Experimental investigation of fatigue damage formation of Epoxy Composite subjected to impact loading under internal prestress

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Abstract

The interacting notched laminates of plain weave E-glass fiber reinforced with epoxy were fatigued at predetermined frequency in tension–tension to investigate the fatigue damage and residual properties. The results from stress-life curves summarize that damage growing around the notches due to stress concentration is the underlying cause for the variation in fatigue strengths among the geometrically different specimens considered. The residual strength and modulus decay with respect to cycle number at 50 % of the ultimate tensile strength were investigated. It is evident from the experimental data that the residual strength decreases with cycle number and increases due to redistribution of stress around the notches. The detailed study of the damage development under cyclic loads also explains the causes of modulus reduction for all the laminate geometries.

Keywords

Fatigue damage Unnotched Centrally notched Interacting notched Modulus Residual strength.

1. Introduction

The damage around the notch of a fatigued laminate deteriorates locally the mechanical properties. The stress redistribution ahead of the notch due to reduction in stress concentration increases the residual strength over unfatigued laminate [1-3]. The damage accumulates, propagates and finally the fracture occurs [4]. Some studies [5- 7] on notch strengthening under cyclic loading reveal that the residual strength of the laminates increases following cyclic loading. There were also similar efforts [8-9] on the increase of the residual strength by the damage propagation. The damage mechanisms and stiffness reduction levels depend on volume fraction, type of loading and fiber orientation. The stiffness degradation generally occurring in three stages is respectively rapid, linear with cycle number and abrupt [10]. The seriousness of damage such as fiber breakage, delamination etc. in third stage leads to final fracture. Ferreira et al. [11] chose the stiffness as a damage parameter to determine its loss in E-glass/polypropylene composite during fatigue tests. The fatigue damage process was monitored by Reis et al.

This paper presents the results of fatigue behavior of E-glass fiber-epoxy laminates containing single hole and two holes. Tests were also performed on unnotched specimens. The reported literature still explains the lack of interest on the study of the interaction of fatigue damage between two holes drilled in a laminate off the loading axis at different angular positions. The main aim of this work was to study the damage mechanisms with load cycles and to assess their effect on modulus loss and residual strength yet the performance of interacting notched woven fabric laminates needs to be understood as the fabric weft and warp flows are intertwined with each other.

2. Experimental

The ends of the specimens used in the experimental investigations were bonded for gripping on both sides to the aluminium tabs with equal parts of epoxy and hardner. The surfaces of the aluminium tabs and specimen ends on both sides were roughened with abrasive paper of fine grade before bonding. The ends bonded to the tabs were kept for 24 h in a mechanical vice applying enough pressure. These end tabs reduce stress concentration, prevent crushing and slipping of specimen ends in the grips. The geometry of the unnotched (UN) specimen was confirmed to ASTM D638-I. The geometry of a centrally notched specimen (CN specimen) is shown in Fig. 1a. Two different configurations of interacting notched (IN30 and IN60) specimens employed are shown in Fig. 1b, c. In this paper discussions are done with the convention IN30 for a specimen with centre line of holes at 30° and IN60 for a configuration with centre line of two holes at 60° to their axes. The diameter of drilled holes is 4 mm and the centre distance 8 mm. A diamond core drill was used for drilling circular holes.

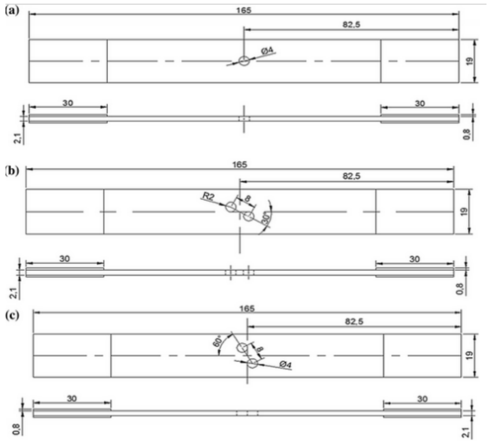

Fig. 1 Geometries of a CN, b IN30 and c IN60 specimens for tensile and fatigue tests

The static tests were performed on a 20 kN Tensometer at a cross head speed of 0.2 mm/min. The fatigue tests were conducted in load control mode on 10 kN single axis fatigue testing machine at consecutive stress levels with a stress ratio of 0.1 and frequency from 3 to 5 Hz. The tests were conducted at room temperature in a closed and clean laboratory. The stress level is meaning that the ratio of maximum cyclic stress (σmax) to the ultimate tensile strength (σu) of the virgin specimen. Five specimens were tested at each stress level and a little scatter was noticed among the data points. No specimen was observed fracturing at the grips. The fatigue tests were run to one million cycles and a little beyond without notice of the failure. The failure could mean in both the static and fatigue tests the complete separation of the material into two parts. The residual properties were also determined at 50 % σu and 0.1 stress ratio.

3. Results and discussion

Typical load displacement curves of the unnotched, centrally notched and interacting notched laminates are shown in Fig. 2. The initial stiffness of all the laminates is nearly same and the change in material stiffness was noted beyond the knee point [12]. It signifies the initiation of transverse microcracks in the resin which can be considered the first matrix cracking. They reach to the regions of the warp and weft interface within the same ply and propagate in thickness direction during static loading. The influence of hole location on stress concentration in fact considerably reduces knee point stress. Hence the knees occurred on the load displacement curves of unnotched and centrally notched specimens at 26 and 23 % σurespectively are shown in Fig. 2a, b. Similar observations from Fig. 2c, d reveal that for IN30 and IN60 specimens, they occur at 22 and 30 % σu respectively. It can be noted from Fig. 2c that the sudden drop in load represents fiber breakage in the laminate before complete physical separation of the material which quiet often occurred for samples of other configurations also. The fiber breakage at the knee was noticed by audible sound during static test.

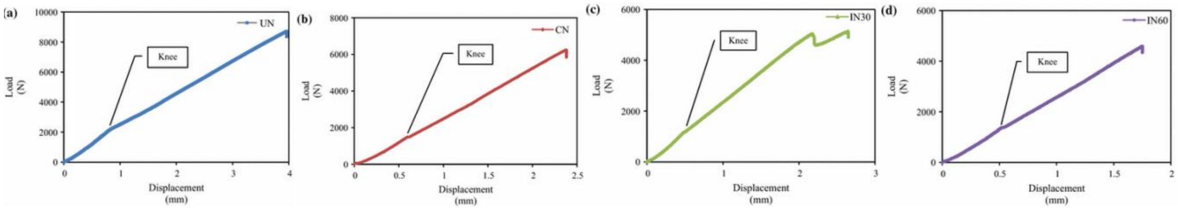

Fig. 2 Load displacement curves of a UN, b CN, c IN30 and d IN60 specimens

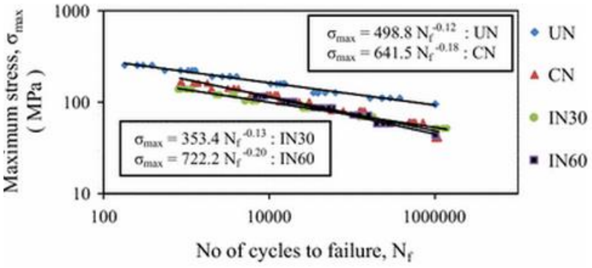

Fig. 3 S-N curves of unnotched, centrally notched and interacting notched specimens

Figure 3 shows the experimental data plotted as representative stress-life curves of the unnotched, centrally notched and interacting notched laminates drawn on log paper with power fit. It has been noticed that the fatigue strengths of all four geometrically different specimens are at one million cycles respectively 95.04, 53.35, 58.64 and 45.56 MPa with no distinction between fatigue strengths of centrally notched and IN30 laminates carrying different tensile strengths.

Figure 4 shows the typical specimens containing these damage modes without free edge delamination which were fatigued at 50 % σu to the desired number of cycles and terminated from the test for visual examination. The observations of Fig. 4 tell us that the damage patterns are considerably distinct and the location of notch influences the performance of the laminate, particularly the mutual influence of interacting circular holes changes the failure mode. Figures 5, 6, 7 and 8 show the seriousness of the damage in the specimens. The SEM examinations (Figs. 6, 7, 8) confirm the occurrence of many matrix cracks with wide openings from the hole edges in transverse direction and further observations show successively debonding at the matrix/fiber interface. Delamination is initiated in the areas where extensive matrix cracking occurs due to stress concentration.

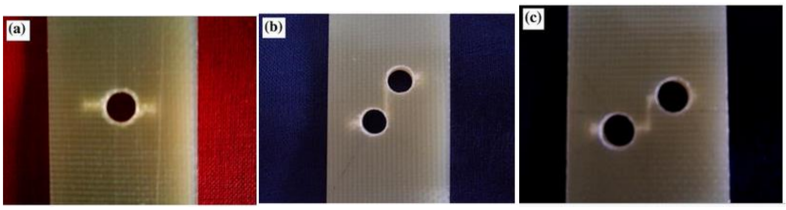

Fig. 4 Photographs of specimens a CN for 63,000, b IN30 for 18,000 and c IN60 for 75,000 cycles fatigued at 0.5 stress level

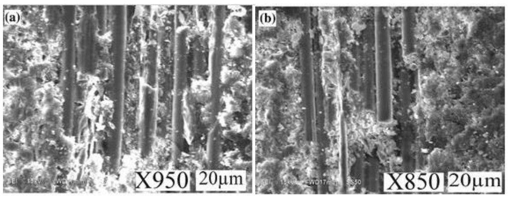

Fig. 5 Edge view damage observation on UN specimens (sectioned in lateral direction) after a2,200 and b 6,600 cycles at 50 % σu

Figure 9 shows the residual strengths after fatiguing for various durations at 0.5 stress level. The ordinate represents the residual strength (σr) and the abscissa represents normalized fatigue life (N/Nf). The effect of stress cycles on the residual strength of the laminate sample is noted here.The data in Fig. 9represents the enhancement in residual strength after these fatigue durations due to the progressive removal of stress concentration. The stress concentration is reduced by increased damage zone from the hole(s) through splitting and delamination. It can be thought that the load carrying ability of the damage zone hence decreases and results in increased tensile strength. Figure 9 also summarizes that the location of hole(s) influences the residual strength of the laminate. The reduction in residual strength of IN30 samples is quite large during first stage with increase of stress cycles due to higher stress concentration induced by the normal load acting on the thinner section between the hole and the free edge of the specimen compared to CN samples.

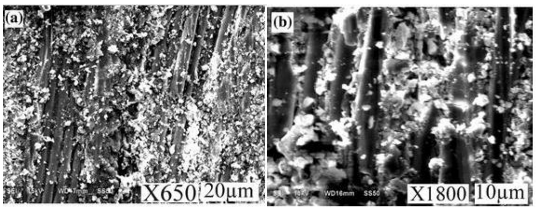

Fig. 6 Damage on the sections of CN specimens (cut in loading direction on the notch) after a14,000 and b 21,000 cycles at 50 % σu

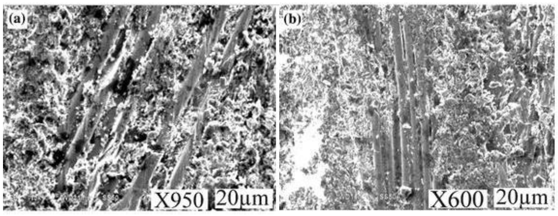

Fig. 7 Damage on the sections of IN30 specimens (cut in longitudinal direction on the hole) aftera 6,000 and b 15,000 cycles at 50 % σu

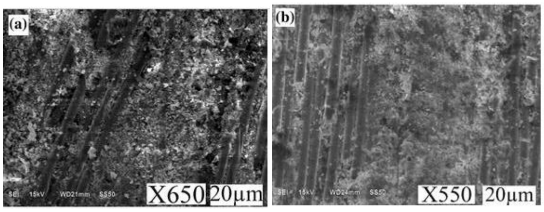

Fig. 8 SEM images of the damage on IN60 specimens cut in the warp direction on the hole aftera 30,000 and b 60,000 cycles at 50 % σu

The curves representing modulus loss in Fig. 10 go through three stages. In first stage, the modulus reduction occurs rapidly in short period of time whereas in second stage the modulus reduction is very gradual which takes place over a little longer proportion of life and the third stage corresponds to rapid modulus degradation during a longer life.

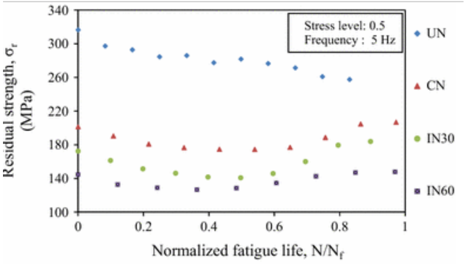

Fig. 9Variation in residual strength with normalized fatigue life

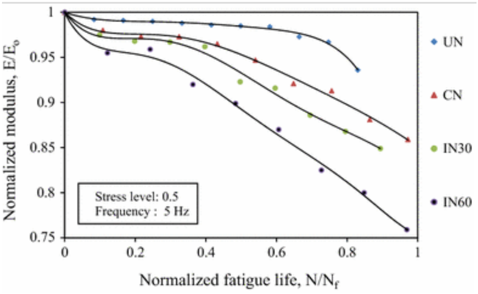

Fig. 10Curves showing the variation of normalized modulus with normalized fatigue life

4. Conclution

The fatigue behavior, damage and residual properties of unnotched, notched and interacting notched plain weave glass fiber reinforced laminates have been quantified and the following conclusions may be drawn.

Acknowledgements

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