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Post-tensioning of glulam timber with steel tendons

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HIGHLIGHTS

- Four-point bending of reinforced and post-tensioned glulam timber with steel tendons.
- Strength and stiffness increased for reinforced timber compared to unreinforced.
- Strength and stiffness further increased for post-tensioned compared to reinforced.
- Active reinforcement offers additional benefits over the commonly used passive form.
- Preliminary long-term tests show no excessive losses in post-tensioning force.

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ABSTRACT

This paper describes a series of four-point bending tests that were conducted, under service loads and to failure, on unreinforced, reinforced and post-tensioned glulam timber beams, where the reinforcing tendon used was 12 mm diameter toughened steel bar. The research was designed to evaluate the benefits offered by including an active reinforcement in contrast to the passive reinforcement typically used within timber strengthening works, in addition to establishing the effect that bonding the reinforcing tendon has on the materials performance.

The laboratory investigations established that the flexural strength and stiffness increased for both the reinforced and post-tensioned timbers compared to the unreinforced beams. The flexural strength of the reinforced timber increased by 29.4%, while the stiffness increased by 28.1%. Timber that was post-tensioned with an unbonded steel tendon showed a flexural strength increase of 17.6% and an increase in stiffness of 8.1%. Post-tensioned beams with a bonded steel tendon showed increases in flexural strength and stiffness of 40.1% and 30% respectively.

1. Introduction

Timber sourced from sustainable forests is not only considerably less damaging to the environment than other construction materials, the act of forestry is regarded as a beneficial process as it has the potential to reduce the concentration of atmospheric carbon dioxide by sequestrating carbon. Timber has an excellent strength to weight ratio, as well as being renewable with a potentially low embodied energy. Despite the many benefits offered by timber use over other construction materials it remains underused in the industry [1]. The underuse of timber as a structural material may be attributed to the naturally occurring defects within its structure. Undesirable characteristics include the presence of knots and grain defects, susceptibility to the effects of moisture and other time dependent vulnerabilities, such as the occurrence of creep, which will affect the material's structural performance.

The limitations experienced when using timber in construction have been continually addressed in the past with the development of LVL and glulam to reduce the presence of natural defects. More recently, research has been undertaken regarding the reinforcement of timber using various metals and fibre reinforced polymers as an attempt to enhance the timber's strength and stiffness [2–5]. Steel is a typical material used in various situations as a strengthening material and, as such, was regarded as an appropriate initial benchmark to use within this investigation of post-tensioned timber. A 12 mm diameter steel bar has sufficient tensile strength to comfortably permit a 20 kN tensile force to be applied directly, while additional loading is then applied to the beam.

Research in reinforcing timber has been previously undertaken resulting in some researchers concluding that the addition of reinforcement can be equated to the addition of a single timber lamina [4,6]. It is therefore arguable that the reinforcement utilised in

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these investigations is not being fully exploited as only a fraction of their structural potential is used. By initially tensioning the material and therefore using active reinforcement a number of advantages can be further realised as, 'prestressing effectively increases flexural strength by introducing an initial compressive stress into the timber fibres that in service are under tension' [7]. Initial research investigating the effect of prestressing using steel plates bonded in the tension zone of glulam timbers was completed in the past decades, indicating the interest and feasibility of the process [8–10]. Research regarding the post-tensioning of timber has recently resulted in the creation of multi-storey, box beam buildings with a degree of seismic tolerance [11,12].

This research evaluated the feasibility of strengthening timber beams by the addition of a post-tensioned steel tendon. Throughout the full investigation, a combination of unreinforced, reinforced and post-tensioned glulam timber beams, with both unbonded and bonded steel tendons, were tested experimentally to determine the structural advantages. This paper discusses the investigation of unreinforced and steel reinforced timber sections. Extensive material testing and theoretical investigations examining the various stresses occurring throughout the materials, during the testing process, were undertaken and analysed to enable the development of a theoretical stress model capable of accurately predicting the behaviour of the system.

2. Material and methods

Twenty glulam timber beams (grade GL28), 3 m length, were machined to a cross-section of 45 mm × 155 mm. Members that were to be reinforced were further machined to create a 16 mm diameter circular void throughout the length, its centre located 22.5 mm from the soffit. The void was created by removing half a lamina, 22.5 mm, from the soffit of the timber and subsequently routering two semi-circular groves, diameter of 16 mm, into each surface. The two sections were then bonded under pressure using a two-part epoxy resin to create the glulam beams with a 16 mm void. The beams were then divided into four groups of five members (see Table 1), with moisture content and a visual inspection being recorded for each;

- solid GL28 control beams [C series]
- beams passively reinforced with a 12 mm diameter steel bar [R series]
- post-tensioned beams with an unbonded 12 mm diameter steel tendon [U series]
- post-tensioned beams with a bonded 12 mm diameter steel tendon [B series]

The materials used throughout this investigation were purchased from a number of manufacturers, as detailed below, with the structural properties being further verified by material testing in the university laboratory, in accordance with BS EN 408:2010 [13] where appropriate.

2.1. Glulam

The European Spruce was visually classified by the manufacturer as GL28C, with the structural properties shown in Table 2. Material tests were completed to obtain accurate values for the compressive and tensile strengths. Samples of glulam timber were removed to facilitate the material tests;

- 45 × 155 × 270 mm blocks were crushed parallel to the grain using an accurately calibrated hydraulic actuator to obtain the mean ultimate compressive strength
- 9 × 12 mm dog bone samples were tested in an accurately calibrated direct tension testing machine to obtain the mean ultimate tensile strength.

Table 2
GL28 material properties from manufacturer.

Material property	Value (N/mm^2)
Bending strength	28
Tensile strength parallel to the grain	16.5
Tensile strength perpendicular to the grain	0.5
Compression parallel to the grain	24
Compression perpendicular to the grain	3.0
Shear strength	2.7
Modulus of elasticity, mean value	12,600
Modulus of elasticity, 5% value	10,200

Results from preliminary material tests showed that the mean compressive strength of the glulam used within the experimental series was 37.5 N/mm^2 with a standard deviation of 1.9. The mean tensile strength of a sample of the glulam timber was 38.4 N/mm^2 with a standard deviation of 6.8, indicating the high level or variability caused by the defects inherent in timber.

To date a full set of material tests is incomplete and as such only the mean compressive and tensile values are known. Therefore, until characteristic values are obtained through testing, the manufacturers supplied values have been used throughout the theoretical research.

2.2. Steel tendons

Steel tendons, 12 mm in diameter, where obtained for use within the series of experimental tests. Preliminarily tensile tests were conducted to ensure the tendon would not deform or rupture during the post-tensioning and subsequent loading of both the U and B series of tests.

2.3. Adhesive

The adhesive [14] used in all aspects of the experimental research was a two-part thixotropic epoxy adhesive specifically manufactured as a slow setting, gap filling epoxy adhesive and therefore ideally suited for use within this investigation. The slow setting nature of the epoxy adhesive allowed both; sufficient manipulation during the construction of the glulam timbers with the 16 mm duct and time for the adhesive to flow, filling the void, during the bonding of the reinforcement and post-tensioned tendons. The manufacturer's material properties and basic, preliminary investigations and previous studies conducted within the university [15] determined that the adhesive would be sufficient for all aspects of this research.

Fig. 1, below, illustrates results of the preliminary testing that was conducted to ensure a sufficient bond between the steel tendon and the timber would be achieved. Epoxy adhesive was injected through pre-drilled holes in the soffit to members that were both passively and actively reinforced following elastic testing. As is evident the preliminary testing offered positive results, with a uniform 2 mm bond-line being achieved around the tendon.

2.4. Flexural test procedure

The glulam timber beams were tested using the four point bending method in accordance to BS EN 408:2010 [13], with the experimental arrangement as shown in Fig. 2. Beams were supported on roller supports, as was the spreader bar below the loading point. Lateral supports were provided to resist any lateral torsional effects that may have occurred. The timber was air dried and stored in a constant laboratory environment to ensure that the moisture content of every specimen ranged from 9% to 11%.

Due to the variability of timber it was necessary to test each beam elastically to allow an accurate comparison of the various states of reinforcing to occur. To assess the benefits provided by both simple reinforcing and post-tensioning each timber beam was tested elastically as follows;

- control, solid timber beam
- 12 mm steel tendon slotted slack through the timber beam
  and either;
  - 12 mm steel tendon bonded as passive reinforcement [R series]
    or;

Table 1
Series and Specimen Information.

Series reference	No. of samples	Reinforcement				
		Type	Diameter (mm)		Cross-section ratio (%)	Post-tensioning force (kN)
C1–C5	5	None	–	–	0.00	–
R1–R5	5	Steel tendon	12	Bonded	1.67	0
U1–U5	5	Post-tensioned steel tendon	12	End Anchor	1.67	20.0
B1–B5	5	Post-tensioned steel tendon	12	Bonded	1.67	20.0