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Fatigue behaviour study on repaired aramid fiber/epoxy composites

Abstract: *Aramid fiber reinforced polymer composites have been used in a wide variety of applications, such as aerospace, marine, sporting equipment and in the defense sector, due to their outstanding properties at low density. The most widely adopted procedure to investigate the repair of composites has been by repairing damages simulated in composite specimens. This work presents the structural repair influence on tensile and fatigue properties of a typical aramid fiber/epoxy composite used in the aerospace industry. According to this work, the aramid/epoxy composites with and without repair present tensile strength values of 618 and 680MPa, respectively, and tensile modulus of 26.5 and 30.1 GPa, respectively. Therefore, the fatigue results show that in loads higher than 170 MPa, both composites present a low life cycle (lower than 200,000 cycles) and the repaired aramid/epoxy composite presented low fatigue resistance in low and high cycle when compared with non-repaired composite. With these results, it is possible to observe a decrease of the measured mechanical properties of the repaired composites.*

Keywords: *Fatigue behavior, Aramid/epoxy composite, Structural composites, Mechanical behavior.*

INTRODUCTION

In recent years, fiber-reinforced composites have gained much attention due to their use in aerospace, marine, automobile, medical and other engineering industries. Among thermoset polymers, epoxy resins are the most common matrices for high performance aramid-fiber composites due to their easy processing conditions (Botelho et al., 2002; Botelho et al., 2003; Botelho et al., 2005a; ABARIS, 1998; Cerny et al., 2000).

The continuous use of structural polymer composites in the aeronautical industry has required the development of repairing techniques of damages found in different types of composites. The first step of a repair procedure is to determine the extent of the damage sustained by the structure. One must always assume that the actual damage can be more extensive than the visible damage. This is especially true for aramid fiber-reinforced composites made with brittle standard cured epoxy resins (177°C cured epoxy matrix resins). After an impact with a foreign object, there is generally, but not invariably, some visual indication in the form of paint damage. However, due to the elasticity of high modulus fibers, the composite often springs back, leaving residual subsurface damage in the form of broken fibers, ply splitting and, in the case of sandwich panels, crushed core and disbonded face sheets

(Ashcroft et al., 2001; Kawai et al., 2001; Roudet et al., 2002; Gregory et al., 2005; Botelho et al., 2005b).

A similar fatigue damage tolerance mechanism may maintain the inherent properties of the repaired aramid fiber/epoxy composites when compared with non-repaired aramid composite. Fatigue damage results in a change of strength, stiffness and other mechanical properties of composite material. Damage phenomena under various loading conditions are significantly different for polymeric composites. Damages can occur by: crack formation due to fiber breakage, matrix crack propagation, fiber-matrix debonds, void growth and delamination. Any one or a combination of these mechanisms may lead to a reduction of the overall modulus and strength. Therefore, fatigue failure is a progressive process during which the overall modulus and strength decrease progressively until their values cannot longer resist the applied loading and hence total failure occurs (Botelho et al., 2005a; Ashcroft et al., 2001; Kawai et al., 2001; Roudet et al., 2002; Gregory et al., 2005).

In many fatigue studies, the fatigue performance of materials is analyzed by investigating the relationship between the fatigue load, either applied stresses or applied strain, and the fatigue life (or number of cycles to failure). The applied fatigue stress can be expressed as the maximum fatigue stress. This normalized applied stress is the ratio of the maximum fatigue stress to the

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ultimate quasi static stress or strength of the composite. The normalized applied stress is often used to compare two or more materials with different values of ultimate tensile stress (Ashcroft et al., 2001; Kawai et al., 2001; Roudet et al., 2002; Gregory et al., 2005).

The objective of the present study is to evaluate the effects of the fatigue behavior on repaired aramid fiber/epoxy composites. Mechanical tests were performed in order to verify possible degradation on static mechanical properties, before the specimens undergo fatigue experiments. The stress as a function of the number of fatigue cycles (S-N curve) is then obtained. Also, the specimens were analyzed by microscopic techniques before and after the mechanical experiments.

MATERIALS AND EXPERIMENTAL PROCEDURE

Aramid fiber fabric/epoxy (AF/E) prepreg was used for the composite preparation. In this work plain weave fabric style was used (each fiber cable presented 3,000 monofilament). The composite was prepared by using an autoclave system. The fiber content in each composite was of approximately 60% (v/v). The epoxy resin used has the number F584 as specification, manufactured by Hexcel Company and it is a structural resin with a cure temperature of up to 181°C and glass transition temperature of 154°C (ABARIS, 1998).

The composites were cured in autoclave, under a pressure of 0.69 MPa and vacuum of 0.08 MPa, following a heating cycle of up to 181°C. The aramid fiber/epoxy composites obtained were divided into two batches. The first batch of these composites was used as a reference material. The second batch of the continuous fiber/epoxy laminates was cut and machined. Figure 1 shows this process, where the cut used to simulate the removing of the damaged part of the specimens (20 mm x 200 mm) can be observed. After this procedure, the same aramid fiber/epoxy prepregs, used in the original laminate preparation, are carefully stacked in the damaged region using the scarf technique (ABARIS, 1998) in order to repair the laminate.

The cross section micrographs of the studied composites were obtained by optical microscopy (OM) in order to evaluate how homogeneous was the lamination and to examine in detail the specimen after the mechanical tests. The morphological evaluation was performed using a Nikon Epiphot 200 equipment. Measurements of tensile properties of aramid fiber fabric composites with and without repair were performed under ASTM standard D3039-93 normative (ASTM, 1985a). The tensile tests were carried out in an Instron machine 8801. The extensometer device was attached to the specimen to measure displacements in longitudinal direction. Fatigue

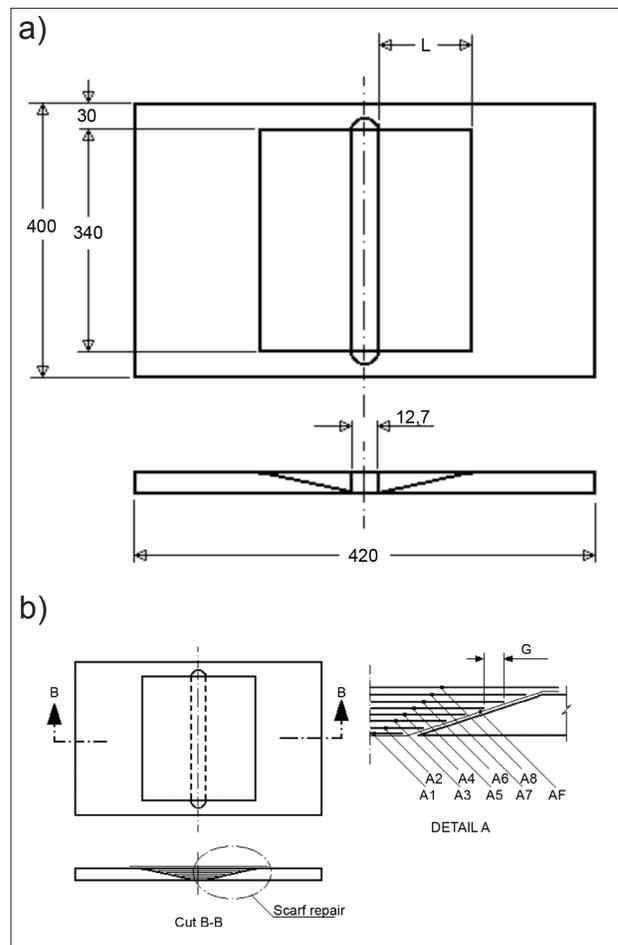


Figure 1: Details of the cut and machined area of the laminate used to simulate a damage to be repaired (a) and scheme of the scarf repair used (b).

tests were performed using a servo-hydraulic machine (25 kN) at constant load amplitude. Fatigue tests were carried out according to ASTM 3479 (ASTM, 1985b) and the stress ratios, S_{max} ($\sigma_{min}/\sigma_{max}$) was 0.1, where σ_{max} and σ_{min} are the maximum and the minimum applied stresses, respectively, and σ_{ult} is the ultimate strength of the composites. The fatigue frequency was 10 Hz. Glass fiber/epoxy end tabs with a length of 40 mm were attached at both ends of the specimens to avoid failure around the gripping device during the tests. The specimens were cycled up to 1,000,000 and in this work the same fatigue tensile value in both laminates were used and the fatigue life was measured.

RESULTS AND DISCUSSION

Figure 2 depicts a representative optical microscopy of the repaired aramid fiber/epoxy cross-sections showing the repaired area performed in this composite. The repairing technique used induces small resin rich regions in the

composite. Tensile and fatigue tests were conducted in order to evaluate this possible decrease in the mechanical properties.

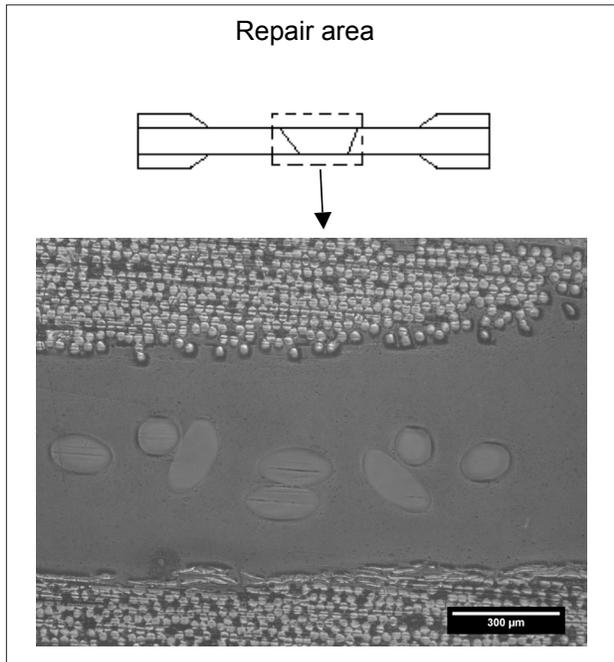


Figure 2: Optical microscopy of the repaired area of aramid fiber/epoxy composite.

Table 1 presents the experimental tensile properties for non-repaired and repaired aramid fiber/epoxy composites. The tensile properties of non-repaired aramid fiber/epoxy composites showed good agreement (6% mismatch) with the results available in the literature, around 720 MPa for non-repaired and 660 MPa for repaired specimens (Botelho et al., 2005a; ABARIS, 1998a; Cerny et al., 2000; Ganczakowski and Beaumont, 1989). The differences between experimental and literature results are expected for polymer composites since the interface effect or void presence can be induced during different processing conditions (Ganczakowski and Beaumont, 1989).

Table 1: Tensile properties for the specimens studied.

Material	Non-repaired composite	Repaired composite
Tensile stress (MPa)	680±37	618±32
Tensile strain (%)	1.37±0.09	1.34±0.07
Elastic Modulus (GPa)	30.1±1.1	26.5±2.1

According to the results presented in Table 1, repaired composites present a decrease of around 10% on tensile stress when compared with non-repaired composites,

due to the heterogeneity of the resin and discontinuity of the reinforcement on the repaired area. Hence, by using this repair technique, it is possible to reconstitute up to 90% of the original properties of the aramid fiber/epoxy composite. In spite of such tensile stress reduction, it is observed, in this work, that the ultimate tensile strain value is almost the same for both non-repaired and repaired specimens (~3% mismatch). Additionally, a decrease of ~12% in the tensile modulus values is observed in non-repaired specimens, confirming the results obtained by ultimate tensile stress.

Figure 3 presents the S-N fatigue curves for repaired and non-repaired aramid fiber/epoxy composites. In this experiment, it should be mentioned that in all specimens

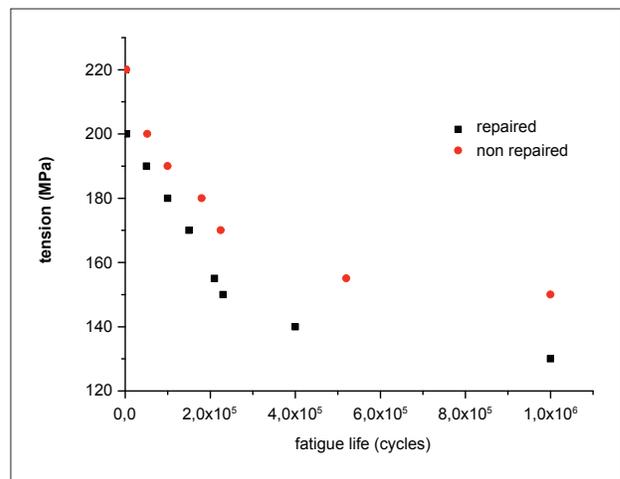


Figure 3: Fatigue performance of non-repaired and repaired aramid fiber/epoxy composites.

plain weave textile was used, therefore, in 0° and 90° the load will be almost the same.

By means of Figure 3, it can be observed that in both cases, at low and high number of cycles (using the same frequency value), the repaired aramid fiber/epoxy composites show a decrease in the fatigue life values, by around 10% (low cycle) and 18% (high cycle), when compared with non-repaired composites. At a low number of cycles (lower than 200,000.00 cycles), the non-repaired composite reached fatigue resistance values between 170 and 220 MPa and for the repaired composites these values were between 160 to 205 MPa. For a high number of cycles, (higher than 200,000.00 cycles) these values are lower when compared with those found in low cycles, with 150 to 170 MPa for the non-repaired aramid fiber/epoxy composites and 130 to 150 MPa for the repaired composites. According to Figure 3 both composites present a similar behavior.

According to the results presented in Figure 4, it is observed that when fatigue tests are performed at high and low number of cycles, the repaired specimens can be affected by void rich regions created during repair. These voids are responsible for delaminations but, due to the low loads, the composite did not present catastrophic fracture but can most likely be affected by debonding (ABARIS,1998). The debonding occurred randomly in the specimen before the rupture, but parallel to the fatigue loading direction (ABARIS,1998; Ganczakowski and Beaumont,1989). When this kind of debonding propagation occurs, fatigue damage can be concentrated in one particular region of the specimen. As a consequence, that region will become weaker and critical.

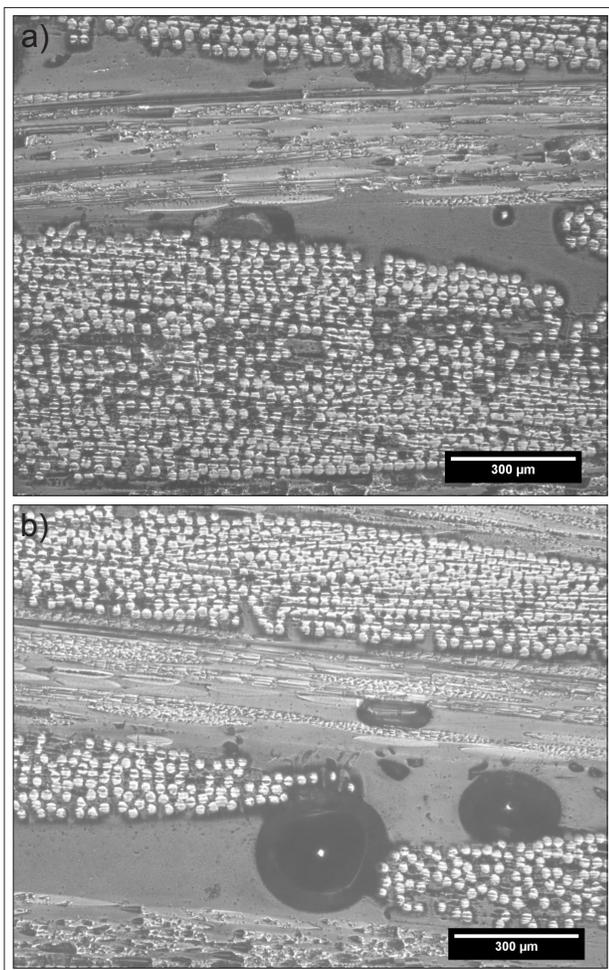


Figure 4: Optical microscopy of aramid fiber/epoxy composites after high cycle fatigue test: a) non-repaired; b) repaired

CONCLUSION

Aramid fiber/epoxy repaired composites presented void rich regions in the repaired area, creating delaminations, when assessed under fatigue at high and low number

of fatigue cycles. Debonding can occur randomly in the specimen, but mainly parallel to the fatigue loading direction. As a consequence, the debonded regions became weaker and critical.

The results in this study demonstrate that the repaired aramid fiber/epoxy composites show a decrease in the fatigue resistance values, of approximately 10% (low cycle) and 18% (high cycle), when compared with the non-repaired. Thus, this repair process can be used in aerospace applications. These results can be associated to the good morphological aspects (good interface and no voids and cracks) and the mechanical behavior when both laminates composites are compared, which shows that a decrease of 12.1% in the tensile modulus values is observed in non-repaired specimens, corroborating the results obtained by fatigue tests.

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