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Mechanical performance of glued-laminated timber beams symmetrically reinforced with steel bars

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ABSTRACT

The technology of glued laminated (glulam) timber has enabled the design of composite structures with large dimensions. The laminations are generally derived from the sawing of small trees and species of rapidly growing, which yields laminates with low mechanical properties. This study evaluates the benefits of the reinforcement of glulam beams, by employment of steel reinforcement ratios of 2% and 4%. In the beams with a ratio of reinforcement of 2%, in relation to the unreinforced glulam beams, the stiffness increased approximately 52% and the serviceability load increased 53.1%, and with the employment of steel ratio equal to 4% these increases were in the order of 73% and 79.2%, respectively. The results showed that the insertion of steel bars can reduce the inherent variability of wood and increase significantly the stiffness of glulam, which consequently increases the beam capability for serviceability limit states.

1. Introduction

The wood laminations employed in the production of glulam are generally derived from the sawing of rapidly growing trees, which yield low density values. The laminates of lumber that are employed to construct glulam exhibit low moduli of elasticity, which produce certain limitations regarding the loading capacity of a structure composed of glulam. In this context, De Vecchi et al. [1] reported that improvements in glulam should be developed to increase the stiffness of wood; for this purpose, reinforcement options should be explored.

Raftery and Harte [2] emphasized the use of glass fiber-reinforced polymer (GFRP) as a reinforcement solution for glulam beams. GFRP can increase load capacity, prevent brittle rupture and enable the use of timber of low-resistance categories. However, the studies performed by Fiorelli and Dias [3] and Carvalho [4] showed that reinforcement with GFRP produces minimal contribution to the rigidity of the beams. This result can be attributed not only to the value of the modulus of elasticity of the applied reinforcement and its limitation of adhesion to the glulam but also to the fact that this type of reinforcement is exclusively applied in the tensioned region of a beam.

The glulam that is reinforced with steel bars provides a more versatile system, which simultaneously improves its characteristics, such as rigidity and loading capacity. This finding can be attributed to an increase in the inertia of the composite section, the effect of the bars that were inserted in the tensile region to avoid brittle rupture and the effect of the inserted bars in the compressive region to prevent crushing of the timber. The use of metals to reinforce timber has been investigated for many decades. Dagher et al. [5] cites studies of steel and aluminum strips that were glued to low-quality timber, which occurred after World War II due to the shortage of wood. The technique of laminated reinforcements was patented by Gardner and Eaton [6]; the Arma-lam® [7], for example, has applied this technique.

Negrão [8] employed internal prestressed steel bars to improve the stiffening of glulam beams and to increase their load capacity. The excellent results regarding the deflections of the beams were attributed to the redistribution of the internal forces and the moments between the wood and the steel. However, due to limitations of the steel adherence, the gain that was originally expected for the rigidity of reinforced beams was not attained.

The prestressed bar system that was previously employed by [9] provided the ductile behavior of the glulam beams, which is a suitable feature for structures that are subjected to seismic actions. De Luca and Marano [9] highlight the importance of analyzing beams that have been reinforced with steel bar systems. Few existing studies have addressed the evolution of adhesives.

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Pellis et al. [10] applied the transformed cross-section method to calculate the rigidity of glulam beams that have been reinforced by steel bars. This method considers the ratio between the modulus of elasticity of steel and the modulus of elasticity of wood and transforms the actual section of a beam in a fictitious section of wood. The difference between the theoretically calculated stiffness and the experimentally calculated rigidity was 5.5%.

As known one of the limitations encountered in the use of glulam beams is related to the vertical displacement limits imposed by standards. In order to overcome this mechanical deficiency related the wood properties, the application of beams with more robust cross sections, resulting a great stiffness, is an interesting alternative to be adopted. However, this solution is not always feasible for architectural design, due to a reduction of the internal space of the construction, which should cause an attractive and/or functional loss of the building. The technique of reinforcing glulam, carried out in this study, focused on the serviceability limit states, and brought technical contribution to solve situations, in which a reduction of vertical displacements or even an increase the loading capacity of the structure is required. This benefit of reinforcing glulam beams was shown in this research, with details presented as follows, highlighting an increase of 53.1% and 79.2% in the service loading capacity, with the employ of steel reinforcement ratios of 2% and 4%, respectively. This study investigates the increase in the experimental values of the mechanical properties of stiffness and the load capacity of the glulam beams that were symmetrically reinforced with steel bars. The calculation model for the gain stiffness is based on the transformed cross-section method.

2. Materials and methods

A total of nine beams with a cross-section of 52 mm × 154 mm were prepared. The 3000-mm-length beams were constructed with seven laminates (Fig. 1). Three of the laminates of a lower category (elastic constant) were placed in the central part of the cross-section of the beams and two of the laminates of higher categories were utilized at each edge. For this classification of the laminates (Table 1), a propagation of ultrasonic waves was employed.

Table 1
Classification of the laminates. Elastic constant (C_{LL}).

Category	C_{LL} *mean* (MPa)	Standard deviation (MPa)	Number of laminates in batch
Higher	16364.25	2593.16	27
Lower	10921.31	1715.85	36

A group that was referred to as Glulam was formed by three beams without reinforcement. For the reinforced beams, two reinforcement ratios (ratio of the steel area to the cross-section of the beam) were employed: a group of three beams with a ratio of 2% (RGlulam2) and group of three beams with a ratio of reinforcement of 4% (RGlulam4). This maximum value of the reinforcement ratio was adopted based on the research of De Vecchi et al. [1], who described indicative rates from 0.2% to 4%. Pellis et al. [10] employed a reinforcement ratio of 4%. The intermediate value of 2% was applied to compare the effect of reducing the reinforcement ratio by 50%. Considering the necessity to protect the reinforcement from the weathering, the positioning of the steel bars inside the beam was adopted, being glued in the second lamination. This detailing is shown in Fig. 1 (b) and (c), enabling an improved monolithism between steel and wood as well. De Luca and Marano [9] also reported a beam collapse by buckling of compressed steel bar, which was arranged in the external lamination and not fully embedded by the wood lamination.

2.1. Specification of the materials for the manufacture of the beams

The beams were produced with 22-mm-thick laminates of *Pinus elliottii*, with a moisture content of 10.5%. The selected laminates (total of 63) were subjected to an ultrasonic inspection. Considering the elastic coefficient that was calculated by Eq. (1), the laminates were grouped into two categories (high level and low level) according to Table 1. For the purpose of this classification, the propagation time of the longitudinal wave was obtained with USLab equipment (USLab, AGRICEF, Brazil) and exponential transducers with a frequency of 45 kHz.

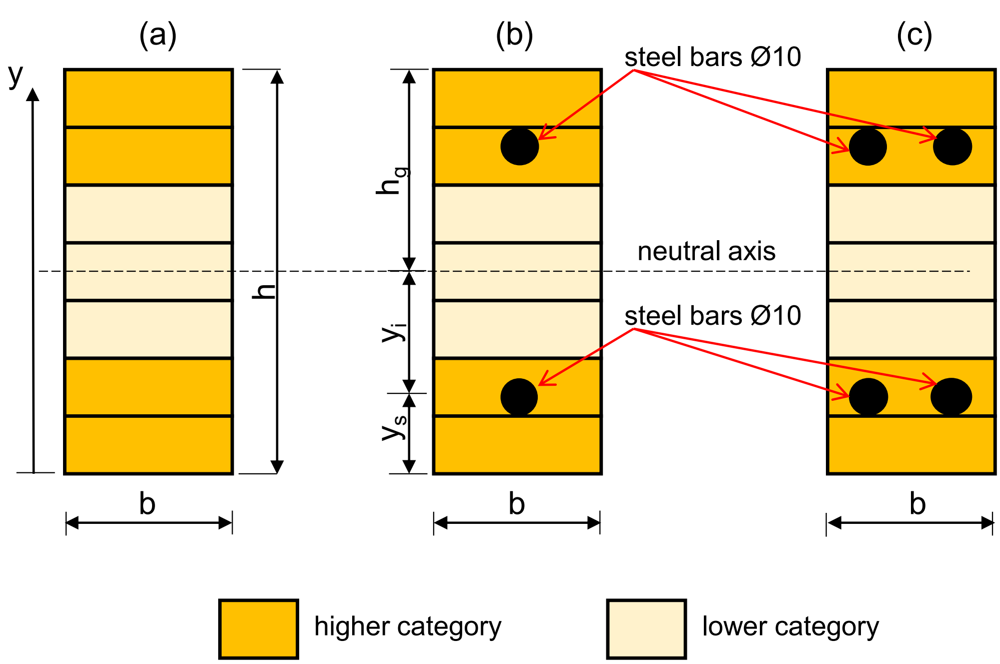

Fig. 1. Cross-section of the beams and geometric parameters. (a) Glulam without reinforcement, (b) RGlulam2, and (c) RGlulam4.