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Damage Assessment in Composites using Acoustic Emission Monitoring

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Abstract

This article presents a simple and reliable methodology for assessing the damage in composite structures through acoustic emission monitoring. To demonstrate the adequacy of the suggested approach, test data available on carbon/carbon composites is utilized. Minimum cumulative counts or percentage of failure load will be specified for the composite structures to estimate well in advance the load bearing capacity of the structures.

1. Introduction

Aerospace, defense and automotive structural design engineers prefer high specific strength, stiffness and fatigue resistant composite materials as the construction materials. Composite structures joined by mechanical fasteners need drilling of accurate, precise high quality holes to ensure durable assemblies. Drilling of composites can cause delamination, fibre-pull-out, edge chipping like damages, which results in poor assembly tolerance, reduces structural integrity of material and the potential for long term performance deterioration. The failure of composite materials can thus basically be classified into fiber-dominated mode and matrix dominated mode. The sensitivity of a laminate to a notch, in terms of its mechanical performance, is dependent on notch size and geometry, ply orientation and thickness, machining quality, and material constituents. All these factors affect the mechanical properties by changing the extent of damage growth during loading, and interact with each other to enhance the individual effects.

The extraordinary success of a fracture model lies in its ability to combine a theoretical framework with experimentally measured quantities [1-4].Acoustic emission (AE) is one of the non-destructive testing (NDT) techniques currently being adopted for detection of material defects and deformations through closely related AE signatures [5-7]. The transient elastic waves emitted during fracture incidences are recorded by transducers that are fixed on the surface of the

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component under test. These are usually piezoelectric and transform the pressure felt on their surface to electric signals. Figure 1 shows the pre-amplification and digitization of the transformed electric waveform in an acquisition board.

Though AE is a promising damage detection technique, it is essential to develop the necessary expertise to interpret AE signals, which can contain many overlapping AE transients from many sources in the material; or, can be emitted from the friction of crack surfaces and the damage growth during fatigue and fracture of composites.

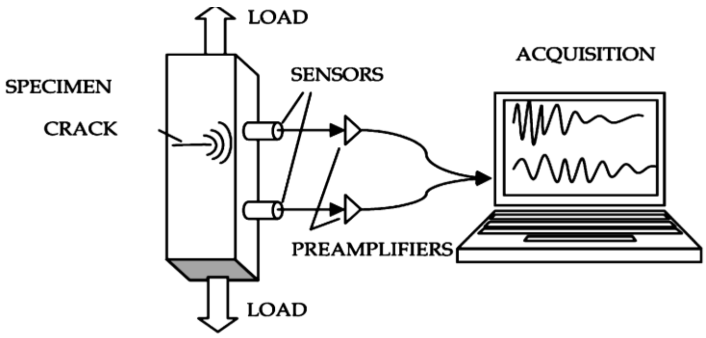

Figure 1. Schematic representation of AE experiment [7].

The task is involved, if not impossible to establish a relationship between the damage and its specific AE signature [8, 9]. Owing to the inherent complexity in the notched strength evaluation of composites this article examines the possibility of assessing the damage in composite structures through acoustic emission monitoring.

2. Fracture Data Acquisition

The fracture data of Kostopoulos and Pappas [8] generated from the straight strip 2D C/C composite plate specimens is examined in the present study. The specimens having 225 mm long, 25.2 mm wide and 3 mm thick were cut from the composite plate. This plate was reinforced by orthogonally woven 8-harness satin fabric, stacked together in a symmetric (0O / 90O) way. The fabric contains the bulk density of 1.49 g cm-3; tensile modulus of elasticity of 94 GPa and the Poisson’s ratio of 0.07. The acrylic plastic sheets were placed at both sides of the specimens to minimize the formation of delamination at edge of the hole during drilling. Specimens were tested on a closed-loop servo-hydraulic testing machine equipped with a hydraulic gripping system at room temperature in air. The static tensile tests performed using displacement control with a crosshead velocity of 0.1 mm/min.

The acoustic emission (AE) activity was monitored during the tests utilizing a 150 kHz resonant transducer and tracked AE cumulative counts by a PAC system [9]. Total amplification was 45 dB.Threshold level was 50 dB.Peak definition time was 30μs.A high-pass filter with a 100 kHz cut-off frequency was used. For the applied stress, AE cumulative counts were found to increase with increasing the hole-diameter. This may be due to the stress around the hole creating the damage while loading the specimen.

3. Finite Element Analysis

Finite element analysis has been carried out on the centre-hole orthotropic thin 2D C/C composite plate tensile specimens. Dimensions of these specimens are 225 mm long, 25.2 mm wide and 3 mm thick.Because of the geometry and loading, quarter plate model is generated utilizing the 8-node quadrilateral plane stress element (PLANE183) of ANSYS software package. From the orthotropic in-plane stiffness values of the laminate [8], the axial, transverse and shear modulus as well as the Poisson's ratio specified are: $E_{xx} = E_{yy} = 6.712 GPa; G_{xy} = 0.9024 GPa$; and $\nu_{xy} = \nu_{yx} = 0.04303$.The displacements Ux and Uy along X and Y-axes are in the directions of length and width of the laminate respectively. Symmetry boundary conditions are specified properly for the displacements, whereas a tensile stress of 100 MPa is applied on the edge along X-direction. Figure 2 shows the stress contour plot.The stress concentration factor(K_T) for this configuration is worked out to be 3.94. Since the ratio of width to hole-diameter of the plate is above 16, the stress concentration factor (K_T) of the finite width plate corresponds to that of the infinite width plate (K_T^∞).

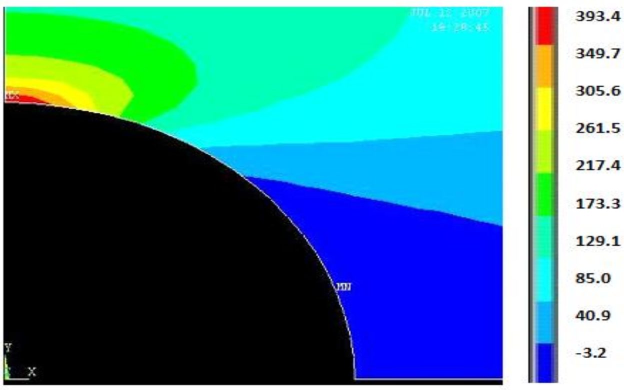

Figure 2. Stress contour plot for a quarter portion of a center-hole 2D carbon/carbon tensile specimen having 225 *mm* long, 25.2 *mm* wide, 3 *mm* thick and 1.5 *mm* open hole-diameter for the applied tensile stress of 100 MPa.

Table 1 gives the finite element analysis results of different hole-diameters of the carbon/carbon tensile specimens and the finite width correction factor (α) of the stress concentration factor. It should be noted that α =1 for the above dimensions of the carbon/carbon tensile plate configuration having hole-diameter, D$\leq$ 1.5.

Table 1. Stress concentration factor (K_T) for a centre-hole carbon/carbon tensile specimens (Length, L=225mm; Width, W=25.2mm; Thickness = 3mm).

Diameter, D (mm)	1.5	2.5	4	6	8	10
K_T	3.94	4.05	4.15	4.31	4.53	4.86
$\alpha = \frac{K_T}{K_T^{\infty}}$	1	1.028	1.053	1.094	1.150	1.234

4. Results and Discussion

Failure assessment on centre-hole carbon/carbon tensile specimens has been carried out considering the data of the Acoustic Emission (AE) cumulative counts (Nt) versus the applied stress (σ_{APL}) plots generated by Kostopoulos and Pappas [8]. Anempirical relation in a power-law form is developed from the AE cumulative counts (Nt) versus the normalized stress $\left(\frac{\sigma_{APL}}{\sigma_{NTS}}\right)$ as

$$\frac{\sigma_{APL}}{\sigma_{NTS}} = 0.0052\, N_t^{0.5125} \qquad (1)$$

Here σ_{NTS} is the notched tensile strength of the centre-hole carbon/carbon specimens. It is possible to predict the notched tensile strength of the centre-hole carbon/carbon specimens using equation (1) by specifying the recorded AE cumulative counts (N_t) and the corresponding applied stress (σ_{APL}).

An empirical relation developed from the fracture data [8] for the notched tensile strength (σ_{NTS}) of the carbon/carbon composite specimens is

$$\sigma_{NTS} = \frac{\sigma_{TS}}{\alpha K_f} \qquad (2)$$

Here σ_{TS} is the tensile strength; α is the finite width correction factor on the stress concentration factor; $K_f = 1 + q(K_T^{\infty} - 1)$ and $q = \{1 + \frac{20.68}{R}\}^{-1}$.

Table 2 gives the notched tensile strength estimates from the stress levels corresponding to the AE cumulative counts of 10000 and also using equation (2). Figure3 shows the comparison of experimental results with the developed empirical relation (1). Analytical results are matching well with test data [8], which confirms the adequacy of the empirical relation (1). It is noted from the results in Table-2 that the tensile strength of the centre-hole carbon/carbon specimens can be predicted through AE monitoring well in advance when the specimen is loaded 60% of its failure load.

Table 2. Notched tensile strength estimates of centre-hole carbon/carbon composite specimens(Specimen Length, L=225mm; Width, W=25.2mm; Thickness = 3mm; Tensile strength, σ_{TS} = 173.2 MPa).

Hole-diameter, D (mm)	Applied Stress, σ_{APL} (MPa) for N_t = 10000	Notched Tensile Strength, σ_{NTS} (MPa)		
		Test [8]	Equation (1)	Equation (2)
0	100	173.2	171.4	173.2
1.5	87.5	157.0	150.0	157.0
2.5	74.0	150.5	126.8	144.3
4	75.0	134.2	128.5	130.6
6	62.5	114.9	107.1	115.4
8	62.5	100.0	107.1	102.0
10	50.0	89.7	85.7	89.3

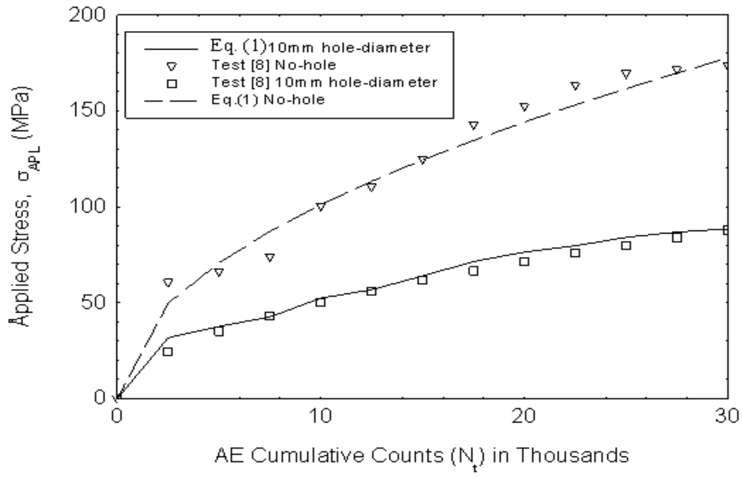

Figure 3. Comparison of experimental results [8] with the empirical relation (1).

5. Conclusions

This article deals with the failure assessment on 2D carbon/carbon composite plates under tension using acoustic emission monitoring. An empirical relation is developed from the AE cumulative counts (N_t) and the stress ratio $\left(\frac{\sigma_{APL}}{\sigma_{NTS}}\right)$, which serves as the calibration curve. This approach provides reasonably accurate notched tensile strength prediction whenever the notched specimens are loaded up to 60% of their residual strength. Using the empirical relation (1) and the applied stress corresponding to the recorded AE cumulative counts, it is possible to predict the tensile strength of the damaged carbon/carbon composite structures.

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