SIZE AND GEOMETRY EFFECTS ON THE OPEN-HOLE STRENGTH OF COMPOSITE LAMINATE SPECIMENS. FINITE FRACTURE MECHANICS PREDICTIONS AND TEST RESULTS

F. Folgado*, J. Cañas, V. Mantič

Grupo de Elasticidad y Resistencia de Materiales, Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain
**Corresponding Author: folgado91@gmail.com*

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Abstract

The strength of open-hole composite laminate specimens under tension is studied. In particular, the influence of the stress concentrator size and specimen geometry on the crack onset and consequently on the final open-hole strength is analyzed. A model based on the Finite Fracture Mechanics (FFM) including the coupled stress-energy criterion is applied to predict the failure onset. These predictions are compared with the experimental data obtained.

1. Introduction

Due to new design requirements on laminate composites, a deeper and physically based understanding of their failure mechanisms is necessary to take advantage of their full potential. A characterization of the open-hole strength behavior is of the utmost importance since holes appear in many composites structure. Therefore, the effect of the size of the stress concentrator and of the specimen geometry on the strength of open-hole composite laminates is analyzed in the present work. In particular, symmetric laminates under uniaxial tension load are studied.

2. Failure prediction by a coupled criterion of FFM

Currently there is no a complete confidence in the capability of the existing failure criteria for composites to predict neither the open-hole strength nor the crack propagation in these materials. The Finite Fracture Mechanics (FFM) provides an efficient and sensible solution to this problem as it involves a suitable combination of stress and energetic criteria for failure initiation and propagation [1,2]. On the one hand, the normal stresses averaged over a distance l along the potential crack path should reach the material strength (X_T), and on the other hand, the energy available for the crack onset (or propagation of an existing crack) must be equal to a critical value defined by the fracture toughness (K_{Ic}). When both the stress and energetic criteria are fulfilled, onset of a crack of a finite length (or advance of an existing crack by a finite increment) can occur. In the present work, an unstable crack growth along the direction perpendicular to the load is assumed, neglecting the three-dimensional stress field in the hole neighborhood and considering only fracture mode I.

A composite laminate with a central circular hole of radius R and width W subjected to longitudinal tension is considered. The following system of equations should be satisfied at specimen fracture [1]:

$$\frac{1}{l}\int_{R}^{R+l}\sigma_y(x,y=0)dx = X_T \tag{1}$$

$$\frac{1}{l}\int_{R}^{R+l}G(a)da = G_c \tag{2}$$

The fracture mechanics for anisotropic elastic materials allows rewriting the energetic criterion as

$$\frac{1}{l}\int_{R}^{R+l}K_I^2(a)da = K_{Ic}^2 \tag{3}$$

In the following the above equations are rewritten in a dimensionless form by using definitions (4) and (5) in the stress criterion, and (6) and (7) in the energetic criterion (the brittleness number γ defined in (6) will sometimes be denoted as γ_{2R}),

$$\sigma_y = \sigma_\infty \cdot \hat{\sigma}_y \tag{4}$$

$$\sigma_\infty = X_T \cdot \hat{\sigma}_\infty \tag{5}$$

$$\gamma = \frac{K_{Ic}}{X_T\sqrt{R}} \tag{6}$$

$$K_I = \sigma_\infty\sqrt{R}\hat{K}_I \tag{7}$$

The dimensionless form of the stress and energy criteria, respectively, (8) and (9) below, are obtained by including (5) in (4) and then (4) in (1), and by including (5) in (7) and then, using (6), in (3),

$$\hat{\sigma}_\infty = \frac{\sigma_\infty}{X_T} = \frac{l}{\int_{R}^{R+l}\hat{\sigma}_y(x,0)dx} = s(l) \tag{8}$$

$$\hat{\sigma}_\infty = \frac{\sigma_\infty}{X_T} = \gamma\sqrt{\frac{l}{\int_{R}^{R+l}\hat{K}_I^2(a)da}} = \gamma\sqrt{k(l)} \tag{9}$$

The functions $s(l)$ and $k(l)$ defined in (8) and (9), respectively, will sometimes be denoted as $s_{W/2R}(l)$ and $k_{W/2R}(l)$. By combining (8) and (9) a non-linear equation with the only unknown the crack extension after its onset, l, is obtained

$$s(l_c) - \gamma\sqrt{k(l_c)} = 0 \tag{10}$$

The integral in (10) is computed by using Simpson's rule. Once this equation is solved and l is known, it is possible to calculate the remote stress at failure, σ_∞, using (8) or (9).

A FEM code has been used to approximate stresses in an anisotropic open-hole laminate of a finite width, as no suitable analytic expression is available. The obtained stress distribution along the x-axis, for a particular width-to-diameter ratio (W/2R), has been interpolated by a polynomial, and can be used for other specimens with the same ratio W/2R,

$$\hat{\sigma}_y(\zeta) = \sum_{i=0}^{n} c_i \zeta^i , \qquad \zeta = \frac{W_0}{W} x \tag{11}$$

The stress intensity factor K_I has been evaluated by the following very approximate empirical formula, approximating the actual anisotropic laminate by a similar orthotropic one and by using a correction factor taking into account the finite width of the specimen which is usually used for isotropic specimens, see [1,3], giving:

$$K_I = f_o f_w f_h \sigma_\infty \sqrt{\pi a} \tag{12}$$

where f_h is the hole effect correction factor given in [1]

$$f_h = f_n \sqrt{1 - \frac{R}{a}} \tag{13}$$

$$f_n = 1 + 0.358\lambda + 1.425\lambda^2 - 1.578\lambda^3 + 2.156\lambda^4, \quad \lambda = R/a \tag{14}$$

where f_w is the finite width correction factor obtained from [3,4]

$$f_w = \frac{1 - 0.5(a/W) + 0.37(a/W)^2 - 0.044(a/W)^3}{\sqrt{1 - a/W}} \tag{15}$$

and the f_o is the orthotropy factor for a laminate composite given in [5] as

$$f_o = 1 + 0.1(\rho - 1) - 0.016(\rho - 1)^2 + 0.002(\rho - 1)^3 \tag{16}$$

where the constant ρ involves the ply-elastic properties of the composite laminate in an orthotropic axis calculated by the laminate theory,

$$\rho = \frac{\sqrt{E_x E_y}}{2G_{xy}} - \sqrt{\nu_{xy}\nu_{yx}} \tag{17}$$

Curves obtained for both stress and energy criteria are plotted in Figures 1 and 2, where the intersection points define the minimum value of the applied longitudinal stress in the specimen that fulfills both criteria (8) and (9).

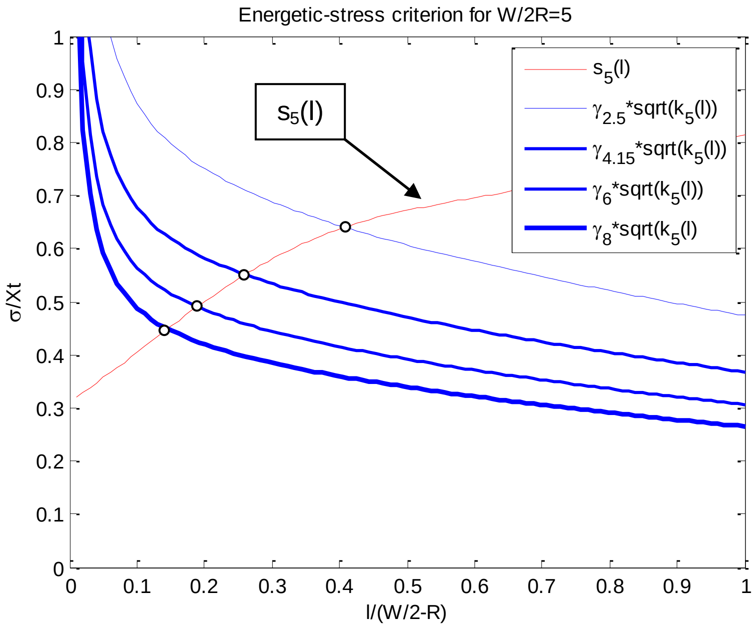

Figure 1. Curves for stress and energy criteria for several sizes of the specimen.

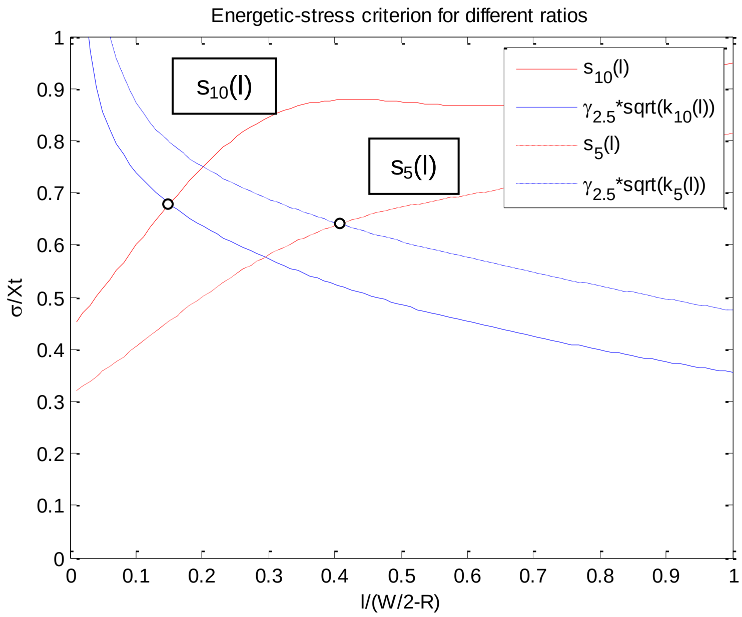

Figure 2. Curves for stress and energy criteria for different ratios *W/2R*.

3. Tests

2.1. Experimental tests

To compare the above methodology for predicting the failure load in the open-hole laminates with some experimental results, a series of experimental tests has been carried out, see Figure 3. Each single rectangular laminate with a particular width and width-to-diameter ratio is subjected to uniaxial tension at the outer boundary in order to elucidate the size effect on failure load. The values of hole-diameter are $2R$ = 2.5 mm, 4.15 mm, 6 mm, 8 mm and 10 mm with constant width-to-diameter ratio ($W/2R$). The tests are performed for three different ratios, *W/2R*=2 and 5, where each single case consists of three specimens. Additionally, specimens with ratio *W/2R*=10 and diameters from 2.5 to 8 mm have been tested, each single case consisting of two specimens. The holes are made by milling machine with a reamer tool, and to avoid delamination glass fiber is used in the opposite side of perforation. In the tension test, each specimen is loaded by displacement rate 5mm/min until the ultimate tensile load. A crack appears at the vicinity of the circular hole growing initially along *x*-axis until it changes its direction growing in the -45º direction (Figure 4). Additional specimens with 1 mm of hole-diameter will be tested soon.

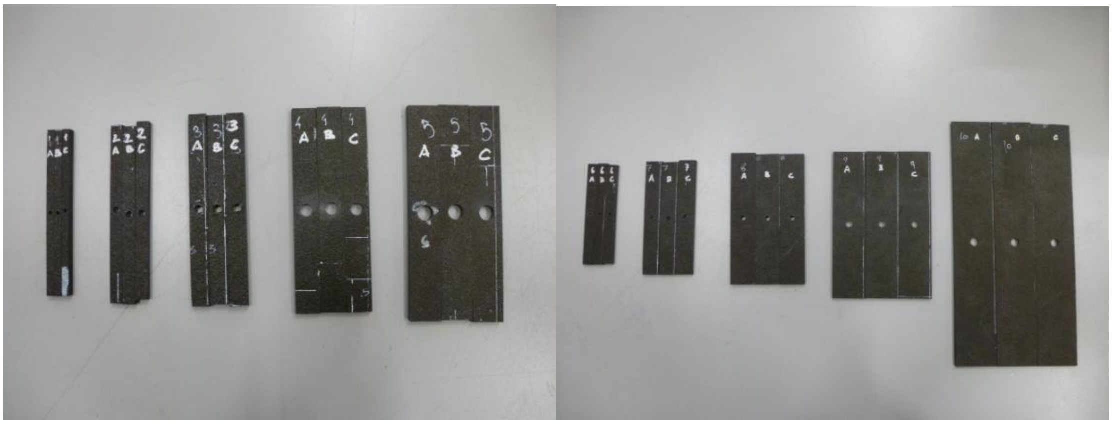

Figure 3. Test specimens.

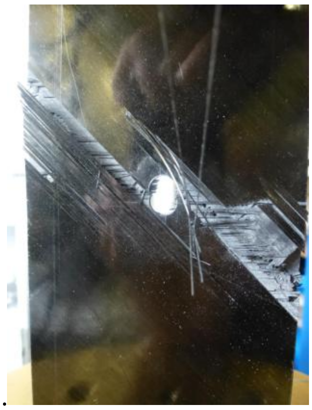

Figure 4. Tested specimen and crack propagation.

2.2. Characterization

The tested material is a symmetric 24-plies laminate of AS4/8552 Grade B carbon epoxy unidirectional laminate with 0.184 mm of nominal ply-thickness. The properties of the tested specimens are given by: the characteristic geometry of the specimen, the laminate lay-up, the ply elastic properties, the unnotched tensile strength and the mode I fracture toughness. The experimental tests provide the failure load.

The material has the following lay-up sequence $[-45/90/45/0_4/45/90/-45_3]_s$ with a nominal thickness of 4.7 mm. The unnotched tensile strength and longitudinal elastic modulus of the laminate was measured using standard AITM 10007 as a guideline. The average values obtained are X_t = 804.80MPa, E_y = 55.80 GPa and E_x = 36.00 GPa. The rest of elastic properties were evaluated by the laminate theory using the ply elastic properties shown in Table 1.

Property	Value
E_{11} (GPa)	135.0+/-15.0
E_{22} (GPa)	10.0+/- 1.2
υ_{12}	0.3
G_{12} (GPa)	5.0+/-1.5

Table 1. Ply elastic properties.

It appears there is not any standard to measure the fracture toughness in anisotropic laminates, for this reason a specific test is performed. The calculation of the fracture toughness is based on a FFM proposal, analyzing a plate with a central crack. The test is performed using three laminate plates with width W equal to 25.30 mm in which a crack is created using milling machine for a 2 mm central-hole and special razor blade with 0.4 mm of thickness to increase the crack length $2a$ up to 3.09 mm. The critical stress intensity factor value is obtained by solving equations (1) and (3), where Westergaard's stress solution (18) for a crack inside in an infinite plate is used,

$$\sigma_y(x, y=0) = \frac{\sigma_\infty x}{\sqrt{x^2 - a^2}} \tag{18}$$

Knowing the remote stress at failure σ_∞ and the laminate unnotched strength X_t, the problem is solved for the unknown variables l and K_{Ic}. The hole-factor f_h (13) is equal to 1 since there is no hole inside. As a result the average value of K_{Ic} is 45.62MPa√m.

4. Experimental results and their comparison with the semi-analytical prediction

4.1. Experimental results

A total number of 29 specimens have been tested, the results are presented in Table 2.

Specimen	W/2R	2R (mm)	σ_∞ (MPa)	$\sigma_{n\infty}$ (MPa)	σ_∞/X_t
1	2	2.5	346.89	673.98	0.43
2		4.15	276.35	549.96	0.34
3		6	280.71	555.76	0.35
4		8	269.52	533.17	0.33
5		10	287.99	574.05	0.36
6	5	2.5	483.74	603.37	0.60
7		4.15	483.18	603.67	0.60
8		6	446.78	557.91	0.56
9		8	504.02	629.83	0.63
10		10	442.32	552.64	0.55
11	10	2.5	577.82	641.59	0.72
12		4.15	558.72	620.66	0.69
13		6	510.31	566.97	0.63
14		8	495.90	550.86	0.62

Table 2. Experimental data.

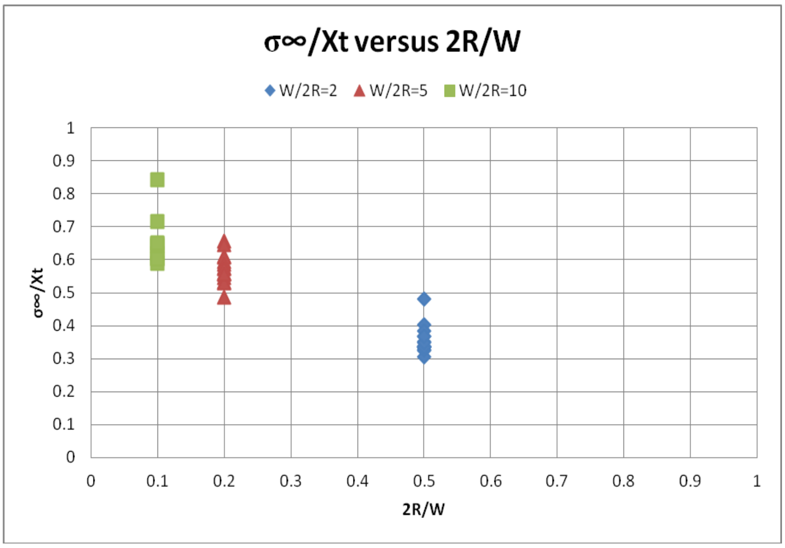

Figure 5. Variation of the dimensionless failure stresss with the specimen size and geometry effect.

A size effect is observed as increasing the hole-diameter decreases the notched strength. Every single specimen breaks due to the stress concentrator since the net-stress $\sigma_{n\infty}$ is not reached in any case. The dispersion of the results is higher in the smallest specimens, possibly due to the presence of micro-failures in the material. The other effect, the geometrical effect is observed as an increase in the notched strength with the ratio *W/2R*. For a characteristic value of the hole-diameter the behavior of the failure stress tends to be constant, this critical value is quite important from engineering point of view because an operational limit can be defined. In the world of aeronautical sector the smallest hole is 4 mm, so this tested laminate can be used without any restrictions.

4.2. FFM predictions

For two particular ratios *W/2R* the predictions for failure stress has been obtained using proposal in [1] and the explained approximate methodology for an anisotropic plate, see Table 2 and Figure 6. Only two problems were necessary to be solved by FEM, one for each ratio.

Specimen	W/2R	2R (mm)	σ_∞ (Exp.) (MPa)	σ_∞ (FFM) [1] (MPa)	σ_∞ (FFM) (MPa)	Error (%) [1]	Error (%)
6	5	2.5	483.74	492.72	511.66	1.86	5.77
7		4.15	483.18	432.93	443.91	10.40	8.13
8		6	446.78	391.79	398.72	12.31	10.76
9		8	504.02	363.29	367.18	27.92	27.15
10		10	442.32	343.86	345.29	22.26	21.94
11	10	2.5	577.82	524.31	566.22	9.26	2.01
12		4.15	558.72	455.76	494.88	18.43	11.43
13		6	510.31	410.22	445.43	19.61	12.71
14		8	495.90	379.18	412.75	23.54	16.77

Table 3. Predictions by the FFM proposal presented in [1] and that developed in the present work.

When comparing the predictions and the experimental data, all predictions are below the real failure stress, thus these predictions are on the safe side. An increasing in the estimation error for large specimens can be observed, see Table 3.

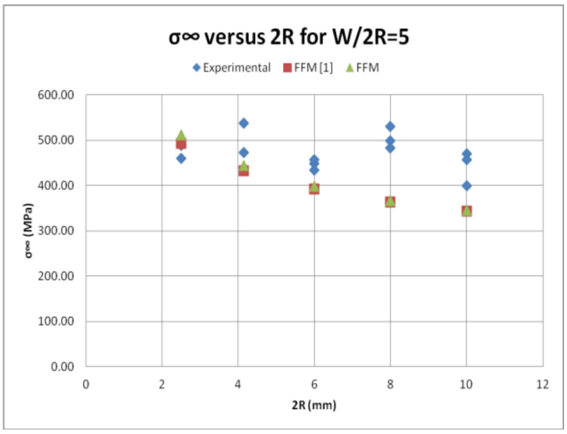

Figure 6. Evolution of the notched-stress vs. hole-diameter.

The proposal in [1] considers an orthotropic stress distribution and an isotropic stress intensity factor for quasi-isotropic plate, and the one introduced here uses an anisotropic stress distribution and an orthotropic stress intensity factor. There is no much difference between both predictions.

We expect that the FFM predictions could improve if the actual laminate would be well modeled taking into account the laminate anisotropy. In particular, an improvement in the stress distribution and stress intensity factor evaluation seems to be mandatory, in addition to considering mixed mode of fracture.

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