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Structural behaviour of glued laminated timber beams pre-stressed by compressed wood

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ABSTRACT

In this study, glulam beams were strengthened by inserting compressed wood (CW) blocks into the pre-cut rectangular holes with one-thirds of the beam depth from the top of the beams. This practice was to make use of moisture-dependent swelling nature of the compressed wood which was conditioned with the moisture content significantly lower than the ambient one. The test results showed that a pre-camber was produced in the mid-span of the beam reinforced due to expansion of the compressed wood blocks on the top part of the beam. As a result, significant initial tensile and compressive stresses were generated on both the top and the bottom extreme fibres of the beam, respectively. Subsequent bending tests revealed that the initial stiffness and load carrying capacity of the pre-stressed beams were increased significantly in comparison to the beam without pre-stressing.

1. Introduction

Glued laminated timber or glulam have been used in Europe since the middle of the 19th century [1]. Glulam 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 using bonded reinforcing materials and pre- or post-stressing techniques has been studied for many decades. 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 [2–4]. Recently, research on glulam beams reinforced with fibre and fibre-reinforced polymers (FRPs), such as carbon, aramid and glass fibres, has been increased significantly, due to the high specific strength and stiffness of the FRP materials. Plevris and Triantafillou [5] studied the effect of reinforcing fir wood with carbon/epoxy fibre-reinforced plastics (CFRPs). Plevris and Triantafillou [6] investigated the creep behaviour of FRP-reinforced wood and developed an analytical approach to predict time-dependent deflections of timber beams reinforced with CFRP laminates with different thickness. Triantafillou and Descovic [7] also studied the effect of pre-stressed CFRP reinforcement bonded to European beech lumber. A lot of research work has been undertaken to investigate structural behaviour of glulam beams and solid timber beams reinforced by FRP sheets or bars [8–13].

Issa and Kmeid [14] undertook research on glulam beams reinforced with two types of reinforcement: steel plate and carbon fibre reinforced polymer. The reinforcement has changed the mode of failure from brittle to ductile and has increased the load-carrying capacity of the beams. Borri et al. [15] discussed the use of FRP materials to strengthen the existing wood elements under bending loads.

Guan et al. [16] studied glulam beams pre-stressed by pultruded GRP tendons. Finite element models were developed and validated, which is capable of simulating the pre-camber introduced into the beam due to transfer of the pre-stressing force. Corradi and Borri [17] also studied reinforcement of timber beams reinforced with pultruded GFRP elements. The results indicated significant improvement in flexural stiffness and capacity compared with unreinforced timber beams. Fiorelli and Dias [18] developed a theoretical model of fibre glass reinforced glulam beams with necessary validation. Johnsson et al. [19] studied reinforced glulam using pultruded rectangular carbon fibre rods and established the

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Nomenclature

a	distance between the support and the point load (mm)
b	beam width (mm)
h	beam depth (mm)
f	the actual pre-camber (mm)
t	time (day)
t_0	the thickness of the wood plate in the radial direction before the densification processes (mm)
t_1	the thickness of the wood plate in the radial direction after the densification processes (mm)
w_2–w_1	incremental deflection corresponding to $F_2 - F_1$ (mm)
y	the measured deflection (mm)
y_{SB}	pre-camber deflection for the short beam (mm)
A_1, B_1	constants for the best fit line equation of pre-camber deflection at mid span of the short beam
A_2, B_2	constants for the best fit line equation of the initial tensile strain on the top extreme fibre of the short beam
A_3, B_3, C_3	constants for the best fit line equation of the initial compressive strain on the bottom extreme fibre of the short beam
A_4, B_4, C_4	constants for the best fit line equation of the initial tensile strain on the bottom extreme fibre of the long beam
CR	compression ratio (%)
CW	compressed wood
E_L	modulus of elasticity in the longitudinal direction (MPa)
E_R	modulus of elasticity in the radial direction (MPa)
F_2–F_1	incremental load in elastic range (N)
L, R, T	longitudinal, radial and tangential direction, respectively
MC	moisture content (%)
MoE_g	global modulus of elasticity (MPa)
$(\varepsilon_t)_{SB}$	the measured extreme fibre tensile strain on the top of the short beam
$(\varepsilon_C)_{SB}$	the measured extreme fibre tensile strain on the bottom of the short beam
$(\varepsilon_t)_{LB}$	the measured extreme fibre tensile strain on the top of the long beam

anchorage length for this system. The proposed reinforcement method increased the short-term flexural load-carrying capacity by 49–63% on average.

However, reinforcements currently used to strengthen glulam beams cover almost whole bottom surface of the beam. Although they are effective, however due to various limitations, applications of strengthening the beam using CFRP, GFRP and other metallic materials are limited up to date. Possible problems of the existing strengthening techniques facing are likely compatibility, de-bonding, stress relaxation and complex procedures.

The above problems may be overcome by the newly developed strengthening techniques using compressed wood, which is to make use of moisture-dependent swelling nature of compressed wood. In the reinforcing practice, glulam beams were strengthened by inserting compressed wood blocks with the lower moisture content than the ambient one into the pre-cut rectangular holes on the top part of the glulam beams. Once the CW blocks were inserted, they would be gradually swelling due to 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 with respect to the neutral axis that would create a pre-camber of the beam. As a result, the up-lift deflection would also produce initial tensile and compressive stresses at the top and bottom extreme fibres of the beam before applying a service loading. When such beam is used in construction, the pre-camber will cancel out some downward working deflection and the initial extreme fibre stresses will cancel out some working stresses. Therefore, the beam size can be reduced (so material saved) but still having the desired load carrying capacity, or more load can be carried by the same beam, also with the bending stiffness increased. There are some major advantages of the above reinforcing technique, i.e. (1) it is very cost effective, (2) it uses timber to strengthen timber beams so that it is purely green, (3) very small amount of compressed wood is needed, (4) it is an easy and simple practice, (5) it will have significant impact on timber construction (domestic houses and large span commercial structures), material savings, sustainability and environmental protection by reducing CO_2 and volatile organic compounds (VOC) emissions.

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 part of a glulam beam, could generate pre-camber and further enhance the structural performance of the beam reinforced. In addition, the ultimate failure modes of both the pre-stressed short and long glulam beams were presented.

2. Sample preparation

In this research, Japanese cedar (*Crytomeria japonica* D Don) was used to manufacture compressed wood blocks and glulam beams with the initial density of 300–420 kg/m^3 and moisture content (MC) of 12% in a dry air condition.

2.1. Compressed wood

Compressed wood is made of lower grade timber through densification processes, which requires wood with free of knot and no other defects to ensure that it can be compressed uniformly 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 produced. 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 densification processes, respectively. In this research programme, the compression ratio of CW blocks was set to 70%. In order to obtain the possible maximum swelling of compressed wood, low moisture content needs to be conditioned. Here the initial moisture content of 6% was chosen.

The density of the compressed wood block is 1163 kg/m^3 in average which was increased by over 200% from that of the softwood. Material properties of CW blocks with CR = 70% were greatly enhanced, e.g. the Young's modulus in the *L* (longitudinal) and *R* (radial) directions increase significantly to 32,858 MPa and 3111 MPa respectively in comparison to the normal Japanese cedar with E_L = 8017 MPa and E_R = 753 MPa [20]. Compressed wood