

Experimental Study on Structural Behaviour of Glulam Beams Pre-stressed by Compressed Wood

Buan Anshari, Akihisa Kitamori, Kiho Jung, Kohei Komatsu, and Zhongwei Guan

Abstract

This paper presents the study on structural behaviour of glulam beams pre-stressed by compressed wood (CW) in terms of load carrying capacity, strength and stiffness. Glulam beams were strengthened by inserting CW blocks into the pre-cut rectangular holes on the top of the beams. This practice was to make use of moisture-dependent swelling nature of the compressed wood. The CW block was placed in a way in which its radial direction was coincident with the longitudinal direction of the beam to be strengthened. After pre-stressing process, all beams were placed in a chamber with Relative Humidity (RH) fluctuated between 40% until 80% and a constant temperature of 20°C until the maximum swelling of the CW block was reached. The glulam beams with the size of 3800 mm long, 200 mm deep and 120 mm wide were reinforced by 3, 5, 7 CW blocks respectively, all with the same thickness of 45 mm. In addition, there were two beams which were reinforced at the bottom extreme fibre with one lamella made of compressed wood. There were also three beams without any reinforcement for control purpose. The test results showed that a pre-camber was produced in the mid-span of the beam reinforced. At both the top and the bottom extreme fibres of the beam significant initial tensile and compressive stresses were generated respectively. Bending tests indicated that the load carrying capacity of the reinforced beams increased significantly in comparison to the beam without reinforcement.

Key words: glulam, compressed wood, moisture-dependent swelling, pre-stressing, pre-camber.

Introduction

Glued-laminated timber or glulam have been used in Europe since the end of the 19th century (Andre 2006). Glulam timber is made of wood laminations glued together to form a specific piece of wood for a specific load. The interest to use this technology is to decrease product variability and make it less affected by natural growth characteristics like knots. Besides, the glulam technology offers almost unlimited possibilities of shape and design for construction, and is widely used for load bearing structures in houses, warehouses, pedestrian bridges, etc.

Reinforcement of structural wood products has been studied for more than 40 years. In the earlier stages of the research, the focus was mainly on using metallic reinforcement, including steel bars, pre-stressed stranded cables and bonded steel and aluminium plates. Recently, research on glulam beams reinforced with fiber and fiber-reinforced polymers (FRP), such as carbon, aramid and glass fibres has been increased significantly, due to the high specific strength and stiffness of the FRP materials. Many attempts have been conducted to reinforce wood or glulam timber beam by using fibre reinforced plastics. Nikolaos and Thanasis (1992) studied the effect of reinforcing fir wood with carbon/epoxy fiber-reinforced plastics (CFRP). The study revealed that even very small area fractions of fiber-composite reinforcement resulted in significant improvement of the member's mechanical behaviour. Triantafillou and Deskovic (1992) also studied the effect of prestressed CFRP reinforcement bonded to European beech lumber. The method used in this study involved external bonding of

pretensioned FRP sheets on the tension faces of beams through the use of epoxy adhesives.

Guan *et al.* (2005) studied glulam beams pre-stressed by pultruded glass fibre reinforced plastic (GRP) tendons. Finite element models were developed and validated. It was shown that the models had successfully simulated the pre-camber introduced into the beam due to transfer of pre-stressing force. Also Corradi and Borri (2007) studied reinforcement of timber beams reinforced with pultruded glass fibres reinforced polymers (GFRP) element. The result indicated significant improvement in flexural stiffness and capacity compared with unreinforced timber. Johnsson *et al.* (2007) studied reinforced glulam using pultruded rectangular carbon fibre rods and established the anchoring length for this system. The proposed reinforcement method increased the short-term flexural load-carrying capacity by 49~63% on average.

Wood densification by thermal transverse compression has attracted many researchers as a process to improve the strength and surface properties of low-density wood species, such as modulus of elasticity, tensile/compressive strengths, surface hardness and abrasion resistance. Zhou *et al.* (2000) investigated the bending creep behaviour of hot-press wood under cyclic moisture condition. The thickness swelling increased with moisture cycle, which led to increase in the dimension of hot-press specimen by the end of cyclic moisture sorption. Jung *et al.* (2008) applied compressed wood made of Japanese cedar, as a substitute for high density hardwood, to make shear dowels. CW with its annual ring radial to loading direction (0°) had a unique double shear performance characteristic, and showed good

properties as a dowel material by virtue of its strength and rich ductility. Kitamori *et al.* (2010) also studied the mechanical properties of compressed Sugi subject to its various compression ratios. The results indicated that elastic shear modulus and strength on the LT plane increased almost in proportion to density. Young's modulus increased with increasing compression ratio mainly in longitudinal direction.

In order to make use of moisture-dependent swelling nature of compressed wood, a new approach to strengthen a glulam beam was proposed and investigated. In this study, glulam beams were strengthened by inserting compressed wood blocks into the pre-cut rectangular holes on the top of the glulam beams. Once the CW blocks were inserted, they would be gradually swelling by absorbing moisture from air until they reached the equilibrium state, i.e. the balance between the moisture-dependent swelling and the constrained expansion by surrounding glulam. The expansion on the CW blocks on the top part of the beam would generate bending moments that would create a pre-camber of the beam. As a result, the up-lift deflection would also produce the initial tensile and compressive stresses respectively at the top and bottom extreme fibres of the beam before applying a service loading.

This paper aims to investigate how the moisture dependent swelling of the compressed wood, which was inserted in a pre-cut hole on the top of beam, could enhance the structural performance of a glulam beam reinforced.

Materials and Methods

Sample Preparation

Compressed Wood. In this research, Japanese cedar (*Cryptomeria japonica* D Don) wood was used to manufacture compressed wood blocks and glulam with the initial density of 300–420 kg/m³ and MC of 12% in a dry air condition.

Compressed wood is made of lower grade timber through densification processes, which requires wood free of knot and without any defects to ensure that it can be compressed in the radial direction. The manufacturing processes consist of preheating, pressing and cooling. The preheating temperature was 180°C to ensure dimension stability of compressed wood. The level of densification which is also known as compression ratio (CR) can be represented as follows:

$$CR = \frac{(t_0 - t_1)}{t_0} \times 100\% \quad (1)$$

where t_0 and t_1 are the thickness of the wood plate in the radial direction before and after the compression treatment, respectively. In this research programme, the compression ratio was set to 70%. In order to obtain the possible maximum swelling of compressed wood, wood with low

moisture content needs to be conditioned. Here the initial moisture content of 6% was chosen.

The dimensions of the CW blocks with CR = 70% for the reinforcement are 65 × 45 × 65 mm coincided with the L, R, and T directions of wood respectively are shown in Figure 1. Compressed wood lamella was made of Japanese cedar with the initial dimensions of 1200 × 60 × 150 mm to produce CW size of 1200 × 30 × 120 mm coincident with the L, R, T directions. The compression ratio of CW lamella was 50%. For glulam beam with total length 3.8 m which are reinforced by CW lamella, there are 3 finger joints to compose CW lamella as required length.

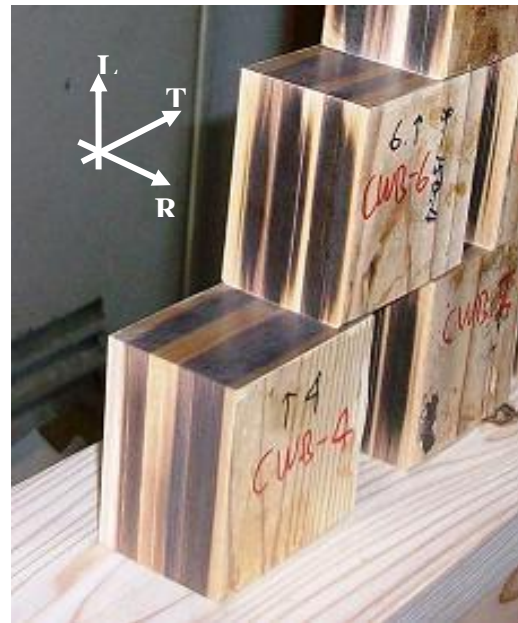


Figure 1. CW blocks for beam reinforcement.

The density of the compressed wood is 1163 kg/m³ in average which was increased from (300–420) kg/m³ of the softwood. Material properties of CW with CR = 70% were greatly enhanced, e.g. the Young's modulus in the L and R directions increase significantly to 32858 MPa and 3111 MPa respectively in comparison to the normal Japanese cedar with $E_L = 8017$ MPa and $E_R = 753$ MPa.

Glulam Beams. Glulam beams were produced from a glulam factory (Meiken Co. Ltd. Yamaguchi) in Japan, which were made of Japanese cedar with specifications as follows. The dimensions of the glulam beam were 3800 mm long, 200 mm deep and 120 mm wide. The beam size satisfies the requirement from Eurocode 5, BS EN 408:2003 where the ratio between the span (3600mm) and the depth (200mm) equals to 18. The grade of glulam beam based on Japanese Industrial Standard (JIS), JASE65f225. According to the data from the factory the modulus of elasticity of glulam beams without CW lamella were varied between 7205 and 7832MPa.

Table 1 shows that there are total 7 beams in which two of them were reinforced at their bottom surfaces with a lamella made of compressed Japanese cedar. Also, there were three beams without any reinforcement for control purpose. CW lamellas as reinforcement for two glulam beams were prepared in Laboratory of Structural Function, Kyoto University.

Figure 2 shows the beams reinforced by 3 and 5 CW blocks with dimensions of 65 × 45 × 65 mm coincide with the L, R, T directions of compressed wood. The arrangement of CW blocks was symmetrical.

Experimental work

Pre-stressing Process. Pre-stressing technology developed is to make use of moisture-dependent swelling nature of compressed wood. Since there is the largest

swelling in the radial direction of compressed wood, the CW block was placed in a way in which its radial direction is coincident with the longitudinal direction of the beam to be strengthened. The CW blocks were conditioned to have MC of 6% prior to the insertion. The beams pre-stressed would be placed in an ambient condition with MC of 12%. In this process the thickness of CW in R direction 1 mm larger than width of hole to allow generating initial stress at beam. Once the CW blocks were inserted, they would be gradually swelled by absorbing moisture from air.

Universal testing machine (Instron 1125 with capacity 50 kN) was used to insert CW blocks into pre-cut holes with crosshead movement set at 5mm/min, as shown in Figure 3. Two transducers CDP50 were connected to data logger and PC to record the vertical displacement of the CW block during the insertion process.

Table 1. Glulam beam specimen and type of reinforcement.

No.	Beam specimen	No. of CW on the top	No. CW Lamella at the bottom	No. of specimen	Grade
1	LB_0CWB_0CWL	0	0	3	JASE65f225
2	LB_3CWB_0CWL	3	0	1	JASE65f225
3	LB_5CWB_0CWL	5	0	1	JASE65f225
4	LB_5CWB_1CWL	5	1	1	JASE65f225
5	LB_7CWB_1CWL	7	1	1	JASE65f225
Total		20	2	7	

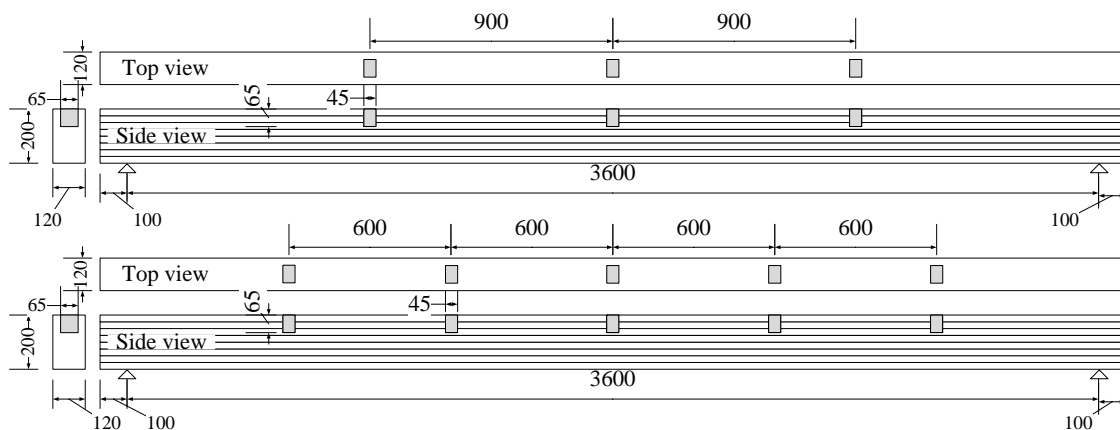


Figure 2. Glulam beams with 3 and 5 CW block reinforcement.



Figure 3. Insertion process of CW block into a full-size beam.

Measuring the Pre-camber and Initial Strain State of the Pre-stressed Beams.

After finishing insertion and setting up gauges for measurement, all beams were placed in a conditioning chamber where the Relative Humidity was fluctuated between 40% and 80% (3 days in RH 40% and 3 days in RH 80%) but the temperature was kept at 20°C. Readings of transducers and strain gauges were recorded by a Personal Computer through a data logger. The measurements would be terminated when readings from displacement transducers and strain gauges were stabilised, i.e. the compressed wood blocks had reached the maximum swelling after absorbing moisture. The beam specimens which were placed horizontally along the longitudinal direction and separated by two LVL blocks with a vinyl sheet underneath. The beams were subjected to strain measurements at the selected positions. Total 46 strain gauges were attached to five beams, in which 10 strain gauges were for each of four beams strengthened (Figure 4) and six gauges for the beam without reinforcement. The time interval set to record measurements was 30 min for a period of six and an half weeks.

Measurements of the pre-camber deflections were taken manually by using steel I beam, long clamp, and also automatically by a transducer CDP-25 set at the mid-span underneath the beam. Figure 5 shows the setting up of pre-camber deflection measurement. As assumption the actual pre-camber (f) is equal to the measured deflection (d) as shown in Figure 5. To validate the result, it was repeated the same procedure by change the clamped end

Destructive Bending Tests. Four-point bending tests were undertaken for seven glulam beams including three beams without any reinforcement for control purpose. The Universal Testing System (UTS) Instron was used to carry out the tests, with the maximum capacity of 1000 kN and the crosshead speed set to 2 mm/min. The arrangements of the destructive bending test are shown in Figure 6. Two transducers (DTP-05) were placed at mid span and CDP-50 at each support to measure the relative displacement of the support to determine the final deflection of beam. There were also two transducers (CDP-10) and one CDP-25 at

two side of mid span and the top surface of mid span to measure curvature of the beam.

From measured parameters of the above tests, the local modulus of elasticity, and the global modulus of elasticity in bending and the modulus of rupture of the tested beams may be calculated using the following equations (BS EN 408:2003):

$$MoE_l = \frac{al_1^2(F_2 - F_1)}{16I(w_2 - w_1)} \quad (2)$$

$$MoE_g = \frac{l^2(F_2 - F_1)}{bh^3(w_2 - w_1)} \left[\left(\frac{3a}{4l} \right) - \left(\frac{a}{l} \right)^3 \right] \quad (3)$$

$$MoR = \frac{3aP_{max}}{bh^3} \quad (4)$$

where:

a = distance between the support and the point load (mm)

l_1 = gauge length for the determination of modulus of elasticity (mm)

$F_2 - F_1$ = incremental load in elastic range (N),

$w_2 - w_1$ = incremental deflection corresponding to $F_2 - F_1$ (mm)

I = moment of inertia (mm⁴)

b = width (mm)

h = height (mm)

P_{max} = maximum load (N)

MoE_l = local modulus of elasticity (MPa)

MoE_g = global modulus of elasticity (MPa)

MoR = modulus of rupture (MPa).

Result and Discussions

Pre-camber Deflection

As mentioned in the previous section the pre-camber deflections of pre-stressed glulam beams were measured 45 days after inserting the CW blocks. The result shows that the glulam beams reinforced by three, five and seven 45 mm thick CW blocks produced pre-camber significantly at mid span as shown in Table 2. The highest pre-camber deflection occurred at the glulam beam reinforced by 7 CW blocks which reached the ultimate deflection of 8.6 mm. The pre-camber deflection of the glulam beam reinforced by 5 CW blocks without CW lamella was higher than the similar glulam beam but with CW lamella. This was due to the high stiffness compressed wood lamella at the bottom layer which reduced the pre-camber deflection at mid span generated by the expansion of CW blocks on the top part of the beam.

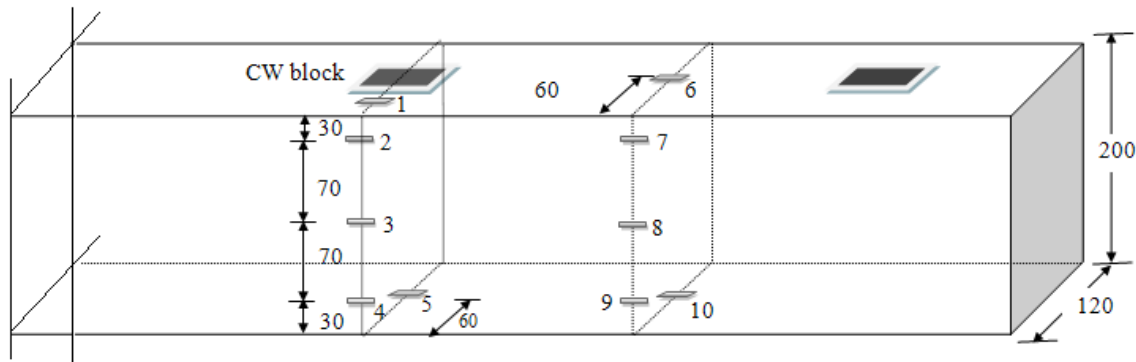


Figure 4. Strain gauge location through glulam beam depth.

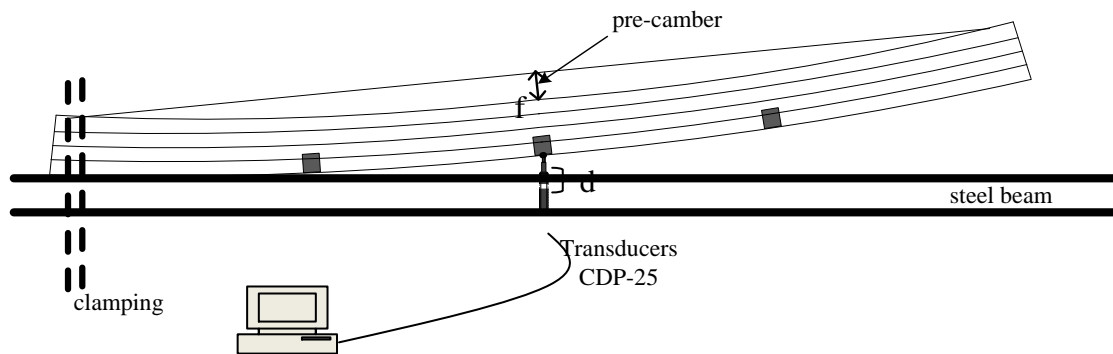


Figure 5. Set-up for measuring the pre-camber deflection of full-size beam.

Table 2. Summary of precamber test results.

No.	Beam specimen	Pre-camber _{avg} (mm)
1	LB-0CWB-0CWL	0
2	LB-3CWB-0CWL	4.48
3	LB-5CWB-0CWL	8.13
4	LB-5CWB-1CWL	7.46
5	LB-7CWB-1CWL	8.63

Initial Stress State

Figure 7 shows the measurements of the top extreme fibre strains of the pre-stressed beams building up for 45 days. Clearly, the measured strains were gradually increased until the end of testing. The maximum extreme fibre strain measured was 1150 micro-strain on the glulam beam reinforced by 7 CW blocks and a CW lamella, which was related to an extreme fibre stress of 8.6 MPa based on modulus of elasticity of 7478 MPa. For beams reinforced by three 45 mm CW blocks and five 45 mm CW blocks without CW lamella, the increases in the tensile strain were mild throughout the whole stage of testing. The measured strains on the top extreme fibre were 481 and 556 micro-strain for the former and the latter beams, respectively. Within elastic range, these strains indicated that the initial tensile stresses of 3.8 and 4.3 MPa were generated on the top extreme fibres of the beams pre-stressed, respectively.

The initial compressive strains were also generated at the bottom extreme fibre due to the pre-camber deflections as shown in Figure 8. Figure 8 also indicated that the glulam beam which was not reinforced by CW lamella show relatively constant strain reading other than those of reinforced by CW lamella. This is due to the effects of swelling and shrinkage of CW lamella during measurements in a chamber with cyclic RH.

Destructive Bending Tests

Generally, the load-deflection curves (Figure 9) demonstrate overall linear features initially until a certain loading level, which was varied from curve to curve. However, there were slope reductions in the later stage, which were again likely caused by local deformations in the CW-timber interface regions. The chart clearly shows the distinguished initial stiffness of beams with different pre-stressing arrangements comparing with beams without any reinforcement. The beam reinforced by seven 45mm thick CW blocks and a CW lamella at the bottom layer has the highest stiffness of 1032 kN/m, which is a 45.81% increase in comparison to the beam without any CW reinforcement. The initial bending stiffness for beams reinforced by three 45 mm and five 45 mm CW blocks but without CW lamella also increased by 8.6% and 16.8% respectively, compared with the control beam. It clearly indicated that the reinforcement with CW lamella contributed to increase on bending stiffness, as expected.

Results of the destructive bending tests are summarised in Table 3. They demonstrated that in comparison to the control beam the strength was increased by 11.2% for glulam beam reinforced by five 45 mm thick CW blocks and a CW lamella. However, glulam beam strength was multiplied by three and five 45 mm CW block without CW lamella were increased slightly to 1.4% and

3.8% respectively in comparison to that of the control beam without any CW blocks. Bending test of glulam beams reinforced by seven 45 mm thick block and a CW lamella was terminated at load of 32 kN due to premature failure caused by knots at extreme tensile fibre. However, this specimen still shows the highest initial bending stiffness.

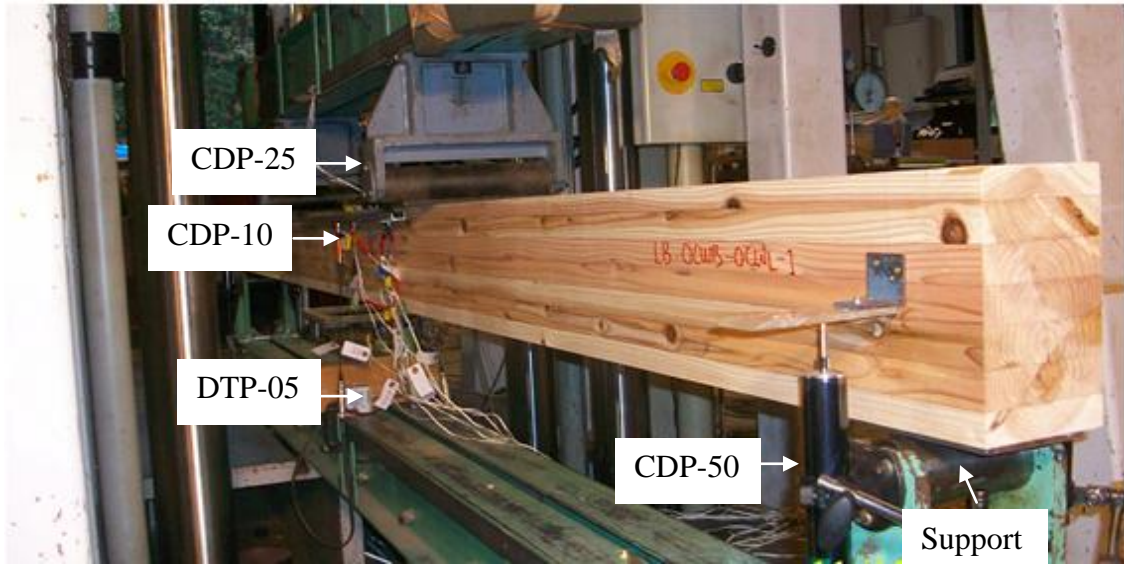


Figure 6. Set-up of the four-point bending test.

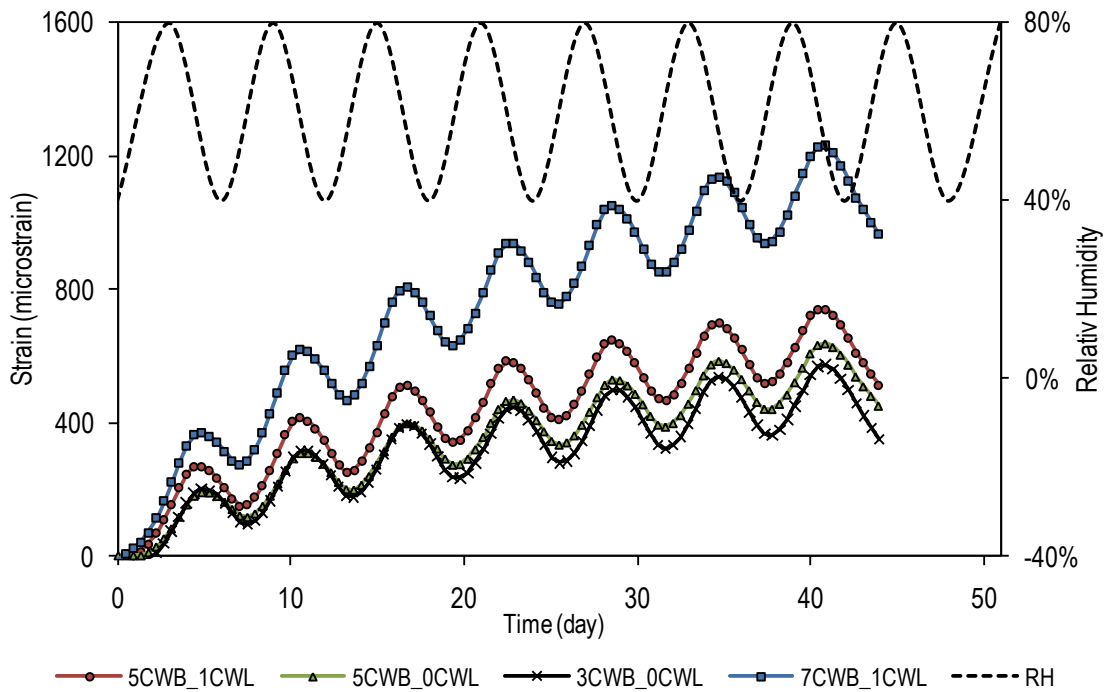


Figure 7. The measured and the predicted tensile extreme fibre strains at the top mid span based on best fit curve.

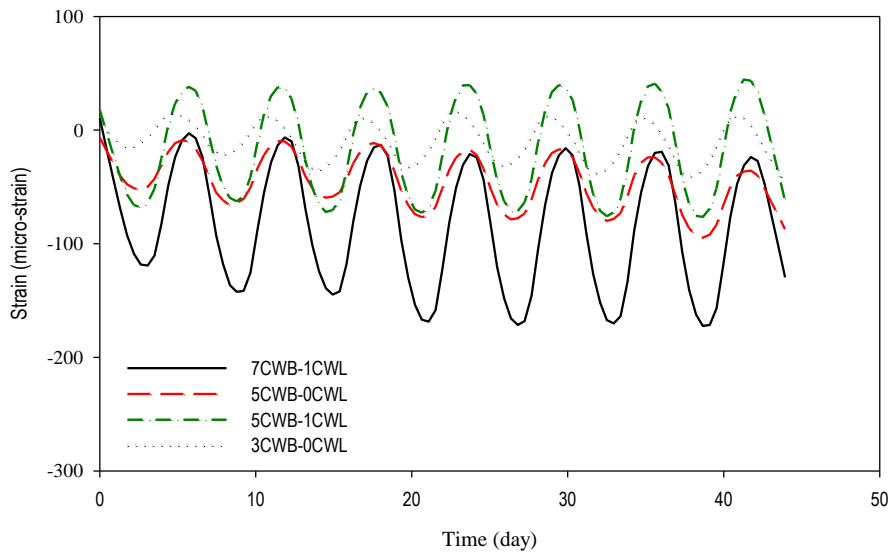


Figure 8. The measured compressive strains at the bottom extreme fibre.

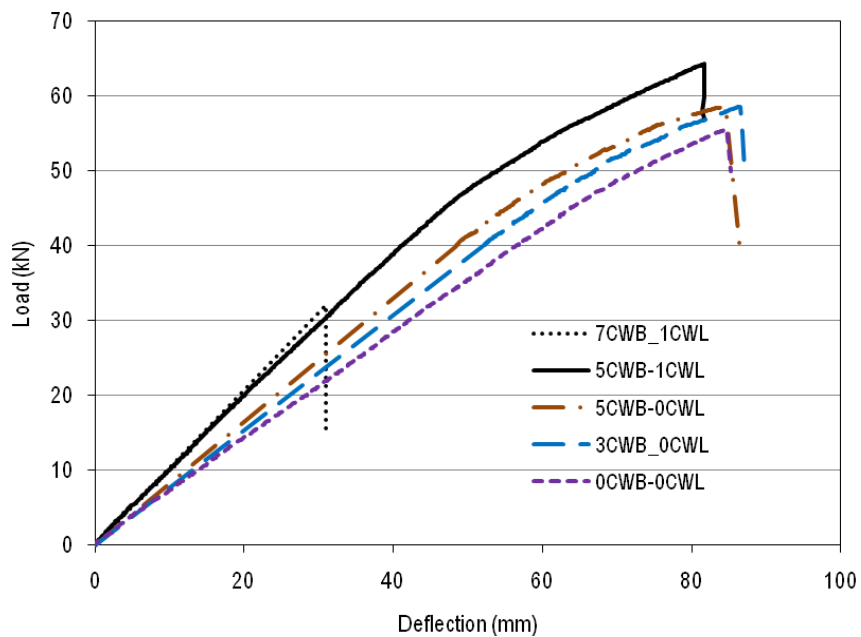


Figure 9. Load-deflection relationships of glulam beams reinforced differently.

Table 3. Summary of bending test results.

Specimen	P_{max}	Stiffness	MoE _L	MoE _G	MoR
	kN	N/mm	MPa	MPa	MPa
LB-0CWB-0CWL	57.76	707.7	7789	7186	43
LB-3CWB-0CWL	58.59	768.6	7645	7311	44
LB-5CWB-0CWL	58.67	826.6	6881	7978	45
LB-5CWB-1CWL	64.30	970.2	10833	10187	48
LB-7CWB-1CWL	32.67	1032.2	10356	9185	25

Global modulus of elasticity in bending for the pre-stressed beam was obtained from the relationship between the load and the total deflection at whole beam region. The results indicated that the global bending modulus increased significantly by increasing the amount of CW blocks with or without CW lamella. The maximum bending modulus was 10187 MPa for the beam reinforced by five 45 mm thick CW block and a CW lamella. However, the MoR for a beam reinforced by seven CW blocks and a CW lamella was quite low, which indicated a premature failure as mentioned before. The bending strength or modulus of rupture for the beam reinforced with five 45 mm CW blocks and a CW lamella increased by 11.6%, i.e. from 43 MPa to 48 MPa.

Conclusions

A new approach to strengthen glulam beams has been established in this research. The use of compressed wood made of a lower grade wood through densification as a reinforcing material has been approved effective. As only small amount of compressed wood are needed and no bonding between the CW and the beam is necessary, the techniques developed are economical and environmental friendly.

The measured pre-camber deflections of glulam beams pre-stressed after inserting CW blocks for 45 days are significant. The highest pre-camber deflection occurred in the beam reinforced by 7 CW blocks, which is 8.6 mm. There was also initial tensile strain of 1150 micro-strain on the top extreme fibre generated by the pre-camber for the above beam.

Destructive bending tests for all beams pre-stressed by the compress wood have also indicated that there are significant enhancements on the bending capacity and the initial stiffness. The enhancements of bending stiffness were 37.1 and 45.8% for the beam reinforced by five and seven CW blocks and a CW lamella respectively. In term of load carrying capacity, a beam reinforced by five CW blocks and a CW lamella reach the maximum of 64.3 kN.

Acknowledgments

Authors are grateful to the Ministry of National Education, the Republic of Indonesia for the financial support of this project. We specially would like to express our sincere thanks to the Laboratory of Structural Function, RISH, Kyoto University for supporting all experimental work.

References

Andre, A. 2006. Fibres for Strengthening of Timber Structures. Research Report 3: 1-91.
Anonymous. 2003. Eurocode 5, Timber Structures-Structural Timber and Glue Laminated Timber-

Determination of Some Physical and Mechanical Properties. BS EN 408:2003: 1-15.
Corradi, M.; A. Borri. 2007. Fir and Chestnut Timber Beams Reinforced with GFRP Pultruded Elements. Composites Part B: Engineering 38(2): 172-181.
Guan, Z.W.; P.D. Rodd; D.J. Pope. 2005. Study of Glulam Beams Pre-stressed with Pultruded GRP. Computers and Structures 83(28-30): 2476-2487.
Johnsson, H.; T. Blanksvärd; A. Carolin. 2007. Glulam Members Strengthened by Carbon Fibre Reinforcement. Materials and Structures 40(1): 47-56.
Jung, K.; A. Kitamori; K. Komatsu. 2008. Evaluation on Structural Performance of Compressed Wood as Shear Dowel. Holzforschung 62(4): 461-467.
Kitamori, A.; K. Jung; K. Komatsu. 2010. Mechanical Properties of Compressed Wood in Accordance with the Compression Ratio. Mokuzai Gakkaishi 56(2): 67-78.
Nikolaos, P.; C.T. Thanasis.1992. FRP-Reinforced Wood as Structural Material. Journal of Materials in Civil Engineering 4(3): 300-317.
Triantafillou, T.C.; N. Deskovic .1992. Prestressed FRP Sheets as External Reinforcement of Wood Members. Journal of Structural Engineering, ASCE 118(5): 1270-1284.
Zhou, Y.; M. Fushitani; K. Sato; M. Ozawa. 2000. Bending Creep Behaviour of Hot Pressed Wood under Cyclic Moisture Change Conditions. Journal of Wood Science 46: 423-430.

Buan Anshari
Department of Civil Engineering, Mataram University,
Jl Majapahit 62 Mataram, West Nusa Tenggara 83125,
Indonesia.
Tel./Fax. : +62 370 636126
E-mail : buan.anshari@unram.ac.id

Zhongwei Guan and Buan Anshari
Department of Engineering, University of Liverpool,
Brownlow Street, L69 3GQ, Liverpool, U.K.
Tel./Fax. : +44-151-7945095/7945218
E-mail : zguan@liverpool.ac.uk,
buan.anshari@liverpool.ac.uk

Akihisa Kitamori and Kohei Komatsu
Research Institute for Sustainable Humanosphere,
Kyoto University, Uji, Kyoto 611-0011, Japan
Tel./Fax. : +81-774-38-3675/3678
E-mail : kkomatsu@rish.kyoto-u.ac.jp;
kitamori@rish.kyoto-u.ac.jp

Kiho Jung
Faculty of Education, Shizuoka University, Japan
E-mail : ekjung@ipc.szhizuoka.ac.jp