PRESENCE OF HOLE UNDER TENSILE TEST IN FGRP: FRACTURE CHARACTERISTICS AND ANISOTROPY

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Abstract. *The damage mechanism of reinforced plastics may be present in many different ways, since it depends on many factors. Highlights may be given to the effect of stress concentration in the presence of geometric discontinuity in the sections of these structural elements, which in general always leads to certain characteristics of the fracture. In the case of plastics reinforced by glass fibers (**FGRP**) it is expected the same tendency, beyond the influence of reinforcement and its internal orientation in the layers (anisotropy). The aims of this research work is detailed study of the influence of the holes (longituninal section) in the characteristic fracture in composite laminates based on glass fiber-E. All the study is conducted to tensile loading. Three different configurations of composite laminates were studied: two reinforced with Eglassfiber bidirectional textil fabric and the other only with short mats, also Eglassfiber. The orthophthalic polyester resin was used in impregnation of composite laminates. The results showed the influence of all parameters listed above in the final characteristics of the fracture.*

Keywords*: Fiber Glass Reinforced Plastics, Fracture, Hole, Anisotropy.*

1. INTRODUCTION

The continuous search for new materials that combine high performance and easy conformation (manufacture) has been the focus of a large number of studies in recent decades. Composite materials and reinforced plastics have been important in these investigations, given that they meet these requirements as well as their added advantage of being low weight, an indispensable parameter in numerous structural applications.

Fiberglass reinforced polymer matrix composites (***FGRP***) are among the most widely used because of their varied properties and low fiber cost when compared with other synthetic fibers such as carbon and aramid.

Fracture characteristics of composite materials are strongly influenced by the properties of their components, such as type of reinforcement and matrix, proportion of these components and most importantly fiber distribution and orientation (anisotropy) (Herakovich, 1997). Anisotropy becomes a limiting factor when applying composite materials as laminar structure.

In addition to this complexity, the application of these elements may also exhibit sharp differences in the cross-sectional area, such as holes and notches. These types of geometric discontinuities are often necessary to establish links between structural project mechanisms and may generate serious problems in the distribution of internal stresses to the structural element, originating "stress concentration areas" (Zhao *et al.*, 2000; Yang and Pitchumani, 2004; Toubal *et al.*, 2005; Hufner and Accorsi, 2009; Pihtili, 2008). This phenomenon has a direct influence on final fracture, since it concentrates the fracture region in the geometric discontinuity section, primarily in polymer composites composed of a material considered "brittle" (Aquino and Tinô, 2009).

The effect of stress concentration becomes much more complex in composite materials, since it does not depend only on geometry and type of loading, as in conventional materials (Awerbuch and Adhukar, 1985; Nuismer and Whitney, 1975). For this reason, some theoretical and experimental models have been seeking to quantify it based on the damage zone, that is, the final fracture region (Shin and Wang, 2004).

This study investigates the influence of central holes in the longitudinal area (with a reduced cross-sectional area) on fracture characteristics of two composite laminates, under uniaxial tensile loading. The configurations of these laminates are defined as a composite laminate based only on E-glass (**ML**) fiber mats (short) with seven layers, whereas the other laminate is composed of bidirectional fabric of the same type of fiber (**FL**) and 4 layers. The influence of anisotropy is studied for the case of the **FL** composite, where different fiber orientations are observed in its layers in relation to the direction of the applied load. Fiber orientations in composites are defined as **FL ±45º** composite and **FL 0/90º** composite.

Fiber orientation in their layers (configuration) with respect to applied load direction may simultaneously influence the previously mentioned properties (Yeh and Rashid, 2006).

To make it easier to understand the properties under study, composites were defined as **ML** and **FL** for the case of composites without a central hole, while **HML** and **HFL** refer to composites with a central hole.

Finally, microscopic analyses of final fracture characteristics were conducted to understand the effect of a hole in the composite section on final fracture. Analyses were carried out using optical microscopy.

2. MATERIALS AND METHODS

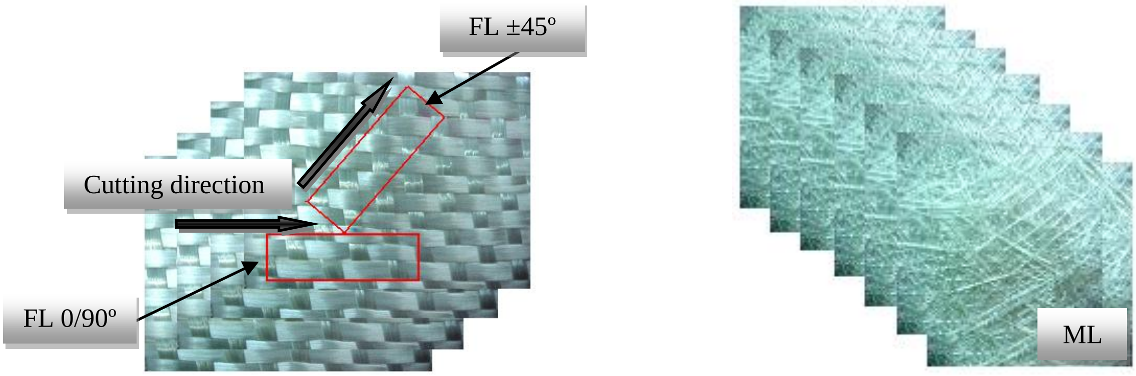
The hand layup process was used to manufacture the composite laminates, which were fabricated by Tecniplas Nordeste Indústria e Comércio Ltda in the form of two 1.0 m^2 plates. The raw materials used were orthophthalic polyester resin (Novapol L 120) as matrix and E-glass fibers as reinforcement. One plate was defined as a composite laminate of short E-glass fiber mats (450 g/m^2) denominated **ML**. The other plate was an E-glass fiber reinforced composite laminate with bidirectional fabric (600 g/m^2) designated **FL**. The **ML** plate was manufactured with seven layers and mean thickness of 5.0 mm, while the **FL** plate was built with only four layers and mean thickness of 3.7 mm.

The reason for choosing a smaller number of layers for the **FL** composite is due to an ASTM D5766-07 standard testing method requirement, stating that it is advisable to use a hole diameter (6.0mm)/laminate thickness ratio between 1.5 and 3.0. For the **ML** composite, the choice was based on the fact that this number of layers is traditionally used in industry, primarily in the manufacture of medium-sized reservoirs.

In the case of the **FL** composite, two configurations with different fiber layer orientations with respect to applied load direction were created: **FL 0/90º** and **FL ±45º**. It is important to underscore that for both **FL** composites the same plate was used to obtain test specimens and that the orientation of the **±45º** and **0/90º** fiber occurred as a function of cut direction, resulting in the anisotropy effect.

Test specimens destined for hole geometries were **HML, HFL 0/90º** and **HFL ±45º.** Holes were made by enlarging an initial 2.0 mm pre-hole to the standard diameter (ASTM D5766-07) of 6.0 mm. Diamond thread drills were used to avoid possible irregularities on the hole surface.

Figure 1 shows the test specimen cutting scheme for the **FL** configuration of both study composites.



(a) (b)

Figure 1. (a) Configurations and cut direction for **FL 0/90º** and **FL ±45º** composites, (b) **ML** composite configuration

After appropriate test specimen dimensions were obtained, the regions where the cut was applied were smoothed and polished.

Displacement velocity in uniaxial tensile testing was 1.0 mm/min (standard) for all test specimens. All tests were carried out at ambient temperature using a mechanical universal testing machine (Shimadzu AGI-250 KN) with maximum capacity of 25 T.

Dimensions of test specimens without a hole were defined by ASTM D 3039-08, while for those with a hole ASTM D 5766- 07 was used. All composites had a useful length (gage) of 127 mm and widths of 36mm (**HML**, **HFL 0/90º**, **HFL ±45º**) and 25 mm (**ML**, **FL 0/90º**, **FL ±45º**). All test specimen dimensions were within the standard tolerance of ±1%.

Microscopic and macroscopic analyses in the fracture region of the test specimens were conducted to study final fracture characteristics (pre-fractured specimens). An Olympus MG optical microscope was used for microscopic analysis.

3. RESULTS AND DISCUSSION

3.1. Fracture analysis of composites without hole

Figure 2 shows some of the post-test specimens of the **ML** composite. Damage was concentrated in the final fracture region, with no significant variations observed in other areas.

According to ASTM D 3039-08, **LGM** (Lateral Gage Middle) was the type of fracture observed, which is perfectly valid for the test.

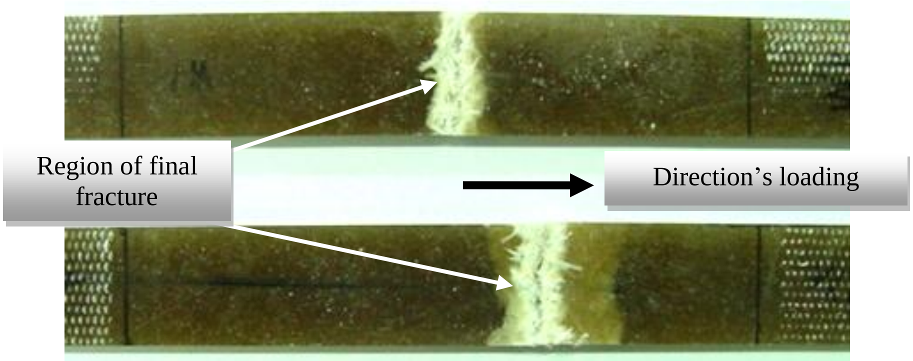
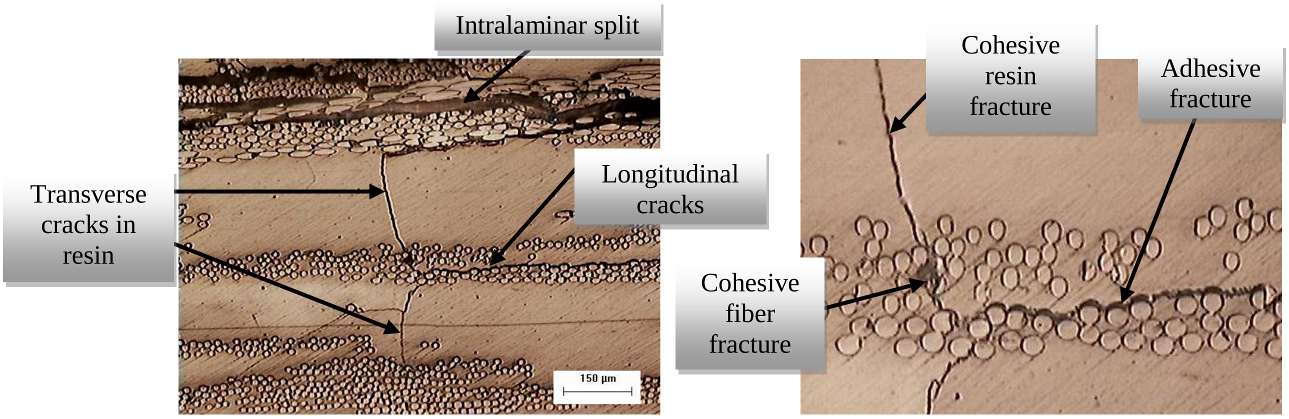


Figure 2. Post-test specimens of the **ML** composite.

The fragile fracture in the **ML** composite exhibited maximum deformation of 4% of final fracture. Figure 3(a) depicts an optical micrograph of a region near the final fracture, showing cracks spreading through the fiberglass layers.

Figure 3(b) shows that cracks initially spread perpendicularly to load direction, then become intralaminar split spreading in the direction of the applied load (longitudinally). It was also observed that when cracks spread longitudinally they caused a "rupture or non-adhesion" on the fiber/matrix interface, characterizing adhesive fracture.

Cracks that spread only in the matrix are called cohesive matrix fractures and those that cross fibers longitudinally are known as cohesive fiber fractures (Fig. 3b).



(a) (b)

Figure 3. (a) Region near final fracture, (b) cohesive and adhesive fracture near final fracture region – Uniaxial tensile of **ML** composite.

The **ML** composite showed no interlayer delamination, which was expected since it is composed only of fiberglass mats, causing little discrepancy between interlaminar stresses.

Fractures in the **FL 0/90º** composite initiated with progressive cracking perpendicular to load application, spreading along the entire length of the test specimen (Fig. 4), exhibiting a state of saturation before the final fracture. They also displayed fiber pull-out phenomenon in the final fracture region, characteristic damage in fabric-based polymer composites. This fiber pull-out becomes noticeable after test specimens are removed from the machine clamps.

Figure 5 shows the final fracture region of the **FL 0/90º** composite, which according to ASTM D 3039-08, is the **LGM** mode and therefore valid for this type of test.

In addition to matrix cracking, microscopic fracture analysis revealed adhesive fractures, delamination and fiber pull-out.

Optical microscopy showed that delaminations occur when transverse cracks in the matrix spread to the interface between composite laminate layers (Fig. 6a). The adhesive fracture (non-adhesion to the fiber/matrix interface) is shown in Fig. 6(b).

Despite the existence of manufacturing defects in the composite (Fig. 6b), they caused no damage during loading, even though an adhesive fracture was observed very close to them, but in a region without any apparent damage.

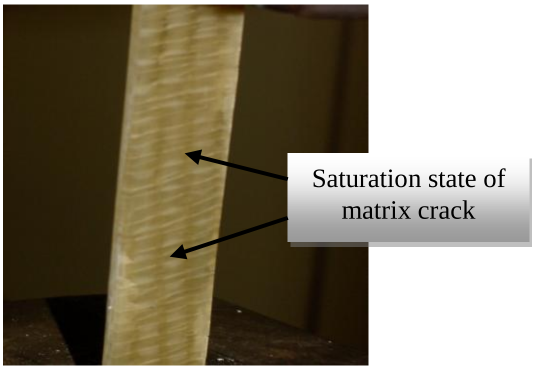


Figure 4. Saturation state of transverse matrix cracking in the **FL 0/90º**composite.

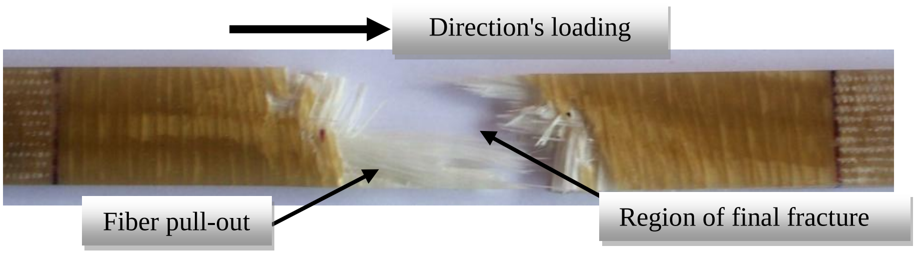
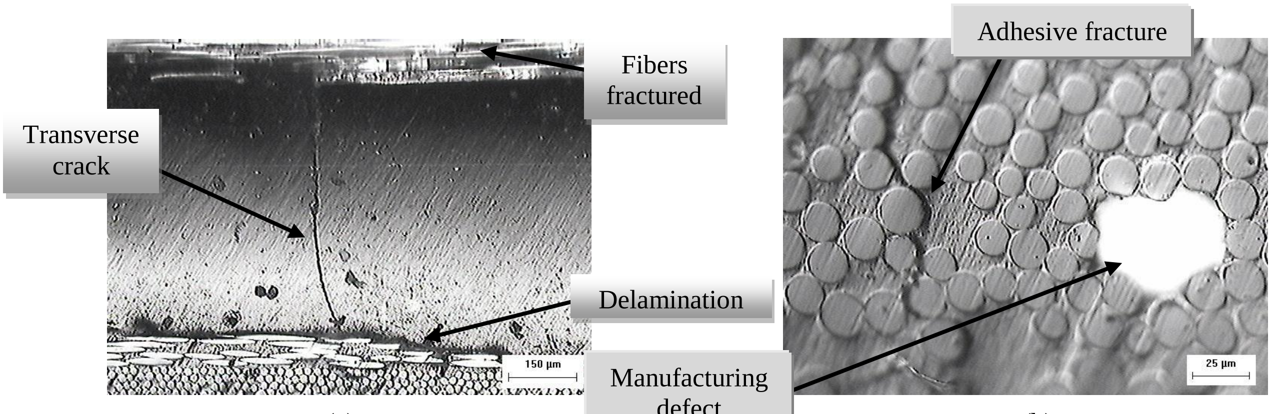


Figure 5. Final fracture characteristics of the **FL 0/90º** composite test specimen**.**



(a) (b)

Figure 6. (a) Fracture characteristics, (b) adhesive fiber fracture and manufacturing defect. **FL 0/90º** composite.

Fracture characteristics of the **FL ±45º** composite were similar to those of the **FL 0/90º** composite, that is, cracking in the entire matrix occurs progressively, exhibiting a saturation state before final fracture (Fig. 7). Being a fabric-reinforced composite, it also displayed the fiber pull-out phenomenon (Fig.7), although less intense than the **FL 0/90º** composite**.** According to ASTM D 3039-08 an **LGM** fracture was also observed in the composite.

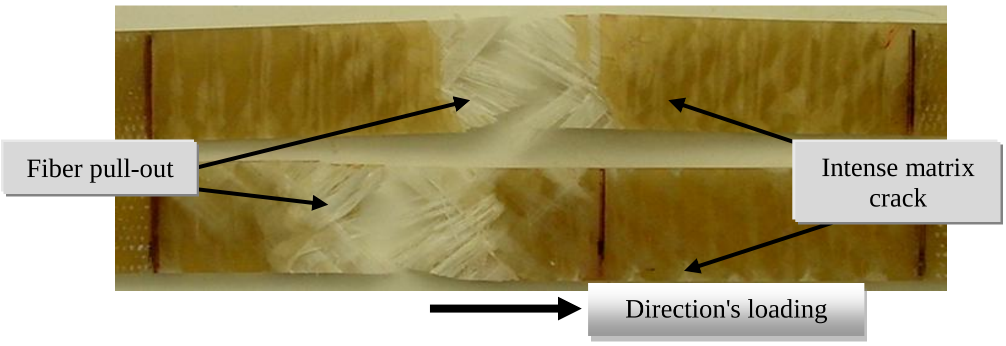


Figure 7. Macroscopic fracture analysis the **FL ±45º** composite.

Microscopic fracture analysis of this composite showed no interlayer delaminations. All cracks occurred at 45º (Fig. 8), in the direction of shear and fiber orientation. As cracks spread they gave rise to adhesive and cohesive fractures (matrix and fibers), as well as splits between strand intersections.

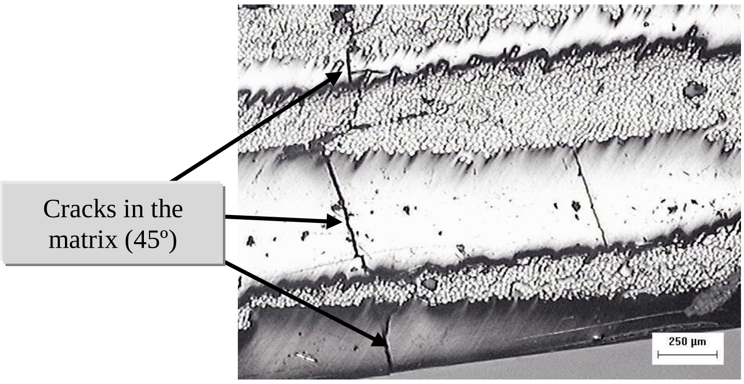


Figure 8. Microcracks at 45º in the **FL ±45º** composite.

An important characteristic of this composite was the presence along the entire length of the test specimens of split in the strand intersections region due to strong shearing that occurs in the reinforcement direction at 45º. Figure 9 demonstrates the effect of this strand intersections fragility owing to longitudinal and interlaminar splits. It was also observed that adhesive fractures in the fiber/matrix interface and cohesive fractures in the fiber and matrix originate in these splits.

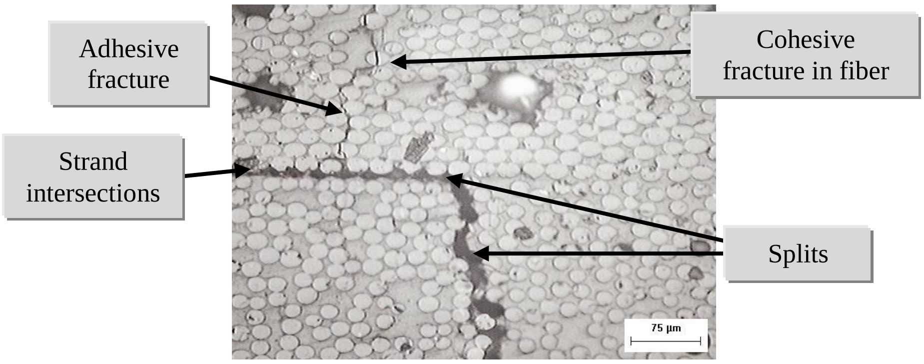


Figure 9. Splits, adhesive and cohesive fractures in the **FL ±45º** composite.

3.2. Fracture analysis for composites with hole

Macroscopic analysis of final fracture characteristics for the **HML** composite showed localized damage, which was expected due to the type of reinforcement used (randomly distributed short fiber mats).

This fracture is classified as **LGM** and is valid only if it is located in the hole section, owing to the stress concentration effect that occurs there. Figure 10 shows final fracture characteristics of the **HML** composite after the uniaxial tensile test.

This type of composite can be considered to have macroscopically isotropic behavior in relation to elastic properties (characteristic of deformation). Damage that occurred in the **HML** was concentrated in the cross-section where the hole is located, according to ASTM D 5766-07 standard testing. Figure 11 shows a micrograph of the final fracture region of the **HML** composite, where a very high concentration of cracks can be observed in the matrix along with the presence of splits.

The macroscopic study of final fracture characteristics for the **HFL 0/90º** composite shows damage that initiates with matrix cracks, transverse to the applied load, which spread progressively along the entire length of the test specimen, exhibiting saturation state before final fracture.

Thus, as with the **HML** composite, the final fracture (**LGM** mode) in the **HFL 0/90º** composite occurs in the hole section, as foreseen in the standard.

Figure 12 depicts the test specimen after uniaxial tensile testing of the **HFL 0/90º** composite. Macroscopic analysis of fracture characteristics shows the fiber pull-out phenomenon, typical of fabric-reinforced composites.

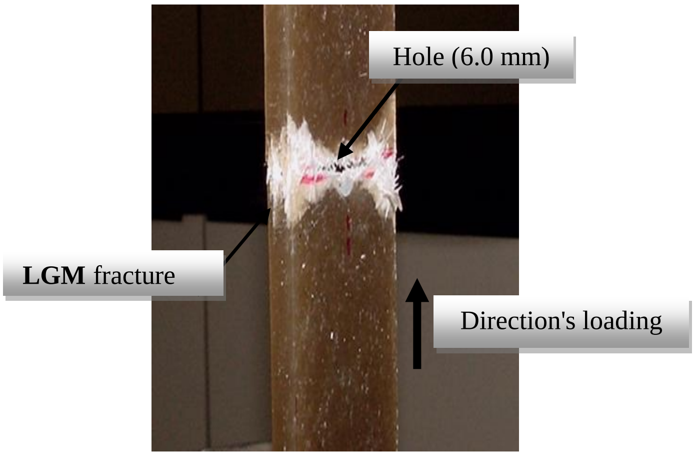


Figure 10.. Post-test final fracture characteristics – **HML** composite.

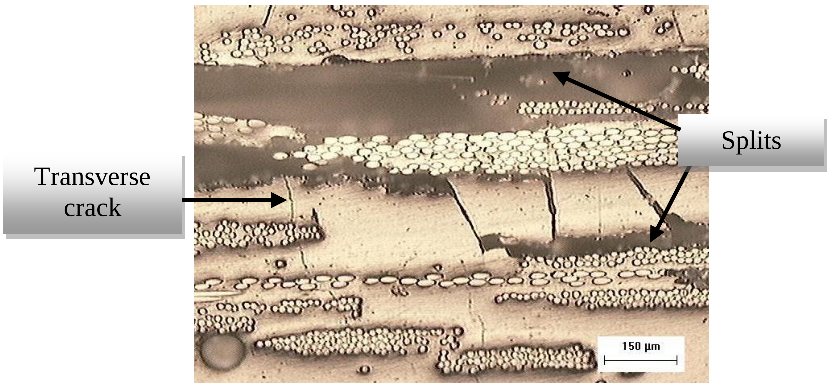


Figure 11. Splits and transverse cracks in the **HML** composite.

It is also important to note that the presence of a hole in the composite did not significantly alter final fracture behavior when compared to the **FL 0/90º** composite. However, as shown in Fig. 13, the final fracture region is saturated in the matrix, underscoring that these transverse cracks are more intense in the hole region, characterizing the stress concentration phenomenon. Microscopic analysis of the **HFL 0/90º** composite shows high concentration of splits in the final fracture region of the matrix (Fig.14).

Figure 15 shows a test specimen during uniaxial tensile testing of the **HFL ±45º** composite, in which cracks initially form in the hole section, where stresses are concentrated.

Macroscopic analysis of final fracture characteristics for the **HFL ±45º** composite also shows damage initiating with matrix cracks (Fig. 15). These progressively spread along the entire test specimen, behavior that repeated itself for all bidirectional fabric-reinforced composites, with or without a hole. This composite also exhibited matrix crack saturation before final fracture.

Final fracture of the **HFL ±45º** composite (**LGM** mode) was concentrated in the hole section, in accordance with the standard, that is, lateral in the middle of the gage, which is perfectly valid for this test (Fig. 16).

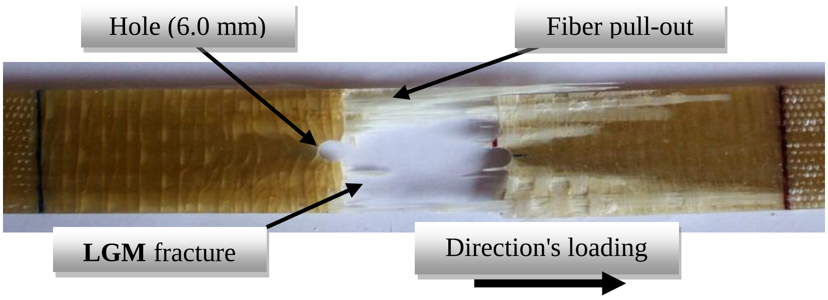


Figure 12. Final fracture region - **HFL 0/90º** composite.

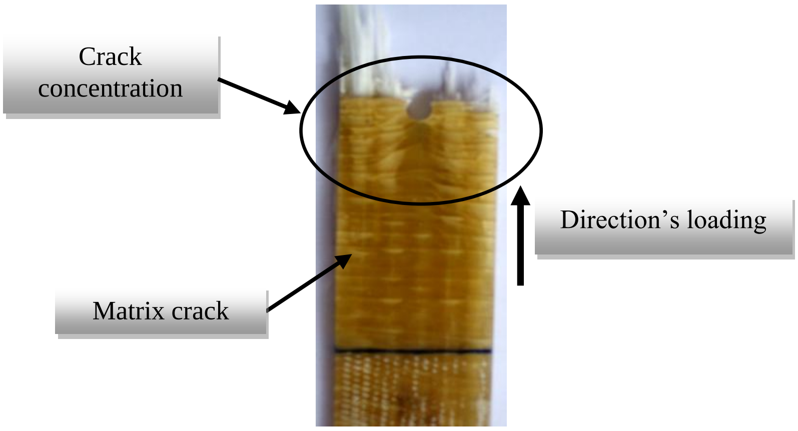


Figure 13. Matrix cracks in the **HFL 0/90º** composite.

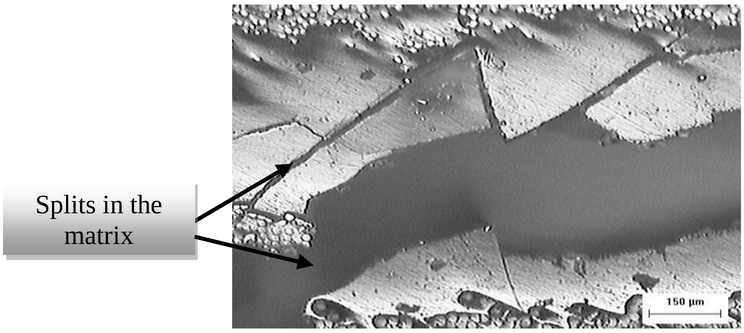


Figure 14. Splits in the matrix. **HFL 0/90º** composite.

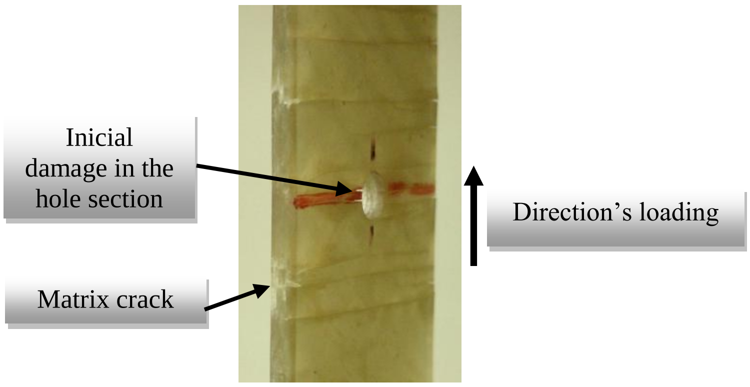


Figure 15. Initial damage in the hole section - **HFL ±45º** composite.

Figure 16 shows final fracture characteristics in the hole section for the **HFL ±45º** composite. Fiber pull-out was also observed in all fabric-reinforced composites studied here (Fig.16).

With respect to microscopic analysis, Fig. 17 shows that, in addition to reaching the reinforcement layer (intralaminar crack), initial cracking provoked matrix cracks that spread at approximately 45º, following fiber orientation.

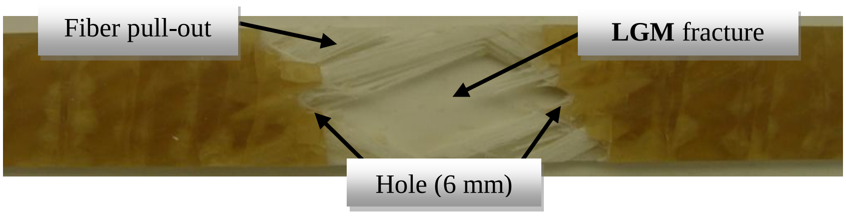


Figure 16. Fiber pull-out phenomenon in the **HFL ±45º** composite.

Figure 17. Matrix cracks in the reinforcement direction - **HFL ±45º** composite.

3.3. Comparison of fracture characteristics for the composites analyzed

Figure 18 shows fracture characteristics observed in the composites under study, with the aim of determining the influence of the hole and/or anisotropy existing in the composite composites.

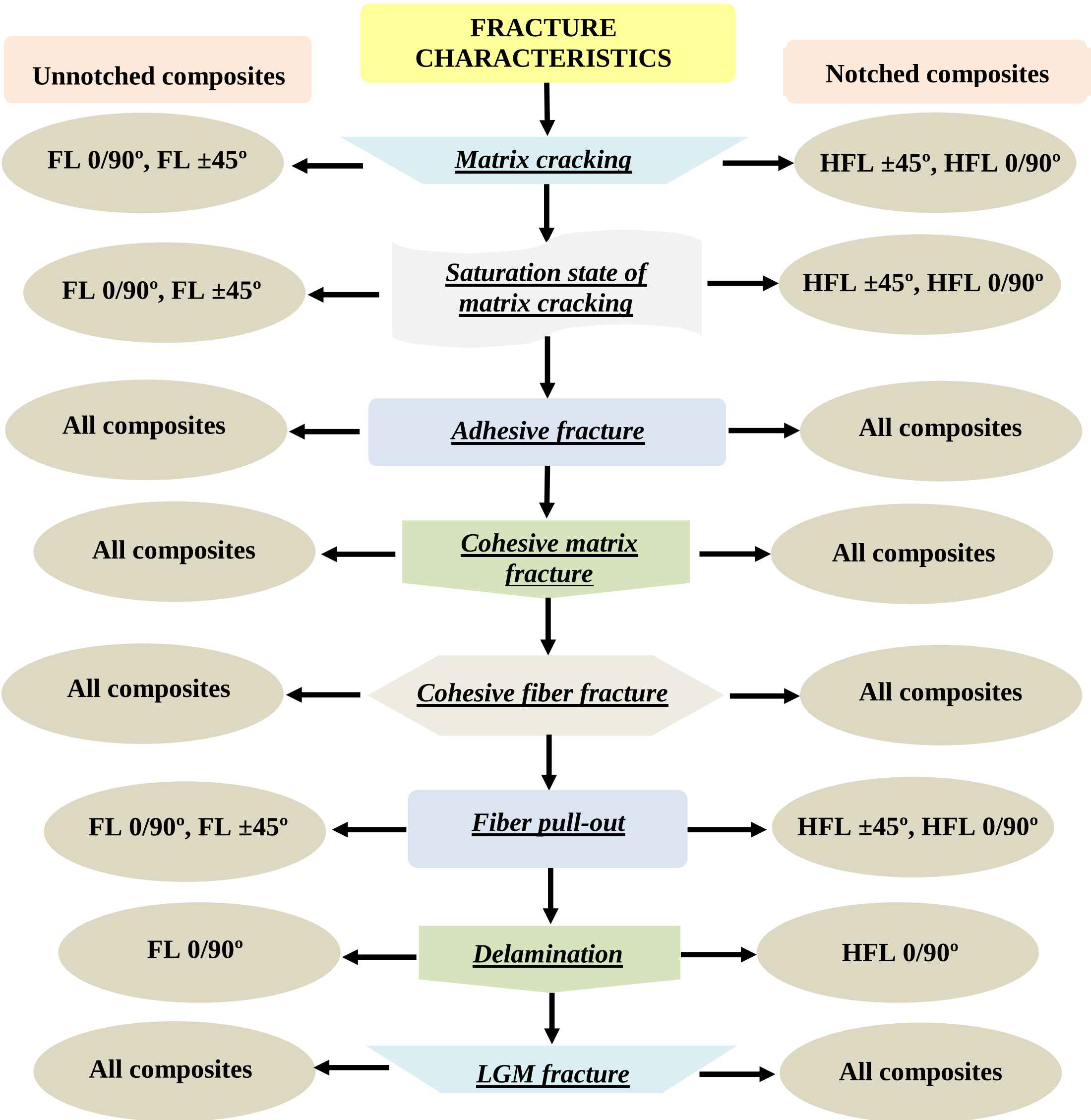


Figure 18. Comparison of damage mechanisms in the composites under study.

The presence of a center hole in the composites analyzed did not significantly change final fracture characteristics, but rather how it spread along the entire length of the test specimens. In the case of test specimens with geometric discontinuity, fractures were concentrated in the region near the hole, where matrix cracks were spaced closer together due to the effect of stress concentration.

With respect to the configurations used, there were significant differences when all the composites were compared, given that fiber pull-out was only observed in composites with anisotropy. Delamination, another fracture characteristic, was observed only in the **FL 0/90º** composite.

4. CONCLUSIONS

The **ML**, **HML, FL 0/90º, HFL 0/90º, FL ±45º** and **HFL ±45º** composite fractures generally exhibited **LGM** mode final fracture. The Micrographic fracture analysis showed the presence of cohesive matrix and fiber fractures and adhesive (fiber/matrix interface) fractures in the other composites studied, since delaminations (non-adhesion between laminate layers) occurred only in **FL 0/90º** and **HFL 0/90º** composites.

With regard to fracture behavior of the laminates under study, intense cracking was observed in the matrix along the entire length of the test specimen only in bidirectional fabric-reinforced composites, with characteristics peculiar to the composite at **±45º**, where cracking occurred in the reinforcement direction due to shear forces in the direction of the reinforcement used.

The matrix saturation occurs only in fiberglass fabric-based composites, irrespective of a hole, but is more concentrated in the hole section, owing to the effect of stress concentration, while the pull-out phenomenon was recorded only in the fiberglass fabric-based composite (anisotropic).

In general form, the comparative study of fracture characteristics shows that the presence of a hole was more significant for anisotropic composites (**FL 0/90º and FL ±45º**), giving rise to a more intense fracture process.

5. ACKNOWLEDGEMENTS

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5. RESPONSIBILITY NOTICE

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