The effect of tension-tension fatigue and lay-up configuration on damage accumulation in carbon/epoxy composites.

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ABSTRACT

The effect of tension-tension fatigue (T-T) on carbon/epoxy composites (CFC) has been investigated in this paper. Load controlled fatigue tests were conducted in the tension-tension (T-T) cyclic mode with the R-ratio values of 0.1 and 0.3 and subsequently the specimens with the fatigue life over 10^6 cycles have been studied by means of tensile testing, ultrasonic inspection and quantitative data of the internal damage accumulation. Different damage mechanisms under cyclic loading are expected for the chosen lay-up configurations and are reported herein.

1. INTRODUCTION

Different fatigue models have been established for the life time prediction of CFC. The first fatigue life models extract information from the S-N curves or Goodman-type diagrams and propose a fatigue failure criterion. This model does not take into account damage accumulation [1]. One of the first fatigue failure criterions was proposed by Hashin and Rotem [2]. Phenomenological models were established to predict residual stiffness and strength; meaning that the failure occurs when the applied stress equals the residual strength [3, 4]. A comprehensive review paper on the fatigue damage in composite laminates has been published by Saunders and Clark [5]. In order to predict damage growth of CFC, the progressive damage models have to be used, that are based on actual damage mechanisms [1, 6]. Additionally non-destructive techniques for monitoring the integrity of CFC, ultrasonic testing of fully cured composites and acoustic emission (AE), have been reported [7, 8 and 9]. The present work reflects a number of further references and the occurrence of the different mechanisms will be shown.

2. EXPERIMENTAL

Two different lay-up configurations of thickness 3 mm were investigated. Specimens were water jet cut from panels to a final coupon geometry dimension of 20 × 200 mm. Static tensile tests were with a cross-head speed of 0.5 mm/min at 23°C, obtaining the values of the elastic modulus, ultimate tensile strength (UTS) and failure strain. Fatigue tests were undertaken on two different lay-up designs of CFC, a symmetric [0°/90°] and a [+30°/-30°/0°/90°]s arrangement. Each lay-up design should give another type of damage mechanism when tested under cyclic loading. Tensional loading induces transverse matrix cracking in the [0°/90°]s configuration. The presence of these cracks causes larger stresses in the 0° direction due to stress concentrations. The stress concentrations and larger stresses lead to the laminate failing in the 0° direction at a lower load than it would occur if the 90° layers were not present. [+30°/-30°/0°/90°]s lay-ups are known to delaminate at low tensile strains. The fatigue T-T tests were carried out under a load control mode at a frequency of 10 Hz to minimize the inner heating of CFC and R ratio of 0.1 and 0.3. Load levels of 90%, 80%, 70% and 60% of UTS (ultimate tensile strength) were used for this fatigue study. Fatigue tests were stopped at 10^6 cycles. After the fatigue tests, the pulse-echo ultrasonic measurements were performed using a 10 MHz focused transducer. The ND technique of ultrasonic Cscan analyses was used to define the level of damage due to using the so called "damage factor", the quotient of the area mean value of the rear wall echo amplitude after and before the fatigue tests. Higher values of the so called "damage factor" means higher damage accumulation after cyclic testing. ND tests were performed for samples with a fatigue life of more than 10^6 cycles. The residual strengths and fatigue modulus were determined subsequently for the samples that survived 10^6 cycles. Fatigue life models based on information from the S-N curves, phenomenological models of residual stiffness and strength and partially progressive damage models have been used to predict damage growth of CFC.

3. EXPERIMENTAL RESULTS

3.1 Static tensile tests

Results from the quasi-static tensile test are presented in Table 1.

Tensile properties of CFC				
Lay-up design	Modulus [GPa]	Max. force [N]	UTS [N/mm2]	Failure strain [%]
[0°/90°]s	129	54812	1284	0.028
[+30°/-30°/0°/90°]s	42	19421	454	0.038

Table 1: Tensile properties of [0°/90°]s and [+30°/-30°/0°/90°]s specimen

3.2 Tension – tension fatigue testing

Fatigue tests were stopped at 10^6 cycles or at final rupture. The SN data obtained from the cyclic loading are presented in Tables 2 and 3.

Fatigue properties of [0°/90°]s CFC				
Stress ratio R	σ [N/mm2]	Stress level	F_{max} [N]	Cycles number
0.1	1156	90 %	49330	2259
0.3	1156	90 %	49330	31867
0.1	1027	80 %	43850	$>10^6$
0.3	1027	80 %	43850	$>10^6$
0.1	899	70 %	38368	$>10^6$
0.3	899	70 %	38368	$>10^6$
0.1	770	60 %	32887	$>10^6$
0.3	770	60 %	32887	$>10^6$

Table 2: Fatigue properties of [0°/90°]s CFC

Fatigue properties of [+30°/-30°/0°/90°]s CFC				
Stress ratio R	σ [N/mm2]	Stress level	F_{max} [N]	Cycles number
0.1	409	90 %	17478	576948
0.3	409	90 %	17478	$>10^6$
0.1	363	80 %	15537	$>10^6$
0.3	363	80 %	15537	$>10^6$
0.1	318	70 %	13595	$>10^6$
0.3	318	70 %	13595	$>10^6$
0.1	272	60 %	11650	$>10^6$
0.3	272	60 %	11650	$>10^6$

Table 3: Fatigue properties of [+30°/-30°/0°/90°]s CFC

[0°/90°]s specimens survived 10^6 cycles when they were loaded at 80% of UTS for both R=0.1 and R=0.3. Different R-ratio values were set up by different mean-stress values and minimum load while maximum load was the same for R=0.1 and R=0.3. Specimens with lay-up design [+30°/-30°/0°/90°]s presented the highest resistance to fatigue loading, specimen survived 10^6 fatigue cycles for the load level of 90% of UTS and R=0.3. Generally specimens with fatigue life less than 10^6 cycles showed that increase of R ratio causes increase of fatigue life of CFCs.

3.3 Loss of stiffness and strength degradation

Static tensile tests for the samples with the fatigue life over 10^6 fatigue cycles are presented in figures 1, 2, 3 and 4.

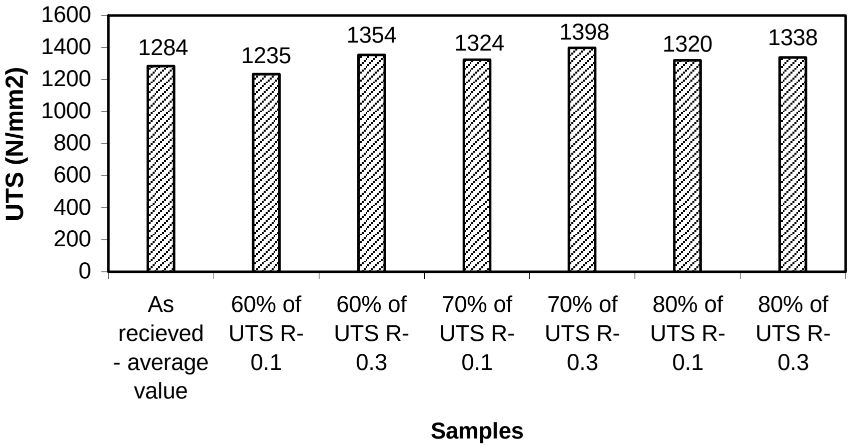

Figure 1: Residual strength values of [0°/90°]s samples as received and after cyclic testing

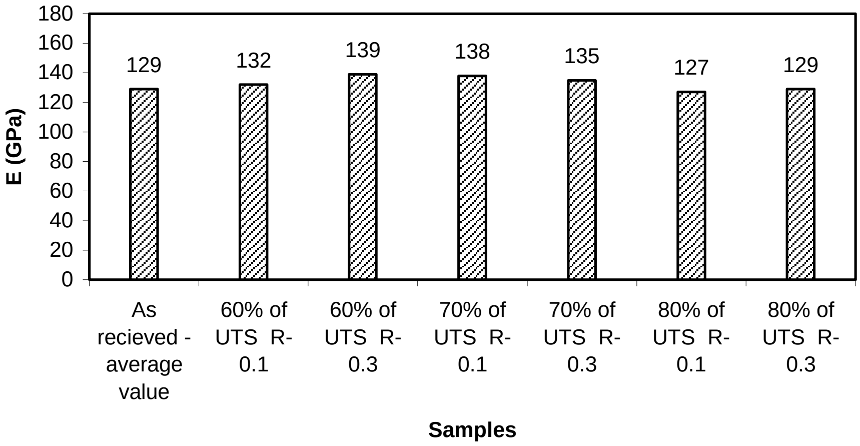

Figure 2: Elastic modulus values of [0°/90°]s samples as received and after cyclic testing

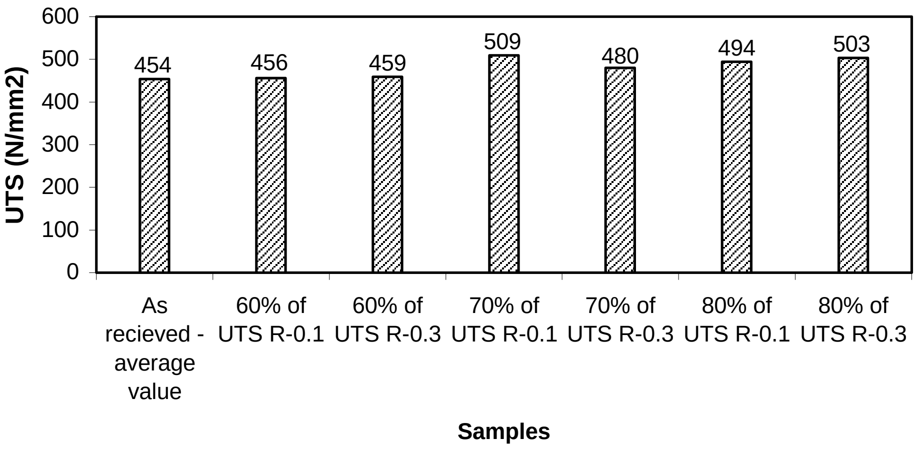

Figure 3: Residual strength values of [+30°/-30°/0°/90°]s samples as received and after cyclic testing

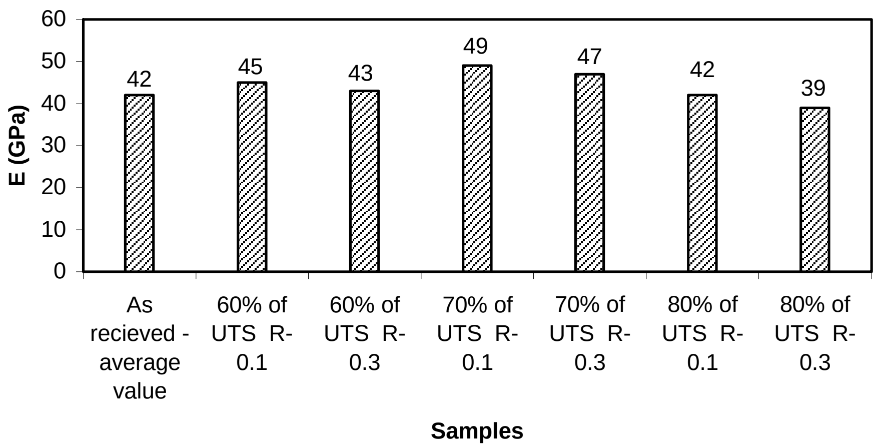

Figure 4: Elastic modulus values of [+30°/-30°/0°/90°]s samples as received and after cyclic testing

It is observed that the stress-strain relation of the specimens with the fatigue life over 10^6 fatigue cycles is linear at lower and higher strains, and no explicit yield points were presented on the stress-strain curves. When compared to the as received state, residual strength and modulus values after T-T are nearly constant or show a slight increase. This behaviour can be described by Chou and Croman sudden death model [4] for residual strength. The residual strength as a function of number of cycles is initially nearly constant and decreases dramatically when the number of cycles to failure is being reached. The sudden death model is especially used for high-strength composites and higher level state of stress. Nearly constant or higher values of residual strength of [0°/90°]s and [+30°/-30°/0°/90°]s specimens, can be explained by Rotem [10] residual strength model. For T-T, Rotem stated that the initial static strength is maintained almost up to final failure by fatigue. He defined an imaginary strength in the first loading cycle, which has a higher value than the static strength. As long as the degradation of the residual strength is situated in the region between the imaginary strength and actual strength, there is no apparent degradation of the strength. In addition, Caprino [11] presented that the experimentally measured residual strength of CFC after tension-tension fatigue does not follow the residual strength law of flexural fatigue, showing that the residual strength undergoes a continuous decay.

3.4 Ultrasonic

The samples with fatigue life over 10^6 cycles have been subjected to a non-destructive ultrasonic inspection. The quantitative determination of the damage was investigated by the mean of analyzing the C-scans of the back wall echo. The histograms were used as basis for the evaluation of the so called "damage factor". The damage factor was defined as the quotient of area averaged mean value of the amplitude after and before the fatigue tests.

$$D = \frac{p_{average,after}}{p_{average,before}}$$

The damage factor was calculated for each tested sample and plotted against the load value. Figures 3 and 4 show the "damage factor" as a function of load and R-ratio for a two different configurations of CFCs. Samples with final failure after fatigue testing reached a damage factor of 1 and the total number of life cycles is shown in the figures.

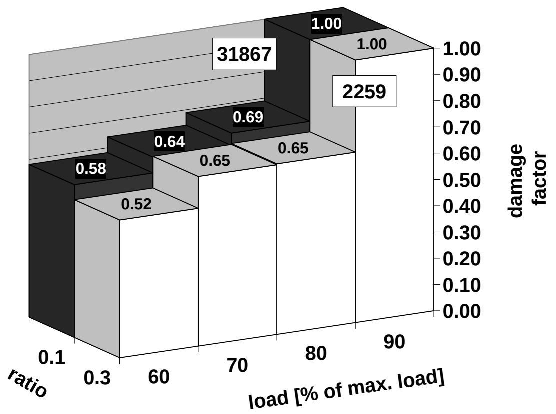

Figure 5: Damage factor of [0°/90°]s CFC as function of the load and stress ratio

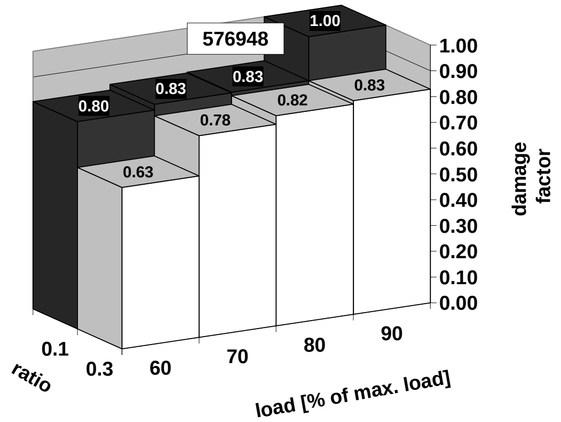

Figure 6: Damage factor of [+30°/-30°/0°/90°]s CFC as function of the load and stress ratio

Damage factor increased continuously with increased load and decreased stress ratio for lay-up configuration [0°/90°]s and [+30°/-30°/0°/90°]s. Higher initial value of damage factor was already observed for the load level of 60% of UTS in [+30°/-30°/0°/90°]s configuration with R-ratio 0.1. Initial damage factor of [0°/90°]s CFC was lower in comparison to [+30°/-30°/0°/90°]s configuration and only slight differences were presented for different R-ratio values even if the SN data showed positive influence of increased R-ratio. It could be explained by higher sensitivity of ultrasonic e-scan analyses to increasing amount of matrix micro-cracks in [0°/90°]s and [+30°/-30°/0°/90°]s configurations. Also other coexisting damage mechanisms controlling the fatigue life can affect the fatigue life of these configurations.

4. CONCLUSIONS

An increase of the R ratio caused an increase of fatigue life of CFC. A damage factor calculation from data obtained after ultrasonic testing proved that higher R ratio values caused lower damage accumulation for all tested specimen designs and give a good quantitative overview on real damage accumulation. Applied failure criterion of residual stiffness and strength data can not effectively describe the damage accumulation, no evident changes were observed in the as-received and tested states. This behaviour can be described by Chou and Croman sudden death model [4] for residual strength. The residual strength as a function of number of cycles is initially nearly constant and decreases dramatically when the number of cycles to failure is reached. The sudden death model is especially used for high-strength composites and higher level state of stress. Nearly constant or higher values of residual strength of [0°/90°]s and [+30°/-30°/0°/90°]s specimens, can be explained by Rotem [10] residual strength model. For T-T, Rotem stated that the initial static strength is maintained almost up to final failure by fatigue. He defined an imaginary strength in the first loading cycle, which has a higher value than the static strength. As long as the degradation of the residual strength is situated in the region between the imaginary strength and actual strength, there is no apparent degradation of the strength. In addition, Caprino [11] presented that the experimentally measured residual strength of CFC after tension-tension fatigue does not follow the residual strength law of flexural fatigue, showing that the residual strength undergoes a continuous decay. Quantitative and qualitative progressive damage models are important source of damage accumulation and residual life prediction.

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