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FATIGUE BEHAVIOR OF A PULTRUDED GLASS-REINFORCED POLYMER-MATRIX COMPOSITE MATERIAL

L. B. Godefroid[1], W. A. Morais[1], G. P. Silva[1] and J. A. Martins[2]

[1] Dept. of Metallurgical and Materials Engineering, School of Mines, Federal University of Ouro Preto, Campus Universitário Morro do Cruzeiro – Ouro Preto – 35400-000 – MG – BRAZIL
[2] ENMAC Composite Materials Ltd. Rua Joaçaba,10 – São José dos Campos – 12238-530 – SP - BRAZIL

ABSTRACT

Most of the commonly used continuous fibers-reinforced polymer composite materials work with pultrusion. This process can produce a variety of reinforced solid, tubular or structural profiles, with very interesting chemical, physical and mechanical properties. Recently, the increase in the use of pultruded composites through critical applications in automobile and aerospace industries requires a complete and precise knowledge of its properties, mainly the fatigue resistance. This paper presents several aspects of the fatigue behavior of a glass-reinforced polymer composite, with particular emphasis on the Wöhler curve (S-N curve). Effects of R-ratio, frequency and overloads were studied. Damage by fatigue is measured by two different forms: residual strength obtained from tensile tests, and continuous measure of deformation of the composite material from fatigue tests.

KEYWORDS

Fracture, Fatigue, Damage, Composite Material.

INTRODUCTION

Without doubt fatigue is the most serious damage process in using engineering materials. With composite materials, as the same form of any other material, the major utilization problem is fatigue. However, in the most utilized composite material – fiber reinforced plastics –the formation and propagation of a crack or a few cracks does not happen, as in metals or ceramic materials. Due to its own inhomogeneity, these does not exist an unique (or few) crack propagating freely in the material's structure. A typical fiber reinforced composite continually damages under fatigue. The experimental verification of this dynamic fatigue response of composites can be found in many works [1-5]. The generated defects may reach a stable condition sometimes called [4] "characteristic damage stage" or CDS. In this condition the mechanical properties of the composite slightly change during the fatigue process. The alteration on mechanical properties is almost always easier and more representative to measure and to register than either a crack size or an effective crack size in fatigue of composites.

If we compare many processes, pultrusion is probably one of the most versatile composite processes [6]. It is a continuous process used to produce fiber-reinforced plastic structural shapes. The process involves pulling resin-impregnated fiber reinforcements through a preformer and a heated die to cure the resin. Pultruded composites exhibit all of the features produced by other composite processes, and also additional advantages inherent to this process.

With the support of a great industry of composite materials in Brazil, the authors made fatigue tests on a pultruded composite rod bar. Initially, tension-tension fatigue tests were executed to determinate a possible fatigue limit and the S-N curve for this material. Tests were made to verify the effects of R-ratio (low to high tension level ratio $_{min}/_{max}$), frequency and an overload. Cyclic deformation was measured and analyzed in conjunction of residual strength obtained from tensile tests. Similar methodology is mentioned in several references but almost always for non pultruded composites [2,4,5].

EXPERIMENTAL PROCEDURE

The materials used in this study were E-glass fibers and a polyester resin. The product was a unidirectional composite in the form of rod, 12.7mm in diameter, developed at the ENMAC by Martins [7]. The composite contains 70% fibers (about 0,016mm in diameter) by weight. Room temperature tensile strength was around 900MPa. Figure 1 illustrates the configuration of specimens used for fatigue tests, the tensile tests were done with the same only that these had smaller head. All tests were conducted on a closed-loop servo-hydraulic MTS testing machine with a capacity of 10tons. Tension tests were performed at room temperature under stroke control (displacement rate = 25mm/min).

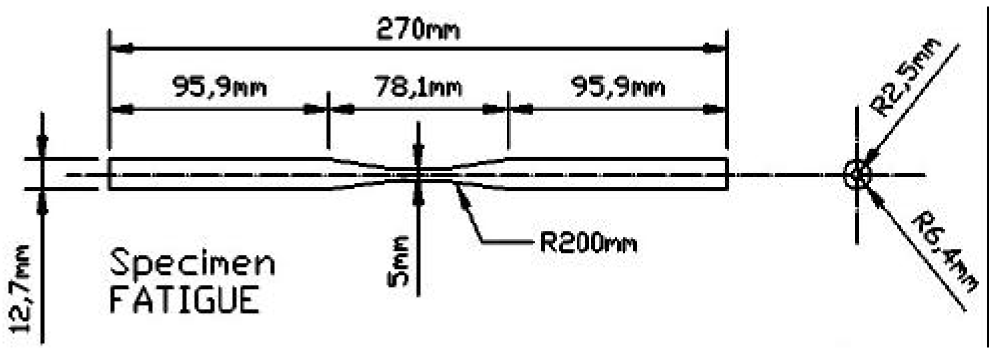

Figure 1 : Fatigue specimen configuration.

Fatigue tests were carried out in tension-tension with a sinusoidal waveform, at frequency ranging from 3 to 30Hz, at a stress ratio R ranging from 0.1 to 0.5, all tests at room temperature. Load, stroke and time data were collected and stored in a PC throughout the tests. These data were used to monitor the strain and the evolution of damage during fatigue tests. After the creation of a S-N curve of the composite, two extreme stress levels were fixed, to study the influence of mechanical parameters on fatigue life: frequency, stress ratio R and a single overload (overload ratio = 2.0). Damage propagation in fatigue was monitored by two different techniques: decrease of tensile strength and increase of strain with fatigue cycles. The specimens had their temperature observed during the test to confirm no heating on cycling.

RESULTS AND DISCUSSION

The plot of stress amplitude versus number of cycles of failure is showed in Figure 2 (S-N curve). A power-law correlation between the cyclic stress and fatigue life was observed. The corresponding life equation is of the form:

$$s_a = s_{uts}\left(2N_f\right)^b \quad (1)$$

where $_a$ is the stress amplitude, $_{uts}$ is the monotonic tensile strength, $2N_f$ is the number of reversals to failure and b is the fatigue strength exponent. The results obtained for b was –0.177 for $_{uts}$=910MPa. This type of correlation has been observed for other authors [8-10].

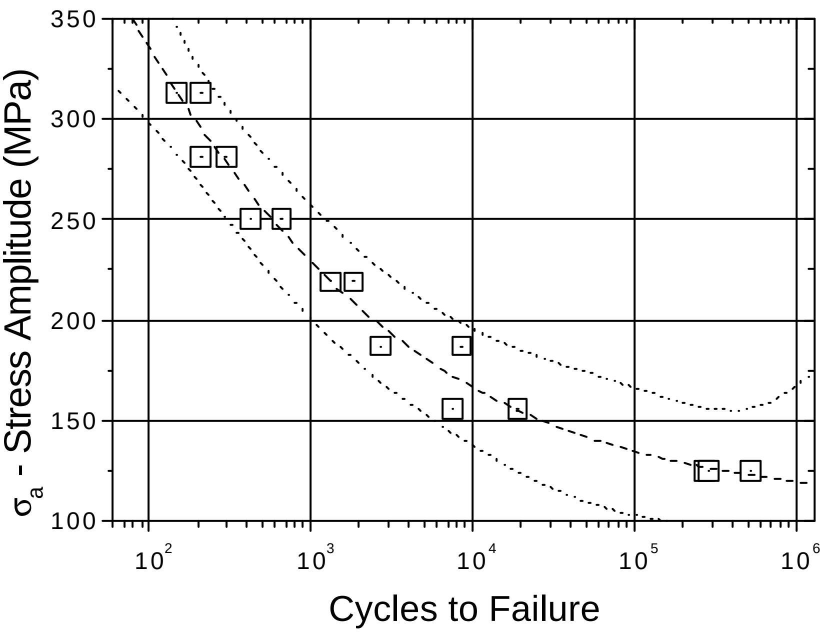

Figure 2: Stress amplitude versus number of cycles of failure.

The obtained results indicate a tendency of this material to not present a fatigue stress limit like some metals as aluminum alloys. This may be explained by the great presence of small defects in the matrix structure due the fabrication process. Obviously the $_a/N_f$ rate decreasing in high cycles of fatigue make the possibility of flaw more remote in these load levels.

The effect of stress ratio R in the composite fatigue life is showed in Figure 3. As we can see, fatigue life tends to increase with increasing stress ratio R. Many authors have showed the opposite result [8,11-13]. We explain this controversy by the fact that in our study the increasing R is made by increasing minimum load, at a constant maximum load. With this procedure we decrease the stress level and decrease the stress field in the fiber-resin system. Damage per cycle is then decreased, and fatigue life increases. This effect is more important when the stress amplitude is decreased (125MPa than 250MPa).

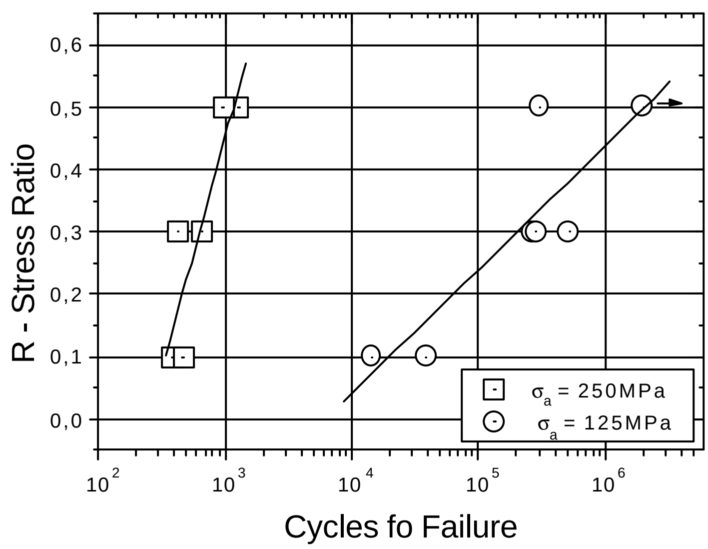

Figure 3 : Effect of stress ratio R in fatigue life.

The effect of frequency in the composite fatigue life is showed in Figure 4. As we can see, fatigue life tends to increase with increasing frequency. The effects of test frequency have been studied by several workers [14-17], who produced conflicting results. We believe that a low frequency induces a higher damage level in the fiber-resin system. This effect is again more important when the stress amplitude is decreased (125MPa than 250MPa).

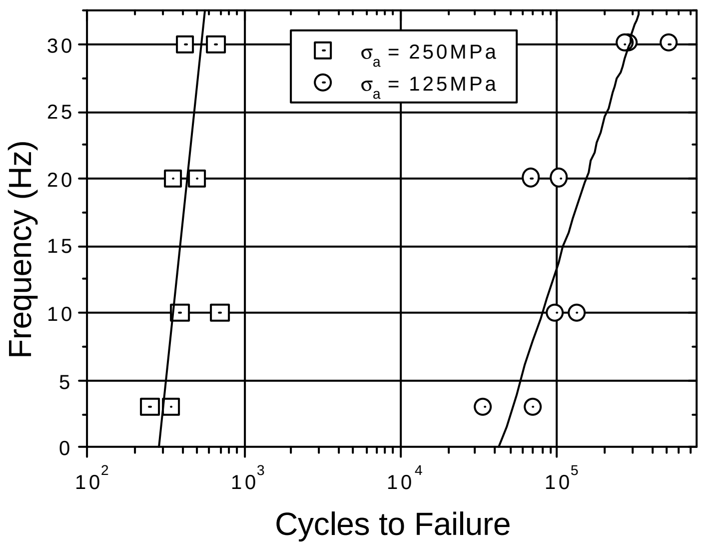

Figure 4: Effect of frequency in fatigue life.

The effect of a single overload in the composite fatigue life is showed in Figure 5. Three results are presented for a normal loading and two results after an overload. The overload stress was applied after 20% of fatigue life in 125MPa of stress amplitude. The value of this overload was equal to 250MPa. We can conclude that the effect of the overload is detrimental to composite life, due the generation of incremental damage in the fiber-resin system. This effect cannot be neglected.

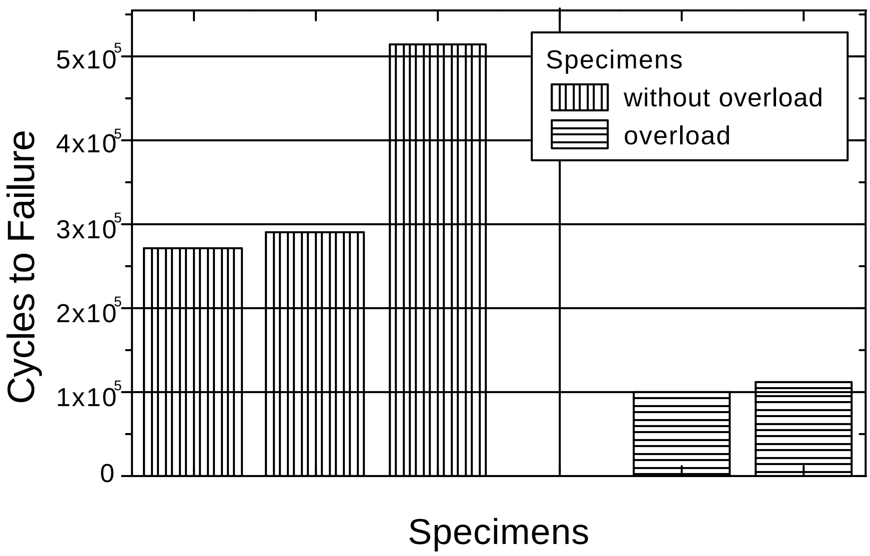

Figure 5: Effect of overload stress in the fatigue life.

Damage by fatigue is measured by two different forms : residual strength obtained from tensile tests, and continuous measure of deformation of the composite material from fatigue tests. A residual strength curve was obtained in tensile tests, with specimens cycled at stress ratio R of 0.3, frequency of 30Hz, stress amplitude of 125MPa and three different life fraction at this amplitude: 5%, 20% and 50%. Figure 6 shows this curve.

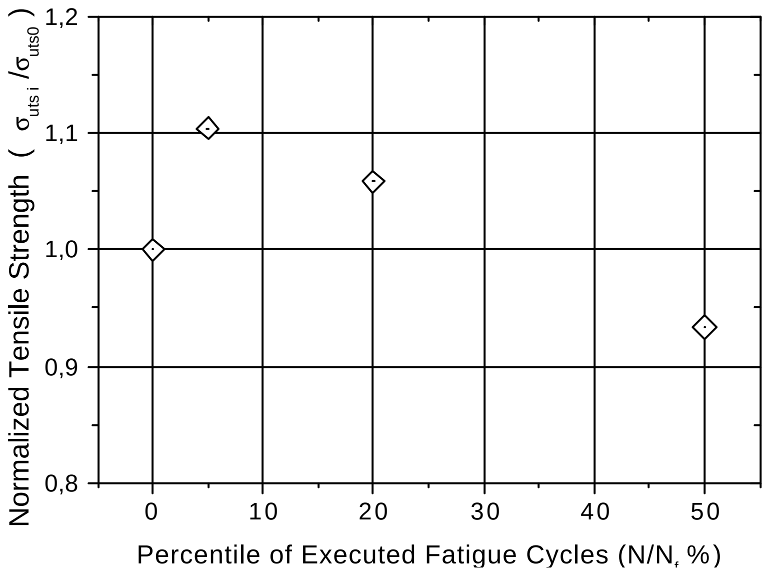

Figure 6: Residual strength results.

Tensile strength increases to a peak, then decreases with number of cycles. This technique is dangerous, because we can admit an erroneous conclusion that fatigue damage is good to the composite until the peak. In composite materials the initial evolution of fatigue damage promotes a stress redistribution in the fiber-resin system that dissipates energy. Consequently, tensile strength increases until a maximal damage concentration, that is enough to promote its further decrease. This result is observed by other authors [18-20]. We conclude that this method is not a good procedure to estimate fatigue damage.

In a load-controlled test, stroke response versus cycles will help understand the evolution of constitutive behavior during fatigue cycles. Figure 7 shows a typical plot of the displacement versus percentage fatigue life (both normalized) for three specimens tested on fatigue. The plot shows that displacement increases with cycling with a large CDS region. This observation is a good result that can be used to follow the fatigue damage progress. This result is observed also by other author [2].

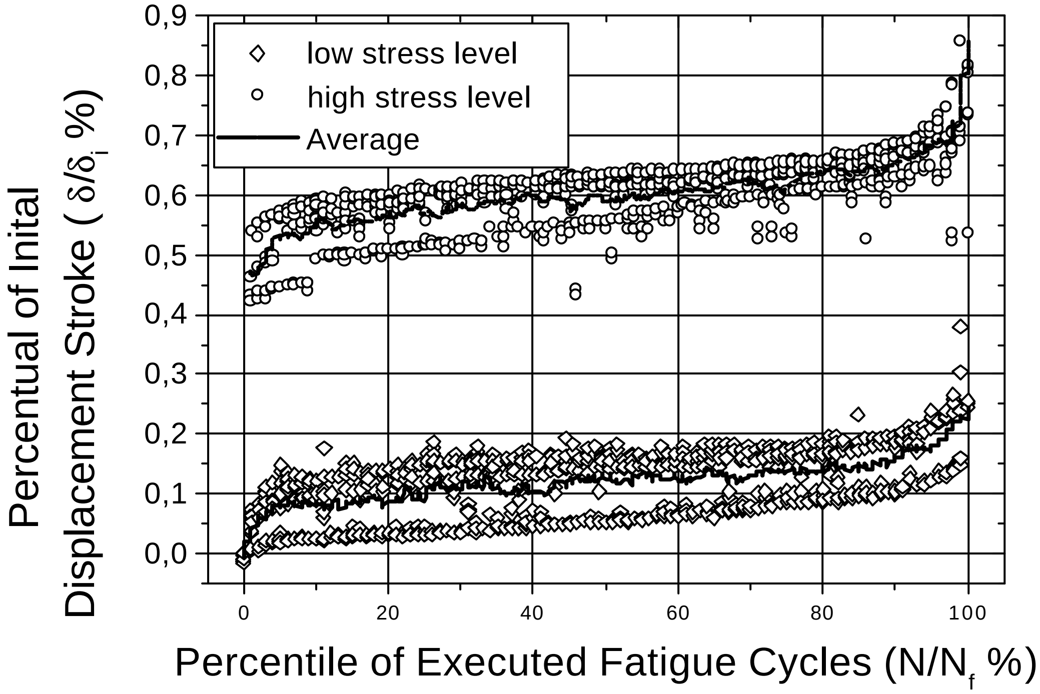

Figure 7: Stroke (%) versus fatigue cycles (%).

CONCLUSIONS

The fatigue life was found to decrease with increasing cyclic stress level. A power-law relationship of the form $_{a}$ = $_{uts}$ $(2N_f)^b$ was found to exist. The effect of R – maintaining constant the high stress level ($_{max}$) – was to decrease the fatigue life with the decrease of R (or increasing the $_{a}$). The frequency dependence was not obvious, but there are indications that decreasing the frequency decreases also the fatigue life. The application of an overload decreases the overall fatigue life of the composite. A way to accompany the fatigue life is to measure the apparent rigidity of the material by recording the lower and higher stroke (displacement) during the test.

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