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Glued Laminated Timber Beams Reinforced With Sisal Fibres

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***Abstract*—The current appeal for sustainable building materials has expanded the use of timber in construction. However, due to timber be a raw material, natural defects are present, what reduce its strength capacity and cause, in particular, brittle failures in the tensile region of timber beams. In order to increase the mechanical properties of these beams, fibre reinforcement can be applied. In this context, natural fibres, such as Sisal fibres, already used in various fields of construction, are an alternative for reinforcement of timber structural elements, by taking into account their adequate mechanical properties and, in special, for low-mechanical resistance wood species, such as Pinu sp, a species used widely in timber construction. This paper deals with an experimental analysis glued laminated timber beams (Glulam) of Pinus sp species, reinforced by Sisal fibres. Bending tests were performed on six beams with the following dimensions, 53 mm-width by 180 mm-height by 3000 mm-length, which were prepared with eight lamellas by 8 mm-thickness. These beams were reinforced with Sisal strips that were glued by Epoxy adhesive on the bottom part of these beams. In addition, comparisons of result with non-reinforced Glulam were carried out. From the analyses of the experimental results, a decrease of 20 to 30% for the normal stresses, 5 to 10% for the shear stresses and 8 to 12 % for the displacements in relation to non-reinforced beams were verified.**

***Index Terms*—natural fibres, Sisal fibres, Glulam, reinforcement, bending test**

I. Introduction

In long duration life, structural systems are subjected to permanent and variable loads, chemical and biological agents´ interaction or design load variations. These actions can affect a structure in such way that it can no longer maintain its initial design resistance, causing the necessity to repair or reinforce it.

According to Ref [1], there are two main methods to rehabilitate affected timber elements, which are: (i) the replacement of the damaged sections; (ii) the utilization of reinforcement materials that complement the mechanical resistance of the damaged timber structural elements. The main issue with the first solution is that it is sometimes restricted by various facts, such as environmental impact, lack or incompatibility of the required wood species and high costs. This generates the necessity to seek other effective alternatives, as the second method, turning the use of FRP (Fibre Reinforced Polymers) materials into a very interesting option that deserves to be specifically studied.

Addressing to composite materials used in constructions, they can be divided into three major groups: fibrous composites, laminated composites and particulate composites, with a possible combination among these types [2].

The laminated composites formed by the union of lamellas can consist of the same or different materials or also have different geometrical characteristics and dimensions.

Focusing on glued laminated timber beams, it is important to consider the natural defects, such as knots, or the orientation of the fibres, that can influence the mechanical characteristics of the lamellas and in the beam as a whole. This affects the timber mechanical properties reducing, for example, the tensile strength and can cause a brittle failure with a lesser load than the one established in structural design [3]. Thus, the use of fibres as a reinforcement of the structural elements intends to avoid the brittle failure and increase the tensile strength as well.

As found in technical literature, natural fibres have attracted attention for presenting adequate mechanical characteristics for such application. The use of natural fibres, as Sisal fibres for example, associated with glued laminated timber beams, in particular, those manufactured with wood species from reforestation, is in accordance with the current economic interest and sustainable appeal [4].

The Sisal fibres are commercialized in Brazil in several formats such as: fabric, cords, strips, wire, rolls, etc. Table I presents the tensile strength and the modulus of elasticity for some fibres [5].

TABLE I. Mechanical Characteristics of Natural Fibres

Fibre	Tensile Strength(MPa)	Modulus Elasticity (GPa)
Coconut	131-175	4-13
Sisal	511-635	9,4-22
Curau á	859-1404	20-36
Juta	393-773	26,5

The failure strength and the modulus of elasticity, besides the lengthening in rupture, depend on the amount

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of cellulose and the orientation of the micro-fibres. As a natural product, these characteristics have a wide variation from one plant to another.

Further the mechanical characteristics of Sisal, associated with other advantages such as, the facility to find, extract and process the material, low cost and biodegradability has led to a significant amount of scientific research of unquestionable importance regarding the use of natural fibres. Nevertheless, the Sisal fibre utilization is only interesting when applying with low resistance wood species.

In this context, this paper covers an experimental analysis of glued laminated timber beams reinforced by Sisal fibres by considering bending results of the six tested beams.

II. Fibres and Matrix

Fibres are characterized by the ratio between length and diameter. For ratios less than 100, the fibres are considered short and for greater than 100 the fibres are long. Sisal fibres are an example of long fibres. In general, the characteristics of the fibres are classified resistance by density and rigidity by density as well [6].

In order to use fibres as a reinforcing material, they need to be connected to the structure. The material of union is called the matrix and has the following main characteristics: to maintain and protect the arrangement of fibres and to distribute stress between the substrate and the fibre. The matrix is mainly responsible for providing resistance to shear stress on the lamellas.

Usually the matrix has mechanical properties lesser than that of fibres and a lower density (which provides greater lightness in structural elements). It can be constructed with polymers, metal, ceramic or other materials.

The materials presented in the matrix are varied, depending largely on the type of use of the composite as well as the type of fibres involved in the construction. Examples of materials in the matrices are epoxy, plastics and polyester.

Epoxy, in general, is classified as a structural adhesive or engineering adhesive. This high-performance adhesive is used in the construction of aircraft, cars and many other products where a high resistance, stiffness and low density are required. Currently this type of adhesive can be used with great efficiency in wood, glass, metals and plastic.

III. Sisal Fibres

Agave Sisalana Perrini, known worldwide, is a native species to the Yucatan peninsula, Mexico; the plant and also the fibres known as Sisal belong to the class of natural hard fibres. Currently, Sisal represents a natural fibre with great commercial applications, and is estimated to be in more than half of the total amount of the natural fibres used in Brazil, being the largest producer and exporter of Sisal fibre, [7]. The Sisal fibres are found commercially, in several formats: fabric, cords, strips, wire, rolls (See Fig. 1), etc. and Table I previously presented the tensile strength and the modulus of elasticity for a number of different fibres.

Figure 1. Rolls of Sisal fibres.

The Sisal plant is a monocotyledonous, whose roots are fibrous, emerging from the base of a pseudo stem. The fibres of Sisal are made of elementary fibres of 4 to 12 μm diameter that are aggregated by a natural bond of small cells of 1 to 2 μm. Such arrays are found along the length of the plant on a regular shape, with lengths of 45 to 160 cm.

The leaves of Sisal are an example of natural composite with lignocellulosic material presenting in 75 to 80% of the total weight of the leaves, reinforced by helical micro fibres of cellulose, which represent about 9 to 12% of the total weight. The composition of Sisal fibre is cellulose, lignin and hemicelluloses, [6].

Fig. 2 shows Sisal plants and Fig. 3 presents an image of Sisal fibre bundles from a scanning electron microscope, produced by the authors of this paper.

Figure 2. Sisal plant.

According to Ref [6], the failure strength and the modulus of elasticity, besides the lengthening of rupture, depend on the amount of cellulose and the orientation of the micro-fibres. As a natural product, these characteristics have a wide variation from one plant to another.

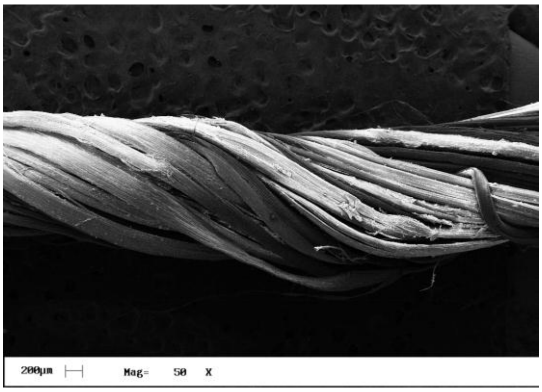

Figure 3. Microscope electronic image of Sisal fibre bundles- scale bar 200 µm.

Another issue to take into account is related to the chemical treatment of the Sisal fibres, [8] and [9]. The chemical treatment has the function of removing from the surface fibres waxes and lubricants of the handling and manufacturing process, and also remove the lignin present on the surface as shown in Fig. 4 and Fig. 5 (both produced by the authors of this paper). This helps to improve the interaction between the fibres and the matrix because the lignin in the fibres prevent direct contact of cellulose (which is resistant fibre material) with the matrix, creating a good bonding between the two products. With the removal of lignin, the roughness of the fibre surface increases the adherence with the matrix. This procedure, on the other hand, reduces the tensile strength of Sisal fibres when compared to fibres that do not receive chemical treatment.

The treatment alkali for the preparation of fibres in a 2% NaOH solution at 25 °C for 1 hour was used.

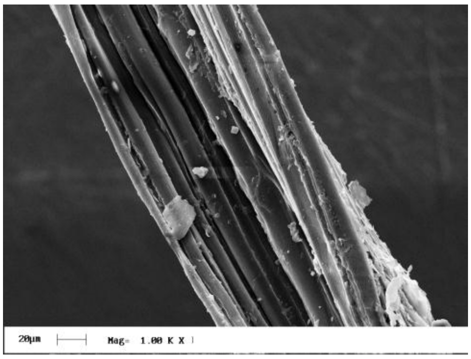

Figure 4. Microscope electronic image of Sisal fibre bundles- scale bar 20 µm without treatment.

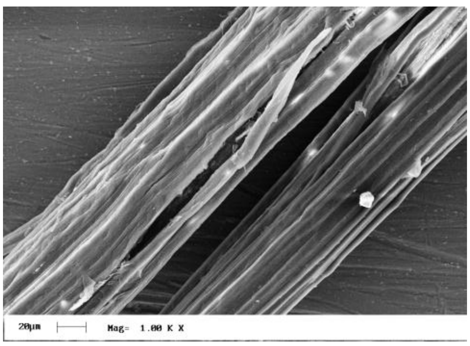

Figure 5. Microscope electronic image of Sisal fibre bundles- scale bar 20 µm after treatment.

IV. Materials and Methods

A. *Tensile Test for Sisal Strips*

To evaluate the mechanical properties of the Sisal fibres, 32 strips were obtained from rolls of raw material. The dimensions of the strips were 2 mm depth by 50mm width by 3000 mm length. The Sisal density was 1,588 g/m3 and its grammage 1,393 g/m^2. Fig. 6 shows the strips of Sisal used to evaluate their elastic and strength properties.

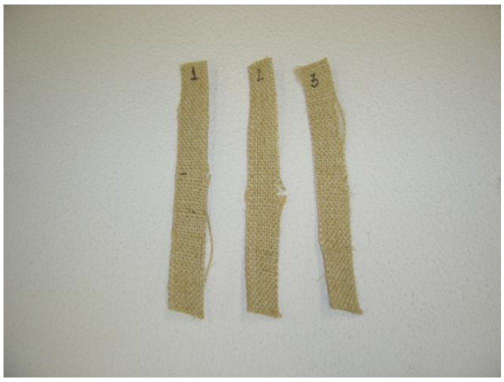

Figure 6. Strips of Sisal fibres.

For evaluating its tensile strength and the modulus of elasticity, the universal testing machine, WDW 100e, was used, which an electronic universal is testing machine produced by TIME-Shijin Group. Fig. 7 illustrates the tensile test set up used for Sisal based on the ASTM D3379 [10] whereas Fig. 8 the load-extension results obtained in the tests.

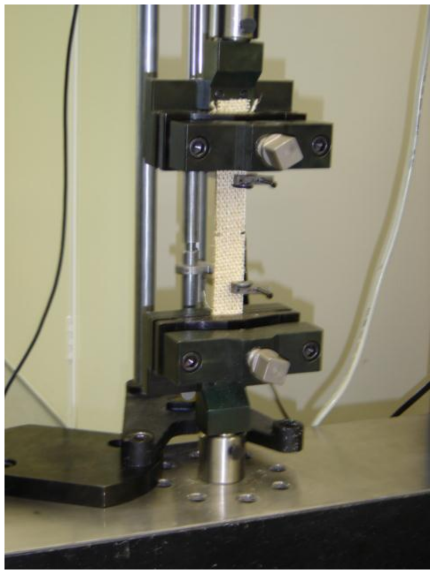

Figure 7. Details of the Sisal strip in tensile test.

The average properties obtained in the experimental tensile tests are: for strips of Sisal fibres: modulus of elasticity E_x = 15,2 GPa, tensile strength Polyurethane adhesive,PU. It is important to note that the yarn mechanical properties for Sisal are much greater than for the strips [11].

B. Bending Tests for Beams

Six beams of glued laminated timber (as shown in Fig. 8) were used in the bending tests. These beams were manufactured with 8 layers of *Pinus elliotti* pieces, 22.5 mm of thickness, 53 mm of width and 3000 mm of length glued by Polyurethane adhesive, PU.

The final dimensions of the beams were 53 mm thick, 180 mm height and 3000 mm length.

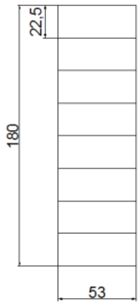

Figure 8. Scheme of the cross section (dimension in mm) and the layers to manufacture the beams.

The mechanical properties of *Pinus elliotti* obtained by compressive tests according to the Brazilian code [12], and the average values were for the longitudinal modulus of elasticity (axis x) Ex = 11.9 GPa, and for the tensile strength f_t = 31 MPa. This species is considered a low-resistance class according the Brazilian code.

In order to evaluate the mechanical performance of the reinforced laminated timber beams, the mechanical classification through non-destructive bending test was carried out, thus obtaining the mechanical properties of stiffness and elasticity of the beams before the fibre reinforcement application.

The bending classification test was performed up to the load corresponding to 50% of the reference mean ultimate load.

After the classification stage, reinforcements of strips of Sisal fibres were applied at the bottom region of the laminated timber beams using epoxy resin Sikadur 32. The modulus of elasticity and the tensile strength for the epoxy resin were adopted as: E_x equal to 2 GPa and f_t of 50 MPa.

According to Ref [1], the usual percentage of synthetic fibres that can be used to reinforce laminated timber beams 3.3% of the beam section, since from this point the resistance and stiffness gain becomes no longer significant. For the beams used in this experimental procedure it was used 4.4% considering both the natural fibre thickness be greater and the mechanical properties be smaller than synthetic fibres.

These reinforced beams were subjected to the destructive bending test, taking the beam to failure, in order to acquire the stiffness property and the ultimate load to verify the failure modes.

The bending test adopted for the beams was the three-point load system with load applied at the mid- span of the beam. The span was 2800mm.

The static scheme of the laminated timber beam used in the present analysis is shown in Fig. 9 and Fig. 10 shows the bending test of a laminated timber beam.

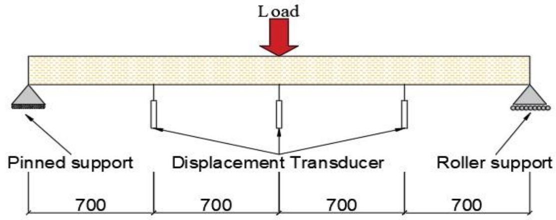

Figure 9. Static scheme of laminated timber beam for bending test (dimension in mm).

Figure 10. Glued laminated timber beam for bending test.

Kyowa KFG-5-120-C1-5 (Kyowa Electronic Instruments Co., Ltd.) strain gauges with gauge factor 2.1 ± 1% and electrical resistance 119.8 ± 0.2Ω were used to measure strains on the beams.

The strain gauges were positioned near the mid-span of the beam (see Fig. 11), in order to obtain the strains in some points of the cross section height and at the top and the bottom surface as well to consequently, evaluate the normal and shear stresses acting on that section. The location of the strain gauges was at 20 cm from the mid-span of the beam to avoid the region of non-uniform stresses.

Figure 11. Central region of the beam positioned for testing with strain gauges positioned in its section.

C. Transformed Cross-section Method

The calculation of the trend stress lines and the displacement curves were based on the transformed cross-section method, [3]. Summarily this method consists of transforming a straight section, which contains more than one material, into an equivalent cross section formed by a unique material. Usually the outer lamella is used as a reference, which is denoted by R, for the process, determining a modular ratio between the modulus of elasticity, E_R and the other lamellas E_i and multiplying the width h_i , where i indicates each lamella, by this relation. In the calculations presented in the results, the reference adopted was the Sisal fibre.

In general, the cross section is symmetric, and as a consequence, the neutral line is in the middle of the central lamella. The width of a generic lamella and the modulus of elasticity are adjusted using the following modular ratio as shown by (1):

$$h_i = \frac{E_{xi}}{E_{xR}} h_R \quad (1)$$

The normal (σ) and shear (τ) real stresses in each lamella depend on the modular ratio and the stresses acting in cross section constituted by a unique material and can be written respectively by (2) and (3):

$$\sigma_i^k = \sigma_R \frac{E_i}{E_R} \quad (2)$$

$$\tau_i^k = \tau_R \frac{E_i}{E_R} \quad (3)$$

Finally, by using the transformed section the displacement of the laminated beam can be calculated using the beam width (h), and the properties of each lumber lamella: its modulus of elasticity (E_{xi}), thickness (b_i) and distance from the centre of each lamella to the neutral axis (z_i) of the cross section as (4):

$$E_x I = \sum_i^n \frac{E_{xi}}{12} h b_i^3 + E_{xi} h b_i z_i^2 \quad (4)$$

The stiffness ($E_x I$) shown in (4) for the laminated beams, with and without reinforcement, was calculated via Ref. [12], as indicated in (5).

$$E_x I = \frac{\Delta P L^3}{48 \Delta \delta} \quad (5)$$

Where: $E_x I$ is the beam stiffness; ΔP is the applied load; L is the span and Δδ is the measured vertical displacements.

V. Results and Discussion

A. Bending Results

In order to verify the improvement in structural performance from the use of Sisal fibres as a reinforcement in the laminated timber beam the following results are presented by the following figures and a table, which were based on the analytical [3], numerical [13] and experimental results. The analytical and numerical results converged and only the numerical one is presented.

These results are related to the critical position of the section beam for both the non-reinforced and the reinforced beams with fibres on the tensile region considering a load of 7 kN, according to Fig. 12. This load corresponds to 40% of the failure load level considered to bending strength, according to the procedures of the Brazilian code for timber structures [12] for the design purposes, i.e, addressed to the elastic regime.

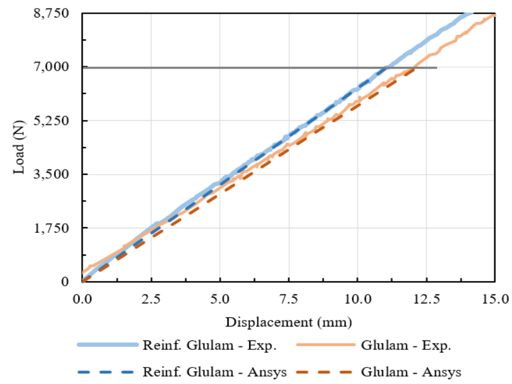

Figure 12. Load versus deflection of laminated timber beam.

Fig. 13, Fig.14 and Fig.15 show the typical experimental results for the normal and shear stresses and for the displacements.

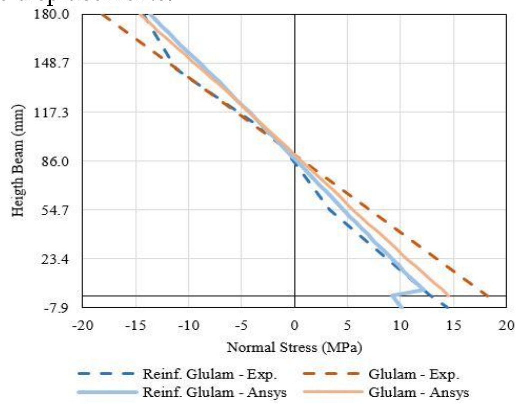

Figure 13. Normal stresses of the laminated timber beam at the critical cross section.

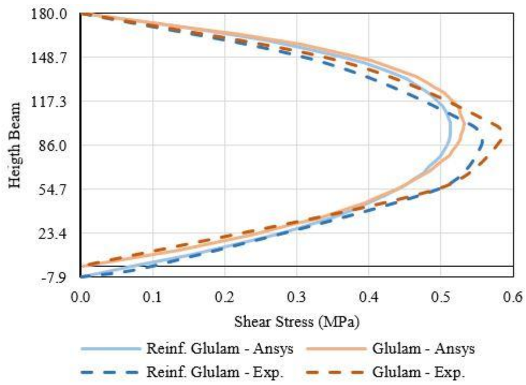

Figure 14. Shear stresses of the laminated timber beam at the critical cross section.

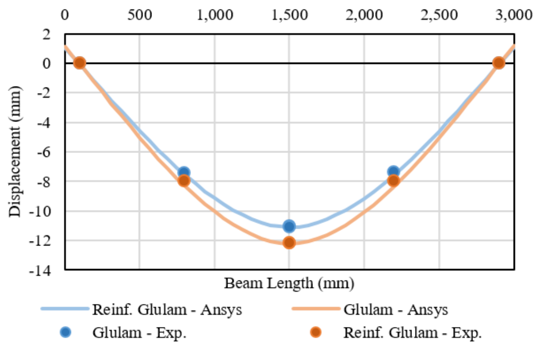

Figure 15. Displacements of the laminate timber beam.

These results are taken at the critical position of the beams and took into consideration the load of 7,000N, according Fig. 12, Table II lists a summary of the comparison between numerical and experimental values for reinforced and non-reinforced demonstrating the greater difference for the maximum tensile normal stress.

TABLE II. DIFFERENCE BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS FOR P = 7,000N

Comparisons	Reinforced Glulam (%)	Glulam (%)
Max. compressive Stress Normal	4.65	19.62
Max Tensile . Normal Stress	30.07	19.93
Max. Shear Stress	7.67	8.82
Displacement at midspan	0.11	0.07

Specifically, the results for the six reinforced beams demonstrated a decrease in the range of 20 to 30% for the normal, 5 to 10% for the shear stresses and 8 to 12 % for the displacements in relation to non-reinforced beams. Ref. [14] found similar results in studies for natural fibres (Curau áand Sisal fibres).

In addition, the tests indicated that reinforcement led to an increase of 11 to 22 % for the ultimate load and a reduction in these load variations as well. The ultimate load variation reduces of 35% for non-reinforced laminated beams to 10% for reinforced beams.

B. *Failure Modes*

Failure must be considered one of the most significant mechanical properties. Much of material engineering is based on establishing economic design without failure. The absence of failure is a necessity of safety as well as for other fundamental considerations. Bending results in longitudinal tension and compression stresses distributed over the height of the cross section. The unreinforced beam failed within the elastic region due to a tension failure of the bottom laminations. Splintering tension occur and this failure consists of a considerable number of slight tension failures, producing a splintery break on the surface of the beam. Because of the timber's brittle nature when exposed to tension, the beam failed in a brittle way without visible failures before reaching ultimate load.

The ultimate load verified in tests was 26.5 kN, in average, the compressive stress 61 MPa, the tensile stress in timber 60 MPa and in Sisal 62 MPa. The compressive and tensile strain values measured around the ultimate load were around 6,000 x 10^{-6}.

Experimental test carried out on reinforced beams demonstrated in this research that the most frequent failure mechanism is the one in which tension failure occurs, with or without partial plasticization of the compression zone. The adhesion between timber and composite material failed only after timber failure. The following types of failure mechanisms prevailed for the beams: the timber fracture at the end of the bonded reinforced composites, timber longitudinal splitting (a combination of tension and shear as also observed by Ref. [15] and Ref. [16], and compressive failure was observed in one of the specimens. The glulam beams reinforced with Sisal especially revealed a ductile behavior. The amount of ductile behaviour in the reinforced beams mostly depends on the quality of the bottom timber laminations. The fibre-adhesive-timber composites act like connectors over the timber defects and make the structural member section more ductile.

Fig. 16 and Fig. 17 show some details of the Sisal strip on the beam and the failure of the tensile lamella in bending test.

Figure 16. Region of the mid-span of the beam and the failures of the lamellas and Sisal fibres in bending test.

Figure 17. Compressive region of the beam and the failure of the upper lamellas in bending test.

Research findings [17], based on the theoretical approach of Ref. [18], and stated that the reinforcement layer absorbs a great portion of the acting stresses, which results in a reduction of the maximum tensile stress acting in the timber portion of the composite. Another issue to be considered is related to the high concentration of compressive stresses that were close to the point where the load was applied, resulting in a crushing area. In addition, Ref. [19] highlight these high compressive stresses for FRP reinforcements. Fig. 18 and Fig. 19 show this stress distribution according studies of Ref. [20] using a numerical procedure [13] to obtain this result.

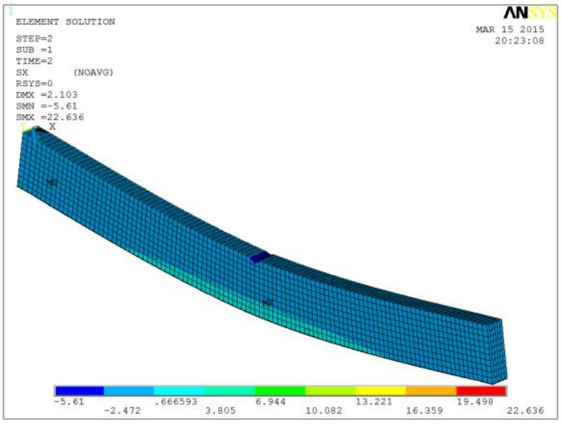

Figure 18. Stress distribution in the reinforced laminated timber beam (in MPa).

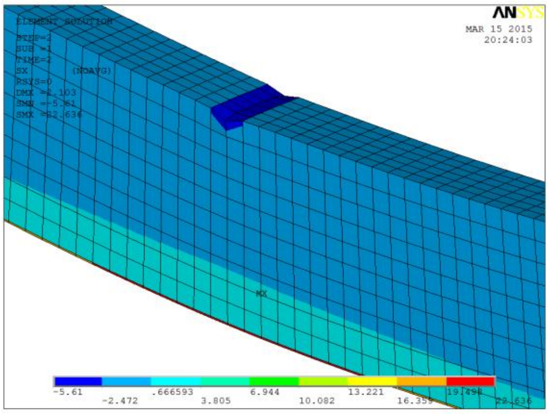

Figure 19. Details of Stress distribution in the reinforced laminated timber beam at the applied load region (in MPa).

It is also to be noted that the tests showed that reinforcement leads to an increase of 11 to 22 % for the ultimate load and a reduction in these load variations as well. The ultimate load variation reduces of 35% for non-reinforced laminated timber beams to 10% when reinforced beams are tested. In other words, the use of reinforced laminated beam produces a material with greater quality control.

VI. Conclusions

An experimental study of timber laminated beams reinforced by Sisal fibres was developed in this study. Based on the analysis of the experimental results from the bending tests the following conclusions are drawn:

The use of the Sisal fibres for low-mechanical resistance wood species demonstrated to be an efficient method for reinforcement, as it increased the values of stiffness properties, modified the brittle mode for a more ductile failure. In addition, the variation of the overall stiffness properties of the laminated timber beam is reduced, presenting an easy workability and can be applied both locally and in the process of beam manufacturing.

Specifically, the results for six reinforced beams demonstrated a decrease in the range of 20 to 30% for the normal, 5 to 10% for the shear stresses and 8 to 12 % for the displacements in relation to non-reinforced beams.

In addition, the tests indicated that reinforcement led to an increase of 11 to 22 % for the ultimate load and a reduction in these load variations as well. The ultimate load variation reduces of 35% for non-reinforced laminated timber beams to 10% for reinforced beams.

In general, the use of the Sisal fibres as a reinforcing material in timber laminate beams is feasible. The Sisal fibres contribute towards preventing brittle failure on critical tensile areas of the beams as well as being more effective for timber beams constituted by elements with the modulus of elasticity at least equals to these fibres.

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