



Mix Sustentável

Reinforcement of glulam: a review of methods, materials, and numerical modelling

Reforço de vigas de madeira lamelada colada: uma revisão sobre métodos, materiais e modelagem numérica

Refuerzo de vigas de madera laminada encolada: una revisión sobre métodos, materiales y modelación numérica

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Abstract: Glued Laminated Timber (GLULAM) has been widely used in construction due to its high strength and versatility. However, it is susceptible to

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brittle failure under bending, which requires structural reinforcements to improve its performance. This work presents a literature review of reinforcement methods for GLULAM beams, focusing on the use of fiber-reinforced polymers (FRP). It discusses GLULAM characteristics, the main reinforcement materials, bar insertion methodologies, and numerical modeling using the Finite Element Method (FEM). The reviewed studies show that FRP reinforcement improves the strength and stiffness of beams, although issues such as adhesion and behavior under fire still require further investigation. This review highlights gaps in the literature and suggests approaches for optimizing reinforcements by combining experimental and numerical approaches.

Keywords: Glue Laminated Timber (GLULAM); FRP Reinforcement; Finite Element Method (FEM).

Resumo: A madeira lamelada colada (MLC) tem sido amplamente utilizada na construção civil devido à sua alta resistência e versatilidade. No entanto, sua ruptura sob flexão pode ser frágil, exigindo reforços estruturais para melhorar seu desempenho. Este artigo apresenta uma revisão da literatura sobre métodos de reforço de vigas de MLC, com foco no uso de polímeros reforçados com fibra (FRP). São abordadas as características da MLC, os principais materiais de reforço, as metodologias de inserção das barras e as modelagens numéricas aplicadas, incluindo o Método dos Elementos Finitos (MEF). Os estudos mostram que o reforço com FRP melhora a resistência e a rigidez das vigas, embora desafios como aderência e comportamento em situação de incêndio ainda exijam investigações futuras. A revisão destaca lacunas na literatura e sugere direções para otimização dos reforços, combinando abordagens experimentais e numéricas.

Palavras-chave: Madeira Lamelada Colada (MLC); Reforço com FRP; Método dos Elementos Finitos (MEF).

Resumen: La madera laminada encolada (GLULAM) se ha utilizado ampliamente en la construcción debido a su alta resistencia y versatilidad. Sin embargo, es susceptible a fallas frágiles a flexión, lo que hace necesarios refuerzos estructurales para mejorar su desempeño. Este trabajo presenta una revisión bibliográfica de los métodos de refuerzo de vigas de GLULAM, con énfasis en el uso de polímeros reforzados con fibras (FRP). Se abordan las características del GLULAM, los principales materiales de refuerzo, las metodologías de inserción de barras y la modelación numérica mediante el Método de los Elementos Finitos (MEF). Los estudios revisados muestran que el

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refuerzo con FRP mejora la resistencia y la rigidez de las vigas, aunque aspectos como la adherencia y el comportamiento frente al fuego aún requieren investigaciones adicionales. Esta revisión identifica vacíos en la literatura y propone enfoques para optimizar los refuerzos mediante la combinación de métodos experimentales y numéricos.

Palabras clave: Madera laminada encolada; refuerzo con polímeros reforzados con fibras; Método de los Elementos Finitos.

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1 INTRODUCTION

Wood is a natural composite composed of lignin, cellulose and hemicellulose, and it is a renewable material widely used in civil construction (MLOTE and BUDIG, 2022; WALKER, 2006). Wood has been historically used in construction, paints and receptacles due to its strength and abundant availability (SHMULSKY and JONES, 2011). Structurally, wood has compressive strength parallel to its fibers comparable to concrete with the added advantage of lower density, which simplifies logistics and decreases structural weight (RAMAGE et al., 2017). However, its anisotropic nature and presence of natural imperfections such as knots and cracks can compromise its mechanical performance (NBR 7190-2, ABNT, 2022; WADOWIAK-POSTULAK et al., 2023).

In order to mitigate such limitations, engineered wood products were developed such as Glued Laminated Timber (GLULAM), which consists of bonded laminates of wood in layers to achieve greater control of mechanical properties. The manufacturing process allows the selection of higher quality laminates to be used in regions with higher structural loads in order to minimize variations and obtain a more homogeneous material (MIRSKI et al., 2021). Thus, GLULAM beams can achieve strength equal or superior to solid wood (SHMULSKY and JONES, 2011), but failure under bending can be brittle and requires techniques to increase ductility and load bearing capacity (LACROIX and DOUDAK, 2018; TOMASI, PARISI and PIAZZA, 2009).

Structural reinforcement is widely used to improve structural performance of GLULAM beams and steel is one of the most common materials used (ALKHUDERY, AL-TAMEEMI and AL-KATIB, 2023; BULLEIT, SANDBERG and WOODS, 1989; GHARAIBEH and DOUDAK, 2023). Metallic rebars, plates or tendons inserted in the material improves stiffness and strength but incurs disadvantages such as increased weight and susceptibility to corrosion (WADOWIAK-POSTULAK et al., 2023; MCCONNELL, MCPOLIN and TAYLOR, 2014). As an alternative, fiber-reinforced polymers (FRP) have been increasingly used due to their high strength, light weight and durability in aggressive environments (HOLLAWAY and TENG, 2008; MICELLI, SCIALPI and LA TEGOLA, 2005; YANG et al., 2016b). Reinforcement of GLULAM beams can be accomplished with FRP bars, fabric, plates or tendons (RAFTERY and HARTE, 2009; RAFTERY and KELLY, 2015; Yang et al., 2016a). Different types of fibers with specific characteristics are available: glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), basalt fiber reinforced polymer (BFRF) and aramid fiber reinforced polymer (AFRP). In general, CFRP presents superior structural gains but higher financial cost while GFRP is the most economical alternative due to its substantial availability in the national supply chain (NADIR et al., 2016; WADOWIAK-POSTULAK and ŚWIT, 2021).

In addition to structural reinforcement, placement of FRPs also directly affects fire safety: while FRPs

are heat resistant, the polymer matrix could lose its mechanical properties at high temperatures (HOLLAWAY and TENG, 2008). Consequently, reinforcements inserted in between laminates in the manufacturing process are afforded a greater degree of passive fire protection. This reduces heat exposure and extends structural integrity over a larger period of time (WDOWIAK-POSTULAK, ŚWIT and DZIEDZIC-JAGOCKA, 2024). This factor added to the mechanical and durability advantages has further increased interest in the use of FRPs in GLULAM beams.

Due to the increasing use of FRPs as structural reinforcement in GLULAM beams, the objective of this study was to conduct a critical review of the main research of this topic. The analysis evaluated methodologies, materials and the effects on stiffness, strength and ductility of GLULAM beams. It is a systematic review which organized and condensed main current analysis techniques. The main issue examined was the viability of FRPs over steel with regards not only to mechanical gains but also adhesion, configuration and performance over extended periods of time. The contribution of numerical analyses was also examined and, based on the conclusions, gaps in knowledge were identified and topics for further studies on GLULAM beam reinforcements suggested.

2 REVIEW METHODOLOGY

This review focused on studies of GLULAM elements with reinforcement bars subjected to bending. To this end, searches were conducted on Scopus, Web of Science and Capes Periodicals databases on April 16, 2024.

A complete search key encompassing the topic was assembled based on three groupings: glued laminated timber, reinforcement and bars. For each grouping, synonyms and similar words both in Portuguese and English were verified in each publication as shown in Table 1.

Table 1 – Search groupings used in systematic review.

Grouping 1	Grouping 2	Grouping 3
MLC	reforço	barras
madeira lamelada colada	reinforced	barra
madeira laminada colada	reinforcement	bar
glulam	reforçada	bars
glue-laminated timber		rebar
glue laminated timer		rebars
glued laminated timer		vergalhão
glued-laminated timer		vergalhões
laminated timber beam		rod
timber laminated beam		rods

Source: elaborated by the authors.

The search engines of each database allowed the identification and exporting of studies encompassing the keywords of all 3 groupings. In total, 314 studies were identified with 112 from Scopus, 110 from Web of Science and 92 from Capes Periodicals database. Out of the 314 studies, 143 were duplicates listed in more than one database so that 171 individual studies remained for evaluation. Exclusion/inclusion criteria were adopted in order to remove studies that were not directly related to the topic. The main criteria selected were: reporting bar reinforcements in GLULAM beams subjected to bending; GLULAM beams had to have superimposed laminates in the conventional orientation (larger surface parallel to the ground); study must have been published in a periodical, congress or review work; reinforcement was applied to pristine elements (in order to exclude studies on structural repair) and the study must have been in Portuguese or English language.

After applying the criteria, 32 studies remained and were reviewed. These consisted of 24 experimental studies, 5 numerical studies and 3 containing both methodologies. The most used reinforcement material was steel (16 studies), followed by BFRP (9 studies), CFRP (6 studies) and GFRP (5 studies), while AFRP was used in only 1 study. The main parameter examined was reinforcement ratio (20 studies), followed by reinforcement position (10 studies) and bar material (4 studies).

3 FUNDAMENTAL CONCEPTS

3.1 GLULAM ductility and rupture modes

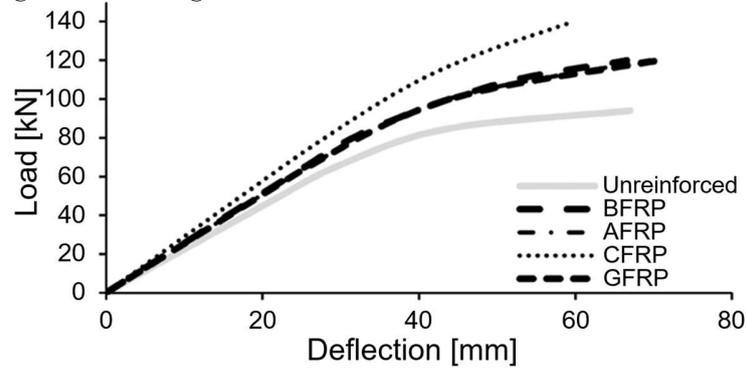
The ductility of a structure is related to its ability to undergo deformations without presenting brittle rupture (TOMASI, PARISI and PIAZZA, 2009). In the case of wood, this behavior varies in accordance with loading. When subjected to tension, wood presents a linear response with little plastic deformation until rupture. However, when subjected to compression parallel to its fibers, wood presents progressive localized buckling with a representative plastic response (TOMASI, PARISI and PIAZZA, 2009). This difference in behavior directly affects the performance of GLULAM beams under bending.

Wood anisotropy and the presence of natural defects such as knots and cracks can lead to brittle rupture in regions under tension while gradual rupture tends to occur in regions under compression (MLOTE and BUDIG, 2022; WDOWIAK-POSTULAK et al., 2023). Studies showed that non-reinforced GLULAM beams frequently suffered brittle failure in the region of tension (ALKHUDERY, AL-TAMEEMI and AL-KATIB, 2023; DE LUCA and MARANO, 2012; MCCONNELL, MCPOLIN and TAYLOR, 2014). In order to minimize this behavior, higher quality laminates could be used in the critical region or structural reinforcements could be inserted in the element (RAFTERY and WHELAN, 2014).

The insertion of reinforcements can alter the rupture mode of GLULAM beams. Experimental studies have determined that reinforcements placed in the region under tension induced a more ductile behavior and

transferred rupture to the region under compression where fiber buckling occurred (RAFTERY and WHELAN, 2014). However, if reinforcement was applied to both regions under tension and compression, the brittle behavior returned with rupture occurring in the region under tension (YANG et al., 2016b). These results denoted the importance of correct placement of reinforcements to optimize structural safety. Figure 1 presents the bending behavior of GLULAM beams with different reinforcements.

Figure 1 – Bending behavior of GLULAM beams with different reinforcements.



Source: adapted from Jończyk (2021).

Rupture modes of GLULAM beams can be classified in accordance to reinforcement type and placement. Studies have found that bar reinforcements could prevent brittle ruptures by resisting crack formation (WDOWIAK-POSTULAK et al., 2023). This is illustrated in Figure 2 which presents common rupture modes in beams with no reinforcement and localized reinforcement, and highlights the importance of studies on ductility and rupture mechanisms in order to optimize performance.

Figure 2 – Rupture modes in bending tests of GLULAM beams: (a) no reinforcement, (b) reinforcement in the region under tension and (c) reinforcement in both regions under tension and compression.



Source: adapted from Raftery and Whelan (2014).

3.2 Structural Reinforcement Materials: Steel and Fiber-Reinforced Polymer (FRP)

Structural reinforcement to improve strength and stiffness of GLULAM beams has been widely studied. Steel is the most traditional material used in the form of rebars, plates or tendons (ALKHUDERY, AL-TAMEEMI and AL-KATIB, 2023; BULLEIT, SANDBERG and WOODS, 1989; MIRSKI et al., 2021). Metallic reinforcements provide significant gains in load-bearing capacity but higher weight and susceptibility to corrosion can compromise overall structural durability (WDOWIAK-POSTULAK et al., 2023;

MCCONNELL, MCPOLIN and TAYLOR, 2014).

As an alternative to steel, fiber-reinforced polymers (FRP) have increasingly been used in GLULAM beams due to high specific strength, low density and corrosion resistance (HOLLAWAY and TENG, 2008; MICELLI, SCIALPI and LA TEGOLA, 2005). These materials have been applied in different forms such as bars (RAFTERY and HARTE, 2009; RAFTERY and KELLY, 2015), fabric (NADIR et al., 2016) and plates (GLIŠOVIĆ et al., 2017) which allow greater flexibility in the methodology of reinforcement.

The selection of FRP type directly affects beam performance. Studies have determined that CFRP offered higher stiffness and strength but at a higher financial cost which could be a limiting factor (NADIR et al., 2016). On the other hand, GFRP had a more favorable cost-benefit relation and was widely available with national suppliers, which makes it a viable reinforcement material (WDOWIAK-POSTULAK and ŚWIT, 2021).

4 REINFORCEMENT METHODOLOGIES OF GLULAM BEAMS

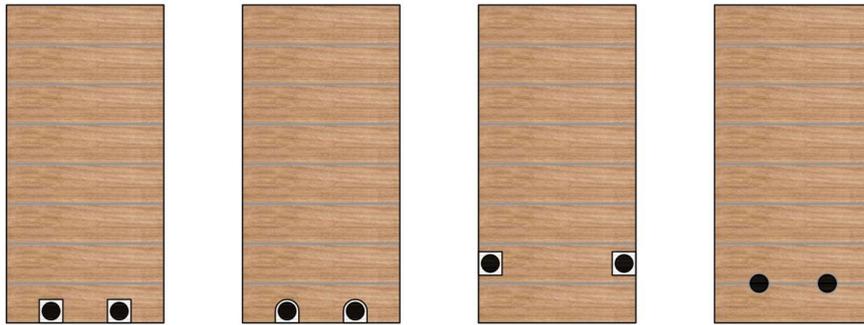
Reinforcement of GLULAM beams could be achieved with different methodologies but bar insertion is the most studied. This reinforcement can be applied in two techniques: after manufacture with grooves drilled for bar insertion or during the manufacturing process by inserting reinforcements in between laminates before bonding (ALKHUDERY, AL-TAMEEMI and AL-KATIB, 2023). The former technique is used in completed structures under load and can be used for repair of existing elements. However, the latter technique has significant advantages such as not requiring special epoxies to fix the bars in place, lower cost and optimization of the manufacturing process (SARDIKO et al., 2017).

Nonetheless, post-manufacture bar insertion has advantages such as adapting already existing elements without interference to the production line processes GLULAM mills. It allows the insertion of metallic or FRP reinforcements under different geometric configurations such as shown in Figure 3 (ALKHUDERY, AL-TAMEEMI and AL-KATIB, 2023). However, this technique depends directly on the quality of the interface between the bars and wood and requires correct epoxy adhesive and application (WDOWIAK-POSTULAK et al., 2023). Additionally, part of the beam cross section must be removed in order to drill grooves and this can decrease initial strength of the element (RAFLERTY and WHELAN, 2014).

Bar insertion during GLULAM beam manufacture removes the need of additional epoxy since the structural adhesive used on the laminates also bonds the reinforcements (SARDIKO et al., 2017). This technique also allows a better distribution of internal loads, decreasing the possibility of delamination and conferring greater protection against external agents like humidity and fire (WDOWIAK-POSTULAK, ŚWIT and DZIEDZIC-JAGOCKA, 2024). Studies indicated that steel or FRP bars inserted in between laminates could significantly improve stiffness and load-bearing capacity without compromising aesthetics or changing

external geometries (MIRSKI et al., 2021).

Figure 3 – Sample geometric configurations of bar insertions in a GLULAM beam cross section.



Source: elaborated by the authors.

The efficiency of reinforcements depends not only on insertion methodology or type of adhesive between wood and FRP but also on cross-section reinforcement ratio (WDOWIAK-POSTULAK, ŚWIT and DZIEDZIC-JAGOCKA, 2024). Experiments indicated that reinforcements in the regions under tension could significantly increase ultimate material strength of the beams while allowing a more predictable structural behavior (YANG et al., 2016b). On the other hand, reinforcement applied both to regions under tension and compression could produce greater rigidity but allow brittle rupture, which must be controlled with adequate reinforcement ratio (RAFTERY and HARTE, 2009). In addition, adhesion between wood and FRP was a critical factor affected by type of adhesive and insertion method (WDOWIAK-POSTULAK, ŚWIT and DZIEDZIC-JAGOCKA, 2024). Groove geometry and bonding technique also affected the result and it was recommended that grooves had the same geometry as the bars to decrease the amount of adhesive and improve adhesiveness (RAFTERY and WHELAN, 2014).

The selection of the ideal beam reinforcement should consider not only improvements to mechanical performance but also economic viability and ease of execution. While post-manufacture insertion had greater flexibility to reinforce pre-existing structures, insertion during manufacture allowed optimizations and offered greater protection to reinforcement materials. Recent studies indicated that hybrid methodologies could be an alternative to maximizing structural efficiency of the beams (WDOWIAK-POSTULAK et al., 2023).

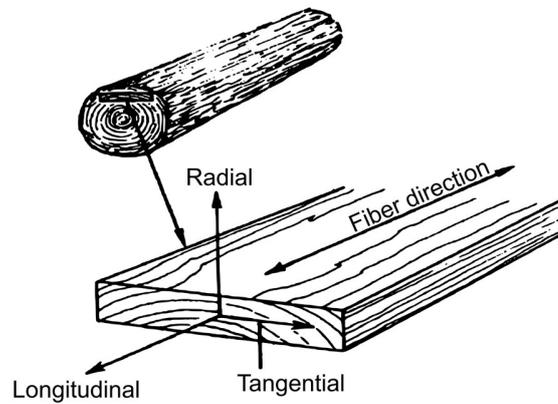
5 NUMERICAL MODELS AND COMPUTATIONAL SIMULATIONS

5.1 Main numerical models used in literature

The evolution of numerical methods has allowed the simulation of the structural behavior of reinforced GLULAM beams under different loads. These computational models can predict stresses, deformations and rupture modes which decrease the need of more extensive experimental analyses (CRESPO et al., 2020).

However, precise material characteristics are fundamentally needed so that mechanical properties fed to the numerical model yield proper results (RAFTERY e HARTE, 2009). Figure 4 shows the main orientations on a segment of wood along which mechanical properties vary.

Figure 4 – Main orientations on a segment of wood.



Source: Ritter (1990) apud Dias et al. (2019).

The main challenge in numerical models of GLULAM materials are the anisotropy and heterogeneous nature of the material. These produce significant variations in strength along the directions shown in Figure 4 (TOMASI, PARISI and PIAZZA, 2009). Simplified models that assume homogeneous properties can produce discrepancies between theoretical and experimental results (WDOWIAK-POSTULAK, ŚWIT and DZIEDZIC-JAGOCKA, 2024). Consequently, more refined techniques incorporate orthotropic models to more accurately simulate material properties (JOŃCZYK, 2021).

The effect of reinforcements has also been extensively evaluated through numerical simulations. Some studies evaluated the interaction between wood and reinforcement through discrete models in which the stiffness of the reinforcement was considered separate from wood (PEIXOTO et al., 2022). Alternatively, other studies considered cross-sectional homogeneous properties combining wood and reinforcement strength to create an equivalent material (CHRISTOFORO et al., 2022). Both approaches had advantages and limitations and their choice was based on the desired level of precision.

Another factor to be considered in modeling reinforced beams is the adhesiveness between reinforcements and wood. Experimental studies indicated that ruptures on the adhesive interface compromised reinforcement effectiveness. Thus, numerical models must include delamination or elements with non-linear contact behavior (WDOWIAK-POSTULAK, ŚWIT and DZIEDZIC-JAGOCKA, 2024). Adhesion behavior was particularly critical in post-manufacture reinforcements in which the epoxy adhesive was used to fill the grooves and directly affected the load bearing capacity of the beam (SARDIKO et al., 2017).

In addition to structural analysis, numerical models have also been used to predict reinforced GLULAM beam behavior under extreme conditions such as fire or long-term exposure to humidity. Simulations have shown that internal cross-sectional reinforcement could offer greater protection against thermal degradation

(WDOWIAK-POSTULAK and ŚWIT, 2021). This type of analysis reinforced the value of simulations to evaluate long-term durability and safety of the beams.

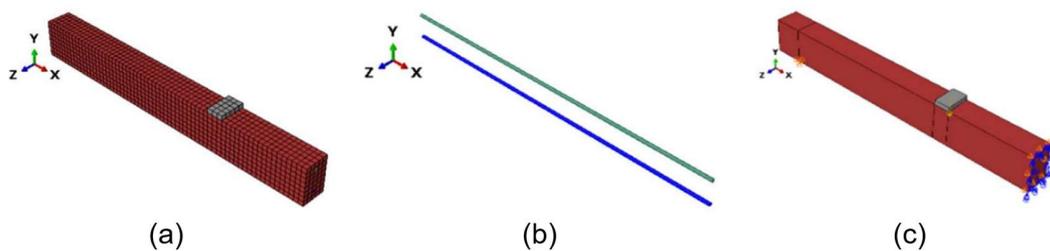
5.2 Structural behavior prediction with Finite Element Method (FEM)

The finite element method (FEM) has been widely used to study GLULAM beams and provide detailed simulations of mechanical behavior. This technique allows the evaluation of stresses, deformations and rupture modes by discretizing the beam in small elements in which balance equations are solved numerically (CRESPO et al., 2020). The reliability of FEM depends on adequate calibration of input parameters which include material mechanical properties and realistic boundary conditions (JOŃCZYK, 2020).

Reinforced GLULAM beams require different discretization strategies. Some studies incorporated solid three dimensional elements to model each beam component, including wood, adhesive and reinforcement (JOŃCZYK, 2021). Other studies adopted a simplified model with shell or beam elements which allowed quicker and less computer-intensive analyses (CHRISTOFORO et al., 2022). The choice of simulation approach affects the accuracy of the results and should be decided in accordance to objectives.

Wood and reinforcement interaction is a determining factor in FEM analysis. Advanced models included contact interface between the materials to simulate the joint between reinforcement and beam (WDOWIAK-POSTULAK, ŚWIT and DZIEDZIC-JAGOCKA, 2024). In addition, the use of cohesive elements to connect elements has been shown to allow efficient prediction of ruptures in the adhesive interface and improved correlation with experimental results (RAFTERY and WHELAN, 2014). Figure 5 shows a sample discretization of a beam with its elements, reinforcements and support loads.

Figure 5 – Sample discretization of reinforced GLULAM beam: (a) FEM elements, (b) reinforcement bars and (c) support and applied loads.



Source: Christoforo et al. (2022).

Another fundamental aspect of FEM analysis was calibration with respect to experimental data. Experimental data were used to validate numerical results and adjust model parameters to experimental results (PEIXOTO et al., 2022). This was essential to ensure the accuracy of the simulations with respect to real beam behavior under loads.

Finite element models have also been used to optimize structural projects. Numerical methods could

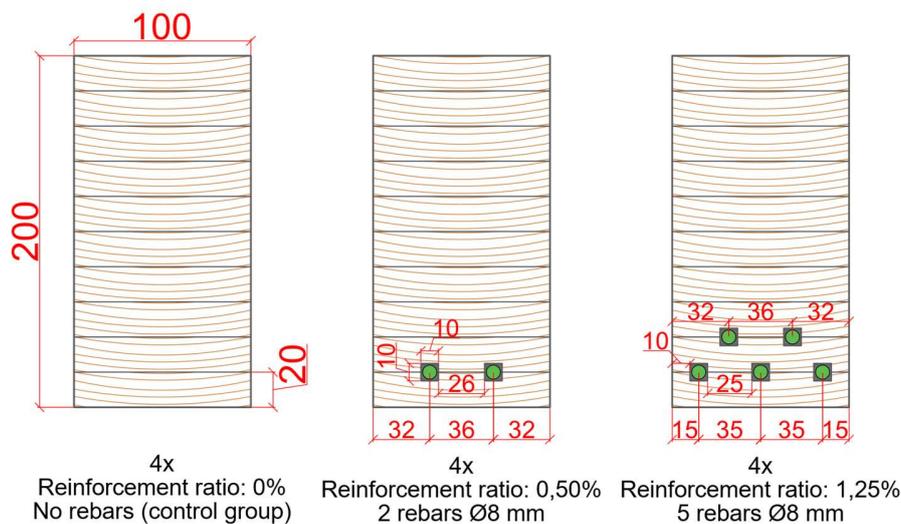
evaluate of different reinforcement configurations and allow the choice of reinforcement ratio and positioning that maximize structural efficiency (WDOWIAK-POSTULAK and ŚWIT, 2021). This demonstrated the potential of numerical simulations not only to predict structural behavior but also to improve project design and durability of reinforced GLULAM beams.

6 CURRENT ONGOING UFSM RESEARCH

Current ongoing research at Universidade Federal de Santa Maria (UFSM) involves studies to evaluate the efficiency of GFRP rebars as reinforcement for GLULAM beams under tension. Reinforcements were inserted in between laminates during the manufacture process of the beam. The wood type of the beams was *Pinus ellioti* and the structural adhesive was polyurethane-based JowaPUR 686.60.

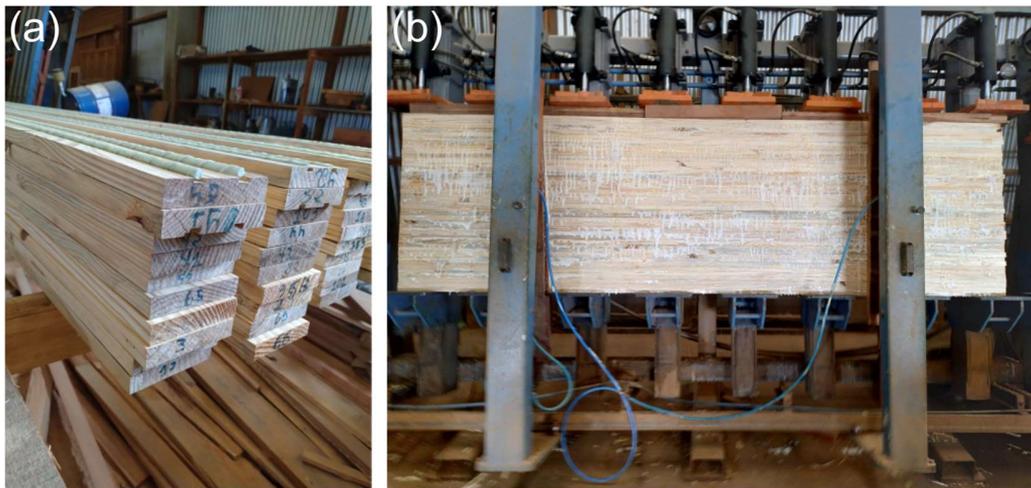
A total of 12 beams were manufactured measuring 100 mm x 200 mm x 2,700 mm. Three distinct reinforcement configurations were used in the samples: no reinforcement reference (4 beams), 2 rebars in between the last 2 laminates for a 0.50 % ratio (4 beams) and 5 rebars in between the last 2 laminates for a 1.25 % ratio (4 beams). These configurations are shown in Figure 6. Each laminate was 20 mm thick and the beam contained 20 layers. The rebars had a nominal diameter of 8 mm.

Figure 6 – Schematic cross section of reinforcement GLULAM beams in ongoing UFSM study.



Source: elaborated by the authors.

Figure 7 presents the reinforced GLULAM beams being manufactured. Figure 7(a) shows the laminates being prepared and placement of rebars prior to gluing. Figure 7(b) shows the assembled beam in a press for curing. The beams were later subjected to a 4-point bending test at LMCC (Laboratório de Materiais de Construção Civil - UFSM).

Figure 7 – Reinforced GLULAM beam manufacture: (a) preparation and placement of rebars and (b) curing and pressing.

Source: elaborated by the authors.

7 FINAL CONSIDERATIONS

Reinforcing glued laminated timber (GLULAM) beams with fiber-reinforced polymers (FRP) has demonstrated advantages with respect to strength, stiffness and durability of a structure. Experiments indicated that the addition of FRP reinforcement could increase load-bearing capacity and decrease deformation of beams under loads (YANG et al., 2016b; WDOWIAK-POSTULAK, ŚWIT and DZIEDZIC-JAGOCKA, 2024). Additionally, FRPs have high resistance to corrosion and lighter weight than steel, which offered further advantages in aggressive environments in which metallic reinforcement could degrade over long periods of time (HOLLAWAY and TENG, 2008; MICELLI, SCIALPI and LA TEGOLA, 2005).

Despite its advantages, some issues remained that limit the applicability of this technique. For example, adhesiveness between reinforcements and wood was a critical factor that could directly affect the efficiency on the structure (WDOWIAK-POSTULAK et al., 2023). The two application methodologies: post-manufacture reinforcement insertion or incorporating reinforcement during the manufacturing process yielded different performances and required precise control of the adhesive interface to prevent premature ruptures (RAFTERY and HARTE, 2009).

Another relevant issue was the behavior of the beams under extreme conditions such as fire exposure. Extreme heat could compromise the polymer matrix of the FRP and decrease mechanical performance before a total evacuation of the structure was completed (HOLLAWAY and TENG, 2008). To mitigate this risk, studies recommended the insertion of reinforcements during beam manufacture to ensure greater passive protection of the reinforcement material and improve structural safety (WDOWIAK-POSTULAK and ŚWIT, 2021).

This literature review found knowledge gaps that require further examination. For example, the interaction between wood and reinforcement requires more advanced numerical models that consider the effect

of the adhesive interface and progressive delamination (WDOWIAK-POSTULAK, ŚWIT and DZIEDZIC-JAGOCKA, 2024). There is also a need to examine long-term behavior of reinforced structures with respect to fluidity, fatigue and environmental degradation under different conditions (UCHIMURA, SHIOYA and HIRA, 2016).

Future research could be dedicated to optimizing FRPs to determine geometric configurations that maximize structural gains with lower financial cost. Additionally, further more advanced insertion techniques and new materials could increase viability and allow large-scale application of this technique (SARDIKO et al., 2017). To this end, the integration of experimental tests and computational models will continue to be essential to the evolution of this topic and improvement of reinforced GLULAM beams.

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