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Behaviour of Jute Fibre-Reinforced Glued Laminated Timber Beams under Short-Term and Long-Term Loading

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The use of natural fibre-reinforced polymer (NFRP) composites has been increasing constantly due to their significant advantages in civil engineering and in the automotive and aerospace industries, among others. Fibres such as jute are ecological, renewable, and completely or partially biodegradable. This allows them to contribute to the development of new high-performance polymer materials with excellent strength properties (e.g., tensile strength, flexural behaviour, fracture toughness, and fracture resistance). This paper discusses the results of experimental tests of the performance in bending and shear of glued beams reinforced with prestressed jute fibre rods and fabrics. Twenty-four technical-scale wooden beams were used for four-point bending shear tests, each beam having a different reinforcement percentage. The study found that high performance was achieved with FRP jute reinforcement, with a single layer increasing load-bearing capacity by approximately 13% and stiffness by approximately 12%. A double layer provided even greater performance, with increases of approximately 27% and 14%, respectively. Moreover, in the case of unreinforced beams at mid-span the deflection under long-term load was 28%, while it was approximately 35% for a mid-span beam made of solid laminated timber with single jute reinforcement, and approximately 36% for a double jute reinforcement. In the numerical analysis, the differences between the experimental and numerical models were approximately 5%, representing satisfactory results for design prediction.

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Introduction

Laminated timber or cross-laminated timber (CLT) is commonly found in modern buildings nowadays as an environmentally friendly alternative to other building materials such as concrete and steel (Goodwin et al., 2025; Zeitz, Griffin et al., 2019). The use of structural timber has created a need to develop methods for modernising and strengthening structures in order to adapt them to changes in use or to reduce deterioration of structural properties during operation, allowing the material advantages of timber structures to be fully exploited throughout their life cycle. Wood is a very versatile and widely used building material because of its ease of processing and remarkable functional qualities. It is a material used both in ancient historic buildings and in contemporary architecture, ensuring environmentally friendly construction. Windmills are also an important part of cultural heritage, being unique examples of folk architecture and pre-industrial craftsmanship (Agnantopoulou et al., 2023). Wooden buildings require maintenance due to age and environmental factors (Alaşalvar et al., 2025). Recently, the development of structural wood products such as laminated veneer lumber (LVL), glued laminated timber (Glulam), OSB, plywood, and cross-laminated timber

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(CLT) has had a significant impact on the production of large and durable structural elements. These materials are very economical and sustainable, and serve as an alternative to hardwood products (Youn et al., 2025). Unfortunately, there are challenges associated with designing long-span wooden beams to meet serviceability limits. It should also be noted that the wear and tear of wooden elements and their susceptibility to environmental factors, including water, biodegradation and technical wear, seriously complicate the protection of historical and contemporary wooden structures. Therefore, it is necessary to develop and apply new methods of conservation and restoration in order to slow down processes of deterioration, improve the functional properties of old timber, and ensure the safety of structures. Thus, solutions for the maintenance of historical and contemporary wooden structures are recommended, using, among other things, advanced fibre-reinforced plastics (FRPs) (Alaşalvar et al., 2025). The use of innovative materials such as resins, various adhesives and composite materials offers good prospects, although they require in-depth research.

Fibre-reinforced plastics (FRPs) are composites consisting of polymer resins as a matrix and other types of fibres, such as glass or carbon, as reinforcements. They offer a number of advantages, such as lightness, high durability, corrosion resistance, and versatility of design. They are used in many sectors of industry, such as construction, aviation, shipbuilding, the automotive industry, etc. (Perçin, 2025). Likewise, the growing demand for advanced composite materials has led to the development of new polymer composites (Tan et al., 2010). As mentioned above, FRPs offer many advantages as a component that has been used for decades to protect the integrity of structures and increase their strength. This material is therefore useful for various types of reinforcement and load-bearing connections, including renovation, production of I-beams, bridge decks, beams and wooden posts. FRP reinforcement is used to increase the stiffness and load-bearing capacity of wooden beams (Karaman, 2025). Composite materials in the form of FRPs can be produced from glass, carbon and aramid fibres, and are typically used to improve the physical and mechanical properties of wood and wood-based composites (Karaman et al., 2021).

All FRP reinforcements are manufactured by pultrusion; aramid fibres are used for aramid fibre-reinforced plastics (AFRPs), and similarly basalt fibres for BFRPs, carbon fibres for CFRPs, and glass fibres for GFRPs (Hammad et al., 2024). It is worth noting that due to its high production efficiency, E-GFRP is considered the most cost-effective composite among FRPs. Aramid fibre is not a good solution because it has lower compressive strength (Liu et al., 2025; Zeitz et al., 2019; Alaşalvar et al., 2025; Youn et al., 2025). In general, carbon fibre is the best of all the materials due to its high strength, creep resistance and better fatigue properties. Thanks to the availability of carbon fibres and manufacturing processes, carbon fibre is also available in many different versions with varying strength and quality (Liu et al., 2025; Zeitz et al., 2019; Alaşalvar et al., 2025; Youn et al., 2025). Until now, modernisation of structures has been based mainly on the use of carbon, glass or aramid fibres, with little attention paid to improving structures using available natural materials or natural fibres. The use of composites in structures is primarily focused on increasing the strength of the structure using synthetic fibres, with sustainability issues being ignored. Similarly, with the growth of the world's population, the demand for raw materials necessary to reinforce structures to meet market demand is growing rapidly. Therefore, while polymer prices cannot be expected to stay steady, and consumption is increasing constantly, it is necessary to create new, cheaper materials offering equal or better properties, or to modernise various structural components. It has become necessary to develop and utilise new materials for structural reinforcement, as they are promising materials with good properties. Given the economic situation and other factors in many developed countries that have abundant natural fibre resources, science must develop technologies that allow these fibres to be used as effectively and cost-efficiently as possible for building renovation or new construction (Sen et al., 2013; Peled et al. 2000; Kim et al., 2011; Sim, et al., 2005; Grace et al., 2004; Wdowiak-Postulak, 2020; Wdowiak-Postulak et al., 2023; Wdowiak-Postulak, 2023; Wdowiak-Postulak et al., 2023; Salčin et al., 2022; Wdowiak-Postulak et al., 2024; Wdowiak-Postulak et al., 2025). Natural fibres are a simple type of fibre that may or may not be synthetic and can be found in plants and animals. They are either renewable or non-renewable. There are various types of these natural fibres, such as flax, hemp, sisal, banana, kenaf, jute and oil palm fibre. It should be mentioned that jute fibre composite materials have recently aroused much interest among researchers (Keya et al., 2019). Jute fibre is characterised by high insulation properties, high strength in relation to weight, high elongation, excellent technical properties and good thermal properties (Keya et al., 2019). These properties concern the basal fibres themselves, not the main wood tissue (xylem) located in the central part of the stem. The researchers Karzan and Habeeb (Keya et al., 2019; Mahmoud et al., n.d.; Karzan, 2011) investigated the strength of jute fibre-reinforced cement composites in six groups of samples measuring 25×150×600 mm^3, which were reinforced with jute fibre ropes. In the study (Karzan et al., 2011), the materials were tested in the form of a cementitious composite, i.e. a cement matrix with fine aggregate, where jute fibres in the form of ropes were used as reinforcement. It was found that the ratio of destructive load increase was approximately 6–24% and 10–46%, respectively, with an increase in the volume fraction of jute fibres. Alam et al. (Keya et al., 2019; Alam et al., 2015) analysed the reinforcement of reinforced concrete (RC) beams using jute rope panels as a substitute for carbon fibre (CFRP) in the reinforcement of concrete beams subjected to bending. The experiment involved composite jute rope plates measuring 80×100×2000 mm^3 and a reinforcement concentration of 25%. The maximum load of the beam reinforced with composite jute rope plates was 131 kN, which is an increase of 58% compared with the unreinforced beam. Liu et al. (2025) demonstrated that FRP bars inhibit the deformation of wood. Further research (Abdulla et al., 2021) showed that the use of jute fibre reinforcement increased the load-bearing capacity of wooden beams by 30–101%. Further studies on composite timber-concrete structures have shown that properly designed timber-concrete connections significantly improve stiffness and load-bearing capacity compared with typical timber beams (Cvetković et al., 2023; Fragiacomo et al., 2018). Analyses of concrete-timber composite beams show that the use of FRP composites at the interface between materials leads to improved load-bearing capacity and interaction between them (Yehia et al., 2018; Vlcek, 2014). Such research is also being conducted by the present author, but this is outside the scope of this paper. Further studies (Bula et al., 2023) compared the effect of reinforcing wooden beams with composite panels (e.g., CFRP) and composite bars. The results showed a significant increase in load-bearing capacity and reduced cracking when using the panels. Another paper (Nowak et al., 2016) presents an overview of methods for reinforcing timber beams with steel plates. A further report (Morales-Conde et al., 2015) also discusses the impact of various joining methods and highlights the need for additional mechanical joining. That publication concerned reinforcements with glass fibre plates (GFRP) glued to the element, including bending and shear analysis.

This paper describes experimental studies involving three groups of beams, each of which was used to examine the effect of reinforcement on static bending and shear analysis. The main objective of this research was to investigate the reinforcement of laminated timber beams using a newly developed, eco-friendly method of reinforcement with FRP composites. With ecology in mind, natural jute rods were selected for the production of the composite. The aim of this study is to evaluate the performance of jute-reinforced laminated beams in bending and shear tests, which is of great importance for practical applications. The method of reinforcing wooden beams against bending and shearing with these rods is easy to implement in practice as longitudinal reinforcement along the entire length of the beam. These lightweight, durable non-woven materials provide passive protection, increasing the strength and ductility of the entire beam, including the tension zone.

The importance and novelty of this study stems from the fact that, despite growing interest in sustainable construction and the use of natural materials, there is little existing literature on the reinforcement of glued laminated timber beams using natural fibres. This type of research can not only increase the strength, load-bearing capacity and stiffness of structural elements, allowing the use of smaller beam cross-sections and lower-quality sawn timber in view of its increasing scarcity, but can also reduce the consumption of synthetic materials, which is important for the ecology and durability of structures. The main objective of the study will be to analyse the impact of jute rod reinforcement on the mechanical properties of glued laminated timber beams, including their bending strength in shear and stiffness. The results may form a basis for designing more effective and environmentally friendly wooden elements, which will open up opportunities for the use of natural fibres in construction engineering.

The originality of the research relates to, in particular, the use of jute fibre rods as reinforcing elements for laminated timber beams. Previous research on the reinforcement of wooden elements has predominantly focused on solutions using synthetic materials, such as FRP composites, while the potential of natural fibres in this type of application remains relatively unknown. The introduction of jute fibre reinforcement is a more environmentally friendly alternative and can also contribute to improving the mechanical parameters of structural elements. Another important innovative element is a comprehensive analysis of the impact of this type of reinforcement on the properties of laminated timber beams subjected to bending and shearing, which allows a more accurate assessment of the effectiveness of the proposed solution. The research has yielded new knowledge about the interaction of laminated timber with natural fibrous materials and has identified possibilities for their use in engineering structures. An important innovative aspect is the possibility of using lower strength grade timber and designing elements with smaller cross-sections, while maintaining the required load-bearing capacity and stiffness parameters. This approach can contribute to a more efficient use of timber resources and is in line with the principles of sustainable development in construction.

Materials and methods

1. Materials

Glued laminated timber beams (GL22c) of Norway spruce (*Picea abies*) from Scandinavia and Scots pine (*Pinus sylvestris* L.) originating from the Małopolska Natural and Forest Region of Poland, and from the beginning and end of the growing season from the end of October, were created by gluing four layers together so that the grain directions were parallel, which reduced wood defects (Figs. 1 and 2). This resulted in wooden elements with improved properties and a variety of desired prefabricated product shapes. First, KG lamellas (PN-D-94021:2013-10) of a lower quality class (T8; EN 14080:2013-07) and KS lamellas of a medium quality class (T13) were sorted and classified according to the PN-D-94021:2013-10 standard. Each structural sawmill element was taken from the inner, core, and outer layers of each log (taking into account USM – Marginal Zone Knot Index, USC – General Knot Index, graininess, etc.). The beams were then constructed by combining and gluing KS and KG lamellas. The lamellas had nominal cross-sectional dimensions of 41 × 83 mm^2 and a length of 4000 mm. The moisture content of the lamellas and their density before gluing are specified in Tables 1 and 2. The final average density of the beam was 390.14 kg/m^3, and the average moisture content was 12.15% immediately before mechanical testing. The density was determined from the mass and volume of the sample according to the EN 408 standard. Wood moisture content was measured by the electrical resistance method using a moisture meter according to the EN 13183-3:2007 standard. The measurement points were free of defects (knots, resin, stains). Measurements were taken at points approximately 300 mm from the ends of the element and halfway along its length. The main objective of the research is to determine the breaking strength, compressive stress, tensile stress, shear stress, deformation, and modulus of elasticity of wood. All parameters were determined by full-scale bending shear tests on beams, in accordance with the EN 408 standard, as described below. In glued laminated beams, a mixture of arrangements was used, alternating radial and tangential arrangements, with radial lamellas placed in the outer zones of the beam, where the stresses were the highest.

Polyurethane-glued beams were created by embedding jute rods into the final lamella using an epoxy adhesive characterised by excellent adhesion, low viscosity, and ease of application. In addition, jute fabric (0.08 × 3.65 m^2) with a thickness of 2 mm and a weight of 350 g/m^2 was glued along the entire length of the beam. The adhesive had a density of 1.10 g/ml, viscosity 13,000 mPa.s, and water resistance class D4; its manufacturer is Kleiberit (colour: white, pH: approx. 3, open time (20 °C): 6–10 min, bleaching point: approx. +5 °C, application rate: 100–130 g/m^2 – surface gluing, 150–200 g/m^2 – solid wood, pressing force:

Fig. 1. Preparation of glued laminated beams for reinforcement

Fig. 2. Moisture measurement of an example beam (BEAMJ1-2)

Table 1. Mechanical properties of T8 structural timber (T8 according to EN 14080:2013-07)

Parameter	Average value	Standard deviation
Bending strength [N/mm^2]	39.92	5.06
Compressive strength parallel to fibre [N/mm^2]	31.23	3.46
Modulus of elasticity on bending [N/mm^2]	7092.14	425.3
Density [kg/m^3]	325.16	-
Moisture content [%]	10.09	0.4

Table 2. Mechanical properties of T13 structural timber (T13 according to EN 14080:2013-07)

Parameter	Average value	Standard deviation
Bending strength [N/mm^2]	59.21	6.11
Compressive strength parallel to fibre [N/mm^2]	47.42	5.23
Modulus of elasticity on bending [N/mm^2]	11113.13	872.3
Density [kg/m^3]	392.15	-
Moisture content [%]	13.13	0.8

Table 3. Characteristics of GL22c beam (according to EN 14080:2013-07)

Parameter	Average value	Standard deviation
Bending strength [N/mm^2]	23.21	1.08
Compressive strength parallel to fibre [N/mm^2]	21.05	1.27
Modulus of elasticity on bending [N/mm^2]	10580.19	79.45
Density [kg/m^3]	390.14	-
Moisture content [%]	12.15	0.95

0.7–1.0 N mm^2, pressing time: 20 °C: from approx. 15 min, 50 °C: approx. 5 min, 80 °C: approx. 2 min).

The mechanical properties of structural Scandinavian spruce timber (*Picea abies*) and Scots pine (*Pinus sylvestris* L.) lamellas are presented in Tables 1–3 and Fig. 3. The parameters given in Tables 1 and 2 were determined on the basis of strength tests of lamella elements in accordance with the EN 408 standard, bending strength tests and compression tests along the grain. The results for parameters of the entire glued beams, determined in accordance with the EN 408 standard, are shown in Table 3. The GL22c glued beam consisted of KG (T8) and KS (T13) lamellas.

Epoxy adhesive (LG815 + HG353) was used to bond jute fibre to wooden beams. To obtain an epoxy resin-based adhesive layer, LG 815 epoxy resin (density 1.13–1.17 g/cm^3, viscosity 1100–1300 mPa.s) was mixed with HG 353 hardener (density 0.98 g/cm^3, viscosity 100–150 mPa.s). Some of the parameters were provided by the manufacturer GRM Systems sp. z o.o. The remaining ones were determined on the basis of bending strength tests in accordance with the EN 408 standard.

The experimental studies took into account the arrangement of wood fibres parallel to the beam, identical to the arrangement of bars and fabrics corresponding to the orientation of jute fibres parallel to the wood fibres of the beams. The jute fibre used is a delicate but very resistant plant fibre with excellent tensile strength and low extensibility at breaking point. Besides, jute fibre is considered by many to be one of the cheapest natural fibres.

First, the rods were prepared, cleaned with acetone, and cut to the required dimensions, i.e., a length of 3750 mm, for installation in the beams. Furthermore, the jute fibre rods were cut for tensile strength testing to determine the strength properties according to the guidelines for isotropic and orthotropic fibre-reinforced polymer composites. Smaller pieces of the rods were then placed in an oven at 45 °C for 72 hours. They were then placed in a sealed chamber to prevent moisture absorption. It should be noted that heat-treated natural fibre composites have greater strength than untreated natural fibre composites. In this study, a natural fibre-reinforced polymer (NFRP) was used as a tough, lightweight composite material.

The installation of the jute reinforcement (see Fig. 3) consisted of the following steps:

1. Assessment of the technical condition of glued laminated timber beams (identification of biological damage, cracks, knots and other structural and geometric features, degree of degradation, etc.).
2. Cleaning of dirt from the beam surfaces.
3. Milling of grooves along the beam axis adapted to the diameter of the jute rods (rod diameter 8 mm) – 14 x 14 mm^2.
4. Embedding of jute rods in the prepared grooves and their prestressing.
5. Permanent bonding to the beam achieved by filling the grooves with epoxy glue.
6. Levelling of unevenness, sanding, and preparation of the surface for reinforcement with jute fabric.
7. Application of a layer of jute fabric glue to the beam surface, fully saturating it.
8. Application of another layer of glue.
9. Assessment of reinforcement adhesion.

To create the reinforced beams, water-based glue was applied to the holes, initially poured using a dispensing container and then brushed with a synthetic bristle brush. Water-based epoxy glue was used to better penetrate the wood pores and properly fill the wood casing around the beam, which increased the bond adhesion. Due to the surface properties, an adhesive with a grammage of approximately 250–300 g/m^2 was used between the jute beam and the batten. The beams and composites were acclimatised at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5% for at least two weeks. To reinforce the wooden beams, rods and jute fabrics glued with two-component epoxy glue were used. The mechanical parameters of the jute are given in Table 4. Mechanical parameters were obtained based on tensile strength tests for composite rods. An adhesive joint approximately 1–2 mm thick was used, as excessive amounts of epoxy glue are ineffective and function as a substitute for the reinforcement.

The gluing process began with the application of jute rods along the stress zone along the entire length of the beams, followed by the application of fabrics. After application, the rods and fabrics were allowed to cure and bond to the wooden elements for at least seven days. This was the procedure recommended in the manufacturer's catalogue to achieve the full strength of the epoxy adhesive.

A total of 24 glulam beams were prepared for these experiments. Eight of these were selected as reference beams without reinforcement, eight with a single layer of bars and one layer of fabric, and another eight with two layers of bars and one layer of fabric. The following variables were considered in the experimental study: structural lumber quality class, lumber sampling location, and reinforcement type. Samples were taken from a cross-section of the trunk at breast height (1.3 m from the ground surface), from the outer sapwood zone, at a distance of approximately 25–35% of the trunk radius from the heartwood–sapwood border, excluding

Fig. 3. Reinforcement of glued laminated timber beams with rods and fabrics – final stage

Table 4. Mechanical properties of jute fibres

Fibre	Modulus of elasticity GPa	Tensile strength MPa	Tensile strength of epoxy resin-coated jute MPa
Jute	16.8	55	99.7

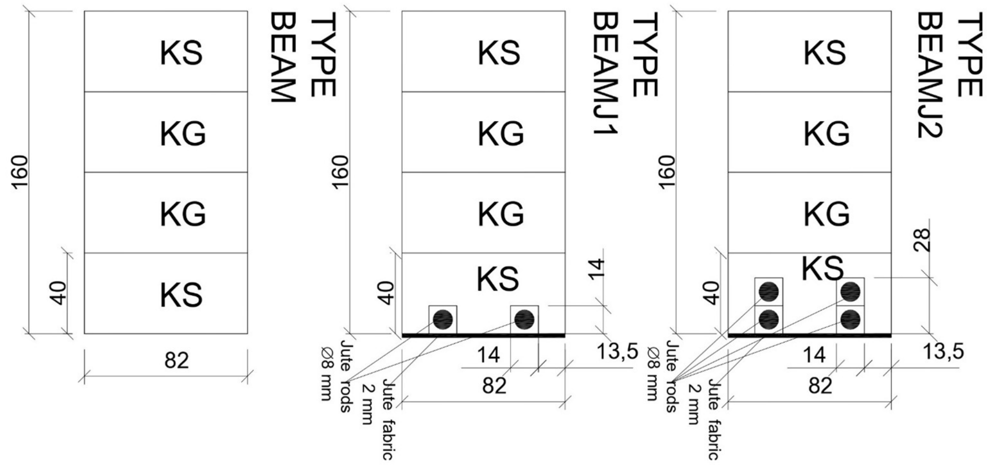


Fig. 4. Reinforcement diagrams for glued laminated timber beams

the core and bark layer. The reinforcement in the tension zone was additionally secured to prevent premature detachment of the jute fibres by using appropriate anchors at the beam supports. Jute anchors with a diameter of 10 mm were inserted at a distance of 10–15 cm from the ends of the beams into previously drilled holes with a diameter of 11–12 mm, filled with epoxy glue. The reference beams were designated as BEAM, while the beams with a single layer of reinforcement were designated as BEAMJ1 and those with two layers of reinforcement as BEAMJ2 (Fig. 4). Tables 1–3 present the sample type names and variable characteristics.

2. Methods

The laminated beams were subjected to a four-point bending shear test, loading them hydraulically. The loading was exerted at a constant speed using two actuators with a maximum load capacity of 100 kN and a precision of 0.1% of the maximum applied load. The load was maintained until the wooden beams failed. During the tests, the load, deformation of the wood and composite, and displacement were recorded. The displacement value was measured at the mid-span and at a length of 5 *h*, where *h* is the beam height, using mechanical dial gauges. Load was measured with an uncertainty of 0.1 kN, and deflection with an uncertainty of ±0.1 mm.

As described above, the tests used the jute fibre reinforcement method, employing a loading system compliant with EN 408 + A1. One aim of the research was to determine by how much the cross-section of reinforced beams can be reduced compared to the strength requirements for unreinforced beams. Similarly, the experimental setup was designed in accordance with the EN 408 standard. In accordance with the standard, a four-point loading system was used to test the bending shear strength of laminated timber elements, with a support spacing of 15–18 *h* (where *h* is the cross-sectional height) and two symmetrical load points 6 *h* apart. The distance between the two supports was 3000 mm (see Fig. 5). All experiments were carried out under controlled laboratory conditions at a temperature of 18 ± 2 °C and at a relative humidity of 65 ± 2%. The beams' moisture content was monitored during the experiments.

The long-term tests used two-point loads, and the loading period was set at three months. Concrete slabs were placed on steel plates to prevent indentation. However, this was not the main purpose of the study; these tests were conducted to determine long-term deflections and stresses. The displacement value was measured in the middle part of the cross-section and at a distance of 5 *h*, and the deformation of the glued beams and jute was also measured on the beam supports using a mechanical extensometer. The test was carried out in an environment with a constant temperature of 18–20 °C and a relative humidity of 65–70% to determine the stress state in the beams under normal

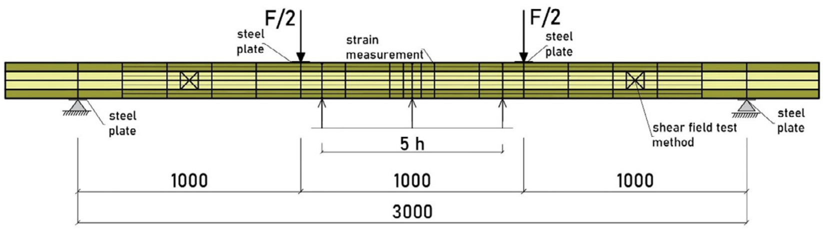


Fig. 5. Schematic diagram of a four-point bending shear test (EN 408+A1:2012)

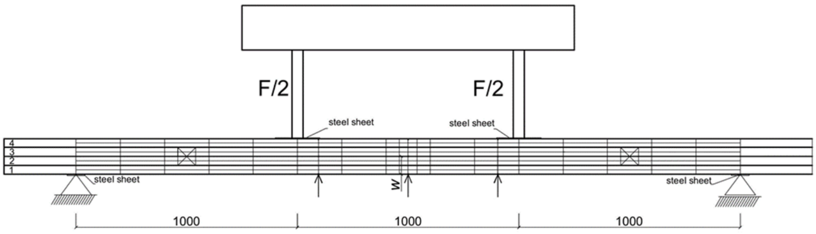


Fig. 6. Long-term load diagram

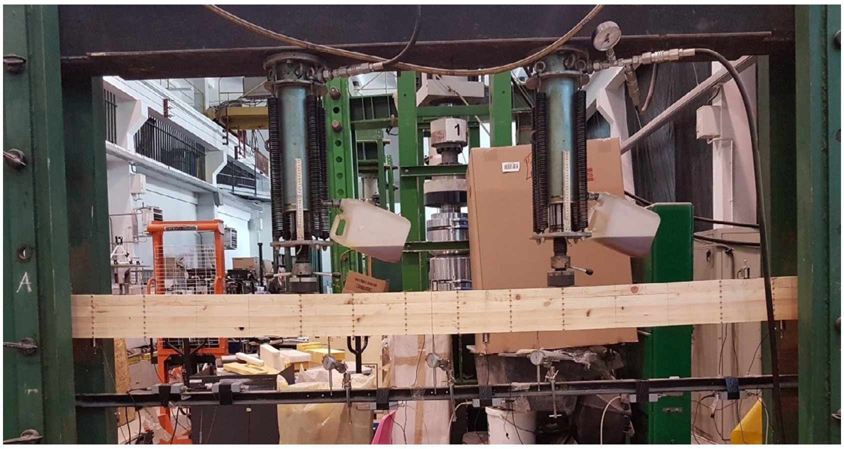


Fig. 7. Experimental study scheme

operating conditions. Temperature and relative humidity affect creep behaviour; as temperature and relativity humidity increase, the creeping deformation of wood increases. The long-term load value was approximately 8 kN (see Fig. 6).

During the beam tests, displacement measurements were taken at three points, as shown in Figs. 3, 4, 5 and 6. Analysis of structural and geometric characteristics (i.e. USM, USC, graininess) of all measurement databases is shown in Table 5. In addition, displacement sensors were installed on the supports to measure beam displacement in order to determine the difference in displacement between the centre of the span and the supports (deflection at the centre of the beam minus the average deflection at the supports). The supports were installed as shown in Figure 5, i.e., the left side was hinged and fixed, while the right side was hinged and sliding. For accurate verification, deflection sensors were installed. Consequently, the final deflection was specified as the sum of the instantaneous deflection and the deflection caused by creep. Therefore, additional tests were carried out on these beams under long-term loading, which allowed the determination of a ratio that takes into account the increase in displacement over time caused by the combined effects of creep and moisture changes. The unreinforced and reinforced beams were subjected to long-term loads for a period of 6 to 9 months. Each reinforcement used (bars) was also checked for horizontal displacement to ensure that it did not shift. This means that the reinforcement (bars, fabrics) deflected elastically and the test determined how it behaved under sustained loading (as deflection under gravity, not caused by loads from working actuators). Under sustained loading, the reinforcement

Table 5. Measuring bases for glued laminated beams (USM – marginal zone knottiness index, USC – overall knottiness index)

Lamella	USM	USC	Graininess
I	0.13	0.085	2.4
II	0.21	0.27	4.7
III	0.13	0.075	2.1
IV	0.22	0.28	3.3

(jute, bars, fabrics) was checked for elongation along the beam and for the flow of the epoxy adhesive, as well as the susceptibility of this adhesive. These extensions were checked with a mechanical extensometer. The prestress was achieved by connecting the wood and composite using anchors, pins, screws, pins, other mechanical connectors, etc., and using flat bars, angles, pipes and other steel and composite profiles. Installing the connectors, setting the prestress at 15 MPa, and introducing compressive and tensile forces resulted in internal forces within the system, which occur before the applied load and improve material interaction. This maintained the prestress and prevented slippage.

Shear bending tests were conducted on:

– 8 unreinforced beams measuring 3650 × 160 × 80 mm^3;
– 8 beams reinforced with a single layer of jute, measuring 3650 × 160 × 80 mm^3;
– 8 beams reinforced with a double layer of jute, measuring 3650 × 160 × 80 mm^3.

3. Numerical modelling

The numerical analysis of glulam beams was conducted in ANSYS 16.0 using the Static Structural module. The Finite Element mesh comprised hexagonal and quadratic elements. For the geometry of lamellas and supports, hexagonal elements with a size of 10 mm were used. Five-millimetre quadrilateral elements were used for the reinforcement and for the gluing area due to their relatively small size in relation to the rest of the geometry. The adhesive joint between successive lamellas was also included in the analysis, introducing a "bonded" connection between adjacent lamella surfaces. The boundary conditions assumed in the analysis should accurately reflect the deflection of the beam. Therefore, two concentrated forces of equal magnitude were applied to the upper surfaces of the blocks. The supports were the lower blocks, spaced further apart. One of the supports acted as a fixed support and the other as a movable support. The assumptions were implemented by using the Fixed Support function for the fixed support and the Displacement function for the movable support; movement of the second block was possible only in the X axis (Fig. 8).

Experimental research was used to obtain the data for the numerical models of material parameters. Wood was modelled as an orthotropic material, exhibiting different values of Young's modulus, Poisson's modulus, and shear modulus for three principal directions, designated in the ANSYS environment by Cartesian coordinates X (longitudinal direction), Y (transverse direction), and Z (radial direction). An orthotropic material model was also used for the reinforcement. The model was supplemented with values for Young's modulus and Poisson's modulus, as shown in Tables 1, 2, 3, and 4. The material data introduced into the model are presented in Table 6.

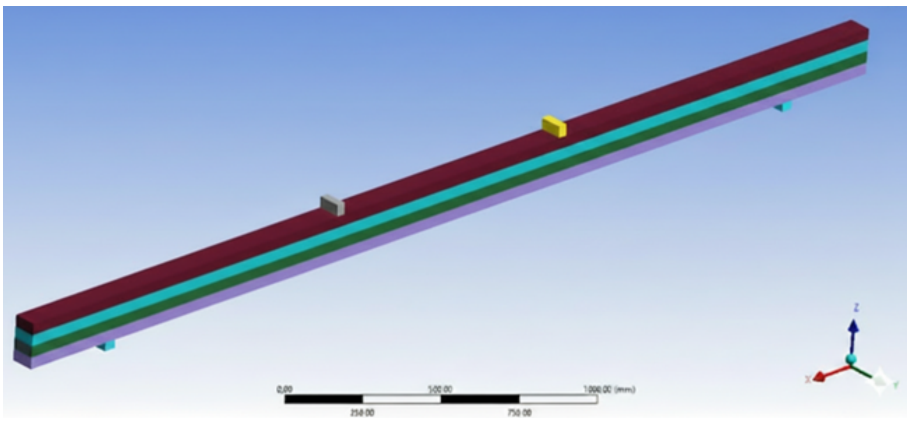


Fig. 8. Numerical model of a glued laminated beam

Table 6. Material data for the numerical model

Type	Young's modulus (MPa)			Poisson's modulus			Shear modulus (MPa)		
	X	Y	Z	X	Y	Z	XY	YZ	XZ
T8	7092.14	234	234	0.54	0.027	0.54	650	65	650
T13	11113.13	367	367	0.54	0.027	0.54	650	65	650
Jute fibres	16800	554	554	0.35	0.0175	0.35	-	-	-
Epoxy glue	3000	-	-	0.3	-	-	-	-	-
Structural steel	200000	-	-	0.3	-	-	-	-	-

The other materials used in the analysis are the bonded area around the reinforcement and the standard structural steel material used for the support blocks and pressure in the analysis.

Results and discussion

1. Results

1.1. Load–displacement and description of beams' destruction

The load–deflection diagram is presented below as laboratory test results for all beam types (BEAM, BEAMJ1, BEAMJ2). Figure 9 shows the average load–deflection values for all beams. Load F/2 is the loading force as shown in Figure 5. Tables 7 and 8 show the beam type, span in bending l [mm], maximum load F [kN], maximum shear force at ultimate load V [kN], maximum bending moment at ultimate load M [kNm], and type of failure mode.

The load–displacement diagram shown here is based on various parameters, such as a load of up to 26 kN and the displacement at that load. It should be noted that the maximum load is the highest recorded load value, and the deformation under this load can be determined by the deformation under the maximum load. Unfortunately, this is not shown here because the deflection sensors were removed before failure. The variable impact of the reinforcement on load and displacement characteristics was determined in the study. It was observed that the increase in load-bearing capacity and decrease in deflection for double-layer jute reinforcement were 27.09% and 13.75% respectively, and for single-layer jute reinforcement 12.91% and 12.21% respectively, compared with unreinforced beams.

During beam failure, jute fibres performed well, improving the beams' bending and shear strength.

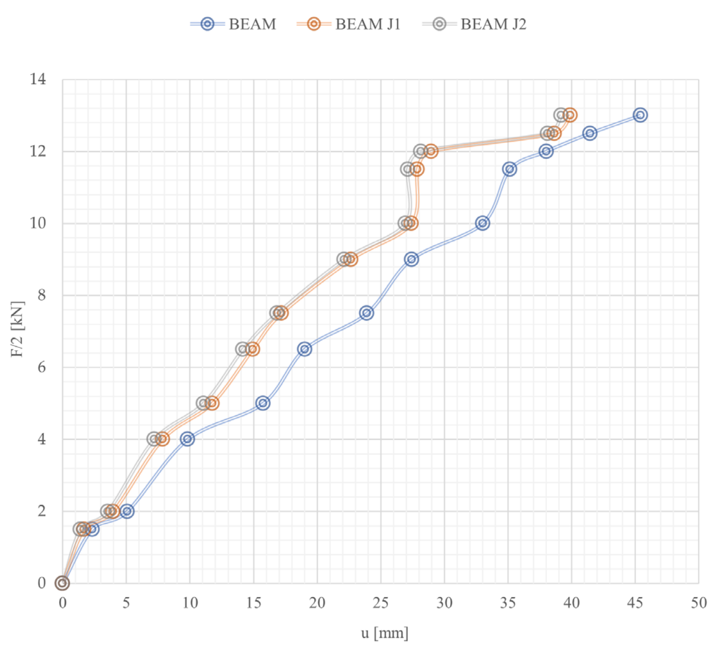


Fig. 9. Graph of load "F/2" vs. deflection "u" for all beams

Table 7. Experimental test results for all beams

Type	l (mm)	Prestress [MPa]	F (kN)	St. dev.	V (kN)	St. dev.	M (kNm)	St. dev.	Failure mode
BEAM	3000	-	39.5	**4.72**	19.75	**1.86**	19.75	**1.89**	Bending
BEAMJ1	3000	15	44.6	**5.01**	22.30	**2.05**	22.30	**2.17**	Bending
BEAMJ2	3000	15	50.2	**4.97**	25.10	**2.16**	25.10	**2.56**	Shear

Table 8. Images of destruction

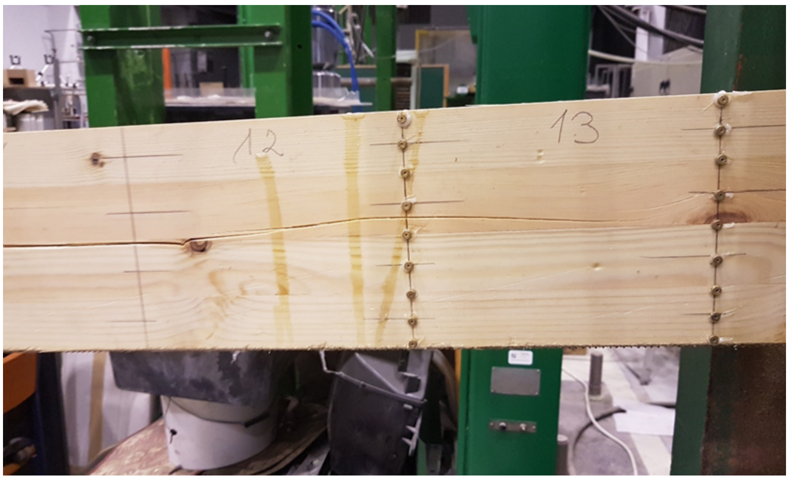
BEAM	
BEAMJ1	
BEAMJ2	

Table 9. Short-term and long-term deflections at mid-span of beams

Type	Short-term deflection (mm)	Long-term deflection (mm)
BEAM	10.05	3.92
BEAMJ1	8.17	2.86
BEAMJ2	7.12	2.57

The jute reinforcement was 3750 mm long and worked very well in the tension zone, especially in the middle of the beam span. Its effect on the test results at the supports was thus deemed negligible. Unreinforced beams primarily exhibited deep longitudinal cracks in the tension zone. Damage to the fibres in the stress zone was similar in all beams, with the cracks being deep and long, running parallel to the fibres. Furthermore, fibre shearing occurred, particularly in reinforced beams, in the tension zone, causing fine cracks to form. Consequently, various types of damage were noted in the experimental bending tests of beams reinforced with natural fibres.

The first group of unreinforced beams (BEAM) failed in bending, indicating a lack of bending strength, and cracks developed first on the lower surface. The average failure force was 39.5 kN. The second group of beams (BEAMJ1) broke during bending, and their final load-bearing capacity was significantly higher than that of the first group. During testing, it was observed that the fibre matrix initially began to crack after the load was applied. Subsequently, as the load increased, the jute FRP fibres began to fracture, and then, as the next load increased, the cracks in the jute material began to widen. In general, the damage to the beams was highly ductile, and the beams withstood significant deflections before their ultimate load was reached. It was observed that there was no separation of the jute FRP from the beam, even at higher loads. The mean load capacity of the second group of beams was 44.6 kN.

Beams from the next group (BEAMJ2) suffered similar failure, showing damage caused by bending shear. In this group, some beams initially showed jute fibre cracks in the middle of the span and close to the load zone, followed by delamination in the middle of the span to the end of the beam. It is clear that the reinforcement first cracked and then detached. As the load increased, cracks appeared in the lower part of the beam, and the mean load-bearing capacity was 50.2 kN.

Figure 9 shows the load deflection characteristics for all beams. The deflection at mid-span of each beam is compared with the deflection of beams in the group without reinforcement. The deflection behaviour under load for both reinforcement schemes is also presented. The experimental results show that the mid-span deflections were smaller after the application of a double jute reinforcement connection. Similarly, the use of jute rods was observed to delay crack formation.

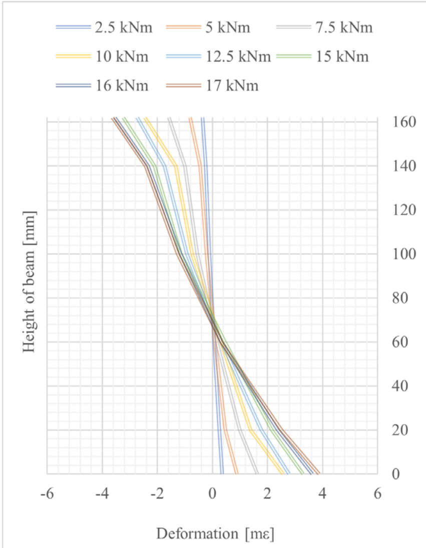
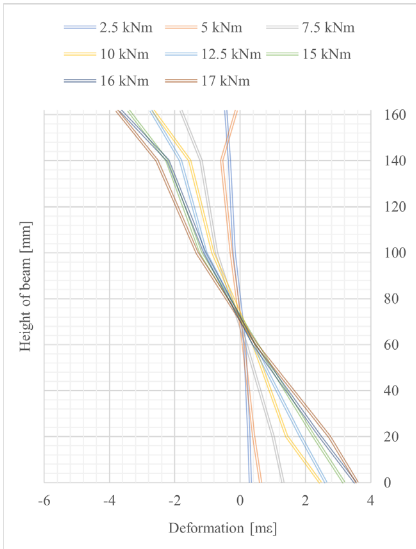
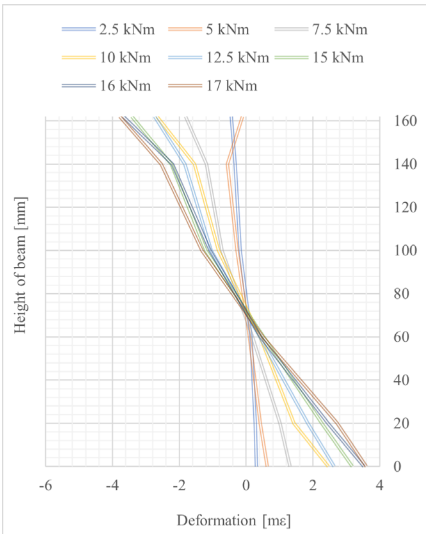
Results of the tests of beams under long-term loading, which allowed the determination of a coefficient taking into account the increase in displacement over time caused by the combined effect of creep and moisture changes, are shown in Table 9. Wood creep and long-term loading caused a significant decrease in stresses in the jute reinforcement in glued laminated beams, as well as significant long-term mid-span deflection. The glulam beams were subjected to a three-month long-term loading test. The study analysed the impact of long-term loading, reinforcement coefficient and compression level on jute reinforcement stresses and long-term mid-span deflection. It was observed that the lower the load level, the lesser the contribution of long-term deflection to the overall deflection. As the reinforcing ratio increased, the loss of jute reinforcement stress and the proportion of long-term deflection decreased. As the prestress increased, the loss of reinforcement stress and the proportion of long-term deflection increased. Visible cracks in the nodes did not expand significantly under long-term loading, and the long-term load applied was a service load, so no visible cracks or other defects were observed, except for changes in deflection. Short-term deflection at mid-span was measured immediately after the applied external load. Long-term deflection was measured three months later, after long-term loading, reflecting the deflection of the beam caused by the creep of the glued laminated timber.

1.2. Deformations

Table 10 shows the distribution of deformations over the entire height of the cross-section in the mid-span of the beam in selected load phases, up to the moment of beam failure. Similarly, the deformation distribution throughout the FRP material is more evenly distributed along the main fibre direction in the case of wood, as wood is a non-homogeneous material. During the test, the average strain of the jute fibre near the mid-span at the tested maximum possible load before failure was approximately 7.25 mε.

The loading capacity of beams reinforced only in the tension zone may also be limited by the compression

Table 10. Tensile and compressive strain charts for timber for all beam types

TYPE	Average timber deformations at mid-span height for all beam types
BEAM	
BEAMJ1	
BEAMJ2	

strength of the timber. In such cases, further increases in the loading capacity can be attained by adding additional reinforcement in the compression zone. Additional reinforcement in the compression zone can be provided by using composite overlays (flat bars, angles, tapes, mats, profiles) or additional layers of laminated veneer lumber (LVL). It is important to note that the reinforcements in the tensile zone worked correctly because the beams had adequate fastening to keep the jute fibres from coming loose too soon.

The aim of this study was to investigate the suitability of using jute fibre-reinforced polymer (FRP) for strengthening wooden beams. Anchors were strategically employed in the tests to prevent the jute fibre reinforcement from detaching prematurely. Anchors were mainly used to prevent shearing (sliding) at the interface between timber and composite elements. In timber girders reinforced with composite materials, especially when they are prestressed, significant longitudinal shear forces are generated at the interface between these materials, which can lead to a loss of composite interaction. Additionally, pins, screws, double pins, and other mechanical fasteners were used to connect the composite and wood. This was done to achieve better prestressing efficiency. The study used prestressing to reduce the level of tensile stress in the lower beam fibres, reduce deflections in the initial load range, and thus increase the initial stiffness of the system and the load-bearing capacity of the entire structural element. During assembly, the axial force in the connectors was estimated and the level of prestress introduced was indirectly determined. The initial prestress was 15 MPa.

1.3. Results of numerical analysis

Numerical analysis yielded displacement, stress, and shear stress values. The displacement values are shown below as the main analyses for comparison. Table 11 shows a comparison of the results obtained by the laboratory and numerical methods. The differences between the numerical analysis results and the laboratory test data may be due to simplifications, as wood is a composite of organic material with anisotropic mechanical and strength properties. The limitations of computer modelling and numerical analysis make it impossible to take into account all of the intricate structural properties of wood, such as wood structure irregularities, wood defects, cracks, etc.

2. Discussion

The reinforcement provided by the jute FRP was highly effective. Compared with beams without reinforcement, a single layer of jute FRP resulted in a significant increase in loading capacity of 12.91% and an increase in stiffness of 12.21%. Furthermore, increasing the number of layers resulted in even greater improvements. Beams reinforced with a double layer of jute fabric showed a 27.09% increase in loading capacity and a 13.75% increase in stiffness. Similar innovative research is presented in a previous paper (Benfratello et al., 2025). Researchers investigated the implementation of fibre-reinforced geopolymers (FRGs), which incorporate various fibres to increase strength, ductility, and fracture resistance. Geopolymers demonstrate potential in new construction and repair applications.

These results suggest that jute rods and fabrics are an effective alternative to traditional FRP rods for strengthening wooden beams in bending and shear. Beams reinforced with jute fibres exhibited significant strain values, indicative of the ductility of the fibres themselves. This ductile behaviour is a major advantage as it provides sufficient warning before final, catastrophic beam failure, enabling hazards to be detected and prevented. Studies have found that reinforcement improved compressive and flexural strength after changes in the prism failure mode. The fibres inhibit crack propagation in the reinforcement layer, thereby enabling better redistribution of internal stresses within the prisms (Diniță et al., 2024; Farias et al., 2024).

During testing, it was observed that externally bonded jute fibres were resistant to brittle fracture in the tension zone of glued wooden beams, promoting more ductile fracturing in the compression zone. After the application of jute rods, the damage consisted of the appearance of successive cracks: first

Table 11. Comparison of results from laboratory tests and numerical methods

Type	w_{max} (mm) numerical methods	w_{max} (mm) laboratory methods	Difference [%]
BEAM	47.90	45.44	5.4
BEAMJ1	42.15	39.89	5.7
BEAMJ2	41.21	39.19	5.2

in the fibres of the wood in the tension zone (when the beam was sheared), and then in the compression zone. Crucially, no brittle fracture of the beam was observed. This good performance was attributed, in part, to the effective restraint provided by the epoxy glue (at negligible thickness) and the anchors at the supports (Wdowiak-Postulak et al., 2025).

The application of jute fibre reinforcement was successful in reducing the development of initial cracks. The natural fibres effectively inhibited and limited crack growth, meaning that the initial cracks appeared only at higher loads than those experienced by unreinforced beams. A previous study resulted in significant improvements in compressive strength. It was found that the strength and ultimate strain of the JFRP samples decreased as the fibre orientation angle β increased from 0° to 45° (Gao et al., 2022).

Similarly, jute-reinforced beams resulted in significantly lower deflections under load than unreinforced beams, confirming the effectiveness of the reinforcement in improving structural performance. Following the shearing damage to two beams along the grain, the necessity for additional anchors was noted. This suggests that the number of anchors on the beam should be increased, particularly in the zone of constant bending moment, to further enhance shear resistance. The use of natural fibre composites in sandwich structures was analysed in another previous study, and the mechanical and energy absorption properties of sandwich structures based on natural fibres under different compressive loads were determined (Alsubari et al., 2021). A further study found that jute biolaminates exhibited the highest stiffness and strength. Henequen biolaminates exhibited high strain values. It was concluded that rigid and semi-rigid biolaminates could lead to new applications as lightweight, low-cost, and sustainable composites (Torres-Arellano et al., 2020).

Long-term load tests were conducted to determine ultimate deflection, accounting for both instantaneous and creep-induced deflection. A coefficient was determined and applied to account for the increase in displacement over time due to the combined effects of creep and moisture changes. In a previous study, a sustainable geopolymer concrete with high crack resistance was created by adding natural jute fibres, which has practical applications in the construction sector (Mohammed et al., 2024). While not the main focus of this research, critical future research areas were outlined, primarily because FRP rods are a newer material than steel reinforcement and lack extensive long-term data. These include the influence of longitudinal displacement of the reinforcement, flow of the epoxy adhesive, durability of the reinforcement (fabrics, rods and anchors), corrosion of the reinforcement, adhesion/bonding, UV and fire resistance, stiffness and brittleness, susceptibility to bending over time, and issues related to the lower operating temperature compared with steel, which leads to resin degradation (Acosta Ortiz et al., 2023; Maciel et al., 2024; Iquilio et al., 2024).

Conclusions

Experimental and numerical tests conducted on wooden beams reinforced using prestressed jute fibres have indicated the following:

1. High efficiency: reinforcement with jute FRP proved very satisfactory, with a single layer increasing the load-bearing capacity by 12.91% and stiffness by 12.21%. A double layer provided even greater gains (27.09% and 13.75%, respectively). Beams reinforced with prestressed jute fibres have an increased bending capacity compared with unreinforced beams, enabling fuller use of the strength of the jute fibres.
2. The subsequent increase in the load-bearing capacity of beams reinforced with prestressed jute fibres unfortunately requires the simultaneous strengthening of the compression zone, because this then becomes the element that determines the destruction of the cross-section.
3. It should be noted that applying prestress increases the initial stiffness of the beam and reinforcement. This results in less deflection and a more linear force–deflection relationship in the initial phase of beam operation.
4. The use of prestressed jute fibres allows the reinforcement to engage in load transfer earlier, even before the actual load is applied. This reduces tensile stresses in the lower wood fibres and reduces deflections in the initial load range.
5. Reinforcement with prestressed jute fibres shifts the failure mechanism from tensile wood fibre breakage to crushing or instability in the compression zone. This means that the beam's load-bearing capacity begins to be reduced by the compression zone, rather than the tension zone.
6. Prestressing the jute fibres limits the development of cracks in the lower part of the beam cross-section and delays the appearance of local damage in the stress concentration zones.
7. Crack control: the jute fibres reduced and limited the development of initial cracks, causing them to appear only at higher loads compared with unreinforced beams. Jute fibres effectively absorb tensile stresses, limiting the development of cracks.
8. Ductile behaviour: jute-reinforced beams exhibited significant strain, indicating good ductility. This ductile failure mechanism provides a sufficient warning before cata-strophic failure, distinguishing it from brittle fracture.

9. Deflection improvement: jute reinforcement led to significantly lower deflections un-der load and helped resist brittle fracture in the tensile zone.
10. The use of anchors as anti-shear elements is important for the effectiveness of prestressing because they prevent slippage at the interface between the wood and jute fibres, ensure the joint work of the entire cross-section, and permanently maintain the introduced prestress.
11. Alternative: natural jute fibre is considered a very effective reinforcing material for strengthening wooden structures in bending and shear, serving as a good alternative to traditional FRP methods. Jute, a reinforcement based on natural fibres, has good compatibility with wood in terms of mechanical properties and deformation. Therefore, when properly protected against moisture, it constitutes a durable, innovative, future-proof, and environmentally friendly solution.
12. Long-term focus: while the research showed positive short-term results, the text outlined several critical future research areas, including the long-term effects of creep, moisture, durability, and corrosion, which are less studied for natural FRP materials than for steel.
13. At a load of approximately 13% of the estimated limit load, for unreinforced beams in the middle of the span, the share of long-term deformation in total deformation was 28.06%, while for a beam in the middle of the span made of solid glued laminated timber with single jute reinforcement it was 35%, and with double jute reinforcement it was 36.10%.
14. Design consideration: the testing indicated a need to potentially increase the number of anchors, especially in the zone of constant bending moment, to prevent shear damage along the grain.
15. The differences between the experimental and numerical models were approximately 5%. This was due to the inherent complexities of wood and the development of a new composite material with different material components and new mechanical properties.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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