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Effect of damage progression on the heat generation and final failure of a polyester–glass fiber composite under tension–tension cyclic loading

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ABSTRACT

The use of glass/polyester composite materials in wind turbines is increasing due to their low cost and favorable mechanical properties. The existing knowledge about the fatigue characteristics of such composites leads to rather conservative designs which are over dimensioned and hence costly. The aim of this work is the development of an approach for the characterization of composites under cyclic loadings. An investigation is performed on the reduction of stiffness and the heat generated during the progression of damage. It is shown that even in the matrix mode failure the fatigue limit can be above the monotonic damage criterion, where the composite losses its rigidity either due to plasticity or matrix fiber separation. Thus showing that polyester resins are rather brittle in nature and brittle material fracture models can be used for modeling these composites in fatigue. However the role of fibers in initiation or arresting of the cracks is not presented in this study.

1. Introduction

In the field of wind energy, glass fiber–polyester composites are being increasingly used. The wind turbine blades while turning under the effect of wind, generating power, generally undergo tension–tension type cyclic loading (weight of the blade cancelled by its lift). Although studies are also carried out on tension–compression and variable cycle WISPER and WISPERX type regimes. The fatigue tests done in the laboratory for the characterization of these materials can be done using a tension–tension regime ($R = 0.1$). Up until recently fatigue life determination based on self heating has been used primarily, for metallic materials; whereas for long fiber composites there have not been a lot of detailed investigations [1–8]. For addressing this issue this study has been performed on a ±45° biaxial tissue type composite. The motivation of using such a method as opposed to classic Wohler curves for which abundant data is available in the literature [9,10], is that, in the Wohler curve the run out (stress at which fatigue life is determined) bases on the judgments of the researcher or application for which the materials are to be used; therefore it can lie anywhere between 1 and 10 million cycles. Furthermore keeping in view the practicality of this approach the tests are performed on specimens manufactured using the same process as for the real structure, and the tests pieces are kept rather massive to keep their stress concentration and edge effects to a minimum.

The heat released during fatigue tests in composite materials is due to the internal damages taking place, such as fiber breakage, delaminations [11,12]. In general the heat generated can be related to the stresses generated and the dynamic Young's modulus [13,14] as given in [15] (1)

$$Q_R = E\varepsilon_a^2 \omega \sin\delta \tag{1}$$

2. Experimental setup and specimens

The test machine used is an INSTRON (150 kN) tensile fatigue test rig. The specimen surface temperature is recorded using thermocouples between the knives of the extensometer, placed at mid span of the specimen, and two thermocouples are placed on the machine grips to record the temperature rise of the grips. A simple calculation can isolate the self heating of the specimen from the temperature rise in the machine.

Rectangular specimens of 250 × 25 mm and 4.5 mm thick are used for the fatigue tests. The specimens are kept fairly massive to reduce the edge effects and stress concentrations. Since the specimens are made up of thick plies hence a thicker section permits shielding against stress concentrations due to internal defects. Table 1 shows the material and specimen properties of the composite.

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Table 1
Properties of the test specimens.

Material/specimen properties	
Ultimate strength (MPa)	110
Elastic limit (MPa)	18.5
Young's modulus in elastic (GPa)	19
Glass transition temperature of matrix (°C)	80–89
No. of plies	7
Dimensions of specimens (mm)	250 × 25 × 4.5–4.7

3. Mechanical testing and measurements

The specimens are equipped with a thermocouple and an extensometer at their mid span. These record the strain over a 12.5 mm gauge length as well as the surface temperature of the specimen. The temperature rise is calculated assuming that the temperature gradient in the specimen between the lower and upper machine grip is linear. If T_0 is the initial temperature of the test piece, T_l and T_u the temperature of the lower and upper grips respectively and T_S is the surface temperature of the specimen then the temperature rise is given by (2);

$$T_{\text{rise}} = \theta = T_S - T_0 - \left(\frac{(T_l - T_{0l} + (T_u - T_{0u}))}{2} \right) \qquad (2)$$

To promote self heating and to have enough residual strength left in the specimen to last for the total range of solicitations, the frequency is kept sufficiently high and the no of cycles to a minimum for stabilized temperature to be attained. In our case a frequency of 5 Hz for 10,000 cycles was chosen.

For higher load cases a frequency of 2.5 Hz was used to limit the effects of "overheating". The whole of the experiments have been maintained to a level below 28 °C. Given the polymer matrix has a glass transition temperature of around 85 °C this temperature limit is chosen to ensure heat induced softening of the polymer matrix.

4. Temperature rise and reduction of stiffness

Typically the rise in temperature should stabilize at a certain level, provided the intensity of loading is below a certain limit where the damage stops progressing after a given number of cycles. The rise in temperature is inferred to be as a result of damage progressing in the specimen.

To support this final hypothesis refer to the temperature plots shown for each loading condition. For loads from 2.5 to 5.0 kN the specimens show a definite flattening of the temperature rise curve showing that the heat generated in the specimen has become equal to heat dissipated to the surroundings from the specimen. But it should be remembered that the temperature of the whole experimental setup keeps on rising as long as the test keeps on running, Fig. 1a and b.

Comparing this to the reduction of stiffness per cycle one can see a definite decrease in stiffness as the temperature of the experimental setup rises. Thus one can infer that this reduction of stiffness is due to the thermal softening of the specimen and not due to actual increase in damage. One other way of supporting this hypothesis (although not reported in this study) is that for all practical purposes the loads up to 5.0 kN are lower than the endurance limit of the material hence the specimen can attain a high number of cycles without progressive damage.

At load levels higher than 5.0 kN the rise in temperature can be seen to be rather accelerated and does not stabilize even at the end of 10,000 cycles. Keeping within the protocol of the experiment it was interrupted at 10,000 cycles but if left till total failure of the material the temperature keeps on rising, suggesting that the damage keeps on propagating and hence the fatigue limit should lie somewhere below this load state.

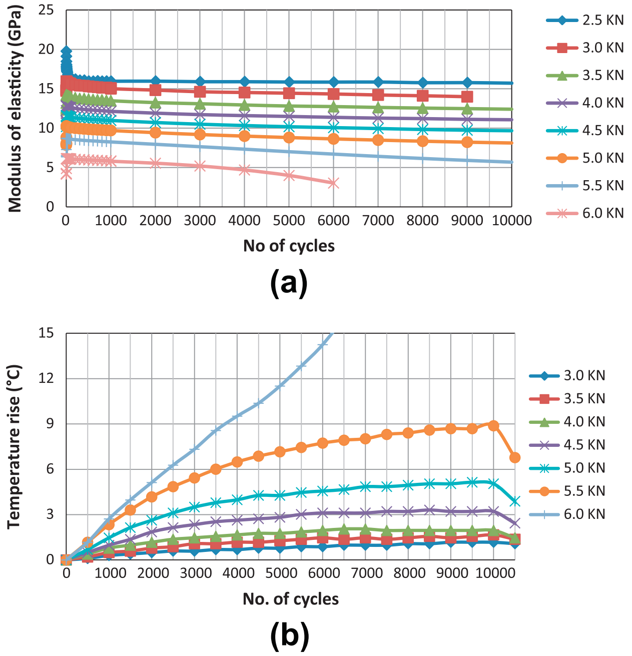

Fig. 1. (a) Reduction of stiffness during cyclic loading and (b) self heating curves for specimens loaded cyclically at 5 Hz.

5. Plastic response

Polymer matrix composites show a certain plastic response when loaded beyond their elastic limits. In some cases the elastic region can be so small that all effective loading is done in the plastic region. Although polyester resins show a fairly brittle behavior but the presence of plasticity should be investigated for ascertaining the loading domain.

Some experiments were carried out to look for the plastic response and the onset of plasticity at different strain rates. For this purpose quasi static displacement rates of 5, 15, 30, 45, 60 and 150 mm/s have been chosen. These rates cover all the displacement rates used for the fatigue testing.

Referring to Fig. 2b and c as a representative for all the loading states one can see visible cracks appearing in the composite as compared to when the specimen is in the region of less than 0.1% strain. This suggests most of the degradation in stiffness comes from actual physical damage (fiber matrix separation) taking place in the specimen though plasticity of the matrix is also a factor.

6. Endurance limit using self heating

From the data generated in the above experiments the fatigue or endurance limit of the material can be found. For this purpose, two different approaches are used, Figs. 3 and 4.

Different authors have reported different methods for determining the endurance limit from the above given graphs. There are a number of parameters to be understood about plotting the straight fitting lines for the above data. We have chosen the higher temperature rise stress levels as one region for curve fitting while the other low temperature rise as the second. Even after these fittings are done one can either choose the intersection of the two