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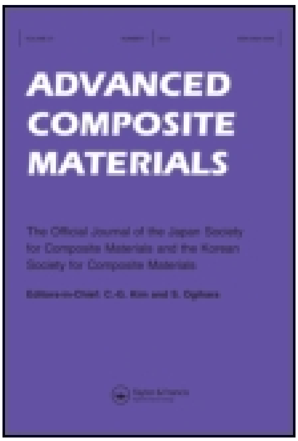

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Fracture strength of composite laminates containing surface notches

P. K. Govindan Potti [a] , B. Nageswara Rao [b] & V. K. Srivastava [c]

[a] Structural Engineering Group, Vikram Sarabhai Space Centre, Trivandrum-695022, India

[b] Structural Engineering Group, Vikram Sarabhai Space Centre, Trivandrum-695022, India

[c] Department of Mechanical Engineering, Institute of Technology, Banaras Hindu University, Varanasi-221005, India

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Fracture strength of composite laminates containing surface notches

P. K. GOVINDAN POTTI [1], B. NAGESWARA RAO [1] and V. K. SRIVASTAVA [2]

[1] *Structural Engineering Group, Vikram Sarabhai Space Centre, Trivandrum-695022, India*
[2] *Department of Mechanical Engineering, Institute of Technology, Banaras Hindu University, Varanasi-221005, India*

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Abstract—An empirical relationship developed recently between the failure stress and stress intensity factor at failure is examined for the estimation of fracture strength of thick graphite/epoxy laminates containing surface notches. The results are found to be reasonably in good agreement with the existing test results.

Keywords: Fracture strength; composite laminate; surface notch; stress intensity factor.

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1. INTRODUCTION

The fracture phenomena of fibrous composite materials are complex in nature, owing to the complexity and diversity of composite systems and lay-up constructions. Unlike metallic materials, a composite (or a composite laminate) containing a hole or a notch fractures in a complicated way. It is well known fact that the tensile strength of a laminate decreases with increase in the size of the crack. This implies that the fracture stress decreases and the apparent fracture toughness or critical stress intensity factor increases with crack size. Since the intensity of the stress at the crack tip is a function of load, geometry and crack size, it is more appropriate to have a relationship between the apparent critical stress intensity factor and the fracture strength from the fracture data of cracked laminates. A three parameter fracture criterion recently applied to composite laminates containing through thickness cracks is in the form [1]

$$K_{\max} = K_{\mathrm{F}}\{1 - m(\sigma_{\mathrm{f}}/\sigma_{\mathrm{u}}) - (1 - m)(\sigma_{\mathrm{f}}/\sigma_{\mathrm{u}})^{p}\}, \qquad (1)$$

where, $K_{\max}$ is the elastic stress intensity factor at failure, σ_{f} is the fracture strength, σ_{u} the ultimate tensile strength of the material, K_{F}, m and p are the three material fracture parameters which are dependent on laminate lay-up sequence, thickness and loading. These parameters are generally determined from simple laboratory through-cracked specimens like center notch, single edge notch, double edge notch and compact tension specimens.

The fracture strength estimations made recently by the present authors [1] using the above three parameter criterion correlate well with the test data [2] generated from the center cracked carbon fibre/epoxy and glass/epoxy composite laminates. In the three parameter criterion, no characteristic dimension, as in Refs. [3–5], is involved. The damage zone near the crack-tip of the laminates was taken into account indirectly by the three parameters (K_F, m and p). Although through-the-thickness cracks do not commonly occur in composite laminates, fracture mechanics based results may be useful in quantifying damage tolerance of thick laminates with surface damage. Foreign object impact, for example, can create damage to various depths of laminate thickness, depending upon mass and shape of the impactor, velocity of impact, and composite material system. It may be possible to partially model impact damage through surface flaws and to determine the strength of damaged laminates using fracture mechanics concepts. Most of the test results available in literature for composite materials were generated from through thickness crack specimens. Several fracture models cited in Ref. [1], namely, WEK fracture models [3], two stress fracture criteria known as the point stress criterion and the average stress criterion of Whitney–Nuismer [4, 5], damage zone model of Aronsson and Backlund [6], damage zone criterion of Eriksson and Aronsson [7] and the effective crack growth model of Khatibi, Ye and Mai [2], were developed and validated using the test data from through-thickness cracked specimens. Applicability of these models for surface notched specimens is not straightforward whereas the three parameter fracture criterion given by equation (1) demands a stress intensity factor for the intended cracked geometry and may not have such limitations. Though fracture strength estimations using equation (1) were found to correlate well with the test data (Ref. [1] and references cited therein), for through and part through cracked metallic configurations as well as through cracked composite laminates, its applicability to composite laminates having surface notches need to be examined.

The objective of the present study is to correlate the existing experimental data on 80-ply quasi-isotropic laminates of T300/5208 graphite/epoxy having several combinations of flaw depth and flaw aspect ratios. The notched strength estimations using the present three parameter fracture criterion are found to be reasonably in good agreement with the test results.

2. FRACTURE STRENGTH DETERMINATION

For the determination of fracture strength, the stress intensity factor for the cracked geometry should be used in equation (1) to set up the fracture strength equation. The stress intensity factor should be calculated analytically or numerically, using finite elements, for the given material and lay-up. However, in practice, a

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mixed type of orthotropic laminate is frequently encountered. It is reasonable to expect that the effect of anisotropy would be less for these materials because they are less directional. The isotropic solution is within approximately 4% of the considered mixed laminates. If most of the fibres are perhaps perpendicular to the crack, then the calculated isotropic stress intensity should perhaps be increased by approximately 10% for a conservative strength estimate. For engineering calculations a similar approximate correction could also be applied to the isotropic solution for [±45] laminates except for extremely short edge cracks; but for most mixed laminates the isotropic solution appears to be sufficiently accurate for most practical applications [8, 9]. Overall, it would appear that the isotropic solutions are adequate except where extreme anisotropy is involved when it may be useful to compute K_{I} values. For cracked plates it is necessary to consider local fields, but rather complicated analysis leads to be result that the stress intensity factors are almost the same as the isotropic case.

In the present study the fracture strength data [10] of quasi-isotropic graphite/ epoxy laminate containing surface notches (Fig. 1) is examined. The isotropic stress intensity factor, K for surface notches, which is obtained from the finite element solution and represented empirically in Ref. [11] is considered here. The isotropic stress intensity factor K, is given by

$$K = \sigma(\pi a)^{1/2} M/\varphi, \qquad (2)$$

where,

$$\varphi^2 = 1 + 1.464(a/c)^{1.65}, \quad \text{for } a/c \leqslant 1,$$
$$\varphi^2 = 1 + 1.464(c/a)^{1.65}, \quad \text{for } a/c > 1,$$
$$M = \left\{\left[M_1 + \left[\varphi(c/a)^{1.65} - M_1\right](a/t)^g + \left[\varphi(c/a)^{1.65}(M_2 - 1)\right](a/t)^{2g}\right]\right\} f_{\mathrm{w}},$$
$$M_1 = 1.13 - 0.01c/a(a/c), \quad \text{for } 0.03 \leqslant a/c \leqslant 1,$$
$$M_1 = [1 + 0.03(c/a)](c/a)^{1/2}, \quad \text{for } a/c > 1,$$
$$M_2 = (\pi/4)^{1/2}, \quad \text{for } a/c \leqslant 1,$$
$$M_2 = 1 + (c/a)\left[(\pi/4)^{1/2} - 1\right], \quad \text{for } a/c > 1,$$
$$f_{\mathrm{w}} = \left\{\sec\left[(\pi c/W)(a/t)^{1/2}\right]\right\}^{1/2}, \quad g = (\pi)^{1/2},$$

and W is the width of the specimen. It should be noted that the magnification factor, M is geometry dependent. Using equations (1) and (2), one can set up the following equation to determine the fracture strength σ_{f} for a specified crack size

$$(1 - m)(\sigma_{\mathrm{f}}/\sigma_{\mathrm{u}})^p + \left\{m + \left[\sigma_{\mathrm{u}}(\pi a)^{1/2} M/\varphi K_{\mathrm{F}}\right]\right\}(\sigma_{\mathrm{f}}/\sigma_{\mathrm{u}}) - 1 = 0. \qquad (3)$$

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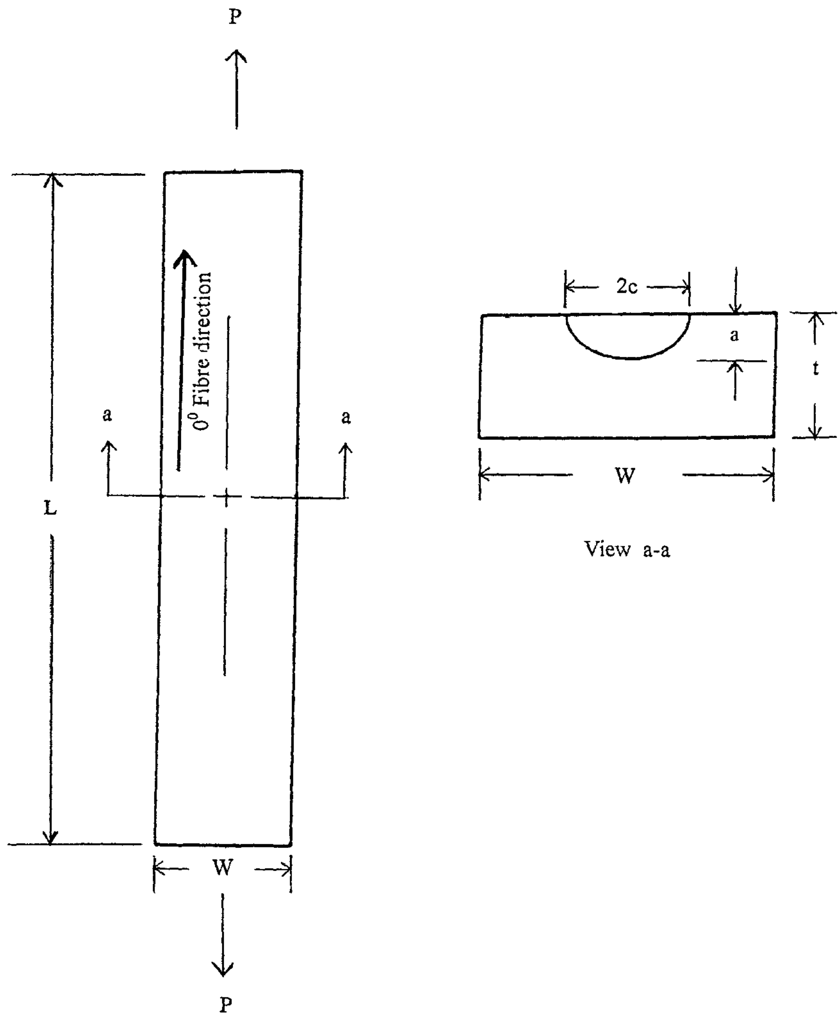

Figure 1. Geometry of $[0/\pm45/90]_{10S}$ T300/5208, graphite/epoxy specimen along with notch geometry ($L = 305$ mm; $W = 25.4$ mm; $t = 10.16$ mm).

The non-linear equation (3) is solved for σ_f using the Newton–Raphson iterative scheme.

3. RESULTS AND DISCUSSION

The fracture data of $[0/\pm45/90]_{10S}$ T300/5208, graphite/epoxy laminate containing surface notches reported in Ref. [10] is considered. The width and the thickness of the laminates are about 25.4 mm and 10.16 mm respectively. Table 1 gives the average fracture strength values for determining fracture parameters (namely, K_F, m and p) in equation (1). Using equation (2), the elastic stress intensity

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Table 1.
Fracture strength (average values) data of graphite/epoxy, T300/5208 composite laminate used for evaluation of fracture parameters K_F, m and p in equation (1). Width = 25.4 mm; thickness, t = 10.16 mm; and σ_u = 538 MPa. Lay-up: $[0/\pm 45/90]_{10S}$; $K_F = 73.5\ \mathrm{MPa}\sqrt{m}$; $m = 0.9$; $p = 58.7$

Crack dimension $2c \times a$ (mm)	Fracture strength σ_f (MPa) Test [10]	K_{max} ($\mathrm{MPa}\sqrt{\mathrm{m}}$)	Fracture strength σ_f (MPa) Analysis	Relative error (%)
aspect ratio $(a/c) = 0.5$				
5.20 × 1.30	351	20.0	400.4	−14.1
5.88 × 1.47	414	25.0	390.3	5.7
6.72 × 1.68	380	24.5	378.6	0.4
7.52 × 1.88	353	24.1	368.1	−4.3
9.16 × 2.29	337	25.3	347.5	−3.1
11.40 × 2.85	307	25.6	320.9	−4.5
14.64 × 3.66	254	24.0	283.1	−11.5
aspect ratio $(a/c) = 1.0$				
5.08 × 2.54	359	21.2	387.9	−8.0
6.60 × 3.30	392	26.5	360.3	8.1
2.54 × 1.27	379	15.8	442.3	−16.7
1.32 × 6.60	249	23.4	248.8	0.1
1.02 × 5.08	321	26.9	299.8	6.6
aspect ratio $(a/c) = 2.0$				
2.39 × 2.39	448	23.0	414.6	7.5
3.38 × 3.38	374	22.7	386.3	−3.3
4.17 × 4.17	341	22.9	366.4	−7.4
4.78 × 4.78	424	30.3	351.9	17.0
6.40 × 6.40	351	28.4	315.7	10.0
7.93 × 7.93	294	25.6	283.1	3.7

Relative error range = ±17%; Standard error (SE) = 0.095.

factor K_{max} is computed for the different flaw sizes given in Table 1. The fracture parameters are determined following the procedure given in Ref. [1]: These are: $K_F = 73.5\ \mathrm{MPa}\sqrt{\mathrm{m}}$; $m = 0.9$; $p = 58.7$. In order to examine the adequacy of these fracture parameters, the fracture strength values obtained by solving equation (3) are presented in Table 1 and Fig. 2. The relative errors between theory and the average value of the test results are presented in Table 1. In the present analysis, the relative error between theory and test results is defined by

$$\text{relative error}(\%) = 100 \times \{1 - (\text{Theoretical result}/\text{Test result})\}. \quad (4)$$

The analytical results are in reasonably good agreement with those test results. The best fracture criterion as suggested by the guide lines of the round robin (which was conducted in 1979–1980 by American Society for Testing and Materials (ASTM) Task Group E 24.06.02 [12]) is the one which can predict the failure loads within

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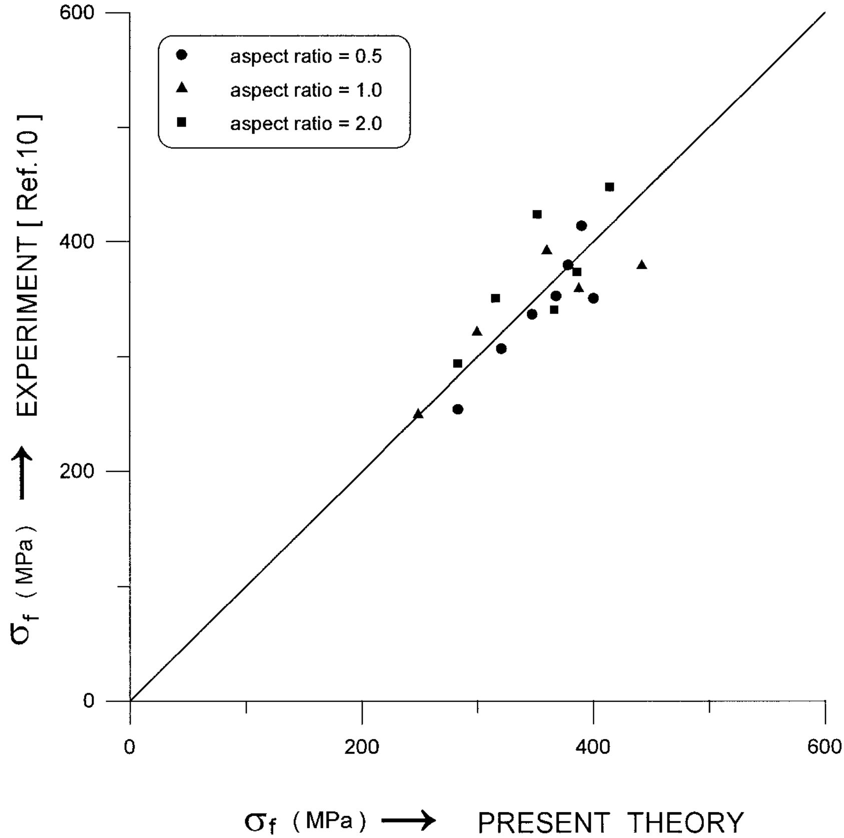

Figure 2. Comparison of experimental and theoretical fracture strength, σ_f (MPa) average values of graphite/epoxy laminates containing surface notch.

±20% of the test results and has the average standard error of less than 0.1 in the ratio of predicted-to-test failure loads. The standard error (SE) is defined by

$$\mathrm{SE} = \left[\sum_{i=1}^{N}(1 - (\text{theoretical result}/\text{test result}))_i^2/N\right]^{1/2}, \tag{5}$$

where N is the number of test specimens. The fracture strength estimations were found to be within ±17% of the test results and has 0.095 as the standard error.

The fracture strength estimations are also compared with the individual tested results in Table 2. These results are also presented in Fig. 3. For the specimens having the same aspect ratio ($a/c = 0.5$), same width ($W \cong 25$ mm), crack depth ($a = 1.30$ mm) and crack length ($2c = 5.20$ mm), it can be seen that the tested values are 332 MPa and 370 MPa while the analytical results are very much closer, i.e. 400.2 MPa and 400.4 MPa. Hence it is concluded that the high relative error of −20.6% is because of the large scatter in the tested value. Similarly, for the aspect ratio ($a/c = 2.0$), width ($W \cong 25$ mm), crack depth ($a = 4.78$ mm) and crack

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Table 2.
Surface-notched strength tests on graphite/epoxy, T300/5208 composite laminate (thickness, t = 10.16 mm). Lay-up: $[0/\pm 45/90]_{10S}$; $\sigma_u = 538$ MPa; $K_F = 73.5$ MPa$\sqrt{m}$; $m = 0.9$; $p = 58.7$

Width W (mm)	Crack depth a (mm)	Crack length $2c$ (mm)	Fracture strength σ_f (MPa) Test [10]	Analysis	Relative error (%)
aspect ratio $(a/c) = 0.5$					
24.80	1.30	5.20	332	400.2	−20.6
25.49	1.30	5.20	370	400.4	−8.2
25.39	1.47	5.88	414	390.3	5.7
25.10	1.68	6.72	380	378.5	0.4
24.21	1.88	7.52	353	367.4	−4.1
24.41	2.29	9.16	331	346.7	−4.8
24.61	2.29	9.16	342	346.9	−1.4
25.00	2.85	11.40	294	320.4	−9.0
25.00	2.85	11.40	319	320.4	−4.0
25.00	3.66	14.54	247	282.3	−14.3
24.90	3.66	14.54	260	282	−8.5
aspect ratio $(a/c) = 1.0$					
25.79	1.27	2.54	379	442.4	−16.7
25.59	2.54	5.08	359	387.9	−8.1
25.20	3.30	6.60	411	360.1	12.4
24.21	3.30	6.60	382	359.3	5.9
25.20	3.30	6.60	405	360.1	11.1
25.20	3.30	6.60	370	360.1	2.7
25.98	5.08	10.16	324	300.8	7.1
26.08	5.08	10.16	317	301.0	5.0
24.61	6.60	13.20	240	246.3	−2.6
24.61	6.60	13.20	243	246.3	−1.4
25.10	6.60	13.20	273	247.9	9.2
24.80	6.60	13.20	239	246.9	−3.3
aspect ratio $(a/c) = 2.0$					
25.89	2.39	2.39	394	414.7	−5.3
25.00	2.39	2.39	452	414.5	8.3
25.10	2.39	2.39	466	414.6	11.0
25.20	2.39	2.39	481	414.6	13.8
24.51	3.38	3.38	374	386.0	−3.2
25.89	4.17	4.17	341	366.7	−7.5
25.20	4.78	4.78	392	351.7	10.3
25.10	4.78	4.78	452	351.7	22.2
25.00	4.78	4.78	427	351.6	17.7
25.10	6.40	6.40	341	315.3	7.5
25.10	6.40	6.40	384	315.3	17.9
24.11	6.40	6.40	313	313.9	−0.3
25.20	7.93	7.93	366	315.5	13.8
25.10	7.93	7.93	285	282.5	0.9
24.90	7.93	7.93	305	282.0	7.5
24.61	7.93	7.93	294	281.4	4.3
25.10	7.93	7.93	292	282.5	3.3

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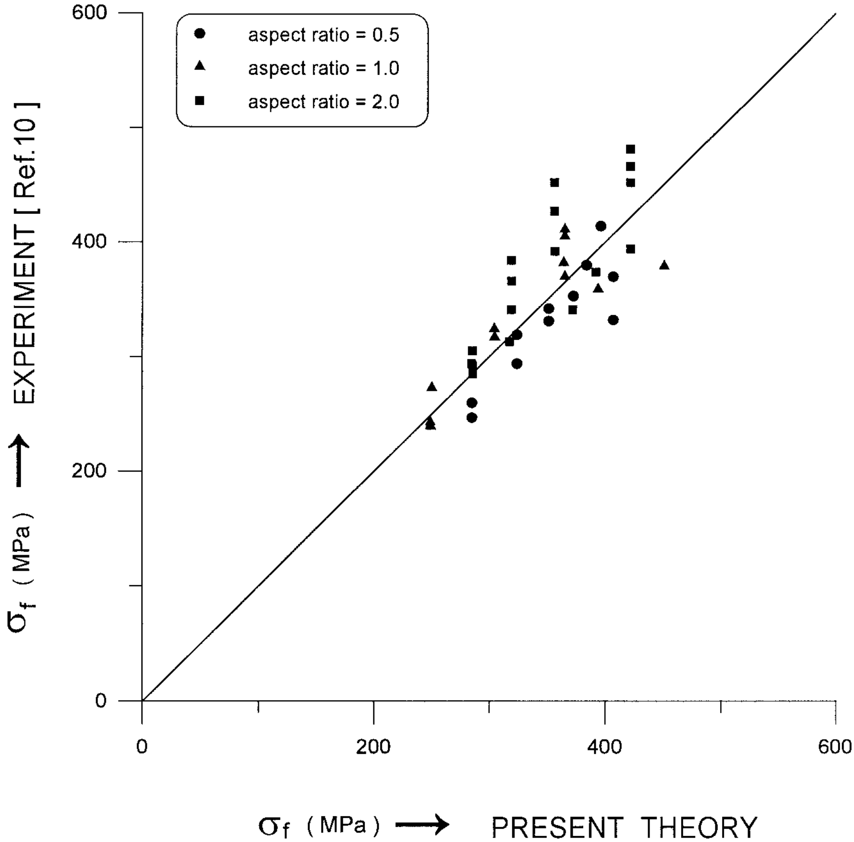

Figure 3. Comparison of experimental and theoretical fracture strength, σ_f (MPa) values of graphite/epoxy laminates containing surface notch.

length ($2c = 4.78$ mm), it can be seen that the high relative error of 22.2% is also because of the large scatter in the test result. In general the present analytical results are found to be in good agreement with the test results.

4. CONCLUDING REMARKS

This paper provides an empirical approach towards predicting fracture strength of composite laminates containing a surface notch subjected to tensile loading. The empirical relationship between K_{max} and σ_f through fracture parameters K_F, m and p in equation (1) will be useful for the determination of fracture strength of any structural components containing cracks. For the determination of the fracture parameters, the test results of simple laboratory specimens like center crack specimens can be used. Since fracture parameters are dependent on laminate lay-up sequence, thickness and loading, these are to be determined from the laboratory specimens of the same laminate lay-up sequence. For the determination of fracture strength of any other structural configuration of the same lay-up sequence, the stress intensity factor corresponding to the geometry should be used in equation (1) to set up the necessary fracture strength equation which has to be solved using Newton–Raphson method.

In the present case it is noted that there is a large variation in the test results of the material (average ultimate strength = 538 MPa and coefficient of variation, C.V. = 7%). Hence a statistical analysis will be more meaningful to take account of such variability and better prediction of tolerances in fracture strength.

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