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Evaluation of fatigue behavior on repaired carbon fiber/epoxy composites

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Abstract The continuous use of structural polymer composites in aeronautical industry has required the development of repairing techniques of damages found in different types of laminates. The most usually adopted procedure to investigate the repair of composite laminates has been by repairing damages simulated in laminated composite specimens. This work shows the influence of structural repair technique on mechanical properties of a typical carbon fiber/epoxy laminate used in aerospace industry. When analyzed by tensile test, the laminates with and without repair present tensile strength values of 670 and 892 MPa, respectively, and tensile modulus of 53.0 and 67.2 GPa, respectively. By this result, it is possible to observe a decrease of the measured mechanical properties of the repaired composites. When submitted to fatigue test, it is observed that in loads higher than 250 MPa, this laminate presents a low life cycle (lower than 400,000 cycles). The fatigue performance of both laminates is comparable, but the non-repaired laminate presented higher tensile and fatigue resistance when compared with the repaired laminate.

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Introduction

Advanced composites composed of high-strength, high-modulus and low-density continuous fibers embedded in polymer matrices became available some 40 years ago. Since then, composite aircraft structures have transitioned from laboratory curiosities into low-risk and light-weight alternatives for metal structures. Thousands of safety-of-flight composite components are flying in regular service on military and civil aircraft [1–4].

Major advantages of high-performance composite structures include weight savings, material tailorability, improved fatigue, and corrosion resistance. Inside this concept, carbon fiber/epoxy composite materials are being more widely used in many applications. With the increase of applications of polymeric composites, more and more knowledge is needed to get a better understanding of the bonding of these materials, which can lead to different mechanical properties of them [5–9].

Disadvantages are primarily cost related. To the manufacturer, weight reductions, structural requirements, manufacturability, and production costs have long been obvious priorities. Only recently, however, and only as a consequence of persistent user demands, have maintainability and reparability been added to this list. However, the maintenance problems associated with composites cannot be underestimated and may well be regarded as the weak link in the new technology chain [10–13].

The continuous use of structural polymer composites in aeronautical industry has required the development of repairing techniques of damages found in different types of laminates. Prior to any repair action, it is important 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 carbon fiber-reinforced composites with non-toughened 177 °C cured matrix resins. After an impact with a foreign object, there is generally, but not invariably, some visual indication in the form of damage of paint. However, because of the elasticity of high-modulus fibers, the laminate often springs back, leaving residual subsurface damage in the form of broken fibers, ply separations and, in the case of sandwich panels, crushed core and disbanded face sheets [14–17].

In service, composite structures are often subjected not only to static and impact loads but also to fatigue loads. This way, it is necessary to know the performance of repaired composites on fatigue loads to qualify this laminate to be used in structural applications [18, 19].

Fatigue loading creates fatigue damage, which in turn decreases the in-plane mechanical properties of the composite material (strength and stiffness). Under fatigue loads, metals exhibit one failure mode, namely a nucleation and then the propagation of one dominant crack, until the failure occurs. On the other hand, fatigue failure mode of composites consists of many modes including matrix cracking, fiber breakage, fiber-matrix debonds, void growth, and delamination. Any one or a combination of these mechanisms may lead to the reduction of the overall modulus and strength. Therefore, fatigue failure is a progressive process during which overall modulus and strength decrease progressively until their values can no longer resist the applied loading, and hence total failure occurs [18–22].

The objective of the present study is to evaluate the effects of the fatigue behavior on repaired carbon fiber/epoxy composites. Mechanical tests were performed to verify possible degradation on static mechanical properties, before the specimens were submitted to S-N fatigue experiments. In this work, the specimens were analyzed by microscopic techniques before and after the mechanical experiments.

Materials and experimental procedure

Composite manufacturing

Carbon fiber fabric/epoxy (CF/E) prepreg having F155 specification (Hexcel Co) was used for the composite preparation. In this work plain weave fabric style was used. The composite was prepared by using an autoclave system. The fiber content in each composite was approximately 60% (v/v). The composites were cured in autoclave, under a pressure of 0.69 MPa and vacuum of 0.083 MPa, following a heating cycle up to 181 °C. The carbon fiber/epoxy laminates obtained were divided into two batches. The first batch of these laminates was used as a reference material. The other batch was fractured by usinage operation and, so, repaired by using both the same matrix and the same manufacturing process used in the original laminate preparation.

Repair procedure

After being submitted to the curing process, one batch of the carbon 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 can be observed. After this procedure, the same carbon fiber/epoxy prepregs, used in the original laminate preparation, are carefully stacked in the damaged region (scarf technique [23]) as depicted in Fig. 2, to repair the laminate.

Processing evaluation

Carbon fiber/epoxy composites with and without repair were evaluated by SEM (scanning electron microscopy) technique by using an equipment from Zeiss Company, model 950.

Micrographs of the cross section of the studied composites were also observed by optical microscopy (OM) to evaluate how homogeneous was the lamination and to observe the specimen in detail after the mechanical tests. The morphological evaluation was performed in an Olympus BH equipment.

Ultrasound evaluation

The composite laminate consolidation quality was evaluated by ultrasonic C-Scan to detect the existence of

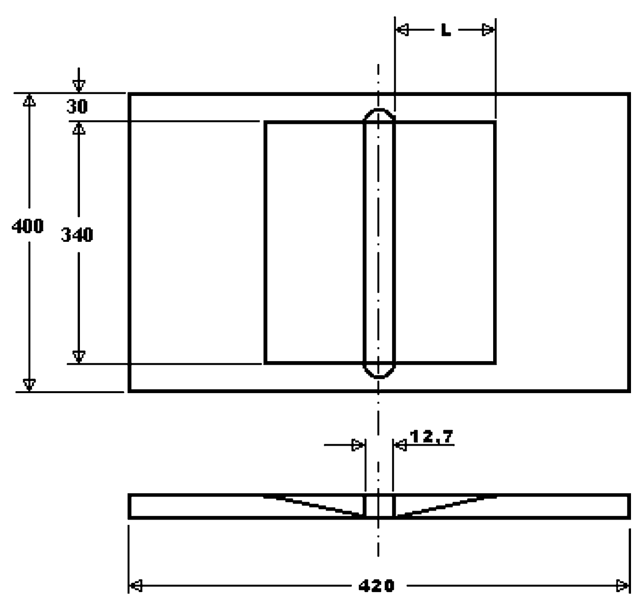

Fig. 1 Details of cut and machined area of the laminate used to simulate a damage to be repaired

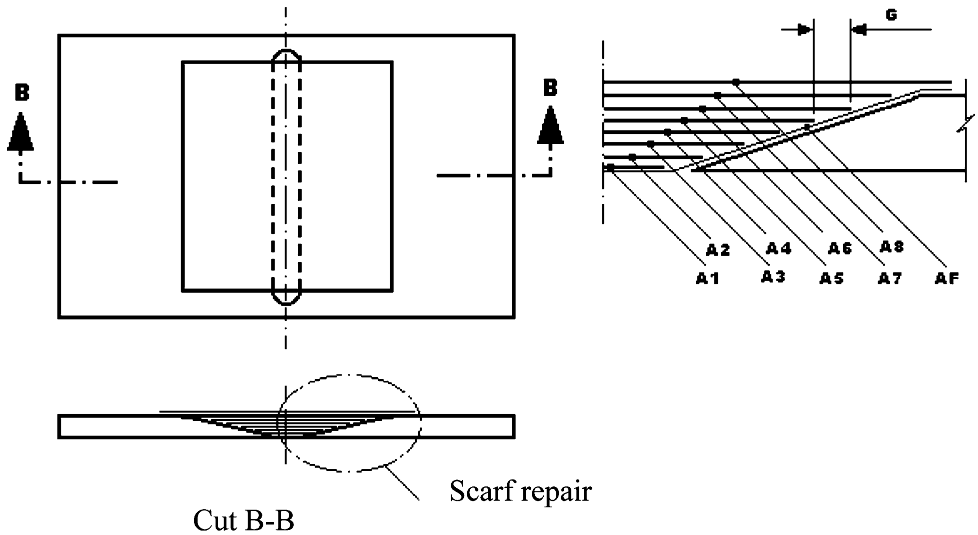

Fig. 2 Scheme of the scarf repair used

manufacture-induced defects, by using an ultrasound equipment from Staveley Instruments, Sonic Bondmaste model.

Carbon fiber content determination

The fiber and matrix contents were determined by acid digestion of the polymer matrix, according to the ASTM D 3171 normative [24]. The composite specimen was weighted and then immersed in a hot sulfuric acid solution to remove the composite epoxy matrix. Afterward, the residue (carbon reinforcement) of the composite specimen was weighted and expressed in volume fraction, according to Eq. 1:

$$\frac{m_m}{m_f} = \frac{\rho_m}{\rho_f} \times \left(\frac{1-f}{f}\right) \quad (1)$$

where, m_f and m_m are the carbon fiber and matrix weights (g), respectively, ρ_f and ρ_m are the carbon fiber and matrix densities (g/cm^3), and f is the fiber volumetric fraction (%).

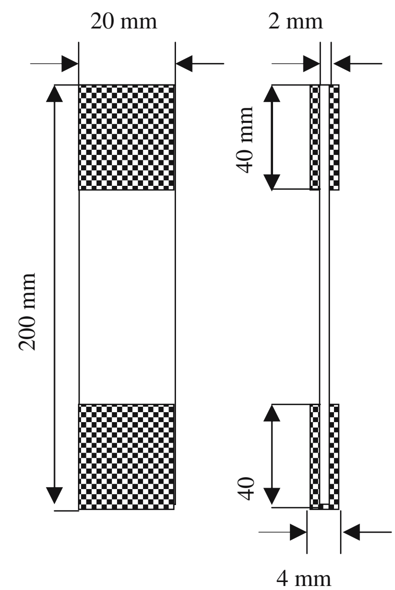

Fig. 3 Geometry and dimensions of the specimens tested in the longitudinal tensile and fatigue tests

Tensile tests

Measurements of tensile properties of carbon fiber fabric composites with and without repair were performed under ASTM standard D3039-93 normative [25]. The tensile tests were done in an Instron machine 8801. The extensometer device was attached on the specimen to measure displacements in longitudinal direction. The test speed was 1.5 mm/min. Two end tabs made of epoxy resin reinforced with glass fabric were bonded on both ends of each specimen to facilitate the gripping in the testing machine (Fig. 3).

To compare the experimental results of carbon fiber/epoxy composites in relation to the theoretical values the Fabric Geometry Model (FGM) Code was used [26]. The program allows the prediction of stiffness of composite materials having spatially oriented reinforcements, from constituent material properties, using composite micromechanics approach. The FGM Code allows the calculation of the elastic constants for the carbon fiber/epoxy composites, taking into account the fiber orientation.

Fatigue tests

Fatigue tests were performed on a hydraulic fatigue machine (25 kN) at constant load amplitude. Fatigue tests were carried out according to ASTM 3479 [23] at different maximum 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 8 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.

Results and discussion

Processing evaluation

Ultrasound C-scans of the carbon fiber/epoxy composites, with and without repair, detected regions with a low number of voids in the central part of the laminates, while more voids were found in the corners of the laminates. From this observation, the specimens were cut from the central part of the processed thermoset laminates. This result was confirmed by scanning electron microscopy (SEM) as can be observed in Fig. 4.

In Fig. 4, it is possible to observe that there is no rich area in resin neither voids nor defects inside the composite laminate. So, it can be concluded that this laminate was produced with good quality, presenting good homogeneity and adequate interface between matrix and interface.

Figure 5 presents a representative scanning electron microscopy of the repaired carbon fiber/epoxy cross sections showing the repaired area carried out in this laminate. As can be observed, the used repairing technique induces small resin-rich regions in the laminate. This area can contribute to strength reduction of composite due to the matrix to support less effort when compared with the carbon fiber reinforcement. On the other hand Fig. 5 also shows good interface between carbon fiber and epoxy resin.

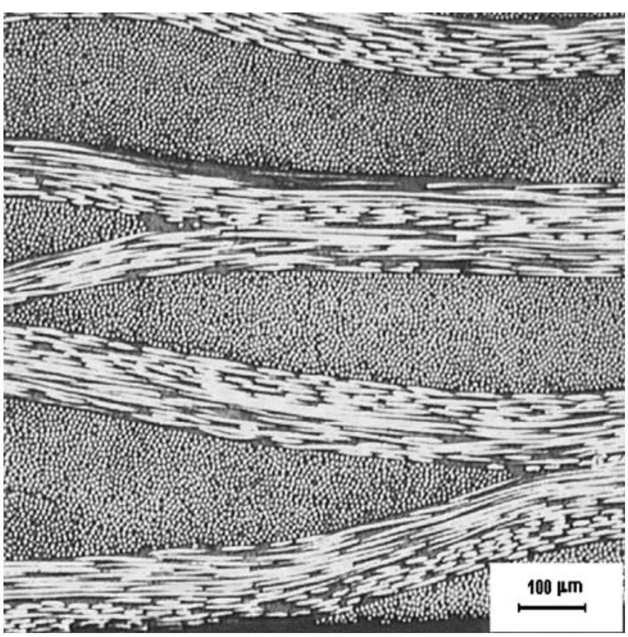

Fig. 4 SEM of a non-repaired carbon fiber/epoxy laminate

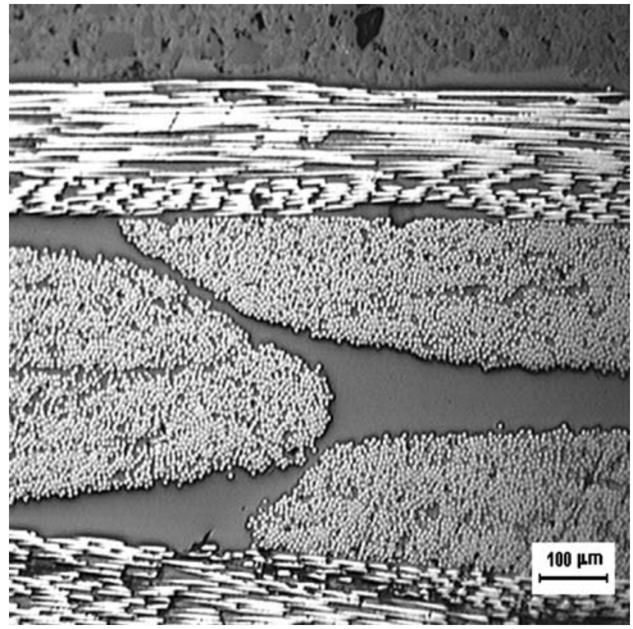

Fig. 5 SEM of repaired area of carbon fiber/epoxy laminate

Table 1 presents the volume content of carbon fiber and epoxy resin for both laminates, with and without repair. According to these results, it is possible to observe that in both cases the reinforcement contents were almost the same, approximately 60%, in volume. This result indicates that the used repair procedure does not imply adding high amount of resin, nor modifying the percentage relation between fiber and matrix. Therefore, the repair procedure generates a higher standard deviation (around 0.5) when compared with the results obtained by non-repaired specimens. The higher deviation values can be attributed to the resin-rich region observed in microscopic analyses. The results presented in Table 1 were also used to calculate the tensile theoretical values.

Tensile properties

The static tensile properties of non-repaired carbon fiber/epoxy laminates were first compared with the theoretical results. The engineering elastic constants used in FGM program are listed in Table 2 [3]. By using this Table and

Table 1 Reinforcement contents results

Laminate	Carbon fiber (%)	Epoxy (%)
Non-repaired	59.2 ± 0.2	40.8 ± 0.2
Repaired	57.4 ± 0.5	42.6 ± 0.5

Table 2 Parameters used in the FGM program and the mixture rules

Material	E_x (GPa)	E_y (GPa)	G_{12} (GPa)	v_{12}
Epoxy	5.00	5.00	1.85	0.30
Carbon fiber	220.0	220.0	22.3	0.14

Table 3 Tensile properties for the specimens studied

Material	Non-repaired laminate	Repaired laminate
Tensile stress (MPa)	892 ± 42	670 ± 38
Tensile strain (%)	0.82 ± 0.06	0.78 ± 0.03
Elastic modulus (GPa)	67.2 ± 2.1	53.0 ± 2.1

FGM program, the theoretical elastic modulus was calculated, presenting the value 71.3 GPa.

Table 3 presents the experimental tensile properties for non-repaired and repaired carbon fiber/epoxy laminates. When compared with the theoretical calculations, the experimental measurements of non-repaired carbon fiber/epoxy composites present good agreement (the difference is around 6%). Differences between experimental and theoretical calculations are expected for polymer composites since the interface effect or void presence are not considered in the approached model. Moreover, as known, the elastic modulus in composites is dominated by fibers and the interfacial adhesion effects are only marginal.

Table 3 presents a comparison between tensile properties of non-repaired and repaired carbon fiber/epoxy composites. According to these results, repaired laminates present a 23% decrease in tensile stress when compared with non-repaired laminates. This difference can be attributed to the heterogeneity of the resin and discontinuity of the reinforcement on the repaired area. According to these results, it can be concluded that by using this kind of repair technique, it is possible to reconstitute up to 80% of the original properties of the carbon fiber/epoxy laminate. In spite of this reduction of tensile stress, it is observed, in this work, that the ultimate tensile strain value is almost the same for both specimens, non-repaired and repaired (the difference is around 8%).

When the tensile modulus values are compared, it is observed that specimens that are non-repaired present a decrease of 21.2%, confirming the results obtained by ultimate tensile stress.

Figure 6 is representative of the specimens of repaired carbon fiber/epoxy composites after being submitted to tensile test. In both specimens, non-repaired and repaired, a similar morphology is observed. In this work, it is also observed that in 100% of the cases the rupture occurs in the repaired area and in all cases the pull out effect is not observed, showing a good interface between the two components carbon fiber and epoxy resin inside the

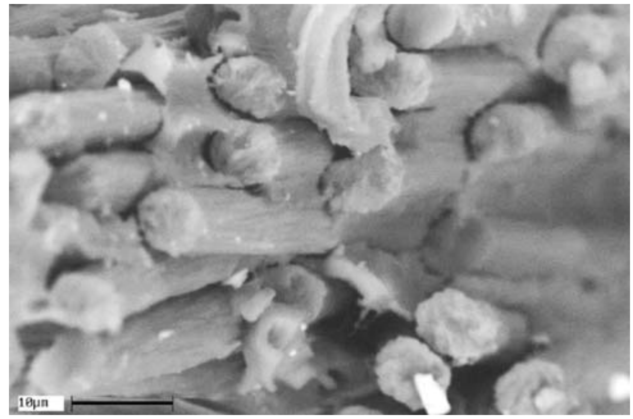

Fig. 6 SEM of repaired carbon fiber/epoxy laminate after tensile test

repaired area. It is also verified that in all specimens evaluated, the ultimate rupture occurs between the end tabs.

S-N curves

In many fatigue studies, the fatigue performance of materials is analyzed by investigating the relationship between the fatigue load (either applied stress 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 S_{max}. This normalized applied stress is the ratio of the maximum fatigue stress to the 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 stress.

Figure 7 shows a curve of the maximum fatigue stress plotted against the fatigue cycles for repaired and non-repaired carbon fiber/epoxy laminates. In this experiment,

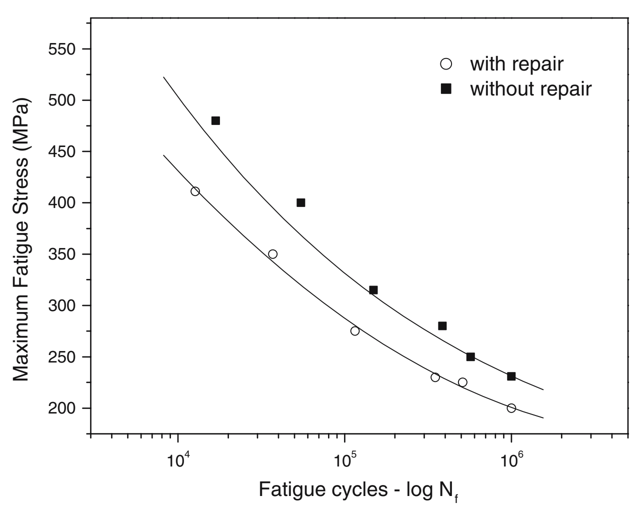

Fig. 7 Fatigue performance of non-repaired and repaired carbon fiber/epoxy laminates

it is necessary to mention that in all specimens plain weave textile was used, so in 0° and 90° the load will be almost the same.

According to Fig. 7, it can be observed that in both cases, low cycle and high cycle, the repaired carbon fiber/epoxy laminates show a decrease of the fatigue resistance values, by around 15%. This difference is constant during all cycles of material life, confirming the mechanical results presented before. In low cycle the fatigue resistance for the non-repaired laminates is between 380 and 550 MPa, and for the repaired laminates the values are in the range of 320–480 MPa. For high cycles, these values are lower when compared with the ones found in low cycles, being 250–300 MPa for the non-repaired carbon fiber/epoxy laminates and 200–220 MPa for the repaired laminates.

Figure 8 shows the comparison of the fatigue performance based on the relationship between the normalized fatigue stress and the fatigue cycles. The fatigue performance of the non-repaired composites is comparable to the fatigue performance of repaired laminates. The lowest fatigue performance is found for the repaired laminates due probably to the following factors: the repaired area and the resin-rich area inside the laminate. As the fatigue performance based on the normalized and absolute applied stress gives different results and conclusions, it is important for structural and material engineers to consider both approaches.

According to Figs. 7 and 8, it is observed that both laminates present a similar behavior.

Fatigue damage mechanisms

In this work, the fatigue damage is evaluated by optical microscopy. Therefore, the fatigue damage development in fabric composites is difficult to investigate due to the complexity of the damage. The main disadvantage of optical microscopy is that this technique is a destructive one allowing the investigation only in cut specimens and this one can be only applied to a certain damage level or number of fatigue cycles. According to the results presented in Fig. 9, it is observed that fatigue tests, when performed in high cycles, create void regions. These voids are responsible for delaminations but, due to the low loads, the laminate did not present catastrophic fracture but only debonding. The debonding occurred randomly in the specimen, but parallel to the fatigue loading direction. When this kind of debonding propagation occurs, fatigue damage can be concentrated in one particular region of the

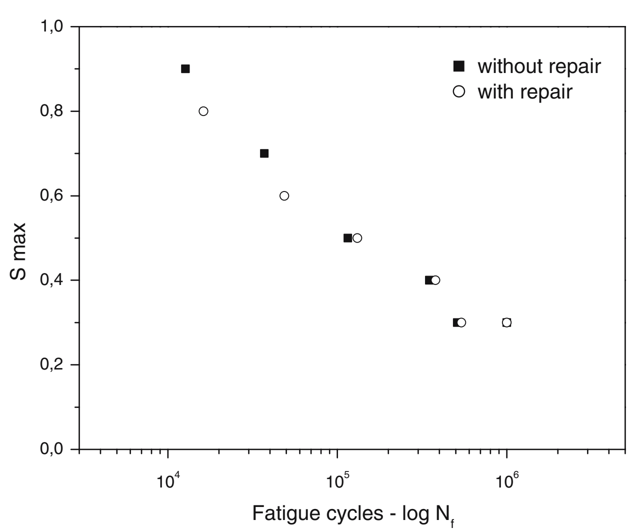

Fig. 8 Fatigue performance for normalized maximum fatigue stress in function of fatigue cycles

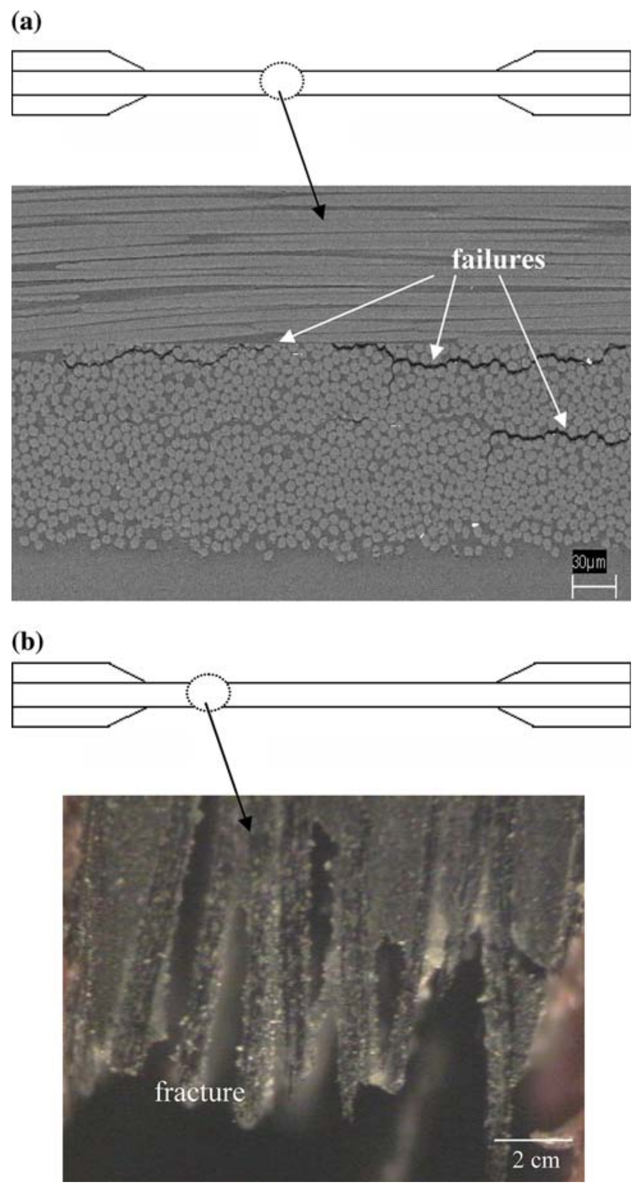

Fig. 9 Optical microscopy of repaired carbon fiber/epoxy laminates after fatigue test: (**a**) high cycle, (**b**) low cycle

specimen. As a consequence, that region will become weaker and critical. The localized fatigue damage stage, where the final failure takes place, is defined as the second or final failure stage that started at 26,300 fatigue cycles for repaired laminates and 32,400 for non-repaired laminates.

Conclusion

The tensile fatigue behavior of carbon fiber/epoxy, with and without repair, has been studied. In general the fatigue performance of both laminates is comparable, but the non-repaired laminate presented higher tensile and fatigue resistance when compared with the repaired laminate. In terms of normalized stress, the fatigue performance of the non-repaired laminates is comparable to the fatigue behavior of the repaired laminates.

The fatigue damage development in both laminates is strongly influenced by the fatigue loading direction. The fatigue damage in the laminates studied was characterized by fiber-matrix debonding in the part of the fiber bundles with a direction parallel to the applied fatigue load.

According to the results obtained in this work, it is possible to conclude that the repaired laminates can be used in aerospace applications due to the good morphological aspects (good interface and no voids and cracks) and the mechanical behavior presented, but these laminates should be used in applications that require low loads when compared with non-repaired laminates.

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