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DEVELOPMENT OF A NOTCHED TENSILE STRENGTH NOMOGRAPH THROUGH FINITE ELEMENT MODELING OF CENTRE-HOLE 2D C/C LAMINATES

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Abstract: Numerical solution is obtained through finite element modeling of 2D carbon/carbon (C/C) laminates having central opening utilizing the commercial software package ANSYS. The stress concentration factor is evaluated from the normal stress distribution and found to increase with increasing diameter in a finite width plate, whereas it remains same in the infinite width plate. In the finite element modeling, edge effects can be neglected by considering the width of the plate as 20 times the hole-diameter, which simulates the results for infinite width plate. When the failure load is applied to the centre-hole specimen, the normal stress adjacent to the hole is exceeding the tensile strength of the composite, which indicates the possibility of reduction in the stress concentration due to local stress redistribution near the central opening or discontinuity region prior to failure. For linear elastic behaviour of composites simulation of such deformation is involved and hence one of the stress fracture criteria referred as the point stress criterion is followed for the development of the fracture strength nomograph useful in the design of composites having central openings and validated through comparison of test results.

Keywords: Carbon/carbon composite, Finite element analysis, Notched strength, Point stress criterion, Stress concentration factor, Tensile strength.

1. Introduction

Carbon fiber reinforced carbon matrix composites referred as the carbon-carbon (C/C) composites possess superior properties at elevated temperatures, and attracted to a variety of engineering applications [1,2]. Fig. 1 shows the F-14 Tomcat aircraft of 1970 model in which 2% carbon fiber composites are used for the back stabilizer fans, whereas 50% composites are used in the components of the Boeing 787 Dreamliner (such as brake disks and exhaust parts) [2,3]. C/C composites are being used forre-entry bodies, rocket nozzles, shuttle orbiter vehicles (such as nose tip and wing leading edges), missile engines (components of hot section), hypersonic vehicles (components of fuselage and wing), space satellite structures, hot glass handling tools, hot press dies and pistons [2]. They are also needed for long blade designs in wind energy; for significant mass reduction in vehicle technologies; for offshore structural components in oil and gas; for less bulky structures with zero CLTE in power transmission; for hydrogen storage in vessels; and for rapid repair and installation, time and cost savings in the civil infrastructures [4].

Figure 1. Components of C/C composites used in aircrafts [2, 3]

To utilize the maximum strength of the composite materials, it is essential to acquire knowledge on the fracture behavior of notched and holed parts of machine elements [5-10]. Fracture mechanism becomes the important parameter to assess the behavior of composites. Depending on the nature of laminated composites, fiber orientation, loading, fabrication and manufacturing processes, the fatigue and failure response of composite materials exhibit the combination of fiber breakage, matrix cracking, delamination, and also interlaminar and interfacial debonding. Notched sections become the primary concern for examining the failure mechanism of composites [11-14]. Damage detection and characterization studies are made on C/C composites using AE (acoustic emission), ESPI (electronic speckle pattern interferometry) and SQUID (superconducting quantum interference device) techniques [15-21].

Motivated by the work of the above researchers, studies are made in this paper by obtaining numerical solution through finite element modeling of 2D C/C laminates having a central opening utilizing the commercial software ANSYS. The stress concentration factor is found to increase with increasing diameter in a finite width plate. When the failure load is applied to the center-hole specimen, the normal stress induced is exceeding the tensile strength of the laminate mainly due to the assumption of fibers intact in the finite element analysis (FEA), which results high stress concentration. In fact composites are linear elastic in nature and it is very difficult to capture the local stress redistribution near the openings or discontinuity regions. The task is involved to quantify the actual stress distribution near central opening regions and the estimates of laminate strength in the presence of discontinuities like central openings. Several failure criteria have been proposed/adopted owing to the inherent complexity in estimating the strength of composite laminates containing discontinuities like openings [22,23], which can be categorized in to fracture mechanics models [24]; models of stress-fracture criteria [25-27]; and progressive damage models [28,29]. However, these models are unable to correlate well with the fracture strength of different composite laminates openings or crack like slit. One of the stress fracture criteria known as the point stress criterion is followed here for the development of the fracture strength nomograph useful in the design of composites having central openings and validated through comparison of test results.

2. Numerical Solution

Kostopoulos and Pappas [11] have conducted experiments on a closed-loop servo-hydraulic testing machine with a crosshead velocity of 0.1 mm/min and generated the fracture data of 2D C/C laminates containing central opening. The laminate is reinforcing with orthogonally woven 8-harness satin fabric (possessing Young's modulus of 94000 MPa, Poisson's ratio of 0.07, and the bulk density of 1.49 g/cm^3) and stacked together in a symmetric ($0^O/90^O$) way. To avoid hole-edge delamination during drilling, they have placed two acrylic plastic sheets at both sides of the $225\times 25.2\times 3\,mm$ specimens. The curves of AE (Acoustic Emission) cumulative counts (N_t) versus applied stress (σ_{appl}) indicate increasing of N_t for the σ_{appl} with increasing the hole-diameter, and showing at failure the total N_t recorded for the tensile specimen without central opening. This observation is in-line with the reduction in tensile strength with increasing the hole-diameter of the specimen. An empirical relation is established for the notched tensile strength (σ_{Nh}) considering the applied stress (σ_{appl}) level and the measured N_t in the form [20]

$$\sigma_{Nh} = 192.31 N_t^{-0.5125} \qquad (1)$$

From the orthotropic laminate in-plane stiffnesses [11]: $A_{11} = A_{22} = 20172\,N\,mm^{-1}$; $A_{12} = 868\,N\,mm^{-1}$ and $A_{66} = 2707\,N\,mm^{-1}$, the evaluated Young's modulus in axial and transverse directions are: $E_{xx} = E_{yy} = 6712\,MPa$; Shear modulus, $G_{xy} = 902.4\,MPa$; and the Possion's ratio, $\nu_{xy} = \nu_{yx} = 0.04303$. $\sigma_0 = 173.2\ MPa$, is the tensile strength of the laminate. The eight-node quadrilateral plane stress element (designated by PLANE183 in ANSYS) is utilized for modeling a quarter portion of the tensile specimen containing central opening and specified symmetric conditions, material properties and the tensile stress of 1 *MPa* as appliedload. By considering the width of the plate as 20 times the hole-diameter in the finite element modeling, edge effects will be absent and simulates the results for infinite width plate. Fig. 2 shows the stress contour near the central opening region for the infinite width plate, which indicates the stress concentration as 4.06, which is found to be in good agreement with result 4.08

obtained from the expression the stress concentration factor (K_T^∞) [30]

$$K_T^\infty = 1 + \sqrt{2(k_1 - k_2) + k_3} \qquad (2)$$

Where $k_1^2 = E_{yy} / E_{xx}$; $k_2 = \nu_{yx}$; and. $k_3 = E_{yy} / G_{xy}$.

Assuming origin as the reference to the centre of the hole, the normal stress distribution $\sigma_y(x,0)$ adjacent to the hole for the applied stress σ_{appl} is shown in Fig. 3. The stress distribution is unchanged in the infinite width plates for 1.5 and 10mm hole-diameters under the same applied stress. The stress concentration factor (K_T) for a finite width plate having central opening is [30]

$$K_T = \left\{ \alpha + \frac{1}{2}\left(K_T^\infty - 3\right)\left(1 - \beta\right)\beta^3 \right\}^{-1} K_T^\infty \qquad (3)$$

Where $\beta = \frac{1}{2}\left(\sqrt{9 - 8\alpha} - 1\right)$, $\alpha = 3\alpha_1\,(2 + \alpha_1^3)^{-1}$, $\alpha_1 = 1 - (D/W)$, $D=2R$, is the hole-diameter, R is the hole-radius and W is the specimen width. Finite element analysis (FEA) results in Table 1 indicate reasonably in good agreement with those obtained from Eq. (3).

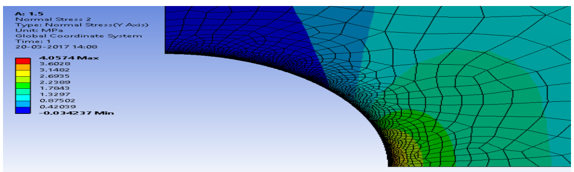

Figure.2 Stress contour near the central opening of the infinite width C/C composite laminate under a tensile stress of 1 MPa.

Table1. Comparison of the stress concentration factor (K_T) for a finite width C/C laminate having central opening.

Solution	Hole-diameter, D (mm)					
	1.5	2.5	4	6	8	10
Equation (3)	4.08	4.10	4.18	4.34	4.58	4.93
FEA	4.07	4.09	4.16	4.29	4.51	4.83

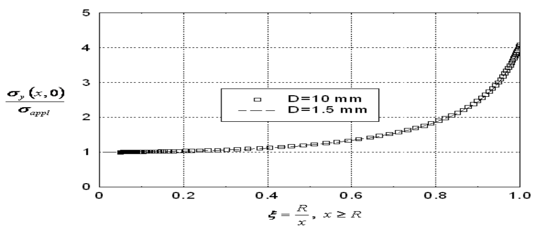

Figure.3 The normal stress distribution $\sigma_y(x,0)$ adjacent to the central opening in an infinite width C/C laminate under a uniform stress σ_{appl} .

When the failure load is applied to the center-hole specimen, the maximum normal stress adjacent to the hole is exceeding the tensile strength of laminate. This is the reason why the notched tensile strength (σ_{Nh}) estimates in Ref. [14] utilizing the tensile strength (σ_0) of the laminate and the stress concentration factor (K_T) are found to be highly conservative. There is a possibility of reduction in the stress concentration due to local stress redistribution near the hole prior to failure. Following one of the stress fracture criteria known as the point stress criterion [25], the tensile strength nomograph for C/C laminates containing central opening is developed here.

The notched strength (σ_{Nh}^∞) of central opening wide tensile C/C laminate is obtained from the experimental notched strength (σ_{Nh}) of the finite width tensile C/C laminate from

$$K_T\,\sigma_{Nh} = K_T^\infty\,\sigma_{Nh}^\infty \qquad (4)$$

Here K_T^∞ and K_T are the stress concentration factors for the infinite width plate and the finite width plate respectively. Since, the normal stress distribution $\sigma_y(x,0)$ adjacent to the hole in an infinite width plate under a uniform stress σ_{appl} with respect to ξ in Fig. 3 is found to be same for any hole-diameter, it is preferable to find the notched strength (σ_{Nh}^∞) from the Eq. (4). The value of ξ for $\frac{\sigma_y(x,0)}{\sigma_{appl}} = \frac{\sigma_0}{\sigma_{Nh}^\infty}$ obtained from Fig. 4 is presented in Table 2 for different hole-diameters. It is noted from the results in Table 2 as well as in Fig. 4 that ξ is changing with the hole-diameter, which can be expressed in the form

$$\xi = \left(\frac{D}{D_{ref}}\right)^{0.3732}, \text{ where } D_{ref} = 21.2\,mm \qquad (5)$$

Table 2. Notched tensile strength and the ξ value for different hole-diameters of 2D C/C laminate.

Hole-diameter, D (mm)	Notched strength σ_{Nh} (MPa) Test [11]	σ_{Nh}^{∞} (MPa) Equation (4)	$\frac{\sigma_y(x,0)}{\sigma_{appl}} = \frac{\sigma_0}{\sigma_{Nh}^{\infty}}$	ξ (Figure-4)
1.5	157	157.52	1.0995	0.3866
2.5	150.5	151.85	1.1406	0.4391
4	134.2	137.31	1.2614	0.5370
6	114.9	121.29	1.4282	0.6528
8	100	110.65	1.5653	0.6994
10	89.7	106.08	1.6327	0.7324

From Eq. (5) and Fig. 4, one can generate the notched strength (σ_{Nh}^{∞}) curve with hole-diameter as shown in Fig. 5. Test data in Table 2 also presented in Fig. 5. It indicates that the test data is close to the generated notched strength (σ_{Nh}^{∞}) curve. For the specified hole-diameter, Fig. 5 provides the notched strength (σ_{Nh}^{∞}) of the infinite width plate. Using Eq. (4), one can find the notched strength (σ_{Nh}) of the finite width tensile specimen. Fig. 6 shows the variation of notched tensile strength (σ_{Nh}) with hole-diameter for different plate widths. The test data [11] also presented in Fig. 6. The notched tensile strength is decreasing with reducing the plate width. The notched tensile strength curve can be utilized to estimate the failure load of the C/C composite for any specified width and diameter of the plate.

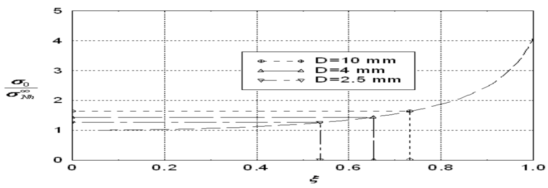

Figure.4 The value of ξ in Table-2 corresponding to $\frac{\sigma_0}{\sigma_{Nh}^{\infty}}$ for different hole-diameters.

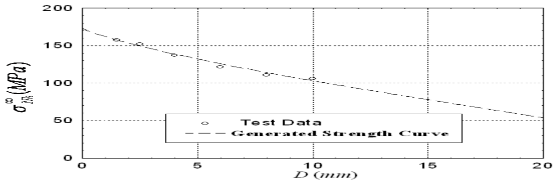

Figure.5 Variation ofnotched strength (σ_{Nh}^{∞}) with hole-diameter.

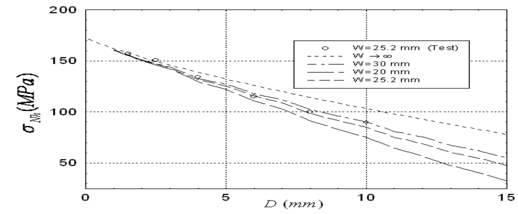

Figure.6 Notched strength (σ_{Nh}) variation with hole-diameter for different plate width.

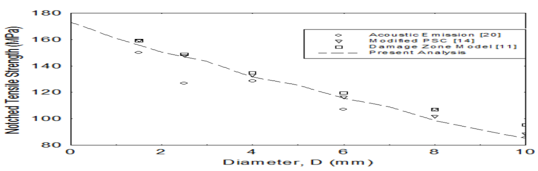

Figure.7 Comparison of fracture models on the notched tensile strength estimates of 225x25.2x3mm C/C composites.

A comparative study is made here on the notched tensile strength estimates of C/C composites utilizing the damage zone model [11]; the modified point stress criterion [14]; and the applied stress (σ_{appl}) level corresponding to the recorded AE cumulative counts (N_t). The notched tensile strength of the laminate (σ_{Nh}) is estimated in Ref. [20] from Eq. (1) specifying the applied stress (σ_{appl}) level corresponding to the recorded 10000 AE cumulative counts (N_t). The notched tensile strength estimates of C/C composites from the above fracture models presented in Fig. 7 are close to the present notched strength curve.

3. Concluding Remarks

Understanding the failure behavior of composites is involved due to variety of damage mechanisms occurring in a loaded laminate. Upon application of loads there is a possibility of damage occurrence which may lead to laminate failure or simply cause local stress redistribution. Utilizing the commercial software package ANSYS, numerical solution is obtained for 2D C/C laminates having central opening under tension. Existing empirical relation for the stress concentration factor is comparable with the present numerical results. The stress concentration factor is found to increase with increasing diameter in a finite width plate, whereas for the infinite width plate it is unchanged. By considering the width of the plate as 20 times the hole-diameter, the finite element model simulates the results for infinite width plate. When the failure load is applied, the normal stress close to the central opening region is found to be very high when compared to tensile strength of the laminate, which indicates the possibility of local stress redistribution adjacent to the hole prior to failure. The notched tensile strength nomograph is developed following the point stress criterion and validated through comparison of test results and fracture analysis results utilizing the damage zone model of Kostopoulos and Pappas [11]; the modified point stress criterion of Kannan et al. [14]; and the applied stress (σ_{appl}) level corresponding to the recorded AE cumulative counts (N_t). The procedure adopted for the development of notched tensile strength nomograph is quite simple and can be applied for complex geometries.

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