FATIGUE PERFORMANCE OF SANDWICH COMPOSITES

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ABSTRACT

This paper delineates the results of fatigue testing performed to characterize, i. tensile fatigue lifetime and ii. flexure fatigue lifetime as a function of the thickness of foam core. Sandwich composites were made of single ply carbon fiber facesheets with urehane foam core. Acoustic emission analysis indicated core damage to be the predominant failure activity while fiber rupture served as a precursor to catastrophic failure. Near crack tip region was observed to have multiple crack initiation sites before the onset of crack growth. Crack path was found to erratic on the facesheets while the crack in the foam primarily followed a planar growth along the interface with the facesheets. Both mode I and II cracking was observed in the core and along the interface between the core and the facesheets. Flexural fatigue life was found to be unlimited below 75% of the ultimate static load. Foam core size effect is found to be significant in the crack growth and lifetime behavior. An AE based stiffness reduction model was developed to quantify the extent of damage and stochastic analysis was performed to account for large scatter in the lifetime data.

1 INTRODUCTION

Fatigue damage in sandwich composites is generally difficult to observe until the onset of catastrophic failure [1]. The detection, however, is greatly facilitated with the use of acoustic emission (AE) technique as it permits continuous damage inspection, classification and identification of modes of failure in various constituents of the composite in real time [2,3]. However, in spite of extensive use of AE technique in engineering applications [2-6]; literature on its application in fatigue crack growth (FCG) and especially in sandwich composites is scarce [1].

Sandwich composites are generally designed to carry flexural loads, however, accidental impacts, voids and micro-cracks inherent in sandwich composites can inevitably subject the component to tensile loading conditions. Therefore, an effort related to tensile fatigue characterization is outlined in this paper. In addition, preliminary results of an ongoing flexural fatigue process as a function of foam thickness are also presented.

2 RESULTS

Sandwich composite beams made of 1-ply facesheet of 0.5mm thickness 161g plain weave epoxy matrix carbon fiber and a core material of 6.0mm thick urethane foam filled kraft paper honeycomb bonded to the facesheets with 1.5oz vinyl ester resin were used in this study. Tensile fatigue testing was performed on SEN specimens of dimensions 250mm x 38mm x 12.7mm (60^o notch depth) under three point bending. Flexural fatigue testing was performed on specimen of similar dimensions but without a notch and thickness varying from 3mm to 13mm.

Flexural fatigue tests were performed between stress levels of 60 and 95% of the ultimate static load at a load ratio of 0.1 and a frequency of 2hz. Fatigue life was observed to be unlimited below 75% of the ultimate static strength. The test setup of a specimen under tensile loading conditions is shown in Fig. 1.

With the analysis of AE events, energy and position, damage was classified in various constituents of the sandwich composite; such as, core, interface between core and the facesheets, resin and facesheets. Fig. 2a shows the load-deflection curve, while Figs. 2b shows corresponding energy vs amplitude curves for a typical specimen tested under quasi-static loading conditions.

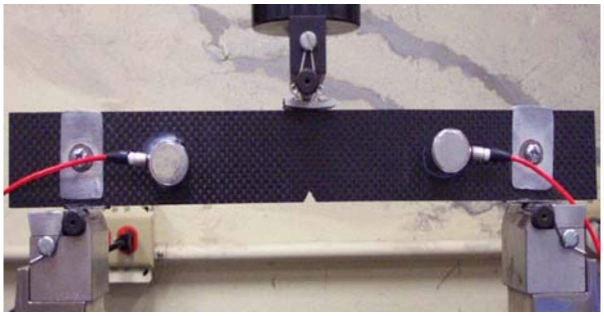

Fig. 1 Test Setup

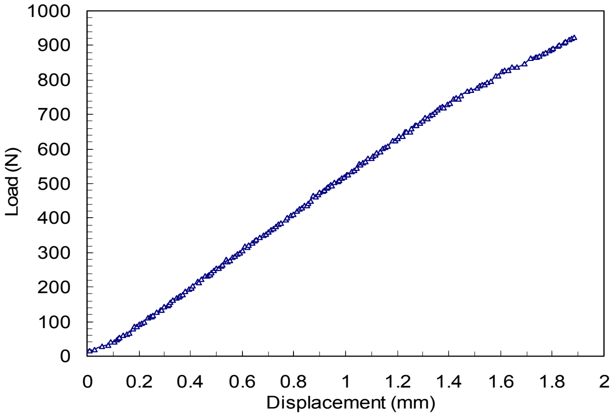

Fig. 2a Typical Load vs Displacement Curve

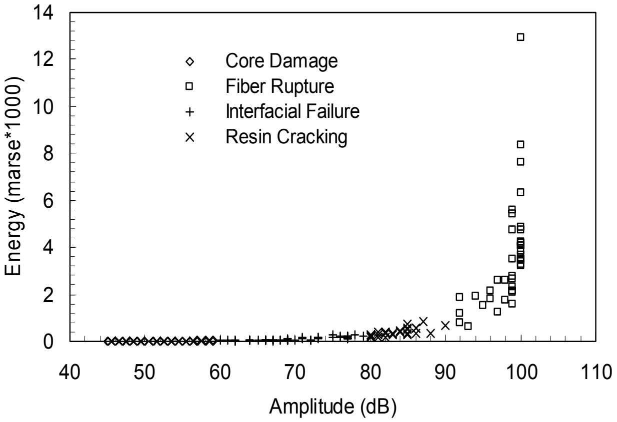

Fig. 2b Energy vs Amplitude corresponding to Fig. 2a

Based on AE analysis under quasi-static and fatigue testing, damage was classified in various constituents of the sandwich composite as a function of AE parameters as presented in Table 1. Amplitude and energy level were found to be solely a function of material composition and independent of specimen geometry or mode of failure. This classification matched reasonably with the qualitative results reported in the literature [1,7,8].

Test results indicate presence of multiple crack initiation and growth sites and periodic FCG with long intermittent dormant intervals as evidenced by AE and optical analysis. Both mode I (opening) and mode II (shearing) were observed, however, catastrophic failure consistently occurred under mode I. Crack growth activity was dominated by the propagation near the interface between the facesheets and the core that lead to weakening of the two phase action and subsequent cracking of the facesheets. Some similarities to the failure sequence reported in the literature were observed except that in the current work significant fiber rupture never took place until catastrophic failure [1,7,8]. In the literature, the endurance limit for sandwich composites has been reported to be as low as 60% of the ultimate static load [7], however, life was found to be unlimited below 75% in the current study. Energy dissipation as a result of multiple crack initiation and propagation sites may be responsible for the high endurance limit as it effectively reduces crack tip stress intensity and, therefore, stagnates crack tip(s) advancement.

Core thickness effect is significant in sandwich composites. Preliminary results indicate reduction in lifetime as the thickness of foam core is increased for the same facesheet thickness. Further studies in this area are currently underway.

Table 1: Sequence of failure and corresponding amplitude and energy ranges.

Failure Mode	AE Amplitude (dB)	AE Energy (marse)
Core Damage	45-59	0-25
Interface Failure	60-79	3-219
Resin Cracking	80-89	88-374
Fiber Rupture	Above 90	347-13568

2 STIFFNESS REDUCTION MODEL

Difficulties in FCG and lifetime assessment arise as a result of multiple crack fronts and large differences in elastic properties of the constituents (core, interface, facesheet) do not yield data suitable for the implementation of existing models. Therefore, an AE based stiffness reduction model was developed based on the overall AE activity during the fatigue test. The underlying assumption was that the extent of the damage (or cracking) in each constituent of the sandwich composite is directly proportional to the AE activity in that constituent. This is a reasonable assumption as AE activity can not take place unless a particular constituent of the sandwich composite suffers damage during fatigue. Additionally, Kaiser's effect prohibits replication of AE activity associated with a particular event [10].

This model was based on the percentage of total AE energy released by each constituent, which was taken as being proportional to the percentage of damage. This energy percentage, in turn, was determined from the overall number of events corresponding to each constituent of the sandwich composite within a given interval. An important parameter in this model is the weight factor, κi, for each constituent. κ was calculated from the static test results as the sum of the product of the total number of events for each constituent and respective energy level divided by the total energy during a given time interval. The weight factor contains information as to the role that each constituent plays in maintaining the integrity of the sandwich composite. Stiffness reduction parameter '$\Delta\epsilon(t)$' under static or fatigue testing can then be represented as,

$$\Delta\varepsilon(t) = \sum_{1}^{n} \phi_i(t)\kappa_i \qquad (1)$$

Where ϕ_i reflects cumulative percent damage in the core, interface and the facesheet for a given time (or #cycles) interval, respectively; and κ_i are the corresponding weight factors. This model is robust in its application as it can be implemented in real time while AE data is continuously collected for a component in service. Thus this model becomes an important tool for calculating remaining lifetime or loss of lifetime at a given instant in the fatigue life.

3 STOCHASTIC ANALYSIS

To evaluate large scatter observed in the fatigue lifetime data, stochastic analysis was performed utilizing three parameter Weibull distribution [11],

$$\ln\left[\ln\left(\frac{1}{SF(N)}\right)\right]=\alpha_s \ln(N)-\alpha_s \ln(\upsilon_s) \qquad (2)$$

where the survival probability SF(N) is the probability that life will be longer than N , N is a random variable denoting fatigue life, α_s is the shape parameter designating the spread in the data and $\nu_s$is the scale parameter. $n_{o,s}$, the location parameter denoting minimum life was set equal to zero in the current analysis. Eq. 2 can be applied at any number of cycles to obtain the survival probability. Regression analysis plots of ln(ln(1/SF)) vs. ln(N) were generated, a typical example is shown in Fig. 3. The accuracy of Fig. 3 increased as the number of lifetime data was increased. Calculation of shape (α_s) parameter indicated substantial scatter in the lifetime data independent of the stress level. However, the scale parameter (νs) indicates a clear ascending trend as a function of stress level. The main advantage of using this survival probability method is its simplicity in ascertaining remaining lifetime information.

To check the accuracy of the proposed Weibull distribution, Kolmogorov Smirnov (K-S) Goodness-of-Fit tests were performed. To perform this test, F*(Ni), the observed cumulative distribution histogram and F*(Ni), the hypothesized cumulative distribution function were evaluated at 5% confidence level. K-S test assured the proposed stochastic model to yield the results within 5% accuracy.

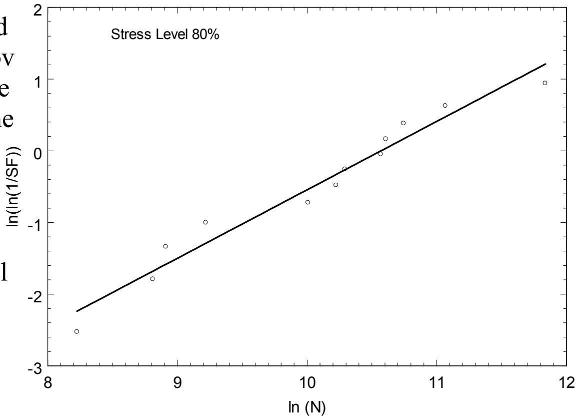

Fig. 3 Typical result of regression analysis performed at 80% stress level.

4 CONCLUSIONS

AE proved to be very robust in determining the extent and location of damage, that lead to lifetime stiffness reduction model. Core failure dominated the damage mechanism, whereas, fiber rupture triggered the onset of catastrophic failure. Large scatter in fatigue lifetime and crack growth data was analyzed using Weibull distribution.

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6 REFERENCES

1. Burman M. Fatigue Behavior Initiation and Propagation in Sandwich Structures, Royal Institute of Technology, Report No. 98-29, ISSN 0280-4646, 2000, Sweden.
2. Bakukas J, Prosser W and Johnson W. Monitoring Damage Growth in Titanium Matrix Composites Using Acoustic Emission. Journal of Composite Material 1994:28(4):305-328.
3. Harris D. and Dunegan H. Continuous Monitoring of Fatigue Crack Growth by Acoustic Emission Technique. Third SESA International Congress on Experimental Mechanics, 1974, Los Angeles.
4. Li F and Li Z. Acoustic Emission Monitoring of Fracture of Fiber-Reinforced Concrete in Tension. ACI Materials Journal 2000:97(6):629-636.
5. Huang M. Using Acoustic Emission in Fatigue and Fracture Materials Research. JOM, 1998:50(11):1-14.
6. English L. Listen and Learn, AE Testing Composites. Physical Acoustic Corporation, TR103-75-6/87, 1987, New Jersey.
7. Mahi A, Farooq M and Sahraoui D. Mechanical behavior of Sandwich Composite Material under Cyclic Fatigue, New Trends in Fracture and Fatigue-Metz, 2002:April, France.
8. Kulkarni N, Mahfuz H, Jeelani S and Carlsson L. Fatigue Crack Growth and Life Prediction of Foam Core Sandwich Composite under Flexural Loading, Composite Structures 2003:59: 499-505.
9. Caprino G. Predicting Fatigue Life of Composite Laminates Subjected to Tension-Tension Fatigue, Journal of Composite Materials 2000:34(16):1334-1355.
10. Nondestructive Testing Handbook, 2nd ed. American Society for Nondestructive Testing 5, ASNT, 1987, New Jersey.
11. Sobzcyk K and Spencer B, Random Fatigue: From Data to Theory, 1992, Academic Press, New York.