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Research Article

Experimental Analysis of Pretensioned CLT-Glulam T-Section Beams

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The bending behavior of T-section beams composed of a glulam web and an upper cross-laminated timber flange was studied. The influence of two fundamental factors on the bending strength and stiffness was considered: the wood species used for the webs and pretensioning with unbonded tendons. Sixteen specimens with a 9 m span were tested until failure: eight of them were non-tensioned (4 *Picea abies* webs and 4 *Quercus robur* webs) and the other eight were pretensioned using threaded bars with 20 mm diameter anchored in plates fixed at the ends of the specimens (4 *Picea abies* webs and 4 *Quercus robur* webs). Pretensioning with unbonded tendons showed a clear improvement in the load capacity of the specimens with *Picea abies* webs, while the difference was not significant for the specimens with *Quercus robur* webs. Considering deflection, pretensioning gave the advantage of an initial precamber but also generated slight variations in the stiffness as a result of increasing the portion of the section that was in compression. The variation in the stiffness depended on the relation between the compressive and tensile moduli of elasticity parallel to the grain, and its influence on the deflection was analyzed using a finite element method.

1. Introduction

Pretensioning techniques are widely used for beams and slabs in concrete structures due to their ability to efficiently compensate for the reduced tensile strength of concrete through precompression. The improvement in strength achieved by pretensioning enables the use of thinner sections and provides an efficient solution for controlling material splitting and avoiding excessive deflections. For materials that have a tensile strength similar to or higher than their compressive strength, such as timber or steel, pretensioning offers significantly reduced advantages. Moreover, timber has problems with its long-term behavior; its inherent creep deflection can reduce the pretensioning effects over time, decreasing its capabilities. Therefore, the pretensioning technique is rarely used for timber.

Defect-free timber has a higher tensile strength than compressive strength. However, the inherent defects (cracks, knots, grain deviations, etc.) that are present in structural timber reduce its tensile strength. Furthermore, typical bending failure is reached instantaneously after a brittle fracture is caused by tension in the fibers. This phenomenon has motivated research on different reinforcement solutions to improve the bending behavior of timber.

The reinforcement systems that have been used can be divided in two basic typologies: passive and active reinforcements. Passive reinforcement is made of metallic elements [1–3] or fiber-reinforced polymers (FRPs) [3–13] that are glued to the timber with structural adhesives. Active reinforcement can be made with unbonded tendons or with bonded tendons that are glued to the timber with adhesives. Active reinforcement has been used to both reinforce frame connections [14, 15] and improve the behavior of beams [16–25].

Some authors [20, 24] have studied the loss of prestressing force for LVL and glulam beams prestressed using unbonded tendons. They found a reduction in prestress from 1.4% to 10% for beams loaded parallel to the grain exposed to controlled and uncontrolled environmental conditions. They

Table 1

Bending strength	$f_{m,k}$	33 MPa
Tensile strength parallel to the grain	$f_{t,0,k}$	23 MPa
Tensile strength perpendicular to the grain	$f_{t,90,k}$	0.6 MPa
Compressive strength parallel to the grain	$f_{c,0,k}$	45 MPa
Compressive strength perpendicular to the grain	$f_{c,90,k}$	8 MPa
Shear strength	$f_{v,k}$	4 MPa
Modulus of elasticity parallel to the grain	$E_{0,\text{mean}}$	14,400 MPa
Modulus of elasticity parallel to the grain	$E_{0,05}$	12,000 MPa
Modulus of elasticity perpendicular to the grain	$E_{90,\text{mean}}$	800 MPa
Modulus of elasticity perpendicular to the grain	$E_{90,05}$	660 MPa
Shear modulus	G_{mean}	850 MPa
Shear modulus	$G_{0,05}$	700 MPa
Characteristic density	ρ_k	690 kg/m^3

Table 2

Bending strength	$f_{m,k}$	24 MPa
Tensile strength parallel to the grain	$f_{t,0,k}$	14 MPa
Compressive strength parallel to the grain	$f_{c,0,k}$	22 MPa
Shear strength parallel to the grain of the boards	$f_{v,k}$	2.5 MPa
Modulus of elasticity parallel to the grain of the boards	$E_{0,\text{mean}}$	12,500 MPa
Shear modulus parallel to the grain of the boards	G_{mean}	460 MPa
Characteristic density	ρ_k	420 kg/m^3

concluded that controlling the relative humidity would reduce the losses. The use of bonded reinforcements could contribute to reduce the creep deformations in wood members [5].

This paper focuses on using active reinforcement with unbonded tendons. Therefore, an important reference is the experimental study conducted by McConnell et al. [26], regarding straight beams of laminated timber with a rectangular cross section. Their study analyzed the behavior of three types of reinforcements: beams with passive reinforcement of a 12 mm diameter steel bar, posttensioned beams with an unbonded 12 mm diameter steel tendon, and posttensioned beams with a bonded 12 mm diameter steel tendon. They concluded that posttensioning with unbonded tendons increased the bending strength by 17.6% and the stiffness by 8.1%. The small effect of pretensioning on the bending stiffness coincides with the results previously obtained by Bohannan [16].

This paper analyzes the bending behavior of T-section beams formed of glulam webs and upper cross-laminated timber (CLT) flanges. This analysis aims to determine the influence of using different wood species with different mechanical properties for the webs and the effect of pretensioning with unbonded tendons on the strength and bending stiffness of beams. The inherent loss of effectiveness of prestressing in a long-term process is assumed, but it is not considered as a determinant for the purpose of this analysis, as it is carried out in conditions of instantaneous loading.

2. Materials and Methods

2.1. Materials. The characteristics of the materials used in the experimental study were as follows:

(i) Glulam webs made of *Picea abies*, with a strength class of GL28 h [27].

(ii) Glulam webs made of *Quercus robur* sheets LS13 [28]. The physical and mechanical properties provided by the manufacturer are in Table 1.

(iii) The CLT flanges, CLT90S L3S [29], were 90 mm thick and were composed of three sheets of 30 mm *Picea abies* C24 [30]. The physical and mechanical properties provided by the manufacturer are in Table 2.

(iv) The connection between the webs and the flanges of the T-sections was made with 410 × 80 × 4 mm perforated plates in S235 hot-dip galvanized finish steel. The circular drills of the plates had a diameter of 10 mm spaced at 5 mm. The plates were glued to the wooden specimens with a 2-component polyurethane adhesive.

(v) The pretensioning of the specimens was conducted using threaded bars of Y1100H [31] steel with a 20 mm diameter, an elastic limit of $f_{pk} = 900\,\text{N/mm}^2$, and a tensile strength of $f_{p\max,k} = 1100\,\text{N/mm}^2$.

2.2. Test Specimens

2.2.1. Preliminary Tests. Two series of nondestructive tests were conducted. The aim of the first test series was to determine the global bending modulus of elasticity ($E_{m,g}$) of the timber used. The following specimens were tested:

(i) 4 *Picea abies* glulam webs with a cross section of 160 × 210 mm

(ii) 4 *Quercus robur* glulam webs with a cross section of 160 × 210 mm

(iii) 4 CLT planks with a cross section of 600 × 90 mm

Four-point bending tests were conducted with a span of 9 m between the supports. The tested specimens were used later to form the T-sections without pretensioning, as described in Section 2.2.2.

The purpose of the second preliminary test series was to determine the compressive elastic modulus of the webs parallel to the grain ($E_{c,0}$). The following specimens, which were obtained from the samples previously tested for bending, were tested under centered compression:

(i) 4 *Picea abies* glulam specimens of 55 × 55 × 330 mm

(ii) 4 *Quercus robur* glulam specimens of 55 × 5 × 330 mm

2.2.2. Tests of the T-Section Specimens. The following characteristics of the T-sections were tested.

(1) T-Sections without Pretensioning. Eight specimens were formed using a glulam web (4 *Picea abies* specimens and 4 *Quercus robur* specimens) and upper CLT flanges (Figure 1(a)). The total length of the specimen was 9160 mm, and

the distance between the supports was $L = 9$ m. The geometric characteristics of the T-section were as follows (Figure 1(b)): $b_1 = 600$ mm, $b_2 = 160$ mm, $h_1 = 90$ mm, $h_2 = 210$ mm, and $H = 300$ mm.

The total depth (H) was established by considering the slenderness of the specimen ($L/30$). A thickness of $h_1 = 90$ mm was adopted for the CLT since this is the minimum commercial configuration for 3 plates. The width of the webs (b_2) was determined by considering the restriction of the longitudinal channel in which the tendon was placed. Finally, the width of the CLT (b_1) was selected to efficiently use the most common commercial dimensions of CLT. The adopted configuration of the T-section enables extending the results to π-shaped sections, a highly efficient typology for constructing structural floors.

The perforated plates of the connection between the web and the flanges (Figure 2) were placed as shown in Figure 3(a) for the *Picea abies* webs and as shown in Figure 3(b) for the *Quercus robur* webs.

To determine the number and distribution of the connection plates, the load capacity of the T-sections with different configurations (the pretensioned and nontensioned specimens and *Picea abies* and *Quercus robur* webs) was estimated. The load capacity was calculated considering a homogenized section obtained from the material characteristics described in Section 2 and assuming a bending failure mode.

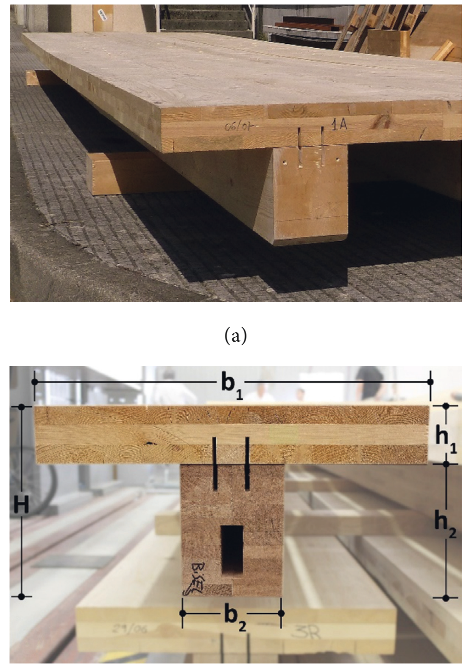
A finite element method (FEM) analysis was performed with the obtained load values to assess the required lengths and positions of the connection plates. The adopted distribution proved to be efficient because none of the tested specimens failed at the connection between the web and flange.

(2) Pretensioned T-Sections. Eight beams were formed with a glulam web (4 *Picea abies* webs and 4 *Quercus robur* webs) and upper CLT flanges with the same characteristics as described for the nonpretensioned beams. The web cross section had a bottom groove or a cable channel of 35×85 mm, which was located 30 mm away from the bottom edge, where the tensioning tendon was placed (Figure 1 (b)). The vertical dimension of the groove was oversized to accommodate two tendons, which was utilized in another test series using the same specimens. To make the groove, each web was manufactured with two 80 mm wide specimens and the groove was machined before being glued to form the final 160 mm wide web. The distribution of the perforated plates that connected the web and upper flange is shown in Figure 3(b) (*Picea abies*) and Figure 3(c) (Quercus *robur*).

Table 3 shows the geometric characteristics of all the tested specimens.

2.2.3. Test Setup. The preliminary tests conducted to determine the global bending elastic modulus (Figure 4) and the compression elastic modulus (Figure 5) considered the general criteria of regulation [32] using a frame with a 600 kN load cell. The bending tests were conducted using a 9 m span between the supports, and point loads were applied at one-third and two-thirds of the span; the midpoint displacement was measured using an extensometer with 100 mm of standard measurement stroke (Figure 4). The bending elastic modulus parallel to the grain ($E_{0,\mathrm{mean}}$) was calculated using the following equation:

$$E_{0,\mathrm{mean}} = \frac{3 \cdot a \cdot L^2 - 4 \cdot a^3}{2 \cdot b \cdot h^3 \cdot \left(\left(2 \cdot \left(w_2 - w_1 \right) / \left(F_2 - F_1 \right) \right) - \left(6 \cdot a / 5 \cdot G_{\mathrm{mean}} \cdot b \cdot h \right) \right)}, \tag{1}$$



(a)

(b)

Figure 1: Picture of a solid transversal section without pretensioning (a) and a piece with a groove prepared to place the pretensioning tendon (b).

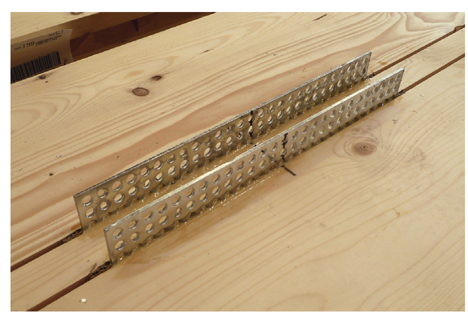


Figure 2: Discontinuous flange-to-web joint made with glued-perforated steel plates.

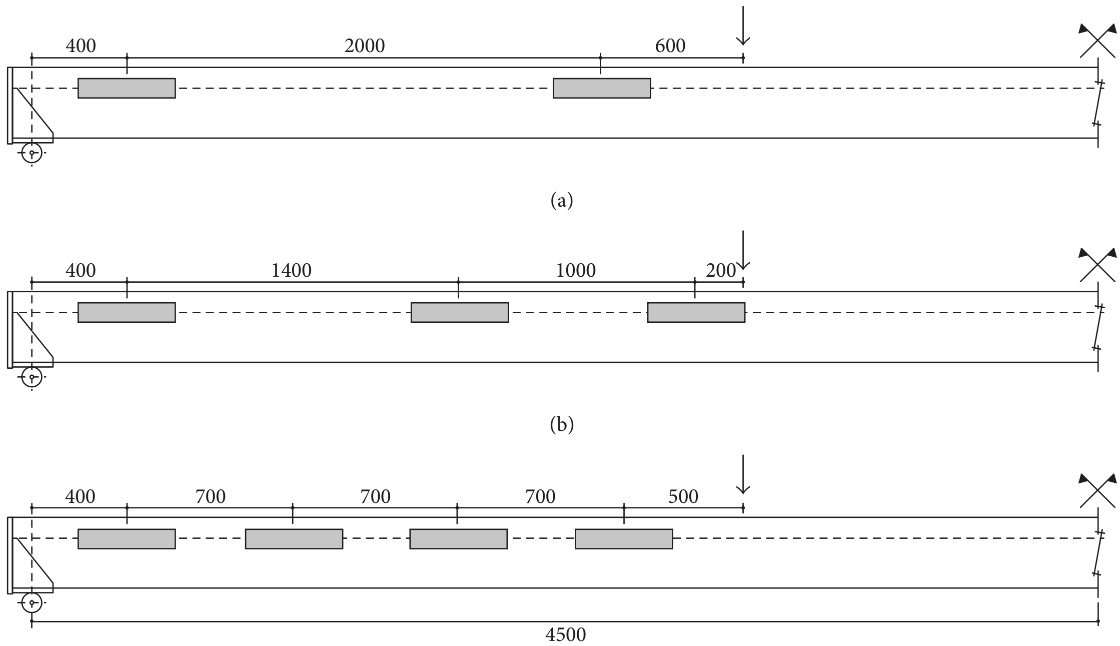


Figure 3: Dispositions of perforated steel plates adopted according to the type of piece. Nonpretensioned pieces: (a) *Picea abies* glulam webs and (b) *Quercus robur* glulam webs. Pretensioned pieces: (b) *Picea abies* glulam webs and (c) *Quercus robur* glulam webs.

Table 3: Geometric characteristics of the tested specimens.

Type	Wood	Specimen number	Specimen geometry						Test	Tensioning tendon
			L (mm)	H (mm)	h_1 (mm)	h_2 (mm)	b_1 (mm)	b_2 (mm)		Φ (mm)
B/PIC-1 to 4	*Picea abies*	4	9000	—	—	210	—	160	Bending	—
B/OAK-1 to 4	*Quercus robur*	4	9000	—	—	210	—	160	Bending	—
B/CLT-1 to 4	CLT	4	9000	—	90	—	600	—	Bending	—
C/PIC-1 to 4	*Picea abies*	4	330	55	—	—	—	55	Compression	—
C/OAK-1 to 4	*Quercus robur*	4	330	55	—	—	—	55	Compression	—
F1/PIC-1 to 4	T-section with *Picea abies* web	4	9000	300	90	210	600	160	Bending	—
F1/OAK-1 to 4	T-section with *Quercus robur* web	4	9000	300	90	210	600	160	Bending	—
F2/PIC-1 to 4	T-section with *Picea abies* web	4	9000	300	90	210	600	160	Bending	20
F2/OAK-1 to 4	T-section with *Quercus robur* web	4	9000	300	90	210	600	160	Bending	20

where a is the distance between a loading point and the nearest support, L is the span of the structural element, b and h are the dimensions of the cross section of the beam, $F_2 - F_1$ is the load increase in the straight part of the load-deflection curve, and $\omega_2 - \omega_1$ is the deflection increase corresponding to load $F_2 - F_1$.

The compression elastic modulus parallel to the grain ($E_{c,0}$) was calculated using the following equation:

$$E_{c,0} = \frac{L_1 \cdot (F_2 - F_1)}{A \cdot (w_2 - w_1)}, \quad (2)$$

where L_1 is the length, 4 times the smallest dimension of the specimen; $F_2 - F_1$ is the load increase in the straight part of the load-deflection curve; A is the cross-sectional area of timber; and $\omega_2 - \omega_1$ is the deflection increase corresponding to load $F_2 - F_1$.

Figure 4: Bending test to determine the global bending MOE.

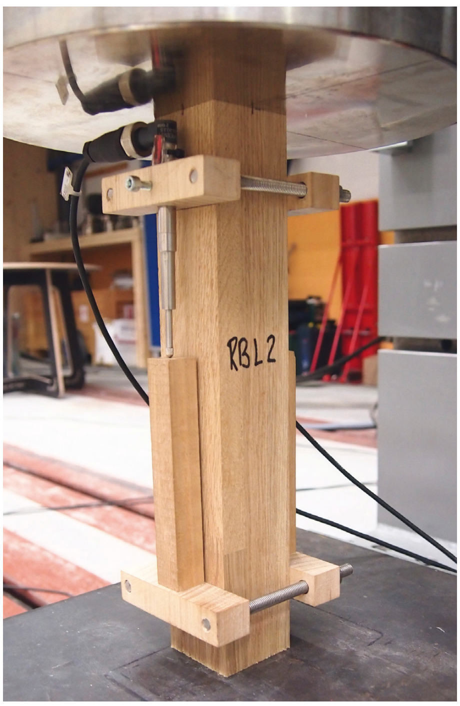


Figure 5: Test to determine the compression MOE parallel to the grain.

The T-section was tensioned using a hydraulic jack until a precamber of 18 mm ($L/500$) was obtained. The tension force applied to reach the precamber was different for each specimen due to their different stiffnesses. The tendon was locked against the plates using a domed anchor nut [33]. The tendon was placed in the groove of the web 105 mm from the tendon axis to the bottom edge of the specimen (Figure 6).

3. Results

Table 4 shows the results that were obtained from the previous tests to determine the modulus of elasticity parallel to the grain for bending and compression. The average value of the global bending modulus of the CLT specimens from the experiments was 6% lower than the one declared by the manufacturer. Compared to the theoretical values listed in Section 2, the specimens with *Picea abies* and *Quercus robur* webs exhibited much more significant decreases in the modulus of elasticity (13.7% for *Picea abies* and 17.3% for *Quercus robur*).

Figure 6: Test of a pretensioned T-section with *Picea abies* webs.

Table 5 shows the tensioning force applied to each specimen to reach the initial precamber (the maximum force at failure in the bar) and the failure load.

Table 6 presents the midpoint displacement of each T-section beam for two point loads of 14 kN; each load was applied at one-third of the span length. In terms of deflection, these point loads were equivalent to a uniformly distributed load of 7 kN/m^2, which is a common value for public buildings ($G_k = 2$ kN/m^2 and $Q_k = 5$ kN/m^2). The displacements listed in Table 6 do not include the deflection caused by the self-weight of the specimen because the extensometers were installed after the specimen was supported and the load had been applied. In the case of the pretensioned specimens (F2/PIC and F2/OAK), the displacement was measured after pretensioning, so such displacements were measured after some deflection had occurred; therefore, the self-weight was already considered. Thus, to determine the midpoint displacement, the 18 mm of initial precamber was subtracted from the corresponding value in Table 6.

Figures 7 and 8 show the load-displacement results that correspond to the bending tests of pretensioned and nontensioned T-sections with *Picea abies* (Figure 7) and *Quercus robur* webs (Figure 8). The minimum and maximum values obtained from the action of the two 14 kN loads applied to one-third and two-thirds of the span length are provided. For an approximate displacement of 15 mm, the load-deflection curves corresponding to the pretensioned beams show a clear change in slope caused by the increase of the effective stiffness when the wood comes into contact with the steel bar. This contact occurs when the deformation generated by the beam's self-weight and the loads applied during the test offset the 18 mm precamber produced by the initial pretensioning force.

The failure of all T-sections, both nontensioned and pretensioned, occurred instantaneously as a result of the tension in the glulam web. In the nontensioned specimens, the predominant failure mode was typical glulam bending failure (Figure 9). In the F1/PIC-3 specimen, the failure was accelerated due to the presence of significant knots in the bottom sheet of the glulam web (Figure 10). As a result, the failure load of this specimen was the lowest of all the tested specimens (Table 5). Finger-joint failure occurred in the F1/OAK-3 specimen (Figure 11), and significant variation was not observed in the failure loads of the other tested

Table 4: Modulus of elasticity parallel to the grain.

Type	Experimental test series							Theoretical value	
	Value for each specimen (MPa)				Standard deviation	Average value $E_{c,0,\ \text{test}}$ (MPa)	Average value $E_{0,\text{mean,test}}$ (MPa)	Average value $E_{0,\text{mean}}$ (MPa)	$\frac{E_{0,\text{mean,test}}}{E_{0,\text{mean}}}$
	1	2	3	4					
B/PIC	10,880	11,450	10,510	10,658	413	—	10,875	12,600	0.86
B/OAK	11,641	11,884	12,222	11,894	238	—	11,910	14,400	0.83
B/CLT	10,913	11,091	12,833	12,157	908	—	11,748	12,500	0.94
C/PIC	10,208	11,365	11,115	8616	1244	10,326	—	—	—
C/OAK	11,676	10,767	13,375	13,248	1264	12,267	—	—	—

Table 5: Force in the tensioning bar and ultimate load.

Type	Initial prestressing force Maximum force in the bar (kN)						Total failure load Sum of the two specific loads applied (kN)					
	Specimen				Standard deviation	Average value	Specimen				Standard deviation	Average value
	1	2	3	4			1	2	3	4		
F1/PIC	—	—	—	—	—	—	55.25	64.15	49.48	61.97	6.67	57.71
F2/PIC	109.20 154.17	117.03 163.79	113.16 176.55	117.89 172.57	3.99 9.95	114.32 166.77	58.15	59.49	95.66	74.18	17.44	71.87
F1/OAK	—	—	—	—	—	—	69.89	87.54	80.36	88.28	8.54	81.52
F2/OAK	115.54 171.81	94.06 147.61	113.29 225.99	116.00 175.49	10.51 32.92	109.72 180.23	73.78	68.92	90.74	84.15	9.88	79.40

Table 6: Displacement at the midpoint of the span for two specific loads of 14 kN applied at one-third and two-thirds of the span.

Type	Value for each specimen (mm)				Standard deviation	Average value (mm)
	1	2	3	4		
F1/PIC	59.14	56.94	60.14	56.50	1.74	58.18
F2/PIC	64.86	68.63	62.01	64.14	2.76	64.91
F1/OAK	53.29	54.70	57.27	52.89	1.98	54.54
F2/OAK	65.09	63.65	62.09	61.78	1.53	63.15

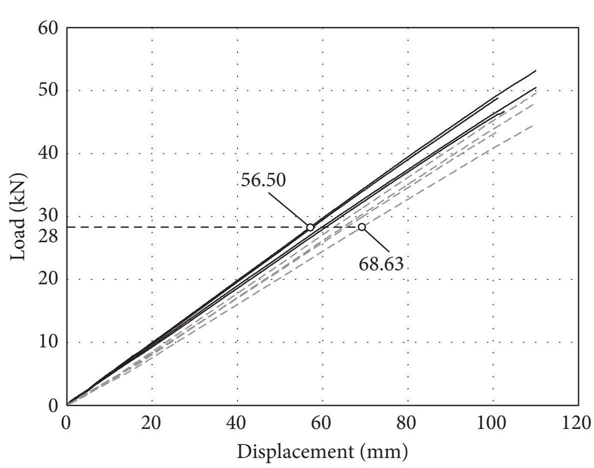


Figure 7: Load-displacement curves of T-sections with *Picea abies* webs: pretensioned (dashed lines) and nonpretensioned (solid lines).

specimens. In all the pretensioned specimens, with both *Picea abies* and *Quercus robur* webs, typical glulam bending failure was observed (Figure 12).

4. Discussion

4.1. Influence of the Type of Wood Used to Laminate the Web without Pretensioning. Using *Quercus robur* laminated timber webs instead of *Picea abies* webs in a nontensioned beam clearly improves the strength. The average failure load was 81.52 kN for *Quercus robur* and 57.71 kN for *Picea abies*, showing an increase of 41.2%. Moreover, the lowest failure load obtained with the *Quercus robur* webs (F1/OAK-1, 69.89 kN) was 8% higher than the highest value obtained for the *Picea abies* webs (F1/PIC-2, 64.15 kN). Since failure of both the *Picea abies* and *Quercus robur* webs occurred because of tension in the glulam web, the larger strength of the T-section with the *Quercus robur* webs was clearly directly related to the enhanced mechanical properties of the hardwood species. This conclusion can be clearly verified by examining the maximum theoretical stress on the bottom fiber (σ_{bottom}) in Table 7, which was analytically obtained using (3) and assuming a pretensioning force (N_{prest}) of zero:

$$\sigma_{\text{bottom}} = -\frac{N_{\text{prest}}}{A} + \frac{\left(M - N_{\text{prest}} \cdot e_{\text{prest}}\right) \cdot y}{I}, \quad (3)$$

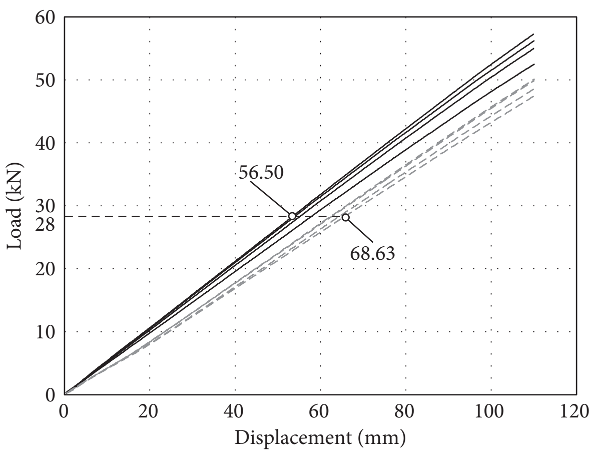


Figure 8: Load-displacement curves of T-sections with *Quercus robur* webs: pretensioned (dashed lines) and nonpretensioned (solid lines).

Figure 9: Typical bending failure in nonpretensioned T-sections corresponding to specimen F1/PIC-1.

Figure 10: Failure due to knots in the specimen F1/PIC-3.

Figure 11: Failure close to a finger joint in the specimen F1/OAK-3.

where A is the cross-sectional area of timber, M is the applied moment, e_{prest} is the eccentricity of the pretensioning tendon with respect to the center of mass of the cross section, y is the

Figure 12: Bending failure in a pretensioned T-section corresponding to specimen F2/OAK-3.

distance to the neutral axis, and I is the moment of inertia of the homogenized section.

The average global modulus of elasticity obtained from the tests on *Quercus robur* webs (11,910 N/mm^2) was 9.5% higher than that obtained from the tests on *Picea abies* webs (10,875 N/mm^2). Using the *Quercus robur* webs instead of Picea abies webs theoretically increased the bending stiffness (EI) of the homogenized T-section, including the upper CLT board, by 5.6%. The homogenized section was calculated using the average global modulus of elasticity obtained in the tests. The theoretical increase in the bending stiffness (5.6%) was similar than the reduction in the average midpoint displacement of the tested specimens (58.18 mm for the *Picea abies* webs and 54.54 mm for the *Quercus robur* webs). This low increase in the bending stiffness was easily achieved by slightly increasing the depth of the *Picea abies* webs. In the analytical case, the increase in the stiffness provided by using the *Quercus robur* webs could be achieved by increasing the depth of the *Picea abies* webs from 210 mm to 215.7 mm (a 2.7% increase in the depth).

In conclusion, the use of laminated hardwood in the webs of a T-section provides a clear increase only in strength. However, in building structures, the dimensions of simply supported specimens with a medium or long span (the appropriate spans for the type of section analyzed) are not usually determined by strength limitations but by deformation limitations. As a result, the increase in stiffness gained from using glulam hardwood can hardly compensate for the increased cost.

4.2. Influence of Pretensioning on the Bending Strength. Simply supported specimens were pretensioned with unbonded tendons to improve their strength; by applying an eccentric tensioning force, the positive bending generated from exterior loads was reduced. The magnitude of the tensioning force must be limited to ensure that the resultant precamber does not surpass the standard values of service limit states. This limitation in the negative bending magnitude that is induced by pretensioning, together with the additional compressive stresses inherent to tensioning, eliminates the relevance of the increased strength.

Table 5 shows the failure loads of all tested specimens. The specimens with *Picea abies* webs reached an average failure load of 71.87 kN in the pretensioned specimens and 57.71 kN in the nontensioned specimens. However, this increase of

Table 7: Maximum tensile stress estimated for the failure load.

Type	Value for each specimen (MPa)				Standard deviation	Average value (MPa)
	1	2	3	4		
F1/PIC	25.75	29.90	23.06	28.88	3.11	26.90
F2/PIC	21.54	21.32	45.67	35.41	11.80	30.98
F1/OAK	33.06	41.41	38.01	41.76	4.04	38.56
F2/OAK	28.67	33.43	44.01	40.81	6.96	36.73

24.5% must be considered in the context of three issues. First, the small number of tested specimens prevents the results from being conclusive. Second, the low value of the failure load (49.48 kN) of test specimen F1/PIC-3 occurred due to the presence of knots on the bottom side accelerating the failure (Figure 10). Finally, the high value of the failure load (95.66 kN) reached by test specimen F2/PIC-3 resulted in a standard deviation for the pretensioned specimens (17.44) that was significantly higher than that of the nontensioned specimens (6.67). The tensioning force applied to the four tested specimens is shown in Table 5. The negative bending moment produced by tensioning was calculated using the global modulus of elasticity of each specimen and the eccentricity of the tendons in relation to the center of gravity of the homogenized sections: 12.83, 13.42, 15.93, and 15.15 kN·m for specimens F2/PIC-1 to 4, respectively. As shown, the largest negative moments (specimens 3 and 4) corresponded to the specimens that reached a higher failure load. However, expressing the negative moment values as a percentage of the isostatic moment produced by the failure load gives the following results: 33.10%, 33.84%, 24.97%, and 30.64% for specimens F2/PIC-1 to 4, respectively. The lowest percentage of the counterbalance moment was produced using specimen F2/PIC-3, which reached the highest failure load, and very significant differences were observed regarding the other specimens.

As a result, since the pretensioning and moment generated by the eccentric pretensioning load were very similar for the 4 specimens, the excellent strength behavior of such specimens could have been a direct consequence of the inherent variations in the mechanical properties of timber. This variation is also reflected in the theoretical tension at the moment of failure (Table 7).

In the specimens with *Quercus robur* webs, pretensioning did not increase the average failure load; these values were even lower than those of the nontensioned specimens (79.40 kN and 81.52 kN, resp.). Table 7 compares the results in terms of the average theoretical stress at the moment of failure. The tensioning force applied to the four *Quercus robur* test specimens and the maximum force reached by the tendon are shown in Table 5. The negative bending moments produced by the eccentric tendon at the moment of failure were 13.88, 11.89, 19.16, and 14.71 kN·m for specimens F2/OAK-1 to 4, respectively. The highest value of the counterbalance moment was once again observed in the specimen that reached the highest ultimate load value. This result was also observed when the moments were expressed as a percentage of the isostatic moment at the ultimate load: 28.21%, 25.89%, 31.68%, and 26.23%, respectively. The obtained results reveal that the differences in the ultimate loads of the pretensioned and nontensioned specimens with *Quercus robur* webs were more closely related to the specific material properties than to the influence of pretensioning.

As a result, although it was not possible to reach definite conclusions, the test results indicate that the benefits of pretensioning on the bending strength of the specimens were not especially relevant. This observation was attributed to the fact that the maximum precamber that could be initially applied with eccentric tensioning was limited by meeting the deflection standards. An efficient way to avoid this limitation in the pretensioning force is to apply a variable tensioning force that generates a counterbalance effect relative to the applied forces. With this goal in mind, the authors developed the SsS© (Self-stressing System) [34, 35].

4.3. Influence of Pretensioning on the Bending Stiffness. Increasing the bending strength of a specimen is not usually the fundamental objective of pretensioning because the dimensions of simply supported specimens are not typically determined by the ultimate limit states but by the service limit states.

The first positive effect provided by pretensioning is to impart a precamber to a specimen. In this way, the deflections caused by permanent actions are offset, helping to meet the service restrictions imposed by appearance considerations. Nevertheless, a precamber can be easily imparted in laminated timber during its manufacturing process. Therefore, pretensioning is not necessary if offsetting the deflections caused by permanent loads is the only goal. The other two in-service deflection conditions that must be satisfied are to ensure the integrity of the construction elements and user comfort. The essential parameter for fulfilling both requirements is the bending stiffness of the element; this aspect is especially relevant for high live loads.

The stiffness of the pretensioned specimens, with both *Picea abies* and *Quercus robur* webs, was clearly inferior to that of the nontensioned specimens, as shown in Figures 7 and 8. Table 5 shows the midpoint displacement values for a total load of 28 kN (2 loads of 14 kN applied at one-third and two-thirds of the span length, which are equivalent in deflection to a uniform distributed load of 7 kN/m^2). The average displacement value for the specimens with *Picea abies* webs was 64.91 for the pretensioned specimens and 58.18 mm for the nontensioned specimens, representing an 11.6% increase in deflection. In the case of *Quercus robur*, the average displacement was 63.15 mm for the pretensioned specimens and 54.54 for the nontensioned specimens; thus, pretensioning increased the deflection by 15.8%. Thus, compared to the equivalent nontensioned specimens, the pretensioned specimens with unbonded tendons presented an effective loss in the stiffness, which was attributed to several factors.

The first factor that could have influenced the obtained deflection results is the use of different plate configurations for the flange-web joint of the two species. The distribution of these connection plates was determined to prevent failure at the joint, which would distort the intended analysis. According to the previous joint design, such failure did not occur; therefore, possible slip or failure was not a determining factor in comparing the results. Finally, the pretensioned specimens experienced a higher deflection than the nontensioned specimens, despite the pretensioned specimens having more connection plates in the flange-web joint.

The second factor that could explain the obtained deflection results is the lower moment of inertia in the pretensioned section because of the groove for the tendon. The groove, as mentioned previously, was vertically oversized to allow for other tensioning configurations. In the specimens with the *Picea abies* webs, the decrease in the bending stiffness (EI) of the homogenized section was 7.6%. The precamber of the nontensioned specimens measured from the tests was 58.18 mm, so the decrease in the stiffness caused by the groove could theoretically improve that value to a maximum of 62.60 mm. However, the total displacement obtained in the pretensioned specimen was 64.91 mm, representing an additional increase of 3.7%.

In the specimens with the *Quercus robur* webs, the decrease in the bending stiffness of the homogenized section, calculated with a modulus of elasticity of 11,910 MPa, was 7.4%. However, that loss did not correspond to the clear higher displacements that were measured in the tests, indicating a greater decrease in stiffness. Preliminary tests to determine the modulus of elasticity were conducted using the same webs that were used to make the nontensioned T-section specimens. The average modulus of elasticity was 11,910 MPa in the *Quercus robur* web and 10,875 MPa in the *Picea abies* web. Surprisingly, the pretensioning force needed to obtain a precamber of 18 mm was lower in the specimens with the *Quercus robur* webs (109.72 kN) than in the specimens with the *Picea abies* webs (114.32 kN). This result can be explained by considering that the timber of the webs in the pretensioned specimen had a lower modulus of elasticity. Given that we know the moment of inertia, tensioning force, and precamber for each of the F2/OAK specimens, we obtained an average modulus of elasticity of 10,090 MPa. As a result, a 16.49% decrease in stiffness was generated by the groove combined with the reduction in the modulus of elasticity E_m (from 11,910 to 10,090 MPa). This decrease in the stiffness increased the average precamber value from 54.54 mm, obtained for the solid specimen, to 63.53 mm in the specimen with the groove. This value is slightly higher than that obtained from the tests (63.15 mm, as shown in Table 8).

Finally, the third factor that explains the obtained displacement results was attributed to the differences between the modulus of the compressive modulus of elasticity ($E_{c,0}$) and the tensile modulus of elasticity ($E_{t,0}$) parallel to the grain. The pretensioning of the section increased the compressive stresses and consequently increased the compression area of the section. These are, the normal bending stresses that originated from the eccentric pretensioning and external force, combined with the normal compressive stresses due to pretensioning, led to a displacement in the neutral fiber that increased the compression area. Depending on the relative values of the tensile modulus of elasticity and the compressive modulus of elasticity, the increase in the compression section led to a slight decrease (if $E_{c,0} < E_{t,0}$) or increase (if $E_{c,0} > E_{t,0}$) in the stiffness.

To verify the proposed theory, an FEM analysis for solid specimens (types F1/PIC and F1/OAK) and specimens with grooves (types F2/PIC and F2/OAK) was conducted, considering both nontensioned and pretensioned specimens.

Three-dimensional models of hexahedral finite elements with 8 nodes containing 24 degrees of freedom (DOFs) were generated. The contact between the elements accounted for the possibility of dynamic behavior from flexible and/or rigid components, with kinematic restrictions on relative movement (displacement and rotation) between the nodes that formed the connection.

Two cases were assumed for the material properties. In the first case, the global modulus of elasticity was considered. In the second case, a bimodulus material was used to define not only the different elastic moduli for both compression and tension but also the different stress-strain curves for compression and tension.

The global bending modulus of elasticity ($E_{0,\text{mean,test}}$) and compression modulus of elasticity parallel to the grain ($E_{c,0,\text{test}}$) were determined in previous tests (Table 4). Using (4) [36], which is well known for determining the virtual modulus of elasticity (E_m) in softwood, we estimated the tensile modulus of elasticity parallel to the grain ($E_{t,0}$), using the global modulus obtained from the tests ($E_{0,\text{mean,test}}$) as the virtual modulus (E_m):

$$E_m = \frac{4 \cdot E_{t,0} \cdot E_{c,0}}{\left(\sqrt{E_{t,0}} + \sqrt{E_{c,0}}\right)^2}. \quad (4)$$

Table 8 shows the average displacement values obtained from the experimental tests and those obtained from the numerical analysis. For the pretensioned specimens, the precamber generated by the pretensioning plus the midpoint displacement is noted in parentheses in this table.

The numerical analysis conducted using the virtual modulus of elasticity (E_m) and the bimodulus ($E_{c,0}$ and $E_{t,0}$) led to interesting conclusions. In the case of the nontensioned specimens, for both the solid section and the section with a groove in the web, the analysis results using the bimodulus showed a high correlation with the results obtained using the virtual modulus of elasticity. This correlation was very similar for the specimens with *Picea abies* webs and was slightly lower for the specimens with *Quercus robur* webs; hence, we recommend checking (4) when using it for hardwood. In contrast, in the case of the pretensioned specimens, the results obtained using the bimodulus were

Table 8: Displacement at the midpoint of the span for two point loads of 14 kN applied at one-third and two-thirds of the span.

Type	Pretensioning force (kN)	Displacement experimental test (mm)	Modulus of elasticity (MPa)			Displacement FEM (mm)	
			E_m	$E_{c,0}$	$E_{t,0}$	With global modulus of elasticity E_m	With bimodulus $E_{c,0}$ and $E_{t,0}$
F1/PIC	—	58.18	10,875	10,326	11,470	58.98	58.95
F2/PIC	—	—	10,875	10,326	11,470	63.56	63.51
	114.32	64.91 (18.00 + 46.91)	10,875	10,326	11,470	63.48 (17.27 + 46.21)	65.64 (18.26 + 47.38)
F1/OAK	—	54.54	11,910	12,267	11,570	55.25	54.81
F2/OAK	—	—	10,090	10,390	9800	66.47	65.25
	109.72	63.15 (18.00 + 45.15)	10,090	10,390	9800	64.77 (17.22 + 47.55)	63.67 (17.38 + 46.29)

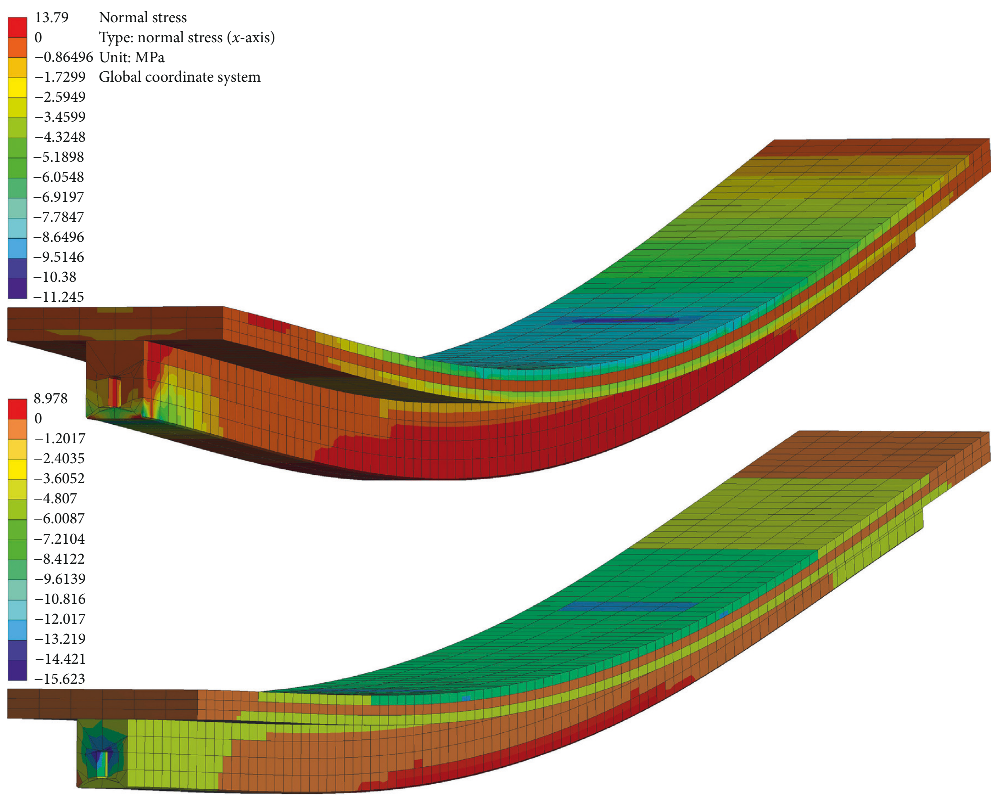


Figure 13: Finite element model. Visualization of the increase of the compressed zone in pieces of T-section with *Picea abies* webs: pretensioned (bottom) and nonpretensioned (top).

clearly closer to the experimental results than were the results from the analysis using the virtual modulus. The displacement of the pretensioned specimen with *Picea abies* webs obtained from the numerical model (65.64 mm) was 11.3% higher than that of the nontensioned solid specimen (58.95 mm). In the experimental tests, this increase was 11.6% (64.91 mm for the pretensioned specimen and 58.18 mm for the nontensioned specimen). In the specimens with *Quercus robur* webs, the displacement in the numerical model increased by 16.2%, which was practically the same as the increase obtained from the tests (15.8%). These results confirm that the variations in the stiffness experienced by the specimens under tension were a consequence of the significant increase in the compression area of the section (Figure 13). To help visualize the pretensioning phenomenon, the areas with tensile stress, regardless of the magnitude, are shown in red in Figure 13.

The results presented here significantly differ from those obtained by McConnell et al. [26]. In our experimental tests, the pretensioned *Picea abies* specimens showed an 11.6% higher deflection than the nontensioned specimens. This 11.6% increase was reduced to 3.7% after disregarding the loss of inertia due to the groove where the tendon was placed. Conversely, in the tests conducted by McConnell et al. [26], the pretensioning reduced the deflection by 8.1%. This disagreement was attributed to the interactions of several factors. First, the tendon was placed much closer to the edge of the specimen (22.5 mm instead of 105 mm). Second, the sizes of the tested specimens were different (sections of 45×145 mm with a 3 m span facing the T-sections with a 300 mm depth and 9 m span). Third, there were possible differences in the relation between the compressive and tensile moduli of elasticity parallel to the grain of the timber used in the tests. The above-mentioned circumstances could generate a greater rotational restraint at the edges of the specimens to reduce the deflection. Moreover, the benefit of pretensioning indicated by McConnell's experiments was also small.

5. Conclusions

Using *Quercus robur* instead of the usual *Picea abies* for laminating the webs of T-section specimens led to a 41.2% increase in the bending resistance and a 5.6% increase in stiffness. Given that the dimensions of simply supported specimens with a medium or long span are normally determined by deflection limitations, *Quercus robur* is generally not used due to its high cost and small benefit. The 5.6% increase in stiffness obtained in the tests could be achieved by increasing the depth of the *Picea abies* web by only 2.7%.

Pretensioning the T-sections increased the bending strength by 24.5% for the specimens with *Picea abies* webs. The average failure load of the T-sections with *Quercus robur* webs was lower in pretensioned specimens than that in the nontensioned specimens, even though the difference was only 2.6%.

The bending stiffness is a fundamental property for dimensioning simply supported specimens, and pretensioning slightly varied the stiffness of the section because of the increased compression area. We proved that such stiffness variations depend on the relation between the compressive and tensile moduli of elasticity parallel to the grain. In the analyzed cases, we found a 3.7% decrease in the stiffness of the specimens with *Picea abies* webs and a very slight increase in the specimens with *Quercus robur* webs (discounting the reduction due to the groove).

Due to the number of tested specimens and the use of different configurations for the flange-web joints with glued-perforated steel plates, we advise conducting another experimental test series to confirm the obtained conclusions.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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