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Numerical Modelling of the Initial Stress and upward deflection of Glulam Beams Pre-stresseed by Compressed Wood

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Abstract

A new approach to reinforce glulam timber beams has been developed by using compressed wood (CW) which is made of a lower grade wood through densification processes. In the reinforcing practice, compressed wood blocks are inserted into pre-cut holes on the top of glulam beams to produce pre-camber and to generate initial tensile and compressive stresses on the top and the bottom extreme fibre of the glulam beam. In order to optimize the size, the number and the location of CW blocks, 3-D finite element models have been developed. 3D non-linear finite element models have been developed to simulate the pre-camber of Glulam beams locally reinforced by compressed wood blocks. The models developed have also produced the initial tensile and compressive stresses at the top and bottom extreme fibres with building-up moisture-dependent swelling on the CW blocks. With the pre-camber and the initial stress state that cancel out proportions of working deflection and stresses.

1. Introduction

Here a new approach to enhance the load carrying capacity or bending capacity of glulam beam is developed, which is to use very small amount of compressed wood to pre-stress the beam. A compressed wood is made of a lower grade wood which is densified in radial direction under a specific pressure and temperature condition, and becomes a wood product with a high density and high strength. The technology developed is to make use of the moisture-dependent swelling nature of the compressed wood. By inserting the CW blocks with the desired initial moisture content on the top part of the glulam beam, a pre-camber deflection and the related initial stresses will be building up due to the swelling. However, the way to reinforce the glulam beam needs to be optimised to find out the effective size, location and number of the CW blocks. To undertake such parametric studies purely by experimental tests will be time consuming and expensive. The better way forward is to develop numerical models and apply the validated models to carry out parametric studies.

Wood as an orthotropic material has three planes of symmetry defined by the longitudinal direction along fibres, the radial direction parallel to the rays, and the tangential direction to the growth rings. The complex stress-strain relationship referred to three planes of symmetry characterizes the mechanical properties. In addition, time-dependent moisture swelling is defined through the strain rate as a function of temperature, moisture flux, etc.

The linear orthotropic constitutive equation can be expressed as follows [1, 2].

$$\{\varepsilon\} = [C^e]\{\sigma\} \tag{1}$$

where $\{\varepsilon\}$ is strain tensor, $\{\sigma\}$ is stress tensor and
$[C^e]$ is orthotropic elastic compliance matrix (6x6), i.e

$$\{\varepsilon\} = \{\varepsilon_L\, \varepsilon_R\, \varepsilon_T\, \gamma_{LR}\, \gamma_{LT}\, \gamma_{RT}\}^T \tag{2}$$

$$\{\sigma\} = \{\sigma_L\, \sigma_R\, \sigma_T\, \tau_{LR}\, \tau_{LT}\, \tau_{RT}\}^T \tag{3}$$

Research on modelling of moisture movement in wood was backed to 1991 [3] to model elastic and shrinkage properties of cell wood structures. Then modelling of long term strength and shape stability of timber columns subjected to the moisture variation was developed [4, 5]. The creep properties of wood under variable climate and moisture changes [6, 7], and mechanical response of wood in various humidity [8] were also modelled. Hanhijarvi [9] studied computational methods to predict the long-term performance of timber beam in variable climates. The method was implemented into a non-linear FE-program, which combined the moisture transport and structural analysis based on non-linear model of the longitudinal creep in wood. The result showed that the creep model was capable to simulate the experimentally observed properties of the mechano-sorptive effect.

Guan et al [10] developed finite element models of glulam beam pre-stressed with pultruded GRP tendon. The result showed that the model was capable of simulating the prestressing procedure adopted for the glulam and also indicated pre-camber at mid span of beam due to transfer of the prestressing force. Mirianon et al [11] studied the long-term response of wooden under variable load and humidity conditions by using the finite element software ABAQUS. Fortino et al.[12] developed a 3D moisture stress finite element analysis for time- dependent problems in timber structures. Oudjen et al. [13] studied the elasto-plastic law for wood behaviour under compressive loading. Kim and Harris[14] made a modelling approach to predict the behaviour of beams strengthened with CFRP composite. The strengthened beams show improved load-carrying capacity and energy absorption when compared to their unstrengthened counterparts.

In this paper, 3-D finite element models have been developed by using commercial code ABAQUS to simulate the prestressing behaviour of reinforced glulam beams using compressed wood blocks. Both glulam timber and compressed wood are modelled as orthotropic linear elastic materials in tension, and as elasto-plastic materials in compression in the embedding areas. Contact conditions between the compressed wood block and the glulam beam are modelled. Moisture-dependent swelling of the compressed wood blocks after they are inserted into the glulam beams is simulated by implementing swelling data obtained from experimental measurements.

2. Finite element modelling and material properties

2.1. FE modelling

3-D finite element models were developed to simulate the pre-camber deflection and the pre-stress state of the glulam beams reinforced. In the modelling, the size of the glulam timber beam was 1500 mm in length, 105 mm in depth, 105 mm in width, and 1200 mm in span length, as shown in Figure 2. Dimensions of the compressed wood blocks were 35x63x(15,30,45) in mm coinciding with L, T, and R directions of wood respectively. To simplify the model, some parameters were neglected, such as distortion in the grain, knots, temperature and density variation. Although there are strain rates and strain ratios in 3 directions of the L, R and T, the swelling ratio in the L direction was neglected.

To model moisture dependent swelling with time the swelling strain rate obtained from tests was implemented into the computer model in conjunction with the 'visco' available in Abaqus to simulate time dependent swelling. Interaction between the glulam and the CW is modelled by defining both the tangential and the normal contact behaviour. Friction formulation is 'rough' in tangential behavior and 'hard contact' for pressure-overclosure in normal behaviour [1,2]

2.2. Material properties

Material properties of glulam and compressed wood used in the modelling were obtained from experiment results of Japanese cedar through shear and compression tests. Orthotropic elastic material properties for glulam are listed as follows.

E_L= 8017 N/mm^2 ; E_R= 753 N/mm^2 E_T= 275 N/mm^2 ; G_{LR}= 972 N/mm^2

G_{LT}= 784 N/mm^2 ; G_{RT}= 31 N/mm^2: υ_{LR}= 0.3 ; υ_{LT}= 0.04 ; υ_{RT}= 0.58 ;

For compressed wood, the CW block was placed in a way in which its radial direction is coincident with the longitudinal direction of the beam. Material properties of the compressed wood blocks are then:

E_L= 32858 N/mm^2 ; E_R= 3111 N/mm^2 ; E_T= 5945 N/mm^2 ; G_{LR}= 878 N/mm^2

G_{LT}= 5717 N/mm^2 ; G_{RT}=1590 N/mm^2; υ_{LR}= 0.15 ; υ_{LT}= 0.50 ; υ_{RT}= 0.10 ;

Strain rate was obtained from measurements of swelling strain of Japanese cedar with the initial MC of 6%. The ultimate swelling strain recorded on the compressed wood in radial and tangential with CR=70 % was about 17 % and 1.5% respectively. Swelling strain in radial and tangential direction respectively may be expressed by the equations as follows.

$$\boldsymbol{\varepsilon_{sw}R = 0.001694(1 - e^{-0.0772t})} \tag{4}$$

$$\boldsymbol{\varepsilon_{sw}T = 0.00001154(1 - e^{-0.072t})} \tag{5}$$

In this study, the swelling law was derived from swelling strain in Eq. (4-5) as stated below in Eq. (6-7). This law was applied to describe swelling behaviour of compressed wood.

$$\dot{\varepsilon}^c = (e^{-0.065\sigma}) \times (A(1 - e^{-B(t+\Delta t)}) - A(1 - e^{-Bt})) \tag{6}$$

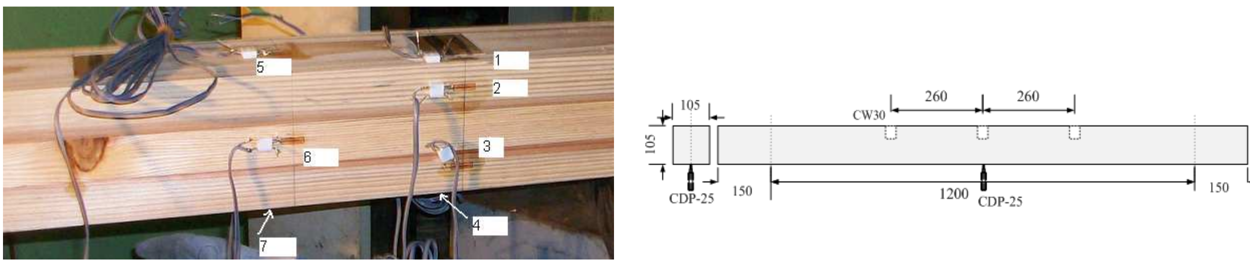
where A=0.1694; B=8.936×10^{-7}; t=time (second), and for creep law which was applicable for Glulam part can be formulated as follows:

$$\dot{\varepsilon}^c = (e^{-0.1\sigma}) \times (0.0159(1 - e^{-B(t+\Delta t)}) - 0.0159(1 - e^{-Bt})) \tag{7}$$

Regarding the anisotropic swelling behaviour, the swelling rate in each material orientation can be

$$\dot{\varepsilon}_{ii}^{sw} = r_{ii}\frac{1}{3}\dot{\varepsilon}^{sw} \tag{8}$$

where $\dot{\varepsilon}_{ii}^{sw}$ is swelling rate (/sec) in *i* direction, $\dot{\varepsilon}^{sw}$ is volumetric swelling strain rate (/sec) and r_{ii}= ratios of swelling in *i* direction.



(a) (b)

Figure 1. (a) Set up initial stress measurement, (b) set up pre-camber measurement

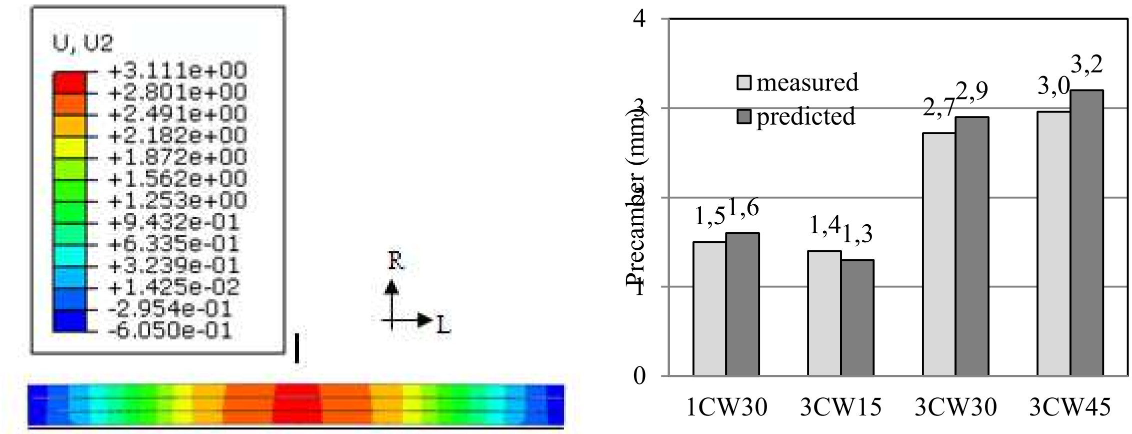
Validation of FE models was based on the measurements of the building-up pre-camber and extreme fibre strains from test setting-up as shown in Figure 1. There were 1 transducer placed underneath of the mid-span and 7 strain gauges attached to the beams reinforced. Readings of transducer and strain gauges were controlled and recorded by a Personal Computer which was connected to a data logger. The time interval for the data recording in the pre-stressing stage was set to 30 minutes which should give enough data for validation of FE models.

3. Results and discussions

3.1. Pre-camber model

Figures 2a show the simulated upward deflection, i.e. pre-camber, for a beam reinforced by three 30 mm thick CW blocks. The pre-camber deflections at the mid-span was 2.8 mm, which were generated by moisture-dependent swelling of CW block(s) after they were inserted into the top region of the beam for 60 days.

Figure 2b summarizes the comparisons of the pre-camber between the predicted values and the experimental measurements for the beams pre-stressed. Reasonably good correlation was obtained. The predicted pre-camber deflections were slightly higher than the experimental results, except for the beam reinforced by three 15 mm thick CW blocks. The differences between the final pre-camber deflections obtained from the tests and the related simulations were less than 7.5% for all reinforced beams.



(a) (b)

Figure 2: (a) Modelling of pre-camber (mm) for a beam reinforced by three 30mm thick CW blocks, (b) Comparison of the simulated and measured pre-camber deflections for beams reinforced.

3.2 Stress and strain

3.2.1 Tensile and compressive strains

In order to validate finite element models from a different angle, the strains at the top and the bottom extreme fibres were predicted, which were compared with the measured strains corresponding to the locations of No. 1 and No. 4 as shown in Figure 1a. Figure 3a shows comparisons of the simulated and measured tensile strains generated at the top extreme fibre of the beams after 60 days of pre-stressing. Clearly, the predicted strains are in reasonably good agreement with the measurements, especially for the beams reinforced by 3 CW blocks with thickness 15, 30, and 45 mm. The predicted strains for the beam with a single CW block of 30mm thick was over estimated, however with a difference less than 15%. The possible reason for the over-estimation might be attributed to the slightly higher overlap than the experimental one set in the numerical modelling. The maximum strain predicted was in the beam reinforced by three 45 mm thick CW blocks, as expected, which was 1615 microstrain.

Figure 3b shows the comparison of the compressive strains built-up at the bottom extreme fibre of the pre-stressed beams obtained from the experimental measurements and numerical modelling. Clearly, reasonably good correlation was obtained. The predicted strains for most of the beams reinforced are very close to the measured ones. The general trend was well simulated. However, the predicted strains for the beam reinforced by one 30 mm thick CW block were underestimated in comparison to the corresponding measurements (Fig.3b). There were relatively large increases on the extreme fibre strain in the first 30 days, which were also picked up by the FE simulations

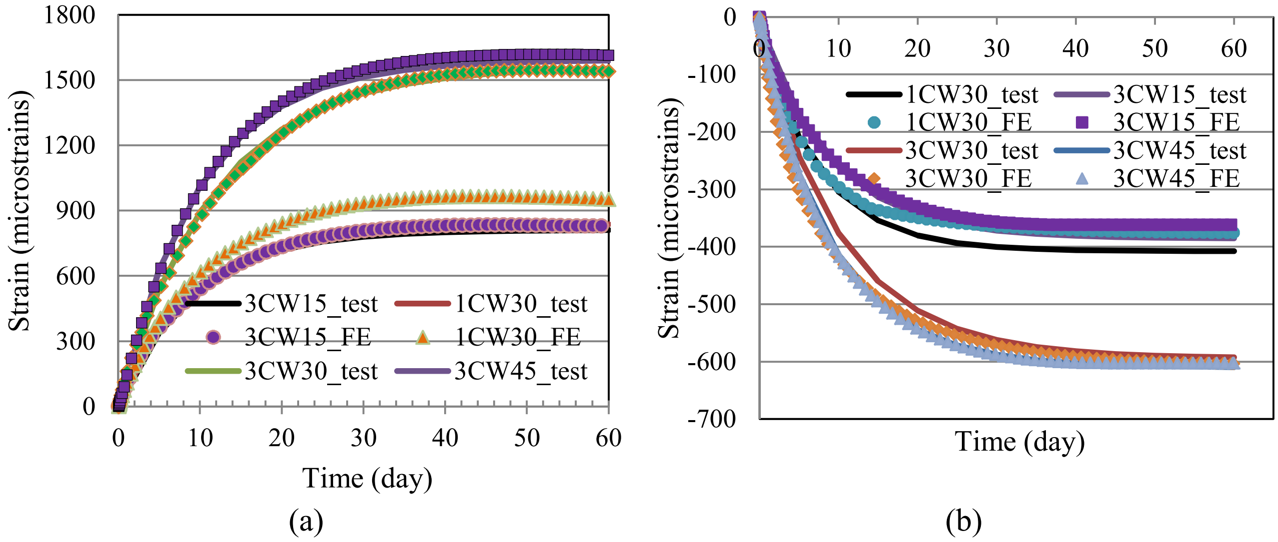


Figure 3: Comparisons of the predicted and measured tensile and compressive strains at the top and the bottom extreme fibre of the beams pre-stressed.

3.2.3 Tensile and compressive stresses

Figure 4 shows the predicted bending stress distribution on the beams pre-stressed by three 30 mm thick CW blocks. Clearly, there are critical tension areas on the Glulam beam adjacent to the transverse edges of the CW block along the longitudinal direction. The maximum tensile stress approached to 32.7 MPa for the beams. However, the high tensile stress region is relatively small. Practically, the stress should be smaller due to stress relaxation, which was not included in the modelling. Also, in all tests carried out there was no tensile failure experienced in the high tensile stress areas. Local compressive stresses also appeared on the top region of the Glulam beam around the CW block along the longitudinal direction due to expansion of the CW block. The regions influenced by compressive stresses are clearly larger than those by tensile stresses.

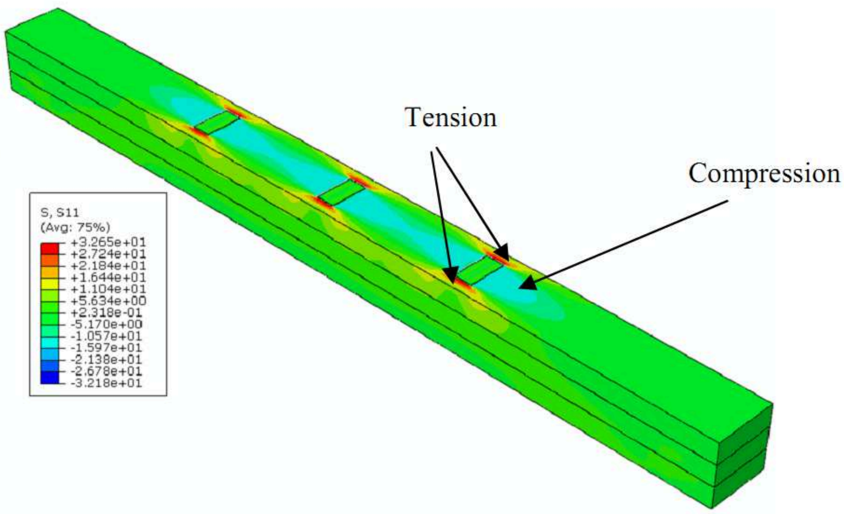


Figure 4: Bending stress (MPa) distributions around the CW block for beams reinforced by three CW 30 mm thick.

4. Conclusions

3-D non finite element models have been developed to investigate the reasonable size, number and location of CW blocks to be inserted in the Glulam beam which could generate effective pre-camber.The final models developed have been validated against the corresponding experimental results in terms of the pre-camber deflection and the initial strains (and therefore stresses)
The predicted extreme fibre strains (and therefore stresses) of all pre-stressed glulam beams have showed good correlation with the experimental results. The FE predictions also showed the highest pre-camber strain (and therefore stress) occurred on the beam reinforced by three 45mm thick CW blocks, which was coincident with the measured results.

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