Mechanical Properties of Compressed Wood with Various Compression Ratios

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

Abstract

This paper investigates five groups of compressed wood (CF), four of them made from compressed Japanese cedar with four different compression ratios (CR) of 33%, 50%, 67% and 70% and one without compression (control). The specimens were conditioned in relative humidity (RH) of 60% with moisture content (MC) of 12%. Mechanical properties tested were shear modulus in LR, LT and RT planes by single cube test method, Young's modulus in the L, R, T directions and poisson's ratios in all planes. Results showed that in comparison with control specimen, the average improvement on density with CR improvement were 25%, 75%, 175% and 261% corresponding to CRs of 33%, 50%, 67% and 70% respectively. It was also found that Young's modulus in the L and T directions increased significantly with the increase of CR. Shear modulus of RT plane increased with the rise of CR. Poisson's ratios tended to decrease with increasing compression ratio of CW.

Keywords: Mechanical properties, compression ratio, compressed wood, Japanese cedar

Introduction

Wood is a hygroscopic material where relative humidity (RH) change in air causes a considerable fluctuation of moisture content (MC) in wood, which results in appreciable dimensional changes. The anisotropic nature of wood cell structure contributes to different elastic properties and swelling-shrinkage behaviour in three distinct directions: longitudinal (L), radial (R) and tangential (T). There would be more significant moisture-dependent behaviour for a compressed wood that is made of low density softwood through densification in the radial direction under a specific pressure and heat treatment conditions. Compressed wood, assuming its pre-conditioned MC lower than that of the ambient one, is likely to swell after absorbing moisture from the ambient in order to reach equilibrium moisture content.

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 surface hardness and abrasion resistance. Dwianto *et al*. (1998) studied sugi wood (*Cryptomeria japonica* D.Don) densification with heat fixation. With the densification level of 50% from original thickness (CR), the retentions of the modulus of elasticity (MOE) and the modulus of rupture (MOR) for compressed sugi by heating at the optimum condition were 89% and 81% respectively. Zhou *et al*. (2000) investigated the bending creep behaviour of hot-press wood under cyclic moisture condition. It was concluded that 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.

Heger *et al*. (2004) investigated mechanical and durability performance of Thermo-Hydro-Mechanically (THM) densified wood. The mechanical, physical and durability properties of THM post treated densified wood were studied. The research was aiming to investigate the chemical changes of wood constituents during THM post-treatments of densified wood and to optimise the high steam treatment process as well as to obtain stable compressed wood with improved hygroscopicity, strength and durability. Densification of wood under saturated steam at 140°C improves the mechanical properties of wood and reduces wood hygroscopicity.

Yoshihara and Tsunematsu (2007a) examined the bending and shear properties of compressed wood (CW). Bending test series were conducted for sitka spruce (*Picea sitchensis* Carr.*)* with various compression ratios (CR). The results showed that Young's modulus increased with increasing of compression ratio when it was determined by load–strain relationship. Modulus of elasticity of CW in the longitudinal direction (E_L) with CR of 33%, 50%, 60% and 67% increased to 25, 26, 28 and 30 GPa respectively in comparison with those of normal sitka spruce with E_L=13 GPa. Yoshihara and Tsunematsu (2007b) also studied the elastic properties of compressed sitka spruce by conducting tension tests and bending tests to measure Young's modulus in radial (R) and tangential (T) directions and Poisson's ratio as well as shear modulus on the cross section. The results showed that Young's modulus in radial direction (E_R) decreased with the increasing of compression ratio, whereas that in the tangential direction (E_T) showed converse tendency, Poisson's ratio (ν_{RT}) decreased with increasing of compression ratio.

Kutnar *et al*. (2008) studied mechanical properties of Viscoelastic Thermal Compression (VTC) wood as specimen mentioned above. The modulus of rupture (MOR) and modulus of elasticity (MOE) were examined. Kutnar study showed the bending properties of VTC wood (MOR and MOE) were significantly increased due to the increased of density. The bonding performance of VTC wood was better than those of control specimen without thermal compression. 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 an 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 L and T plane increased almost in proportion to density, but there is no significant improvement of those on the L and R plane. Young's modulus increased with increasing compression ratio mainly in L direction. This paper investigates the relation of mechanical properties, which are essential for numerical modelling. Mechanical properties of compressed wood with four CRs and normal wood as comparison were obtained, which cover modulus of elasticity in longitudinal, radial and tangential directions of wood, shear modulus and Poisson's ratios in all principle planes.

Materials and Methods

Sample Preparation

Japanese cedar (*Cryptomeria japonica* D. Don) was used for preparation of compressed wood specimens for mechanical property tests and dimensional change in R, and T directions. The average oven-dry density of the cedar plate was 322 kg/m^3. A compressed wood made of lower grade timber through densification processes requires wood with free of knot and no defect to ensure that it could be compressed in the radial direction. The level of densification which also known as compression ratio (CR) can be represented as follows:

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

where t_0 and t_1 are the thickness of the wood plate in the radial direction before and after the compression treatment, respectively as illustrated in Figure 1.

Figure 1. Typical thickness before (t_0) and after compression (t_1)

Manufacturing Processes of Compressed Wood

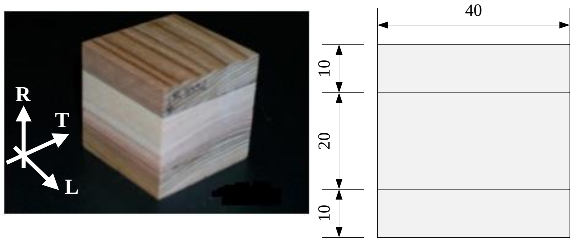
After conditioning processes, the wood plates were densified using pressing machine. In this research, standard pressing machine with maximum pressure force of 2000kN was used. The pressing processes were carried out without applying steam and fixation.

In general, densification processes are performed in three stages:

- Pre-heating. Before compressing the specimen, steel plates of compression machine were heated to a desired temperature of 130°C for about an hour.
- Pressing. The specimen is pressed by upper plate until it reaches a specified thickness, i.e. 15 mm, 20 mm. The pressure was held for 30 minutes before cooling.
- Cooling. Steel plate was cooled down using water circulation system by maintaining pressure and targeted thickness on the specimen to reduce its temperature down to the room temperature. It takes about one to 1.5 hours to complete this process.

Specimens for Elasticity Test

Specimens of 40 mm (L) × 40 mm (R) × 40 mm (T) were prepared for elasticity test. In order to obtain compressed wood with 40 mm thickness in radial direction, three plates of compressed wood were laminated. Three plates of compressed wood with thickness of 20 mm for inner part and two plates of 10 mm thickness as outer parts, as shown in Figure 2. Epoxy adhesive was used to bond the laminates and a clamp pressure of 1MPa was applied.



a. 3D View b. RT plane view

Figure 2. Typical size of specimen for elastic property tests

Two types of test were undertaken to obtain elastic properties of compressed wood with various compression ratios, i.e. shear tests to determine shear modulus of the CW in LT, LR and RT planes and compressive tests to determine Young's modulus in L, R, T directions and Poisson's ratios in three main planes. There were total of 32 cube specimens with size of 40 mm × 40 mm × 40 mm which were consisted of eight specimens for each of three compression ratios and eight specimens for the normal wood.

Density was obtained by weighing each sample before and after densification process divided by its volume. Measurements of moisture content were carried out by storing the specimens in an oven set up with a constant temperature of 105°C until no significant change in weight. Moisture content was then determined by calculating the decreased weight of specimen divided by its initial weight in percentage. It took about 3 to 4 weeks to reach the oven-dry condition.

Experimental Tests

Elastic property were tested to obtain shear modulus, Young's modulus and Poisson's ratios of the normal wood and compressed wood with various compression ratios. Such properties are essential input data for numerical modelling of timber structures using compressed wood. All samples for mechanic property tests were conditioned in chamber with relative humidity of 60% and targeted moisture content of 12%.

Shear tests were performed to determine shear modulus in all planes of compressed wood and normal wood using Single Cube Apparatus (SCA). Hassel *et al* (2009) developed the SCA method to determine shear properties of softwood. A 50 kN-capacity load cell was used to apply compressive load to specimens through the SCA using an Instron 1125 Universal Testing Machine at a cross-head speed of 0.5 mm/min. In order to measure strains in three directions, a tri-axial strain gauge type FRA-10-11 was bonded at back side of the specimen coincided with the main axis plane and 45° from the main axis as shown in Figure 3.

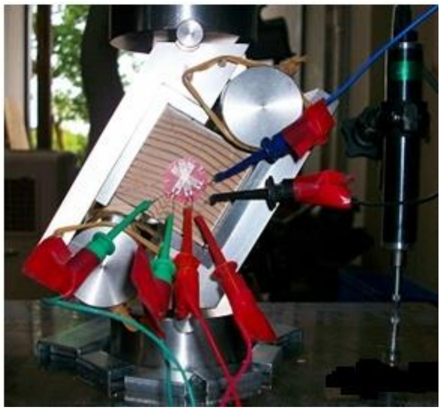


Figure 3. Setting up shear test with the SCA method

Six planes are possible to be tested: RT, TR, LT, TL, LR and RL where the first letter represents the shear direction and the second letter represents the perpendicular direction to the load in the observed plane.

As an example to determine shear modulus on RT plane with load direction inclined 31° from R axis, the shear stress on RT plane (τ_{RT}) is obtained as

$$\tau_{RT} = \frac{F_R \cos 31^0}{A} \quad \text{...} \ (2)$$

whereas the shear strain (γ_{RT}) can be derived by the following relation:

$$\gamma_{RT} = 2\varepsilon_{45} - \varepsilon_T - \varepsilon_R \quad \text{..} \ (3)$$

where ε_R and ε_T are normal strains in the radial and tangential direction of the specimens, respectively and ε_{45} is the normal strain in the 45° inclined direction with respect to R direction. The shear modulus (G_{RT}) was determined from the incremental relationship between the shear stress ($\Delta\tau_{RT}$) and strain ($\Delta\gamma_{RT}$) within the linear elastic region as: $G_{RT} = \frac{\Delta\tau_{RT}}{\Delta\gamma_{RT}}$.

Compressive tests were also undertaken to determine modulus of elasticity in longitudinal (E_L), radial (E_R) and tangential (E_T) directions and Poisson's ratios in all planes. Similar to those used in shear tests of the specimen of 40 mm × 40 mm × 40 mm. Strain gauges were placed in main axes L, R and T of the specimen to record strains and to determine modulus along all principle axes and Poisson ratios in all mutual principle planes as shown in Figure 4.

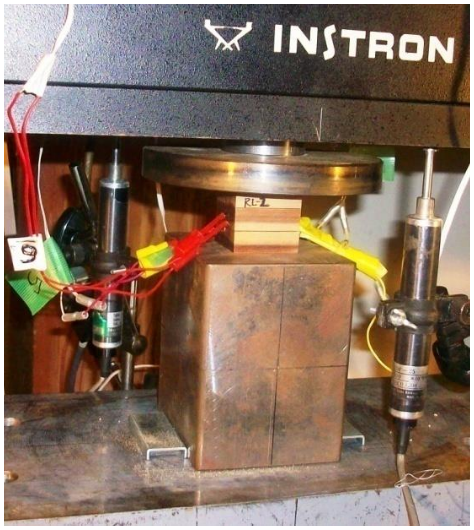


Figure 4. Setting up compression test in RL plane

Young's modulus (E_L, E_R and E_T) were calculated based on the incremental relationship between the compressive stress ($\Delta\sigma$) and strain ($\Delta\varepsilon$) within the linear elastic region as

$$E_i = \frac{\Delta\sigma_i}{\Delta\varepsilon_i}, i = L, R, T \quad \text{..} \ (4)$$

The relationships between strains in mutual principle directions were used to obtain Poisson's ratios (ν_{LR}, ν_{LT}, ν_{RT}, ν_{RL}; ν_{TL} and ν_{TR}) as expressed below.

$$\nu_{LR} = \left|\frac{\varepsilon_R}{\varepsilon_L}\right| \quad \text{..} \ (5)$$

$$\nu_{RL} = \left|\frac{\varepsilon_L}{\varepsilon_R}\right|; \quad \text{...} \ (6)$$

$$\nu_{LT} = \left|\frac{\varepsilon_T}{\varepsilon_L}\right|; \quad \text{...(1)........} \ (7)$$

$$\nu_{TL} = \left|\frac{\varepsilon_L}{\varepsilon_T}\right|; \quad \text{..} \ (8)$$

$$\nu_{RT} = \left|\frac{\varepsilon_T}{\varepsilon_R}\right|; \quad \text{...(2)........} \ (9)$$

$$\nu_{TR} = \left|\frac{\varepsilon_R}{\varepsilon_T}\right| \quad \text{..} \ (10)$$

Results and Discussion

Density and Moisture Content

Summarised results of density measurements and moisture content of all specimens are presented in Figures 5 and 6.

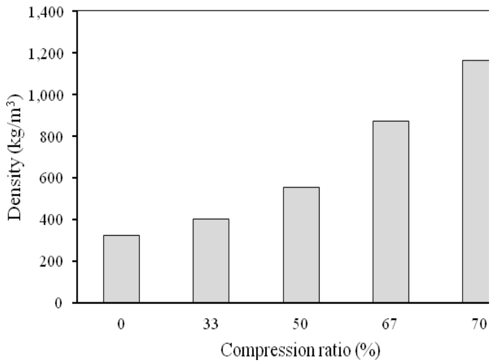


Figure 5. Density of moisture-dependent swelling specimens corresponding to compression ratios with initial MC=6%

Figure 5 shows the relationships between the density of compressed wood with various initial MCs and the compression ratios. The density increases with the increase of the compression ratio, as expected. The average improvement on density with increasing CR were 25%, 75%, 175% and 261% corresponding to CRs of 33%, 50%, 67% and 70% respectively, in comparison to the control specimen.

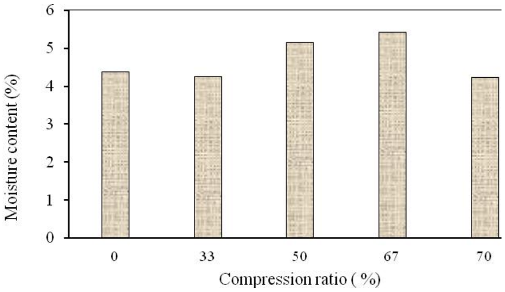


Figure 6. Moisture content of specimens at target MC=6%

Figure 6 shows the actual moisture content corresponding to the compression ratio. In general, the actual moisture was less than the target moisture content due to the manufacturing process of compressed wood in high temperature which leds to evaporation. Compressed wood moisture content is slightly higher than targeted moisture content of 6% with increasing of compression ratio. Compressed wood with 50%, 67% and 70% compression ratio reached actual moisture content of 5.2%, 5.4% and 4.2%, which is lower than targeted moisture content of 6%, respectively.

Mechanical Properties

Table 1 shows shear modulus obtained from Eqs. (4), which also indicated the relationship between the shear modulus and the compression ratio of compressed wood samples tested. It could be seen that the dependence of shear modulus on different compression ratios. The value of G_{RT} increases with increase on the CR due to densification occurring in the radial direction, whereas that of G_{LR} decreases until 50% of CR then increases slightly to 67% of CR and finally steeply increase to 70% of CR. However, G_{LT} decreases initially and then it is in the up-trend to the final 70% of CR. The great changes in percentage were recorded from G_{RT} and G_{LT}.

Table 1. The average of shear modulus

CR (%)	G_{LR}	G_{LT}	G_{RT}
	MPa	MPa	MPa
0	972	784	31
33	300	669	122
50	178	787	170
67	208	1208	256
70	1590	5717	878

Table 2 shows the CR-dependent modulus of elasticity of compressed wood with 12% moisture content in R, L, T directions based on the compression tests. The value of E_L increases greatly with the increase of compression ratio. The highest value of modulus of elasticity was approaching to 33 GPa in the L direction for the CW with 70% CR and 12% moisture content. The value of E_T increases significantly by increasing compression ratio and the maximum value is 3000 MPa at 70% CR. However, the values of E_R of the compressed wood corresponding to CRs of 33, 50 and 67% are lower than that of non-densified wood, with an exception case for 70% of CW. This is due to some fractures of wood cell during densification process. Normally, the fractures along the fibre direction are distributed around mid-thickness of the radial plane (Yoshihara and Tsunematsu 2007b).

Table 2. Modulus of elasticity in the L, R, T directions with various CRs

CR	E_L	E_R	E_T
(%)	MPa	MPa	MPa
0	8017	753	275
33	19864	338	1592
50	27028	354	2267
67	28415	523	2347
70	32858	3111	5061

The ratios between transversal and axial strains on various planes, which are commonly known as 'Poisson's ratio' were obtained. In general, the values of Poisson's ratios decreased with the increase of compression ratio in comparison, except for ν_{LR} and ν_{TL} related to CR=67%. However, the values of Poisson's ratio increased from 67% CR to 70% CR except those recorded in RT and TR planes were decreased. The high values of Poisson's ratio occur on LT plane at 33% CR and 50% of CR on LT plane, i.e. 0.67 and 0.51 respectively. In timber specimen it is likely to produce Poisson's ratio more than 0.5 due to excessive strain in transversal direction.(Anshari, *et.al*. 2011).

Conclusions

In term of density, the increase of CR from 33%, 50%, 67%, and 70% the corresponding densities were increased by 25%, 75%, 175% and 261% respectively, in comparison to the average initial density of the normal wood of 322 kg/m^3.

Shear modulus in LT plane showed significant improvement by increasing compression ratio from 33% to 70%, whereas on the LR plane the shear modulus showed the inverse tendency up to 67% CR. Young's modulus in L and T direction increased significantly with the rise of compression ratio or density. The highest values of E_L and E_T were recorded about 33 GPa and 5 GPa respectively for CW with 70% CR. For Poisson ratios, the values on the RL, TL, RT and TR planes varies significantly, but those on the LR and LT planes changed moderately.

Moisture-dependent dimensional changes behaviour in the R, T direction and material properties were obtained to be implemented in the finite element modelling to carry out structural analysis of timber joints and other structures using compressed wood fasteners.

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