Fiberglass-reinforced Glulam Beams: Mechanical Properties and Theoretical Model

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The glued-laminated lumber (glulam) technique is an efficient process for making rational use of wood. Fiber-Reinforced Polymers (FRPs) associated with glulam beams provide significant gains in terms of strength and stiffness, and also alter the mode of rupture of these structural elements. In this context, this paper presents a theoretical model for designing reinforced glulam beams. The model allows for the calculation of the bending moment, the hypothetical distribution of linear strains along the height of the beam, and considers the wood has a linear elastic fragile behavior in tension parallel to the fibers and bilinear in compression parallel to the fibers, initially elastic and subsequently inelastic, with a negative decline in the stress-strain diagram. The stiffness was calculated by the transformed section method. Twelve non-reinforced and fiberglass reinforced glulam beams were evaluated experimentally to validate the proposed theoretical model. The results obtained indicate good congruence between the experimental and theoretical values.

1. Introduction

When applied to structural elements, Glued-Laminated Lumber (Glulam) refers to the material produced by gluing together the tops and faces of wood chips, in flat or curved shape, with the fibers of all the sheets parallel to the axis of the piece. Long sheets are obtained by joining boards together longitudinally, gluing them face to face and edge to edge to obtain the desired height and width. The sheets can also be bent to produce a curved shape during gluing. All these factors allow for a wide variety of design choices, subject only to production and/or application cost restrictions.

The glulam technique is a rational option for adding value to lumber. The use of fiberglass to reinforce beams ensures gains in the structural element's strength and stiffness, and alters its mode of rupture, which becomes marked by considerable displacements after insertion of the FRPs.

This paper presents a theoretical model for designing FRP-reinforced glulam beams. The proposed model admits the hypothesis of linear strains distributed along the height of the beam, and considers the wood has a linear elastic fragile behavior in stress applied parallel to the fibers and bilinear in compression parallel to the fibers.

To validate the numerical design model, tests were carried out on glulam beams made of *Pinus caribaea var. Hondurensis* species with and without FRP. The experimental results for the bending moment and flexural stiffness are congruent with the values determined by the theoretical model.

2. Literature Review

The idea of reinforcing glulam beams came in response to the need to improve the mechanical properties of strength and stiffness and to increase the reliability of this type of structural element.

Lindyberg[1] stated that various design methods are used to analyze beams with and without reinforcement in bending. These methods can be divided into empirical, deterministic and probabilistic. The ASTM D 3737/96 – Standard Test Method for Establishing Stresses for Structural Glue Laminated Lumber[2] establishes empirical methods for the design of glulam beams, which take into account the flexural strength of defect-free test specimens and establish coefficients of modification relating to the existing defects in these elements. The author concludes that reinforced glulam beams have a complex mode of rupture which makes it difficult to use empirical solutions.

Fiorelli and Dias[3] presented a deterministic model to calculate the stiffness and strength of fiber-reinforced solid lumber beams. The stiffness was based on the transformed section concept. To calculate the mode of rupture, the model considers rupture by compression of the upper fibers or rupture by straining of the lower fibers. To evaluate the ultimate moment, the model considers the ultimate tensile and compressive strength of the lumber. This model is based on the hypothesis of Navier/Bernoulli (plane sections remain plane after straining). A comparison of the experimental and theoretical results demonstrated very similar values of strength and stiffness.

Romani and Blab[4] presented a design model for fiber-reinforced glulam beams. In this work, the authors showed different rupture moduli for the reinforced glulam beam (Figure 1).

The authors experimentally tested 10 x 30 cm glulam beams reinforced with carbon and aramid fibers, comparing their experimental results of the moment of rupture with their theoretical results. The authors stated that the proposed calculation model was quite conservative, showing a difference of approximately 35% below that of the experimental results.

Lindyberg[1] presented a semi-probabilistic computational model to calculate the strength and stiffness of reinforced glulam beams, stating that this is the most efficient solution for evaluating them. His work involves two calculation procedures. The first part consists of a deterministic numerical model that calculates the load-bending curve
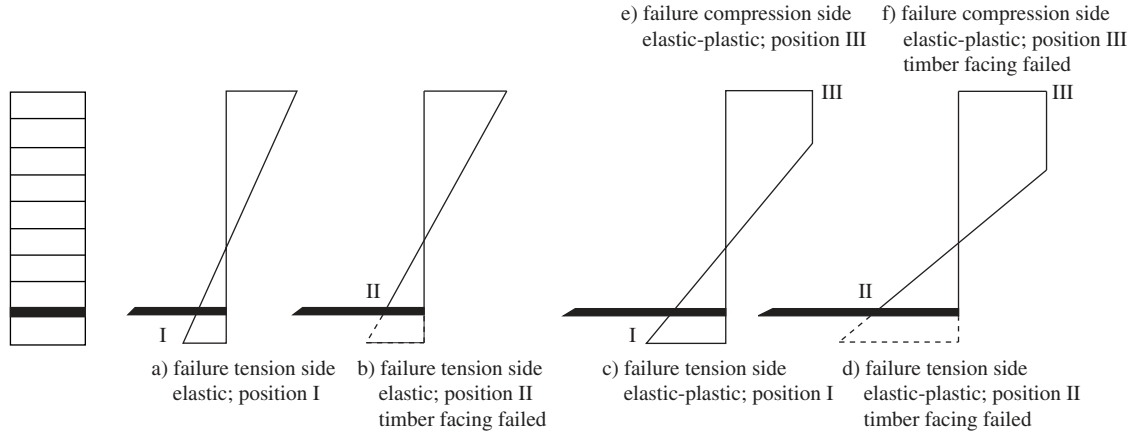
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Figure 1. Rupture modes of glulam beams.

of the reinforced beam. This model is based on the moment of curvature (M-φ). The second part incorporates the deterministic model to a probabilistic model. The Monte Carlo computational simulator is used to develop the probabilistic model within the deterministic one.

From that standpoint, the development of a deterministic numerical model to determine the strength of fiber-reinforced glulam beams based on the lumber's compressive and tensile behavior is an adequate procedure to determine the value of the bending moment of fiber-reinforced glulam beams.

This paper presents a theoretical model to evaluate reinforced glulam beams and an experimental analysis of lumber beams made of *Pinus caribaea var. Hondurensis* species with and without FRP.

3. Theoretical Model

3.1. Moment of rupture

The theoretical deterministic calculation model proposed here considers the behavior of the stressed lumber and fibers realistically. The lumber subjected to compressive loads parallel to the fibers exhibits an initially linear elastic behavior, reaching compressive strength parallel to the fibers (f_c), followed by decreasing levels of stress as the strains increase, until the material breaks up[5]. The lumber subjected to tensile forces parallel to the fibers displays a linear elastic behavior until it approaches the moment of rupture.

Figure 2 depicts the behavior admitted for the material in the calculation model: a linear elastic fragile behavior of the lumber in strains parallel to the fibers and bilinear in compression parallel to the fibers (initially elastic and subsequently inelastic, with a negative decline in the stress-strain diagram).

The value of strain at the level of stress corresponding to the tensile strength and in compression (f_{t0} and f_{c0}, respectively) is obtained from these values and from the modulus of elasticity (E), according to Equation 1.

$$\varepsilon_{tu} = \frac{f_{t0}}{E} \quad \varepsilon_{cy} = \frac{f_{c0}}{E} \tag{1}$$

To calculate the bending moment, after determining the position of the neutral line (N.L.), it is possible to evaluate the loads acting on each sheet of lumber in the transversal section of the glulam beam and in the layer of fiberglass.

With regard to the tensile rupture mode, one considers that failure is reached when the maximum strain acting on the lumber reaches the tensile strength (f_t).
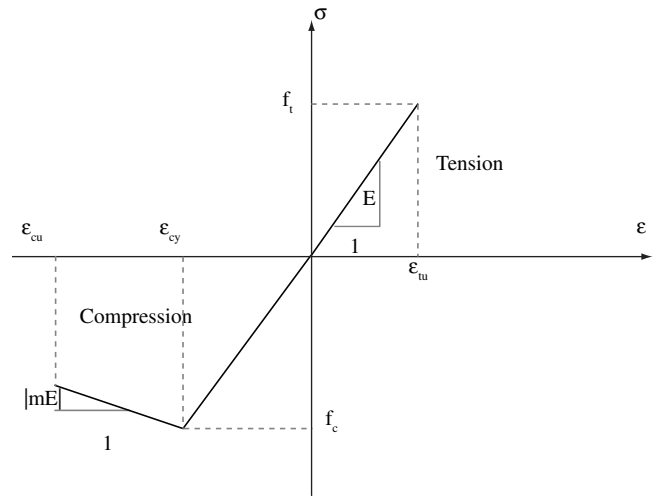

Figure 2. Stress-strain relation of the lumber under strain and compression parallel to the fibers. where: σ - Stress; ε - Strain; f_c - Compressive strength parallel to the fibers; f_t - Tensile strength parallel to the fibers; ε_{cy} - Compressive strain; ε_{cu} - Ultimate compressive strain; ε_{tu} - Tensile strain; and m - Relation between the modulus of elasticity at the elastic and plastic face under compression parallel to the fibers.

As for the compressive rupture mode, after the strain at the compressed edge reaches the value of f_c, the section undergoes gradual plasticization, lowering the neutral line. The flexural strength increases until it reaches a maximum, after which it decreases. The ultimate state for compression is considered at the point where the flexural strength reaches it maximum value.

3.2. Flexural stiffness

The flexural stiffness was analyzed by the transformed section method (Equation 2).

$$\overline{E}I = \Sigma \left(\frac{E_i \cdot b \cdot h_i^3}{12} + E_i \cdot b \cdot h \cdot d_i^2 \right) \tag{2}$$

where:
Ei – Modulus of elasticity in sheet i;
hi – Height of sheet i;
b – Width of the beam;
di – distance from the Center of Gravity (C.G.) of the sheet to the beam's C.G.

4. Materials and Methods

To evaluate the strength and stiffness of the FRP reinforced glulam beams, twelve prototypes were prepared using *Pinus caribaea var. hondurensis* lumber. The glulam beams were reinforced with fiberglass along the last line of glue of the tensioned section. The percentage of fiber employed was equal to 1.2% and 3.3% of the height of the beam. The wood was glued with Phenol-resorcinol (Axo-Nobel) adhesive and the unidirectional fiberglass fabric (UF 0900, FIBERTEX) was glued with AR-300 epoxy adhesive. Four beams were not reinforced. The beams had a nominal section of (7 x 20 x 400 cm) and (7 x 30 x 400 cm) and sheets with a thickness of about 3.3 cm. The size, number of sheets, and thickness of the reinforcement of the glulam beams evaluated experimentally are described in Table 1.

4.1. Classification of the sheets

The lumber sheets used for preparing the glulam beams were classified mechanically through static tests. A visual classification was also done following the procedures established by Carreira[6]. The modulus of elasticity values determined here were used in the theoretical model to evaluate the beam's strength and stiffness.

4.2. Characterization of the fiberglass fabric

The mechanical properties of strength and stiffness (Table 2) of the fiberglass fabrics were determined by means of mechanical tests, following the recommendations of the ASTM D 3039-95 – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, of the American Society for Testing and Materials[7].

4.3. Glulam beam fabrication method

Fabrication of glulam beams must be preceded by visual and mechanical classification of the sheets. The fabrication procedure is divided in two steps; the first consists of applying the adhesive and gluing the sheets together and the second involves applying the fiberglass reinforcement. Figure 3 illustrates the reinforced glulam beam fabrication procedure.

4.4. Instrumentation of the beams

The beams were instrumented with KFG-10-20-120-C1-11 Kyowa extensometers fixed to the mid-span section of the upper and lower faces and at half height on the lateral faces of the next to last sheet, adjacent to the reinforcement (Figure 4). The purpose of this procedure was to evaluate the variation in strain in the beam's cross-sections.

4.5. Bending test of glulam beams

The beams were subjected to a bending test with loads applied at one-third intervals along the span, following the recommendations of the ASTM D198-97-Standard Test Methods of Static Tests of Lumber in Structural Sizes, of the American Society for Testing and Materials[8].

A static design of simply supported beam was adopted for the tests, with the application of equal loads at one-third intervals of the span (Figure 5). The values of the displacements were measure in central region of the beam with dial indicator. The velocity of load application was of 10 MPa per minute, in normal stress maximum.

5. Results

5.1. Fiber characterization tests

Table 2 lists the mechanical properties of the fibers used in the experimental work.

5.2. Bending tests

The results of the bending moment and flexural stiffness (EI) of the beams are given in Table 3.

Two values are presented for the bending moment of the reinforced glulam beams, corresponding to:

- M_1 – value of the bending moment when rupture occurred in the last strained sheet, positioned below the reinforcement; and
- M_2 – value of the bending moment when final rupture of the beam occurred.

5.3. Timber characterization tests

Test specimens were removed from the evaluated beams to characterize the lumber. Table 4 shows the values of compressive strength parallel to the fibers (f_{c0}) and of strain parallel to the fibers (f_{t0}).

6. Analysis of the Results

6.1. Analysis of flexural stiffness

Table 5 compares the results of the experimental ($EI_{exp.}$) and theoretical ($EI_{teo.}$) flexural stiffness (EI).

The analysis of the stiffness of the beams with and without fiberglass reinforcement compares values obtained from experimental tests against theoretical values determined according to the transformed section model. As can be seen, the experimental results generally show good congruence with the theoretically estimated flexural stiffness.

6.2. Strain analysis

The strain values are shown graphically (Figure 6 and 7), with experimental and theoretical values of the strain variations along the height, for different loads and six evaluated beams.

In Figures 6 and 7, the experimental strains are marked by dots, with a dashed line connecting the dots corresponding to a given load-

Table 1. Information of glulam beams.

Glulam Beam	Wood sheet number	w (cm)	h (cm)	Reinforcement thickness (cm)
01	6	6.9	20.0	0.00
02	6	6.9	20.5	0.00
03	6	6.9	20.5	0.25
04	6	6.9	20.2	0.25
05	6	7.0	20.5	0.60
06	7	7.0	24.0	0.70
07	9	7.7	28.9	0.00
08	9	7.5	28.7	0.00
09	9	7.6	30.4	0.35
10	9	7.0	30.2	0.35
11	9	6.9	30.8	0.90
12	9	7.0	30.6	0.90

Table 2. Strength and Stiffness values.

	Strength	Stiffness
Mean (MPa)	1247	56154
Variation coefficient (%)	2.24	2.25

Application of glue on sheets.
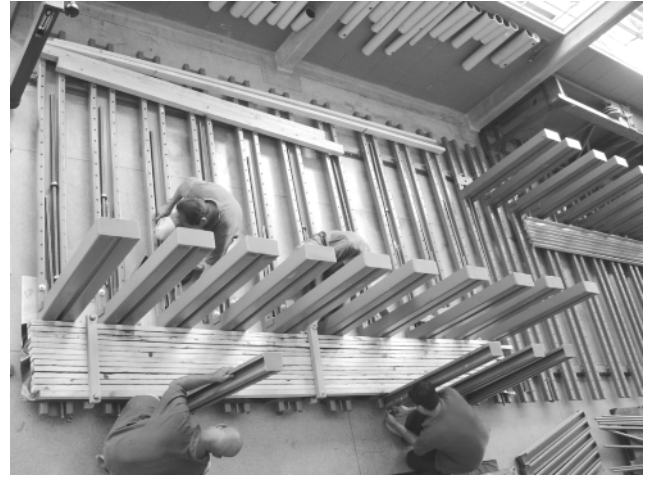
Pressing of the beam.

Application of fiberglass fabric.

Pressing of beam with reinforcement.

Control of pressure using torquemeter.

Detail of the reinforced beam.

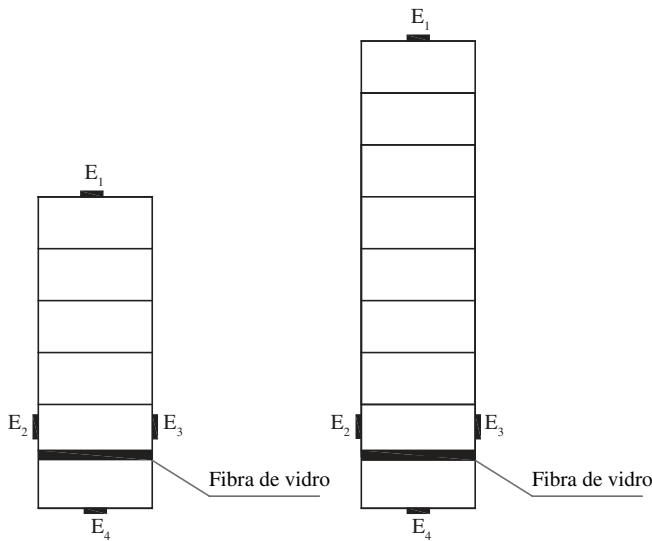**Figure 3.** Fiberglass-reinforced glulam beam fabrication process.

Figure 4. Position of the extensometers on the beam's cross-section.

Figure 5. Bending test.

Table 3. Experimental values of failure moment and bending stiffness.

Beam	Section (cm)		EI (kN.cm²)	Failure moment (kN.cm)	
				M_1	M_2
01	6.9	20.0	6,488,396	2489	-
02	6.9	20.5	6,914,197	2273	-
03	6.9	20.5	6,644,274	2381	2814
04	6.9	20.2	6,766,187	2056	2887
05	7.0	20.5	7,022,504	2561	3283
06	7.0	24.0	9,980,947	3210	3694
07	7.7	28.9	16,826,463	3824	-
08	7.5	28.7	17,179,260	4220	-
09	7.6	30.4	22,050,998	6200	7835
10	7.0	30.2	19,278,948	6143	6875
11	6.9	30.8	24,255,268	8173	8906
12	7.0	30.6	21,978,306	7948	8568

Table 4. Strength mean values.

Beam	Strength (MPa)	
	f_{c0}	f_{t0}
01	52.3	89.2
02	51.4	70.4
03	49.2	67.3
04	51.1	65.3
05	50.5	62.1
06	51.3	70.2
07	44.4	66.2
08	47.2	58.5
09	54.6	78.1
10	51.4	90.0
11	61.3	76.3
12	54.0	98.2

Table 5. Flexural stiffness (experimental and theoretical results).

Beam	$EI_{exp.}$ kN.cm²	$EI_{teo.}$ kN.cm²	$EI_{exp.}/EI_{teo.}$
1	6,488,396	6,864,927	0.94
2	6,914,197	6,882,334	1.01
3	6,644,274	7,402,057	0.90
4	6,766,187	6,711,977	1.01
5	7,022,504	6,972,873	1.01
6	9,980,947	10,245,491	0.97
7	16,826,463	18,179,793	0.93
8	17,179,260	17,458,861	0.98
9	22,050,998	20,186,708	1.09
10	19,278,948	20,080,207	0.96
11	24,386,700	23,300,058	1.04
12	21,601,543	22,844,327	0.94

ing value. The continuous lines represent the strain values obtained theoretically. In each figure, dashed and continuous lines of the same color correspond to the same loading level.

The last continuous line represents theoretical strains calculated for the value of the experimental moment at the first rupture, for which it was not possible to evaluate the strains experimentally.

An analysis of Figure 6 and 7 indicates that the theoretical strains are very close to the experimental strains, except for beam 12. The difference between experimental and theoretical strains in beam 12 may have occurred because this beam had a larger number of sheets (greater height and higher percentage of reinforcement) and hence, the existence of a shear strain of the adhesive, an effect the theoretical model does not take into account. The non-reinforced beams 2 and 8 presented a slight difference between experimental and theoretical strains.

6.3. Analysis of the bending moment

To evaluate the theoretical bending moment using the numerical model, the mechanical properties of strength and elasticity of the lumber and the fiberglass were considered. The tensile strength parallel to the fibers was calculated using the tensile strength values of defect-free CP (f_{t0}) (Table 4) multiplied by the coefficient 0.64, to consider the transposition to the structural element and the existence
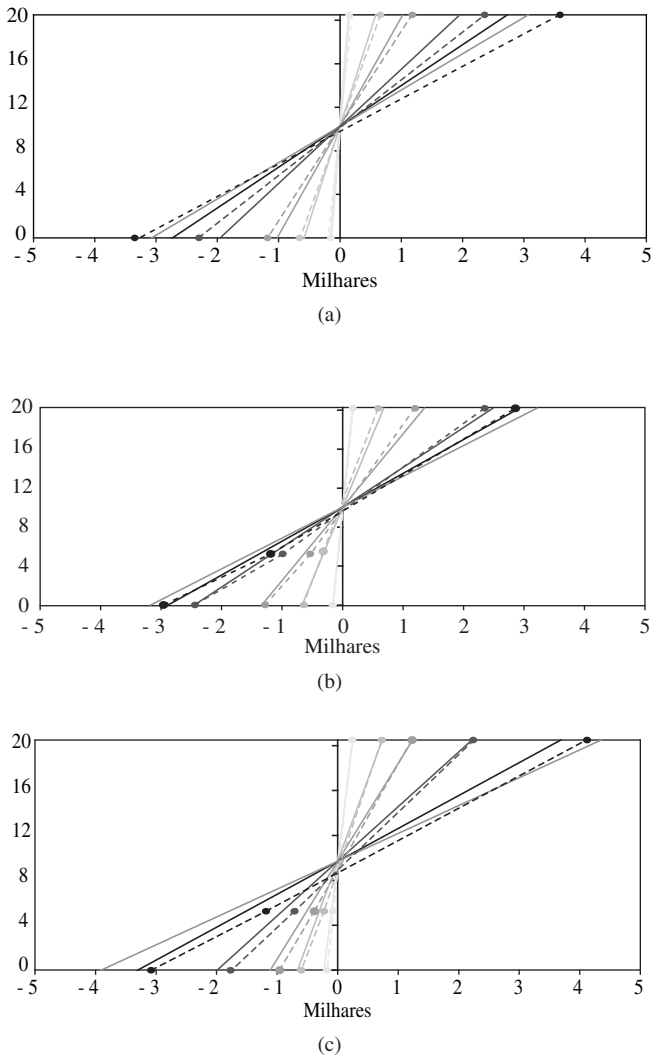
Figure 6. Variation of the strain in the cross-section: a) beam 02; b) beam 04; and c) beam 05. Section: 7 x 20 cm.
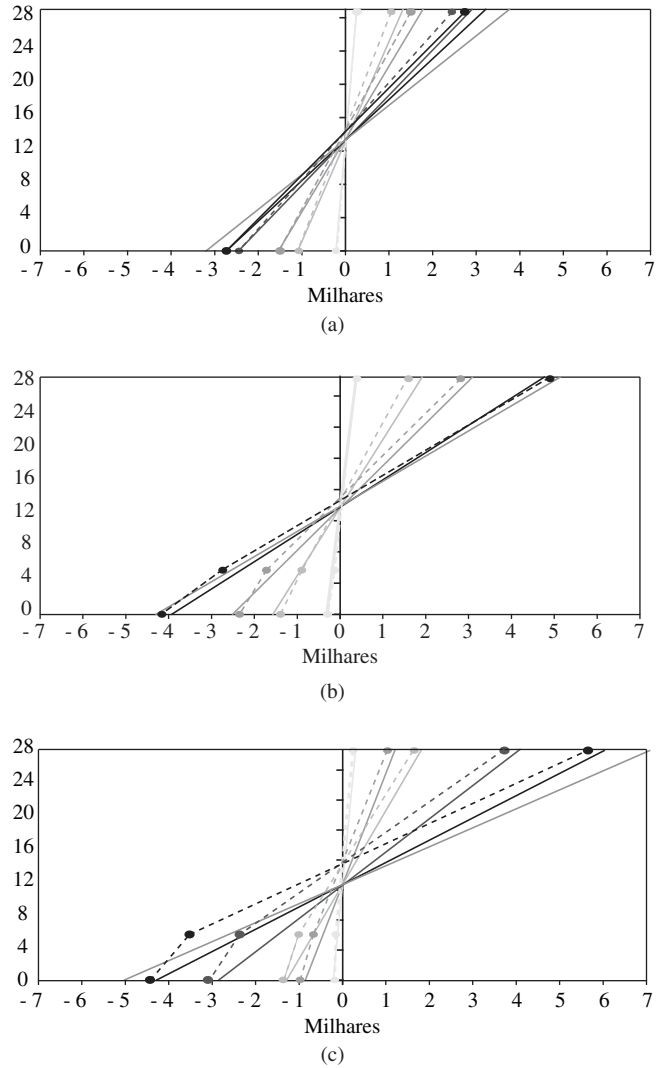

Figure 7c. Variation of the strain in the cross-section: a) beam 08; b) beam 10; and c) beam 12. Section: 7 x 30 cm.

of joins in the sheets[9]. The values of the bending moment correspond to the first rupture (M_1).

Table 6 indicates that the value of the theoretical bending moment correlates well with the experimental values, showing, on average, a maximum variation of 18% below the value of the experimental bending moment.

6.4. Analysis of rupture

The experimentally evaluated reinforced glulam beams presented two modes of rupture. The first occurred by strain on the sheet positioned under the reinforcement layer, while the second consisted of a combination of compressive tensile rupture and shear (Figure 8).

7. Conclusions

The proposed calculation model shows a good correlation between the experimental and theoretical results for the tested beams. In the evaluation of flexural stiffness EI (transformed section method), the values showed a difference of about 5%. A good correlation was obtained between the experimental and theoretical values for the bending moment.

An analysis of the strains of the experimentally tested beams allows us to state that, in most of the beams evaluated here, the theoreti-

Table 6. Failure moment (experimental and theoretical values).

Beam	f_{c0} CP	f_{t0}	$M_{exp.}$ (kN.cm)	M_{teo} (kN.cm)	$M_{exp.}/M_{teo}$
1	52.3	57.1	2489	2449	1.01
2	51.4	45.1	2273	2065	1.10
3	49.2	43.1	2381	2139	1.11
4	51.1	41.8	2056	2014	1.02
5	50.5	39.7	2561	2165	1.18
6	51.3	44.9	3210	3269	0.98
7	44.4	42.4	3824	3888	0.98
8	47.2	37.5	4220	3655	1.15
9	54.6	50.0	6200	5249	1.18
10	51.4	57.6	6143	6161	0.99
11	61.3	48.8	8173	6291	1.29
12	54.0	62.8	7948	7280	1.09

cal strains determined by the proposed calculation model were close to the experimental strains, confirming the validity of the hypotheses adopted. In view of the results obtained for the higher beam containing

a greater percentage of reinforcement, it can be inferred that better results could be obtained by incorporating into the theoretical model the shear strain of the adhesive in the reinforcement layer.

Two modes of rupture were observed, the first by strain in the sheet positioned under the reinforcement layer and the second caused by a combination of compressive tensile rupture and shear.

Acknowledgments

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Figure 8. Rupture modes of the experimentally evaluated glulam beams.