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Polymer Composites Reinforced with Hybrid Fiber Fabrics

***Renata Carla Tavares dos Santos Felipe*[a]**, Raimundo Nonato Barbosa Felipe*[a]*, Ana Claudia de Melo Caldas Batista*[b,c]*, Eve Maria Freire Aquino*[b]**

[a] *Federal Institute of Education, Science and Technology of Rio Grande do Norte, Natal, RN, Brazil*
[b] *Technology Center, Federal University of Rio Grande do Norte – UFRN, Natal, RN, Brazil.*
[c] *Federal University of Semi-Arid – UFERSA, Campus Caraúbas, Caraúbas, RN, Brazil.*

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In an effort to show the influence of the hybridization method in hybrid fabric reinforced composites within the characteristic of the fracture and the mechanical properties, two laminate reinforced with bi-directional woven were developed, where one of them was reinforced with a hybrid strand (hybrid strand composite laminate) and the other with a different strands (hybrid fabric composite laminate). Both laminates used polyester resin, Kevlar-49 and glass-E fibers, had four layers and were prepared industrially by hand lay-up manufacturing. The percentages by weight of fiberglass and Kevlar in each type of woven are equal. The hybrid strand composite laminate showed a higher tensile strength, however the hybrid fabric composite laminate showed superior properties in three-point bending test, for example, 41.7 % superiority in flexural strength. The results showed that the hybridization method in hybrid reinforced composites influences the mechanical behavior of laminates and the formation and spread of damage.

Keywords: *Polymer Composite, Hybridization, Fiber Characterization, Fracture Process*

1. Introduction

The increase of products using polymer composites reinforced with fibers is growing every day. They have been intensively used in all kinds of industries such as aerospace, shipbuilding, transport[1], as well as in sectors of printed circuit and hardware engineering, ballistic components, equipment and pollution control accessories, automotive parts, electrical components and rehabilitation products[2]. Among its advantages, can be highlighted the high specific strength and stiffness, excellent corrosion resistance compared with the metal and its great anisotropy that depends on the type of array and provision of the reinforcing material and the type of configuration[3].

Among the polymeric materials reinforced with fibers, stand out the hybrid polymer composites that offer advantages in the combination of fibers used as reinforcement, producing a material with higher specific properties[1,4-6], which would be difficult to obtain using a single type of fibers reinforcement.

The hybridization is increasing its use and various studies have been made, as can be seen in the work developed by Jung and Kim[3], where they analyzed the influence of the fracture toughness (using a fracture toughness test) on hybrid polymeric composites reinforced with carbon fiber and glass. The test results showed that the fiber arrangement influence significantly the fracture toughness of the composite material; Zhang et al.[7] studied the influence of the configuration using glass fiber and carbon fiber when subjected to tension, compression and three-point-bending tests. The main results show that the hybrid laminates with 50% carbon fiber reinforcement exhibit the best properties of three-point-bending, when the carbon layers are placed on the surface (outer layers), while the alternating configuration carbon/glass provides greater resistance to compression. Zhang et al.[7] concluded in his work that the tensile strength is insensitive to the sequence of configuration (stacking sequence).

Seeking to improve the flexural properties, Dong et al.[8] propose a hybridization in the composite material with different stacking sequence of carbon fiber and glass fiber, where the results showed that the flexural modulus decreases with increasing glass fiber proportion and both the experimental method and the finite elements suggest that there is positive hybrid effects replacing the carbon fibers by glass fibers; Pandya et al. [9] proposed to determine the mechanical properties in hybrid composites with T300 carbon, E-glass and epoxy resin. In the study, the mechanical properties were obtained from tensile and compressive in-plane quasi-static loading, having noticed that, when the glass fiber fabrics were placed in the outer layers and carbon fabric in the inner layers, a higher tensile strength was obtained. Randjbaran et al.[10] confectioned specimens for performing the ballistic impact testing used as reinforcement for composite hybrid using woven fabrics with Kevlar, glass and carbon woven fabrics. As matrix was used to epoxy resin and there were prepared five kinds of hybridization, with different stacking sequence, concluding the author that the configuration (shape

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* e-mail: renata.felipe@ifrn.edu.br

of the distribution of the layers) influence the ballistic energy absorption.

The papers aforementioned sewed materials in which were used a hybridization with different layers (each fabric using one specific fiber), but other types of hybridizations are already been gaining space, as those using hybrid fabrics (in each layer, the fabric has strands with different fibers), for example, Valença et al.[11] studied an comparative mechanical properties of a composite using solely Kevlar fibers as reinforcing and other two laminates using the hybrid composite of glass and Kevlar fibers; where in the composite hybrid structure of Kevlar/glass fibers showed the best results in terms of specific strength as well as bending and impact energy.

The differential of this paper concerns that the studies conducted until now, none deals with the hybridization method, that is, despite being used hybrid composites, they do not hold the fracture mechanism in the mechanical characterization of the material. Therefore, in this work it is developed two hybrid laminates, but one using a hybrid fabric formed by hybrid fiber strands of Kevlar/49 and glass/E fiber; and the other by a hybrid fabric with weft and warp formed of Kevlar/49 and glass/E fibers (strands of a single type of fiber and distributed alternately), respectively.

The laminates were submitted to uniaxial tensile and three-point bending tests in order to obtain a characterization of the fracture mechanical properties. The study was performed by using the morphology of the fracture aiming to explain in fact the influence of the hybridization method. Determination of properties, such as density and volumetric percentage of the constituent phases, has been performed for all the composites. In the latter case, the percentages are characterized by the pyrolysis test taking into consideration different types of fibers.

2. Materials and methods

2.1 Materials – Reinforcement and resin

To perform the study, two laminates were used, both hybrids and with four layers, which both using the thermosetting resin of ortho-terephthalic unsaturated polyester with technical specification Novapol - L20, glass/E fibers and Kevlar/49 fibers; the difference between the laminates is given by the hybridization method of reinforcing fabric.

For matrix catalyzing, methyl-ethyl-ketone peroxide (MEKP) has been used in a proportion of 1 % of the resin volume, being the cure process of the composite laminates at room temperature. The resin has the following characteristics: Viscosity brook (SPD 2/60rpm) 250-350 cP; Density 1.23 g/cm^3 at 25 °C; Gel time (1 % MEKP) 9-13 min at 25 °C; Exothermic peak of 150-190 °C; and acid value: maximum 30 mg KOH/g.

The hybrid fabric where each of the strands consists of glass/E fiber and Kevlar/49 fiber yarns is provided by TEXIGLASS Company and commercially known as KV-650. It has 63 % of Kevlar/49 fibers and 37 % of glass/E fiber by weight, with grammage of 643 g/cm^2 and it has 487 Kgf and 343 Kgf of the breaking load (theoretical) of warp and weft, respectively, according to manufacturer's specification.

The other hybrid fabric is manufactured on a manual loom by using the bidirectional woven glass/E fiber, provided by the company TEXIGLASS, being commercially called WR-600/ 3-1 (with grammage of 610 g/cm^2 and 185 Kgf and 120 Kgf of the breaking load (theoretical) of warp and weft, respectively, according to manufacturer's specification). For this purpose, fiber glass strands were withdrawn from weft and warp alternately; and where their strands were removed, strands of Kevlar/49 fibers (with 18-24 Kgf of the breaking load theoretical, according to manufacturer's specification) were placed, taken from the bidirectional woven of Kevlar fibers, also provided by the company TEXIGLASS, with commercial designation KV 110/1-0. Reservation is made when in the replacement of strands for making the hybrid fabric, the percentages were maintained in weight of fibers (glass and Kevlar), thus giving an approximate final weight of 630 g/m^2 and substantially equal to the woven with hybrid strand. The average values and the standard deviation of the diameters of Kevlar fibers are (12.581 ± 0.478) µm and of glass fibers are (23.356 ± 1.896) µm. Both of the fabrics used are shown in Figure 1.

2.2 Manufacturing of composite laminates

The laminate composite formed from woven with hybrid strand, known as Kevlar/glass Hybrid Strand Composite Laminate (**HSCL**), has four layers in its configuration, while the other laminate formed with hybrid fabric where each section composing the weft and warp are of glass/E fiber and Kevlar/49 fibers, however distributed alternately, also has four layers in its configuration. The laminate is called Kevlar/glass Hybrid Fabric Composite Laminate (**HFCL**). Manual lamination manufacturing process (hand lay-up) was used for manufacturing the laminates, this being done in the industry. Specimens were cut with a diamond-cutting disk, sanded, and polished, according to technical standard. It is necessary at least five specimens per test condition[12].

2.3 Density Testing

To determine the density of the laminates, it was used the ASTM D 792[13] standard. There were prepared five test pieces for each type of composite laminate (dimensions of the **HFCL** laminate samples were (25x25x3.2) mm and the dimensions of **HSCL** laminate were (25x25x4.15) mm) and the results averaged. It was used a digital weighing-machine,

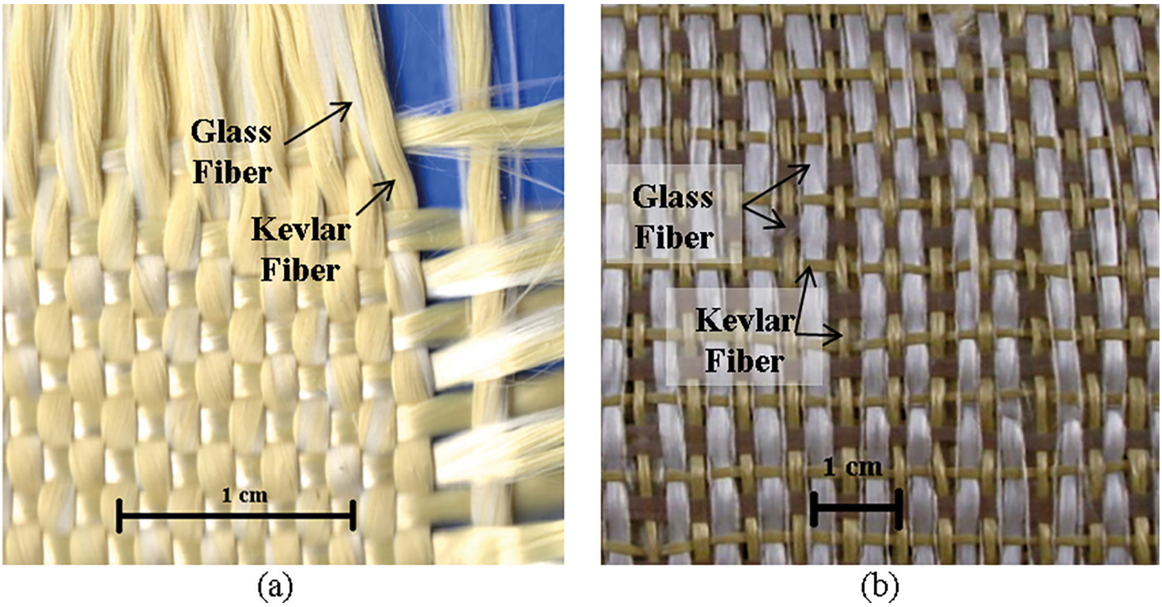


Figure 1. Hybrid fabrics used in the manufacture of laminates; (a) fabric of hybrid strand and (b) hybrid fabric.

of Sartoriun brand BP 210S model with 0.1 mg resolution and a maximum capacity of 210 g, for performing the test.

2.4 Thermogravimetry (TGA)

This technique was used aiming to measure changes (losses) of mass of each constituent of the sample (resin, Kevlar fibers) during the heating, then serving temperatures that occur these losses, as a reference to be used during the calcination process since it is working with two different types of reinforcements, besides the polyester matrix. The atmosphere in the equipment for performing the assay was nitrogen with a flow rate of 40.0 ml/min and a heating rate of 20 °C/min. The temperature range used was from 75 °C to 890 °C. The equipment used was the TGA Q50, TA Instruments.

2.5 Calcinations Testing

This test was used to determine the volume fractions of reinforcement, resin and voids (it is emphasized that the samples used were the same density test). The procedure used was through the use of the oven muffle Fornitec model - Ind e Com. Ltda., where the samples were placed in ceramic crucible and heated for a period of 4 h at different temperatures.

The first heating temperature of the sample was the temperature relating to the resin, being the sample weighed after 4 h at this temperature; this weight was related to the volumetric fractions of Kevlar and glass fibers. Following, this material referring to the fibers was heated for 4 hours at a temperature related to the weight loss of Kevlar fiber and thereby leaving only the glass fibers. The residual mass of the glass fibers after the complete burning of the resin and Kevlar fibers was initial parameter for determining the contents of fibers, resin and voids, according to ASTM D 3171[14] standard.

2.6 Uniaxial tensile test

The uniaxial tensile test was performed according to ASTM D 3039[12] standard. Tests were performed for each type of composite laminate, being eight specimens fractured and five values recorded (required by the standard) of the valid tests considered. Uniaxial tensile test was conducted in the Universal Mechanical Testing Machine (AGI-250 KN Shimadzu), with a loading speed of 1.0 mm/min, and the average ambient temperature during the tests was 25±2 °C. The dimensions of **HFCL** laminate specimens were (250x25x3.2) mm and the **HSCL** laminate were (250x25x4.15) mm, respectively for length, width and thickness. The dimensions have tolerances of ± 1 %. The gauge length of all test specimens was 127 mm.

2.7 Three-point bending test

The three-point bending test was performed according to ASTM D 790[15] standard, being obtained for both laminates proposed: the flexural strength and flexural elastic modulus. The three-point bending test using a Universal Mechanical Testing Machine (AGI-250 KN Shimadzu), and the loading speed of 2.0 mm/min and dimensions of the **HFCL** laminate specimens were (84x13x3.2) mm and span of 50 mm and the dimensions of **HSCL** laminate were (90x13x4.15) mm and span of 68.8 mm. The dimensions correspond to length, width, and thickness, respectively. The specimens vary in size because the thickness of the laminates (**HFCL** and **HSCL**) are different. The average ambient temperature during the tests was 25±2 °C.

2.8 Analysis of fractures.

In order to analyze the real influence of the hybridization method, there were not only analyzed the quantitative data of uniaxial tensile and three-point bending, but also there will be a qualitative analysis of mechanical fracture through the macroscopic and microscopic analysis.

Macroscopy was performed using the scanner HP Photosmart C4280, while in optical microscopy was used the microscope Olimpus MG. For the scanning electron microscopy (SEM), the microscope Shimadzu model Superscan SSX-550 it was used.

3. Results and discussion

3.1 Thermogravimetry (TGA)

The temperatures at which occur weight losses of the **HSCL** and **HFCL** constituent materials laminates can be verified in Figures 2 (a) and (b).

The graph of thermogravimetry (mass as a function of temperature) at the ortho-terephthalic polyester resin is shown in Figure 2 (a), whose mass used was 3.393 mg, where there it is verified a temperature range between 280 °C and 450 °C for this mass loss, the latter being used for the calcination test.

The Figure 2 (b) shows the TGA of Kevlar fiber, being the mass value of the sample used for the test of 1.2650 mg, where may be observed mass loss temperature range between 480 °C and 580 °C, the latter being used as a temperature used in the calcining test. The TGA fiberglass was no longer necessary, once it is the last component of the material.

In Figure 3 (a), it is possible to observe the TGA graph of the **HSCL** laminate being used to test a sample of 6.9964 mg. It is verified two well-defined levels, where the first is related to mass loss range of the resin (280 to 450) °C, and the second (450 to 580) °C corresponding to mass loss of Kevlar fiber. In this way, we can confirm the weight loss temperature of the resin shown in Fig 2 (a). The same conclusion can be reached with respect to the second stage where the weight loss temperature of the Kevlar fiber was 580 °C, also confirming the behavior shown in figure 2 (b).

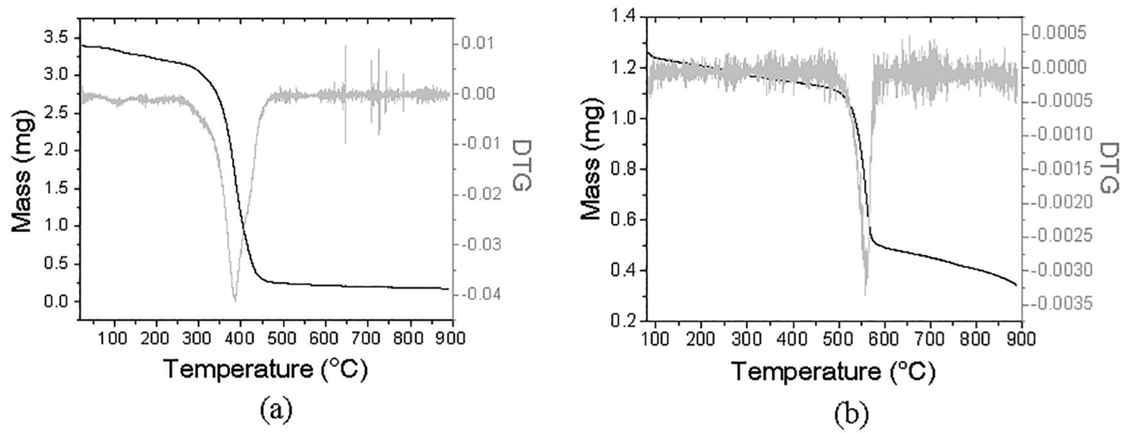
In Figure 3 (b) is shown the graph related to TGA performed in the **HFCL** laminate, where was used a sample with mass of 6.4220 mg. Observed also two thresholds, being the first well defined as the temperature at the mass loss of the resin and the second as the temperature at the Kevlar fiber.

In light of the foregoing, the temperature that were determined in the TGA test served as the basis for carrying out the calcination assay for the determination of the resin, reinforcement and voids contents.

3.2 Calcinations testing

The values of the volumetric densities and volume fractions of reinforcement, resin and voids of **HSCL** and **HFCL** laminates are shown in Table 1.

According to Table 1, it is important to note that for the **HSCL** laminate, the resin content is less than the **HFCL** laminate, observed in microstructural characterization and during the process of manufacturing the same. This fact is explained once the fabric of hybrid strands has a weft and warp extremely closed, in other words, hindering the impregnation of the fabric by the resin during the manufacturing process. The hybrid fabric used to manufacture the **HFCL** laminate has features as the loose weft and warp, allowing passage of resin by respective interweaving, then occurring better impregnation of the fabric. This feature results in a lower percentage of voids in the composite laminate. This statement becomes more clearly after the analysis of the



(a) (b)

Figure 2. Thermogravimetry test: (a) Polyester Ortho-terephthalic resin; (b) Kevlar fiber.

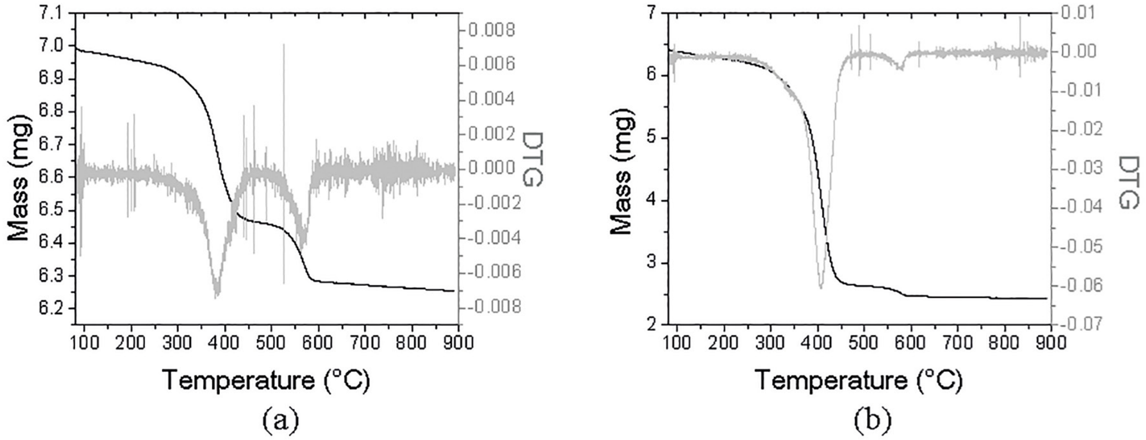


Figure 3. Thermogravimetry test: (a) HSCL; (b) HFCL.

Table 1. Volumetric density and volume fraction of reinforcement, resin and voids.

Laminates	Volumetric density (g/cm^3)	Glass Fiber-E (%)	Kevlar Fiber (%)	Matrix (%)	Voids (%)
HSCL	1.45 ± 0.05	10.1 ± 1.0	45.4 ± 2.5	40.6 ± 3,5	3.9 ± 0.3
HFCL	1.55 ± 0.02	20.0 ± 2.0	31.0 ± 2.9	48.0 ± 2.5	1.0 ± 0.2

mechanical properties and fracture. It is emphasized here that the percentage of fiberglass and Kevlar mass for each fabric type are equal.

3.3 Mechanical properties - uniaxial tensile

Mechanical behaviors related to uniaxial tensile tests of **HSCL** and **HFCL** laminates are first evaluated from the stress-strain diagram, see Figure 4. It is highlighted here the different behavior of the laminates, noting that the **HSCL** laminate has a linearly elastic until the load at initial damage (approximately 40 % of tensile strength), while the **HFCL** laminate shows a linearly elastic behavior until the final fracture of the material.

Table 2 shows the results of the mechanical properties (average values) and standard deviation obtained for uniaxial tensile test of **HSCL** and **HFCL** laminates. With regard to the values of the modulus of elasticity, was calculated before starts load at initial damage, to avoid of the same influence on the stiffness of the material.

Batista *et al.* [16] studied a hybrid composite with o plain bidirectional hybrid fabric, composed of E-glass fiber and Kevlar/49 and as reinforcement and use epoxy vinyl ester thermosetting resin as matrix (Derakane 470-300) and in the uniaxial tensile test was obtained: (106.4±5.8) MPa for tensile strength and (3.9±0.3) GPa for elastic modulus.

In this way, observed that the tensile strength of **HSCL** laminate is 23.9 % above the resistance of **HFCL** laminate.

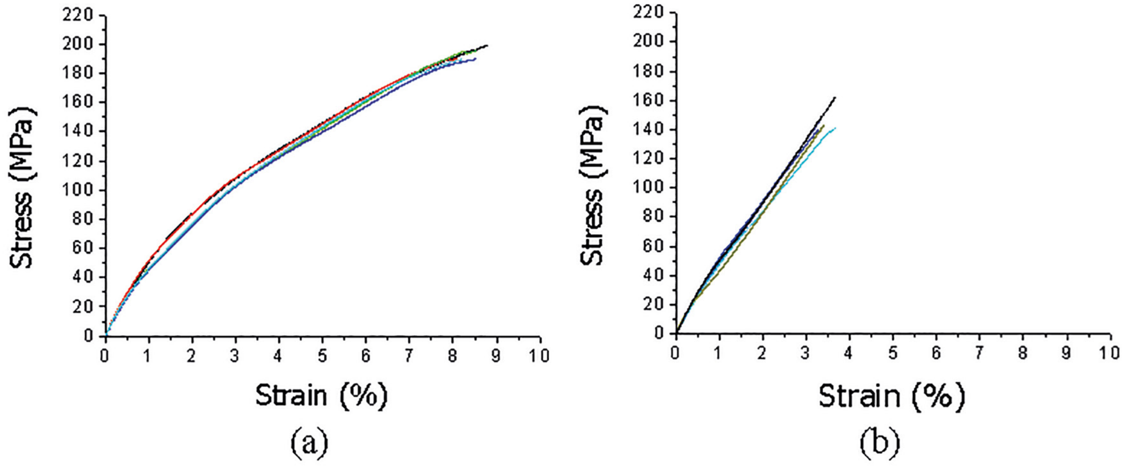


Figure 4. Stress x strain diagram (uniaxial tensile test): (a) HSCL; (b) HFCL.

Table 2. Mechanical properties - laminates HSCL and HFCL - uniaxial tensile.

Mechanical Properties		
Composite Laminate	Tensile Strength (MPa)	Elastic Modulus (GPa)
HSCL	193.04 ± 4.27	5.17 ± 0.34
HFCL	146.96 ± 8.96	5.27 ± 0.34

Almost no variation was observed in elasticity modulus of **HSCL** and **HFCL** laminates, whereas the **HFCL** laminate shows an increase in elastic modulus of about 2 % when compared to the **HSCL** laminate, so within the range of dispersion.

3.4 Mechanical properties – three-point bending

Figure 5 shows the performance of the mechanical properties obtained in the three-point bending test for both laminates, from the stress x flexural strain diagram. The **HSCL** laminate has a linearly elastic until the load at initial damage (approximately 40 % of tensile strength), while that the laminate **HFCL** presents a linearly elastic behavior until the final fracture of the material.

Table 3 it is possible to observe the synthesis of the results of the mechanical properties (average values) determined at the three-point bending test as well as the values of the respective standard deviations. Batista *et al.*[16] obtained to the hybrid fabric with glass/ Kevlar in the three-point bending test the values: (143.1 ± 7.9) MPa for flexural strength and (7.5 ±0.6) GPa for flexural modulus.

Was observed that generally the flexural properties of the **HFCL** laminate are superior when compared with the **HSCL** laminate properties, being strength and elasticity modulus the **HFCL** laminate superior in 41.7 % and 16.3 %, respectively.

Table 3. Mechanical properties – laminates HSCL and HFCL – three-point bending.

Mechanical Properties		
Composite Laminate	Flexural Strength (MPa)	Flexural Modulus (GPa)
HSCL	147.90±15.89	8.24± 0.39
HFCL	253.87±16.97	9.85±0.51

3.5 Global comparative - the type Influence hybridization

In order to conclude the quantitative analyzes for hybridization, in Figure 6 is possible to observe a global view of the strength and stiffness of tension and three-point bending test behavior for **HSCL** and **HFCL** laminates.

Thus, it is evident that the reinforcement fabric hybridization method influences the mechanical behavior of laminates. In this way, the **HSCL** laminate, in terms of uniaxial tensile test, showed a superior strength and high deformation when compared to the **HFCL** laminate. However, when the laminates were submitted to three-point bending test, **HFCL** laminate showed superior properties. Tables 4 and 5 show the percentage of superiority in function of the type of load for each laminate.

In this sense, can say that the **HSCL** laminate showed in their behavior the prevalence of the properties of Kevlar fiber, while the **HFCL** laminate shows a behavior characterized by the predominance of glass fiber properties, which is in agreement with the results of calcining test since **HSCL** shows 45.4 % of Kevlar fibers while **HFCL** shows 31 % approximately.

In accordance with of the foregoing, it can be concluded that when selecting the hybridization method is important to know in fact what type of load that the laminate should be submitted, once hybrids laminate showed different behaviors as the kind of hybrid fabric.

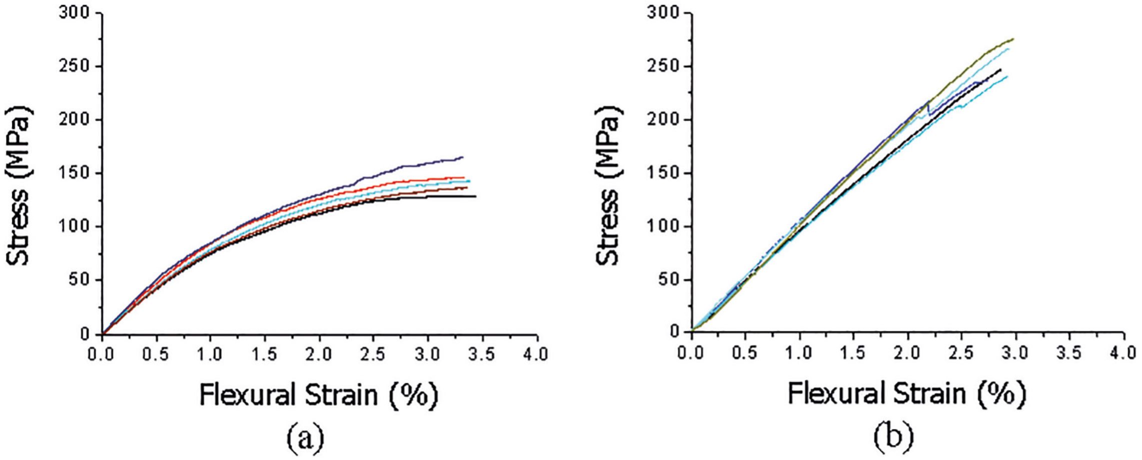


Figure 5. Stress x Flexural Strain (three - point bending): (a) HSCL; (b) HFCL.

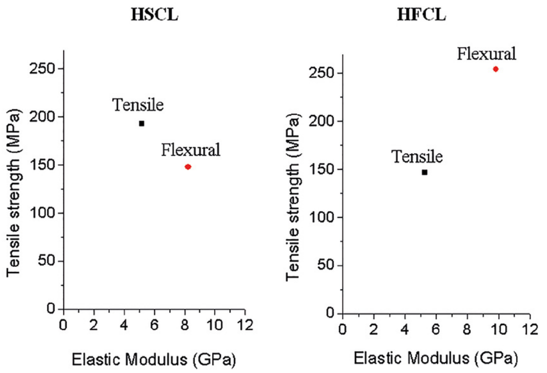


Figure 6. Global comparison diagram - resistance and stiffness.

Table 4. Influence of hybridization method on laminate HSCL specimens.

Mechanical properties	*Superiority* (%)
Strength	Tension > 30.5 % Flexion
Elastic Modulus	Flexion > 59.4 % Tension

Table 5. Influence of hybridization method on laminate HFCL specimens.

Mechanical properties	*Superiority* (%)
Strength	HFCL: Flexion > 72.7 % Tension
Elastic Modulus	HFCL: Flexion > 86.9 % Tension

3.6 Characteristic of mechanical fracture - uniaxial tensile

The characterization of the mechanical fracture starts with a macroscopic analysis of the same, noting that the **HSCL** laminate has a fracture of the DGM type (Edge delamination – Gage – Middle), see Figure 7, while the **HFCL** suffered the fracture LGM type (Lateral – Gage – Middle), see Figure 8, according to the ASTM D 3039[12] standard.

In Figure 7, it is possible to verify the delamination occurred in all layers of the laminate, concentrating on the central region of the specimen.

In is observed the fiber pull-out in the fracture area after rupture and damage characteristic of polymer composites reinforced with fabric. It is important to remember that the characteristic of the final fracture, when macroscopically analyzed, happened differently of the **HSCL** laminate, which was characterized by delamination. It emphasizes that, for all **HFCL** laminates, there was not in fact the "total fracture" of the specimens tested, this fact made it difficult to micrographic analysis because there is no existence of a "final section" of the fracture.

The microscopic study of the fracture, it begins with an analysis of optical microscopy and occurs in the fractured region (along the specimens thickness) of the **HSCL** laminate, as shown in Figure 9. The formation of cracks in matrix cross-section direction of applied load. In Figure 9, it can be seen that the microcracks propagates in the direction of hybrid strand penetrating into the same. In their spread within the strand, the cracks starts to cause fiber/matrix interface debonding, and this type of fracture is called "adhesive fracture."

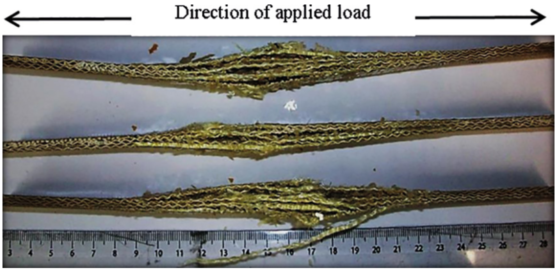


Figura 7. Fracture characteristic - HFCL laminate - uniaxial tensile.

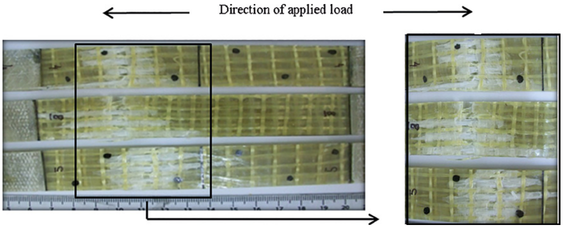


Figure 8. Fracture characteristic - HFCL laminate - uniaxial tensile.

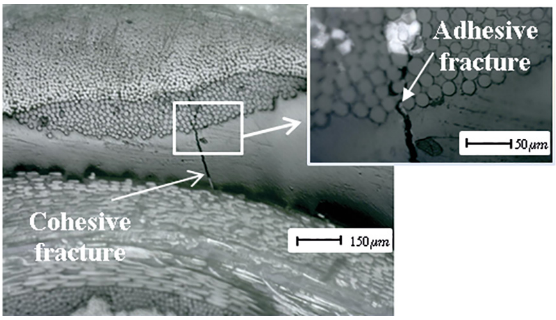
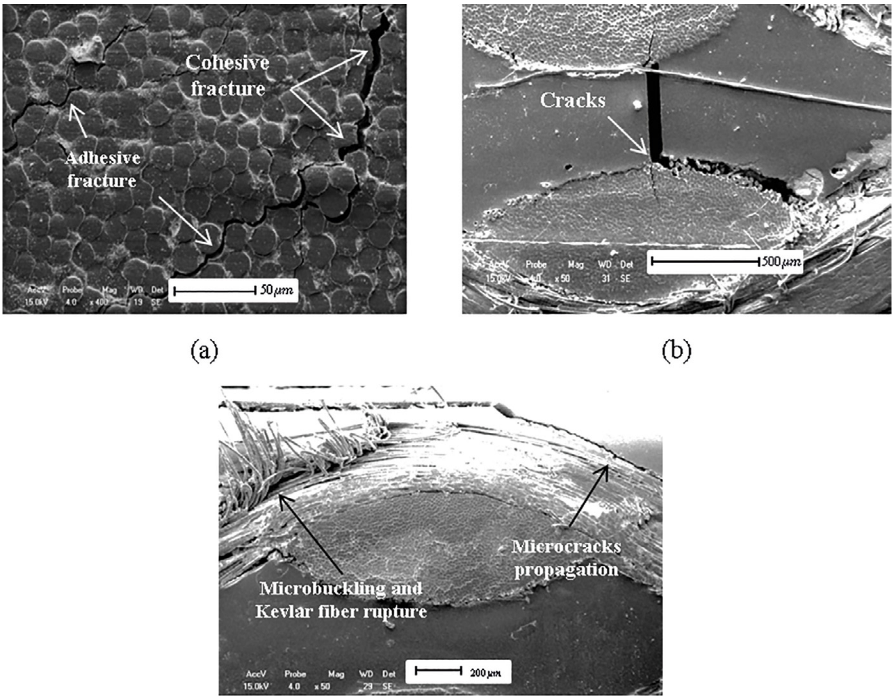


Figure 9. Uniaxial tension - fracture characteristics - HSCL.

Proceeding the microscopic analysis of final fracture in **HSCL** laminated, now using Scanning Electron Microscopy (SEM). In the Figure 10 (a) observed with more detail the crack in the matrix is propagated inside the strand causing the adhesive fractures (fiber/matrix interface debonding) and the cohesive fiber. However, when looking at Figure 10 (b), the presence of transverse cracks is observed to propagation in the matrix at the contour and inside the hybrid strand.

Already in Figure 10 (c) it can be seen that the microcrack propagation both the contour of the strand as well as in the warp, moreover, there is microbuckling and Kevlar fiber rupture and adhesive fracture. Still analyzing the specimens surface of the **HSCL** laminate by SEM, there is cracks cross direction of loading and delamination, see Figure 11.

For the laminate **HSCL**, the microscopic analysis, the final fracture in along the thickness of the specimen, as shown



(a) (b)

(c)

Figure 10. Fracture characteristics - HSCL laminate.

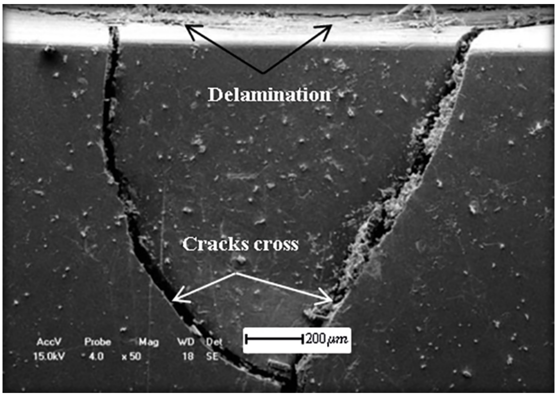


Figure 11. Fracture on the surface - HSCL laminate.

in Figure 12, it is possible to observe the propagation of a microcracks within the reinforcement layers in the cross-section of the final fracture, originating cohesive fracture and adhesive fracture.

Continuing the analysis, by SEM, see Figure 13, observed adhesive and cohesive fractures, as well as Kevlar rupture fiber. Observed that this type of damage tends to break along the fiber, this characteristic being detected in Kevlar fiber, as was also observed in **HSCL** laminate, as well as rupture and pull-out fiber, see Figure 13 (a).

It can be observed in Figure 13 (b), the presence of a few pieces of matrix adhered to the fibers, the cohesive fracture and microbuckling in kevlar fiber. Finishing the fracture analysis for the **HFCL** laminate, shows fiber bundle pull-out (adhesive fracture) and cohesive fracture in fiberglass, see Figure 13 (c).

It is important to explain that the fabric hybridization process had influenced the damage mechanism when analyzed in both levels (macroscopic as microscopic), once there was in the **HSCL** laminate a low resin impregnation in the reinforcing material because of the fabric characteristics, making difficult the resin passage between the reinforcement layers. However, in the **HFCL** laminate, since the strands were not hybrid and the fabric had a weft/warp less tight, in other words, greater flexibility, so facilitating the impregnation of the reinforcing material.

Another important factor is that the values of resin content confirm this theory, lack of impregnation of the reinforcing material since the resin percentage was higher in the **HFCL** laminate.

Observing Figure 14 you can see a comparative flowchart of the fracture for the response of both rolled under tensile loading.

3.7 Fracture of three-point bending test

Characterization of the fracture in **HSCL** and **HFCL** laminates is initiated by macroscopic analysis of the fractured region after the three-point bending test, and can be seen in Figures 15 and 16, respectively.

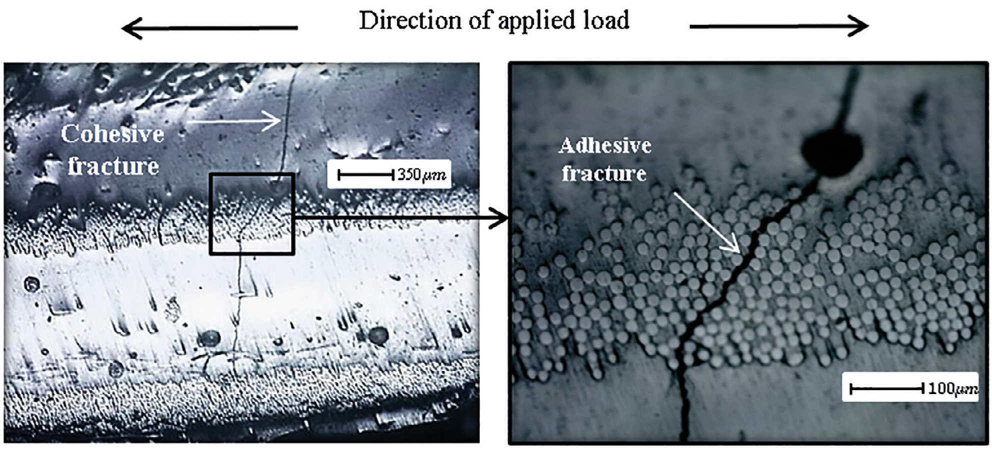


Figura 12. Fracture characteristics – HSCL laminate.

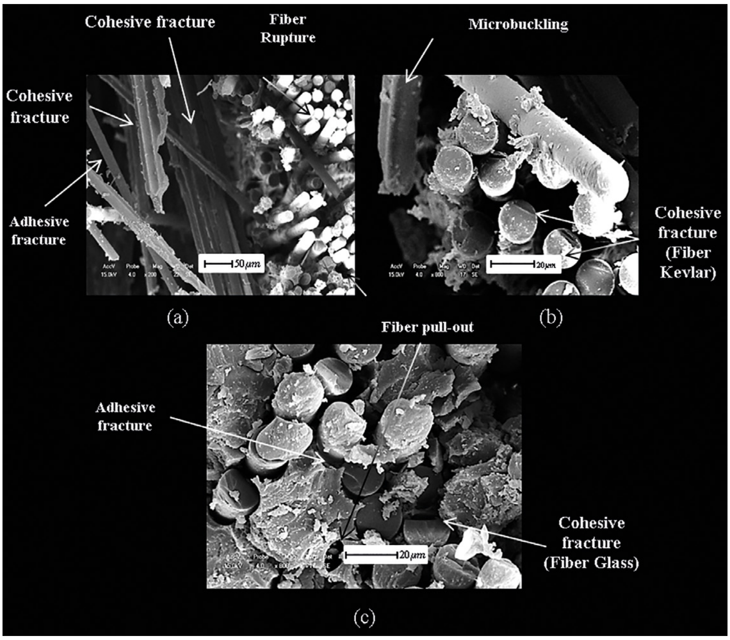


Figure 13. Fracture characteristics – HFCL laminate.

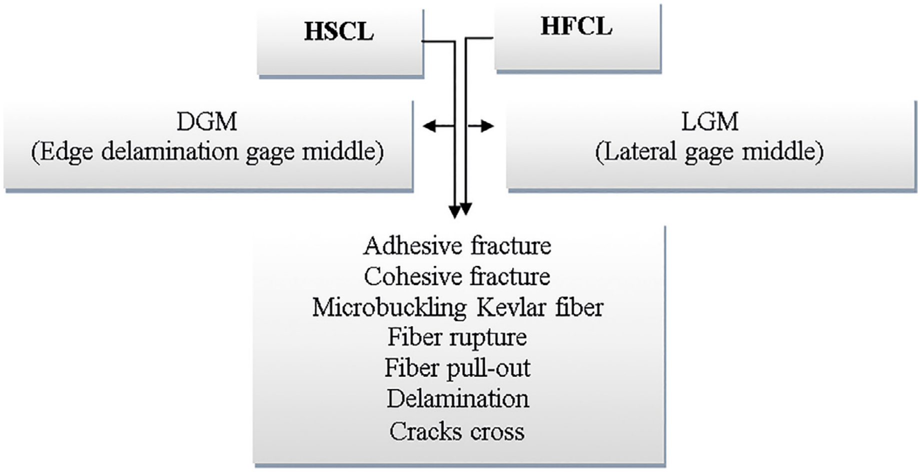


Figure 14. Flowchart: tensile fracture characteristics

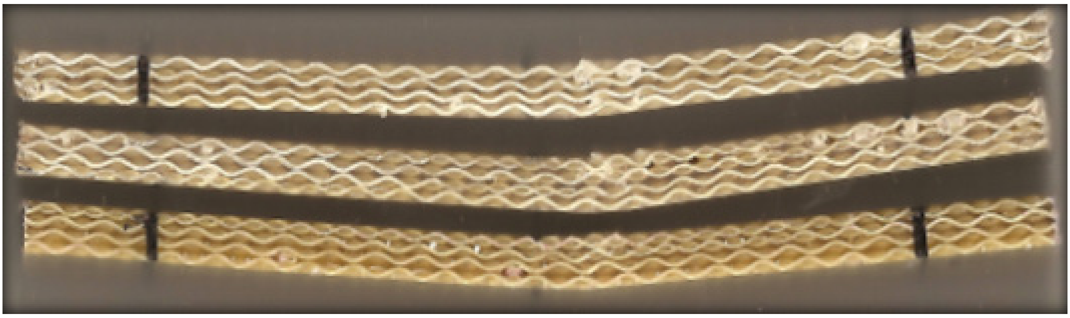


Figure 15. Fracture characteristic – HSCL laminate – three-point bending.

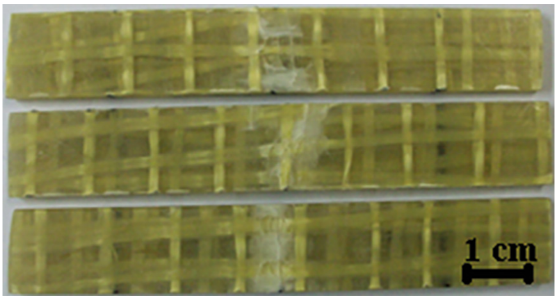


Figure 16. Fracture characteristic – HFCL laminate – three-point bending.

Analyzing the Figure 15, observed that there was no complete fracture of the test body resulting in a whitened area only in the final fracture region, located in the cross-section of specimens. Regarding the analysis of **HFCL** laminated fracture, as seen in Figure 16, it is clear that the fact the specimens were broken by bending once tensile side there is the presence of points of cracking the matrix, being evidenced by the whitened region.

For the study conducted through the optical microscope, the **HSCL** laminate, and thickness of the specimens. In the tensioned layer, it is possible to observe some fracture characteristics such as the presence of cohesive fracture in the matrix, where the microcracks propagate around the weft (hybrid strand) fabric, so causing fiber/matrix debonding (adhesive fracture), see Figure 17.

The Figure 18 shows details of the fracture mechanism from the analysis via scanning electron microscopy (SEM), where can be observed the crack formation in the tensile side with branch on contour of hybrid strand, and the location of this matrix split as a characteristic of good performance of the laminate against the bending load, as shown in Figure 18 (a). It is also seen the spread of same in the warp, causing fraying of Kevlar fiber, being evidenced by the appearance of the Kevlar fiber, as shown in Figure 18 (b). However, it also occurs a groove matrix formation caused by the lack of fiber/matrix debonding interface and/or even by the fibers pull-out. Furthermore, it is also seen the adhesive fractures in the fiber being evidenced by observing the fiber surface, because it presents no residue of matrix, see Figure 18 (c). This same type of damage suffered in Kevlar fibers was also detected in the work developed by Alagar et al.[2] e Nilakantan et al.[17].

Regarding the analysis of the fracture from the optical microscope held at **HFCL** laminate, emphasize the fracture cohesive kind in the matrix (generation of the crack in the tensile side of the specimens), with the spread of it within the layer, causing the fiber/matrix debonding, Figure 19.

Regarding the fracture analysis by SEM in the **HFCL** laminate, in Figure 20 (a) is clear that the fracture is concentrated in the load application area, having initially the formation of parallel split to the direction of the applied load and then its spread occurs perpendicularly the same. It

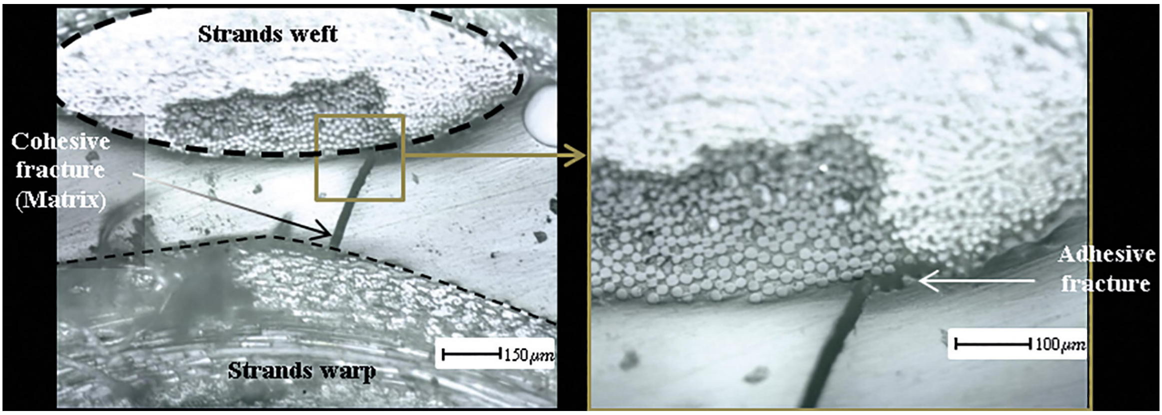


Figure 17. Fracture - HSCL laminate.

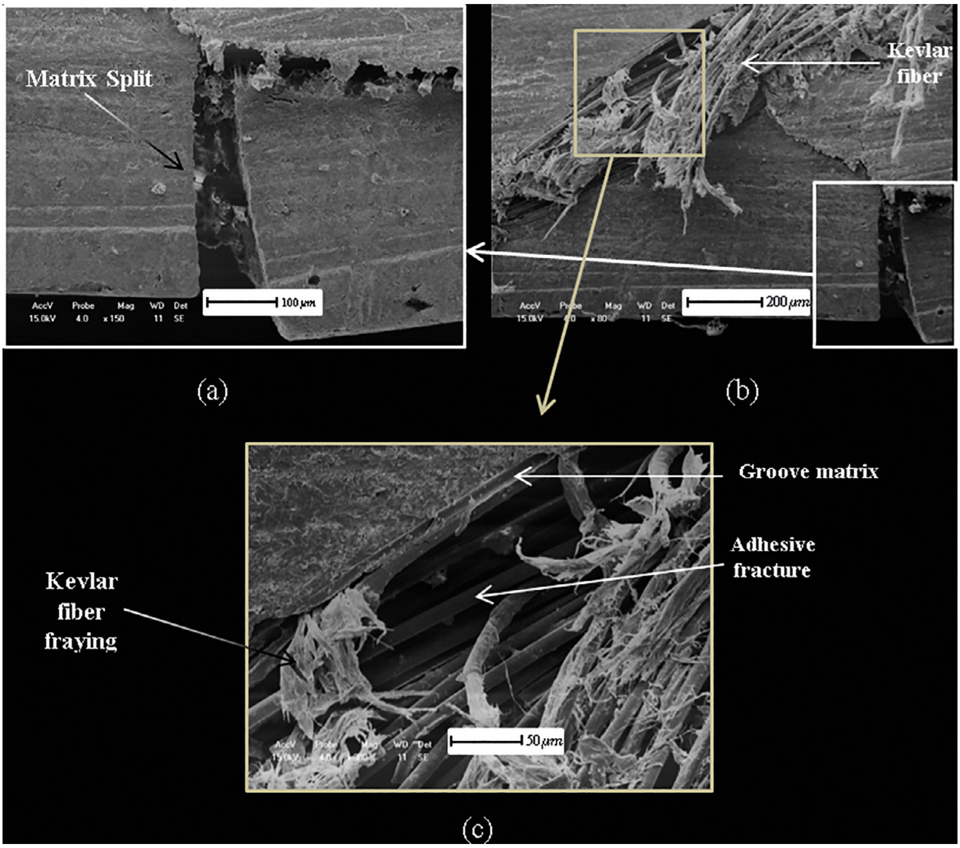


Figure 18. Fracture - HSCL laminate

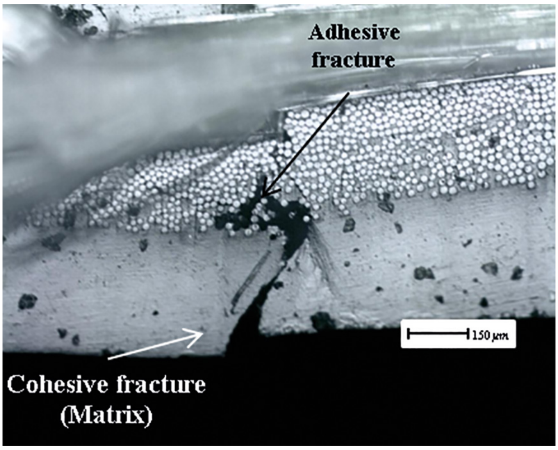


Figure 19. Fracture characteristic – HFCL laminate

should be noted, moreover, the occurrence of the rupture in Kevlar fibers. Now in Figure 20 (b) are evident phenomena of rupture and microbuckling of Kevlar fibers, since they appear frayed, one of the same fracture characteristic. In the Figure 20 (c), adhesive fracture and fraying is evident in the Kevlar fibers and also the fibers pull-out characterized by groove matrix formation.

The Figure 21 shows a comparative flowchart of the microscopic and macroscopic fracture characteristics in the **HSCL** and **HFCL** laminates bending under loading.

4. Conclusions

Given the above, it can be concluded that:

- Higher incidence in the number of manufacturing defects (microcracks and voids) in the **HSCL** laminate due to the hybrid fabric configuration, so hindering the resin impregnation through the layers of reinforcements;
- As regards the percentages of the constituents (by volume), the laminate **HSCL** showed a lower percentage of resin and higher percentage of fibers and voids when compared to the **HFCL** laminate, this being expected since there was less impregnation of the fabric by matrix;
- The **HSCL** laminate showed a higher resistance to uniaxial tensile when compared to laminated **HFCL**. The different behavior of elastic modulus can is related precisely because of the damage

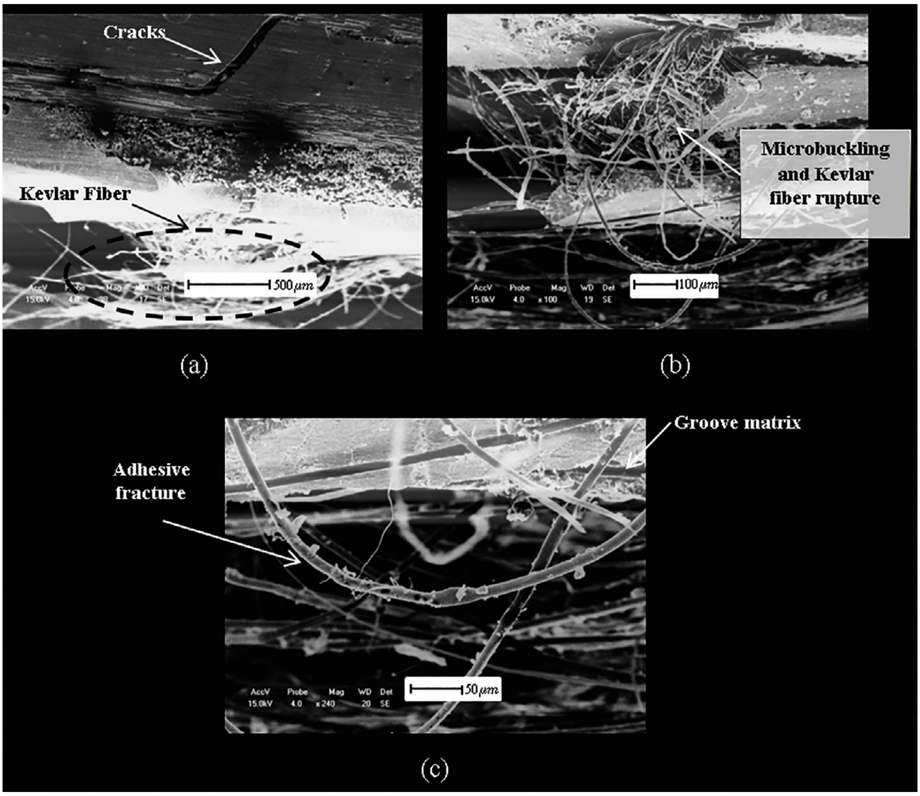


Figure 20. Fracture characteristics – HFCL laminate.

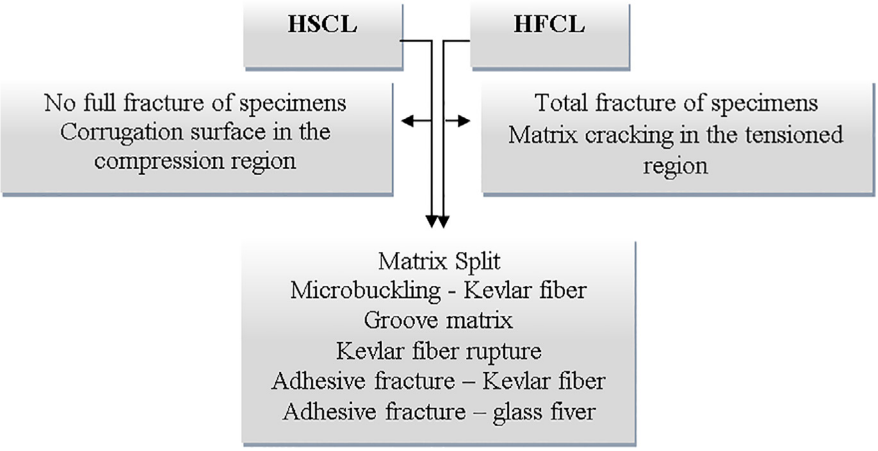


Figure 21. Flowchart: three-point bending test fracture characteristics.

initiation loads; and can be different depending upon the hybridization method;

- The **HFCL** laminate had a better three-point bending behavior when compared to the uniaxial tensile, showing that the hybridization method influences the mechanical behavior of laminates;
- The final macroscopic fractures of **HSCL** and **HFCL** laminates were the type **DGM** and **LGM** respectively according to ASTM D 3039 standard in the uniaxial tensile test;
- In the micrographic analysis of the fracture have been detected for all the tests and all the laminates the presence of common types of damage such as microbuckling of Kevlar fibers, glass fiber ruptures, cohesive fracture, adhesive fractures and cracks in the matrix. The influence of the hybridization method of reinforcement fabrics came in the formation and spread of damage, being different in **HFCL** and **HSCL** laminates.

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