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Advancing Timber for the Future Built Environment

SHORT-TERM PERFORMANCE OF REINFORCED GLULAM BEAMS

Shuyi Yang [1], **Hamid Valipour** [2]

ABSTRACT: Timber structures are easy to assemble and dismantle with a relatively high strength over density ratio and low embodied energy and carbon compared to conventional reinforced concrete and steel structures. Over the past decades, huge efforts have focused on adopting and promoting greater and more efficient use of timber in the construction industry through the development of composite and hybrid timber structures that exploit the advantages of timber in conjunction with other materials. Among various methods for developing hybrid/composite structural systems, timber-steel encased structural elements or reinforced timber elements have received much attention. These structural elements are lightweight and adaptable with higher strength, stiffness, and ductility than their bare timber counterparts. Considering the numerous benefits of combining timber with steel, this project aims to evaluate the structural performance of steel-reinforced timber beams under short-term ultimate and service limit state loading conditions. The project involves the design, fabrication and testing of reinforced glulam (timber) beams under 4-point bending.

KEYWORDS: Four-point bending, glue laminated timber, short-term loading, steel bar

1 – INTRODUCTION

The demand for both new constructions and the renovation and upgrading of the existing structures have rapidly increased due to the fast pace of urbanisation which has had a determinal impact on the environment. One sustainable solution is the application of timber, as a natural alternative renewable material that could replace carbon-intensive conventional construction materials. Compared to traditional construction materials such as steel and concrete, natural timber elements and engineered wood products have relatively lower embodied energy and carbon footprint. In addition, timber has a high strength-density ratio and timber structures are easy to fabricate, assemble and dismantle after use.

Kliger, Haghani, Brunner, Harte, and Schober (2016) reported that wood-based engineering product structures such as glulam beams, floors and roofs need strengthening to improve their performance under short- and long-term loads. Although glulam structures can satisfy the ultimate limit state criteria, it is still of vital importance to consider stiffness, vibrations as well as long-term performance. O'Ceallaigh, Sikora, McPolin, and Harte (2020) confirmed that the reinforced timber shows less deflection (higher stiffness) and superior performance when subjected to variable environments, i.e. relative humidity and temperature. However, there is limited study on the structural behaviour of glulam beams with encased steel bars which is the focus of the current paper.

2 – BACKGROUND

Timber is a natural construction material; however, as a natural product, there are large variability in wood properties. Blaß and Sandhaas (2017) point out pure timber has large variations in mechanical properties due to natural imperfections such as knots and fibre deviations. Moreover, timber is an anisotropic material, which means the mechanical properties can vary largely depending on the different axes and tend to fail in a brittle manner. For better behaviour of strength and serviceability, engineered wood products (EWPs) have been adapted for mass timber structures as EWPs usually have better dimensional stability and stiffness. The variability of timber-based structural members can be

[1]Shuyi Yang, Ph.D. Candidate, School of Civil and Environmental Engineering, Univ. of New South Wales (UNSW) Sydney, Sydney, NSW 2052, Australia. Email: shuyi.yang1@student.unsw.edu.au.

[2] Hamid Valipour, Professor, Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, Univ. of New South Wales (UNSW) Sydney, Sydney, NSW 2052, Australia. ORCID: https://orcid.org/0000-0002-8415-3340.

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reduced by adding reinforcement such as steel bars and/or laminating solid wood panels.

Glue-laminated timber, cross-laminated timber, and laminated veneer lumber are the most popular engineered wood products. Glue laminated timber, also known as Glulam or GLT, is usually produced by softwood with several laminates and bonded with structural glue. Natural defects of timber such as knots are reinforced by the adjacent layers of timber, and the laminar laid up in parallel to the grain direction results in the higher tensile strength of GLT. Cross-laminated timber is a widely used structural material that contains an odd number of timber layers perpendicular to the adjacent layers. The 90-degree angle between the adjacent layers makes CLT have a relatively good two-way action to be used as slabs. Laminated veneer lumber, usually made of peeled wood sheets from the log and glued these thin veneers in parallel to the grain direction. However, De Melo and Del Menezzi (2014) LVL can be a costly product because the thickness of veneers can directly affect the mechanical properties of LVL and adhesives that in between two timber layers can cost up to half of the final price.

The reinforcement material could be classified into steel and fibre-reinforced polymer. Schober et al. (2015) and Kliger et al. (2016) state fibre reinforced polymer (FRP), could provide stiffness, load-bearing capacity durability and good fatigue performance, which is easy to assemble while has a relatively low strength-to-weight ratio. As a result, FRP has been adopted in the industry around four decades ago. According to Franke, Franke, and Harte (2015), the most frequently used FRP are: carbon (CFRP), aramid (AFRP), glass (GFRP), and basalt (BFRP). Though fibre-reinforced polymer (FRP) is lighter than steel while having a better performance in fire resistance, the FRP is brittle, has low ductility, and is costly compared to steel.

The steel reinforcement also substantially enhances the load-carrying capacity, stiffness and ductility of the structural timber members. Tannert, Gerber, and Salenikovich (2024) also point out that composite structures could have enhanced load-carry capacity and bending stiffness. The rods that are glued inside timber could transfer shear and bending and provide an option to build deconstructionable joint types. On the other hand, external reinforcement is not widely adopted due to aesthetical considerations while exposed steel is vulnerable to environmental changes such as relative humidity and temperature.

Steel has better tensile strength compared to timber, so it should be used as a tensile member in steel-timber composite structures. The glued-in rods could enhance the tension strength of bare timber and change the failure mode of glulam beams from brittle tensile failure to ductile compressive failure according to Hosseini and Valipour (2024). In addition, this research also highlights the importance of compression bars, as the increase of flexural capacity and stiffness of the singly reinforced beams are less than double reinforced beams. The timber outside steel bars also provides protection for steel bars from temperature and moisture changes.

3 – PROJECT DESCRIPTION

The main idea of this study is to develop a new reinforced glulam system that takes advantage of the encased bars as reinforcements as well as means for connections. However, this project only focused on the short-term performance of the steel reinforced glulam beams. By conducting short-term four-point bending tests on glulam beams, peak loads, stiffness and ductility could be obtained for the design of long-term structures in future projects.

Table 1: Experiment outline.

Specimen Type	Reinforcement	Number of tests
Douglas Fir Lumber	None	5
Pine Lumber	None	5
Douglas Fir Beam	N20	3
	None	2
Pine Beams	N16	5
	None	3

The experimental outline is presented in Table 1, prior to the short-term beam tests, material tests on 5 specimens of pine MGP10 lumber and Douglas fir F7 lumber are tested under four-point bending according to AS4063.1:2010. The average value of elastic modulus E and bending strength f_b are listed in Table 2. In total of 23 specimens are tested under four-point bending with a length of 4 m and the same shear span; however, necessary lateral restraints are provided to prevent buckling of the specimens. Elastic modulus and bending strength can be calculated using Equation (1) and (2):

$$E = \frac{23}{108}\left(\frac{L}{d}\right)^3 \left(\frac{\Delta F}{\Delta e}\right)\frac{1}{b} \quad (1)$$

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$$f_b = \frac{F_{ult}L}{bd^2} \quad (2)$$

where $(\frac{\Delta F}{\Delta e})$ is the slope of the linear part of the load-displacement curve, while standard specifies a load range between 10% and 40% of the failure load is considered appropriate for determining the slope of the linear section in the load-deformation curve; L represent the test span between two supports; d is depth of the test piece; b is width of the rectangle cross-section; and F_{ult} is the ultimate (failure) load of the test piece.

The moisture content (MC) was derived from the oven dry test according to ASTM D 4442 and BS EN 13183-1:2002. All samples were freshly cut from test pieces and were free from bark, knots and resin pockets. The drying temperature was set to 103℃ and the water content and density of specimens are given in Table 2.

Normal ductility class ribbed bars are used in the project (class N) with nominal diameters of 16 mm and 20 mm, and the mean value of the mechanical properties and their coefficient of variation (CoV) are provided in Table 3. Uniaxial tension tests on N16 and N20 reinforcing steel bars were carried out according to AS 1391-2020 to obtain the characterise mechanical properties of the materials.

Table 2. Mechanical properties of Douglas fir and pine lumber.

	Modulus of Elasticity E		Bending Strength fb		Moisture Content		Density	
	E_{mean} (GPa)	CoV (%)	$f_{b,mean}$(MPa)	CoV (%)	Average (%)	CoV (%)	Average (kg/m^3)	CoV (%)
Douglas Fir	10.02	8.16	43.16	25.04	14.7	1.4	488	3.3
Pine	9.91	11.00	33.73	28.60	15.8	6.1	565	2.7

Table 3. The mean value of mechanical properties of reinforcing bars.

Bar Size	Elastic Modulus		Yield Strength		Ultimate Strength	
	Mean (GPa)	CoV (%)	Mean (GPa)	CoV (%)	Mean (Mpa)	CoV (%)
N16 Bar	194	1.7	517	1.0	588	0.5
N20 Bar	199	3.9	564	0.2	669	0.1

4 – EXPERIMENTAL SETUP

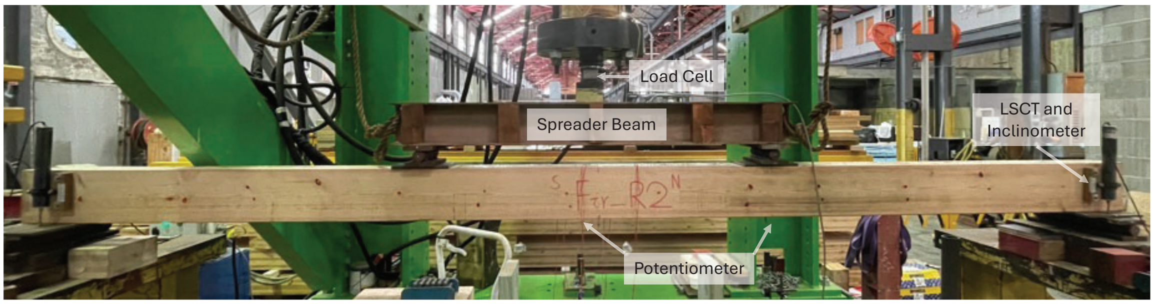
As shown in Figure 1, the specimen is simply supported and tested under displacement-controlled load. A 1.2 MN hydraulic actuator is used for applying the load on a spreader beam transfering the load to the top of the specimens. Two Linear Strain Conversion Transducer (LSCT) measured the crushing at the supports and two Linear Variable Differentntial Transformer (LVDT) measured displacement at loading point and mid-span.

4.1 Material Tests (Pine and Douglas Fir)

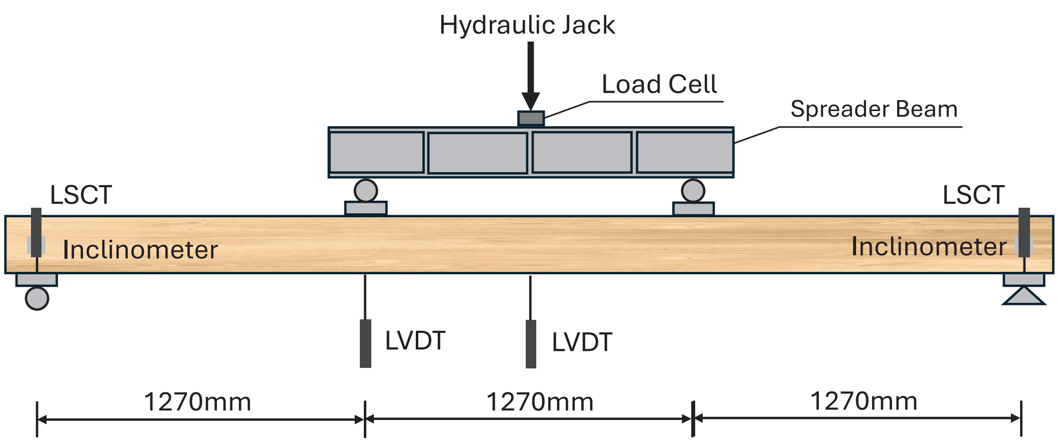
Four-point bending test setup for timber lumber is shown in *Figure 2*, and lateral restrain was provided by the timber frame as required by AS4063.1:2010. LSCTs were installed at the end of the beams to measure vertical movements at the support location, and the inclinometers were installed at the support locations. The vertical movement under the loading point and at the mid-span were measured by two LVDTs installed at the bottom of the beam. A total of 5 Radiata pine lumber (grade MGP10) and 5 Douglas fir (grade F7) were used in the material tests, they all have a nominal cross-section of 190 mm × 45 mm.

4.2 Short-term Four-point Bending Tests

The pine beams were reinforced by 16 mm diameter N class bars and Douglas fir beams were reinforced by 20 mm diameter bars. Timber lumber has been cut into two half-round grooves on one side for the top and bottom lamellae and the middle lamelle has two grooves on both sides. The adhesive used in the beams was polyurethane (PU), LOCTITE 8101B3/LoCTITE 5400. The assembly process is to pour adhesive on empty grooves and then insert steel bars in, and finally apply another layer of adhesive on timber and bars before putting the third layer on. Beams without reinforcement were assembled using three layers of timber lumber with polyurethane between them as the contract group. After assembly, steel box clamps were used for curing. For each beam, there are 8 strain gauges at the mid-span, 2 strain gauges under the loading point, 2 inclinometers and 2 displacement transducers at supports. Same with the material test, the load is displacement controlled and all the beams to failure within 2 to 5 min according to AS4063.1:2010. The time limit set for testing to failure aimed to minimize creep impact on the test results.



(a)



(b)

Figure 1. Four-point bending tests for short-term beams setup (a) and the illustration graph (b).

Figure 2. Material tests for Pine/ Douglas Fir lumber.

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Figure 3. Short-term tests for pine/ Douglas Fir beams.

Table 4. Elastic modulus and bending strength of composite beams with CoV.

	Reinforcement	Peak Load		Elastic Modulus E		Bending Strength f_b	
		Mean (kN)	CoV (%)	E_{mean} (Gpa)	CoV (%)	$f_{b,mean}$ (Mpa)	CoV (%)
Douglas Fir	N20	97.20	7.84	13.42	13.40	79.58	7.87
	None	65.15	21.87	9.85	24.13	52.90	19.35
Pine	N16	75.21	9.57	9.96	24.66	62.44	8.02
	None	52.11	19.31	8.25	17.38	43.15	21.19

5 – RESULTS

The experimental results shown in *Table 4* demonstrate that reinforcement significantly enhances the structural performance of both Douglas Fir and Pine beams. All specimens in this project exhibited flexural (tension) failure, and the reinforcement contributed to a significant reduction in variability across the tested properties. For Douglas Fir specimens, the inclusion of N20 reinforcing bars resulted in a 49% increase in peak load carrying capacity, from 65.15 kN to 97.20 kN, while also reducing the coefficient of variation (CoV) from 21.87% to 7.84%, indicating improved consistency. Similarly, the elastic modulus E_{mean} increased by 36%, from 9.85 GPa to 13.42 GPa, with a corresponding reduction in CoV from 24.13% to 13.40%. The bending strength $f_{b.mean}$ improved by 50%, reaching 79.58 MPa compared to 52.90 MPa in the unreinforced specimens. For Pine specimens, reinforcement with N16 bars resulted in a 44% increase in peak load, from 52.11 kN to 75.21 kN, while reducing the CoV from 19.31% to 9.57%. The elastic modulus E_{mean} increased by 21%, from 8.25 GPa to 9.96 GPa, with a slight increase in CoV. The bending strength improved by 45%, increasing from 43.15 MPa to 62.44 MPa, while the CoV decreased from 21.19% to 8.02%.

The failure mode of all specimens was a tensile failure, with a sudden drop of the load and cracks from the beam. *Figure 4* presents an example of flexural (tensile) failure with a crack starting from the bottom of the beam near a knot. Natural defects such as knots and fibre deviation tend to lead to failure of the beam and those cracks could extend quickly over the depth of the beam and result in sudden failure and loss of load carrying capacity.

Figure 4. Example of failure mode for short-term beams.

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6 – CONCLUSION

This project intended to investigate the structural behaviour of the simply supported steel reinforced glulam beams by short-term 4-point bending tests. A series of short-term bending tests have been carried out to determine the load carrying capacity, stiffness and ductility of each type of specimen. Based on the laboratory results, it is clear that the encased steel bars do improve the structural performance of the beam by 49% for Doglas Fir beam and 44% for pine beams. Beyond strength and stiffness enhancements, reinforcement also contributed to improved consistency, as evidenced by the reduced coefficients of variation in key mechanical properties.

7 – REFERENCES

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