INVESTIGATION OF SELF HEATING AND DAMAGE PROGRESSION IN A POLYESTER FIBERGLASS 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 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

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 is due to the damage such as fiber breakage, delaminations; taking place [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)

$$Q_R = E\varepsilon_a^2 \omega sin\delta \qquad (1)$$

2. Experimental setup and specimens

The test machine used is an INSTRON (150KN) 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 x 25mm and 4.5mm 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 show the material and specimen properties of the composite.

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 x 25 x 4.5 - 4.7

Table 1: Properties of the test specimens.

2.1. Mechanical testing and measurements

The specimens are instrumented with a thermocouple and an extensometer at their mid span. They record the strain over a 12.5mm 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);

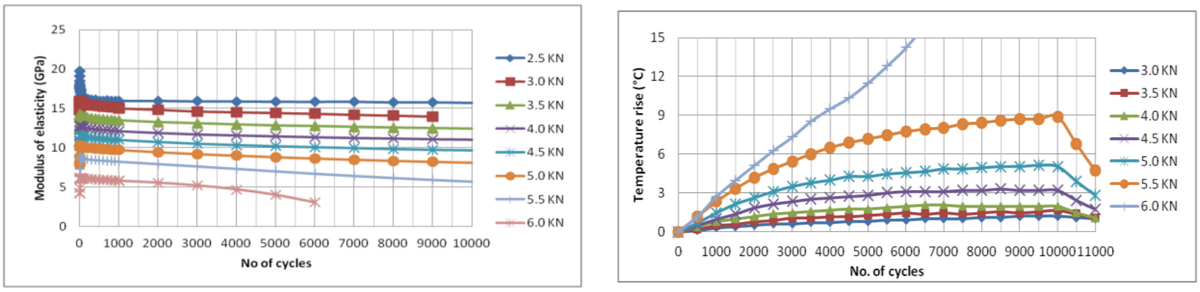
$$T_{rise} = \theta = T_s - T_0 - \left(\frac{(T_l - T_{0l}) + (T_u - T_{0u})}{2}\right) \quad (2)$$

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 5Hz for 10,000 cycles was chosen.
For higher load cases a frequency of 2.5Hz was used to limit the effects of "overheating". All 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 reduce thermal softening.

3. Temperature rise and reduction of stiffness

Typically the rise in temperature would stabilize at a certain level, provided the intensity of loading is below limit where the damage stops progressing after a certain 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 5.0kN 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, Figures 1a & 1b.
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 5.0kN 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.



(a) (b)

Figure 1: (a) Reduction of stiffness during cyclic loading, **(b)** self heating curves for specimens loaded cyclically at 5 Hz

4. 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.

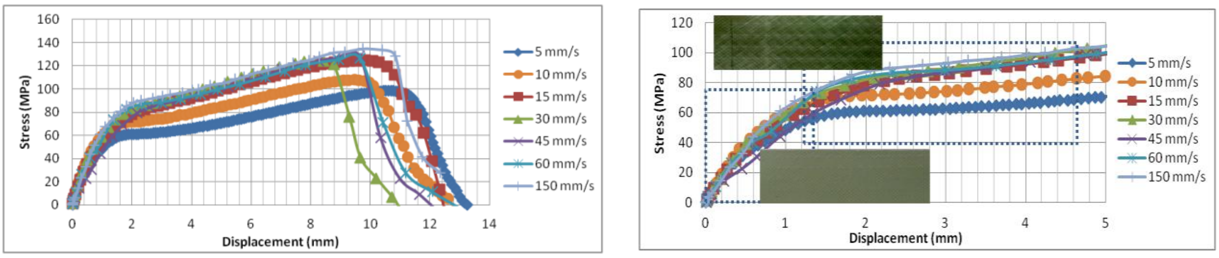


Figure 2: (a) Plastic response of material at different displacement rates, (b) Appearance of visible damage in the non-linear region of stress-displacement curves

Referring to figure 2b 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.

5. 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, Figures 3a and 3b.

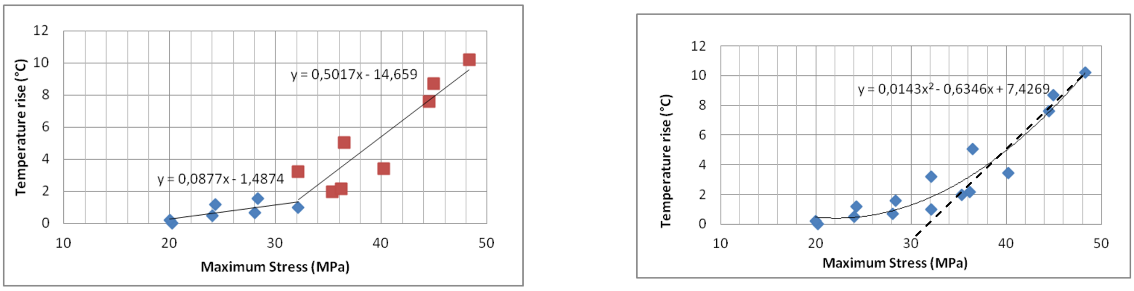


Figure 3: (a) Determination of point of inflexion in a self heating curve, (b) Determination of endurance limit using tangent to the end of best fitting quadratic curve

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 straight lines to give a unique value of endurance limit or find the x-intersects for both straight lines to get a range of endurance limit. Furthermore a tangent at the last point to a quadratic best fitting curve through all the points gives a fairly close value to the aforementioned method as shown in table 2

Endurance limit in terms of maximum applied stress (MPa)		
Self heating	Curve fitting method 1	34.62
	Curve fitting method 2	33,46

Table 2: Comparison of 2 methods of curve fitting for finding the endurance limit

6. Rate of damage progression

As reported by [10, 16] the rate of damage development can be seen to vary during a fatigue loading cycle. However the damage development measurements when done during self-heating tests are done for a specified number of cycles and are not till final failure. Hence here we will consider only the damage progression phase, where it is constant.
The rate of damage development can be seen to increase exponentially with the increase of the maximum applied stress, it can be said to follow a curve fitting rule as.

$$\dot{D} = \alpha e^{\beta \sigma_m} \qquad (3)$$

Where D is the rate of damage development, α, β and σ are curve fitting parameters and the maximum applied stresses respectively. This relation just shows the approximate exponential relation that can be used as an estimate for intermediate values of damage progression.
Furthermore it can be shown that the rate of progression of damage rests rather low, below the limit of endurance determined through self heating. After this threshold value the progression of damage starts to increase exponentially. Figure 5 shows results of some tests that had been run at higher load levels and a lower frequency, until failure. The frequency of loading was reduced to 2.5Hz above a stress level of 45MPa to limit the self heating, so that the temperature of the specimen stays well below the glass transition temperature.

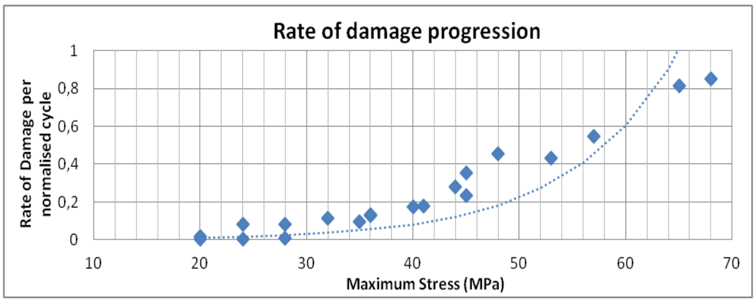


Figure 5: Rate of damage development against different applied stress levels

In other reported tests on polyester resin matrices [17], polyester resins show very little plasticity. The brittle fracture in the case of composite materials can be attributed to crack initiations at the fiber matrix interfaces. A close study of the failed surfaces shows a predominantly délamination type failure with some fiber pull out and almost negligible fiber breakage. This mode of failure is as expected as all the fibers are oriented at ±45° with no continuity in fibers between the two machine jaws. This has been shown in similar experimental work. [18 – 21].

7. Discussion

The above mentioned investigation shows that for certain commercially used and manufactured composites a sharp increase in the damage progression can be used globally to determine a threshold for safe loading and for the characterization of materials. The investigations show that the heat generated due to damage progression follows a direct relation with the reduction in stiffness. Although the stiffness reduces as a result of heating as well but the rise in temperature of the machine was very little as compared to the heat generated by damage and the temperature rise was seen to be linear with each increase of load

step. Hence this linearity of temperature rise can be taken into consideration when we see a constant reduction in stiffness even at below endurance limit stress levels.
Referring to the figures 2a & 2b it can be noted that the threshold for visible damage increases with an increase in displacement rate up to 15 – 30mm/s and then levels for higher displacement rates. Hence for our experiments which lay in between 75 – 150 mm/s the effect of visco-plasticity can be considered as constant.

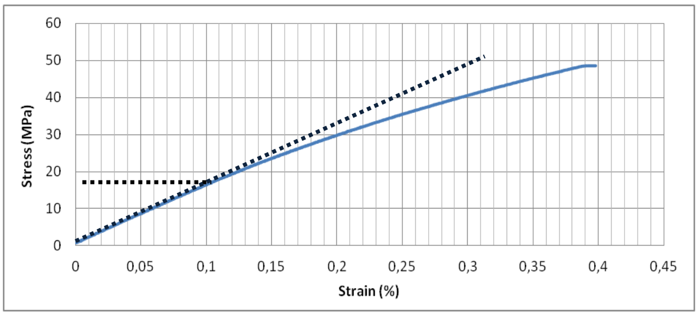


Figure 6: Stress-strain behavior of a test piece under monotonic loading

It can be seen that the material behaves non-linearly above ≈ 18.5 MPa. This can be confirmed by an FEA model using Hashin's damage criteria to see the matrix failure in tension occurs at roughly the same value (uniform stress measured in the central region = 18.9 MPa), although more detailed approaches [22, 23] exist but for simple cases this suffices.

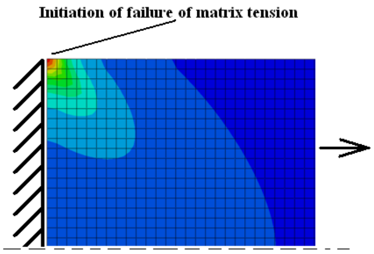
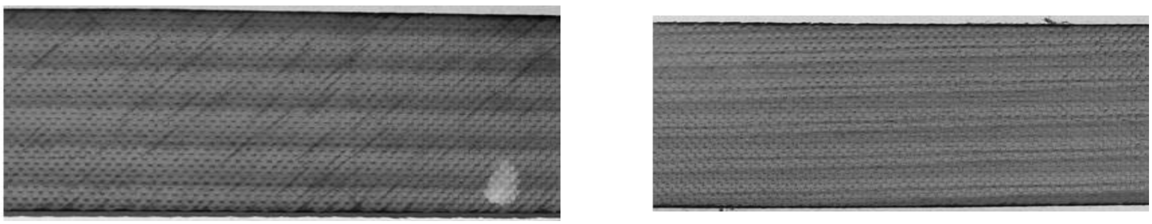


Figure 7: Damage Initiation of matrix in tension as predicted by Hashin's criterion

However visual inspection of the test pieces reveals that at a maximum applied stress level of 30 MPa and even after 1,000,000 cycles there is no visible damage or cracking taking place, on the other hand another specimen tested at 45 MPa for 400,000 cycles shows visible cracks appearing at the fiber-matrix interfaces, Figure 8. These cracks are throughout its thickness when viewed using backlighting.



(a) (b)

Figure 8: Damage development of the test piece loaded at (a) 45 MPa for 400,000 cycles and (b) 30 MPa for 1,000,000 cycles.

It is well seen by the monotonic loading curves that the specimen will be damaged at this load level. However the damage progresses very slowly under cyclic loading below the threshold value shown in figure 2 and there is a less significant degradation of stiffness.
This can be confirmed by the strain curves of this test traced during the cyclic loading. Since the loading regime is force controlled hence we consider the strain curves as better representatives of this behavior.

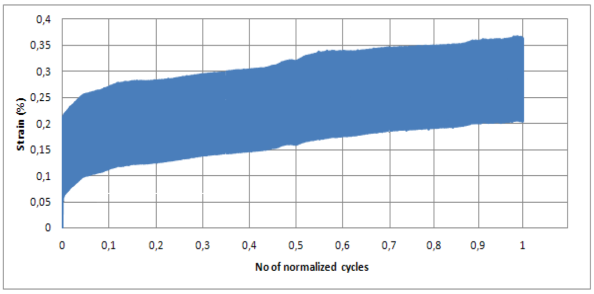


Figure 9: Strain plots until 1.000.000 cycles showing hysteresis in the 30 MPa loaded specimen.

It can be seen from figure 9 that the material shows a certain hysteresis and even though it had been loaded beyond its elastic limit it holds for this regime of cyclic loading without visible damage or cracking. This reduction in stiffness is hence attributed to the hysteresis of the polyester matrix.

8. Conclusion:

The present study shows a definite relationship between the heat generated and the damage taking place in long fiber polymer composite material. The self-heating tests experimentally show that they can be used as a good estimate of the material's endurance limit. However there is always certain level of hysteresis effects due to plastic deformation and visco-elastic behaviors. The 45° Biax test specimen loaded to 30 MPa near to the endurance limit determined by self heating (34 MPa) bore 1,000,000 cycles without any visible damage, although a reduction in elasticity was seen.
From this investigation, although difficult to define endurance limit, it can be inferred that any sharp decrease in rigidity or increase in heat generation are signs of the material fiber-matrix interfacial crack growth, in addition to hysteresis in the polymer matrix. As far as the structure is loaded cyclically under the elastic limit of the material, no sudden fatigue failure should occur.
Another important aspect of this investigation is that, by using plasticity curves one can determine the load threshold even in the damaged state where the structure would sustain under cyclic loading.

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