Fatigue and Failure Analysis of Sandwich Composites using Two Types of Cross-Ply Glass Fibers Laminates and Epoxy Resin

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Abstract: Sandwich structures have become effective structural elements for engineering applications due to their good design flexibility. Understanding the material behavior under static and dynamic loads, as well as the failure mechanisms of these sandwich structures, is of great importance. This work evaluates the fatigue and static bending behavior of epoxy resin specimens and sandwich composites composed of an epoxy resin core with glass fiber laminated faces. The fatigue life, failure modes, and stiffness degradation of these specimens are determined experimentally. The specimens were cycled under constant amplitude and monitored by a data acquisition system that allowed continuous data collection. Three stages of failure were identified using microscope analyses and stiffness degradation curves. In the case of an imposed displacement of 2 mm, the sandwich structures were shown to have a significantly lower fatigue life than the epoxy resin specimens.

Keywords: Sandwich composite, bending fatigue, stiffness degradation, failure modes.

1. INTRODUCTION

Sandwich structures have been the subject of much interest of various researchers and companies for the last few years. Understanding the failure characteristics of these composites under static and dynamic loads is of immense significance to structural analyses. Glass and carbon fiber reinforced polymers are commonly used as skin materials in sandwich structures in the aerospace and automobile industries. The skins are designed to withstand bending stresses in addition to resistance to the sandwich surface, while the core is designed to resist shear stresses. There are various types of materials and geometric shapes that can be used as the core in the sandwich, such as wood foam, honeycomb and corrugated structures. The solid-filled cores are more economically viable and easier to fabricate than honeycomb and corrugated cores. The skins adhere better to solid-filled cores due to the larger contact surface area that minimizes stress concentrations by uniformly distributing the loads [1]. The mechanical strength of a composite sandwich varies according to the geometric and mechanical properties of its constituents, as well as the adhesive interface.

Structural components that use composite materials fail by fatigue 90% of the time [2]. Many engineering materials exhibit a safe stress region in which failure does not occur, regardless of the number of cycles. Fiber-reinforced composites generally do not have a safe stress for fatigue, as these materials have complex damage patterns, such as fiber fractures, matrix cracks, and interlayer delamination [3-5]. Sandwich structures, when under cyclic loading, are subject to core shear failure and face yielding. The occurrence of each failure mode depends on the thickness and strength of the faces [6-8]. Andreazza *et al*. [7], using a solid core of cork agglomerate and glass fiber reinforced epoxy sheets, showed that the composites can sustain infinite cycles for maximum loading less than 45%. Polymer matrix composites do not have a crystalline structure, nor can they deform plastically. Their structure is inhomogeneous and often orthotropic. Damage in composite sandwiches is not localized but rather, is randomly distributed throughout the material. Therefore, monitoring the strength of the material during cyclic loading is very important for predicting the life of the material [9].

Another type of sandwich structure that utilizes a solid core is fiber metal laminate (FML). Although there is an improvement in mechanical properties with FMLs, it is necessary to perform a surface treatment on the metal to ensure proper adhesion between layers [10]. There are reports by some researchers that the cause

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of delamination is poor bonding between resin and metal [11,12]. In order to overcome adhesion issues, studies on the fatigue behavior of epoxy resins reinforced with fibers have become more prevalent. The inherent viscous characteristics of the resin at room temperature allow working on complex geometries with good adhesion between the parts [13-15]. Epoxy resins currently stand out among the thermosets due to their performance and high applicability, as in fiber reinforced materials [16]. Epoxy resins stand out among fiber-reinforced thermosets due to their high applicability and good performance [16]. Due to the possibility of working with different percentages and fiber orientations, these materials exhibit excellent properties, producing optimized and specific structures for different load cases [17,18].

There is a significant number of researches on fatigue in sandwich structures, and most of them are still under development. The process of initiation and propagation of cracks both in the core and in the outer layers are still poorly understood. Experimental and numerical tests need to be better studied in order to better understand the effects of damage on both macro and micro scale [18,19]. Therefore, this study intends to fill a knowledge gap by analyzing the fatigue strength of different composite sandwich structures, verifying the stages and exact instances of crack propagation, as well as determining the influence of skins on fatigue life.

2. MATERIALS AND METHODS

2.1. Manufacturing of the Specimens

In order to better understand the effect of fatigue in sandwich composites with a rigid core, three types of structures were analyzed. Specimens of sandwich composites laminated using five skins (SC5S) and three skins (SC3S) were created along with epoxy resin specimens in order to compare the mechanical properties, Figure **1**. The material used as reinforcement in the skins of the sandwich composites was glass-fiber cross-ply $[0/90]_{s,}$ (200g/m^2), supplied by Owens Corning-Brazil. The epoxy resin used as the solid-filled core in the sandwich specimens and in the homogeneous specimens was provided by Renlam M using hardener Aradur HY951 provided by Huntsman-Brazil. The table

The laminate composites to be used as the skins of the sandwich specimens were manufactured by manual lamination (hand lay-up). The epoxy resin was mixed with hardener (10:1 weight ratio) and was homogeneously distributed over each layer in order to obtain a volumetric fraction of 40% fibers. The vacuum lamination process was performed with a pressure of 75 kPa on a flat mold at room temperature, which equally distributed the resin throughout the fibers, Figure **2**. The curing process occurred at 25°C during seven days. After the curing process, some laminates were used to obtain of specimens for the mechanical tests and the other to use as faces in the construction of the sandwich composites. The sandwich composites were manufactured using molds to ensure the same overall thickness. An epoxy resin core was selected for use to ease the specimen manufacturing processes, to provide a better adhesion between the core and faces, and to make direct comparisons to a purely epoxy resin specimens. Similar technique is also present in the work of Ferreira *et al*. [20].

2.2. Static Tests

On each individual material of the composite were performed uniaxial tensile tests using a Universal Mechanical Test Machine. The specimens of laminated skins were analyzed according to ASTM standard D3039-14 using a cross-head speed of 2 mm/min, at temperature of 25ºC. The specimens of pure epoxy resin were made with molds and analyzed according to ASTM standard D638.

The standard BS EN 2562 was considered to perform the three-point bending test for the epoxy resin specimens and for the SC3S and SC5S, using the universal mechanical test machine, at the same speed used on tensile test.

2.3. Bending Fatigue Tests

The fatigue analysis of the three different specimens in this study were conducted at room

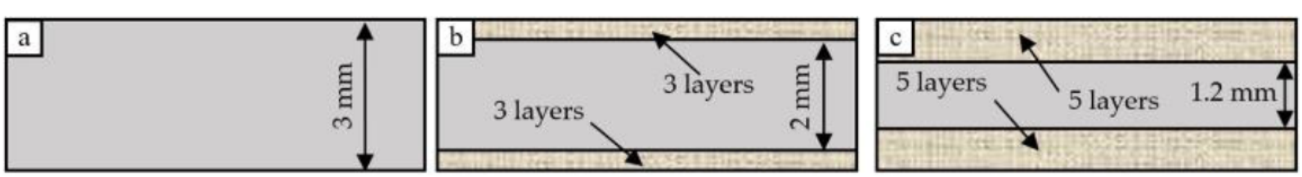

Figure 1: Schematic layout of samples: (**a**) epoxy resin; (**b**) SC3S; (**c**) SC5S.

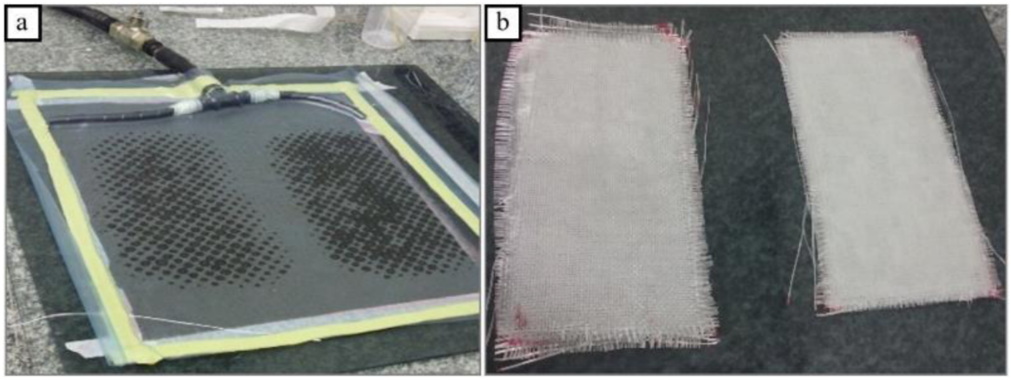

Figure 2: (**a**) Vacuum bag lamination process and (**b**) laminated glass fiber.

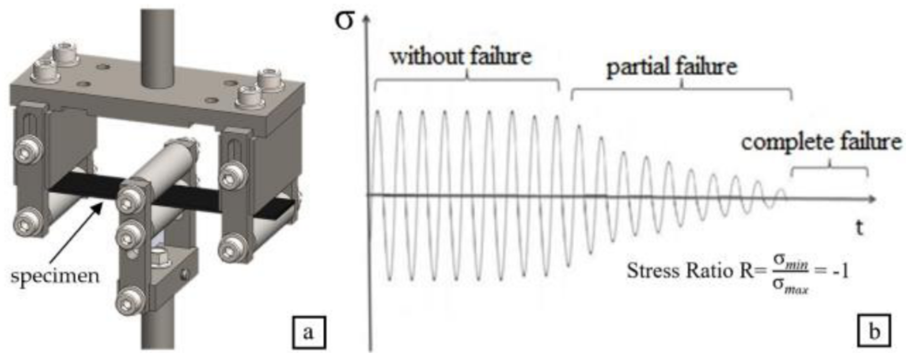

Figure 3: (**a**) Three-point fatigue machine and (**b**) expected bending fatigue behavior of the sandwich composites.

temperature, using a three-point flat bending fatigue machine, according to ASTM standard D7774-12. The mechanical scheme, shown in Figure **3a**, uses a span length of 80 mm, a frequency level of 14.25 Hz and provides a fixed stress ratio R (the ratio of the minimum stress to the maximum stress in one cycle) of -1 to fully reverse the load. The machine utilizes a displacement system control and produces a sinusoidal waveform, Figure **3b**. The specimens were tested using two different displacements, 2.0 mm and 2.6 mm. These displacements were selected after several preliminary tests to obtain the high cycle fatigue (over 1000 cycles) of the specimens. The machine was instrumented with strain gages and a data acquisition system that allowed continuous monitoring of the reaction forces during cycling. Therefore, it was possible to identify when the specimens began to lose strength and determine the number of cycles to failure (fatigue life). The rupture of the core was used as the termination condition in the sandwich specimen tests. The specimens had dimensions of 100 mm in length, 10 mm in width and 3 mm in overall thickness, Figure **4**.

2.4. Fracture Analyses

In order to evaluate the loss of strength of the specimens during the fatigue tests, a qualitative analysis was carried out on each layer of the sandwich composite. This analysis was made in three stages according to the stiffness degradation curves generated from the fatigue tests. The specimens were examined using a Scanning Electron Microscope (SEM) and performed on specimens dedicated for this purpose. The specimens were tested until the first stage of stiffness degradation appeared in the Load vs

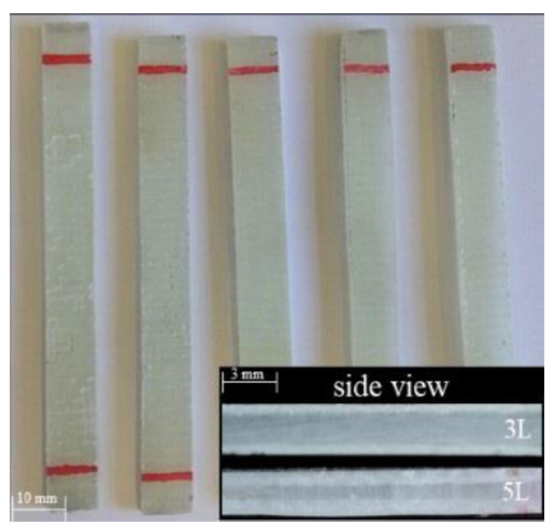

Figure 4: Specimens of the SC3S and the SC5S used in bending and fatigue tests.

Table 1: Mechanical Properties

Materials	Tensile		Bending	
	Strength [MPa]	Modulus [GPa]	Strength [MPa]	Equivalent Modulus [GPa]
Cross-ply Laminated	329.15 ± 30.07	16.14 ± 2.09	-	-
Epoxy	19.08 ± 2.02	1.60 ± 0.20	18.45 ± 1.55	-
SC3S	-	-	292.76 ± 5.30	12.70 ± 1.10
SC5S	-	-	293.43 ± 5.80	17.14 ± 0.83

Cycles curves. The test was interrupted and the specimen conducted for SEM analysis and discarded. A new specimen was tested and only in the second stage of stiffness degradation, the test was interrupted. SEM analysis was performed and the specimen was discarded and so it was done successively in all stages analyzed.

3. RESULTS AND DISCUSSION

3.1. Static Tests

The main mechanical properties obtained from tensile and bending tests of epoxy resin, cross-ply fiberglass laminate and sandwich composites are shown in Table **1**.

The equivalent modulus of the SC5S is 35% higher than the SC3S which is justifiable, since the equivalent moment of inertia of the SC5S is greater than that of the SC3S. However, the resulting bending moment during the test is also higher, making the maximum bending strength practically equivalent in the two sandwich specimens, by the composite beam method.

After the bending tests, different failure modes were observed according to the specimens tested. The epoxy resin specimens exhibited a fragile and sudden fracture. However, the sandwich composites demonstrated broken fibers and delamination due to compression on the top faces, as shown in Figure **5a** and **b**, which agrees with similar results in others studies [18,21]. Another noticeable failure mode was delamination between the faces and core.

3.2. Fatigue Analysis

Figure **6** shows the number of cycles to complete failure from the fatigue tests against the two displacements used in this study for the epoxy resin and sandwich composite specimens. All specimens lasted less than 1.0E+05 cycles using 2.6 mm as the displacement, whereas, using the 2 mm displacement, the epoxy resin lasted more than 1.0E+06 cycles to failure and the sandwich composites withstood around 7.0E+05 cycles.

The maximum reaction load against the number of cycles to failure in the fatigue tests is shown in Figure **7**. From this, it is observed that the SC5S experienced the highest reaction loads. A significant change in the number of cycles is shown as the load values decrease, especially for the epoxy resin specimens. Due to the low stiffness of epoxy resin, the reaction loads in these specimens are very low when compared to the reaction loads on the sandwich composites. From Figure **6**, it is possible to note the better fatigue performance of the SC5S.

3.3. Failure and Fracture Analysis

The stiffness of the specimens during the fatigue tests was evaluated by measuring the reaction loads. The epoxy resin specimens exhibited constant stiffness until the sudden rupture, which is characteristic of

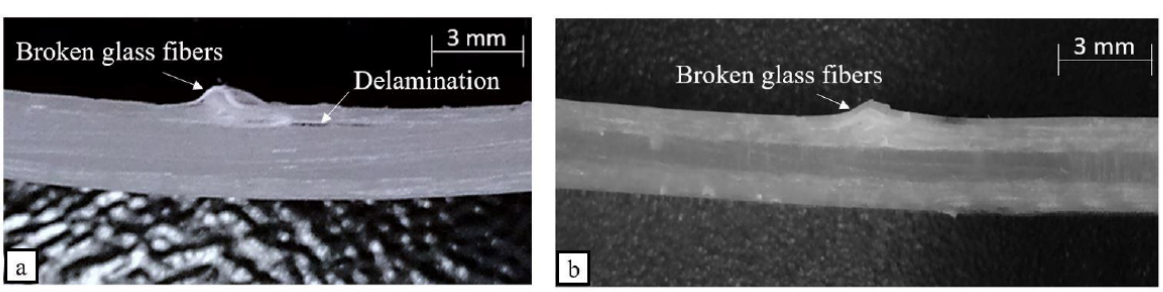

Figure 5: Specimens of (**a**) SC3S and (**b**) SC5S after bending test.

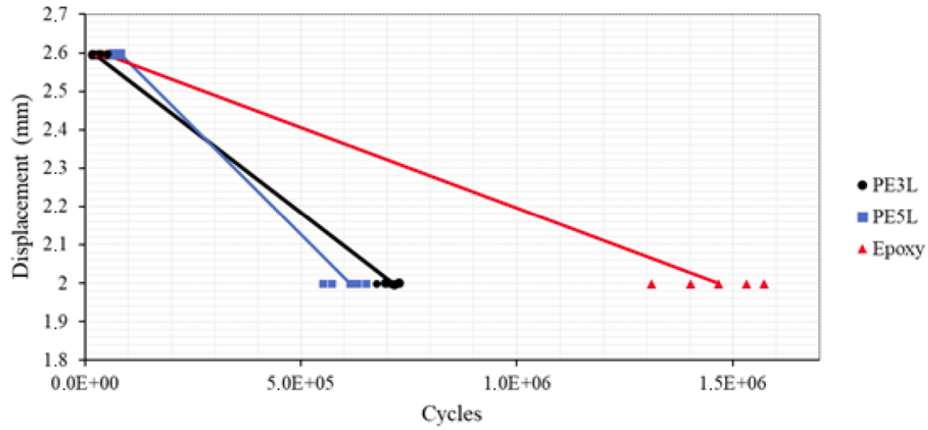

Figure 6: Displacement per Cycle diagram for specimens in fatigue tests.

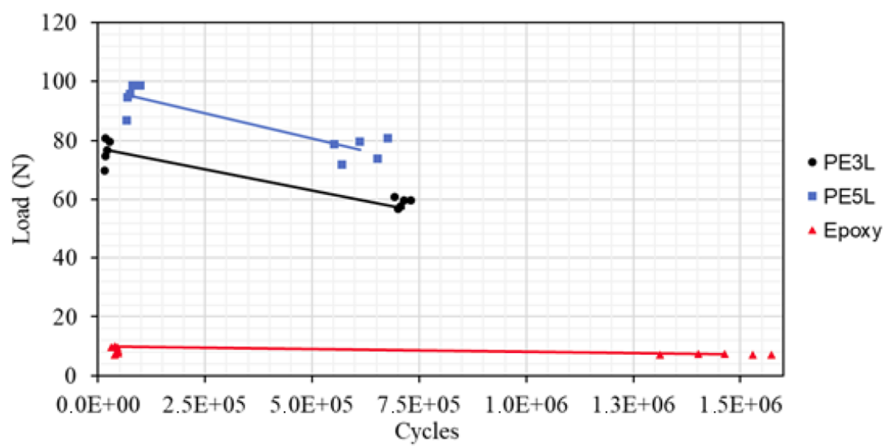

Figure 7: Load per Cycle diagram for specimens in fatigues tests.

fragile materials. The specimens reached 4.0E+04 cycles using the applied displacement of 2.6 mm and reached 1.5E+06 cycles using the applied displacement of 2 mm.

Specimens of sandwich composites showed different behavior depending upon the applied displacement. A progressive decrease in stiffness was noted due to accumulated damage in the laminate skins. This decrease continued until the core ruptured, causing a quick fall in the reaction load during the applied displacement of 2.6 mm, as shown in Figure **8**.

When analyzing the sandwich composites under the applied displacement of 2.0 mm, three stages of material degradation were noted during the tests. To understand and identify the causes of the stiffness reduction, microscopic analyses were performed at each stage to observe what type of damage the specimens suffered. As is known from the literature,

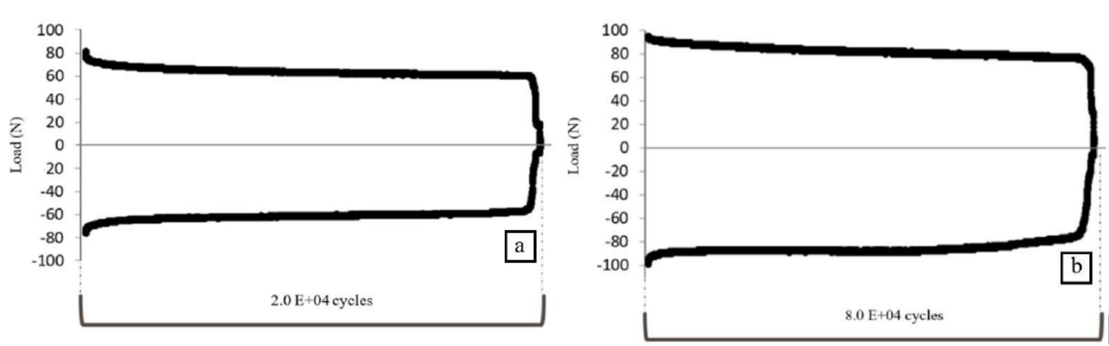

Figure 8: Stiffness degradation during fatigue tests for (**a**) SC3S and (**b**) SC5S, applying displacement of 2.6 mm.

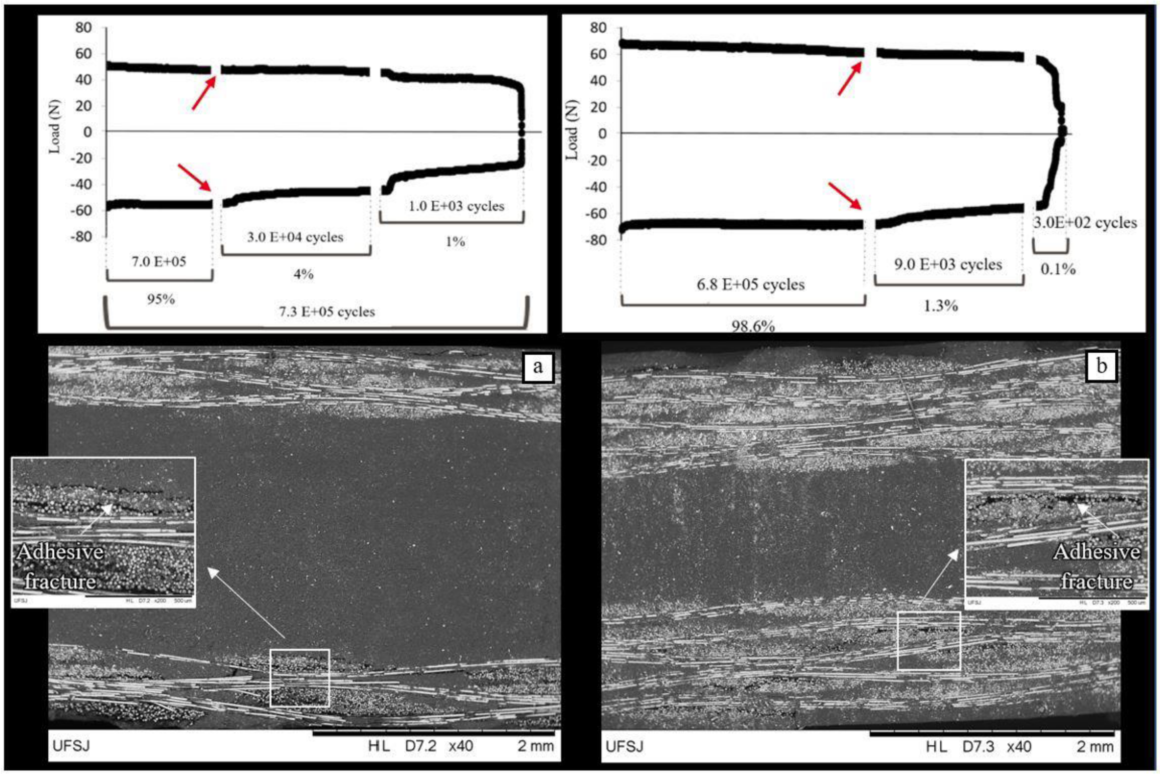

Figure 9: Stiffness degradation during fatigue tests for (**a**) SC3S and (**b**) SC5S applying displacement of 2 mm. First Failure Stage.

the higher bending stresses occur in the outer skins. However, Figure **9** shows that the first stage of failure is characterized by adhesive fracture due to debonding of the interface between the fiber and matrix, specifically in the fibers perpendicularly oriented to the length and located in the middle of the skins. Similar results with these types of failure were obtained in earlier studies [22]. The SC3S reached this stage of failure at around 95% of its total life and the SC5S at around 98%. The overall percentage of cycles in Figure **9** is not to scale because the authors want to show the decrease in reaction load in finer detail during the failure stages.

In the second failure stage, Figure **10**, the fiber/matrix fracture in the laminated faces increased and the delamination process between the face and core began. During this stage, a significant reduction in the reaction load is perceived and the curve shows an asymmetric behavior due to the delamination occuring more intensely on one side of the material. This side of the material begins to experience only tensile stresses because the interface has begun to debond but most of the fibers have not yet broken. At this stage, the crack propagates in the core near the delaminated region. This process was noted at around 99% of the specimens life, when the final failure stage begins.

At the third and final stage, the crack propagates completely through the core, Figure **11**. Adhesive fractures are observed on the upper and lower faces, and it is possible to see some broken fibers. However, some fibers remain unbroken and hold the specimens together. The crack propagated through the entire core causing core rupture and total loss of stiffness of the sandwich composites.

The mechanism of the phenomenon that SC3S and SC5S have different fatigue lives can be explained as long as the fiber and matrix debonding is the first stage and it takes longer to happen due to less accumulated damage and less crack in the specimen. After the intensification of the debonding, the crack propagates and generate the second stage. This crack propagation and the accumulated damage cause a reduction of the fatigue strength, leading the specimen to fail faster. In the third stage, the crack propagates through the core, which is a fragile material, with few cycles the crack tends to break the material and cause the abrupt failure characteristic of this type of material.

4. CONCLUSIONS

- All specimens exhibited similar number of cycles to failure (below 1.0E+05 cycles) using the

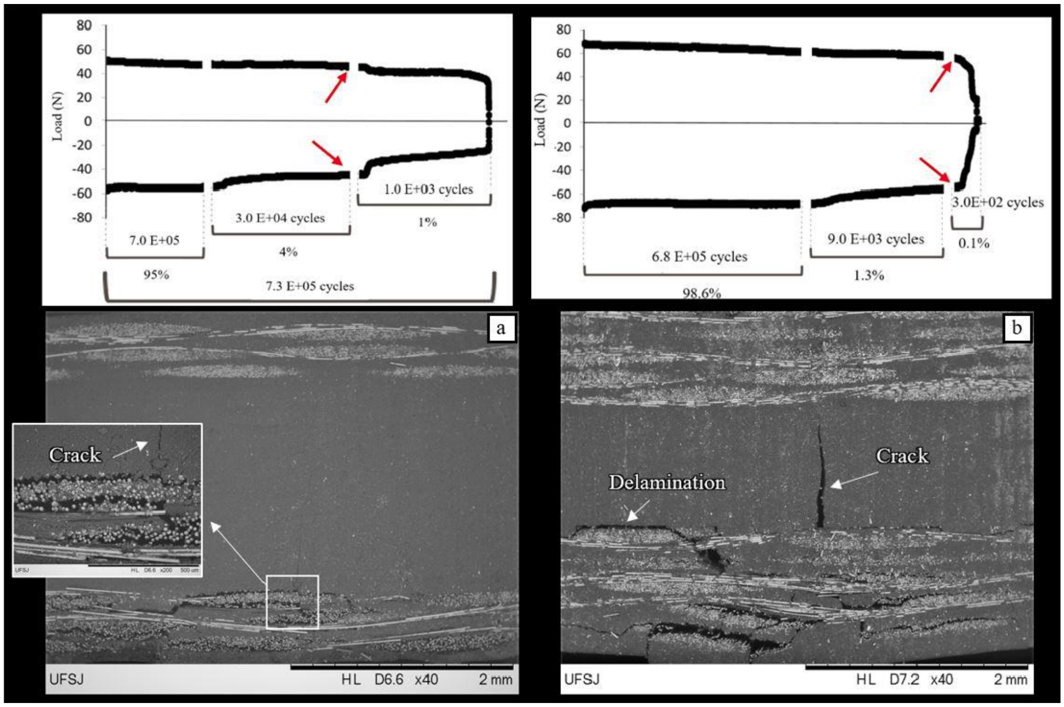

Figure 10. Stiffness degradation during fatigue tests for (**a**) SC3S and (**b**) SC5S applying displacement of 2 mm. Second Failure Stage.

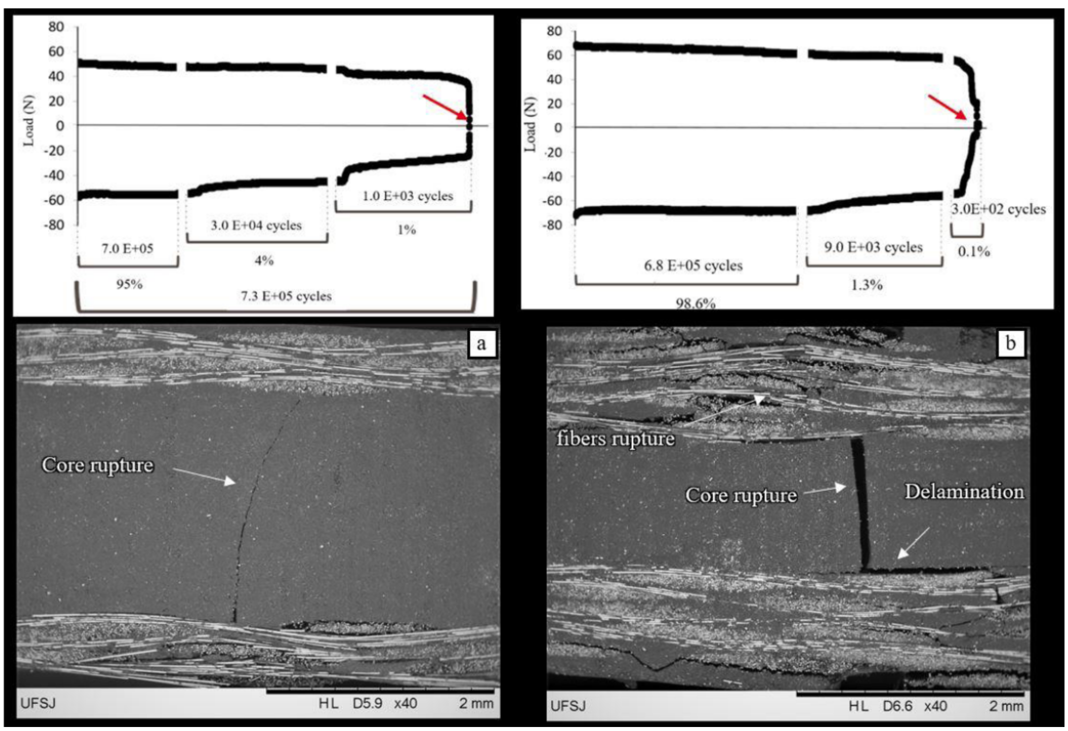

Figure 11: Stiffness degradation during fatigue tests for (**a**) SC3S and (**b**) SC5S applying displacement of 2 mm. Third Failure Stage.

applied 2.6 mm displacement, as shown in Figure **6**. However, when the applied displacement was 2 mm, the difference between the number of cycles to failure of the specimens increased. The epoxy resin was shown to have the best results, followed by the SC3S, and finally, the SC5S. This analysis shows that increasing the amount of laminated faces in the sandwich composite does not improve the fatigue life in situations where there is a small, fixed displacement. In this test case, a homogeneous epoxy resin specimen was shown to have the best fatigue life performance.

- As shown in Figure **7**, the epoxy resin specimens experience very low reaction loads compared to the sandwich composite specimens. This is because of the low stiffness of epoxy resin. The SC5S exhibited the best fatigue performance in this case, indicating that when the objective is to withstand high loads, it is practicable to use sandwich composites with laminated faces for static and cyclic loading.

- From the data in the stiffness degradation curves, a gradual reduction of the material properties during the fatigue tests for the sandwich composites was perceived. However, only the epoxy resin specimens maintained the same stiffness throughout the fatigue tests until the sudden rupture. Another observation was the presence of three stages of degradation in the sandwich composites under the applied 2 mm displacement. The microscopic analyses showed that the first failure stage was debonding between the interface and matrix in the intermediary skins of the laminate. The second noted failure stage was the crack propagation and delamination between the faces and core, and the final stage was the complete propagation of the crack through the core which caused the core to rupture.

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