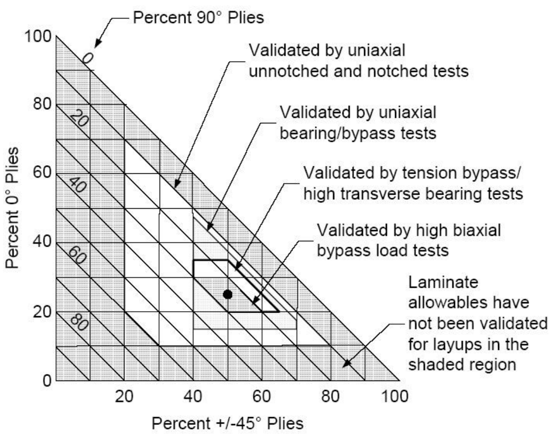
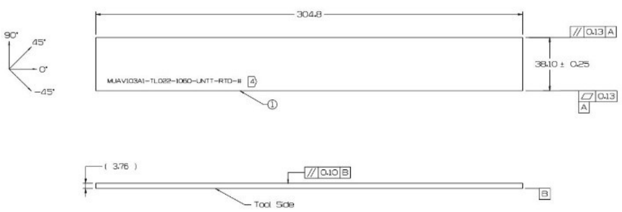
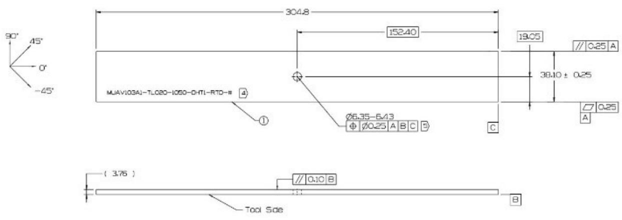


Fig. 1. Validated layup ranges for laminates.

The specimen configurations to be tested are provided in Fig. 2.



(a) UNC laminate specimen



(b) OHC laminate specimen

Fig. 2. Specimen configuration for UNC and OHC laminate.

The specimens were designed with plies oriented in four standard orientations of 0°, +45°, -45° and 90°. All specimens contained a minimum of 10% plies in each of the 0°, +45°, -45° and 90° orientations, thus ensuring that all test experienced a fiber failure mode without significant non-linearities in the load-strain response. The recommended specimen designations are provided as follows.

(a) The recommended specimen is from 0.08 inch to 0.20 inch thick.

(b) Variations in individual specimen thickness must be within 0.0004 inch to ensure uniform gripping in the test fixture.

(c) The specimen laminate must be symmetric and balanced with respect to the test direction.

2.2 Test Method

The ASTM D 6484D standard [3] was used for the test method. Forty-two (42) compression tests for unnotched laminate and open hole laminate, respectively, were conducted on specimens from six (6) distinct laminates at room temperature with ambient conditions. The test matrix is shown in Table 2.

Table 2. Test matrix for UNC and OHC laminate respectively

Specimen (0/±45/90% plies)	No. of specimen	Specimen (0/±45/90% plies)	No. of specimen
(25/50/25)	7	(30/60/10)	7
(30/40/30)	7	(50/40/10)	7
(30/50/20)	7	(60/20/20)	7

The stacking sequences of specimen for UNC and OHC laminate are shown in Table 3.

Table 3. Stacking sequence of specimens for UNC and OHC laminate.

No. of Plies	(0/±45/90% plies)	Stacking sequence
16	(25/50/25)	[45/90/-45/0/90/0/-45/45]s
20	(30/40/30)	[45/90/-45/0/90/0/-45/90/45/0]s
20	(30/50/20)	[45/90/-45/0/-45/45/0/90/-45/0]s
20	(30/60/10)	[45/90/-45/0/-45/45/0/45/-45/0]s
20	(50/40/10)	[45/90/-45/0/0/0/-45/0/45/0]s
20	(60/20/20)	[45/90/0/-45/0/0/0/90/0/0]s

The ASTM-D-6484D standard was used to determine the unnotched compressive strength (F^t_{UNC}), open hole compressive strength (F^t_{OHC}) and modulus (E^c) of an advanced composite multidirectional laminate. Each specimen is tested to failure to obtain the maximum load from which the compressive strength is calculated. A load-strain curve to failure is obtained, from which compressive moduli are calculated.

The test set-up configuration and specimens for UNC and OHC laminate are shown Fig. 3 and Fig. 4.

(a) Test set-up (b) Before test (c) After test

Fig. 3. Test set-up configuration and specimen for UNC laminate.

(a) Test set-up (b) Before test (c) After test

Fig. 4. Test set-up configuration and specimen for OHC laminate.

Compressive strength is calculated using the following equation:

$$F^c_{UNC} = \frac{P_{max}}{(w)(t_{calc})} \quad (1)$$

$$F^c_{OHC} = \frac{P_{max}}{(w)(t_{calc})} \quad (2)$$

where,

F^c_{UNC} = unnotched compressive strength (psi)
F^c_{OHC} = open hole compressive strength (psi)
P_{max} = maximum compressive load (lb)
w = measured width at midsection (in)
t_{calc} = calculated nominal laminate thickness (in)

The calculated nominal laminate thickness (t_{calc}) is obtained by summing the nominal per-ply thicknesses (t_{nom}) of the individual plies in the laminate.

3 Failure Criteria

Consider that a hole of radius R is an infinite orthotropic plate. If a uniform stress, σ, is applied parallel to the y-axis (transverse direction) at infinity, then the normal stress, σ_y, along the x-axis (longitudinal direction) in front of the hole can be approximated by

$$\sigma_y(x,0) = \frac{\bar{\sigma}}{2}\{2 + \left(\frac{R}{x}\right)^2 + 3\left(\frac{R}{x}\right)^4 - (K_T^\infty - 3)[5(\frac{R}{x})^6 - 7(\frac{R}{x})^8]\},\ x > R \quad (3)$$

where K_T^∞ is the orthotropic stress concentration factor for an infinite width plate. This is determined from the following relationship [4]

$$K_T^\infty = 1 + \sqrt{\frac{2}{A_{22}}\left(\sqrt{A_{11}A_{22}} - A_{12} + \frac{A_{11}A_{22} - A_{12}^2}{2A_{66}}\right)} \quad (4)$$

where A_{ij} represents the in-plane laminate stiffness as determined from laminated plate theory [5]. The subscript 1 denotes the direction parallel to the applied stress at infinity. In terms of effective elastic moduli for laminate, Eq. (4) becomes

$$K_T^\infty = 1 + \sqrt{2\left(\sqrt{\frac{E_x}{E_y}} - \upsilon_{xy}\right) + \frac{E_x}{G_{xy}}} \quad (5)$$

For unbalanced laminates, Eq. (5) is not applicable.

Although use of the average stress failure criterion and point stress failure criterion has previously been restricted to uniaxial tensile loading (1-2), the extension of its use to compressive failure seems plausible since the rationale for its use in tension would appear to be equally applicable to compressive loading. However, it is not expected that the same value of the characteristic length, a_{0t} and d_{0t}, used in tensile loading cases would be applicable to compressive failure predictions.

3.1 Average Stress Criterion

The first failure criterion[1], referred to as the "average stress criterion," assumes that failure occurs when the average value of σ_y over some fixed distance, a_{0c}, ahead of the hole first reaches the unnotched compressive strength of the material, F_{UNC}^c, when

$$\frac{1}{a_{0c}}\int_R^{R+a_{0c}} \sigma_y(x,0)dx = F_{UNC}^c \tag{6}$$

Using this criterion with Eq. (3) results in the notched to unnotched strength ratio

$$\frac{\sigma_N^\infty}{F_{UNC}^c} = 2(1-\emptyset_1)/\{2-\emptyset_1^2-\emptyset_1^4+ (K_T^\infty-3)(\emptyset_1^6-\emptyset_1^8)\} \tag{7}$$

where $\phi_1 = R/(R+a_{0c})$ and σ_N^∞ is the notched strength of the infinite width laminate, which is the applied stress $\bar{\sigma}$, at failure.

3.2 Point Stress Criterion

The second failure criterion[1], referred to as the "point stress criterion," assumes the failure occurs when σ_y at some fixed distance, d_{0c}, ahead of the hole first reaches the unnotched compressive strength of the material, F_{UNC}^c, that is, when

$$\sigma_y(x,0)\big|_{x=R+d_{0c}} = F_{UNC}^c \tag{8}$$

Using this criterion with Eq. (3) results in the notched to unnotched strength ratio

$$\frac{\sigma_N^\infty}{F_{UNC}^c} = 2/\{2+\emptyset_2^2+3\emptyset_2^4- (K_T^\infty-3)(5\emptyset_2^6-7\emptyset_2^8)\} \tag{9}$$

where $\phi_2 = R/(R+d_{0c})$ and σ_N^∞ is the notched strength of the infinite width laminate.

3.3 Data Reduction Procedure

From the failure load of each unnotched compression specimen, the failure stress, F_{UNC}^c, was computed using Eq. (1). Similarly, the gross failure stress, F_{OHC}^c, of the notched specimens was obtained from the failure load of these specimens using Eq. (2). These values were then adjusted for all laminates by multiplying F_{OHC}^c, by the isotropic finite width correction factor K_T/K_T^∞ for holes to obtain notched, infinite width plate failure stress (σ_N^∞). An approximate expression for this factor is given by the relationship (6)

$$\frac{K_T}{K_T^\infty} = \frac{2+(1-\frac{2R}{W})^3}{3(1-\frac{2R}{W})} \tag{10}$$

where W is the finite specimen width. Eq. (10) is very accurate for 2R/W ≤ 1/2.

Then, the infinite width plate failure stress σ_N^∞, is given by the relationship

$$\sigma_N^\infty = F_{OHC}^c\frac{K_T}{K_T^\infty} \tag{11}$$

4 Results

The stress analysis of the circular hole specimens must take into account the effects of finite specimen width. In the present paper, these effects were accounted for by approximate methods, and finite width correction factor for isotropic specimen was used as Eq. (10)

In predicted failure ratios, shown in Table 4 and 5, used an approximate expression Eq. (3), for normal stress, σ_y, in an infinite orthotropic plate. This plate contained a circular hole and was subjected to uniaxial compression load, which was multiplied by the appropriate finite width correction factor, Eq. (10), with Eq. (7) and Eq. (9).

In Tables 4 and 5, the values a_{0c} = 0.070 inches and d_{0c} = 0.026 inches were used to provide an approximate best fit for all laminate data. In view of the approximate nature of the stress analysis used, the comparison of predicted strength percentage with those experimentally obtained, as shown in Tables 4 and 5, proves to be acceptable.

Table 4. Prediction of tensile failure strength using the average stress criterion for OHC laminate.

Specimen (0/±45/90% plies)	Failure strength by test (ksi)			% of UNC strength	
	F^c_{UNC}	F^c_{OHC}	σ_N^∞	Test	Average stress
(25/50/25)	99.66	43.11	44.46	44.6	50.6
(30/40/30)	106.50	47.84	49.34	46.3	50.2
(30/50/20)	100.61	48.44	49.95	49.6	50.4
(30/60/10)	101.08	48.01	49.93	49.0	50.6
(50/40/10)	121.94	63.90	65.90	54.0	49.6
(60/20/20)	143.43	68.63	70.79	49.4	48.5

Table 5. Prediction of tensile failure strength using the point stress criterion for OHC laminate.

Specimen (0/± 45/90% plies)	Failure strength by test (ksi)			% of UNC strength	
	F^c_{UNC}	F^c_{OHC}	σ_N^∞	Test	Point Stress
(25/50/25)	99.66	43.11	44.46	44.6	48.9
(30/40/30)	106.50	47.84	49.34	46.3	49.0
(30/50/20)	100.61	48.44	49.95	49.6	48.9
(30/60/10)	101.08	48.01	49.93	49.0	48.8
(50/40/10)	121.94	63.90	65.90	54.0	49.4
(60/20/20)	143.43	68.63	70.79	49.4	50.0

The point stress failure criterion appears to give more reasonable predictions for the compressive strength of laminates with stress concentrations.

It is noted that the characteristic length in compression, a_{0c} = 0.070 inches and d_{0c} = 0.026 inches, is considerably smaller than that obtained for the laminates in tension, a_{0c} = 0.150 inches and d_{0c} = 0.040 inches (2).

5 Conclusions

In this study, a constant value for the characteristic distances a_0 and d_0 was found to result in good strength prediction for circular hole in a number of different laminates. The composite material used in this paper was a carbon/epoxy UD tape prepreg (Cycom G40-800/5276-1) cured at 350°F (177°C).

In the present paper, the good agreement obtained between test results and strengths predicted by both the average stress failure criterion and the point stress failure criterion, for open hole laminate, appears to indicate that these criteria can be extended to compressive loading.

It is shown that use of both the average stress failure criterion and the point stress failure criterion results in acceptable predictions of fracture strength for several carbon/epoxy laminates subjected to uniaxial compressive loads. In addition to predicting the fracture strength reasonably accurately in this case, the average stress criterion and the point stress criterion are shown to predict the mode of failure (net compression for OHC laminate) as well.

The characteristic length in compression, a_{0c} and d_{0c}, is considerably smaller than that observed for the laminates in tension (2).

Although it is difficult to arrive at a definitive explanation for the different results obtained, the application of the point stress criterion is useful because the predicted fracture strength using the point stress criterion for OHC laminate is more similar to test results.

References

[1] Whitney J. M and Nuismer R. J. Stress fracture criteria for laminated composites containing stress concentrations, *Journal of Composite Materials*, Vol. 8, pp 253-265, 1974.

[2] Nuismer R. J and Whitney J. M. Uniaxial failure of composite laminate containing stress concentrations, JASTM-STP 593, *American Society for Testing and Materials*, pp 117, 1975.

[3] ASTM D 6484D, Standard test method for open hole compressive strength of polymer matrix composite materials, 2004.

[4] Lekhnitskii S. G. *Anisotropic plate, translated from the second Russian edition by S. W. Tsai and T. Cheron*, Gordan and Breach, Science Publishers, Inc., New York, 1968.

[5] Ashton J. E and Whitney J. M. *Theory of laminated plates*, Technomic Publishing Co., Stmford, Conn., 1970.
[6] Peterson R. E. *Stress concentration factors*, Wiley, New York, pp 110-111, 1974.

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