ALTERNATIVE STACKING SEQUENCES IN HYBRID COMPOSITES WITH NATURAL AND SYNTHETIC FIBRES

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Abstract: Nowadays, the conjunction of properties inherent to materials has become so important that the future of a great number of structural applications is based on the development of composite materials. The structural application of these composites is based on the conception of reinforcement stacking sequences (designs) and laminar structures with synthetic fibres and polymeric matrices. The use of natural fibres composites has been growing; however its applications are restricted to elements submitted to small and medium loads. To enlarge the application possibilities studies have been conducted with hybrid composites associating natural and synthetic fibres. This paper assess the influence of the stacking sequence (sandwich or laminated) on the mechanical properties of a hybrid composite (jute-glass) reinforcement in a polymeric matrix. The objective is to evaluate a possible use of this composite as substitute for glass fibre composites in some applications. The mechanical properties were determined in tensile and three-point-bend tests. Fracture characteristics were also analyzed. The results showed a direct influence of stacking sequence on the mechanical properties and fractures characteristics.

***Keywords**: Hybrid composites, jute fibres, glass fibres, stacking sequences.*

1. Introduction

The set of properties inherent to materials has become so important that the future of a great number of structural applications is based on the development of composite materials. These are composed of two or more materials differing in form and/or chemical composition and which are essentially insoluble. Thus, for example, polymeric resins are used to agglomerate high resistant fibres forming high-performance composites. The final properties of the composite depend on the combination of physical, mechanical and chemical properties of each component; these should be very well understood during the development of the composite.

The structural application of composite materials has grown considerably in recent years as a result of improvements in manufacturing processes and new reinforcement stacking sequences (Banister M., 2001; Ellyin F. et al., 2004; Dai, J. et al., 2003; Freire Jr. et al., 2005). The growth in natural-fibre based composites has stood out. These include: sisal, jute, curauá and banana leaf fibres, among others (Aziz et al, 2005; Singleto et al, 2003; Herrera et al, 2004). However, the applications are restricted to elements submitted to small and medium loads due to their poor mechanical properties. Thus, hybrid composites involving the combination of synthetic and natural fibres were developed (John K. et al, 2004; Thwe M. M. et al, 2001; Aquino, E. M. F. et al, 2005). These combine a good mechanical performance with low cost without forget the environmental appeal. The stacking sequence of these hybrid composites is of vital importance in their final properties.

In this paper it was evaluate the influence of stacking sequence (sandwich or laminate) on the mechanical properties of hybrid polymeric composites with natural (jute) and synthetic (E-glass) fibres. The study is based on tensile and three-point-bend tests. The work involves a partnership with a local industry that envisions a possible application of the hybrid composite in pipelines and/or reservoirs as a substitute for the glass-E based composites already used.

2. Experimental Procedure

Two industrially manufactured (hand-lay-up) hybrid composites were developed, both with orthophthalic polyester resin as matrix.

The first is a sandwich structure reinforced by E-glass and jute bidirectional fabrics, besides a central layer (core) of non-woven polyester fibre called coremat**.** The sole purpose of coremat is to increase the stiffness of the material. Coremat (a registered trademark of Lantor), is composed of 50% fibres and 50% perforated felt (2 mm thick) polyester microspheres.

The second consists of a hybrid laminate with similar distribution of layers but without the coremat. Just for comparison a third composite using only E-glass fibre layers and coremat was also manufactured. It has the same stacking sequence of the hybrid laminate with the exception that the jute layers were replaced by glass fibre mats. Figure 1 show the used materials.

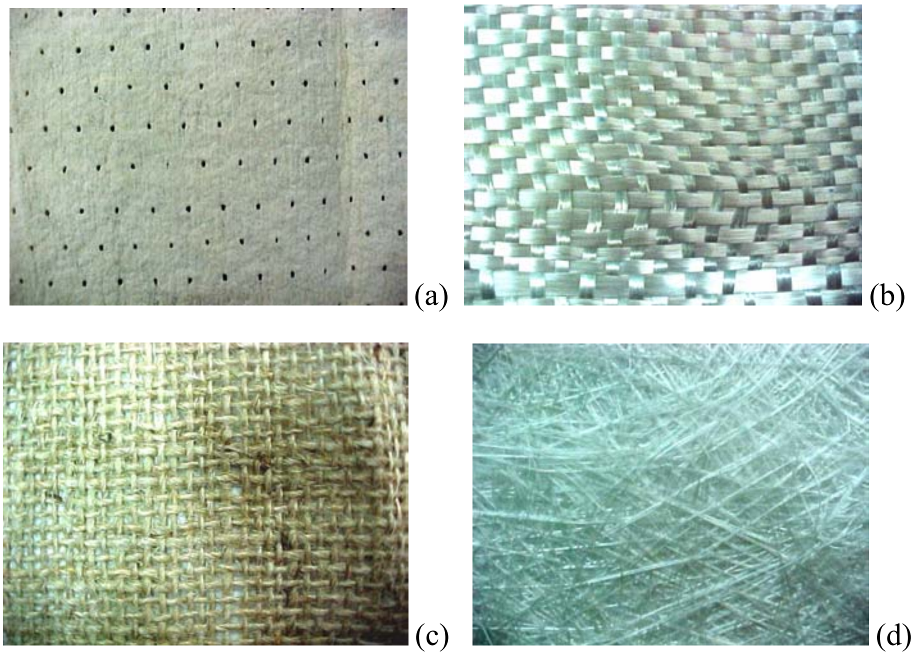


Figure 1 – Materials used in the composites (a) coremat Xi structure, (b) bidirectional E-glass fibre fabric, (c) bidirectional jute fibre fabric and (d) glass fibre mats.

The stacking sequences of the composites are showed in Figure 2 and listed bellow:

$[FJ/FG/FJ/C]_s$ - Hybrid sandwich of glass and jute fibres – **SGJ**
[FJ/FG/FJ/FJ/FG/FJ] - Hybrid laminate of glass and jute fibres – **LGJ**
$[MG/FG/MG/C]_s$ **-** Sandwich of glass fibre – **SG**

Where **FJ** and **FG** are bidirectional fabrics of jute fibre (weft of 3617.1 denier and warp of 3245.4 denier) and E-glass fibre (450g/m^2), respectively and **C** represents the coremat. The letter **"s"** indicates symmetry in the distribution of layers with respect to the core layer. **MG** is the short glass-E fibre mat (450g/m^2).

The composite thicknesses were around 6.7, 6.0 and 7.0 mm for **SGJ, LGJ** and **SG**, respectively. Jute fabric was selected for this work because, during the fabrication process of the composite it absorbs the same amount of resin as the fiberglass mats and only a little more than the fiberglass fabric. It is worth to say that the jute fabric was used without any special treatment to improve the interfacial adhesion. Thus, there is no significant increase in the production cost.

The reason to use jute fabrics in the external layers was to maintain the same configuration of the sandwich composite (just with glass fibre) allowing a direct comparison. The proposal was to change the fibre glass mat in the external layers by jute fabric, in a way that the resin consumption was not increased and the lamination process facilitate.

Due to the use of different materials (natural fibre, coremat and glass fibre) it is not possible to determine the fibre volume fraction by burning test commonly used for glass fibre composites. The determination of fibre weight fraction would be possible; however the results are very imprecise due to the manual lamination process (hand lay-up) and of little scientific value.

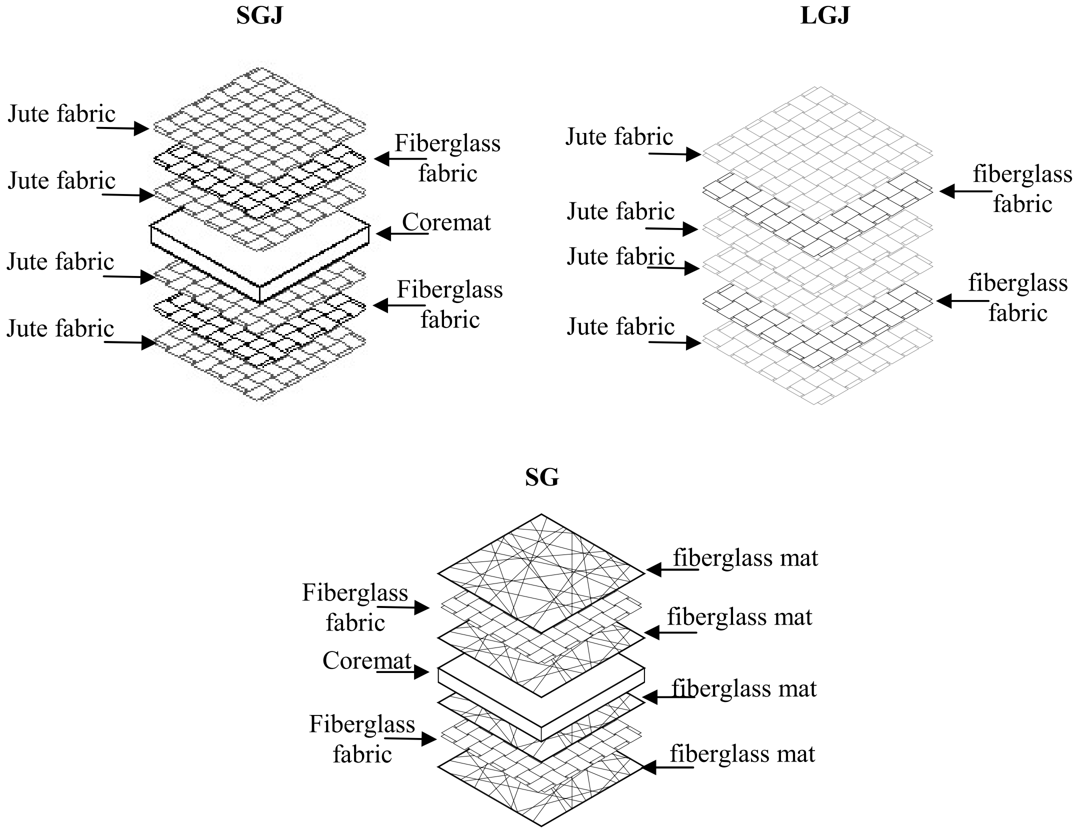


Figure 2 – Composites stacking sequences. (a) **SGJ** (b) **LGJ** and (c) **SG.**

Tensile and the three-point-bend-tests were performed according to ASTM D3039-00 and ASTM D790-96, respectively, in a Shimadzu AG-I testing system. Tests were carried out at room temperature with strain rate of 1.0 and 2.8 mm/min for tensile and the three-point-bend, respectively. In the three-point-bend test the span to depth ratio was 16 to 1. A minimum of ten specimens were tested. The specimen's dimensions were: 200 x 25 mm (length and width) for tensile test and 130 x 13 mm (length and width) for three-point-bend test. Obviously, the depth is the same of the laminated plates (previously mentioned).

In the tensile test, bidirectional fabric fibres are always in parallel (0°) and perpendicular (90°) to the direction of the applied load. In the three-point-bend tests, they were placed perpendicular to the applied load.

After the tests analyses of fracture characteristics in the fractured specimens were performed. These were carried out in two stages: the first consisted of macroscopic analysis of mechanical failure in order to determine the formation and distribution of fractures over the entire length of the composite; the second consisted of microscopic fracture analysis to detect "adhesive" (debonding fibre/matrix) and "cohesive" (fracture of the matrix or fibre) fractures and delamination (debonding between the laminate layers).

3. Results and Discussion

3.1 Mechanical Tests

3.1.1 Tensile test - Hybrid sandwich of glass and jute fibres (SGJ)

Stress x Strain curves for **SGJ** are showed in figure 3. The composite shows a linear behavior until the final fracture. It is worth noting that the hybridization did not alter this behavior; common to most E-glass sandwich laminates.

The mean values of the tensile strength, elastic modulus and elongation were, 68.7 MPa, 1.42 GPa and 4.88%, respectively. Dispersion percentages (absolute difference between the results) were 3.63%, 8.06% and 8.13% for tensile strength, elastic modulus and elongation, respectively. These values dispersion can be considered low once the fibres, glass and jute, have significantly different properties. Thus, it can be said that **SGJ** has very uniform properties in terms of strength and stiffness.

It should be pointed out that for all tests (tensile and three-point-bend), the elastic modulus was determined considering the slope of the curves until 50% of strain, thus avoiding any damage influence. The damage can be noted during the test by low noises due to the microcracking of the matrix, as well as by visual inspection of delamination between the layers.

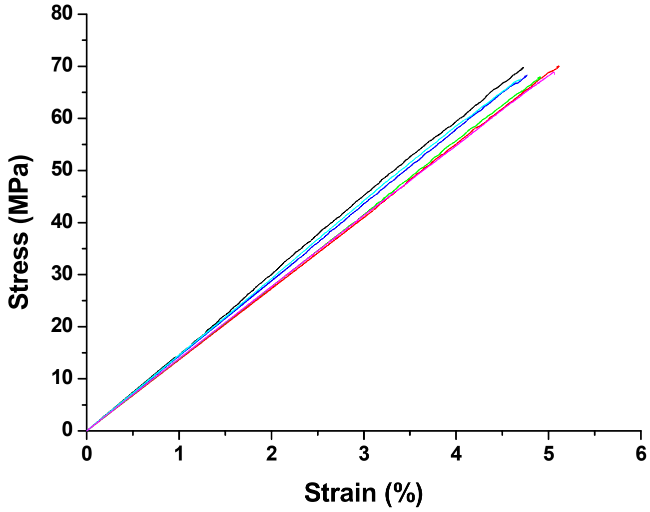


Figure 3 – Stress x Strain curve of the tensile test for **SGJ**.

3.1.2 Three-point-bend test - Hybrid sandwich of glass and jute fibres (SGJ)

The main characteristic of the three-point-bend test was the premature shearing fracture of the coremat in the neutral line of the hybrid composite. After the shearing fracture, the load is insufficient to promote a true flexural fracture, that is, the fracture in the outer fibers on the tensile face of the composite. It should be pointed out that the shearing fracture in the neutral line indicates that the composite displays the same behavior on both surfaces of the specimen, under tensile and compression.

Load x Deflection curves are showed in figure 4. An initial linear behavior can be observed for all tests; this allows the calculation of the flexural modulus. After a certain percentage of strain the composite loses its linearity highlighting the viscoelastic behavior of the resin. Soon afterwards, a sudden load drop-off due to shearing fracture is noted. The shearing in the neutral line of the specimen can be related with two factors: the hybridization (the use of fibres with so different properties) and/or the use of the coremat as filling layer. This topic will be better discussed later.

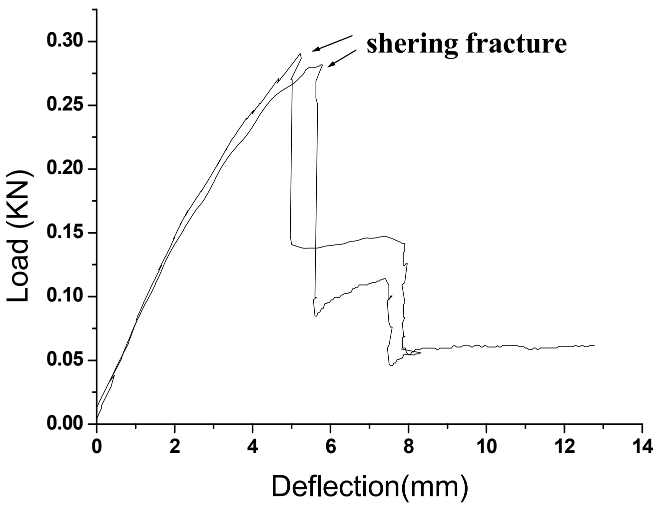


Figure 4- Load x Deflection curve of the three-point-bend test for **SGJ**.

The flexural properties were calculated at the moment of the shearing fracture (exception for the flexural modulus), since there was not the true flexural fracture, as already mentioned. The maximum stress was here denominated “flexural stress”, in opposition to “flexural strength”, once the measured value not correspond the actual flexural strength. The mean values obtained were: 115.4 MPa, 5.6 GPa and 2.3%, for flexural stress, flexural modulus and maximum strain, respectively. Dispersion percentages (absolute difference between the results) were 7.0%, 9.0% and 4.0%, respectively.

3.1.3 Tensile test - Sandwich of glass fibre (SG)

Stress x Strain curves for **SG** are showed in figure 5. The composite shows a linear behavior until the final fracture; typical behavior to most plastics reinforced with glass fibre. The presence of coremat as a filling layer did not alter this behavior.

The mean values of the tensile strength, elastic modulus and elongation were: 99.7 MPa, 1.86 GPa e 5.4%, respectively. Dispersion percentages were: 11.25, 9.98 and 11.40 % for tensile strength, elastic modulus and elongation respectively. These values are higher than those of **SGJ** once it is being used only glass fibre. It is interesting to note this superior behavior in spite of the greater probability of non-uniform interlaminar stress distribution due the association of mats and fabrics.

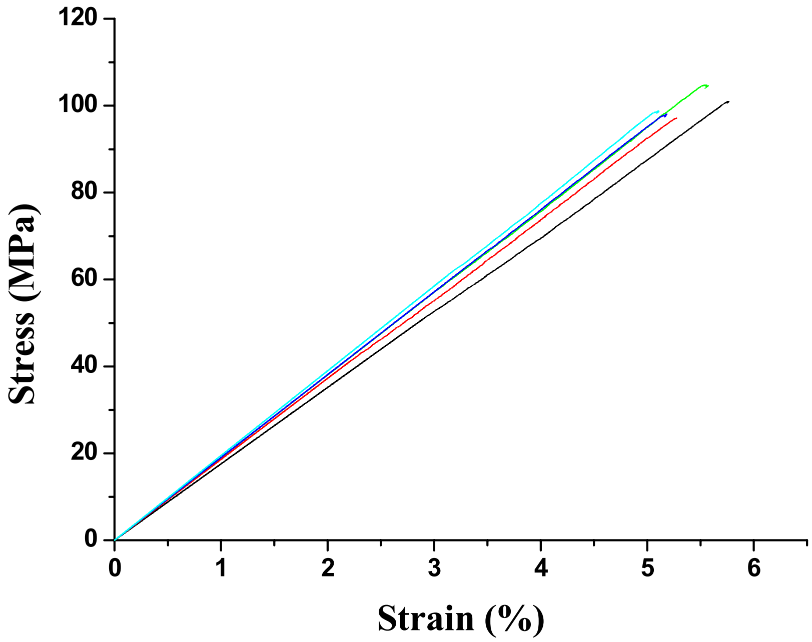


Figure 5 – Stress x Strain curve of the tensile test for **SG**.

3.1.4 Three-point-bend test - Sandwich of glass fibre (SG)

To evaluate if the premature shearing fracture in the **SGJ** composite was caused by the hybridization, it was manufactured a composite just with glass fibre and similar configuration (see Figure 2). Some load-deflection curves of this “new” composite are shown in Figure 6. Again, premature shearing fracture of the coremat was verified, similar to that observed in the hybrid composite (**SGJ**). So, one can say that the premature shearing fracture did not have any relation with the hybridization. The shearing fracture is probably related to the use of the coremat in the neutral line.

The mean values obtained (at the moment of the shearing fracture) were: 101.7 MPa, 8.02 GPa and 1.33%, for flexural stress, flexural modulus and maximum strain, respectively. Dispersion percentages were higher than those found for the **SGJ.** The values were 13.36, 12.8 and 12.67% for flexural stress, flexural modulus and maximum strain respectively.

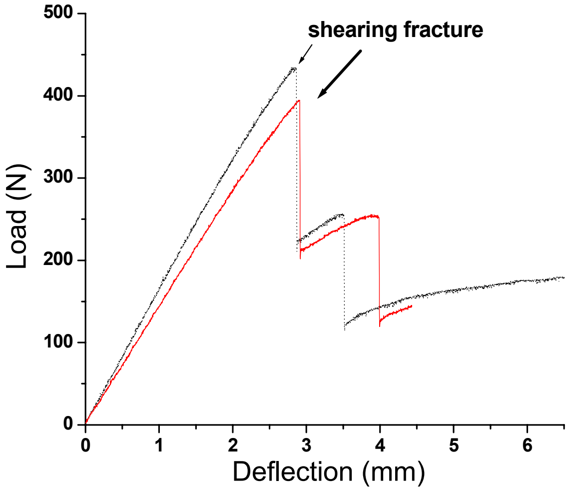


Figure 6- Load x Deflection curve of the three-point-bend test for **SG**.

3.1.5 Tensile test - Hybrid laminate of glass and jute fibres (LGJ)

Figure 7 shows the Stress x Strain curves for **LGJ**. The composite shows a behavior approximately linear, however no as linear as the one of the SG composite. The mean values of the tensile strength, elastic modulus and elongation were: 96.01 MPa, 2.2GPa and 4.5%, respectively. Dispersion percentages were 11.06, 6.6 and 13.6 % for tensile strength, elastic modulus and elongation, respectively. The values of tensile strength and elastic modulus were higher than those for the **SGJ** composite.

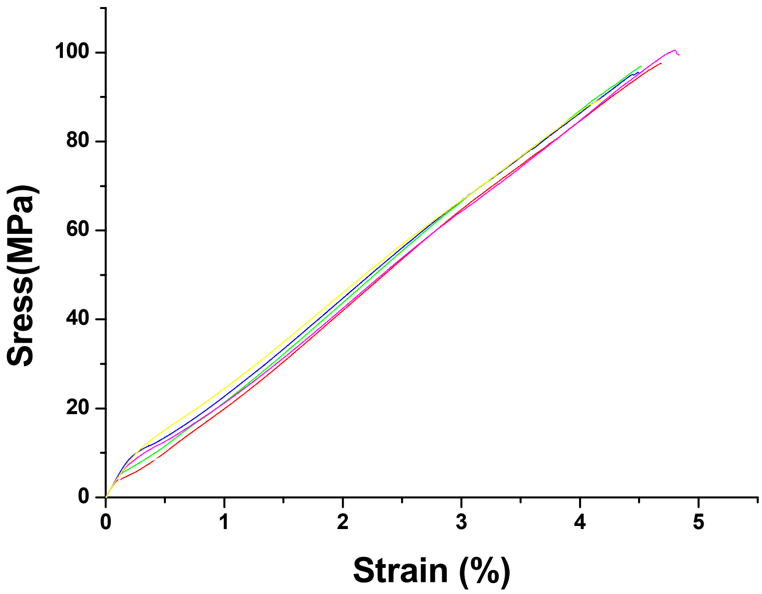


Figure 7 – Stress x Strain curve of the tensile test for **LGJ**.

3.1.6 Three-point-bend test - Hybrid laminate of glass and jute fibres (LGJ)

The absence of coremat in the **LGJ** composite was sufficient to avoid premature shearing fracture in the neutral line. Thus, the true flexural fracture, that is, the fracture in the outer fibers on the tensile face of the composite, was verified. Figure 8 shows the Stress x Strain curves for **LGJ**. The inflections on the curves characterize the initial fracture of the outer layer (jute fabric) followed by loading recovery due to the adjacent layer of glass fabric that is more resistant.

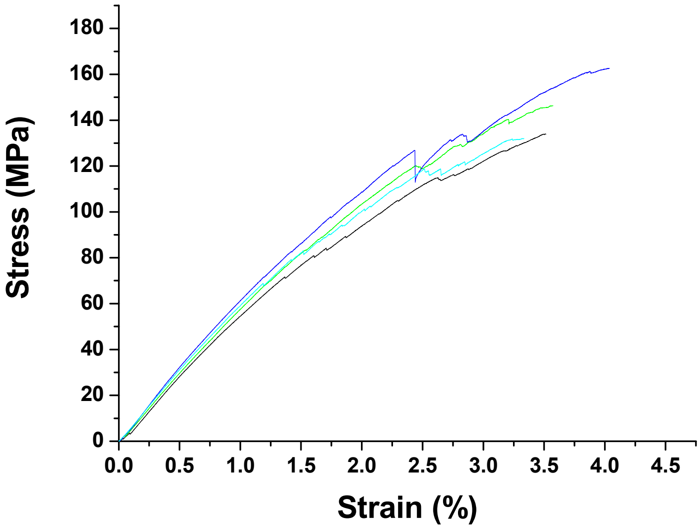


Figure 8: Stress x Strain curve of the three-point-bend test for **LGJ** .

The mean values for flexural strength, flexural modulus and maximum strain were: 143.7 MPa, 4.72 GPa and 3.62%, respectively. The dispersion percentages were 18.2, 10.7 and 17.5 % for flexural strength, flexural modulus and maximum strain, respectively.

In general, the dispersion percentages were higher than those obtained in the tensile test. This, can be related the characteristic of the test itself, once the fracture begins in the outer layer that consist of jute fibre fabric or glass fibre mat. The jute fibres present very dispersive mechanical properties while the glass mat has random fibre distribution. Both can lead to wider dispersion in the results.

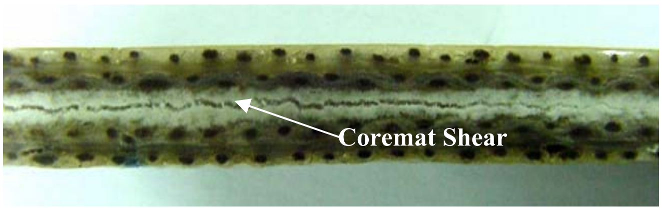
3.2 Fracture analysis

3.2.1 Fracture characteristics – Hybrid sandwich of glass and jute fibres (SGJ)

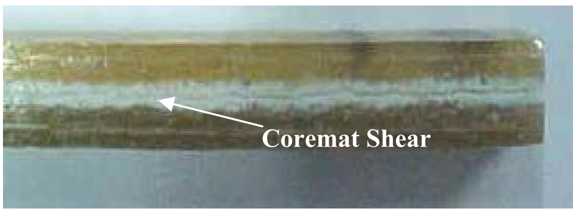
The analysis of the fracture characteristics is based on macroscopic and microscopic examinations of fractured specimens. Macroscopic analysis is based on the fracture propagation along the entire specimen, whereas microscopic analysis is based on microcracking and interfacial adherence (fibre/matrix).

Macroscopic and microscopic analyses of the **SGJ** composite after the tensile test showed the following characteristics: delamination in the interfaces between the layers (except for the interface jute fabric/coremat) and jute and glass fibres fracture in the region of final fracture. Transversal microcracking (in relation to loading direction), was also observed in the matrix causing "adhesive fracture" (fibre/matrix debonding).

In the three-point-bend test the premature shearing fracture in the neutral line of the specimen (coremat) should be pointed out (see figure 9a), as well as the fact that this was the only observed characteristic.



(a)



(b)

Figure 9 – Shearing fracture after three-point-bend test. a) **SGJ** and b) **SG**.

3.2.2 Fracture characteristics – Sandwich of glass fibre (SG)

SG specimens, after tensile test, showed the following characteristics: delamination between all inner glass fibre layers, total or partial fracture of the specimen, fibre/matrix debonding and "cohesive" fractures in the matrix and fibres.

In the three-point-bend test it was observed premature shearing fracture in the coremat, similar that observed in the **SGJ** composite. This shows that the premature shearing fracture did not have any relation with the hybridization (association of natural and synthetic fibres), but rather it was due to the low resistance of the coremat in association with the stacking sequence used**.** Figure 9b shows the shearing fracture in a three-point-bend specimen. Microscopic analysis showed neither delamination nor microcracking in the matrix.

3.2.3 Fracture characteristics – Hybrid laminate of glass and jute fibres (LGJ)

Microscopic and macroscopic analyses of the **LGJ** composite after tensile test, showed the following characteristics: delamination between the jute/glass layers (restricted to the final fracture region) and intense microcracking in the matrix. It was also observed that this microcracking caused fibre/matrix debonding ("adhesive fracture") and fracture of the matrix and fibres ("cohesive fracture") in some layers.

Different from the observed for **SG** and **SGJ** composites there was no premature shearing fracture in the three-point-bend specimens. The fracture in the **LGJ** composite occurred on the tensile face of the test specimen, a typical three-point-bend fracture. So, it can be concluded that the use of the coremat as a core layer was in fact responsible for the shearing fracture in the sandwich stacking sequences. Besides, it was not observed delamination resulting in an extremely localized fracture.

3.3 Comparative Study

In a general analysis of the tensile test results it can be observed that the **SG** (sandwich of glass fibre) displayed similar tensile strength (within dispersion) as compared to **LGJ** (hybrid laminate of glass and jute fibres)**.** The hybrid sandwich stacking sequence (**SGJ**) showed decrease in the tensile strength of 28.4 and 31.1 % as compared to **LGJ** and **SG** composites, respectively. Regarding the elastic modulus, the laminate (**LGJ)** is superior to the others with increase of 35.4 and 15.4 % as compared to **SGJ** and **SG** composites, respectively. So, it can be concluded that the use of coremat did not produce the expected effect of improving the composite stiffness (elastic modulus).

In the flexural test the analysis was compromised because premature shearing fracture in the coremat (sandwich composites - **SGJ and SG)**. The removal of the coremat to produce the laminate composite (**LGJ**) clearly result in better mechanical performance for this composite compared to the others (**SGJ and SG**).

Regarding the flexural modulus better results were obtained for the sandwich composites (**SGJ and SG),** confirming the use of coremat only to increase the composite stiffness in the flexural loading. The highest flexural modulus was found for **SG** composite, with an increase of 41.1 and 30.17 % as compared to the others, **LGJ** and **SGJ**, respectively.

Figure 10 shows a global view of the stacking sequence influence on the mechanical properties (strength versus modulus). Remembering that the flexural strength of the sandwich composites (**SGJ and SG**) actually correspond to maximum stress at the moment of shearing fracture.

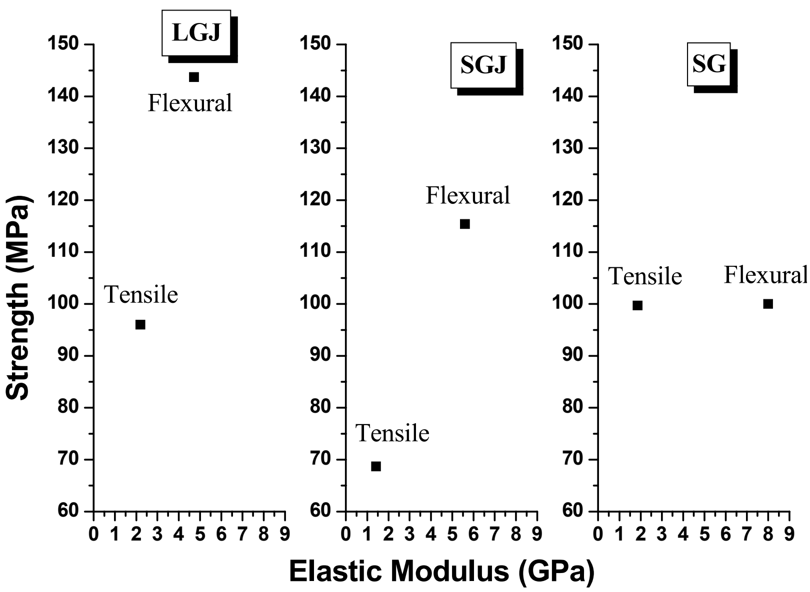


Figure 10: Stacking sequences influence in the mechanical properties of the composites.

4. Conclusions

1. The hybrid laminate composite (**LGJ)** displayed mechanical properties, in tensile and three-point-bend loading, compatible with the **SG** composite. This fact made its application as a structural element feasible once the **SG** composite is usually in applications industrial used of the type reservoirs and pipelines.
2. The use of the filling layer (coremat) in sandwich stacking sequences (**SGJ** and **SG**) improved the elastic modulus in three-point-bend loading, in spite of the premature shearing fracture in the neutral line (coremat). However the flexural strength was harmed.
4. The common fracture characteristics found in the tensile loading were delamination, microcracking in the matrix, adhesive fracture (fibre/matrix debonding) and cohesive fracture (in the matrix and fibre). In the three-point-bend loading was the shearing fracture for sandwich composites (**SGJ** and **SG)** and intense microcracking in the matrix for **LGJ** composite.

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