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DUCTILITY, LOAD CAPACITY AND BENDING STIFFNESS OF SCANDINAVIAN PINE BEAMS FROM WASTE TIMBER STRENGTHENED WITH JUTE FIBRES

The paper presents experimental studies of bending heterogeneous pine beams reinforced with jute fabrics. Pinus Sylvestris L, a Scandinavian wood species, was used in this study, originating from discard, subjected to 5-year atmospheric influences and biological degradation. The use of recoil wood is an excellent choice, forced by the increasing shortage of high-quality assortments and the need for economical management of scarce raw material. The article presents experimental results regarding the effectiveness of pre-stressed jute reinforcements in the tension zone of pine wood. The effects of using jute fabrics in beams were analysed, and the results were compared to beams without reinforcement. Additionally, the aim of the research is to investigate the influence of jute fabrics on the ductility of wooden beams. Research has been conducted on these polymer composites reinforced with natural fibres due to environmental awareness, their many advantages and, above all, the fact that they are sustainable materials. The conducted tests revealed that the jute fibres had a positive impact when applied to wooden beams and the load-bearing capacity increased by 24% and stiffness 24% compared to unreinforced beams. Moreover, the tests confirmed enhanced strength (24%) of reinforced pine beams in relation to the reference beams. In contrast, the ductility increased from 6.6% for reference beams to 75.7% for reinforced pine wood. Reinforcements with jute fibres have considerable ductility, which indicates that jute fibres are an excellent material for reinforcing the structure.

Keywords: wood, strength, strengthening, jute fibres, load capacity, stiffness, ductility, mechanical testing

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Introduction

Recently, it has become increasingly important to develop and promote sustainable materials in the construction industry. Wood has been used by people for thousands of years. Properly used, properly secured and cared for, it is characterised by long durability. It may play a structural role for decades or even hundreds of years [Kotwica 2004, 2005]. Wood as an organic raw material with all its advantages and disadvantages and is still a widely used building material. Its pro-ecological, recycling and aesthetic values are confirmed by a positive physical and mechanical analysis of this material. The use of construction timber and wood-based materials with appropriate mechanical, thermal and acoustic properties is an essential feature of modern frame construction. The desire to obtain an increased level of equipment, comfort and health of space in modern buildings is related to the need to introduce wood to residential interiors. Replacing wood with other materials is usually a disadvantageous procedure forced by the growing shortage of high-quality material and the need to manage its supply economically [Kozakiewicz and Krzosek 2013]. Therefore, one of the problems presented by timber structures is the increasing consumption of wood products, as wood is characterised by a long growth cycle and slow regeneration. On the other hand, it is still in short supply, especially high quality material, which is also the main scope of this article [Wei et al. 2017; Chun et al. 2014; Glišovic´ et al. 2015]. To prevent this problem as well as enhance the properties of wood, various experimental studies have been carried out, combining wood with other materials to form a composite with better mechanical properties [Donadon et al. 2020]. The main advantages of wood include its considerable compressive and tensile strength, in relation to its low density. On the other hand, it should also be borne in mind that the timber beams that worked in the past were not particularly durable and were therefore replaced or reinforced by traditional methods using building materials such as concrete or steel. More recently, timber elements have also been strengthened using various technologies. Nevertheless, in some cases it was impossible to completely replace wooden elements. Therefore, the use of composite materials to reinforce wooden elements subjected to bending [Borri et al. 2002; Borri et al. 2005] or shearing [Borri et al. 2005; Triantafillou 1997] has become more common. This arose, inter alia, because of load increase, deterioration of mechanical properties, and an increase in significant displacements [Borri et al. 2005; Bank 2006].Promising materials with many benefits for reinforcement and wood rehabilitation include fibre-reinforced polymers (FRP). Fibre composites have a favorable strength to weight ratio compared with other building materials. The implementation of fibrous composites to strengthen structural elements in the infrastructure is effective and has been presented in the literature, e.g. [Triantafillou 1997; Bank 2006; Hollaway and Teng 2008; Raftery and Whelan 2014]. Composites are also characterised by high fatigue properties in comparison with common construction materials [Raftery and Whelan 2014; Karbhari 2007]. Their use also reduces maintenance costs. Indeed, fibre composites are more useful as wood reinforcement in comparison with steel due to the tendency of steel to corrode in contact with moisture in wood. Some experimental work has been carried out to strengthen wooden beams with prestressed steel or FRP materials [Raftery and Whelan 2014; Yang et al. 2016; Al-Hayek and Svecova 2014: Bohannan 1962; Brady and Harte 2008; De Luca and Marano 2012; Guan et al. 2005; McConnell et al. 2014; Negrão 2016]. These tests show that the bending strength of the wood was significantly increased due to the widespread use of the reinforcement and the full use of the load-bearing capacity of wooden elements. Almost all existing studies have shown a relatively favorable effect of reinforcing materials on the static work of bent wooden beams [Yang 2016.]. So far, a limited amount of research on the reinforcement of low-quality glued laminated timber with internal reinforcement has been conducted [Raftery and Kelly 2015]. However, basalt and glass fibre reinforcement, associated with low cost and favourable mechanical properties, seems to be most suitable for timber elements [Karbhari 2007]. GFRP bars were also used as shear reinforcement in wooden elements [Raftery and Kelly 2015; Persson and Wogelberg 2011; Svecova and Eden 2004]. BFRP rods are characterised by excellent mechanical properties. These materials are light with good chemical and corrosion resistance [Bank 2006; Raftery and Kelly 2015].

This reinforcement can be considered environmentally friendly, allowing complete recycling without negative impact on the natural environment and humans. Basalt is the most common rock, while basalt fibres have significantly lower thermal activity than steel and other synthetic fibres. In timber engineering, only cursory research has been carried out on using basalt fibre reinforcement. Basalt fibres were used in the research to strengthen low-quality glued laminated timber [Brol et al. 2018]. Pre-compressed basalt fabric was also used to determine the effectiveness of wood reinforcement [Brol et al. 2018; Zachary and Kavan 2012]. In other studies, there has also been a focus on reinforcing wood with BFRP basalt rods because they are derived from natural materials and are economically important due to their lower price compared to CFRP carbon fibre [De la Rosa García 2013; Raftery and Kelly 2015; Yeboah et al. 2013; Wdowiak 2019; Wdowiak and Brol 2019b; Brol and Wdowiak-Postulak 2019; Wdowiak-Postulak and Brol 2020; Wdowiak-Postulak and Świt 2021]. Maintenance and reinforcement of the existing wooden structures will significantly increase their load-bearing capacity and make it possible to reduce the costs of replacing elements. Moreover these reinforcement methods can also reduce the width or height of the timber beams required for construction. Sometimes wooden beams of considerable thickness are difficult to find; therefore, even a small cross-section after reinforcement can have the same load-bearing capacity as a large cross-section [Haiman and Zagar 2002; Yusof and Saleh 2010]. The conducted studies have demonstrated that it is possible to increase the effectiveness of bent and shear wooden beams, depending on the reinforcement technology used. Particular fibrous composites are intended to increase the mechanical properties of the existing structure, while others fully bond the beam, creating a wood-FRP material composite product [André and Kliger 2009]. In a study, it was found that the relatively lower flexural stiffness of timber beams results in higher deflection compared to steel or reinforced concrete of the same section [Yang et. al. 2016]. In order to obtain lower beam heights and reliability with the use of lower quality timber, many methods have been developed to improve static work during the bending of glued and solid timber beams, e.g. by just adding this reinforcement. It is also possible to use FRP fibre composites as a reinforcement for timber beams in the form of sheets, plates, strips or bars [Brol and Wdowiak 2019; Wdowiak-Postulak 2022]. Recently, natural fibres have also been introduced to reinforce timber structures [Yang et al. 2016; Borri et al. 2013a; Gallant 2004; Speranzini and Agnetti 2012: Speranzini and Tralascia 2010; Wdowiak and Brol 2019a; Wdowiak-Postulak 2020; Wdowiak-Postulak 2021]. Fibrous composites, including natural ones, they are used for a light and effective method of strengthening wooden beams [Yang et al. 2016; Plevris and Triantafillou 1992]. Taking into account the low impact of pollutants on the environment, an important aspect of the research is to conduct it with the use of natural fibres (e.g. basalt, flax, bamboo, hemp, etc.). The purpose of performing such tests is to recreate existing structures and design new structures [Borri et al. 2013b]. It should be remembered that beams reinforced with composite materials made of natural fibres acquire increased mechanical properties in terms of tensile strength and lightness, as well as production costs, emission of pollutants and energy consumption for their production and disposal [Speranzini and Tralascia 2010; Speranzini and Agnetti 2012; Lopresto et al. 2011; Kromer 2009; Corradi et al. 2009]. It should also be remembered that the costs of production and disposal are much lower than in the case of synthetic fibres [Wdowiak-Postulak 2020 and Wdowiak-Postulak 2021].

In recent decades, reinforcement with carbon or glass fibres (FRP) in wooden or glued laminated beams has been an effective solution. These fibres have excellent properties and are stiff, low in density and corrosion resistant. Unfortunately, it should be remembered that such fibres are difficult to recycle. On the other hand, the properties of some natural fibres (bamboo, cotton, wool, etc.) began to be investigated, and it was found that the use of natural fibres is an excellent alternative to FRP in many construction applications [Echavarria et al. 2013]. Natural fibres are light, renewable and have high mechanical properties, which makes them suitable for reinforcing construction elements made of wood [Echavarria et al. 2013]. It should be remembered that the increasing production costs of commonly used composite materials encourage research towards natural materials, easily available and much more economical. Composite materials reinforced with fibres based on natural fibres are characterised by a simple structure and versatile use. Based on energetic and mechanical aspects, natural fibres are non-artificial products that are easily available and grown in nature. During their production, there is no emission of carbon dioxide, and the costs of production and disposal are much lower than in the case of artificial composite materials. It should be remembered that the natural reinforcement may have the following advantages: improvement of the mechanical properties of glued laminated and solid historic beams, reduction of the cross-section size and weight of the beam, use of lower density species of wood as well as wood with blue stain. Considering the vast amount of lower quality assortments, it is important to expand the possibilities of using this raw material in construction. By applying various strengthening methods with the use of natural fibres, they can fulfil their role and increase the load-bearing capacity of the obtained structural elements. Thus, different materials were used for the structural reinforcement. The research used kenaf fibre, jute rope and jute fibres to prepare the composites [Alam et al. 2015]. Crop materials can improve the energy profile of buildings. Currently, there is a tendency to use biological or plant products due to increased concerns about the environment, the use of sustainable production methods, reduced energy consumption, sustainable and ecological materials in building structures. Jute fibres are one of the strongest bast fibres available and are rot resistant. Jute fibres are non-abrasive and exhibit moderately higher mechanical properties. Based on the research, it was found that the pretreatment of jute yarn may lead to the improvement of its mechanical properties, and the composites of jute fibres show excellent mechanical properties [Sen and Jagannatha Reddy 2013]. On the basis of tests carried out on small members with a span between supports of 900 mm, it was found that the deflection at mid-span of beams reinforced with jute fibres decreased by approximately (32.1-38.7%), (33.6-38.7%), and (30.6-31.6%) for the U, full and flexural reinforcement methods, respectively, compared to the control beam at the same at the same load. The toughness ratios of the tested beams increased by about (184-320%), (199-401%), and (137-240%) for U, full, and flexural strengthening techniques, respectively at the ultimate loads when compared with the control beam [Abdulla et al. 2020].

An analysis of the literature shows that the use of jute fibres to strengthen wooden beams made of poorer quality sawn timber in construction is not recognised, and so research in this direction is necessary. This article, therefore, presents research into the effectiveness of reinforcement of pine beams obtained from recoil with the use of jute fabrics.

Materials and methods

Timber

Eighteen wooden beams were prepared for the study, nine of which were reinforced with jute fabrics and nine were unreinforced. Beams without an applied reinforcement served as control beams and served as a reference level to determine the effectiveness of the reinforcement of wooden beams. The research will begin with visual method sorting in accordance with PN-D-94021:2013-10 of Scots pine (*Pinus sylvestris L.*) from a selected region of Scandinavia. The construction timber was obtained from Scots pine, originating from the beginning and the end of the growing season. It was sorted visually, carefully examining all elements according to PN-D-94021:2013-10. During the visual grading of each piece of sawn timber, measurements were made of all structural and geometric features present in a given piece, such as: knots, slope of grain, fissures, resin pockets, bark pockets, rots, insects damage, blue stain, compression wood, rate of growth, distortion (bow, spring, cup, twist), sawing defects (wanes, not straight forward ends, non-parallelism of planes and sides). On the basis of this analysis, coniferous construction lumber was divided into inferior quality classes. The last step involved planing the surface, trimming to obtain the assumed dimensions and a smooth surface. Wooden beams, made of inferior quality elements, were reinforced with natural fibres. In order to increase the load capacity of Scandinavian timber beams, natural fibres were used as reinforcement at the bottom of the beam in the tension zone. The surface of the beams were even, clean and dry by planing the wood, especially at the ends of the beam, to ensure proper anchoring. During gluing, the surface were degreased and cleaned. Pre-compressed natural fibres were fixed and stressed on the supports. The use of reinforcement aims to enhance technical strength. Reinforced wooden beams can be a good option as an excellent substitute for high-quality timber beams where forest resources are not available to make solid timber components. Wooden beams originating from waste, subjected to 5-year atmospheric influences and biological degradation, have been reinforced with jute fabrics. The dimensions of all beams were 82 mm × 162 mm in cross-section and a length of 3650 mm. The beams had the strength class C16 (with PN-EN 338:2016-6 characteristic strength values of 16 MPa for bending, 10 MPa for tension and 17 MPa for compression, while the modulus of elasticity of the specimens were observed to be 8 GPa respectively). In this part of the publication, the research topic is described in a concise way. The technical part describes the materials, test methods, and experiments carried out. The economic part outlines the research aim, objective, subjective and spatial scope, and research methods.

Epoxy Adhesive

In the research, epoxy glue (LG815 + HG353) was used to connect the jute reinforcement with the wooden beams. 320 ml/m^2 of glue was applied. The adhesive layer based on epoxy resin was obtained by mixing LG 815 epoxy resin (density 1.13 ÷ 1.17 g/cm^3, viscosity 1100 ÷ 1300 mPa.s) with HG 353 hardener (density 0.98 g/cm^3, viscosity 100 ÷ 150 mPa.s). There was no damage or delamination prior to destruction for all beams during experimental tests. From the bottom of the beams along their entire length, the reinforcement was glued with epoxy glue. Before that, to improve the adhesion of jute fabrics to the wood, the wood surface was cleaned with a brush and a layer of "Acetone" solvent was applied. Thereafter, a preliminary layer of epoxy adhesive was applied to the surface of the wood with an approximate yield of 0.3 kg/m^2. After that, a pre-compressed fabric of approx. 40 MPa was applied, parallel to the longitudinal direction of the beam's fibres, and an epoxy adhesive layer with a capacity of approx. 0.2 kg/m^2 was added.

Jute Fibres

Jute is a soft and strong plant fibre with significant tensile strength, (see Fig. 1). Reinforcement in the form of jute fibre with a grammage of 245 g/m^2 was applied to the lower surface of the beams with an adhesive. Two layers of jute fibres were used in the research. Mechanical properties of jute double reinforced 0.3 mm thick and 82 mm wide in all specimens. Steel sheets with a section of 50 mm by 50 mm were used for reinforced timber (steel grade S235JR with a yield point). The pretension was 130 kN and this was achieved with a torque of 480 Nm on the nuts. Next, a second layer of pre-compressed jute fabric was added. The mechanical properties of jute fibres are shown in Table 1.

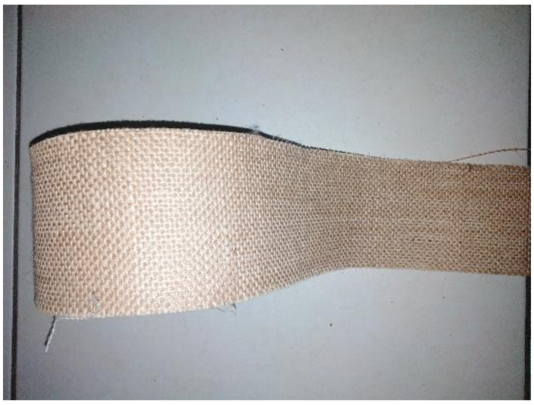

Fig. 1. Jute fibres

Table 2. Mechanical properties of jute fibres

Fibre	Modulus of Elasticity (GPa)	Tensile Strength (MPa)	Tensile Strength of Jute treated with epoxy (MPa)
Jute	16.8	55	99.7

Test Procedure

The beams with a length of 3650 mm and cross-sectional dimensions 82 × 162 mm are illustrated in Figure 2. The beams were divided into two groups: one consisted of nine unreinforced Scandinavian timber beams while the other included nine reinforced beams with jute fabrics. The control beams were divided into three types of beams (URJF 1, 2 and 3), while the reinforced beams were also split into three types of beams (RJF 1, 2 and 3). All dimensions shown in the figures are given in millimetres.

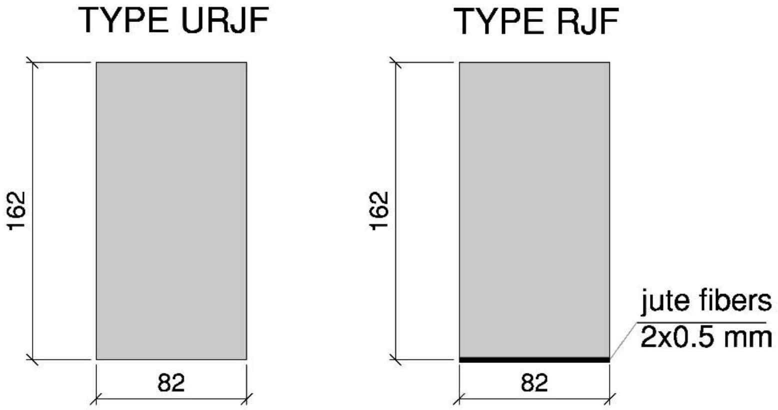

Fig. 2. Cross-sections of tested beams [dimensions in mm]: URJF – a non-reinforced beam, RJF – a reinforced beam

Experimental studies based on an assessment of the effectiveness of the reinforcement of bent wooden beams obtained from the recoil, with the use of jute fabrics were carried out in the laboratory of the Department of Strength of Materials and Analysis of Building Structures. The experimental tests were performed as a four-point bending test in accordance with PN-EN 408+A1: 2012, recording the force value load, beam displacement in the middle of the span and over a length of *5 h*, (where *h* – beam cross-section height), deformations in wood, deformations in the jute fabric, the value of the destructive force. How the tested beams failed was also determined. In the tests, the beams were simply supported at both ends and loaded with concentrated forces symmetrically at two points. Figure 3 shows the load diagram for timber beams during the bending test. The beams spanned 3000 mm between the supports and two loads were applied at 1/3 intervals along the span. The wooden beam was placed on the pin supports of the testing machine, and then mechanical sensors were installed to measure deflection. The mechanical sensors were placed over a length of 5 h, (where h is the height of the beam cross-section), see Fig. 3.

Ductility was determined according to the ratio of maximum deflection at failure minus deflection at yield to the deflection at yield of maximum deflection at failure minus yield deflection to yield deflection. Maximum deflection was defined as the deflection when the load decreased from its maximum value to 95% of this value. In contrast, yield deflection was defined at the point where the elastic offset line crossed the load-displacement curve [Livas et al. 2021]. The ductility of a beam can be defined as its ability to withstand inelastic deformation without losing load capacity before failure. The deformations can therefore be deflections, curvatures or stresses. Ductility can be expressed as deformation or energy absorption. For FRP reinforced beams, determining the yield point is a difficult task. Therefore, ductility is tested in terms of energy parameters. Ductility indices for beams are determined on the basis of deflection, curvature, area under the load-deflection curve. The first is defined as the ratio of ultimate deflection to yield deflection at the mid span of beams. The second – as the ratio of curvature or slope at ultimate load to curvature at the yield load measured at the mid span of the beams. The third – as the ratio of total energy determined as the area under load deflection curve up to failure load to elastic energy determined as the area under load deflection curve up to 75% of failure load [Ahmad and Bhat 2013].

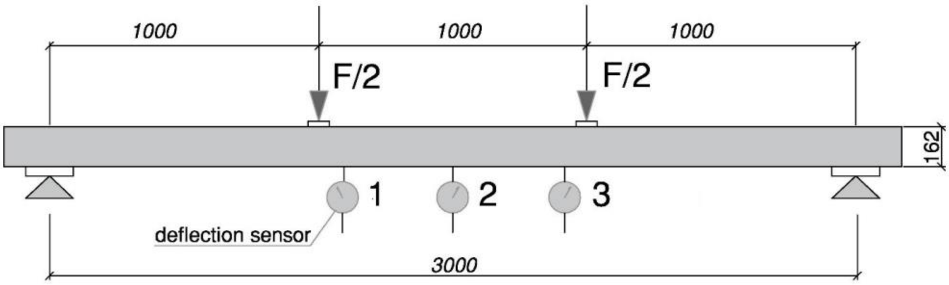

Fig. 3. Four-point bending load system [dimensions in mm]

The load was applied with a hydraulic jack until failure, and the deflections and deformations were read. For each assumed load level, displacements and deformations were read, then re-read after 20 minutes and loaded to the next level of force. During the study, the deformation of wood and jute fabrics was measured using a mechanical extensometer with a fixed measurement base of the “Demec" type. For each assumed load level, displacements and deformations were read, then the level of force was loaded and the next were re-read. In height, the timber beams were divided into 4 measurement bases, denoted in the drawings as 4 lamellas, each 40.5 mm high (lamella I from the bottom in tension, then lamella II in tension, then lamella III in compression, then lamella IV at the very top in compression). In contrast, the lengths of the timber beams between the supports were divided into 13 measurement bases, each the length of one extensometer, i.e. 8 inches equal to 203.2 mm. The placement of measurement bases to determine deformations is presented in Fig. 4.

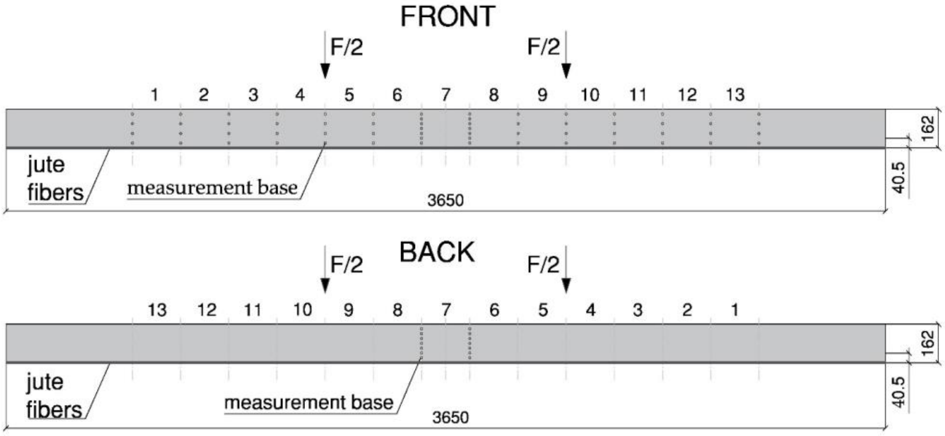

Fig. 4. Measurement bases to measure deformation

Results and discussion

The article presents the results of experimental research on the effectiveness of wood reinforcement of the lowest quality classes with the use of jute fabrics. The research showed that deformation of the timber cross-section was less severe for beams reinforced with jute fabrics than for non-reinforced beams. After the tests, it was found that the jute fabrics significantly reduced the stress on the stretched wood fibres. In tests for a force *F/2* equal to 10 kN, (base 7), for type RJF1, the tensile strains drop was about 32.4%, and in compression 16.8%, the RJF2 type, the tensile strains drop was about 39.1% and in compressive strains – about 15.6%, the RJF3 type – the tensile strains decrease – about 43.1% and the compressive strains – about 9.1% compared to the URJF type. Figures 5 and 6 show charts "*ε – F/2* [kN]" for a reinforced beam type RJF2 and jute fibres. On the basis of the performed tests, it was found that the uneven distribution of normal stresses was mainly caused by the occurrence of wood defects, usually knot cracks, wood fibre cracks, etc. The obtained results are shown and also marked in Figure 5. The jute fabrics absorbed the tensile forces and the stresses therein increased.

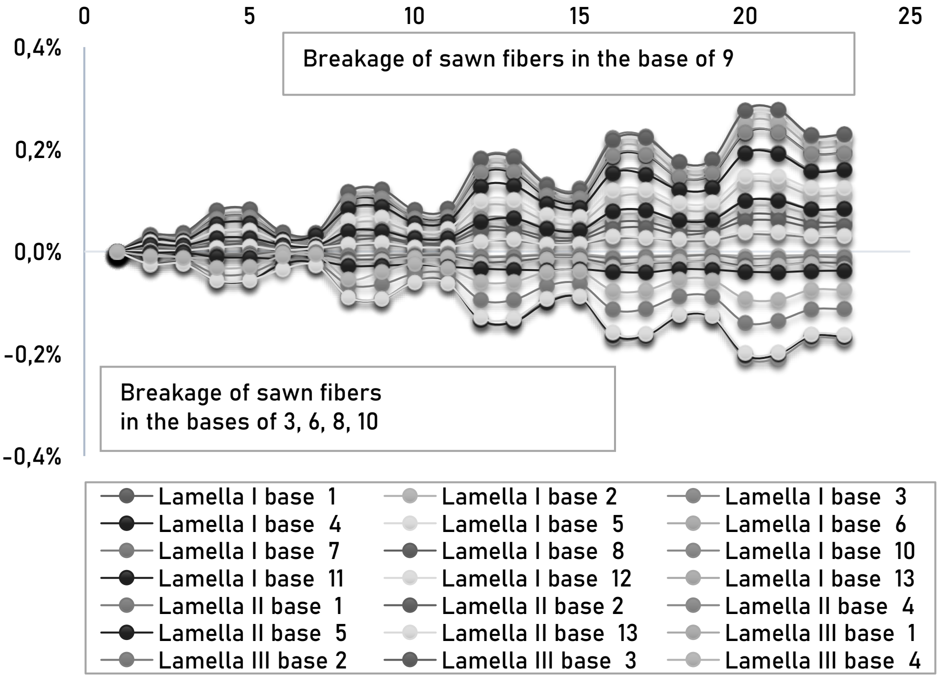

Fig. 5. The dependence curve Ɛ [%] on F / 2 [kN] for the RJF-2 type of reinforced beam [including lamella I, II – tensile zone, lamella III and IV – compression zone, 1 to 13 – number of measurement base along the length of the beam]

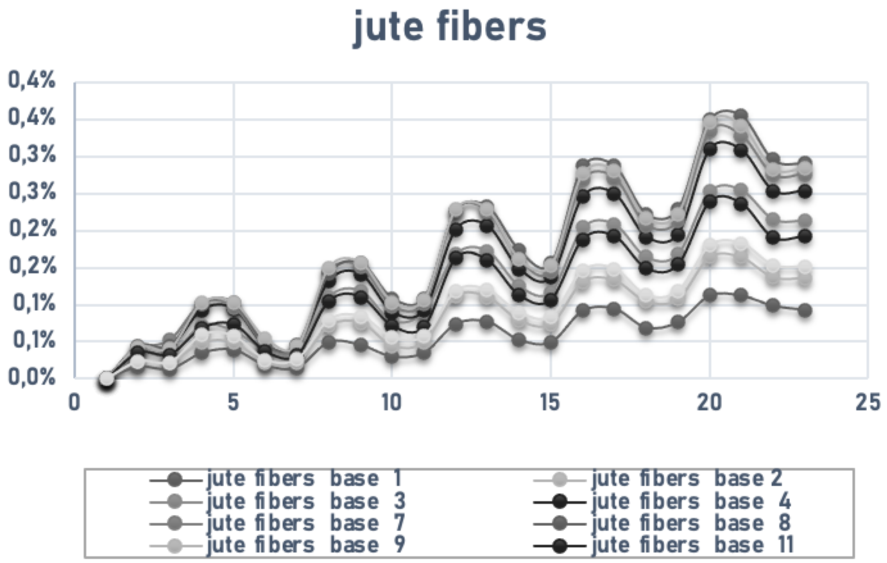

Fig. 6. The dependence curve Ɛ [%] on F / 2 [kN] of jute fibres for the RJF-2 type of reinforced beam [including 1 to 13 – number of measurement base along the length of the beam]

Figure 7 shows load-deformation curves for all beams groups. Figure 7 shows the deflections of the tested beams in the middle of the beam span as a function of the force values. For non-reinforced beams, the lowest average deflection values were recorded for beams of the URJF-1 type. In the study, the deflections of beams reinforced with jute fabrics were much smaller than that of unreinforced beams of the URJF type. For reinforced beams, the lowest average deflection values were recorded for beams of the RJF-1 type. For all elements of unreinforced beams, the mean deflection value for the force *F / 2* equal to 10 kN was 20.2 mm, and for reinforced elements – 15.4 mm. As for the deflection curve, the load was linearly elastic until the initial plasticity in the compression zone.

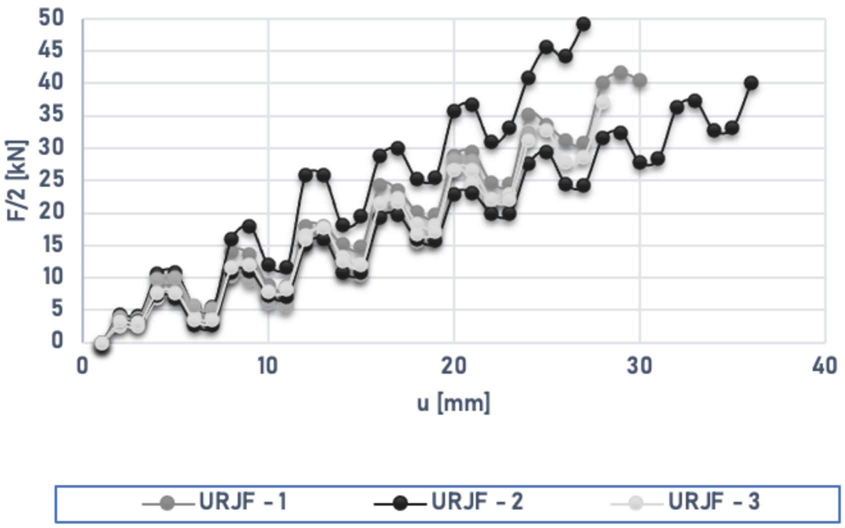

Fig. 7. Load deflection curves "F / 2 – u" for jute fibres reinforced beams [including URJF 1, 2 and 3 – unreinforced beam type RJF 1, 2 and 3 – jute fibre reinforced beam type]

The laboratory test results for the reinforced beams were compared to the control beams to investigate the ductility behaviour of the reinforced wooden beams. Table 2 show the average values of the maximum moment (M_{max}), elastic modulus ($E_{m,g}$) and ductility for each type of beam.

Table 2. Moments (M_{max}), elastic modulus ($E_{m,g}$) and ductility transferred by "RJF" beams

BEAM	M_{max} (kNm)	$E_{m,g}$ (GPa)	Ductility (%)
URJF-1	28.4	10.5	6.6
URJF-2	26.1	10.1	9.1
URJF-3	23.7	9.9	4.1
Average value	26.1	10.1	6.6
Standard deviation	2.4	0.3	2.5
Increase [%]	-	-	-

BEAM	M_{max} (kNm)	$E_{m,g}$ (GPa)	Ductility (%)
RJF-1	35.4	14.6	61.1
RJF-2	32.0	14.3	75.8
RJF-3	29.6	13.8	90.2
Average value	32.3	14.2	75.7
Standard deviation	2.9	0.4	14.6
Increase [%]	24.0 %	-	-

Taking into account reinforced beams from recoil, the highest mean maximum moment (M_{max}) in laboratory tests was obtained for the RJF-1 beam type (reinforcement degree 0.3%), reinforced with two pre-stressed jute fabrics. For the same quality class of wood, in beams reinforced with jute fabrics, the mean maximum moment (M_{max}) is 24.0% higher compared to the non-reinforced URJF beam type. The limit loads were in the range of 47.5–70.8 kN and ductility was in the range of 4.1–90.2%. Unreinforced beams had a mean global modulus of elasticity of 10.1 GPa with a standard deviation 0.3 GPa. For the reinforced beams, they were 14.2 GPa with standard deviations of 0.4 GPa. The increase in stiffness of reinforced beams was about 23.5% in relation to unreinforced beams. The ductility was 6.6% and 75.7%, respectively. Means large increases in ductility for reinforced beams. Unreinforced beams had lower tensile strength than compressive strength due to inherent flaws and defects, such as knots or hidden defects in the wood. In contrast, other studies carried out on small timber members with a span between supports of 900 mm showed that the deflection at mid-span of beams reinforced with jute fibres decreased by approximately (32.1–38.7%), (33.6–38.7%), and (30.6–31.6%) for the U, full and flexural reinforcement methods, respectively, compared to the control beam at the same at the same load. The toughness ratios of the tested beams increased by about (184–320%), (199–401%), and (137–240%) for U, full, and flexural strengthening techniques, respectively at the ultimate loads when compared with the control beam [Abdulla et al. 2020].

Most of the unreinforced beams were destroyed due to cracks starting from the lower lamellas. The modes of failure of all tested timber beams during four-point bending on an engineering scale with a span between supports of 3000 mm arranged parallel to the fibres vary according to the timber defects present. The modes of failure of the test beams represent transverse stresses and the splitting and hidden knots present, as shown in Fig. 8.

Fig. 8. Failure mode for the control beam URJF-1 (destruction of bases 6, 7, 8, 9, 10)

In addition, the mode of failure of the reinforced timber beams in the RJF group was usually transverse tension, while the number and distribution of cracks in the beams of this group were smaller than in the control beams. In beam RJF-15, beam failure occurred in the vicinity of hidden wood defects (knots). In beam RJF-17 there was a detachment of the epoxy glue from the jute fibre. Destruction of the beam occurred in the middle of the span, base 7.

Conclusions

Based on the experimental studies on the effectiveness of reinforcement of Scandinavian wood beams from recoil with the use of pre-stressed jute fabrics, it was found:

- Strengthening wooden beams with jute fabrics can be an effective way to increase the load-bearing capacity and stiffness of the elements.
- Among the beams reinforced with the same type, grade and arrangement of reinforcement, the maximum increase in load capacity was about 24% and stiffness about 24%. The highest load capacity was achieved in RJF-1 beams while the lowest occurred in RJF-2 elements. The greatest deflections occurred in the RJF-3 beams. Jute reinforcements resulted in an increase in strength of 24% and an increased modulus of elasticity of 40.3%. In some beam elements reinforced with pre-stressed jute fabrics, hidden defects of the wood appeared, which slightly increased the deflection of the beam without reducing its load-bearing capacity. Wood defects located in the lower part of the reinforced beams did not significantly affect the load-bearing capacity and deformation of these beams.
- The average ductility was 6.6% for non-reinforced beams, and 75.7% for reinforced beams. Therefore, jute fabrics are an effective reinforcement material in terms of toughness, so people will have enough time to escape a building in an emergency.

- Measurements of tensile and compressive strains showed the position of the neutral axis. The reinforced beams showed lower normal stresses than in the unreinforced beams. In the places of occurrence of wood defects (knots, fibre twist, cracks, resin galls, etc.), increases in the stresses of wood and fibre composite were observed.
- The presence of jute fabrics inhibits or limits the propagation of cracks. Moreover, as can be seen in the $u - F / 2$ (deflection-force) curves, there is a reduction in the scatter of test results due to the neutralisation of the crack. The destruction usually occurred in the tensile zone through the cracking of the wood fibres near the wood defects – knots. Pre-compressed jute fabrics improved the cooperation between the breaking knot and the stiffening "glue-fabric" connection. Careful cleaning of the surfaces of both the reinforcement fabrics and the wood resulted in the two-component epoxy adhesives good adhesion at the boundary of these bonds. The presence of composite fabrics inhibits or limits the propagation of cracks, neutralising local defects in the wood. As a result, the wood can carry higher breaking loads.

The analysis of the test results confirmed the influence of the heterogeneity of the structure on the reinforcement effect in the beams. Pre-compressed jute fabrics are suitable for reinforcing wooden elements of the lowest quality and recoil wood components, and even their production, and compensate for the nonhomogeneous structure of the wood. The applied reinforcement with pre-compressed jute fabrics is useful when significant structural and geometric features are detected that lower the wood quality class (knots, twisted fibres, cracks, resin galls, etc.), both in newly built and historic buildings. Methods of reinforcement using pre-compressed jute fabrics discussed in this research can be used primarily for elements of lower quality classes and for recoil (knots, fibre twist, cracks, resin galls, inbarks, galls, blue stain, rot and insect holes, sclerosis, excessive graininess, insufficient density, wane, curvature and twist). The tests confirmed the possibility of using inferior quality lumber and recoil lumber in the structures, provided that it is glued and reinforced with pre-compressed fibre composites. These methods are recommended when it may be difficult to obtain lumber of the highest class. By developing technology of layered gluing for wood with fibrous composites, such as jute fabrics, to reinforce wooden structures at the production stage, the consumption of wood in beam elements may be reduced.

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