

# Analysis of the stiffness and load-bearing capacity of glued laminated timber beams reinforced with strands

**R Sardiko<sup>1,2</sup>, K Rocens<sup>1</sup>, J Iejava<sup>2</sup>, V Jakovlevs<sup>2</sup> and K Ziverts<sup>3</sup>**

<sup>1</sup> Riga Technical University, Faculty of Building and Civil Engineering, Kalku Str. 1, Riga, LV-1658, Latvia

<sup>2</sup> Meža un koksnes produktu pētniecības un attīstības institūts Ltd., Dobeles Str. 41, Jelgava, LV-3001, Latvia

<sup>3</sup> Marko KEA Ltd., Līci, Stopiņu reģions, LV-2118, Latvia

E-mail: romans.sardiko@edu.rtu.lv

**Abstract.** In this paper a benefit of glulam pinewood beams reinforced strands is discussed. In the first phase, series of pull-out tests were performed on specimens made up of different types of glue (melamine-urea-formaldehyde, epoxy and others) to detect pull-out force and failure mode of a specimens. In the second phase, series of equal cross-section glulam beams with strand and rod reinforcement were theoretically analysed using transformed cross-section method. Additionally, series of experimental testing were made. Benefits of strand reinforcement use as glulam beams' reinforcement were identified and examined the possibility of one glue type application in all operations of reinforced glulam beams manufacturing.

## 1. Introduction

Timber beams have relatively lower stiffness in bending, leading to a larger deflection in comparison with the same cross-section steel or reinforced concrete beams. The use of reinforcement has become a common method to increase stiffness and load-bearing capacity of glued laminated timber beams. The strengthening effects are achieved by inserting rods or a different type of reinforcement into glulam beams.

Steel reinforcement is one of the most popular reinforcing materials for timber beams. Metallic reinforcement includes bars, plates, and stirrups [1-4]. Steel is wide used as a material for metallic reinforcement. Sometimes as reinforcement high strength steel tendons are used [5]. Steel reinforcement for timber beams appears to be structurally efficient and cost-effective [3].

At present modified melamine-urea-formaldehyde (MUF) resins are commonly used in glulam industry for timber bonding [6], because of low price and high strength and durability in long-term loading. Traditionally, steel reinforcement is glued in timber with epoxy resins. The main disadvantages of the use of epoxy resins are high-cost price of an end product and the impossibility of using standard technological tools for the processing of glulam beams after gluing. It is assumed that the use of melamine-urea-formaldehyde glue for steel reinforcement gluing in timber will avoid the main disadvantages of using epoxy glue.

This paper goals are to detect benefits of strands use as glulam beams' reinforcement and to examine the possibility of one glue type application in all operations of reinforced glulam beams manufacturing.



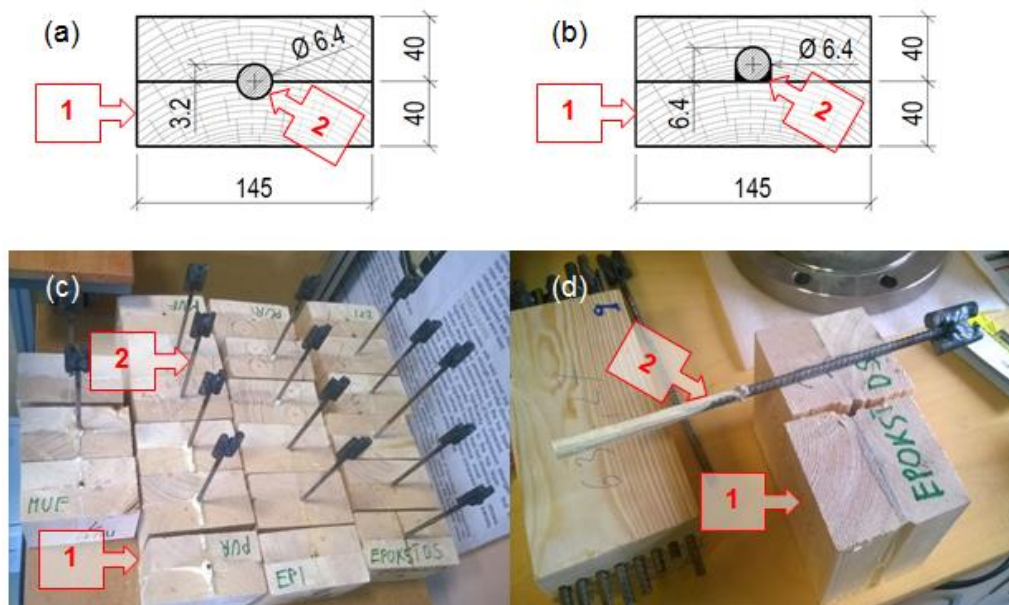
## 2. Definition of glue type

Full-scale program of steel reinforcement glued in timber was conducted for hardwood and softwood and different glue types [7,8]. However, there're no data about use of MUF resins for reinforcement gluing in timber. To detect MUF glue behavior in a steel-timber interface and pull-out force, series of experimental testing were made before execution of the theoretical studies of beams with strand reinforcement.

### 2.1. Specimens

Two types of specimens were manufactured: with double-faced groove and one-faced groove. The dimensions of the timber part of the sample were  $b \times d \times h = 100 \times 80 \times 145$  mm and it consisted of two glued together solid timber parts. Reinforcement with 6.4 mm gross diameter was glued-in timber for 100 mm. Reinforcement was guided parallel to timber grain direction and glue thickness was about 1.0 mm. Specimens are shown in figure 1.

Four types of glue were used for specimens' producing: two-component melamine-urea-formaldehyde (CASCO ADHESIVES 1257/7557 (200:100)), one-component polyurethane (PUR; PURBOND S159), two-component polymer isocyanate (EPI; KESTOKOL WR 125 with KOVETE M (100:15)) and two-component epoxy (EPO; SICADUR 31 CF (300:100)) adhesives. In addition, the specimen was made without glue – cohesion between the reinforcement and the timber is transferred only by friction. For each type of glue, taking into account the groove type, 3 specimens were made. A total of 27 specimens were manufactured tested.



**Figure 1.** Specimen (a) with double-faced groove and (b) with one-faced groove, (c) specimens prepared for pull-out test, (d) failure of specimen with EPO glue after testing: 1 – timber parts, 2 – reinforcement.

### 2.2. Pull-out testing and results

Pull-out tests were performed by using Universal Testing Machine Zwick Z100 (UTM). Specimens were placed in the testing machine so that the top surface of the timber part was in contact with the rigid support frame and the end of the rebar was held by jaws of testing machine. The fixing of a specimen in the UTM precluded the possibility of eccentricities and their effect on the results. A rate of 2 mm/min was chosen and pull-out load was continuously applied to the rebar up to failure. The pull-out force  $F_{\max}$  was automatically recorded through a data logger.

The pull-out test results showed significant difference between maximal average pull-out force  $F_{\text{mean}}$  for double-faced and one-faced grooves (table 1). Specimens with double-faced groove shown from 7.0 % (EPO) till 61.7 % (MUF) greater pull-out force. All tested specimens collapsed by glue interface, except specimens with epoxy glue. For specimens with MUF glue, the pull-out force  $F_{\text{mean}}$  is 59 % of the pull-out force for specimens with EPO glue, which is better than for samples with EPI glue (47 %) and worse than for samples with PUR glue (64 %). The coefficient of variation for specimens with MUF glue was 13.0 %. In general, MUF and PUR glue results were comparable and for further theoretical and experimental part of work, it was assumed to use MUF glue along with a double-faced groove.

**Table 1.** Pull-out test results.

	F <sub>max</sub> (N)			F <sub>mean</sub> (N)	Stand. deviation (N)	Coef. of variation (%)	Percentage of use from EPO (%)	Failure mode by
	1 specimen	2 specimen	3 specimen					
specimens with double-faced groove								
MUF	4321	5575	4762	4886	636	13,0	59	glue
PUR	6507	4603	4746	5285	1060	20,1	64	glue
EPI	3817	3806	4124	3916	180	4,6	47	glue
EPO	7885	8384	8487	8252	322	3,9	100	timber
without glue	653	1122	619	798	282	35,0	10	-
specimens with one-faced groove								
MUF	1966	1577	2052	1865	253	13,6	23	glue
PUR	3598	3159	2125	3294	264	8,0	41	glue
EPI	1551	1564	2634	1916	622	32,4	24	glue
EPO	8704	7454	7766	7975	651	8,2	100	timber

### 3. Analytical studies

#### 3.1. Study object

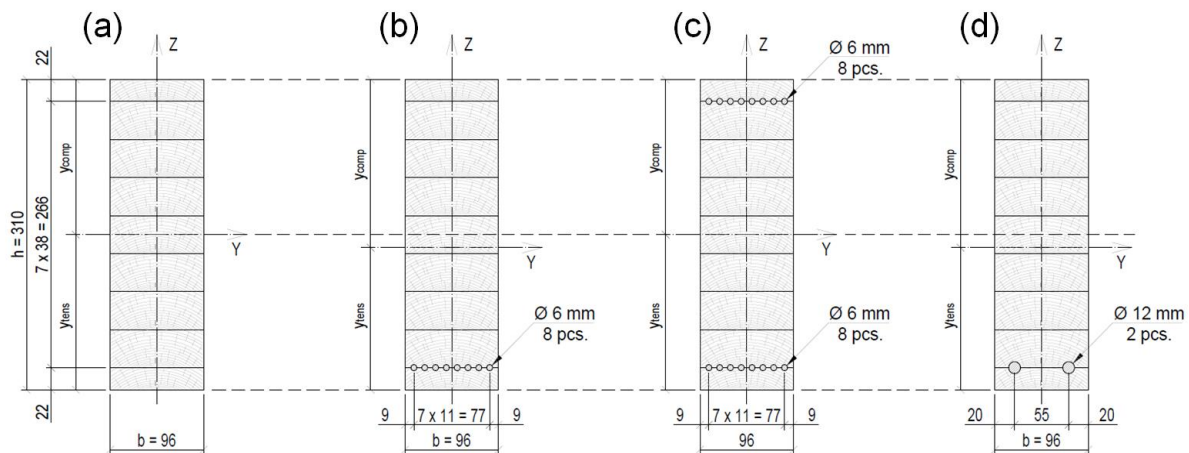
Study object was reinforced glulam beams with different reinforcement types, reinforcement arrangements and also reinforcement ratios. In total 5 beam types were studied: one of the beams was unreinforced, three beams were with strand reinforcement and one with rod reinforcement. Description of the cross-section of the studied beams is shown in table 2.

**Table 2.** Description of the cross-sections of the studied beams.

Name	Cross-section $h \times b$ (mm)	Reinforcement			
		type	$\varnothing$ (mm)	amount (pcs.)	notes
Glulam1	$310 \times 96$	without	-	-	(reference beam)
Glulam2	$310 \times 96$	bottom	6	8	-
Glulam3	$310 \times 96$	bottom	6	8	(with end fixation) <sup>a</sup>
Glulam4	$310 \times 96$	top and bottom	6	$2 \times 8$	(with end fixation) <sup>a</sup>
Glulam5	$310 \times 96$	bottom	12	2	-

<sup>a</sup> End fixation means, that reinforcement is fixed at both beam ends with metal anchor plates.

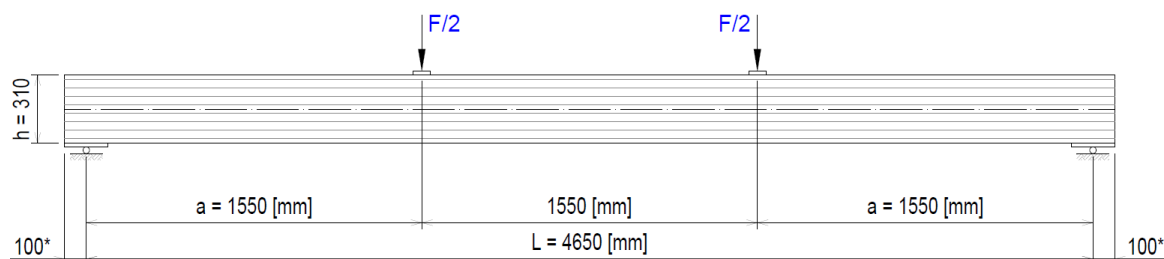
Cross-sections of the studied beams accepted  $h \times b = 310 \times 96$  mm. Each cross-section was composed of 9 laminates of Norway spruce. Thickness of side laminates accepted 22 mm, for internal – 38 mm. Reinforcement diameters  $R$  accepted 6 and 12 mm. Cross-sections sections of the studied beams are shown in figure 2.



**Figure 2.** Cross-sections of the studied beams: (a) Glulam1, (b) Glulam2 and Glulam3, (c) Glulam4, (d) Glulam5.

### 3.2. Static scheme of beams

The static scheme of the beams conformed to 4-points bending test and accepted in accordance with LVS EN 408 [9]. Studied beam's geometric and load application scheme is shown in the figure 3. The span in bending was 4650 mm. The distance between the load application point and the nearest support was accepted to be equal to 1550 mm.



**Figure 3.** Beam's geometric and load application scheme.

### 3.3. Materials

Although it is better to determine used material properties from small scale experiments, in this paper properties of the used materials were adopted on the basis of standards, since the main goal is to test the idea of using strand reinforcement and one glue type as a whole.

All timber laminates were with the same minimal strength class C24 in accordance with LVS EN 338 [10]. Adopted properties were: mean modulus of elasticity parallel to grain direction  $E_{0,mean} = 11000$  MPa, mean modulus of elasticity perpendicular to grain direction 370 MPa, primary Poisson's ratio 0.5, secondary Poisson's ratio 0.02, mean shear modulus 690 MPa, density  $350 \text{ kg/m}^3$ .

As beam's reinforcement steel bars with strength class B500B in accordance with LVS EN 10080 [11] were adopted. Following reinforcing steel properties were assumed: characteristic yield strength 500 MPa, elastic modulus  $E_r = 210000$  MPa, Poisson's ratio 0.3, density  $7850 \text{ kg/m}^3$ .

### 3.4. Analytical model

An analytical model was used to predict stiffness and normal stresses on outer tensioned and compressed fibers of the cross-section of the beams. The theoretical model was based on transformed cross-section method. Section was transformed on timber material, converting reinforcement cross-section width while height remained unchanged.

### 3.4.1. Determination of the transformed cross-section parameters

Transformation ratio was determined by equation (1):

$$n_{red} = \frac{E_r}{E_{0,mean}} = \frac{210000}{11000} = 19.091 \quad (1)$$

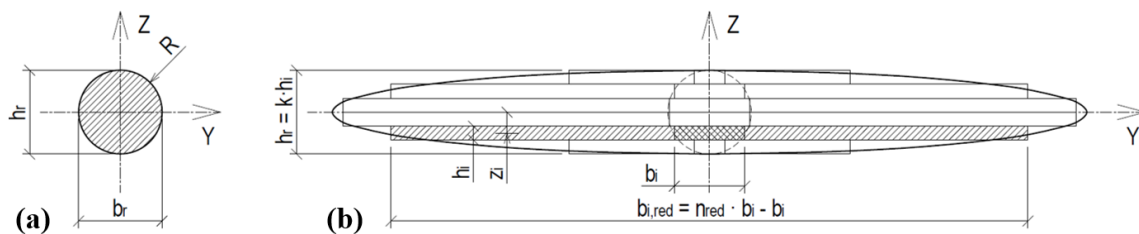
Single rebar's transformed cross-section second moment of area  $I_{r,y,red}$  and cross-section area  $A_{r,red}$  determined using equations (2) ÷ (4).

$$I_{r,y,red} = \sum_{i=1}^k \left[ \frac{b_{i,red} \cdot h_i^3}{12} + z_i^2 \cdot (b_{i,red} \cdot h_i) \right] \quad (2)$$

$$A_{r,red} = \sum_{i=1}^k [b_{i,red} \cdot h_i] \quad (3)$$

$$b_{i,red} = b_i (n_{red} - 1) = \left( \sqrt{R^2 - (z_i + 0,5h_i)^2} + \sqrt{R^2 - (z_i - 0,5h_i)^2} \right) \cdot (n_{red} - 1) \quad (4)$$

where  $h_i$ ,  $z_i$ ,  $b_{i,red}$  and  $R$  are dimensional parameters of the transformed cross-section of single rebar, which is shown in figure 4.



**Figure 4.** Real (a) and transformed cross-sections (b) of the single rebar with dimensional parameters.

Optimum accuracy of the single rebar's parameters was achieved by dividing the height of the rebar into elementary sections with height  $h_i = 0,05$  mm.

In-general, studied beam's neutral axis position  $y_{tens}$  (counting from outer tensioned fibers) determined by equation (5):

$$y_{tens} = \frac{n_{rc} \cdot (A_{rc} \cdot (h - h_{rc})) + n_{rt} \cdot (A_{rt} \cdot h_{rt}) + 0,5 \cdot b h^2}{n_{rc} \cdot A_{rc} + n_{rt} \cdot A_{rt} + b h} \quad (5)$$

where  $n_{rc}$ ,  $n_{rt}$  are amount of compressed and tensioned reinforcement bars in cross-section,  $A_{rc}$  and  $A_{rt}$  – single compressed and tensioned rebar area of the cross-section,  $h_{rc}$  and  $h_{rt}$  – rebar embedment into cross-section for compressed and tensioned reinforcement bars. Beam's neutral axis position, counting from outer compressed fibers, is  $y_{comp} = h - y_{tens}$ .

Studied beams' transformed cross-section area  $A_{red}$  was determined by equation (6), second moment of area  $I_{y,red}$  by equation (7) and section modulus for compressed  $S_{y,red,c}$  and tensioned  $S_{y,red,t}$  zones by equations (8) and (9).

$$A_{red} = n_{rc} \cdot A_{rc} + n_{rt} \cdot A_{rt} + b h \quad (6)$$

$$I_{y,red} = n_{rc} (I_{r,y,red} + (h - y_{tens} - h_{rc})^2 \cdot A_{rc}) + n_{rt} (I_{r,y,red} + (y_{tens} - h_{rt})^2 \cdot A_{rt}) + \left( \frac{b h^3}{12} + (0,5h - y_{tens})^2 b h \right) \quad (7)$$

$$S_{y,red,c} = \frac{I_{y,red}}{y_{comp}} \quad (8)$$

$$S_{y,red,t} = \frac{I_{y,red}}{y_{tens}} \quad (9)$$

Transformed cross-sections parameters for each reinforced beam type and un-reinforced beam are shown in table 3.



**Table 3.** Cross-section parameters of the studied beams.

Name	Reinforcement ratio (%)	Parameters				
		$A_{red}$ (mm <sup>4</sup> )	$I_{y,red}$ (mm <sup>4</sup> )	$S_{y,red,t}$ (mm <sup>3</sup> )	$S_{y,red,c}$ (mm <sup>3</sup> )	$y_{tens} / y_{comp}$ (mm/mm)
Glulam1	-	$2.976 \times 10^4$	$2.383 \times 10^8$	$1.538 \times 10^6$	$1.538 \times 10^6$	155 / 155
Glulam2 <sup>a</sup>	0.76	$3.385 \times 10^4$	$3.019 \times 10^8$	$2.173 \times 10^6$	$1.765 \times 10^6$	138.9 / 171.1
Glulam3 <sup>a</sup>	0.76	$3.385 \times 10^4$	$3.019 \times 10^8$	$2.173 \times 10^6$	$1.765 \times 10^6$	138.9 / 171.1
Glulam4 <sup>a</sup>	1.52	$3.794 \times 10^4$	$3.830 \times 10^8$	$2.471 \times 10^6$	$2.471 \times 10^6$	155 / 155
Glulam5 <sup>a</sup>	0.76	$3.385 \times 10^4$	$3.020 \times 10^8$	$2.174 \times 10^6$	$1.765 \times 10^6$	138.9 / 171.1

<sup>a</sup> Parameters are given for transformed cross-section (base material timber).

### 3.4.2. Analytical global deflection

Theoretical vertical displacement  $w$  at mid-span of the beam calculated by equation (10):

$$w = \frac{F \cdot a}{48 \cdot E_{0,mean} \cdot I_{y,red}} (3L^2 - 4a^2) \quad (10)$$

where  $F$  is total applied force.

### 3.4.3. Theoretical normal stresses

In general, normal stresses  $\sigma$  on outer tensioned and compressed fibers of the cross-section at mid-span of the beam calculated by equation (11):

$$\sigma = \frac{Fa}{2S_{y,red}} \quad (11)$$

where  $S_{y,red}$  is section modulus of the transformed cross-section, that is equal to  $S_{y,red,t}$  for tensioned fibers and to  $S_{y,red,c}$  for compressed fibers.

## 4. Experimental studies

### 4.1. Manufacturing of the beams

For experimental testing 4 beam types were produced – Glulam1, Glulam2, Glulam3 and Glulam4.

According to pull-out tests better conjunction between reinforcement strand and laminate achieved by double-faced grooves. Grooves were made in laminates with a specially manufactured milling cutter (figure 5, 6). Milling cutter consisted of eight parallel fixed cutter blades with appropriate width and separation, to ensure simultaneous milling for all grooves. Separate cutter blade thickness is equal to reinforcement rod diameter (6 mm) and blades shape is semicircle (figure 7).



**Figure 5.** Specimen with double-faced groove.



**Figure 6.** Reinforcement gluing-in process.



**Figure 7.** The milling cutter for groove milling.



**Figure 8.** Specimen pressing and curing.

At the first stage of the beams manufacturing, separate laminate pairs that contained reinforcement and internal core laminates were singly pressed and cured. MUF adhesive was used, that is specified for wood laminations gluing in factories. After adhesive was dried, all parts were glued and pressed together (figure 8). After beams were pressed and cured for 24 hours, experimental testing of the beams was executed.

#### 4.2. Bending tests

Bending test was executed in accordance with LVS EN 408 [9]. During the test failure load  $F_{ultimate}$  was reached and all specimens were crushed. Testing was performed on INSTRON SATEC 600 KN press with loading speed 5 kN/min.

Theoretical measuring instrument arrangement is shown in figure 9(a, b) and in-situ in figure 9(c). One global deflection meter (I-3) and two local average deflection meters (I-1, I-2) were applied. Additionally, two hand-made tensometers (T-1, T-2) were applied for outer tensioned and compressed fibers deformation detection at beams midspan. Tensometers base was applied 1000 mm and theoretical precision was 0.001 mm.

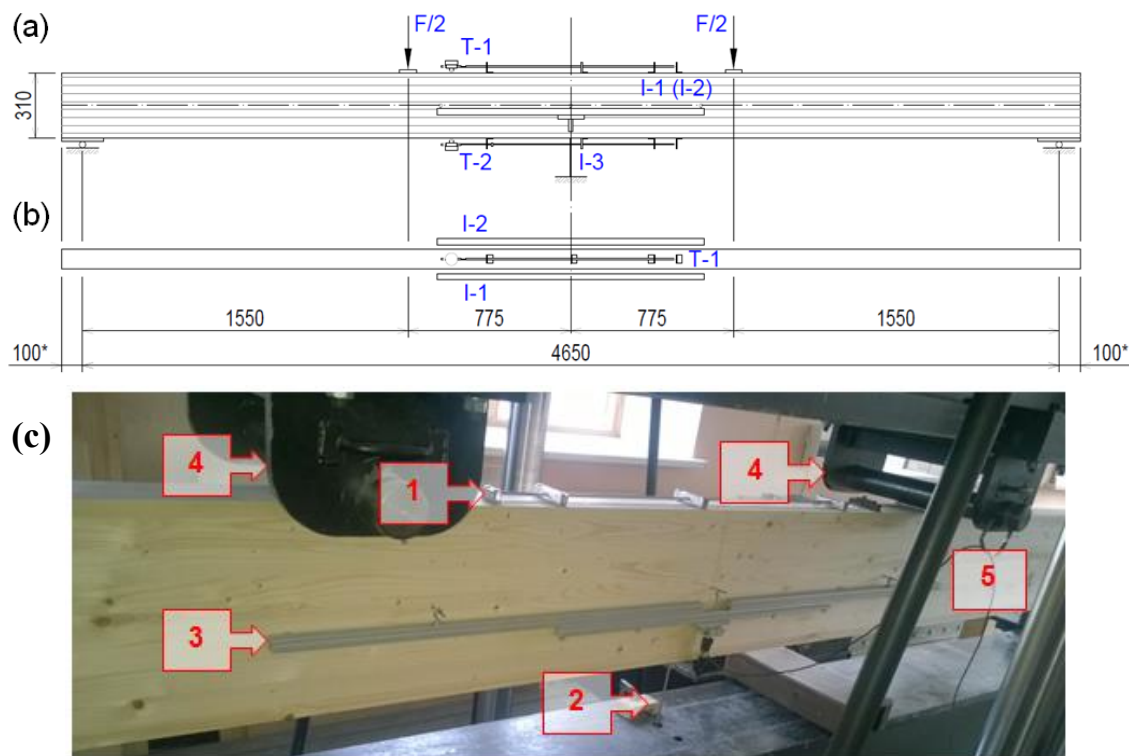
The measurement of the normal stresses and deflections was provided until the moment when normal stresses reached the design bending strength of glulam beams  $f_{m,d}$ . The design bending strength was accepted in accordance with LVS EN 1995-1-1 [12] for ultimate limit state for the following parameters: service class 2, modification factor for medium-term loads  $k_{mod} = 0.8$ , material factor for glulam  $\gamma_M = 1.25$  and cross-section depth increase factor  $k_h = 1.0$ .

### 5. Results and discussions

Based on bending test results, following parameters were determined: experimental global modulus of elasticity in bending  $E_{m,g}$  (by [4] equation (2)), normal stresses for outer tensioned and compressed fibers, the change in the position of the neutral axis along the height of a cross-section during loading. All results were compared with theoretical results.

With the developments of bending tests, the applied load versus global deflection curves (figure 10(a)) plotted. For each beam experimental global modulus of elasticity and stiffness was calculated (table 4). Experimental deflection for Glulam4 good correspond to theoretical values – maximal difference is lower than 3.5%. Glulam2 was for 11.5% stiffer than theoretically calculated and Glulam3 for 3.9%. However, theoretically, deflection values for Glulam2 and Glulam3 have to be equal. A difference in values can be explained by difference in experimental global elastic modulus, which can be caused by a difference in timber lamellas properties. Maximal difference was observed for Glulam1 – experimentally it was for 16.7% stiffer.

All tested reinforced beams showed stiffness increase in comparison with unreinforced Glulam1 beam. For Glulam4 theoretical stiffness increment was 117.9% and experimental 60.7%. For Glulam2 and Glulam3 theoretical stiffness increment was 26.7% and experimental – 56.2% and 39.1%.



**Figure 9.** Measuring instrument arrangement on specimen: theoretical (a) side view and (b) top view, (c) in-situ: 1 - tensometer (T-1, T-2), 2 - global deflection meter (I-3), 3 - local average deflection meter (I-1, I-2), 4 - load applying point, 5 - specimen.

**Table 4.** Summary of theoretical and experimental results of stiffness and load-bearing capacity.

Name	Reinf. ratio (%)	$E_{0,mean}$ (MPa)	$E_{0,mean} \times I_{y,red}$ (Nmm <sup>2</sup> )	Increase (%) from Glulam1	$E_{m,g}$ (MPa)	$E_{m,g} \times I_{y,red}$ (Nmm <sup>2</sup> )	Increase (%) from Glulam1	$F_{ultimate}$ (kN)
Glulam1	-	11000	$2.622 \times 10^{12}$	0.0	12478	$2.974 \times 10^{12}$	0	79.4
Glulam2	0.76	11000	$3.321 \times 10^{12}$	26.7	12145	$4.646 \times 10^{12}$	56.2	105.9
Glulam3	0.76	11000	$3.321 \times 10^{12}$	26.7	10814	$4.137 \times 10^{12}$	39.1	108.7
Glulam4	1.52	11000	$4.213 \times 10^{12}$	60.7	10529	$6.481 \times 10^{12}$	117.9	115.2
Glulam5	0.76	11000	$3.322 \times 10^{12}$	26.7	-	-	-	-

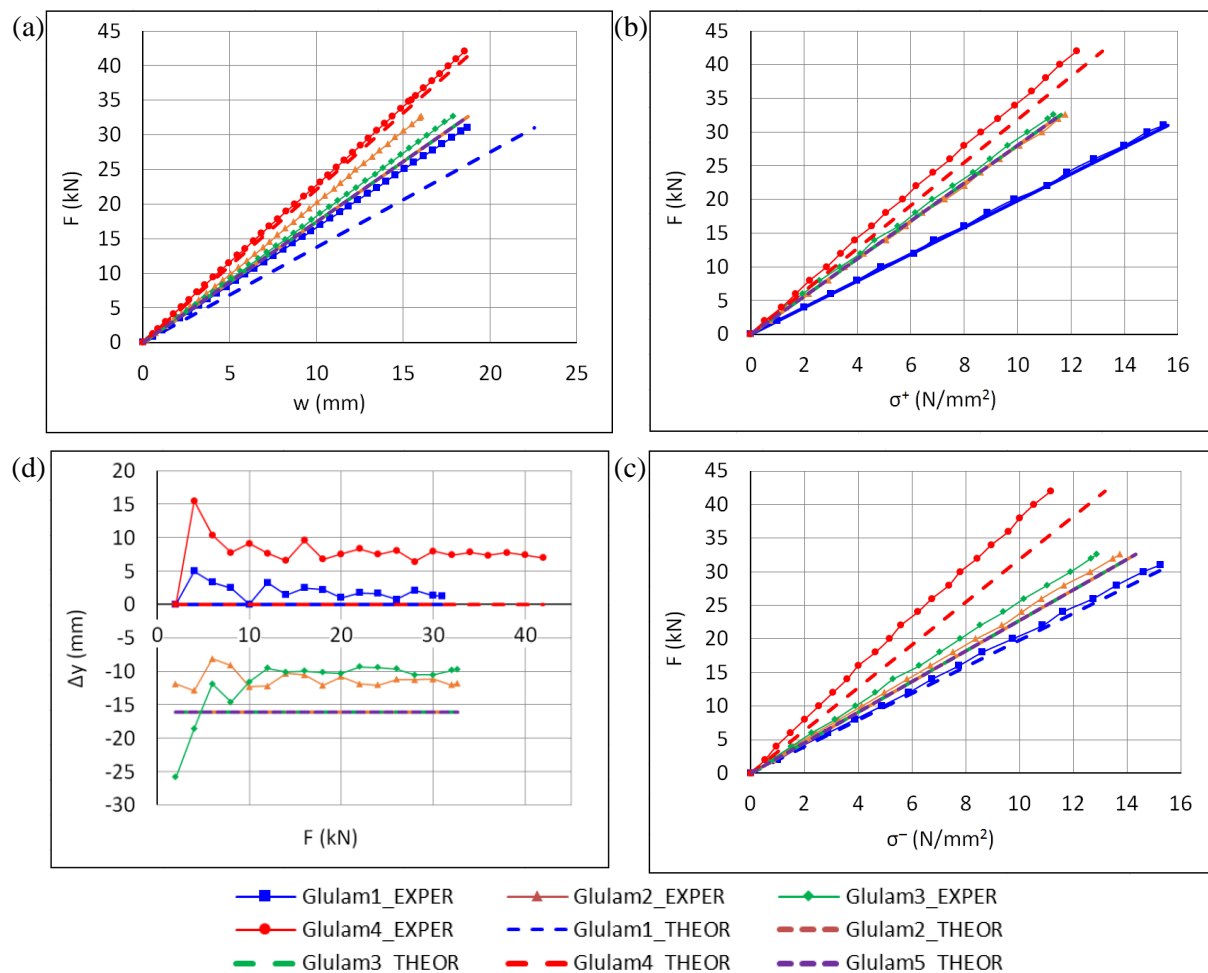
The difference in stiffness theoretical results for Glulam2, Glulam3 and Glulam5 was only 1.0%. It means that strand reinforcement using in glulam are equivalent to rod reinforcement. However, looking from glue cohesion point of view, strand reinforcement provide larger gluing cross-section perimeter in comparison with rod reinforcement. For example,  $2 \times 12$  mm rods and  $8 \times 6$  mm strands have equal cross-section area, but strand reinforcement has up to 2 times longer gluing cross-section perimeter. It means that, for beams with strand reinforcement, normal stresses are distributed more evenly by cross-section width. Besides that, larger gluing perimeter provides better cohesion between timber lamellas and steel reinforcement.

Applied load  $F$  versus normal stress  $\sigma$  on outer cross-section fibers curves plotted. For tension zone stresses figure 10(b) and compression – figure 10(c). For all experimentally tested beams, stress level on outer cross-section fibers was lower than theoretically determined. For example, for Glulam1 decrease was up to 3.7%, Glulam2 – 5.2%, Glulam3 – 11.5% and Glulam4 – 18.0%. Results showed



that modified cross-section method provides increased values for normal stress on outer cross-section fibers and in further studies have to investigate this aspect more detailed.

Neutral axis displacement  $\Delta y$  and applied load  $F$  curves were plotted (figure 10(d)). Experimental data between experimental points obtained by connecting experimental points with straight lines. Experimental neutral axis displacement for Glulam1 conform to theoretical results, mean difference was up to 2.0 mm. Neutral axis displacement for Glulam2 and Glulam3 is for 5 mm or 30% smaller than showed theoretical results. Against theoretical predicted, neutral axis position for Glulam4 moved up for 7.0 mm. This can be explained by insufficient work of tensioned zone reinforcement, by difference of the timber laminate properties or local hidden defect of the tested specimen. To determine true nature of the difference, it is necessary to investigate this aspect more detailed.



**Figure 10.** Graphical interpretation of results: (a) applied load  $F$  and global deflection  $w$  at midspan curves, (b) applied load  $F$  and normal stress  $\sigma^+$  on outer tensioned cross-section fibers curves, (c) applied load  $F$  and normal stress  $\sigma^-$  on outer compressed cross-section fibers curves and (d) neutral axis displacement  $\Delta y$  and applied load  $F$  curves.

Maximal ultimate load  $F_{ultimate}$  equal to 115.2 kN was for a beam with top and bottom strand reinforcement (Glulam4) and reinforcement ratio 1.52%. For beams with bottom strand reinforcement (Glulam2, Glulam3) and reinforcement ratio 0.76 ultimate load was 105.9 and 108.7 kN. For unreinforced beam (Glulam1) maximal ultimate load was by 25% lower than for reinforced beams.

Unexamined questions remained about strand reinforcement anchoring length, delamination problem and its prevention possibilities, FEM modelling and others. All these unexamined questions and the full-scale testing program will be provided in further studies.

## 6. Conclusions

Based on theoretical studies and analyses experimental testing of bending tests results, following conclusions were made:

- Stiffness increase for a beam with top and bottom reinforcement (Glulam4) and reinforcement ratio 1.52% was 60.7% (theoretically) and 117.9% (experimentally).
- Stiffness increase for beams with bottom reinforcement (Glulam2, Glulam3 and Glulam5) and reinforcement ratio 0.72% was 26.7% (theoretically) and 39.1÷56.2% (experimentally).
- Difference in theoretical stiffness for strand reinforced beams (Glulam2, Glulam3) and rod reinforced beam (Glulam5) was only 1.0%. However, strand reinforcement provides larger gluing cross-section perimeter in comparison with rod reinforcement.
- Results showed that transformed cross-section method provides increased values for normal stress on outer cross-section fibers in comparison with experimental testing results.
- Maximal ultimate load  $F_{ultimate}$  equal to 115.2 kN was for a beam with top and bottom strand reinforcement (Glulam4) and reinforcement ratio 1.52%. For beams with bottom strand reinforcement (Glulam2, Glulam3) and reinforcement ratio 0.76 ultimate load was 105.9 and 108.7 kN. For unreinforced beam (Glulam1) maximal ultimate load was by 25% lower than for reinforced beams.
- It is possible to use MUF glue as one type glue for application in all operations of reinforced glulam beams manufacturing.
- For reinforcement gluing with MUF glue it is useful to use two-sided groove instead of one-sided groove in accordance with pull-out test results.

## 7. Acknowledgements

The experimental part of this research was carried out within the project “Technology validation of the latest bonding and decorative, protective treatment for high value-added wood products production”, Central Finance and Contracting Agency (CFCA), project No. 1.2.1.1/16/A/009 co-financed by the European Union within the Project framework of the European Regional Development Fund.

This research work theoretical part carried out within the Latvia state research program under grant agreement “Innovative Materials and Smart Technologies for Environmental Safety, IMATEH”.

## References

- [1] Bulleit W M, Sandberg L B and Woods G J 1989 *Journal of Structural Engineering* Steel-reinforced glued laminated timber **115** (2) 433–44
- [2] Huifeng Yang, Weiqing Liu, Weidong Lu, Shijun Zhu and Qifan Geng 2016 *Construction and Building Materials* Flexural behavior of FRP and steel reinforced glulam beams: Experimental and theoretical evaluation **106** 550-63
- [3] Soriano J, Pellis B P and Mascia N T 2016 *Composite Structures* Mechanical performance of glued-laminated timber beams symmetrically reinforced with steel bars **150** 200-07
- [4] Nowak T, Jasienko J, Kotvica E and Krzosek S 2016 *Drewno* Strength enhancement of timber beams using steel plates – review and experimental tests **59** (196) 75-90
- [5] McConnell E, McPolin D and Taylor S 2014 *Construction and Building Materials* Post-tensioning of glulam timber with steel tendons **73** 426-33
- [6] Kajaks J and Kolbins A 2014 *Material Science and Applied Chemistry* The Study of the Adhesive Activity and Modification Possibilities of Melamine-Urea-Formaldehyde (MUF), Urea-Formaldehyde (UF) Resins **2014/30** 35-38
- [7] Vallee T, Bletz-Muhldorfer O, Myslicki S, Grunwald C, Walther F and Bathon L 2016 *WCTE 2016 e-book* Glued-in rods in hardwood and hardwood laminated veneer lumber – report on

- a large experimental campaign 643-651 (ISBN 978-3-903024-35-9)
- [8] Zhibin Ling, Huifeng Yang, Weiqing Liu, Weidong Lu, Ding Zhou and Lu Wang 2014 *Construction and Building Materials* Pull-out strength and bond behaviour of axially loaded rebar glued-in glulam **65** 440-49
  - [9] LVS EN 408+A1:2012 Timber Structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties
  - [10] LVS EN 338:2016 Structural timber - Strength classes
  - [11] LVS EN 10080:2006L Steel for the reinforcement of concrete - Weldable reinforcing steel - General
  - [12] LVS EN 1995-1-1+AC+A1:2012 L Eurocode 5 - Design of timber structures - Part 1-1: General - Common rules and rules for buildings