Flexural Behavior of Laminated Wood Beams Strengthened with Novel Composite Systems (CFRP and Wire Rope): An experimental study

Mehmet Faruk OZDEMIR
Inonu University

Muslum Murat MARAS (murat.maras@inonu.edu.tr)
Inonu University

Hasan Basri YURTSEVEN

Research Article

Keywords: Timber, beam, strength, FRP, steel rope

Posted Date: May 1st, 2023

DOI: https://doi.org/10.21203/rs.3.rs-2861010/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

In this study, it was aimed to improve the mechanical properties of laminated timber beams by using Novel Composite Systems (Carbon Fiber Reinforced Polymer and Wire Rope). Reducing the cross-sectional area of the beam is important for the strength conditions required in large span systems with structural laminated wood material. Within the scope of this study, it is foreseen that the use of wood, which is an environmentally friendly and sustainable building element, will be made more economical and safe, instead of reinforced concrete and steel elements currently used to pass wide openings.

Structural behavior of hybrid reinforced laminated timber beams was determined under the loading system. Experimental findings show that normal laminated timber beam (0N) has a maximum load of 14 kN and a deflection of 36 mm. On the other hand, the highest increase in the values of laminated beams reinforced with steel ropes was obtained with the (2N) reinforcement, with a maximum load of 38 kN and a displacement of 137 mm. In this way, a load increase of 168% and a displacement increase of 275% compared to the reference sample were obtained. Since the steel rope-reinforced samples absorb the load, crack formation and transfer to the upper layers are prevented. 3F beam specimen reinforced with CFRP and steel ropes obtained maximum load of 28 kN and a displacement of 152 mm. Compared to the reference sample, a load increase of 92% and a displacement increase of 14% were obtained.

Consequently, the fabrics placed between the layers with CFRP prevented crack development and provided a significant interlayer connection. It has been observed that the fiber composite-reinforced wooden beams increase the load bearing capacity by more than 50% and exhibit a ductile behavior. The carbon fabrics placed between the laminated wooden beams with the innovative reinforcement system will not both disrupt the aesthetics and will reduce the effect of earthquake forces, and significant reductions can be achieved in the sections.

1. Introduction

Since the early days of humanity, wood has been a very important building material in meeting the necessary structural needs by using materials found in nature [1]. Since timber is an anisotropic material, it is very difficult to obtain the desired cross-sectional dimensions in building elements [2, 3]. Wood, which is a renewable material, is subjected to a number of processes after the tree is cut down in the forest until it can be used structurally [4]. These processes vary according to where the wood will be used in the structure and what purpose it will serve [5].

When wood is considered in terms of density, it is quite low compared to concrete and structural steel, and its bearing capacity is higher [6–8]. This relationship between density and load bearing capacity provides different advantages in the use of wooden structural elements [9]. One of the most important factors is the earthquake effect, which is directly related to the building mass [10, 11]. The low dead weight of wooden structures compared to reinforced concrete and steel construction provides an advantage in the event of earthquakes [12]. Another effect of density is that it has a positive effect on the shaping of the material. Considering these advantages, the use of wood as a structural element is very attractive in terms of architecture and engineering [13].
Humanity has used wooden building material in every field since the earliest times [14, 15]. After the tree is cut, it is separated from its branches and knots and turned into logs [16]. Logs can be used structurally, and in the course of progress, solid woods could be obtained by drying or not drying after the logs are cut [17]. With the arrival of the log in this form, the more efficient use of the bearing feature of wood has enabled us to build structures with wood in terms of aesthetics and functionality [18].

Laminated wood materials are widely used around the world (bridge construction, wide-span systems, etc.) [19]. Wooden boards used in the lamination process should have a homogeneous structure and show higher strength properties [20]. Carrier system elements can be produced in desired dimensions and openings in wooden structural elements [21, 22]. Fire resistance compared to solid wooden structural elements is quite high [23]. The lightness of the carrier elements in wooden systems provides great convenience in production and assembly [24]: wooden structures can be dismantled and reused and their parts in the system can be changed [25].

Many different studies have been applied to strengthen the building elements. It is aimed to produce high-strength and wide-span wooden beam elements as a result of the use of tensioned steel rope systems used to cross wide spans in wooden elements, as well as FRP material, which is frequently used in reinforced concrete and masonry structures and is known to have a very high effect. Hybrid reinforced CFRP and steel rope materials were used in the reinforcement of wooden beams. In this study, it is aimed to both improve the mechanical properties of the beam element by combining these two methods in the laminated wooden beam element and to obtain a beam element with higher span in smaller sections by reducing the shear and moment values, which will affect the beam element. Through this study, which will be done by combining these two methods in a hybrid way, better structural beam elements will be produced by improving the deficiencies in the methods themselves. In this way, it is foreseen to reduce the cross-sectional areas required for wide-span wooden structural elements.

2. Materials and Methods

2.1. Solid wood

Coniferous woods such as cedar, pine, cypress and fir are wood species used structurally, and tree species such as walnut, beech, oak and poplar are used in broad-leaved woods. Each type of tree has its own distinct characteristics. Common to all species, moisture content, knot condition, amount of fiber and defects exhibit anisotropic behavior in terms of mechanical properties. For this reason, wood is classified according to its quality, especially its moisture content. This classification is used in the dimensioning of the obtained wood and determining its use as a support, carrier or architectural element. The solid wood plate used from spruce type wood was 1200 mm x 3500 mm long and 30 mm thick.

2.2. CFRP

Unidirectional CFRP with 600g/m$^3$ area weight was used as carbon fiber fabric (CFRP). The mechanical properties of the CFRP used are given in Table 1.
2.3. Structural laminated wood

Wooden laminated elements are obtained by gluing two or more layers and joining the layers in such a way that the fiber directions are parallel or perpendicular to each other. If the wood laminate element produced is curved, the fiber directions of the layers must be applied parallel. Different wood species, variable number of layers, different sizes, shapes and layer thicknesses can be applied in lamination. The purpose of using laminated wood is to eliminate the disadvantage of wood having anisotropic properties due to its nature. For this, the laminated wood element is obtained by combining the parts of the tree other than the defective areas by using special glues in certain sizes so that the fiber directions are parallel to each other. In this way, it is possible to produce wooden elements with better properties and in all desired dimensions. Any desired cross-sectional area can be obtained by the lamination process and the joining of the wood pieces. Due to this method, which will be produced as fabrication, a prefabricated production is made.

2.4. Timber beam reinforced with steel rope

Laminated timber beams with steel tension rods are generally used for large span structures. Different constructions are possible for large span roof trusses and bridges. By using a single span beam it is possible to adjust the beam dimensions according to the section forces. If this is done, however, large dimensions are often required, which further increases the section forces (especially the bending moment) relative to their weight.

Another way to deal with large spans is to reduce the maximum bending moment in the beam. With the addition of one or more elastic intermediate supports, the static system transforms from a single span beam to a double span beam or even a continuously supported beam. Intermediate support is placed, changing the behavior of a laminated timber using steel tension rods. The bending moment in the intermediate supports decreases the bending moment in the span. The intermediate support is elastic and tension rods are deformed by flexing under load. Due to the axial compression force, the length of the material becomes shorter and the tension rods lengthen. Considering the variations of the steel rope reinforcement method and the number of samples, three variations, two for each, were applied. Specimen number 1 (1N) steel rope reinforcement method is given in Fig. 2. In this method, the rope is brought into V form with the steel material placed in the middle of the wood.

Specimen number 2 (2N) steel rope reinforcement method is given in Fig. 3. In this method, the rope is formed into an inverted trapezoid with two different steel materials placed under the loading points.
Specimen number 3 (3N) steel rope reinforcement method is given in Fig. 4. In this method, it is brought into a V form with V-shaped steel material placed from the lower part of the loading points.

It was fixed by compression in order not to damage the wood while fixing the steel ropes on the wood using 1 mm steel plates. At the same time, in order to prevent the steel elements from affecting the support and loading points, those areas were cut to certain dimensions with the laser cutting method. The planks were fixed on the wood surface by tightening with mutual bolts and nuts (Fig. 5). In this study, 6 mm diameter steel rope was used. Special clip elements and a key that could be applied tension force at desired loads were used for fixing the steel rope.

### 2.5. Timber beam reinforced with CFRP and steel rope

Laminated wood material is defined as a structural element obtained by gluing wood lamellas, especially fibers, in parallel. It is a building element produced by joining solid timbers at the ends, side by side and on top of each other to create large dimensions. It is obligatory to arrange such structural elements parallel to the fiber direction. In this study, carbon fiber construction material was applied between laminated layers and corner joints in wood by various methods (Fig. 6). Figure 7 shows hybrid reinforced laminated timber beams reinforced using both CFRP and steel ropes.

### 2.6. Test setup and testing procedures

Wooden building elements could be produced in large scales with the lamination process in wide span systems in wooden structures. In this study, different reinforcement methods were applied by using steel rope and FRP composite materials in laminated wood structural elements. These structural elements were tested under the loading system in accordance with the TS EN 408 + A1 standard. According to the findings obtained in this study, it was aimed to reduce the cross-sectional area required for the required strength conditions of the structural laminated wood material in wide openings. The experimental setup was created in accordance with the regulation of TS 5497 EN 408 “Wood Structures - Structural Timber and Glued Laminated Timber - Determination of Some Physical and Mechanical Properties” according to the measurement ratios given in Fig. 8a. According to this regulation, a four point loading system was used to examine the bending behavior of laminated wood elements. The distance between two supports should be 18 times the height. In the breaking of beams, the displacement measurement points were made from three points, as shown in Fig. 8b. While the deflection measuring device numbered 1 (LVDT-1) was taken by the device located on the loading mechanism, the deflection measuring devices numbered 2 and 3 were additionally placed and loaded.

### 3. Results and Discussion

#### 3.1. Load-deflection curve of timber beams reinforced with steel rope
Reinforcement variations are made with steel ropes on laminated wooden beams. These wide span beams can generally be widely used in large span roof, truss and bridge systems. In our study, it was aimed to reduce the maximum bending moment in the reinforced beam. In Fig. 9, the load/ deflection graph of steel rope-reinforced laminated beams in three different variations is shown. Experimental findings show that normal laminated timber beam (0N) specimen has a maximum load of 14 kN and a deflection of 36 mm. On the other hand, the highest increase in the values of laminated beams reinforced with steel ropes was obtained with the specimen (2N) reinforcement, with a maximum load of 38 kN and a displacement of 137 mm. Structural behavior of a laminated wood using steel tension rods by placing an intermediate support was investigated. The bending moment in the intermediate supports reduced the bending moment in the span. Intermediate support exhibited elastic behavior and studs and tension rods were deformed by flexing under load [26, 27]. In this way, a load increase of 168% and a deflection increase of 275% compared to the reference sample were obtained. Because of the axial clamping force, the working length is shortened and the tension rods are elongated [28]. Due to these deformations, the intermediate support was not fixed vertically as it was with normal supports at its two ends [29, 30].

3.2. Crack pattern and failure modes of timber beams reinforced with steel rope

Typical failure modes and damage patterns of wooden beams under bending load were determined. Compared to the reference sample (Fig. 10a), the steel rope-reinforced samples showed a significant increase in load-deformation curves. Cracks that occur in laminated wooden beams were formed in the junction areas of the solid panel, which is the weakest area. In the normal laminated (0N) timber beam specimen, cracks progressed rapidly from the lowest layer to the upper layers. Since the load of the steel rope-reinforced samples was absorbed by the steel rope, the formation of cracks and their transfer to the upper layers were prevented. In this way, while obtaining more load and deflection, significant increases in energy absorption have also been achieved. It is stated that it is possible to partially restore the bending capacity of damaged wooden beams by strengthening them [31, 32]. When the steel rope reinforcement specimen 1N is examined, under the influence of the four point loading mechanism, the cracks have progressed to the upper layers, starting from the points where the load is applied. Although the steel material used in the specimen 1N wire rope strengthening method in the middle of the wooden beam prevented the formation of cracks under the effect of load, it was less effective compared to other methods (Fig. 10b). The specimen 2N wire rope reinforcement contributed much more than the specimen 1N reinforcement by placing the steel elements just below the point where the loads were applied to the wood (Fig. 10c). In the 3N sample steel rope reinforced beam (Fig. 10d), steel elements placed directly below the loading points have a better effect than reinforcement sample 1N, but it is more difficult compared to reinforcement sample 2N; low strength was obtained. Similarly, as the flexural strength, bond length and bond width of reinforced wooden beams increased, and the ultimate load carrying capacity also improved significantly [32, 33]. When we examine the damage areas, it can be determined that the position of the steel elements has a significant effect on the spread of the beam at two different points in the reinforcement specimen 2N, but the formation of the crack zone is at a single point in the reinforcement specimen 1N and 3N. The use of reinforced laminated wood beams made it possible to
obtain a structural material with higher quality control, with less variation in final loads, thereby reducing the defects of timber in wood-based composite materials [34, 35].

### 3.3. Load-deflection curve of timber beams reinforced with CFRP and steel rope

The structural behavior of wooden beams reinforced with CFRP and steel rope under four point loading was investigated. In Fig. 11, the load/deflection graph of steel rope and CFRP reinforced laminated beams in three different variations is given. Experimental findings demonstrated that the reference laminated timber beam specimen (0F) had a maximum load of 19 kN and a displacement of 125 mm. Specimen (1F) timber beam had a maximum load of 27 kN and a deflection of 120 mm. It can be stated that wooden beams reinforced with FRP composites significantly increased the ductility of the beams with increasing moment capacity [36, 37]. Specimen 3F beam reinforced with CFRP and steel ropes obtained maximum load of 28 kN and a displacement of 152 mm. It was shown that beams reinforced with CFRP composites limit wood defects and prevent severe damage [38, 39]. The highest increase in the values of the laminated beams reinforced with steel rope and CFRP was determined with the number 2 (2F) reinforcement, with a maximum load of 32 kN and a displacement of 143 mm. In this way, a load increase of 92% and a displacement increase of 14% were obtained compared to the reference sample. In many studies, the reinforcement of wooden beams with FRP layers (more than three layers) both reduces efficiency and increases costs [40, 41, 42]. It was observed that CFRP-reinforced wooden beams increase the load bearing capacity by more than 50% and exhibit a ductile behavior.

### 3.4. Failure modes of timber beams reinforced with CFRP and steel rope

Damages in unreinforced wooden beams usually occurred in the lower part of the section close to the loading point. Later, the cracks expanded further and gradually progressed as shear cracks up to the loading point. For wooden beams, the crack propagation process varies depending on the section height and crack opening surface [43, 44]. However, the fabrics placed between the layers with CFRP prevented crack development and provided a significant interlayer connection. Similarly, it was found that fiber polymer composites did not cause damage and contributed significantly to the load carrying capacity of wooden beams [45]. An increase in displacement was observed in the reference CFRP wood sample (0F) (Fig. 12a) compared to the normal wood sample (0N). The CFRP material placed between the layers provided an increase in strength and deformation values by meeting the tensile forces in the lower parts of the beam. These composites with high toughness did not break and this contributed significantly to the structural element by exhibiting a ductile behavior under bending load [46, 47, 48]. When steel rope systems were used, a greater increase was obtained compared to steel reinforcements in normal wooden beams. The biggest factor observed is that the transition of cracks to the upper layers is greatly reduced and, by providing significant adherence between the laminated plates, severe damage has not occurred. The bearing capacity and ductility of wooden elements reinforced with steel ropes increased significantly.
In similar studies, it has been concluded that the use of steel ropes contributes significantly to this behavior and significantly improves their mechanical properties [49, 50].

### 3.5. Toughness

Toughness is an important parameter that measures the energy absorption capacity of all columns up to failure under axial load [51, 52]. In this study, the toughness capacities of hybrid reinforced laminated timber beams under axial load were compared. The load-deformation graph and toughness values of all samples were determined. In this way, a load increase of 168% and a displacement increase of 275% compared to the reference sample were obtained. In addition, considering the toughness, a value of 214 was obtained in the reference sample and a value of 3393 in the specimen 2N reinforcement, an increase of 1486% was obtained. It was observed that laminated timber beams reinforced with CFRP prevent local buckling and provide a significant increase in ductility, axial load carrying and toughness capacities. In addition, studies have shown that increasing the fiber ratio increases the ductility and toughness capacity of wood elements [53, 54]. Compared to the reference sample, a load increase of 92% and a displacement increase of 14% were obtained. In addition, considering the toughness, a value of 1045 was obtained in the reference sample and a value of 3779 in the strengthening specimen 2F; an increase of 262% was obtained. These results show that reinforced wooden beams increase their toughness and absorb a higher amount of energy [55]. As a result, it was revealed that, when the ratio of fibrous polymer composite increased, the fracture and impact energies, toughness and ductility values increased.

### 4. Conclusion

This article discussed the structural performance of wood beams reinforced with hybrid reinforcement. In the study, high ductility in order to strengthen wooden beams with lower cost, methods using hybrid reinforced composites have been developed.

- It was observed that CFRP-reinforced wooden beams increase the load bearing capacity by more than 50% and exhibit a ductile behavior.
- Laminated beams reinforced with steel ropes showed a load increase of 168% and a deflection increase of 275% compared to the reference sample.
- Although the steel material used in the specimen 1N wire rope strengthening method in the middle of the wooden beam prevented the formation of cracks under the effect of load, it was less effective compared to other methods.
- Specimen 3N steel rope-reinforced beam showed steel elements placed directly below the loading points have a better effect than reinforcement specimen 1N, but it is more difficult compared to reinforcement specimen 2N; low strength was obtained.
- Specimen 3F reinforced with CFRP and steel ropes obtained maximum load of 28 kN and a displacement of 152 mm. In this way, a load increase of 92% and a displacement increase of 14% were obtained compared to the reference sample.
• CFRP material placed between the layers provided an increase in strength and deformation values by meeting the tensile forces in the lower parts of the beam.

• Considering the toughness, a value of 214 was obtained in the reference sample and a value of 3393 in the specimen 2N reinforcement; an increase of 1486% was obtained.

• In addition, considering the toughness, a value of 1045 was obtained in the reference sample and a value of 3779 in the strengthening specimen 2F; an increase of 262% was obtained.

Declarations

Acknowledgment

The authors are grateful to the Inonu University Project of Scientific Investigation (PSI) for their financial support for this project, (FYL-2022-2883).

Conflict of Interest

The authors declare that no conflict of interest.

References


12. A.Asiz, I. Smith, Demands placed on steel frameworks of tall buildings having reinforced concrete or massive wood horizontal slabs, StructEngInt, 19 (4) (2009), pp. 395–403


52. K.J. Soderholm, Review of the fracture toughness approach Dent Mater, 26 (2) (2010), pp. e63-e77


Figures

Figure 1

Normal (0N) laminated wooden (mm)
Figure 2

Specimen 1N steel rope-reinforced wooden beam (mm)

Figure 3

Specimen 2N steel rope-reinforced wooden beam (mm)
Figure 4

Specimen 3N steel rope-reinforced wooden beam (mm)
Figure 5

Fixing the steel rope to the wood surface
Figure 6

Laminated timber beam member reinforced with CFRP
Figure 7

Test specimens reinforced with CFRP and steel ropes
Figure 8

Flexural strength tests of timber beams

a) Laminated wooden beam experimental setup measurement points

b) Four point loading test setup according to TS EN 408+A1 standard
Figure 9

Effect of steel rope reinforcement methods on normal laminated timber beams
Figure 10

Typical failure modes of timber beams reinforced with steel rope
**Figure 11**

Load-deformation curve of laminated timber beams reinforced with steel rope and CFRP
Figure 12

Typical failure modes of timber beams reinforced with CFRP and steel rope
Figure 13

Flexural toughness test results