

Michał Bakalarz  orcid.org/0000-0003-1906-2175
mbakalarz@tu.kielce.pl

Paweł Kossakowski  orcid.org/0000-0002-7827-4955
kossak@tu.kielce.pl

Kielce University of Technology, Faculty of Civil Engineering and Architecture,
Department of the Strength of Materials, Concrete Structures and Bridges, Kielce, Poland

THE FLEXURAL CAPACITY OF LAMINATED VENEER LUMBER BEAMS STRENGTHENED WITH AFRP AND GFRP SHEETS

NOŚNOŚĆ NA ZGINANIE BELEK Z FORNIRU KLEJONEGO WARSTWOWO WZMOCNIONYCH MATAMI AFRP I GFRP

Abstract

This paper presents the results of preliminary tests focused on the strengthening of laminated veneer lumber (LVL) beams with aramid fibre-reinforced polymer (AFRP) and glass fibre-reinforced polymer (GFRP) sheets. Edgewise bending tests were performed on elements through 4-point loading. The following two types of strengthening arrangements were investigated: sheets bonded to the bottom face along the entire length of the element, and a U-shaped half-wrapped type of reinforcement. The reinforcement ratios of the beams strengthened with GFRP sheets were 0.3% and 1.0% for the first and second strengthening arrangements, respectively; for the beams strengthened with AFRP sheets, these ratios were 0.2% and 0.64%, respectively. The experimental data revealed an increase in both the bending strength and the stiffness in bending of the strengthened elements. The failure mode was dependent upon the type of the strengthening configuration.

Keywords: LVL, fabrics, timber structures, aramid fibres, glass fibres, strengthening

Streszczenie

W artykule przedstawione zostały rezultaty badań belek z forniru klejonego warstwowo wzmocnionych tkaninami zbrojonymi włóknem aramidowym (AFRP) i szklanym (GFRP). Badania przeprowadzono na próbkach w układzie krawędziowym poddanych 4-punktowemu zginaniu. W badaniach wstępnych przyjęto dwie konfiguracje wzmocnienia: maty przyklejone do dolnej powierzchni elementów na całej długości i tzw. zbrojenie typu U doprowadzone do połowy wysokości przekroju poprzecznego. Stopień zbrojenia elementów wynosił 0.3% i 1.0% dla elementów zbrojonych matami GFRP oraz 0.2% i 0.64% dla belek zbrojonych matami aramidowymi. Wyniki badań wykazały wzrost wytrzymałości na zginanie i sztywności przy zginaniu. Postać zniszczenia zależna była od przyjętej konfiguracji wzmocnienia.

Słowa kluczowe: LVL, tkaniny, konstrukcje drewniane, włókna aramidowe, włókna szklane, wzmacnianie

1. Introduction

The mechanical properties of a wood depends upon the location of the analysed point (heterogeneity) and the orientation of the analysed sample relatively to the direction of the woodgrain [8]. Increasing the bending strength of the cross section by reinforcing the tensile zone using composite strips or sheets has been the subject of many scientific publications. This solution enables the utilisation of the compressive strength of the wooden structure in order to obtain greater ductility of the beams when subjected to bending forces. The first papers regarding the use of glass sheets in this way emerged in the 1960s [21]. Nowadays, a configuration is usually used in which the reinforcement is bonded between two lower lamellas or glued from the bottom of the element [7, 22]. In order to increase efficiency, traditional passive reinforcement of the structure can be replaced by active reinforcement, the key advantage of which is introducing the initial upward camber of the element [6].

Flexural reinforcement with pultruded FRP rods bonded in pre-cut grooves along the longitudinal axis of the beam is a well-known solution. Composite elements obtained in this way, in spite of slight interference in the original cross section, enable the reinforcement to be hidden inside the element's perimeter without increasing it; it also ensures that the adhesive layer is partially covered thus protecting it against external influences. Attempts to strengthen elements with the use of GFRP rods are presented in [5, 14, 23]. Phenomena relating to specific issues of this concept, such as anchoring reinforcement inserts, have also been the subject of research [1, 11, 16].

Unlike glued wood, the application of composite reinforcement for solid beams is related to repairing local damage [10] or restoring and improving the mechanical properties of utilised elements [4, 9] rather than obtaining new structural members. These tests were performed both for reinforcement in the passive state [11] and for prestressed elements [15].

In addition to composites reinforced with only one type of fibre, hybrids – a combination of at least two types of fibres – have also been used as the reinforcement of wooden structures [2, 3].

2. Materials and methodology

2.1. Laminated veneer lumber

The subjects of the experimental research were laminated veneer lumber beams with a cross section dimension of 45×100 mm and a length of 1,700 mm. Each beam consisted of 15 layers of 3-mm-thick veneer – wood fibres in every lamella were oriented in the longitudinal direction. Prior to the application of FRP sheets, the surface was ground and the edges were chamfered. Selected mechanical properties of the LVL beams are presented in Table 1.

Table 1. Selected parameters of the laminated veneer lumber beams [17]

Parameter	Edgewise properties
bending strength [N/mm ²]	44
shear strength [N/mm ²]	4.6
modulus of elasticity – E [N/mm ²]	14000
shear modulus – G [N/mm ²]	600
density [kg/m ³]	480

2.2. Composite fabrics

In the test, sheets reinforced with glass fibres (S&P G-Sheet E 90/10 B) and aramid fibres (S&P A-Sheet 120) were used as the reinforcement of LVL beams. The glass sheet is a bidirectional fabric with 90% of the fibres set along the main direction of the material and 10% in the transversal direction. The aramid sheet is a unidirectional fabric. Selected properties of used fabrics are presented in Table 2.

Table 2. Selected parameters of composite sheets [18, 19]

Parameter	Aramid sheets S&P A-Sheet 120 [290 g/m ²]	Glass sheets S&P G-Sheet E 90/10 B
modulus of elasticity [kN/mm ²]	≥ 120	≥ 73
tensile strength [N/mm ²]	≥ 2 900	≥ 3400
fibre weight [g/m ²]	290	800
weight per unit area of sheet [g/m ²]	320	880
density [g/cm ³]	1.45	2.60
elongation at failure [%]	2.5	4.5
design thickness [mm]	0.200	0.308

2.3. Adhesive

The reinforcement was bonded to the external faces of the elements by means of S&P Resin 55 HP epoxy resin. The hardener and epoxy resin was mixed with a low speed drill at the proportion of two to one by weight [20]. The prepared mixture was applied on the LVL beam surface and was also used to saturate sheet fabrics.

2.4. Methodology

The subject of the experimental tests were laminated veneer lumber beams strengthened with aramid and glass fabrics. The purpose of the research was analysis of the influence of the reinforcement on the behaviour of bending beams under static load. The scope of the research included preparing the following series of test elements:

- ▶ LVL series – reference beams;
- ▶ LVLA series – laminated veneer lumber beams strengthened with one layer of aramid sheet applied to the bottom face of the beam (reinforcement ratio 0.2%);
- ▶ LVLAU series – LVL beams strengthened with an aramid sheet bonded to both sides and the bottom face of the specimen (reinforcement ratio 0.64%);
- ▶ LVLG series – laminated veneer lumber beams strengthened with one layer of glass sheet applied to the bottom face of the beam (reinforcement ratio 0.3%);
- ▶ LVLGU series – beams strengthened with a glass sheet bonded to the soffit and both sides of the specimen – U type reinforcement (reinforcement ratio 1%).

The static tests were conducted in the Laboratory for the Strength of Materials of Kielce University of Technology in accordance with reports [15, 16]. The 4-point bending tests were performed using an MTS-322 universal hydraulic machine. The loading rate was set to 7 mm/min. The static scheme setup is illustrated in Fig. 1.

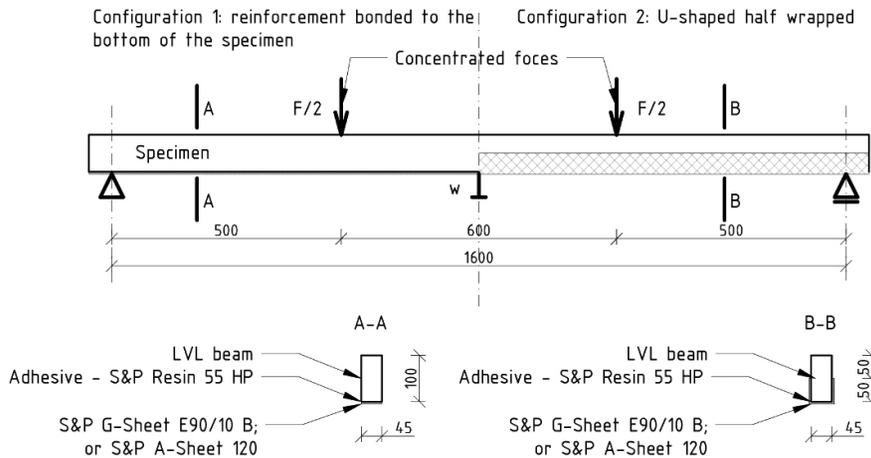


Fig. 1. Static scheme setup

The loading force, test time, actuator displacement and deflection in the centre of the beam were continuously measured during the tests. After the bending tests, the failure modes were recorded. In the next step, values of the bending strength and the global modulus of elasticity in bending were estimated on the basis of experimental data. The bending strength was determined from the following equation according to standard [12]:

$$f_m = \frac{3Fa}{bh^2} \quad (1)$$

where:

- a – distance between loading position and the nearest support axis [mm],
- F – loading force [N],
- b – width of the cross section [mm],
- h – height of cross section [mm].

In the next step, the determined values of bending strength from formula (1) were corrected to the reference width of the laminated veneer lumber elements (300 mm) by multiplying with the correction factor determined from the following equation given in standard [13]:

$$k_{m,corr} = \left(\frac{b}{300} \right)^s \quad (2)$$

where:

- s – shape parameter determined from the expression: $s = 2\nu - 0.05$,
- ν – coefficient of variation of the test results (0.15).

Global modulus of elasticity in bending was determined from the following expression [12]:

$$E_{m,g} = \frac{3al^2 - 4a^3}{2bh^3 \left(2 \frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh} \right)} \quad (3)$$

where:

- $F_2 - F_1$ – increment of load in the range 0.1 – 0.4 of maximum load [N],
- $w_2 - w_1$ – increment of deformation corresponding to the increment of load $F_2 - F_1$ mm,
- G – shear modulus (value adopted in accordance with the manufacturer data as 600 MPa).

3. Test results

3.1. Test results for the reference beams

Figure 2 shows the relationship between the loading force and the mid-span deflection for the reference elements. The behaviour is typical of unstrengthened beam-like specimens. The bending strength is limited by the tension strength of the elements.

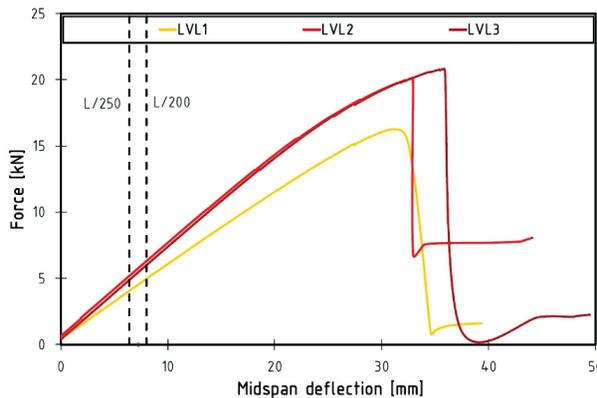


Fig. 2. Force-deflection curves for the reference beams

Figure 3 shows failure modes of the unstrengthened laminated veneer lumber beams. The crack occurred in the pure bending zone between the loading points (Fig. 3). The failure was caused by exceeding the tensile strength.



Fig. 3. Failure modes of reference beams

Table 3 provides the basic information concerning the results of the 4-point bending test for the reference elements including failure load, deflection at the point of failure load, time at which the loading force was reached as well as other identified parameters. In a similar manner, the results for the strengthened elements are presented.

Table 3. Test results for reference beams

Specimen	Failure load [kN]	Deflection [mm]	Time to failure [s]	Bending strength [MPa]	Modulus of elasticity [GPa]
LVL1	15.64	28.73	215	52.15 (39.62*)	11.20
LVL2	20.14	32.86	250	67.14 (51.01*)	14.09
LVL3	20.83	35.86	269	69.44 (52.76*)	14.08

* Values corrected to the reference height

3.2. Test results for the beams strengthened with glass sheets

The LVLG series is characterised by large disproportions in maximum loading force and behaviour during tests. The U-shaped reinforcement caused a significant increase in the the time taken to reach ultimate failure. After reaching the maximum bending strength, the force decreased several times (Fig. 4) before the bending test was ended.

Beams strengthened with the glass fabric sheet bonded to the bottom surface of the elements failed due to the loss of tensile strength of the LVL beam. The failure mode was initiated by fracture above the composite layer in the pure bending zone. The rupture of the fabric sheet or delamination was not recorded in this series. In the case of the LVLGU series, the failure was caused by exceeding the compressive strength of the LVL between the axis of the loading points. For these specimens, the crack was initiated at the top face of the elements. The crack then propagated in a downward direction causing rupture of the glass fabric and splitting of the veneer layers. The rupture of the fabric sheets occurred locally (Fig. 5).

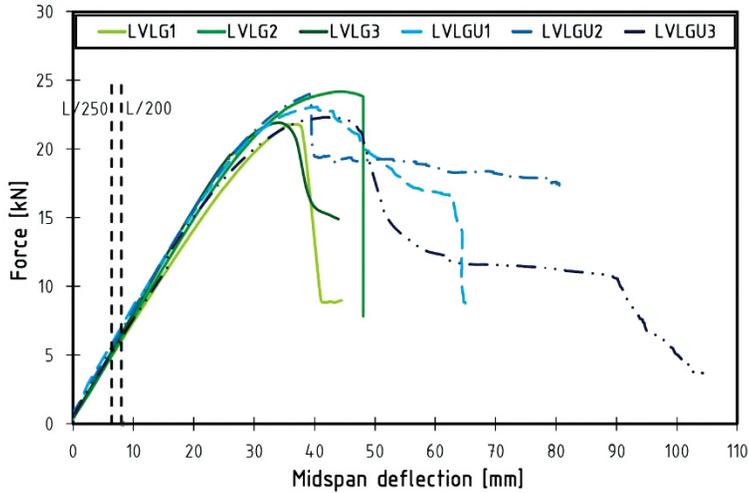


Fig. 4. Force-time curves for the beams strengthened with glass sheets



Fig. 5. Failure modes of specimens strengthened with glass sheets

Table 4. Test results for the beams strengthened with S&P G-Sheet glass sheets

Specimen	Failure load [kN]	Deflection [mm]	Time to failure [s]	Bending strength [MPa]	Modulus of elasticity [GPa]
LVLG1	21.80	35.66	263.7	72.66 (55.21*)	13.89
LVLG2	24.17	44.36	329.0	80.58 (61.23*)	15.10
LVLG3	21.92	34.14	252.9	73.07 (55.52*)	15.58
LVLGU1	23.05	40.48	320.0	76.83 (58.38*)	15.18
LVLGU2	23.99	39.18	299.9	79.98 (60.77*)	15.37
LVLGU3	22.31	41.96	319.5	74.38 (56.52*)	13.73

* Values corrected to the reference height

3.3. Test results for the beams strengthened with aramid sheets

Elements in the LVLA series behave in a similar manner as the reference elements under static load. The load versus deflection curves have a linear shape. For the U-shaped reinforcement, more ductile behaviour was observed for the visible plastic part of the load versus the deflection curves (Fig. 6).

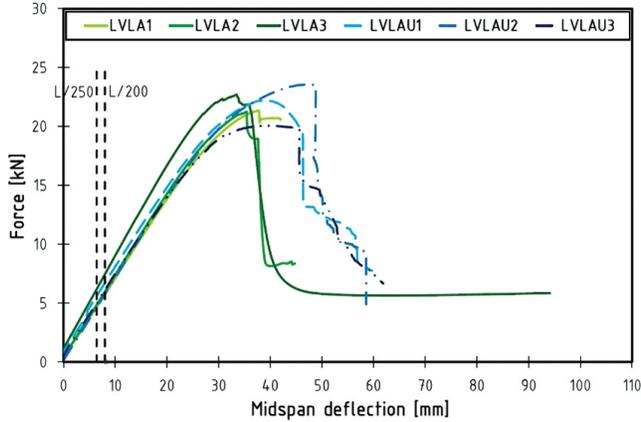


Fig. 6. Force-deflection curves for the beams strengthened with aramid sheets

Failure of the specimens of the LVLA series was caused by exceeding the load-carrying capacity in the tensile zone where the maximum bending moment occurred. Rupture of the aramid fibres was followed by the fracture of the laminated veneer lumber. Fracture propagated from the initiation point along the longitudinal axis of the beam. The exception is the LVLA1 beam for which the failure was caused by torsion of the element with a visible local indentation in the axis of the loading point. For the LVLAU series, failure of the elements was caused by exceeding the compressive strength of the engineering wood product as well as by the rupture of the AFRP sheet in a similar mode to the LVLGU series (Fig. 7).

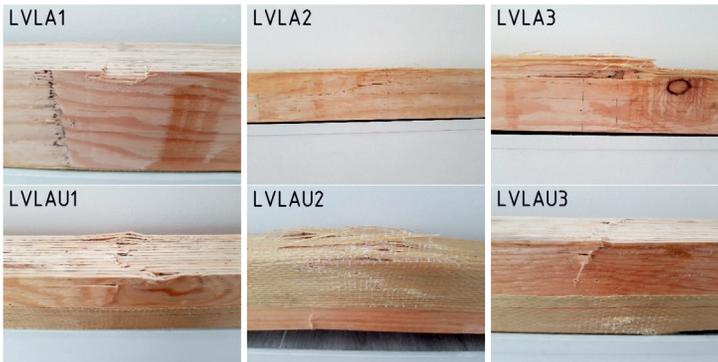


Fig. 7. Failure modes of specimens strengthened with aramid sheets

Table 5. Test results for the beams strengthened with S&P A-Sheet 120 aramid sheets

Specimen	Failure load [kN]	Deflection [mm]	Time to failure [s]	Bending strength [MPa]	Modulus of elasticity [GPa]
LVLA1	21.35	37.82	313.4	71.18 (54.08*)	13.58
LVLA2	21.28	35.46	259.4	70.92 (53.89*)	14.08
LVLA3	22.70	33.54	259.3	75.68 (57.50*)	16.05
LVLAU1	22.18	37.99	289.3	73.92 (56.17*)	14.66
LVLAU2	23.55	47.26	357.8	78.51 (59.66*)	14.21
LVLAU3	20.06	39.63	303.4	66.87 (50.81*)	13.73

* Values corrected to the reference height

3.4. Statistical analysis

Table 6 presents the results of the statistical analysis of the experimental tests data. In the group of elements strengthened with GFRP sheets, the average increase in bending strength was 20% for the reinforcement bonded to the bottom face and 22% for the U-shaped reinforcement. For the AFRP sheets, these values were 15 and 16%, respectively. The insignificant increase in bending stiffness for both analysed sheet types was recorded. Variation of the test results for the strengthened elements was lower in comparison to the reference elements.

Table 6. Statistical analysis of the test results

Series	Bending strength [MPa]			Modulus of elasticity in bending [GPa]		
	Arithmetic mean	Standard deviation	Coefficient of variation	Arithmetic mean	Standard deviation	Coefficient of variation
LVL	62.91 (47.80*)	7.67	0.12	13.12	1.17	0.10
LVLA	72.60 (55.16*) (+15%)	2.18	0.03	14.57 (+7%)	0.32	0.06
LVLAU	73.10 (55.54*) (+16%)	4.79	0.06	14.20 (+10%)	0.90	0.02
LVLG	75.44 (57.32*) (+20%)	3.64	0.05	14.86 (+12%)	0.60	0.04
LVLGU	77.06 (58.55*) (+22%)	2.29	0.03	13.56 14.76 (+12%)	0.62	0.04

* Values corrected to the reference height

4. Summary

The paper presents the results of the preliminary test of the laminated veneer lumber beams strengthened with composite fabrics. Aramid and glass sheets were used as reinforcement. Analysis of the static work of the specimens revealed the following:

- ▶ There was an increase in the bending strength of the strengthened elements in comparison to the reference beams; the average increase was 20% and 22% for the GFRP sheets, and 15% and 16% for the AFRP sheets for the fabrics bonded to the bottom face and the U-shaped reinforcement, respectively.
- ▶ The flexural stiffness of the strengthened specimens increased slightly for both configurations, regardless to the type of fibres used.
- ▶ In the case of the beams strengthened with the U-shaped reinforcement, the failure was due to the loss of the compressive strength of the LVL.

References

- [1] Adam M., Luhring A., Popp M., Fecht S., Vallee T., *Pre-applicable structural adhesives for timber engineering: Glued-in G-FRP rods*, International Journal of Adhesion & Adhesives 67/2016, 121-127. <http://dx.doi.org/10.1016/j.ijadhadh.2015.12.034> (access: 10.12.2018).
- [2] Brol J., *Wzmacnianie zginanych belek z drewna klejonego taśmami GARP na etapie produkcji*, Wiadomości konserwatorskie 26/2009, 345-353.
- [3] Brol J., Grygierek K., *Wzmacnianie zginanych belek z drewna klejonego taśmami GARP nie dochodzącymi do podpór*, 5th International Conference "New Trends on Statics and Dynamics of Buildings", Bratislava Slovakia, 19–20 October 2006, 51-54.
- [4] Fiorelli J., Dias A.A., *Analysis of the strength and stiffness of timber beams reinforced with carbon fiber and glass fiber*, Materials Research 6 (2)/2003, 193-202.
- [5] Gentile C., Svecova D., Saltzberg W., Rizkalla S.H., *Flexural strengthening of timber beams using GFRP*, Proceedings of Advanced Composite Materials in Bridges and Structures, August 2000, 637-644.
- [6] Guan Z.W., Rodd P.D., Pope D.J., *Study of glulam beams pre-stressed with pultruded GRP*, Computers and Structures 83/2005, 2476-2487.
- [7] Hallstrom S., Grenestedt J.L., *Failure analysis of laminated timber beams reinforced with glass fibre composites*, Wood Science and Technology 31/1997, 17-34.
- [8] Kossakowski P., *Influence of anisotropy on the energy release rate $G(i)$ for highly orthotropic materials*, Journal of Theoretical and Applied Mechanics 45/2007, 739-752.
- [9] Kossakowski P., *Load-bearing capacity of wooden beams reinforced with composite sheets*, Structure & Environment 3 (4)/2011, 14-22.
- [10] Madhoushi M., Ansell M.P., *Experimental study of static and fatigue strengths of pultruded GFRP rods bonded into LVL and glulam*, International Journal of Adhesion & Adhesives 24/2004, 319-325.

- [11] Morales-Conde M.J., Rodríguez-Liñán C., Rubio-de Hita P., *Bending and shear reinforcements for timber beams using GFRP plates*, Construction and Building Materials 96/2015, 461-472.
- [12] PN-EN 408+A1:2012 Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties.
- [13] PN-EN 14374:2005 Timber structures. Structural laminated veneer lumber. Requirements.
- [14] Raftery G.M., Harte A.M., *Repair of glulam beams using GFRP rods*, WIT Transactions on The Built Environment 109/2009, 417-427.
- [15] Sedivka P., Bomba J., Bohm M., Zeidler A., *Determination of strength characteristics of construction timber strengthened with carbon and glass fibre composite using a destructive method*, BioResources 10(3)/2015, 4674-4685.
- [16] Sena-Cruz J., Branco J., Jorge, M., Barros J. A.O., Silva C., Cunha V.M.C.F., *Bond behavior between glulam and GFRP's by pullout tests*, Composites Part B: Engineering 43(3)/2012, 1045-1055.
- [17] Steico, <https://www.steico.com/index.php?id=73&L=3> (access: 10.12.2018).
- [18] Technical data sheet S&P A-sheet, <http://www.sp-reinforcement.pl/pl-PL/produkty/maty/sp-sheet> (access: 10.12.2018).
- [19] Technical data sheet S&P G-Sheet E/AR90/10, <http://www.sp-reinforcement.pl/pl-PL/produkty/maty/sp-g-sheet-e-9010-sp-g-sheet-ar-9010-typ-b> (access: 10.12.2018).
- [20] Technical data sheet S&P Resin 55 HP, <http://www.sp-reinforcement.pl/pl-PL/produkty/zywica-epoksydowa/sp-resin-55-hp> (access: 10.12.2018).
- [21] Theakston F.H., *A feasibility study for strengthening timber beams with fibre glass*, Canadian Agricultural Engineering January 1965, 17–19.
- [22] Thorhallsson E.R., Hinriksson G.I., Snæbjorn J.T., *Strength and stiffness of glulam beams reinforced with glass and basalt fibres*, Composites Part B 2016, 1-8.
- [23] Yusof A., Saleh A.L., *Flexural strengthening of timber beams using glass fibre reinforced polymer*, Electronic Journal of Structural Engineering 10/2010, 48-56.

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