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Numerical analysis of the load-bearing capacity of LVL beams reinforced with steel plates

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Abstract:
Laminated veneer lumber is a relatively new engineering wood product. The number of its applications is increasing. For this reason, it is worth knowing how to reinforce laminated veneer lumber elements, if necessary. Reinforcement may be used at the production stage to increase the load-bearing capacity. This paper investigates the effect of steel plate reinforcement on the performance of laminated veneer lumber beams. Using steel plates increased both the load-bearing capacity and the stiffness of the laminated veneer lumber beams. Different reinforcement lengths were analysed, and it was demonstrated that a 2400 mm plate provided equivalent load-bearing capacity and stiffness to a reinforcing plate extending the full length of the LVL beam.

Keywords:
timber structures, laminated veneer lumber (LVL), Hashin damage model, numerical model, reinforcing

1. Introduction

Timber is a renewable material, and its consumption is increasing. However, timber structures should be designed to allow for reduced timber consumption. There are numerous methods used to make wood consumption more sustainable. For example, Łodygowski proposed I or box cross-sections to reduce material consumption [1]. The same effect can also be achieved by using timber elements in composite structures. The components can be used more efficiently, as composite action can increase the load-bearing capacity [2]. Old timber structures may be reinforced instead of being demolished. Rapp presented methods for reinforcing existing timber elements [3]. Jasieńko demonstrated that it is possible to use steel plates and reinforcing bars to reinforce timber elements [4]. Wood may also be effectively used in engineering wood products such as laminated veneer lumber, glued laminated timber or cross-laminated timber. Laminated veneer lumber (LVL) is an engineering wood product with numerous advantages and applications. One of its uses is in floor structures. LVL beams may be used as ribs in timber floors and girders in steel-timber composite floors. Article [5] provides information on why this material is considered sustainable. LVL elements are a relatively new solution used in modern buildings. Existing structures with engineering wood products may need reinforcing, e.g., when the category of use of a building area is changing. It is also possible to reinforce engineering wood products at the production stage to increase their load-bearing capacity. Glued laminated timber beams can be reinforced using carbon fibre reinforced polymer (CFRP) tapes [6], steel, basalt or glass pre-stressed bars [7,8]. Bakalarz and Kossakowski demonstrated LVL beams can be reinforced using CFRP sheets and laminates [9,10]. Majchrzak analysed the resistance of LVL beams strengthened using aluminium and steel plates [11]. In this paper, the authors evaluated the increase in the load-bearing capacity of LVL beams reinforced with steel plates.

2. Theoretical analysis

The load-bearing capacity of an LVL beam reinforced with a steel plate was calculated based on the methodology for timber beams reinforced with aluminium plates, presented in [12]. It was assumed that there was no slip between the LVL beam and the steel plate. The cross-section of the LVL beam reinforced with a steel plate was replaced with an ideal cross-section based on the guidelines for steel-concrete composite elements [13]. The width of the LVL element was reduced using the modular ratio *n* – the ratio between the modulus of elasticity of steel and of LVL (Fig. 1).

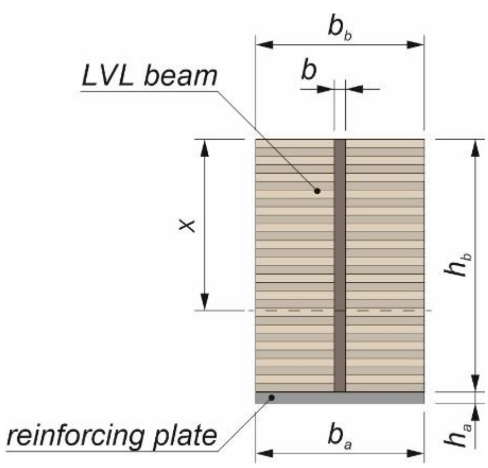

Fig. 1. The ideal cross-section of the LVL beam reinforced with a steel plate [11].

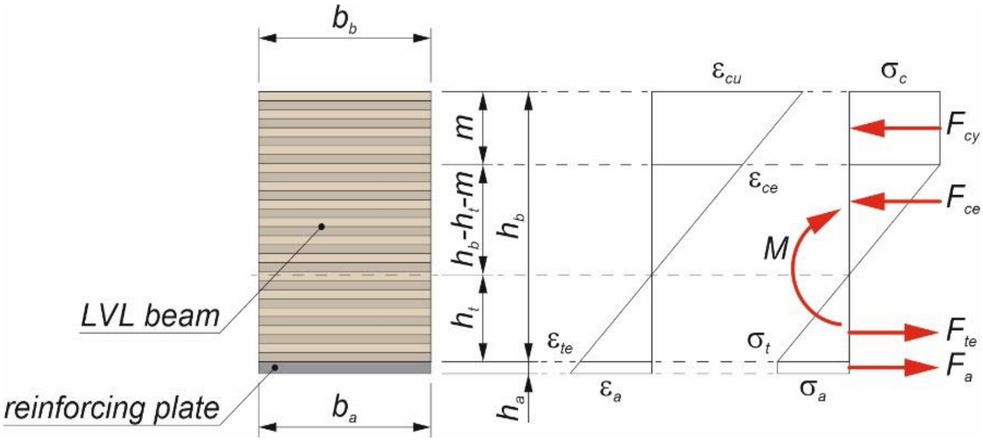

Fig. 2. Stress and strain distribution in the LVL beam reinforced with a steel plate [11,12]

Calculations of the load-bearing capacity of the LVL beam reinforced with a steel plate were presented in Table 1. The load-bearing capacity was calculated based on the equilibrium relation [12]:

$$M = \left(h_b - h_t - \frac{m}{2}\right) m b_b f_c +$$

$$+ \frac{(h_b - h_t - m)^2 f_c}{3} + \frac{b_b h_t^2 f_t}{3} + \left(\frac{1}{2} h_a + h_t\right) b_b h_a f_a \qquad (1)$$

3. Numerical models

Two-dimensional numerical models were developed in the Abaqus program. The plane stress conditions were assumed. The dimensions of the models are presented in Fig. 3. Boundary conditions are presented in Fig. 4. The simply-supported beam was subjected to bending. Vertical displacement (200 mm) was applied in two points to correspond to a four-point bending test. CPS4R finite shell elements (4-node bilinear plane stress quadrilateral elements with reduced integration and hourglass control) were used to model the beam and the steel plates (Fig. 5). The maximum mesh size was set to 10 mm. In this study, it was assumed that the connection between the LVL beam and the steel reinforcing plate is rigid. The rigid connection was modelled by tying the contact surface between the LVL beam and the plate. However, full interaction can be difficult to achieve in a real beam. For this reason, future investigations should focus on the connection stiffness and on the impact of the slip between the LVL beam and the plate. Surface-to-surface “hard” contact and friction were defined between the LVL beam and the load and support plates, and between the reinforcing plate and the support plates (Fig. 6). The friction coefficient was assumed to be 0.45 for steel-to-steel contact and 0.3 for LVL-to-steel contact. The deflection in the vertical direction was measured in the middle of the beam, and the vertical reaction was measured at one support. The steel was described as a linear hardening material (Table 2) based on the material parameters from the paper [14]. Engineering stress–strain data was converted to true stress–strain data. The true stress and the logarithmic plastic strain used in the Abaqus program were calculated using formulas presented in [15,16].

In the case of LVL, an orthotropic material model was used, while LVL failure was captured using the Hashin damage model. The LVL parameters were based on the model presented in paper [17] (Table 3).

In the theoretical calculations, characteristic values of tensile and compressive strength of LVL and ultimate strength of steel were used, whereas in the numerical analyses, the strength values from the laboratory tests presented in the literature were applied.

Table 1. Calculations of the load-bearing capacity of the LVL beam reinforced with a steel plate

Parameter	Value
LVL beam width (b_b)	60.0 mm
LVL beam height (h_b)	90.0 mm
steel plate width (b_a)	60.0 mm
steel plate thickness (h_a)	4.0 mm
modular ratio (n)	15
width of the ideal cross-section (b)	4 mm
position of the neutral axis (x)	61 mm
tensile height of the LVL beam (h_t)	29 mm
height of the plastic section in the compression zone (m)	24.4 mm
LVL compressive strength (f_c)	40 MPa
LVL tensile strength (f_t)	36 MPa
steel strength (f_a)	360 MPa
load-bearing capacity of the LVL beam reinforced with a steel plate (M_R)	6.32 kNm

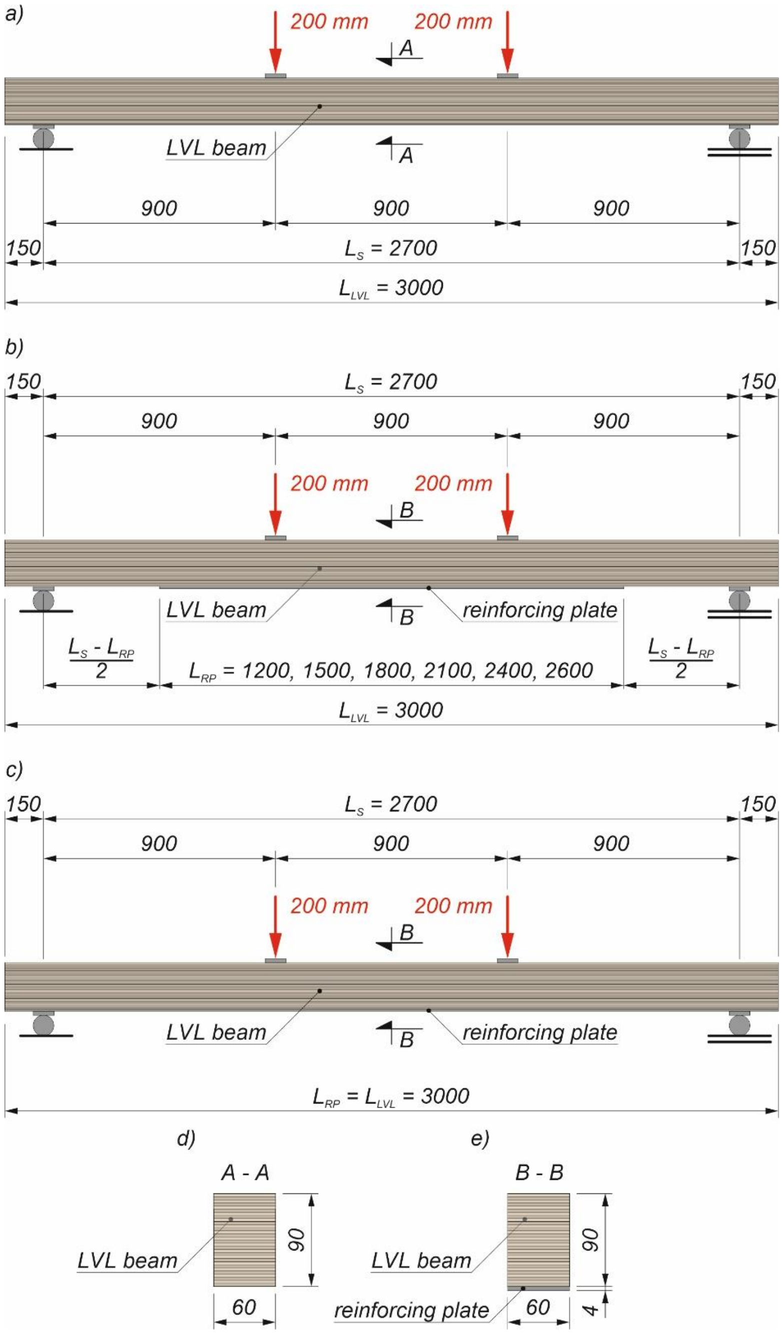

Fig. 3. Numerical model: a) LVL beam without a reinforcing plate, b) LVL beams with reinforcing plates, c) LVL beam with a reinforcing plate along the entire length of the beam; d) cross-section of the unreinforced beam; e) cross-section of the reinforced beam

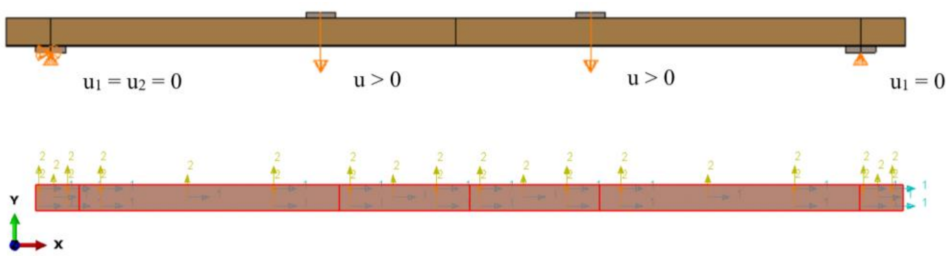

Fig. 4. Boundary conditions [11] and the material orientation for LVL

Fig. 5. The mesh used in the numerical analysis with the maximum size of 10 mm [11]

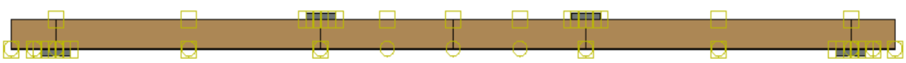

Fig. 6. Interaction locations [11]

Table 2. Properties of S235 grade steel

Parameter	Symbol	Value
Poisson's ratio	υ	0.3
Young's modulus	E	210 000 MPa
Plastic engineering stress [14]	σ_y	362.0; 490.0 MPa
Plastic engineering strain [14]	ε_p	0.0; 0.1912 [–]
Plastic true stress	σ_y	362.0; 583.69 MPa
Logarithmic plastic strain	ε_p	0.0; 0.1720 [–]
Density	ρ_k	7850 kg/m^3

Table 3. The properties of the LVL [17]

Orthotropic material model parameters (laminate type)					
E_1[a] [MPa]	E_2 [MPa]	ν_{12} [–]	G_{12} [MPa]		
16 000[b]	430	0.48[d]	600[c]		
Hashin damage model parameters					
Longitudinal tensile strength [MPa]	Longitudinal compressive strength [MPa]	Transverse tensile strength [MPa]	Transverse compressive strength [MPa]	Longitudinal shear strength [MPa]	Transverse shear strength [MPa]
41.9[e]	50.3[e]	10[d]	15[d]	10[d]	5[d]
Longitudinal tensile fracture energy [kJ/m^2]	Longitudinal compressive fracture energy [kJ/m^2]	Transverse tensile fracture energy [kJ/m^2]	Transverse compressive fracture energy [kJ/m^2]	Viscosity coefficient [–]	
45[b]	45[b]	0.1[b]	0.1[b]	10^{-6}[b]	

[a] direction 1 is parallel to the LVL grain, [b] determined based on comparing the numerical analyses and the laboratory test results, [c] based on [18], [d] based on [19], [e] based on experiments from [17]

4. Results

The comparison of the behaviour of the reinforced and non-reinforced LVL beams is presented in Fig. 7. The load-bearing capacity of the LVL beam reinforced with a steel plate along the entire length was 39.5% higher than the one of the LVL beam without a reinforcing plate.

At the ultimate moment (M = 7.64 kNm) of the LVL beam strengthened using the steel plate along the entire length, the damage initiation was observed in the compressive parts of the LVL slab (Fig. 8). The fibre tension criterion was not met in any finite element. The yield strength was achieved in the reinforcing steel plate under the load. Shortly afterwards, the fibre compressive criterion was met almost the entire height of the cross-section and the mesh distortion occurred. It provided to the deflection reversing observed in Fig. 9.

The impact of the reinforcing plate length on the load-bearing capacity of the LVL beam is presented in Figs 9 and 10.

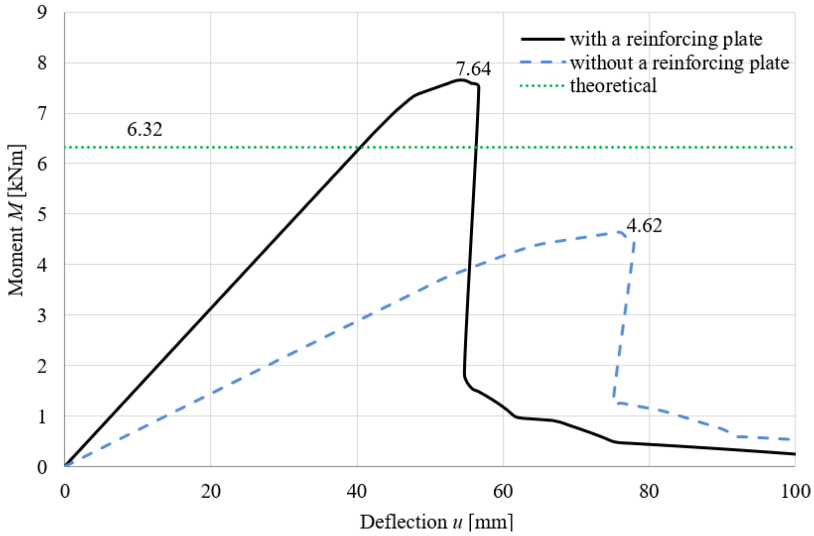

Fig. 7. Moment-deflection curves for the LVL beam reinforced with a steel plate and the LVL beam without a reinforcing plate

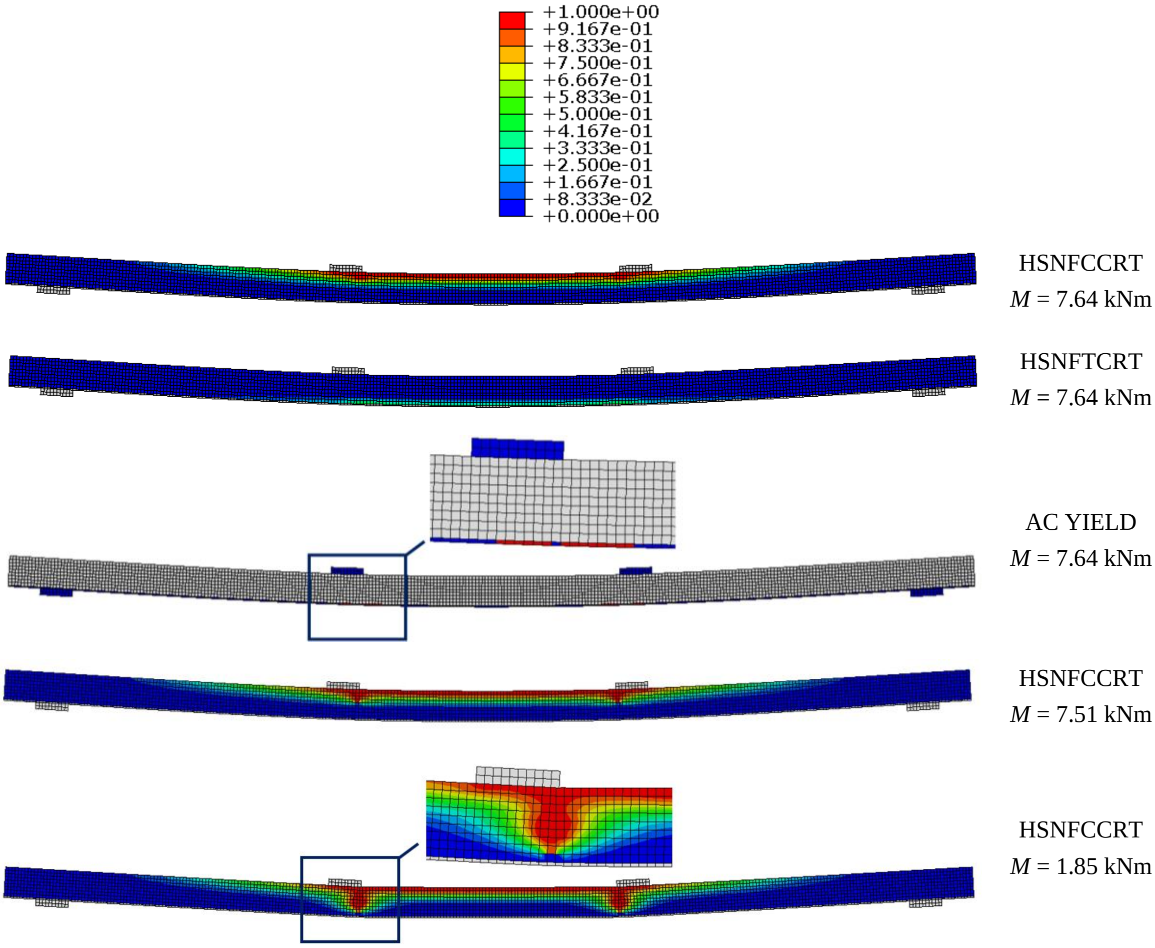

Fig. 8. Damage initiation area in the LVL beam strengthened using the steel plate along the entire length

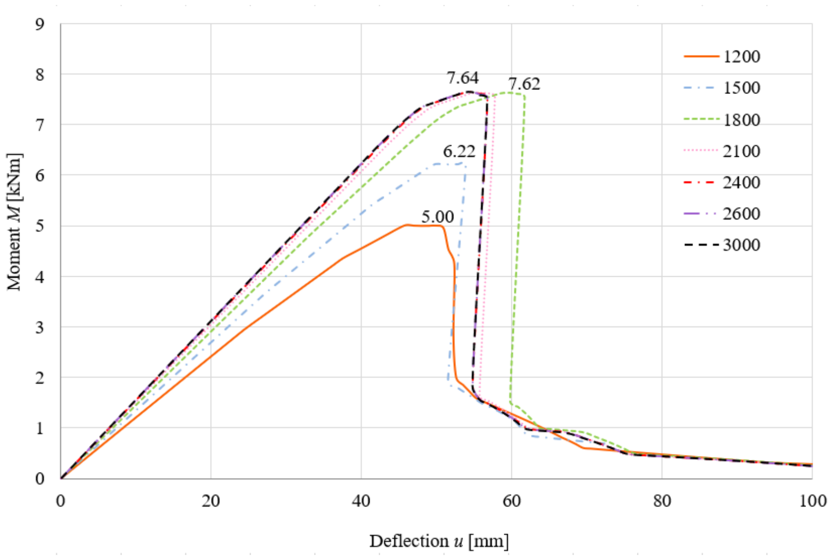

Fig. 9. Moment-deflection curves for LVL beams reinforced with plates of varying length

The load-bearing capacity of the LVL beam without a reinforcing plate was 4.62 kNm. All LVL beams with reinforcing plates had a higher load-bearing capacity than the unreinforced beam. In the case of the LVL beam with the 2400 mm and 2600 plates, the same load-bearing capacity and stiffness as for the LVL beam with the reinforcing plate along the entire length was obtained. In the case of the LVL beam with a 2100 mm plate, the load-bearing capacity was only 0.3% lower than that of the LVL beam with the reinforcing plate along the entire length, and the maximum load was achieved for 1 mm higher deflection. The LVL beam with the 1800 mm plate had the same load-bearing capacity as the LVL beam with the 2100 mm plate, but the maximum load was achieved for 4 mm higher deflection. The load-bearing capacity of the LVL beams with the 1200 mm and 1500 mm plates was 18.6% and 34.6%, respectively, lower than that of the LVL beam with the reinforcing plate along the entire length. The 2400 mm plate provided equivalent resistance and stiffness to that of the reinforcing plate extending along the full length of the LVL beam.

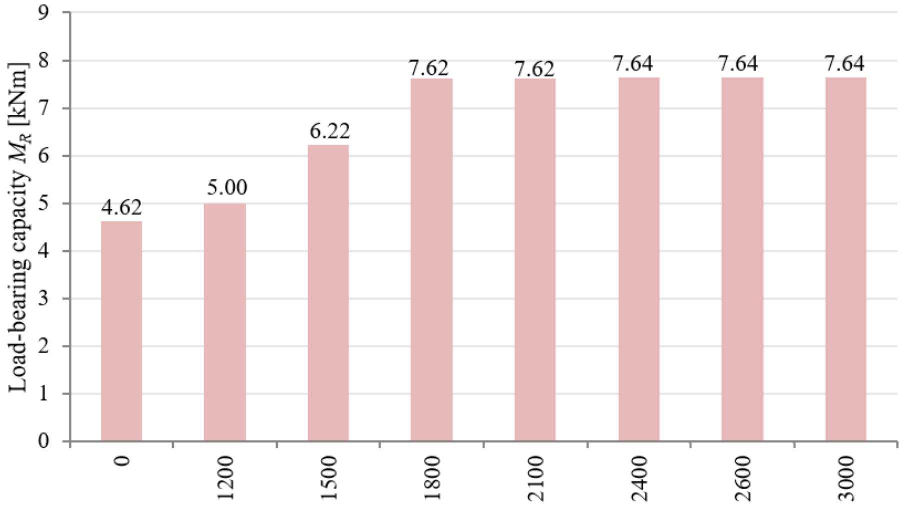

Fig. 10. Comparison of the load-bearing capacity of LVL beams reinforced with plates of varying length

4. Conclusions

In this paper, the effect of the reinforcement plate length on the load-bearing capacity of the LVL beam was investigated. The reinforcement may be used in existing structures and at the production stage of LVL. However, the use of the steel plate along the entire length of the LVL beam at the building operation stage may be difficult. For this reason, different plate lengths were analysed. It was demonstrated that a 2400 mm plate provided equivalent load-bearing capacity and stiffness to that of a reinforcing plate extending along the full length of the LVL beam. Furthermore, a 1800 mm plate provided a similar load-bearing capacity to that of a reinforcing plate extending along the full length of the LVL beam. Further increase in plate length did not significantly increase the load-bearing capacity of the beam.

The study had some limitations. The reinforcing plates were subjected to the load from the start of the numerical simulation. However, reinforcing is conducted for the beams under load [20]. For this reason, reinforcing plates will begin to cooperate when there is some stress in an LVL beam. Furthermore, the connection, slip between the plate and the LVL beam, and delamination were not considered. For this reason, it is only a preliminary analysis of the load-bearing capacity of the LVL beam strengthened using a steel plate. Last but not least, only numerical simulations were conducted. Future laboratory tests are necessary to validate the numerical models.

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