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Post-tensioning of Glulam Timber with Steel Tendons

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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 12mm 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.

KEYWORDS: Post-tension, Glulam, Timber, Steel, Four-point Bending

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 12mm diameter steel bar has sufficient tensile strength to comfortably permit a 20kN 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 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].
   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), 3m length, were machined to a cross-section of 45mm x 155mm. Members that were to be reinforced were further machined to create a 16mm diameter circular void throughout the length, its centre located 22.5mm from the soffit. The void was created by removing half a lamina, 22.5mm, from the soffit of the timber and subsequently routering two semi-circular groves, diameter of 16mm, into each surface. The two sections were then bonded under pressure using a two-part epoxy resin to create the glulam

beams with a 16mm void. The beams were then divided into four groups of five members, with moisture content and a visual inspection being recorded for each;

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

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

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[8] 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;

- 45x155x270mm blocks were crushed parallel to the grain using an accurately calibrated hydraulic actuator to obtain the mean ultimate compressive strength
- 9x12mm 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	12600
Modulus of elasticity, 5% value	10200

Results from preliminary material tests showed that the mean compressive strength of the glulam used within the experimental series was 37.5N/mm^2 with a standard deviation of 1.9. The mean tensile strength of a sample of the glulam timber was 38.4N/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, 12mm 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[9] 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 16mm 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 [10] determined that the adhesive would be sufficient for all aspects of this research.

Figure 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 2mm bond-line being achieved around the tendon.
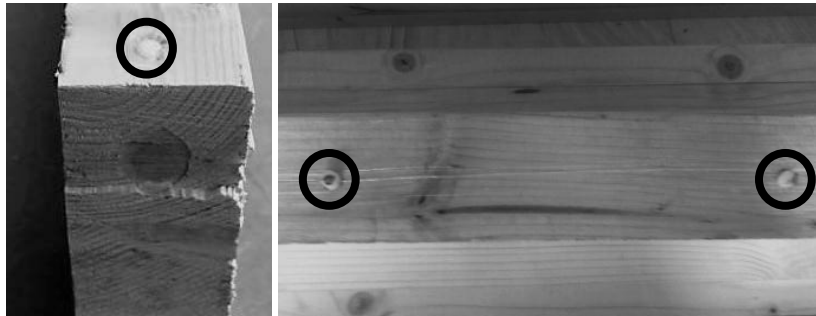

Fig. 1 Results of adhesive testing to ensure sufficient bond is achieved

2.4 Flexural Test Procedure

The glulam timber beams were tested using the four point bending method in accordance to BS EN 408:2010[8], with the experimental arrangement as shown in Figure2. 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 9-11%.

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
- 12mm steel tendon slotted slack through the timber beam
  and either;
- 12mm steel tendon bonded as passive reinforcement [R series]
  or;
- 12mm steel tendon, post-tensioned to 20kN, unbonded [U&B series]
- 12mm steel tendon, post-tensioned to 20kN, bonded [B series]

The elastic tests were conducted by applying an initial load of 10kN, increasing in increments of 1kN, with data recorded at each interval on all instrumentation. The 10kN load was held for five minutes, unloaded incrementally and all load removed for a further five minutes prior to the second elastic loading test which proceeded in the same manner. The tests to failure were carried out using the same process following the previous elastic tests and subsequently loaded to failure. The response was monitored through instrumentation and additionally documented using digital imagery.

The post-tensioned beams where initially tested as above, prior to the application of the tension force. Once complete the steel tendon was tensioned using a 13 ton hollow plunger cylindrical ram, located at one end of the beam. The ram was secured using open grip barrel and wedge clamps, with a load cell and bearing plates located against the timber, typical arrangement shown in Figures 3a&b. The tensile force was applied in increments, with deflection, strain and force data gathered at each interval. Once the tensile force was recorded at 20kN, elastic loading followed by loading to failure occurred as detailed previously.
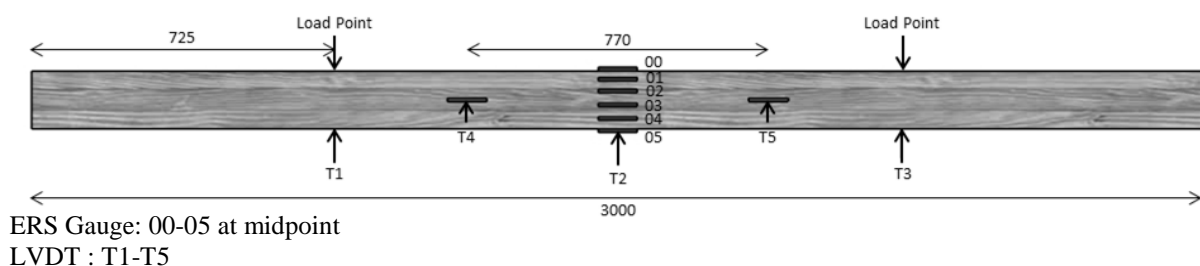

ERS Gauge: 00-05 at midpoint
LVDT : T1-T5

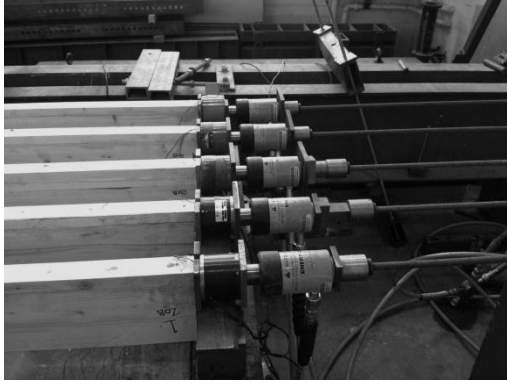**Fig. 2** Test instrumentation and arrangement

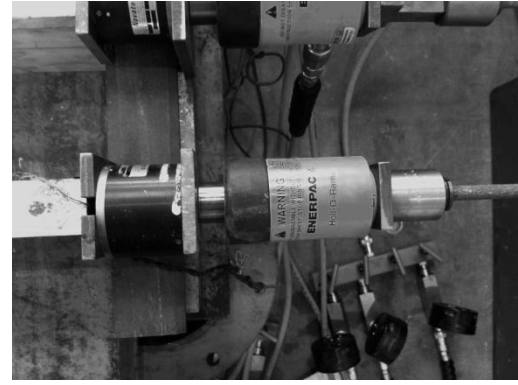**Fig. 3a** Typical post-tensioning arrangement of B Series beams

Fig. 3b Application and monitoring of post-tension force

3.   Theoretical Investigation of Post-tensioning

The behaviour of linear elastic stress is a well-understood concept commonly used within the concrete industry, where the process of post-tensioning is a frequent occurrence. As a preliminary investigation the theory has been applied to this process.

The theoretical approach used throughout this research was two-fold, initially considering the plastic failure of a reinforced glulam timber beam and additionally considering the load required to neutralise the induced stresses resulting from the post-tensioning process. Figure 4 illustrates the stress profiles for both an unreinforced and reinforced timber beam at failure. Throughout this research profile (i) and (iv) were used to calculate the ultimate capacity of the various glulam timber beams.
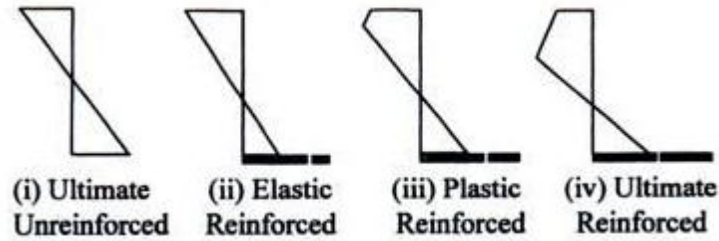

Fig. 4 Stress profiles of unreinforced and tension reinforced glulam timber[3]

The post-tensioned glulam timber was considered as a reinforced beam, but with additional stresses that the process induces, as illustrated by Figure 5. Equation 1 and 2 demonstrate the theoretical approach taken, with the applied moment being calculated as that required to create a zero stress scenario. The calculations assumed that the post-tensioning force was fully and uniformly transferred from the steel tendon to the glulam timber, in addition to both the timber and steel behaving elastically until failure.
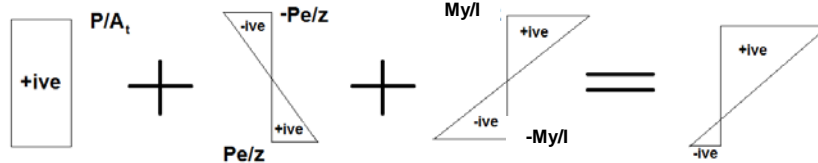
Fig. 5 Stress profiles from post-tensioning and load application

$$\sigma_{top} = \frac{P}{A_t} - \frac{Pe}{z} + \frac{My}{I} \tag{1}$$

$$\sigma_{bottom} = \frac{P}{A_t} + \frac{Pe}{z} - \frac{My}{I} \tag{2}$$

where P (kN): post-tensioning force; A_t (mm^2): area of timber; e (mm): eccentricity of tendon placement; z (mm^3): section modulus; M (kNm): applied moment; y (mm): distance to neutral axis; I (mm^4): second moment of area.

Table 3
Theoretical investigation of bonded, post-tensioned glulam timber

	C Series	R series	B series
Theoretical ultimate capacity (kN)	21.2	26.8	31.7
Average experimental ultimate capacity (kN)	19.9	25.8	29.7
Error (%)	6.5	3.9	6.7

Table 3 highlights the variation between theoretical and experimental values - with the B series calculation based upon the R series it is expected that the error may increase. As the calculations for the passively reinforced timbers are based upon profile (iv) the small error highlights that the glulam behaved in this manner at collapse, further varying this approach as an accurate method of theoretical calculation.

4. Experimental Results & Discussion
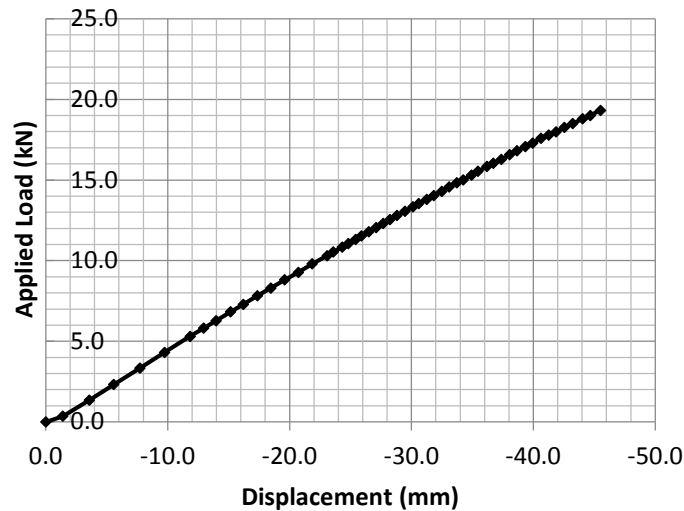- Unreinforced Control Beams

Fig. 6 Typical load/deflection graph for an unreinforced glulam timber beam

Figure 6 represents the typical deflection response of an unreinforced timber beam used throughout the experimental programme. As is evident from the figure the typically proportional trend line continues until the failure of the beam indicating that the failure mode was sudden and brittle, as was witnessed throughout the testing.

The C series of tests provided a benchmark for comparison with the other series experimentally tested and as such a point to measure any benefits provided by the additional reinforcement. To provide further reference the glulam timbers elastic modulus was calculated using the equation shown below, as specified by BS EN 408:2010[8].

$$E_{mg} = \frac{3al^2 - 4a^3}{2bh^3(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh})}$$

(3)

where E_{mg} (GPa): global modulus of elasticity; a (mm): distance to loading point; l (mm): beam length; b (mm): beam width; h (mm): beam depth: w_1 (mm): deformation at F_1; w_2 (mm): deformation at F_2; F_1 (kN): applied load at 10% of estimated maximum load: F_2 (kN): applied load at 40% of estimated maximum load: G (N/mm^2): shear modulus.

Table 4 below illustrates the results calculated from the elastic testing of the unreinforced timber series. As each beam was tested twice elastically a value for young's modulus has been calculated for each, with an average and relevant standard deviation included. As is evident the average calculated for the modulus of elasticity is considerably lower than that specified by the manufacturer, but as previously calculations have been completed using the manufactures specifications until further material testing may be carried out. The value of 9.6, however, will be used as a benchmark throughout this paper to allow a comparison between the various experimental series.

Table 4
Young's modulus of unreinforced glulam timber (C series)

Beam No.	E_{mg} (GPa)		Standard Deviation	Average E_{mg} (GPa)
1	9.20	9.31		
2	10.24	11.05		
3	9.59	10.02	1.22	9.64
4	9.59	10.48		
5	7.27	7.44		

Figure 7 illustrates the average stress profiles gathered at the elastic loading limit and at failure by the strain gauges placed along the face of the timber. The elastic profile is linear, as expected, with the stress values remaining in an acceptable range. The failure profile demonstrates the plastic stress profile discussed by Patrick[3] with the peak compressive occurring below the top surface of the glulam timber. Considering the figures recorded, the peak value was reached on the soffit of the beam and accordingly all timbers in this series failed due to a tensile split along the soffit of the beam – as is expected from unreinforced timber. This plastic profile will be used for further theoretical investigations into the plastic behaviour of the glulam timber.
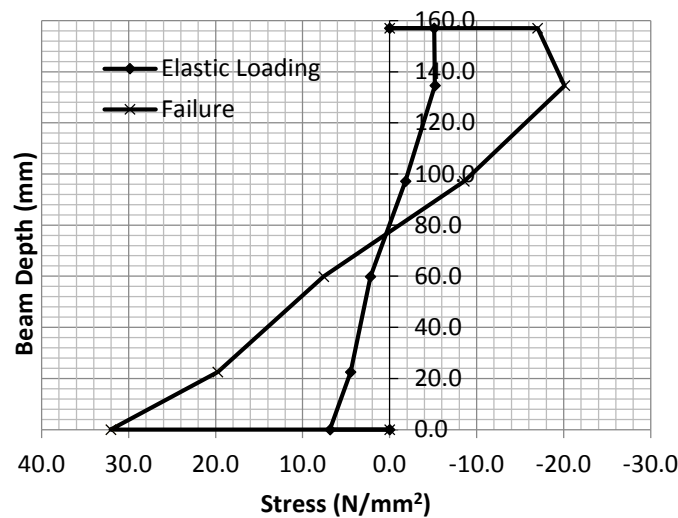

Fig. 7 Typical stress profile for an unreinforced glulam timber during elastic loading and failure

- Passively Reinforced Beams

Timbers with a bonded 12mm diameter steel reinforcing tendon were tested, as detailed previously, to provide a comparison between active and passive reinforcement. Figure 8 graphically illustrates the benefits offered by the passively reinforced sections compared to the solid glulam timber. The load-deflection lines, recorded under elastic loading, show the increase in stiffness that is achieved by the inclusion of the steel tendon. A reduction of 8.2mm in service deflection is evident, equating to 28% increase in stiffness. With an average ultimate capacity of 25.8kN, an increase of approximately 30%, the advantages offered by the inclusion of passive reinforcement are clear.
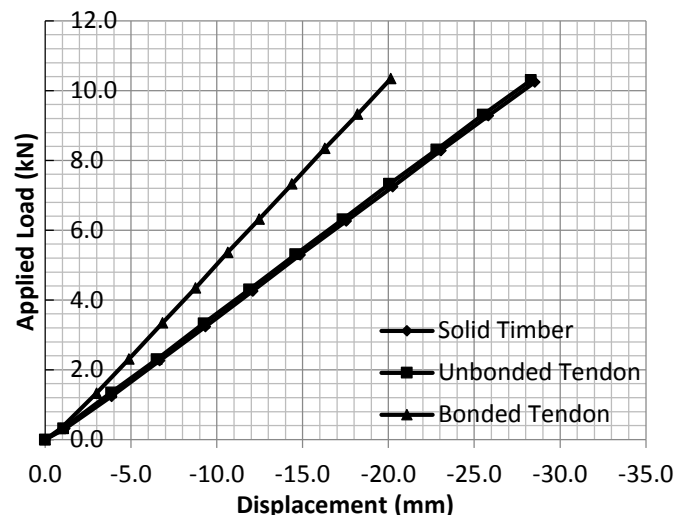

Fig. 8 Typical load/deflection response of a reinforced glulam timber beam

- Post-tensioned Beams, Unbonded

This test series was completed to investigate the benefits the bonding process has on the performance of the post-tensioned glulam timber, providing an intermediary stage between passive reinforcement and traditional active reinforcement.

Figure 9 illustrates the additional stiffness benefit the post-tensioning process offers, by comparing the elastic response of the various states of a single beam. With the further benefit of the induced precamber ignored a stiffness increase of 8% can be seen on average. This may indicate that the lack of bonding between the tendon and the glulam timber has adversely affected the transference of the post-tensioning force. An incomplete transference of the induced stresses may account for the reduction in flexural strength and stiffness in comparison to the reinforced series.
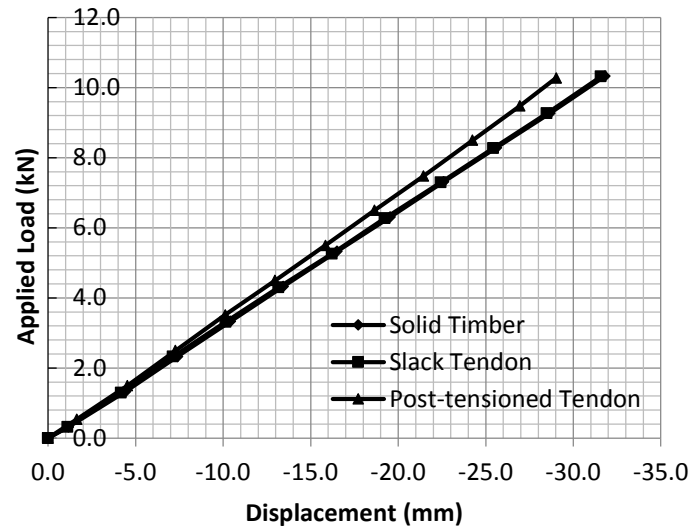

Fig. 9 Typical load/deflection response of a post-tensioned, unbonded, glulam timber beam

From both Figure 9 and Table 5 the advantages afforded by post-tensioning an unbonded steel tendon are evident, with a benefit in both stiffness and flexural strength being observed when compared to an unreinforced glulam timber. Conversely when compared to the passively reinforced experimental data the unbonded post-tensioned timbers preform less effectively with both the stiffness and ultimate capacity being lower.

- Post-tensioned Beams, Bonded

Figure 10 shows a typical load, deflection response of a beam at various stages of construction, under service loading. It is initially evident that with the application of post-tensioning, both with the tendon bonded and unbonded, there is an increase in stiffness, particularly evident under the 10kN applied load. From the figure it can be seen that there is approximately a 7.5mm reduction, approximately 28%, in service deflection between the solid timber beam and the posttensioned beam with the steel tendon bonded in place at a10kN applied load.

As is evident from Figure 10 the simple act of inserting the steel tendon through the 3m long beam has little to no effect on the overall stiffness of the member. Although the steel has a considerably higher elastic modulus the tendon alone is not sufficiently stiff over this length to result in a noticeable difference during this testing phase. This then indicates that the increase of stiffness and the resulting advantages, seen throughout these experiments, can be attributed to the posttensioning process. The graph represents the typical deflection response of the beams under service loading with the precamber induced by the post-tensioning ignored, meaning that there are further benefits offered by the post-tensioning process that aren't initially evident from the figure.
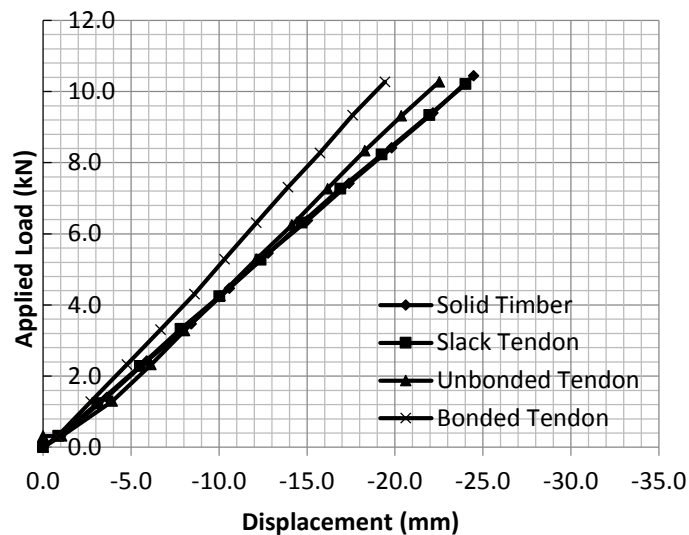
Fig. 10 Typical load/deflection response of a post-tensioned, bonded, glulam timber beam with the precamber ignored

Figure 11 represents the typical deflection response under elastic loading of the same beam represented in Figure 10, but with the induced precamber considered. It is immediately evident that the 8mm precamber combined with the increased stiffness of the composite member greatly reduced the net deflection, with a reduction of 55% being realised in this average case.
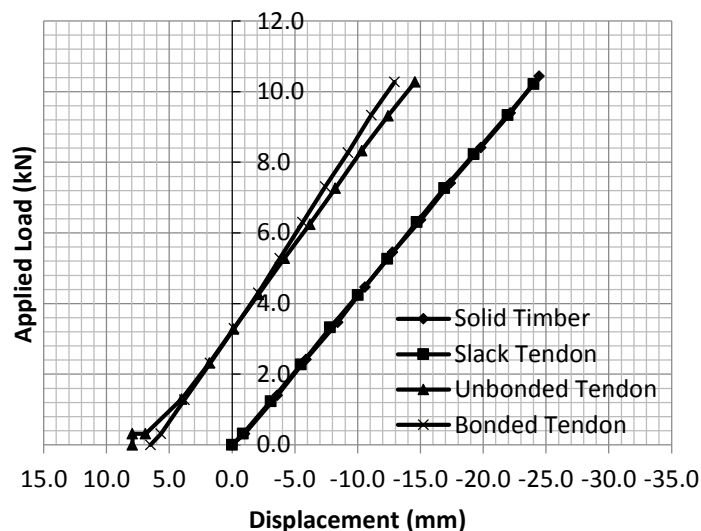

Fig. 11 Typical load/deflection response of a post-tensioned, bonded, glulam timber beam

As is evident from the figure the process of post-tensioning actively reduces the tensile stresses experienced during loading. Timber primarily fails in flexure due to the tensile stresses exceeding the tensile strength of the material, which is weakened through the presence of knots and other defects. A 55% reduction in the stress value on the soffit of the timber is evident when the solid timber specimen is compared to the post-tensioned composite under the service loading. This figure provides a basic explanation of how the addition of post-tensioning strengthens the timber.

The stress profile shown in Figure 12 is comparable to that shown in Figure 8. The typical plastic profile of the glulam timber is still evident, but with the addition of a stress peak at the location of the post-tensioning tendon. The timbers experimentally tested all failed compressively, with splitting occurring on or below the top surface of the beams. Considering Figure 12 in relation to this, the failure mode may not be initially evident, as considerably higher stresses are recorded near the soffit of the member. The observations and recorded data lead to the conclusion that the post-tensioning of the timber overcomes any natural defects that the material may have, such as knots and fissures. By effectively holding these defects together, the tensile strength of the material is considerably increased, causing an overall increase in flexural strength.
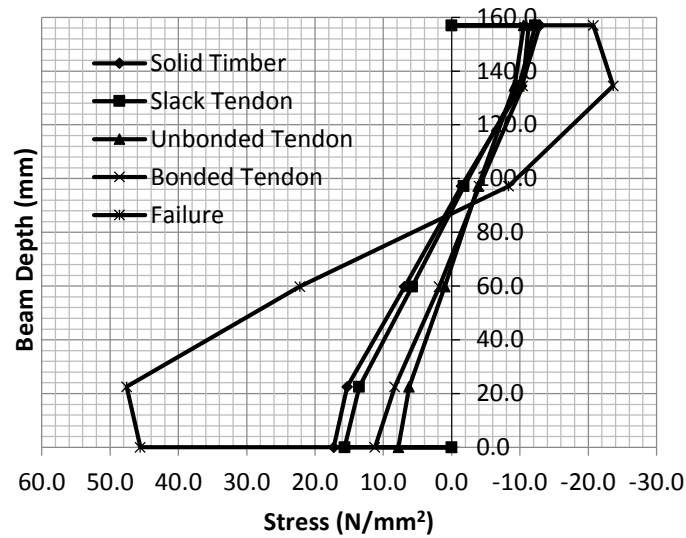
Fig. 12 Typical stress profile for a post-tensioned, bonded, glulam timber during elastic loading and failure

Table 5
Percentage increase of individual beams throughout experimental process

Beam No.	Solid timber		Slack tendon		Unbonded tendon		Bonded tendon	
	E_{mg} (GPa)	% increase	E_{mg} (GPa)	% increase	E_{mg} (GPa)	% increase	E_{mg} (GPa)	% increase
1	7.10	-	7.10	-	8.96	26.2	11.24	58.5
2	9.66	-	9.66	-	10.66	10.4	12.88	33.3
3	7.19	-	7.19	-	8.03	11.7	10.48	45.8
4	9.09	-	9.09	-	10.30	13.3	11.45	25.7
5	8.83	-	8.83	-	10.48	19.1	11.66	32.5
Average	**8.37**	**-**	**8.37**	**-**	**9.99**	**16.1**	**11.54**	**39.2**
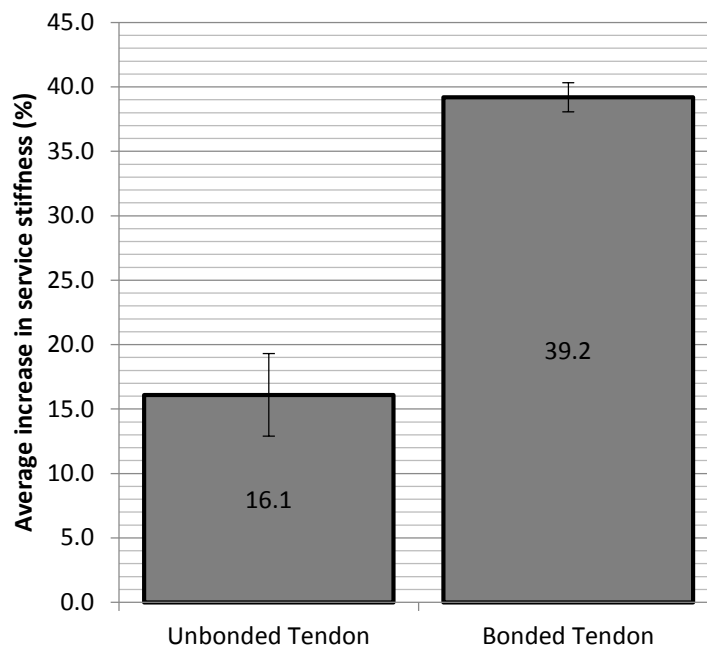
Fig. 13 Average percentage increase in service stiffness of unbonded and bonded post-tensioned glulam timber

Table 5 and Figure 13 illustrate the increase in stiffness, at service level, that the experimental research observed during the process of post-tensioning and bonded the glulam timbers. As timber is a highly variable material it is not accurate to compare results of differing members to one another. By separating the post-tensioning method into various stages and testing each elastically direct comparisons may be drawn, allowing

definitive conclusions to be obtained. Considering the bonded post-tensioned timber members the service deflection was recorded for four differing states:

- solid timber member;
- timber with the steel tendon slotted slackly through the length;
- the steel tendon post-tensioned to 20.0kN;
- the post-tensioned tendon bonded in situ.

Table 5 shows the increase in the timbers modulus of elasticity at each stage, calculated as explained in Equation 3. As expected slotting the slack steel tendon through the length of the member does not improve the stiffness. This section of the research was included to prove that the inclusion of the steel tendon does not cause any improvement to the performance of the timber. Considering the post-tensioned process both the unbonded and bonded service results show an increase in the member's stiffness.
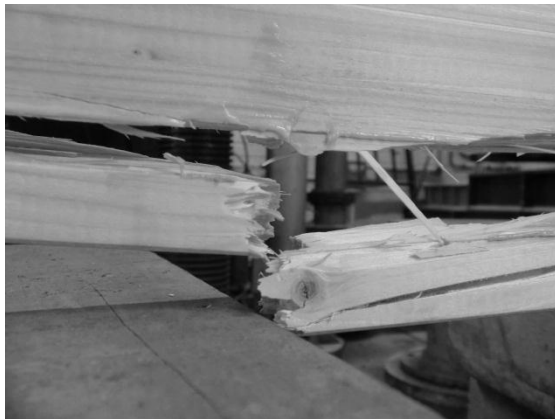
a. Comparison of Experimental Tests

Fig. 14a Typical tensile failure of unreinforced glulam timber

Fig. 14b Typical compressive/shear failure of post-tensioned glulam timber

Figure 14 a&b above illustrate the typical failure modes observed throughout the experimental testing. Figure 14a represents the tensile failure that occurred for the unreinforced glulam timber. As previously discussed this is to be expected as the inherent defects contained within the timber cause weaknesses susceptible to tensile stresses, meaning that all failures occur on the soffit of the beam in a tensile manner. Figure 14b illustrates the typical compressive failure that was observed during the B series of tests. The post-tensioned, bonded, glulam timber specimens failed in a compressive manner, with the origin of the failure frequently occurring below the surface of the beam in accordance with the plastic stress profile previously discussed.
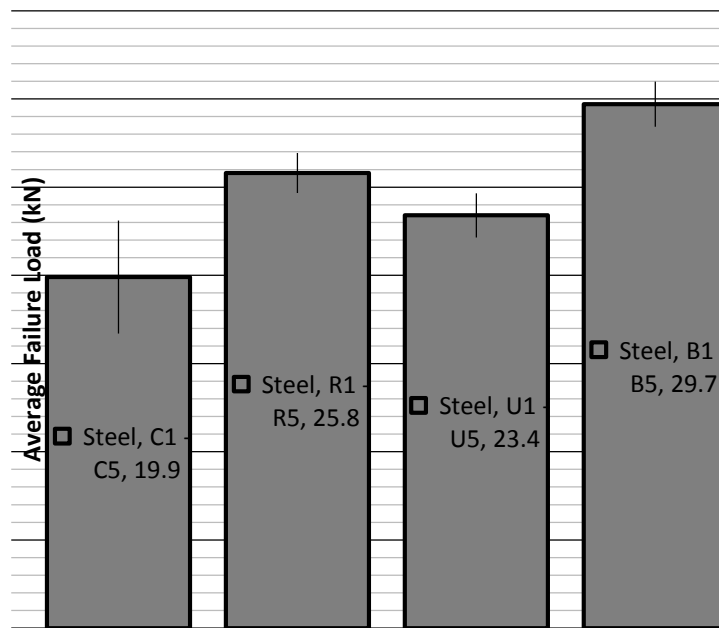
Fig. 15 Average flexural capacity with standard deviation error bars for all experimental testing

Table 6 and Figure 15 further highlight the difference between various test series conducted. Figure 15 represents the average flexural capacity of the various experimental series, with the inclusion of error bars representing the standard deviation of the members within the test. It is evident that post-tensioning positively affects the performance of the glulam timber, with a higher ultimate capacity and lower variation between the members on average.

From the ultimate capacity shown in Table 6, it is evident that there is an increase in strength when timber is post-tensioned. In this particular series of experiments there was a 40% increase in strength when comparing the solid timber to the post-tensioned timber composite. There is an additional 9% increase when the post-tensioned average is compared to the reinforced average, indicating the process of post-tensioned does further enhance timbers flexural strength.

The elastic modulus calculated for each combined with the mid-span deflection recorded under the elastic loading indicates the benefits caused by bonding the steel tendon. Although a slight increase in stiffness was recorded within the U series, when compared to the C series, both the R and B series show a significant increase in stiffness that may be attributed to the bonding of the tendon.

Although timber is not strictly comparable in this manner, due to the inherent variability of its nature, these results indicate a positive shift in the material's capabilities when post-tensioned, in comparison to simply being reinforced.

Table 6
Comparison of experimentally obtained results

Specimen type	Beam code	Elastic Modulus (GPa)	Mid-span deflection at elastic limit (mm)	At ultimate limit	
				Mid-span deflection (mm)	Load (kN)
Unreinforced glulam timber (C series)	C1	9.3	23.7	37.9	16.25
	C2	10.6	23.7	45.5	19.25
	C3	9.8	23.6	62.4	23.75
	C4	10.0	23.5	56.1	22.50
	C5	7.4	25.9	45.3	17.50
	Av.	**9.6**	**24.1**	**49.5**	**19.9**
	St. dev.	**1.2**	**-**	**-**	**3.2**
Reinforced glulam timber (R series)	R1	11.2	19.5	60.5	26.25
	R2	10.1	21.2	58.6	24.40
	R3	10.5	19.1	65.3	27.25
	R4	10.5	21.5	59.7	24.40
	R5	11.0	19.4	56.9	26.50
	Av.	**11.2**	**20.2**	**60.2**	**25.8**
	St. dev.	**0.4**	**-**	**-**	**1.1**
Post-tensioned glulam, unbonded (U series)	U1	9.1	26.8	63.4	24.25
	U2	10.9	21.1	63.8	23.40
	U3	7.8	27.6	62.6	25.00
	U4	10.1	23.7	59.6	22.00
	U5	10.5	22.5	57.5	22.20
	Av.	**9.7**	**23.6**	**61.4**	**23.4**
	St. dev.	**1.2**	**-**	**-**	**1.3**
Post-tensioned glulam, bonded (B series)	B1	11.8	19.1	64.0	27.20
	B2	13.3	16.8	71.1	29.70
	B3	10.6	21.3	70.7	26.60
	B4	11.9	19.0	55.3	26.80
	B5	11.6	19.4	75.3	29.10
	Av.	**11.8**	**19.3**	**67.3**	**27.9**
	St. dev.	**1.0**	**-**	**-**	**1.3**

5. Conclusions

The following conclusions may be drawn for the research regarding the reinforcement and post-tensioning of European Spruce glulam timbers with steel tendon.

- Passive reinforcement of glulam timber using a bonded, 12mm diameter, steel tendon increases the ultimate capacity and the stiffness of the member by 29.4% and 28.1% respectively.
- Active reinforcement of glulam timber using an unbonded, 12mm diameter, post-tensioned steel tendon increases the ultimate capacity and stiffness of the member by17.6% and 8.1% respectively.
- Active reinforcement of glulam timber using a bonded, 12mm diameter, post-tensioned steel tendon increases the ultimate capacity and stiffness of the member by 40.1% and 30% respectively.
- The unreinforced glulam timber failed in bending with a brittle failure occurring primarily on the soffit of the beams.
- Both the passively and actively reinforced glulam timbers failed in bending with a ductile failure mode, characterised as compressive, shear.
- No debonding of delaminating occurred indicating that the timber-adhesive interface had sufficient strength for use within the scope of this research.

The research discussed in this paper highlights the benefits that active reinforcement of glulam timber offers additionally when compared to the traditional passive reinforcement. By post-tensioning the timber increases in both ultimate capacity and stiffness are evident, with the additional benefit of an induced precamber. A ductile failure mode was observed in reinforced timbers, which is considerably more desirable than the typical brittle failure of the unreinforced material. Although the theoretical investigation remains on

going the research indicates that post-tensioning timber ~~is a viable and worthwhile~~ provides a structural benifit. It is therefore considered worthwhile from a ~~d~~development perspective ~~in the efforts~~ to strengthen timber and increase its usability within construction.

Research regarding the long-term behaviour of the system is currently under investigating within the university; however preliminary tests indicate that the epoxy has sufficient strength to prevent significant losses of the post-tensioning force, while creep appears to be progressing at an acceptable rate.

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