

## ARTICLE

# Investigation of Wooden Beam Behaviors Reinforced with Fiber Reinforced Polymers

Şemsettin KILINÇARSLAN\* Yasemin ŞİMŞEK TÜRKER

Suleyman Demirel University, Faculty of Engineering, Department of Civil Engineering, Turkey

## ARTICLE INFO

*Article history*

Received: 1 April 2020

Accepted: 7 May 2020

Published Online: 31 May 2020

*Keywords:*

Wood materials

Beam

FRP

Reinforced

Composite

## ABSTRACT

Wood material can be demolished over time due to different environmental factors. Structural elements may need to be strengthened over time as a result of possible natural disasters or during use. Beams are elements under load in the direction perpendicular to their axes. Therefore, they are basically under the effect of bending. When the studies on the behavior of beams against bending test are examined, it is known that the bottom surface of the material generally breaks. For this reason, fiber reinforced polymers (FRP) materials have been used in recent years to reinforce beam members. It is a scientific fact that it is necessary to prefer FRPs for the solution of this problem, as well as their properties such as lightness, corrosion and flexibility, their application without disrupting the appearance of wood. In this study, it was aimed to investigate the effect of reinforcing wooden beams with fiber reinforced polymer materials with different properties on different bending behaviors such as load bearing capacity, ductility, modulus of elasticity. It was observed that the ductility and bearing capacity of wooden beams reinforced with fiber reinforced polymer materials increased significantly compared to non-reinforced beams.

## 1. Introduction

Many of the historical buildings in our country and in the world consist of wooden elements. Sustaining and renewing our historical heritage requires economic power. Therefore, it is important to investigate the different strengthening methods used for repair and strengthening of historical wooden structures [1,2].

Composite materials generally consist of the main structure and reinforcing element, the main structure is called the matrix. Generally, the reinforcing material is made of fibers; carbon, glass or aramid, matrix material consists of epoxy resin [3]. Although extensive research

has been done on the application of FRP composites for reinforcement, repair and reinforcement in concrete and masonry structural elements, there are limited number of studies on their application in wooden structures. The majority of current studies are focused on strengthening against bending [4-20]. Reinforcement with fiber reinforced polymers (FRP) is among the methods commonly used to repair existing wooden structures or to create high-performance structures in newly constructed wooden structures [21]. In the reinforcement process with these composite materials, various materials such as lining and glue are used during the application of fabric, sheets and rots to the wood material. Reinforcement techniques with fabric,

\*Corresponding Author:

Şemsettin KILINÇARSLAN,

Suleyman Demirel University, Faculty of Engineering, Department of Civil Engineering, Turkey;

Email: semsettinkilincarslan@sdu.edu.tr

sheets and rots are used to increase the strength of the timber [22] and strengthen the existing wooden structure [22,23]. Studies have been done especially on both solid wood [22-25] and glulam materials. Flexural behaviour of glulam timber beams reinforced with FRP cords.

In traditional reinforcement techniques, it is generally recommended to use metal in wooden structures. However, considering the superior aspects of FRP to be used compared to metals, the most important advantages of FRP strips compared to steel strips are; lightness, corrosion and flexibility can be listed. It is inevitable that reinforcements made with steel need maintenance over time, create visual pollution in the reinforced areas and bring extra load to the structure. It is a scientific fact that fiber reinforced polymers, as well as their properties such as lightness, corrosion and flexibility, can be applied without disturbing the appearance of wood, and that FRPs should be preferred in the solution of this problem [3].

In this study, it was aimed to investigate the effect of reinforcing wooden beams with fiber reinforced polymer materials with different properties on different bending behaviors such as load bearing capacity, ductility, and modulus of elasticity.

## 2. Fiber Reinforced Polymer Composite Materials

Composite materials can be briefly defined as “materials formed by the combination of two or more components that are macro-different from one another across an interface”. The components that make up the composite material mostly retain their properties [26]. Understand the behavior of a composite material; it is necessary to know the functions of the fibers and matrix materials in the composite material (Figure 1) [27]. The important duties of fiber fibers and matrix materials can be listed as follows [28].

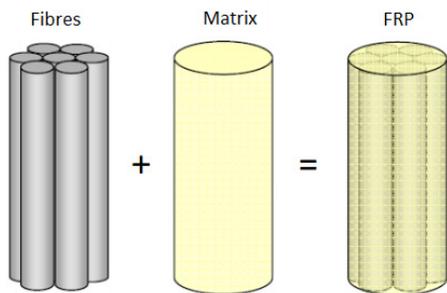


Figure 1. Constituents of Fiber Reinforced Polymers Materials [27]

## 3. Production and Properties of Fibers

Materials such as glass, carbon and aramid, which are

melted at high temperatures, are flowed down by a thin (capillary) perforated tank, and they are suddenly cooled by spraying water on them, and are rapidly drawn by stretching with continuously rotating rollers, and this stretch process produces micron-level fibers. In order for these fibers to have a good adherence with resins, surface improving materials (such as Silane) are coated on them [29]. These stages are shown schematically in Figure 2.

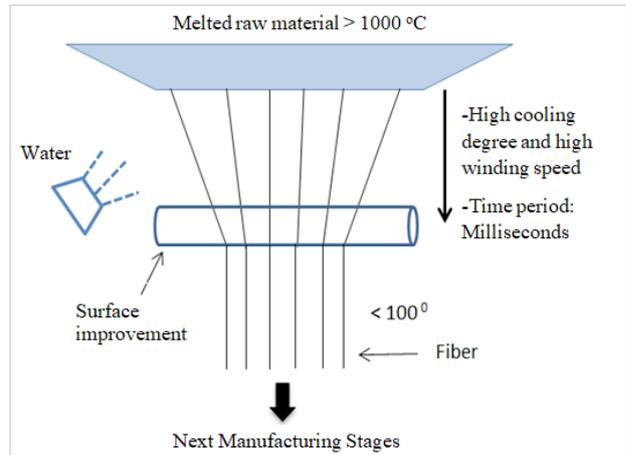


Figure 2. Production stages of fibers

As seen in Table 1, the elasticity module and the highest tensile strength are carbon fibers. PVA fibers are the most likely to have elongation at break.

Table 1. Range of change of mechanical properties of fibers [30]

Properties	Fiber Types			
	Carbon	Aramid	PVA	Glass
Modulus of Elasticity (GPa)	290-400	62-142	8-28	72-78
Tensile Strength (MPa)	2400-5700	2410-3150	870-1350	3300-4500
Breaking Elongation (%)	0,3-1,8	1,5-4,4	9,0-17,0	4,8-5,0

Figure 3 shows the stress-strain curves of the fibers used for reinforcement.

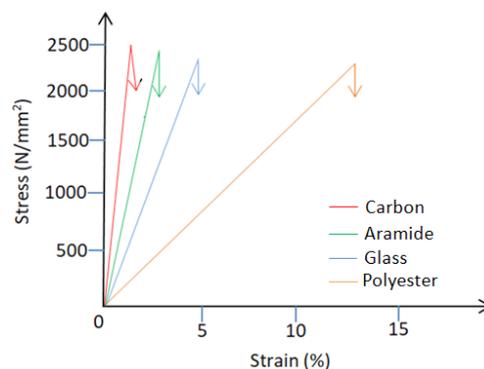


Figure 3. Stress-strain curve of fibers

As seen in this diagram, while the stress-deformation diagram of carbon, aramid and glass (E-glass) fibers are close to each other, deviation is higher in polyester fibers.

#### 4. Use of Fiber Reinforced Polymers in Strengthening Wooden Beams

Nowadays, most of the historical wooden houses have been demolished and many have been damaged. This has led to the need for a safe and fast repair of our existing wooden structures. Classical restoration techniques can be developed in terms of preserving historical texture, time, cost and security. It is of great importance to repair the bearing elements of wooden structures with FRP in a very short time in terms of safety and time and visuality.

Plevris and Triantafillou<sup>[31]</sup> made comparisons between the analytical model and experimental studies they developed to estimate the creep behavior of CFRP reinforced wooden beams in their work titled "Creep behavior of FRP reinforced wooden building elements" and reported that they are compatible with the analytical model. Oga-wa<sup>[32]</sup> made reinforcements and compared their bending strengths by bonding carbon fiber reinforced fiber strip to various regions of laminated wooden beams or by wrapping the entire beam with carbon fiber at certain intervals. It also observed the behavior of reinforced samples under temperature and detected a 300% performance increase. Premrov et al.<sup>[33]</sup> examined the analysis of wooden structural elements reinforced with carbon fiber reinforced polymers. With the reinforcement of wooden building elements with 75 mm CFRP, they achieved a 50% higher strength. Steiger<sup>[34]</sup> conducted studies on the bonding of high performance carbon fiber reinforced polymers to wood with epoxy in wood structures and the effect of epoxy on tensile strength. It has determined the best reinforcement properties at optimum temperature. Author reported that the optimum values of the adhesion temperature of the epoxy resin with CFRP to the wood are in line with the values given by the glue manufacturers. Roberto et al.<sup>[35]</sup> conducted a study on structural classification of completely damaged wooden columns reinforced with FRP composite boards. In the data obtained as a result of bending tests, a 60% improvement was found with FRP composite plates. Borri et al.<sup>[5]</sup>, in their study on the behavior of wooden structural elements reinforced with CFRP under loads, compared the non-linear models of existing wooden structural elements with the estimated load amount.

In the past two decades, research has been done on the structural application of wood-based composites. The performance of glulam timber columns reinforced with

FRP (Fiber Reinforced polymer) sheets was investigated by Taheri et al.<sup>[36]</sup>. Experimental results and computational modeling have shown that stiffness and resistance can be significantly improved with FRP. O'Loinsigh et al.<sup>[37]</sup> conducted experimental and numerical research on wooden dowels and multi-layer wooden beams, demonstrating that a desired bending stiffness can be achieved with a reasonable combination of material and geometric parameters. Chans et al.<sup>[38]</sup> examined the axial resistance of the connections made with steel rods glued to the joints of the wood material. Although there are many experimental studies on the joints of glued laminated timber (glulam), they emphasized that the experimental data on the joints tests are still limited.

Although extensive researches have been made on the application of FRP composites for reinforcement, repair and reinforcement in concrete and masonry structural elements, there are limited studies on their application in wooden structures. The majority of current studies are focused on strengthening against bending<sup>[4-20]</sup>. In addition, regional reinforcement studies have been carried out to increase shear strength perpendicular to the fibers<sup>[23,39,40]</sup> and perpendicular to the fibers<sup>[41]</sup>. Successful application of FRP reinforcement to wooden elements requires the establishment of a high quality and durable bond between two different materials. Various studies have also been carried out to investigate this aspect of strengthening with FRP<sup>[42-47]</sup>.

Lindyberg<sup>[48]</sup> stated that various design methods are used to analyze reinforced and non-reinforced beams in bending. These methods can be divided into empirical, deterministic and probabilistic. ASTM D 3737/96 - (Standard Test Method for Building Stresses) creates empirical methods for the design of beams produced from structural glued laminated timber (Glulam). These methods take into account the bending strength of error-free test samples and create modification coefficients for existing defects in these elements. The author concluded that reinforced glulam beams have a complex tearing mode that makes it difficult to use experimental solutions. Lindyberg<sup>[48]</sup> presented a semi-probability calculation model to calculate the strength and stiffness of reinforced glulam beams. Author stated that the model is the most effective solution to evaluate the resistance and hardness of the material. The calculation procedure consists of two stages. The first part consists of a deterministic numerical model that calculates the load-bending curve of the reinforced beam. This model is based on the moment of curvature ( $M-\phi$ ). The second part includes the deterministic model in a probabilistic model. The Monte Carlo computational simulator was used to devel-

op the probability model in the deterministic model.

Fiorelli and Dias <sup>[8]</sup> provided a decisive model for calculating the stiffness and resistance of fiber-reinforced timber beams. To calculate the rupture mode, the model takes into account tearing by compression of the upper fibers or stretching the lower fibers. To evaluate the final moment, the model takes into account the final tensile and compressive strength of the timber. This model is based on the Navier / Bernoulli hypothesis. If the comparison of experimental and theoretical results is made, they determined that both experimental and theoretical results give very similar strength and hardness values. Romani and Blab <sup>[49]</sup> presented a design model for fiber-reinforced glulam beams. In this study, the authors showed different breaking modules for reinforced glulam beam.

Raftery and Harte <sup>[50]</sup> produced layered laminated beams produced by gluing spruce beams on top of each other. In reinforced beams, FRP plates are placed between the beams. Reinforced and non-reinforced beams were subjected to bending test. They examined the load-displacement behavior, stiffness and final moment capacity of beams. They also developed a finite element model with nonlinear material modeling and nonlinear geometry to estimate these properties.

Li et al. <sup>[51]</sup>, examined the bending behavior of wooden beams reinforced with Glass Fiber Reinforced Plastic (GFRP) rod and Carbon Fiber Reinforced Plastic (CFRP) composite boards. In the study, he examined the load-displacement behavior of beams under bending effect. A cross-sectional analysis method is proposed to obtain the relationship between force-displacement of these wooden beams reinforced with GFRP rod and CFRP boards. Analytical results have been shown to reasonably predict the force-displacement relationships of these wooden beams reinforced with the GFRP rod and CFRP boards.

Xiong et al. <sup>[52]</sup> aimed to discuss the applicability of reinforcement, to evaluate the contributions of different methods and to examine the seismic performance of samples. They used Canadian spruce-pine-fir (SPF) glulam in their studies. They are wrapped with 0.11 mm thick CFRP. All the samples used had a span of 4,110 mm and a height of 2,740 mm. The column sections used in the study are 280 mm x 230 mm; beam sections are 280 mm x 180 mm and support sections are 135 mm x 105 mm. Monotonic and cyclic tests were performed using a hydraulic actuator at Tongji University. They used a hydraulic actuator with a displacement distance of  $\pm 250$  mm and a capacity of 650 kN. As a result of the study, they determined that all samples of the reinforced series regain their load bearing capacity. While the screws used provide a pre-stretching effect, wrapped FRP materials have been determined to

tend to limit cracks passively.

Wang et al. <sup>[53]</sup> summarizes a series of experimental and numerical study results on the mechanical behavior of such connections (bolted glulam column-beam) under various combinations of shear force and bending moment defined by shear-moment ratio  $\lambda$ . Based on the samples tested in this study, they found that the moment resistance in the junction area increased by 31.6% of the pure moment resistance, as the shear-bending ratio ( $\lambda$ ) increased. In the meantime, they determined that the shear-bending ratio ( $\lambda$ ) decreased and the pure shear resistance decreased by approximately 46.1%. The FEM model developed based on the elastic-plastic damage forming the wood and wood foundation model and the test results obtained were determined to give parallel results (16.7% and 11.1% modeling error for bending moment and shear resistance respectively). They stated that the interaction for a small shear-moment ratio ( $\lambda < 1.53$ ) can be expressed by a quadratic function, a linear function would be more appropriate for the large shear-moment ratio ( $\geq 0.53$ ).

Kılınçarslan and Şimşek Türker <sup>[54]</sup> examined the effect of strengthening the wooden beam with FRP fabric on the load bearing capacity and elasticity modulus values of the material. They determined that the final displacement was less in the wooden beams reinforced with FRP fabric and there was an increase in ductility and bearing capacity.

## 5. Conclusions

Besides the many positive properties of the wood material, it also has negative properties. Therefore, the natural strength of the wood material; In other words, changes in durability characteristics can be seen against different environmental factors in the field of use. One of the methods used to increase the resistance properties of wood material is reinforcement with fiber reinforced polymers. In this study, studies that reinforcing wooden beams with fiber reinforced polymers increase the load bearing capacity of beams are researched and it's presented.

Application of fiber reinforced polymers is a solution method that can be used to strengthen wooden systems in cases where load bearing capacity and stiffness are required to be high. In addition, the absence of an abrasive material offers the possibility of reducing long-term maintenance costs and rapid application on the job site. Fiber-reinforced polymers can be applied not only to strengthening the carrier elements while building the structure, but also to the damaged sections of columns and beams as restoration work in wooden houses of historical value and can help increase the resistance of these houses against external influences for a long time. It is important

to expand the use of FRPs in terms of protection, strengthening and sustainability of historical wooden structures.

## References

- [1] González Bravo C. Recovery of the mechanical capacity in pieces of wood requested to flex in traditional structures operating on the upper side by means of reinforcements and metal prostheses. PhD Thesis: 201.
- [2] Kiliçarslan, Ş., Şimşek Türker, Y. The Effect of Different Parameters on Strength Properties of Glulam Timber Beams. ICCES-2019, Antalya-Turkey, 2019: 23-27.
- [3] Şahin, Y. Introduction to composite materials, Gazi Bookstore, Ankara, 2000: 2-33.
- [4] Alhayek, H., Svecova, D. Flexural stiffness and strength of GFRP-reinforced timber beams. *J Compos Constr*, 2012, 16(3):245-252. DOI: 10.1061/(ASCE)CC.1943-5614.0000261
- [5] Borri, A., Corradi, M., Grazini, A. A Method for Flexural Reinforcement of Old Wood Beams with CFRP Materials. *Composites: 2005, Part B*, 36: 143-53.
- [6] Blaß, H.J., Romani, M. Load and deformation behavior of composite beams made of glulam and fiber-reinforced plastics. Research report of the Research Institute for Steel, Wood and Stones, Dept. of Engineered Wood Construction at the University of Karlsruhe (in German), 2000.
- [7] D'Ambrisi, A., Focacci, F., Luciano, R. Experimental investigation on flexural behavior of timber beams repaired with CFRP plates. *Compos Struct*, 2014, 108: 720-728. DOI: 10.1016/j.compstruct.2013.10.005
- [8] Fiorelli, J., Dias, A. A. Glulam Beams Reinforced with FRP Externally-Bonded: Theoretical and Experimental Evaluation. *Mater Struct*, Gentile CJ. Flexural strengthening of timber bridge beams using FRP. MSc thesis, University of Manitoba, 2000, Winnipeg, 2011, 44(8): 1431-1440. DOI: 10.1617/s11527-011-9708-y
- [9] Gilfillan, R.J., Gilbert, S.G., Patrick, G.R.H. The Use Of FRP Composites In Enhancing The Structural Behaviour of Timber Beams. *J Reinf Plast Compos*, 2003, 22(15):1373-1388. DOI: 10.1177/073168403035583
- [10] Hernandez, R., Davalos, J.F., Sonti, S.S., Kim, Y., Moody, R.C. Strength and stiffness of reinforced yellow-poplar glued-laminated beams. Research Paper FPL-RP-554, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1997, Madison.
- [11] Jacob, J., Barragan, O.L.G. Flexural strengthening of glued laminated timber beams with steel and carbon fiber reinforced polymers. MSc thesis, Chalmers University of Technology, Gothenburg, 2010.
- [12] Jankowski, L.J., Jasienko, J., Nowak, T.P. Experimental assessment of CFRP reinforced wooden beams by 4-point bending tests and photoelastic coating technique. *Mater Struct*, 2010, 43(1-2): 141-150. DOI: 10.1617/s11527-009-9476-0
- [13] Johnsson, H., Blanksvard, T., Carolin, A. Glulam members strengthened by carbon fibre reinforcement. *Mater Struct*, 2006, 40(1): 47-56. DOI: 10.1617/s11527-006-9119-7
- [14] Kim, Y.J., Hossain, M., Harries, K.A. CFRP strengthening of timber beams recovered from a 32 year old quonset: element and system level tests. *Eng Struct*, 2013, 57: 213-221. DOI: 10.1016/j.engstruct.2013.09.028
- [15] Li, Y.F., Xie, Y.M., Tsai, M.J. Enhancement of the flexural performance of retrofitted wood beams using CFRP composite sheets. *Constr Build Mater*, 2009, 23(1): 411-422. DOI: 10.1016/j.conbuildmat.2007.11.005
- [16] Micelli, F., Scialpi, V., La Tegola, A. Flexural reinforcement of glulam timber beams and joints with carbon fiber reinforced polymer rods. *J Compos Constr*, 2005, 9(4): 337-347. DOI: 10.1061/(ASCE)1090-0268
- [17] Raftery, G., Harte, A. Low-Grade Glued Laminated Timber Reinforced with FRP Plate. *Compos Part B: Eng.*, 2011, 42(4): 724-35.
- [18] Raftery, G.M., Whelan, C. Low-Grade Glued Laminated Timber Beams Reinforced Using Improved Arrangements of Bonded-in GFRP Rods. *Constr Build Mater*, 2014, 52: 209-220. DOI: 10.1016/j.conbuildmat.2013.11.044
- [19] Schober, K.U., Rautenstrauch, K. Post-Strengthening of Timber Structures with CFRP's. *Mater Struct*, 2006, 40(1), 27-35. DOI: 10.1617/s11527-006-9128-6
- [20] Yusof, A. Bending behavior of timber beams strengthened using fiber reinforced polymer bars and plates. PhD thesis, Technology University of Malaysia, Skudai, 2010.
- [21] Kiliçarslan Ş., Şimşek Türker Y. Evaluation in terms of Sustainability of Wood Materials Reinforced with FRP. *Journal of Technical Sciences*, 2020, 10(1): 23-30.
- [22] J.R. Gilfillan, S.G. Gilbert, G.R.H. Patrick. The use of CFRP composites in enhancing the structural behaviour of timber beams, *J. Reinf. Plast. Compos.* 2003, 22(15/2003): 1373-1388.

- [23] T.W. Buell, P.E. Saadatmanesh, Strengthening timber beams using carbon fiber, *J. Struct. Eng.* 2005, 131(1): 173–187.
- [24] A. André, R. Kliger. Strengthening of timber beams using FRP, with emphasis on compression strength: a state of the art review, in: *Proceedings of the Second Official International Conference of International Institute for FRP in Construction for Asia-Pacific Region APFIS*, 2009.
- [25] D. Svecova, R.J. Eden. Flexural and shear Strengthening of timber beams using glass fibre reinforced polymer bars – an experimental investigation, *Can. J. Civil Eng.* 2004, 31(1): 45.
- [26] Rosato, D. V. *Designing with reinforced composites*: Hanser Gardner Publications, 1997.
- [27] Kaw, A. K.. *Mechanics of Composite Materials*. CRC Press LLC, Boca Raton, Florida, 2006.
- [28] Kaya, A.İ. A study of composite materials that produced from recovered fibers of recycled waste papers, Süleyman Demirel University, Fen Bilimleri Enstitüsü, (Doctoral Thesis), Isparta, 2015: 239.
- [29] H.F.Wu, D.W. Dwight, N.T.Huff. Effects of Silane Coupling Agents on the Interphase and Performance of Glass-Fiber-Reinforced Polymer Composites. *Composites Science & Technology*, 1997, 57: 975–983.
- [30] Çelik, A. Fiber reinforced polymers and application fields in the engineering structures, Master Thesis, Sakarya University, Adapazarı, 2001.
- [31] Plevris, N., Triantafyllou, T. C.. Creep behavior of FRP-reinforced wood members. *Journal of Structural Engineering*, 1995, 121(2): 174–186.
- [32] Ogawa H.. *Architectural application of carbon fibers, development of new carbon fiber reinforced glulam*, Toho R. Co. Ltd., Tokyo, Japan, 1999: 1–9.
- [33] Premrov, M., Dobrila, P., Bedenik, B. S.. Analysis of timberframed walls coated with CFRP strips strengthened fibre-plaster boards. Faculty of Civil Engineering, University of Maribor, Maribor, Slovenia, 2003, 1–12.
- [34] Steiger R.. *Fiber reinforced plastics (FRP) in timber structures*, Wood Department EMPA, Dübendorf, Switzerland, 2003: 1–9.
- [35] Roberto L. A., Michael A. P., Sandford T. C.. Fiber reinforced polymer composite - wood pile interface characterization by push-out tests. *Journal of Composites for Construction*, 2004, 8(4): 360–368.
- [36] Taheri, F., Nagaraj, M., Khosravi, P. Buckling response of glue-laminated columns reinforced with fiber-reinforced plastic sheets. *Compos. Struct.*, 2009, 88: 481–490.
- [37] O’Loinsigh, C., Oudjene, M., Shotton, E., Pizzi, A., Fanning, P. Mechanical behaviour and 3d stress analysis of multi-layered wooden beams made with welded-through wood dowels. *Compos. Struct.*, 2012, 94: 313–321.
- [38] Chans, D. O., Cimadevila, J. E., Gutiérrez, E. M. Withdrawal strength of threaded steel rods glued with epoxy in wood. *International Journal of Adhesion and Adhesives*, 2013, 44: 115–121.
- [39] Hay, S., Thiessen, K., Svecova, D., Bakht, B. Effectiveness of GFRP sheets for shear strengthening of timber. *J Compos Constr*, 2006, 10(6):483–491. DOI: 10.1061/(ASCE)1090-0268
- [40] D. Svecova, R.J. Eden. Flexural and shear Strengthening of timber beams using glass fibre reinforced polymer bars – an experimental investigation, *Can. J. Civil Eng.* 2004, 31(1): 45.
- [41] Andre. A. Benefits of strengthening timber with fiberreinforced polymers. PhD thesis, Chalmers University of Technology, Gothenburg, 2011.
- [42] Davalos, J.F., Qiao, P.Z. Fracture mechanics methods for interface bond evaluations of fiber-reinforced plastic / wood hybrid composites. In: Pizzi A, Mittal KL (eds) *Handbook of adhesive technology*, 2nd edn. Marcel Dekker Inc., New York, 2003: 351–377.
- [43] De Jesus, A.M.P., Pinto, J.M.T., Morais, J.J.L. Analysis of solid wood beams strengthened with CFRP laminates of distinct lengths. *Constr Build Mater*, 2012, 35:817–828. DOI: 10.1016/j.conbuildmat.2012.04.124
- [44] Juvandes, L.F.P., Barbosa, R.M.T. Bond analysis of timber structures strengthened with FRP Systems. *Strain*, 2012, 48(2): 124–135. DOI: 10.1111/j.1475-1305.2011.00804.x
- [45] Lopez-Anido, R.A., Muszynski, L., Gardner, D.J., Goodell, B., Herzog, B. Performance-based material evaluation of fiber-reinforced polymer-wood interfaces in reinforced glulam members. *J Test Eval*, 2005, 33(6): 385–394. DOI: 10.1520/JTE12071
- [46] Raftery, G.M., Harte, A.M., Rodd, P.D. Bonding of FRP materials to wood using thin epoxy gluelines. *Int J Adhes Adhes*, 2009, 29(5): 580–588. DOI: 10.1016/j.ijadhadh.2009.01.004
- [47] A. Zhou, Tam, L., Z. Yu, Lau, D. Effect of moisture on the mechanical properties of CFRP-wood composite: an experimental and atomistic investigation. *Compos Part B-Eng*, 2015, 71: 63–73. DOI: 10.1016/j.compositesb.2014.10.051
- [48] Lindyberg, R.F. A nonlinear, probabilistic model for the analysis of reinforced glulam beams in bending. [Unpublished D. Phil thesis]. Maine: University of Maine, 2000.

- [49] Romani, M., Blab, H. J. Design model for FRP Reinforced Glulam Beams. Proceedings of the International Council Forresearch and Innovation in Building and Construction, Venice, Italy, 2001.
- [50] Raftery, G. M., Harte, A. M. Nonlinear numerical modelling of FRP reinforced glued laminated timber. *Composites Part B: Engineering*, 2013, 52: 40-50.
- [51] Y. F. Li, Tsai, M. J., T. F. Wei, W. C. Wang. A study on wood beams strengthened by FRP composite materials. *Construction and Building Materials*, 2014, 62: 118-125.
- [52] H. Xiong, Y. Liu, Y. Yao, B. Li. Experimental study on the lateral resistance of reinforced glued-laminated timber post and beam structures. *Journal of Asian Architecture and Building Engineering*, 2017, 16(2): 379-385.
- [53] M. Wang, X. Song, X. Gu, J. Tang. Bolted glulam beam-column connections under different combinations of shear and bending. *Engineering Structures*, 2019, 181: 281-292.
- [54] Kılınçarslan, Ş., Şimşek Türker, Y.. The Effect of Strengthening With Fiber Reinforced Polymers on Strength Properties of Wood Beams. 2nd International Turkish World Engineering and Science Congress, Turkey, 2019.