INFLUENCE OF THE RATIO D/h ON THE MECHANICAL PROPERTIES AND FRACTURE OF HYBRID COMPOSITE LAMINATE

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Abstract. *The concept of composite materials is based on materials development, optimizing key parameters of structural performance, such as light weight, low cost, easy processing and high mechanical response. The use of polymer composites has been increasing as an alternative to conventional materials, especially when dealing with hybrid composites (combination of different types of reinforcements), particularly when they involve natural and synthetic fibers. The increasing demand for the use of these materials requires better understanding of their mechanical behavior under various design conditions, such as the presence of geometric discontinuities in their cross and/or longitudinal sections, including varied shapes and sizes. Thus, the purpose of this study is to study the influence of the d/H ratio on the mechanical properties and fracture characteristics of a hybrid composite laminate, with different holes in its longitudinal section. This study is based on the variation of the hole diameter to thickness ratio of the laminate (D/h) and was conducted with a hybrid composite laminate using uniaxial tensile tests. The laminate is made of orthophthalic polyester matrix reinforced with bidirectional fabrics of jute and E-glass fibers. All tests were performed according to ASTM D3039-08 and ASTM D5766-07 standards.*

Keywords*: Hybrid Composites, Notch, Mechanical Properties, Fracture.*

1. INTRODUCTION

Composite materials and mainly polymer matrix-based composites have been important in recent decades, since they exhibit good structural performance, low cost and the added advantage of low weight, an indispensable parameter in many structural applications.

The mechanical response of composite materials is strongly influenced by the properties of their components, such as types of reinforcements and matrices, percentage of each component and primarily fiber orientation distribution (anisotropy) (Herakovich, 1997). In addition to this complexity, applications of these structural elements may also represent abrupt variations in the cross-sectional area, such as a wide variety of holes, cracks and notches. These geometric discontinuities are often required to connection of structural mechanisms.

However, they may cause serious problems in internal stress distribution to the structural element, giving rise to “areas of stress concentration” (Feraboli et al, 2009; Wu and Mu, 2003; Toubal et al, 2005; Hufner and Accorsi, 2009; Pihtili, 2008). This phenomenon has a direct influence on the mechanical response of an element, mainly if it is composed of a material with good brittle behavior such as polymer composites in general (Aquino and Tinô, 2009).

This study aimed to study the influence of discontinuity in the longitudinal cross-section area (with a reduced cross section) of a polymer matrix-based hybrid composite on mechanical properties (strength and stiffness) and fracture characteristics. These properties were studied under uniaxial tensile loads, according to ASTM D 5766-07.

The hybrid composite laminate in question, defined as **CH**, is composed of an orthophthalic polyester matrix reinforced by 1 central layer of bidirectional E-glass fabric (600 g/m²) and 4 adjacent layers of bidirectional jute fiber fabrics (306.10 g/m²). The configuration proposed here was designed for femoral prosthesis application (Queiroz, 2008). The composite was industrially manufactured (Tecniplas Nordeste Indústria e Comércio Ltda.) and obtained using the hand-lay up process. The geometric discontinuity under study is a central hole located in the longitudinal-section (with reduction cross-section) of test specimens.

To conduct this study, it was important to define a parameter related to loss of ultimate tensile strength in the laminate induced by the presence of geometric discontinuity in the material. According to Lin Ye et al. (1998), this parameter is called Residual Strength (RS).

In addition to studying the influence of a central hole on the laminate in question, will also investigate the influence of a variation in hole diameter/ laminate thickness ratio (*D/h*), according to ASTM D 5766-07. It is important to underscore that, according to this standard, there is a preferential ratio for this parameter, but it may vary if the experiment is to investigate its influence, as is the case here. Another ratio specified by the standard is the test specimen width/hole diameter ratio (*w/D*), which must be maintained at 6.0 (six), unless the experiment is to investigate the effect of varying this parameter. This ratio was not altered in the present study.

The mechanical properties studied, such as ultimate tensile strength and Young's modulus (in the direction of the applied load), as well as fracture characteristics, were determined from the static uniaxial tensile test. Tests were conducted for three different types of specimens. The specimens without the presence of hole (normal), defined as **CHN**, and the specimens with two different dimensions to the diameter of the hole. In the latter case, the specimens are defined as **CH6** (hole of 6.0 mm and a width of 36.00 mm) and as **CH7. 5** (hole of 7.5 mm and a width of 45.00 mm). It is important to point out that in both cases, the width/diameter ratio of the hole (*w/D*) was kept constant at 6.0.

To illustrate the influence of the hole, a comparative study of Residual Strength was conducted, where **CHN** test specimens were compared with **CH6** and **CH7.5** specimens. To study the influence of varying the *D/h* ratio, another comparative study was carried out, relating tensile strength and stiffness, where **CH6** and **CH7.5** test specimens were compared.

2. MATERIALS AND METHODS

2.1. Laminate configuration

Configuration of the hybrid laminate composite involves the presence of 1 central layer of bidirectional E-glass fabric (600 g/m²) and 4 adjacent layers of bidirectional jute fiber fabric (306.10 g/m²). NOVAPOL L120 orthophthalic polyester resin was used to manufacture the laminates.

The manufacturing (industrial) process used was hand lay-up. The **CH** laminate configuration is illustrated in Fig. 1, where 0/90º and ±45º refers to fiber orientation in the direction of the applied load. The fabrics are called **GFF** and **JFF**, for bidirectional glass fiber fabric and bidirectional jute fiber fabric, respectively.

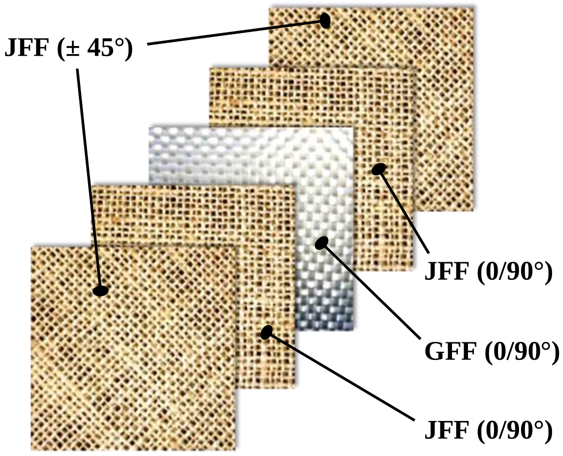

Figure 1: Configuration of Hybrid Composite Laminate **- CH**.

2.2. Specimen cutting and preparation

After the appropriate test specimen dimensions were obtained, the regions where the cutting disk was applied were polished with sandpaper. Since laminate thickness showed variations depending on manufacturing process used, at least 5 measures were needed in the gage region to obtain mean dimension values (width and thickness) of each test specimen.

Dimensions of test specimens with no central hole (**CHN**) were determined using ASTM D 3039-08, while those with a central hole (**CH6** and **CH7.5**) used ASTM D 5766-07, with a *w/D* ratio defined by the standard (6.0). All laminates had a useful length (gage) of 127 mm and widths of 25 mm (**CHN**), 36 mm (**CH6**) and 45 mm (**CH7.5**). It is important to point out that all test specimen dimensions are within the dimensional tolerance required by the standard ±1%.

To obtain holes in the **CH6** and **CH7.5** test specimens, a pre-hole was made using a 2.0 mm drill, followed by widening with a 6.0 mm (**CH6**) and 7.5 mm drill (**CH7.5**). Diamond wire drills were used to avoid possible irregularities on the hole surface. The *D/h* ratio of the **CH6** and **CH7.5** test specimens was 1.16 and 1.44, respectively.

Fig. 2 shows test specimen models for all types of composite laminates studied. Even though the total length of the CHN laminate (Fig. 2a) is greater, its useful length is the same as that of other laminates (127 mm). The modification, therefore, occurred only with better test specimen fit in the machine clamps.

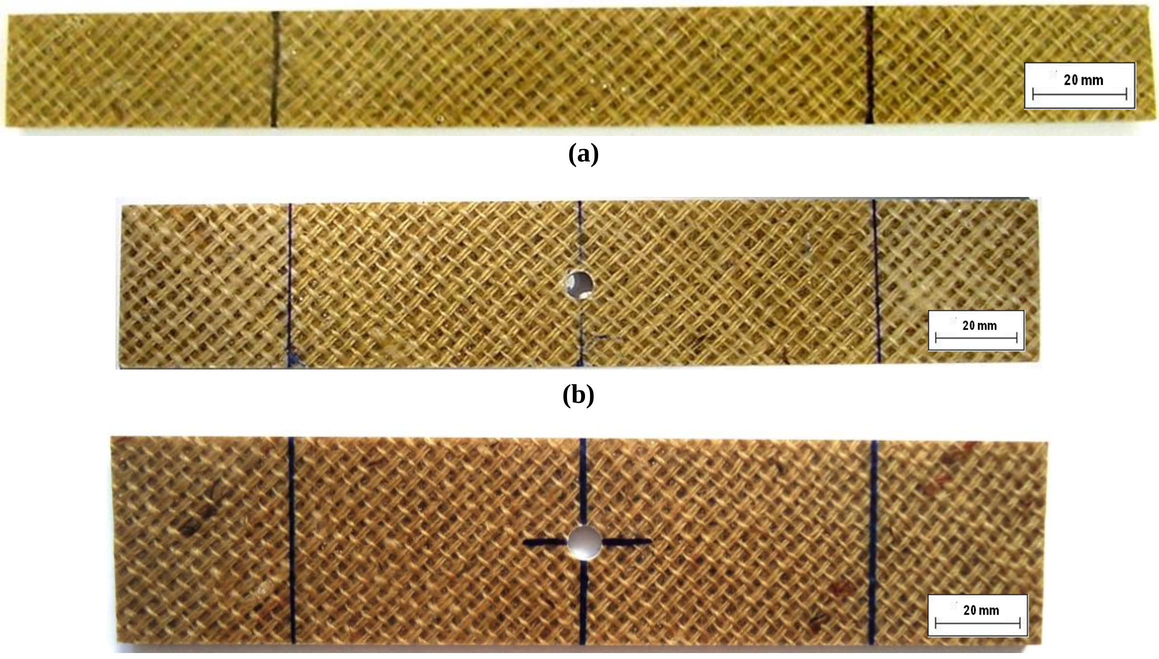

Figure 2: Test specimens used in the tests: (a) **CHN**; (b) **CH6**; (c) **CH7.5**.

2.3. Tensile Test

The uniaxial tensile test was conducted to find tensile strength and Young's modulus (in the direction of the applied load) of the laminate under different experimental conditions. To that end, 8 test specimens were manufactured for each condition (**CHN**, **CH6** and **CH7.5**), and 5 tests were considered valid according to the technical standard.

Tests were performed using the Shimadzu AGI-250 KN mechanical universal testing machine, with maximum capacity of 250 KN.

It is important to underscore that, according to ASTM D 5766-07, the tensile strength of **CH6** and **CH7.5** laminates is determined in the largest cross-sectional area. In accordance with the standard, displacement velocity for all test specimens was 1.0 (one) mm/min. All tests were carried out at ambient temperature (25 ± 2) °C.

The effect of reduced tensile strength in the laminate, due to the presence of a central hole, will be studied using the Residual Strength (RS) value of the composite laminate, defined by Eq. (1).

$$RS = \frac{\sigma_{CD}}{\sigma_{SD}} \quad (1)$$

Where: $\boldsymbol{\sigma_{CD}}$ is the tensile strength of the material with geometric discontinuity (calculated in the largest cross-sectional area); and $\boldsymbol{\sigma_{SD}}$ the tensile strength of the material without discontinuity.

2.4. Fracture analysis in mechanical testing

Macroscopic analysis was conducted to study final fracture characteristics (fractured test specimens) under all the study conditions, in accordance with ASTM D 3039-08 and ASTM D 5766-07 standard test methods.

3. RESULTS AND DISCUSSION

3.1. Uniaxial tensile test for CHN test specimens

Fig. 3 shows the stress-strain diagram obtained in the uniaxial tensile test of **CHN** test specimens. The behavior between stress and strain can be considered linear elastic, a common characteristic of polymer matrix composite materials (Aquino et al, 2007).

Tensile strength (MPa) and Young's modulus (GPa) mean values (determined in the direction of the applied load) are given in Tab. 1. The dispersion values, characterized by the absolute difference between maximum and minimum values of these parameters, are also shown. The Young's modulus of the laminate was determined using stress and strain values prior to damage onset in order to avoid their possible influence on the results.

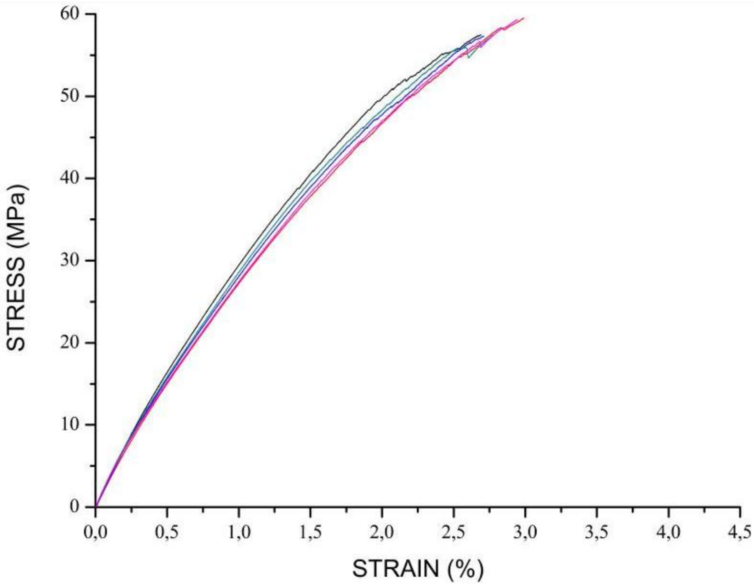

Figure 3: Stress x strain diagram in uniaxial tensile test – **CHN** test specimens.

Table 1. Mechanical properties obtained for **CHN** test specimens in uniaxial tensile test.

MECHANICAL PROPERTY	Mean Value	Dispersion (%)
Tensile Strength (MPa)	**58.2**	3.7
Young's Modulus (GPa)	**2.7**	10.2

Results show that tensile strength and Young's modulus dispersions are considered within the limits established for hybrid composite laminates (Oliveira et al, 2007; Rodrigues et al, 2009). It should be underscored that the presence of fibers with different mechanical and physical properties in the manufacturing process of composite laminates may result in high dispersions compared to laminates reinforced with the same type of fibers, primarily synthetic fibers (Tinô, 2010).

3.1.1. Fracture characteristics of CHN test specimens

Macroscopic analysis of the fracture characteristics of **CHN** test specimens shows little cracking in the matrix, perpendicular to the direction of the applied load and along the useful length of the test specimen, causing an extremely localized fragile fracture in the case of jute fiber layers. On the other hand, the pullout phenomenon can be observed in the central glass fiber layer, characteristic damage in fabric-based polymer composites (Aquino and Tinô, 2009). It is important to remember that this pullout becomes visible after test specimens are removed from the machine clamps.

Fig. 4 shows the final fracture region of **CHN** test specimens, which, according to ASTM D 3039-08, is a lateral gage middle (**LGM**) fracture and therefore, totally valid for this type of test.

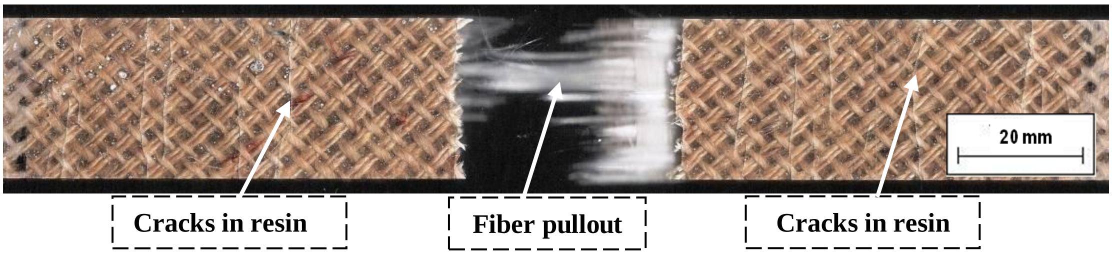

Figure 4: Final fracture region of a **CHN** test specimen.

3.2. Uniaxial tensile test for CH6 test specimens

In contrast to what occurred with **CHN** test specimens, **CH6** do not exhibit linear elastic behavior between stress and strain until fracture. Fig. 5 shows the stress x strain diagram for these test specimens, showing that the presence of a hole has a clear influence on final laminate behavior. Tab. 2 exhibits the mechanical properties mean values and their respective dispersions.

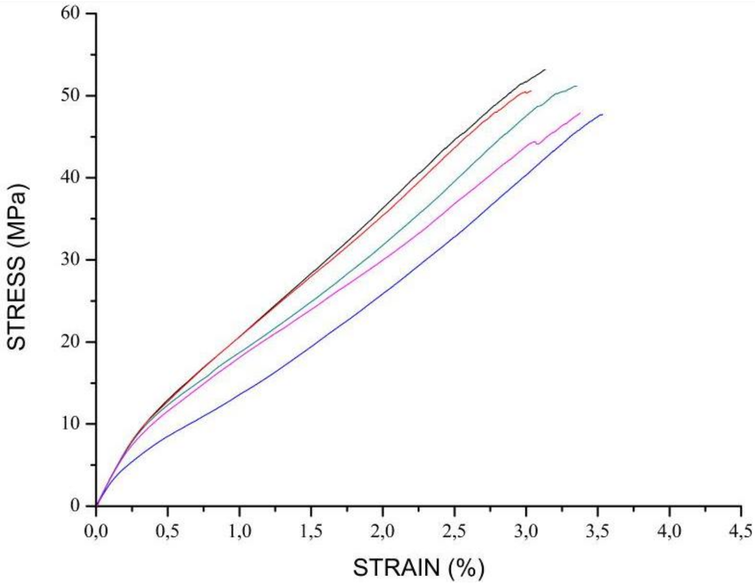

Figure 5: Stress x Strain diagram in uniaxial tensile testing **- CH6** test specimens.

Table 2. Mechanical properties obtained for **CH6** test specimens in uniaxial tensile testing.

MECHANICAL PROPERTIES	Mean Value	Dispersion (%)
Tensile Strength (MPa)	50.1	10.2
Young's Modulus (GPa)	1.4	21.2

Comparison of dispersion values with those found for **CHN** shows that the latter obtained higher values, that is, in accordance with the non-uniformity observed in the **σ x ε** curves.

3.2.1. Fracture characteristics of CH6 test specimens

As observed for **CHN** test specimens, analysis of **CH6** macroscopic fracture characteristics (Fig. 6) shows little cross-sectional cracking and extremely localized damage; in this case in the region around the hole. Tearing can also be observed in the central layer of the glass fibers. In this case, according to ASTM D 5766-07, an **LGM** fracture occurred, which is perfectly valid.

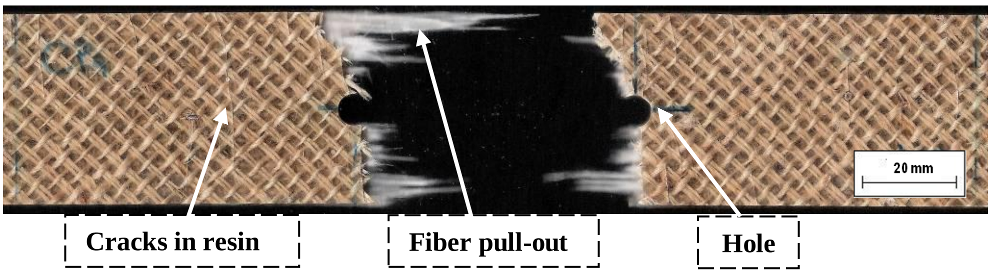

Figure 6: Final fracture region of a **CH6** test specimen.

3.3. Uniaxial tensile test for CH7.5 test specimens

Similar to the results obtained for **CH6** test specimens, **CH7.5** showed no linear elastic behavior stress and strain. Fig. 7 shows the stress x strain diagram obtained in the uniaxial tensile test for these test specimens. Once again, the influence of the hole, characterized by non-uniformity in stress x strain curves, can be observed. Tab. 3 shows the mean values obtained for mechanical properties and their respective dispersions.

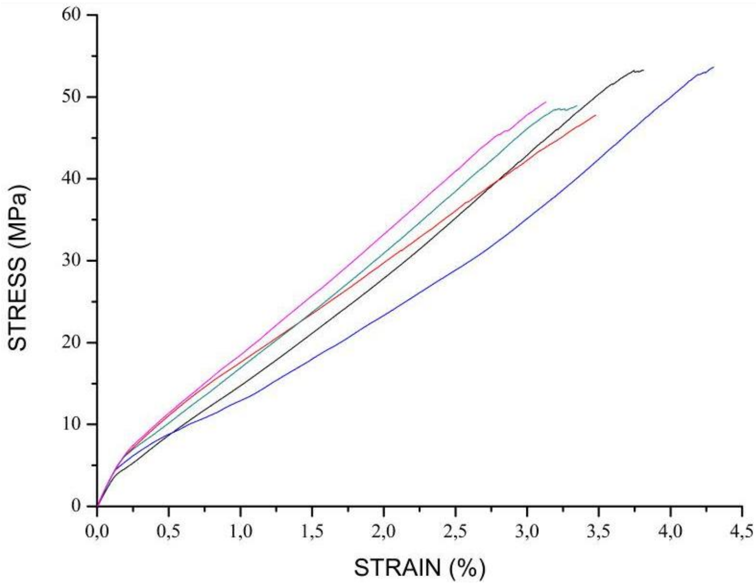

Figure 7: Stress x Strain diagram obtained for **CH7.5** test specimens.

Table 3. Mechanical properties obtained for **CH7.5** in uniaxial tensile testing.

MECHANICAL PROPERTY	Mean Value	Dispersion (%)
Tensile Strength (MPa)	50.6	10.9
Young's Modulus (GPa)	1.3	23.7

Dispersion values are consistent with those found for **CH6**, showing similar behavior and dependent on the presence of the hole.

3.3.1. Fracture characteristics for CH7.5 test specimens

Macroscopic fracture characteristics for **CH7.5** test specimens (Fig. 8) exhibit identical behavior to that of **CH6**. ASTM D 5766-07 shows little cracking in the matrix, glass fiber tearing and **LGM** fracture.

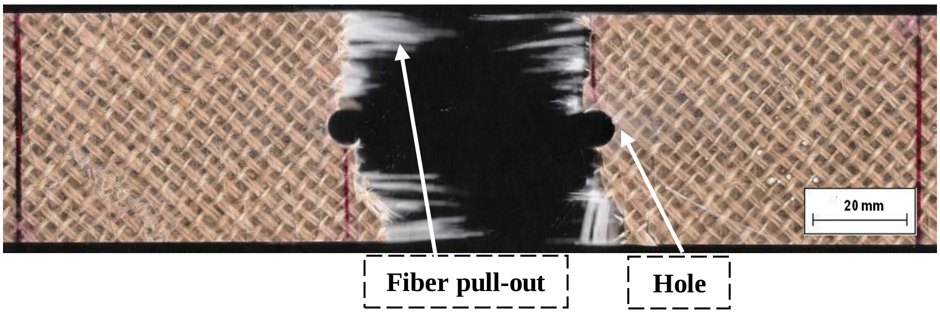

Figure 8: Final fracture region of a **CH7.5** test specimen.

3.4. Influence of geometric discontinuity

With respect to ultimate tensile strength, analysis based on RS (Eq. (1)) was conducted for each condition to determine the influence of a central hole. Residual Strength for **CH6** test specimens was:

$$RS_{CH6} = \frac{\sigma_{CD_{(CH6)}}}{\sigma_{SD}} = \frac{50.1}{58.2} = 0.861$$

Results show a loss of tensile strength of 13.9 %, when **CH6** was compared with **CHN**. This value confirms the negative influence of the hole and a direct consequence of the stress concentration phenomenon, extremely localized in the vicinity of the hole and characterized by discontinuity in stress distribution (Shigley and Mischke, 2002).

Residual Strength for **CH7.5** test specimens was:

$$RS_{CH7,5} = \frac{\sigma_{CD_{(CH7,5)}}}{\sigma_{SD}} = \frac{50.6}{58.2} = 0.869$$

In this case, loss of tensile strength was 13.1 % when **CH7.5** was compared with **CHN**. Geometric discontinuity showed the same behavior in the **CH6** laminate, underscoring the importance ratio of maintaining the *w/D* ratio established in the standard constant.

Comparison of Young's modulus between **CH6** and **CHN**, demonstrates that the presence of a central hole caused a loss of 48.1 %. When **CH7.5** is compared with **CHN**, the loss was 51.8 %. These losses, exhibited by both **CH6** and **CH7.5**, showed a complex behavior with respect to the central hole and deformation capacity of this laminate, thereby reducing its stiffness.

In general, the presence of elements that can concentrate stress in composite materials must be considered in any configuration, regardless of its degree of anisotropy or the presence of hybridization. This is despite the fact that Feraboli et al (2009) consider that stress concentration for discontinued pre-impregnated carbon/epoxy is due to material heterogeneity and not to the existence of geometric discontinuity. They therefore consider the material to be notch insensitive.

3.5. Influence of D/h ratio

A global and comparative diagram of all the test specimens (Fig. 9) was created to better illustrate the influence of the *D/h* ratio. Neither case with a central hole (**CH6**: *D/h* = 1.16; **CH7.5**: *D/h* = 1.44) showed an influence of this parameter, given that the differences for both Young's modulus and tensile strength were within the dispersion ranges obtained in the tests.

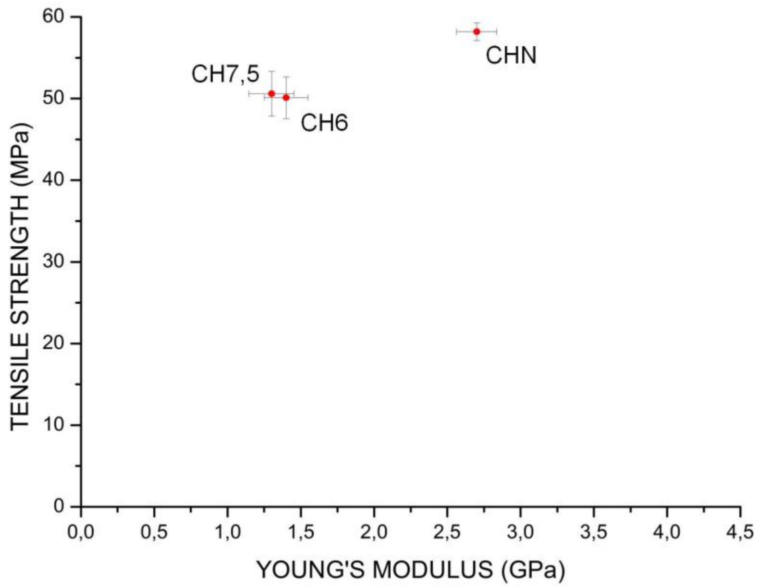

Figure 9: Comparative global diagram of test specimens.

As objective of future works, aiming a better understanding of the results of mechanical properties, the development or adaptation of analytical/numerical models is required.

4. CONCLUSIONS

The response of the hybrid laminate composite in uniaxial tensile testing, in terms of stress x strain behavior, was significantly influenced by the presence of a hole, given the non-uniformity of the curves (large dispersion) for **CH6** and **CH7.5**.

With respect to loss of tensile strength, as a function of the presence of a central hole, Residual Strength for **CH6** and **CH7.5** was practically the same (around 13%). Maintaining the *w/D* ratio constant at 6.0 influenced the results;
In relation to Young's modulus, losses of 48.1% occurred for **CH6** and 51.8 % for **CH7.5**, as compared to **CHN**. These results, in the presence of a central hole, showed a complex behavior, altering the deformation capacity of this laminate, thereby reducing its stiffness.

No influence of the *D/h* ratio was confirmed for the laminate under study, since losses in tensile strength and Young's modulus were within the range of dispersions obtained in the tests.

Macroscopic fracture analysis showed the same damage characteristics of cross-sectional cracking in the matrix, **LGM** fractures, glass fiber tearing and fragile fractures in the jute fiber layers.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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