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Prestressed glulam beams reinforced with CFRP bars

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HIGHLIGHTS

- Four-point bending of reinforced and prestressed glulam beams with CFRP bars.
- Bonded bar and end anchors result into a highly improved strength and stiffness.
- Stiffness further increased for prestressed compared to passively reinforced.
- End anchors with nuts allow for re-tightening and thus reduce the prestress loss.

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ABSTRACT

This paper describes an experimental test program and theoretical analysis which examines the reinforcing in flexure of glued laminated timber (glulam) beams using bonded-in carbon fiber reinforced polymer (CFRP) bars. A series of four-point bending tests were conducted till failure on unreinforced, passively reinforced and prestressed Douglas fir glulam beams in a simply-supported scheme. The focus of this research was to evaluate the reinforcing efficiency of both passively reinforced and prestressed beams. Test results showed that the flexural capacity of the reinforced, prestressed, prestressed & reinforced (bottom prestressed and top reinforced) beams greatly increased by 64.8%, 93.3% and 131%, respectively. While the maximum improvement of the bending stiffness reached 42.0%. Another important finding was that the extreme fiber tensile strain of timber beams at failure could be remarkably increased due to the presence of the tension reinforcement, which indicated it overcomes the effects of local defects and therefore the failure mode was changed from brittle tension failure to ductile compression failure. Based on the experimental results, a theoretical model was proposed to predict the flexural capacity of unreinforced, reinforced and prestressed timber beams, which was validated by the test data.

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1. Introduction

Timber is renewable and sustainable, and it also has the lowest energy consumption and the lowest carbon dioxide emission among many building materials. Thus it is one of the world's most environmentally friendly building materials. Glued laminated timber (glulam), as an engineered wood product, was developed during the 19th century in Europe and is widely used nowadays in buildings and bridges [1]. Glulam has an excellent strength-to-weight ratio, shape and size flexibility, as well as high strength and dimensional stability.

However, despite all of these benefits, glulam beams are usually underused due to the naturally defects such as knots and cross grain [2]. Another problem is the relative low stiffness as a result of which the design of glulam beams is often controlled by deflection limits [3]. For these reasons, many attempts have been made to reinforce or strengthen glulam or solid timber beams by using high tensile strength materials. In the earlier decades, the majority of this work focused on the use of metallic reinforcement [4–7]. More recently fiber reinforced polymers (FRP) was used as structural reinforcement for timber beams, which in the form of sheets, plates and bars [8–19]. It showed from these researches that the reinforcement in the tension zone would improve the strength, stiffness and ductility. Furthermore, both short-term and long-term deflections of the reinforced timber beams were decreased [3,20].

But the reinforcing materials usually has a notable higher ultimate tensile strain than that of wood, which means it was not effectively used while the failure occurs in this kind of timber members with passive reinforcement. Thus its economic efficiency was argued by some researchers [21,22]. Attempt then was made by introducing prestress in reinforcing materials [2,23–27]. As a result, the flexural strength is further increased due to the full

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use of both FRP and wood, while bending stiffness is greatly improved because of the pre-camber produced in the flexural members. Also the introduction of prestress may provide an extra strength at a small additional cost [27].

Since there was less research upon prestressed timber beams especially using FRP bars. In this paper, we focus on the improved performance of flexural behavior of glulam beams reinforced with prestressed CFRP bars. Four-point bending tests were conducted on the unreinforced control, passively reinforced and prestressed glulam beams with longitudinally bonded and end anchored CFRP bars. Subsequently a theoretical model was developed, in which the increased tensile strain of glulam timber resulted from reinforcement was taken into consideration. A calibration of the theoretical model was then undertaken based on the experimental results.

4. Experimental program

2.1. Materials

The glulam beams, CFRP bars and adhesive used in this investigation were purchased from several manufacturers, as detailed below, with the mechanical characteristics either obtained from test results in the university laboratory or furnished by the manufacturers.

2.1.1. Glulams

The Douglas fir homogeneous glulam was visually classified by the manufacturer and then tested in the university laboratory according to BS EN13183-1:2002 [28] and BS EN 408:2010 [29]. The characteristic strength properties (5% value) directly from test results were shown in Table 1. And the moisture content of the glulam ranged from 12.9% to 14.6% with the mean value of 13.8%, while the density ranged from 461 kg/m^3 to 583 kg/m^3 with the mean value of 531 kg/m^3. The experimental characteristic strength and stiffness properties were compared to those presented by BS EN 1194:1999 [30], which including the grade of GL 28 h and GL 36 h, as shown in Table 1.

2.1.2. CFRP bars

The CFRP bars had diameters of 11.0 mm and 16.0 mm to obtain two different reinforcement ratios in the tension zone of the glulam. The bars were composed of 65% unidirectional carbon fiber by volume and 35% thermoset epoxy resin. The tensile strength of the bars was 2300 N/mm^2 and modulus of elasticity in tension was 165,000 N/mm^2, as was provided by its manufacturer.

2.1.3. Adhesive

A two-component epoxy resin named XK390, with the density of about 1430 kg/m^3, was used between CFRP bars and glulam beams in this research. The mechanical properties of the adhesive, provided by the manufacturer, are listed in Table 2.

2.2. Specimens preparation

Twelve glulam beam specimens were tested to failure under monotonic load in four-point bending configuration. The specimens were 6.0 m long with a cross section of 75 mm × 300 mm. The reinforced and prestressed specimens were longitudinally slotted at the corresponding face of the CFRP bars (see Fig. 1). The slots were 30 mm deep and 20 mm wide for bonded bottom CFRP bars, while 30 mm deep and 16 mm wide for bonded top reinforced CFRP bars. The slots were filled with a small timber lamina for all of the specimens with bonded bars after the gluing process. The beam specimens were then divided into four groups with three replicates for each (see Fig. 1 and Table 3).

Prior to the bonding operation, the glulam slots were cleaned with high-pressure air while the CFRP bars were cleaned with acetone. The prestress was produced by the Preflex process [31], as shown in Fig. 2, through the symmetrical four-point bending loads. The end anchorages were tightened then as the glulam beam deformation came to the predicted value. Furthermore, the CFRP bar could be re-tightened if necessary by the nuts of the straight sleeve bonded-type anchorages (see Fig. 3). And a detailed description and comprehensive review of these kind of anchorages without nuts can also be found in the literature [32]. Subsequently, the slots were filled with the adhesive for the reinforcement/prestressed glulam specimens. The preflexion loads remained constant for about 72 h at the environmental temperature of 20 ± 2 °C. And then the applied Preflex load were slowly released while the concerned strains and deflections, including pre-camber, were recorded. The prestress force was then calculated from the average strain values of the CFRP bars at mid-point of the glulam beams and presented in Table 3. The glulam beam was immediately overturned and tested to failure, which presents a detailed report in the following part of this paper.

According to Negrão [27], during specimen preparation and test procedure, the possible prestress loss mainly caused by the contact condition of the anchor nuts and the elastic recovery of the specimens. However, the tensile strain of the prestressing FRP bars has been recording during this stage so that the prestress force is known to us. Also Negrão [27] discussed the prestress loss under long-term condition and pointed out that creep and reinforcement relaxation is one of the most concerning aspects. However, the issue on prestress loss is not the focus of this research.

Table 1
Characteristic strength and stiffness properties of homogeneous glulam.

Material property	Test results (N/mm^2)	GL 28 h [30] (N/mm^2)	GL 36 h [30] (N/mm^2)
Tension strength parallel to grain	32.8	19.5	26.0
Compression strength parallel to grain	37.0	26.5	31.0
Modulus of elasticity parallel to grain, mean value	12,500	12,600	14,700
Modulus of elasticity parallel to grain, 5% value	11,400	10,200	11,900

Table 2
Mechanical properties of the epoxy resin provided by the manufacturer.

Specification	Value (N/mm^2)
Compressive strength	70.0
Bending strength	65.0
Splitting strength	9.2
Modulus of elastic in tension	3320

2.3. Flexural test procedure and beam instrumentation

All glulam beam specimens were tested using the four-point bending method in accordance to BS EN 408:2010 [29], with the test setup as shown in Fig. 4. The loading rate was set to 5.0 mm/min and was held constant until failure. Lateral roller-type restraint was provided to prevent buckling or lateral torsional effects. Since the mid-span deflection is a relative value about that of supports, linear variable differential transformers (LVDTs) were located at both midpoint and end supports of the glulam beam, while strains were monitored by paper based strain gauge at mid-span of the beam both throughout the depth with a space of 75 mm and in CFRP bars. It should be noted that strain gauges just included on one side of glulam beams, so the twist of beams and deviations of wood quality were not accounted for.

2.4. Experimental results and discussion

2.4.1. Load–deflection behavior

Figs. 5–8 represent the load–deflection behavior of the four series of glulam beams including unreinforced, reinforced and prestressed:

- The load–deflection behavior of the unreinforced control beams (C-1, C-2 and C-3) are shown in Fig. 5. All the glulam beams exhibited linear elastic behavior till the failure at tension face due to the presence of either knots or cross grain. No compression yielding occurred in the compression zone of the glulam beams.
- As can be seen from the load–deflection curves of the bottom reinforced beams (R11-1, R11-2 and R11-3) shown in Fig. 6, non-linear behavior is introduced into the beams before the maximum load was reached. This means that the yielding of the wood in the compression zone occurred before the wood of tension face reached the ultimate tensile strain.
- Fig. 7 plots the load–deflection curves of the two bottom prestressed beams (P16-1 and P16-2). The bottom prestressed beams shows almost the same load–deflection behavior as that of bottom reinforced beams. Furthermore, the deflection of the prestressed beam decreased, when compared to the reinforced beams, due to the pre-camber produce by the prestress. The load–deflection data of the specimen P16-3 was not recorded because of the faulty LVDT.
- Fig. 8 illustrates the load–deflection curves of the bottom prestressed & top reinforced beams (P16R11-1, P16R11-2 and P16R11-3). Due to the presence of the top reinforcement in the compression zone, as can be seen from Fig. 8, it shows less non-linear behavior than that of just prestressed beams. It indicates that the compression reinforcement suspend or prevent the wood yielding in the compression zone. And as a result, the ultimate load of this series is even higher.

It should be noted that the post failure behavior of most reinforced or prestressed beams was not recorded during the test. So it is not possible to predict the ductility of the tested beams.

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