Maritime Pine Stress-Laminated Timber Bridges: Losses of Prestress Forces and Flexural Behavior

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Abstract

This article presents a study on stress-laminated timber bridges. The technique is useful for the rehabilitation and construction of bridges. It consists of a series of timber planks placed side by side and compressed transversely with high-strength steel prestressing bars. A prototype of this kind of structure was built in the Department of Civil Engineering at the University of Coimbra. The prototype, a stress-laminated timber bridge deck with butt joints, was 6 m long, 2.7 m wide, and 0.20 m thick. The experimental program was developed with two main objectives: to study the evolution of the prestress value applied to the structure and to observe the bridge structural behavior under the effect of loads simulating the action of a standard vehicle. Practical difficulties and/or limitations and potentialities of the system when maritime pine is used as the timber material are also discussed. This article reports the experimental program and the results, with emphasis on the tension losses in the prestressed steel bars.

A growing interest in wooden structures has recently reappeared in Portugal. As a consequence, new research projects have been carried out. The applications of timber in bridges have also been investigated (Dias et al. 2011). For example, the technique of timber-concrete composite slabs was studied at the University of Coimbra, and the results of such work have been published by Dias et al. (2007a, 2007b). Another possibility that has been studied is the use of Portuguese maritime pine in stress-laminated timber slabs. The use of this technique in the construction and rehabilitation of bridges has been used since the mid-1970s, when it was introduced in Canada. In this respect, works by Ritter (1990) and Ritter et al. (1991) are important. Oliva and Dimakis (1988) have also studied stress-laminated timber bridges by constructing a bridge for laboratory tests, giving them information for constructing a prototype bridge on-site. Dahl et al. (2006) presented a study on the evaluation of stress-laminated bridge decks based on full-scale tests. More recently, Gutkowski et al. (2007, 2008) have carried out a study on an innovative timber bridge technology applied to skew decks. Gentry et al. (2007) reported a study on a stress-laminated deck bridge that was left with no maintenance for 15 years; nevertheless, after this period, the bridge was in good condition.

The stress-laminated technique consists of a series of timber planks placed side by side between supports of the bridge and compressed transversely with high-strength prestressing steel bars. A prototype of this kind of structure was built in the Department of Civil Engineering at the University of Coimbra.

The experimental program was developed with two main objectives: to study the time evolution of the prestress applied to the structure and to verify the bridge structural behavior under the action of loads simulating the action of a vehicle. It also helped to clarify the practical difficulties and/or limitations and potentialities of the system when the most common national structural timber is used as the raw material. This article reports the experimental program carried out to monitor the tension losses in the prestressed steel bars and the flexural tests of the slab.

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Experimental Program

General

The experimental work started by constructing the prototype of a maritime pine stress-laminated timber bridge deck. The prototype, a stress-laminated timber bridge with butt joints, was 6 m long, 2.7 m wide, and 0.20 m thick (Fig. 1). A prestressing force of 235.2 kN was applied to each of the 10 steel bars, following a predefined plan for restressing the bars. This plan was based on the type of behavior described in the literature (Ritter 1990, Ritter et al. 1991, Kainz 1998, Crews 2001, Davalos et al. 2003, European Committee for Standardization [CEN] 2004b, Freedman and Kermani 2006) indicating that the dimensional variations of the wood tends not to be further altered after three rounds of stressing operations (although variations and alterations provoked by hygrometric conditions are always possible). Recording of the prestress forces was possible through the installation of one load cell per bar during the construction phase. Based on the recorded values of prestress forces and taking into account the recommendations by Ritter (1990) and Ritter et al. (1991), a few days after the first stressing operation, the bars were restressed and then restressed again a previously determined number of days after the second restressing. Figure 2 shows a general view of the equipment and of the bridge deck under static load.

Timber

The quality control of the timber planks is essential for the evaluation of the stiffness and strength of the bridge deck. Maritime pine was visually graded to Class E in agreement with the Portuguese Standard NP 4305 (Instituto Portugues da Qualidade 1995). This grade was assigned in EN 1912:1994 to Strength Class C18 (CEN 2004a).

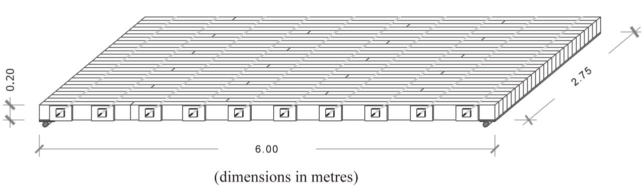

Figure 1.—Perspective view of the bridge deck.

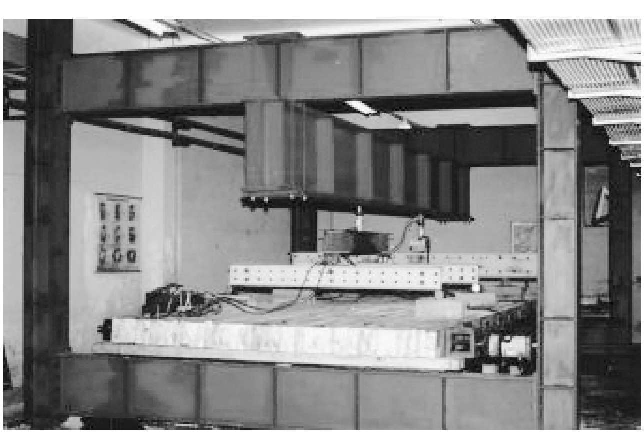

Figure 2.—Test setup.

Properties of maritime pine timber are presented in Tables 1 and 2. No preservative treatment was applied to the timber. Its moisture content was approximately 25 percent, as it was assumed that this value would probably correspond to the actual situation of a timber bridge constructed on-site. The prestressing forces and the air relative humidity were periodically monitored. In agreement with the structural model that was adopted, the individual planks were 0.07 m thick and 0.20 m high. Lengths of 1.20, 2.40, 3.60, and 4.80 m permitted the use of butt joints with a frequency of one in four and the fabrication of a deck 6.0 m long by 2.7 m wide.

Test phases

The experimental program was composed of two phases:

1. The stressing and monitoring of the forces in the transversal rods
2. The flexural tests of the timber deck

Phase 1 took 168 days with the stressing being applied at $t = 0$, $t = 8$, and $t = 84$ days, whereas the flexural tests were relatively quick (a few days were sufficient for this task). Two flexural tests were carried out: the first with a high level of prestress force in the transversal bars and the second with a low level of prestress force in the same bars. The intention was to check any vulnerability, namely, the differences in the slab stiffness caused by a loss of prestress. During the first flexural test, the level of the prestress load at each rod was 180 kN, whereas the level of the prestress in the second flexural test was 110 kN.

Long-Term Evolution of the Prestress Forces in the Bars

The environmental conditions that the prototype was exposed to are presented in Figure 3. The evolution of the prestress force in the bars is presented in Figures 4 through 6. It can be seen that the values of the prestress force are more scattered after the first tightening of the prestress bars and less scattered after the last tightening. After each stressing operation, there was a great loss of the prestress

Table 1.—Physical properties of maritime pine timber.

Property	Medium value
Density (kg/m^3)	530–600
Shrinkages coefficient (%/%)	
Tangential	0.36
Radial	0.21
Volumetric	0.60

Table 2.—Mechanical properties of maritime pine timber.

Property	Value	
Bending strength parallel to the grain	$f_{m,k}$ (MPa)	18.0
Compression strength parallel to the grain	$f_{c,0,k}$ (MPa)	18.0
Tension strength parallel to the grain	$f_{t,0,k}$ (MPa)	10.8
Shear strength parallel to the grain	$f_{m,k}$ (MPa)	2.0
Compression strength perpendicular to the grain	$f_{c,90,k}$ (MPa)	6.9
Modulus of elasticity parallel to the grain	$E_{0,\mathrm{mean}}$ (GPa)	12.0
Modulus of elasticity perpendicular to the grain	$E_{90,\mathrm{mean}}$ (GPa)	0.4

force in the first 4 days. The rate of the prestress losses became lower from cycle to cycle. However, even after about 5 months (168 d), the level of the prestress was not yet completely stabilized. This may have been caused by the changes in the hygrometric conditions of the environment and the consequent slow changes in the moisture content of the timber.

By observing the values of the prestress forces in the bars (Figs. 4 through 6), the following conclusions can be drawn. (1) There was difficulty in achieving the same prestress value in all the bars; normally, the maximum deviations were approximately 5 percent from the average values. (2) The rates of changes in prestress forces of the different bars were almost equal.

Flexural Tests

Two flexural tests were carried out: the first one with a high level of prestress force in the transversal bars and the second one with a low level of prestress force in the bars.

To perform such tests, a six-point load was applied to the bridge deck, as shown schematically in Figure 7. This corresponds to the standard Portuguese load vehicle for secondary roads. The nonfactored load, according to the Portuguese Code of Practice, would be 100 kN per axis, which gives a total of 300 kN. Applying the appropriate serviceability limit states (SLS) load combination (according to the European Codes), the load obtained would be 120 kN. The load was centered with the bridge deck, and the point loads were applied in a 0.4 by 0.2-m area.

The load applied to the deck led to a maximum deflection of 18.5 mm. The theoretical prediction for such load was 17.9 mm. For 120 kN, the expected deflection would be 19.3 mm, approximately L/300 (L = span of the bridge deck; 5.80 m). The authors tried to be as close as possible to L/300; this target conditioned the height of the section.

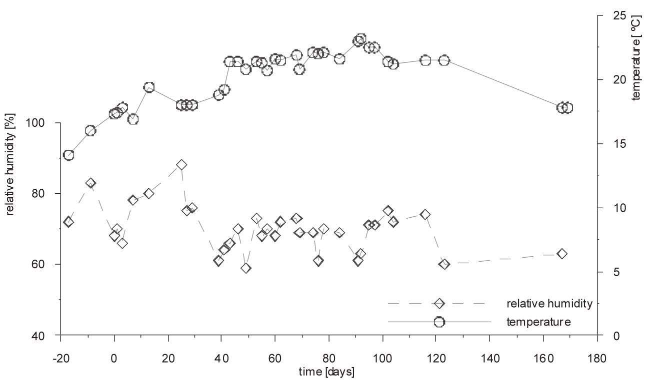

Figure 3.—Environmental conditions surrounding the prototype.

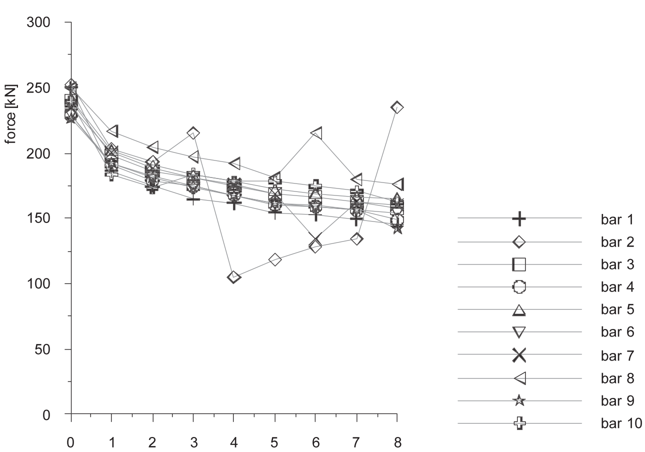

Figure 4.—Evolution of the prestress force after the first tightening.

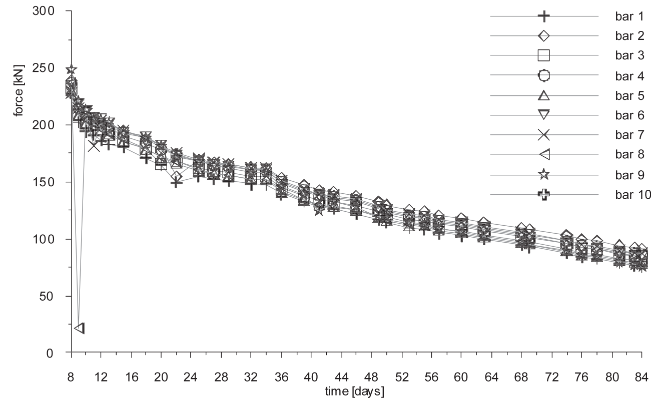

Figure 5.—Evolution of the prestress force after the second tightening.

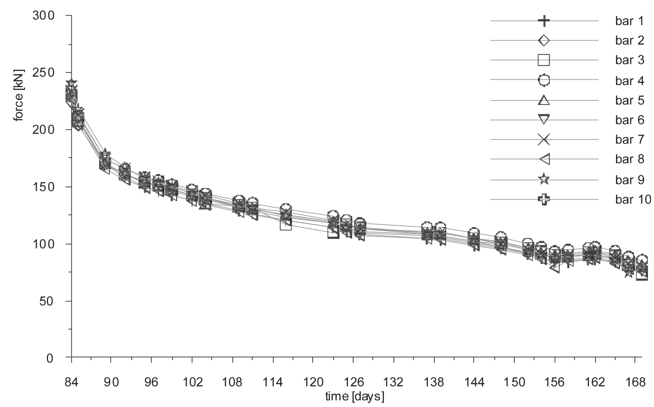

Figure 6.—Evolution of the prestress force after the third tightening.

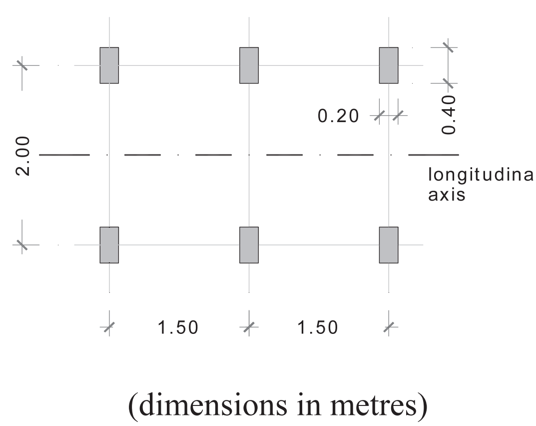

Figure 7.—Plan of the vertical load points.

For the highest prestress level in the transversal bars, the prestress forces were monitored during the bending tests (Fig. 8). It can be seen that the prestress forces suffered very small variations (less than 0.3%), leading to the conclusion that the external load applied to the bridge has a negligible influence (if any) on the prestress forces of the transversal bars.

The vertical displacement of the bridge was recorded by a mesh of nine linear variable differential transformers (LVDTs) placed as shown in Figure 9. Six of the LVDTs coincided with the point loads (LVDTs nos. 1, 4, 7, 3, 6, and 9).

The vertical displacements at different locations are presented in Figures 10 to 12. Figure 13 presents the transversal deformation along the three lines of LVDTs. From the graphs, the following can be highlighted.

1. The load–deflection relationships are approximately linear at every monitored point, indicating that the elastic range was not exceeded,
2. Along all three transversal lines, the deflection in the center of the slab is not as high as that near the ends; this is because the point loads are closer to the ends than to the center of the slab.
3. The deflections are not exactly symmetrical along the transversal lines (Fig. 13), probably because of the different stiffness of the timber planks or some

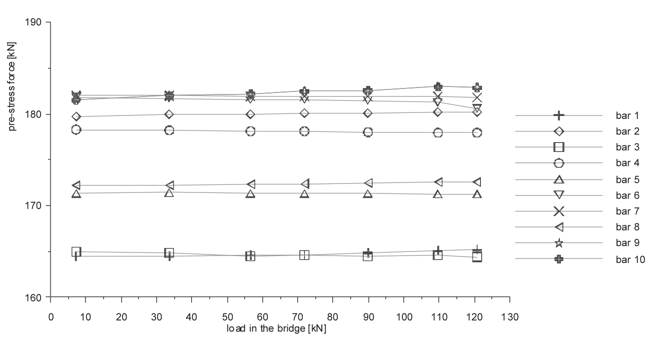

Figure 8.—Prestress forces in the bars during flexural test of the bridge.

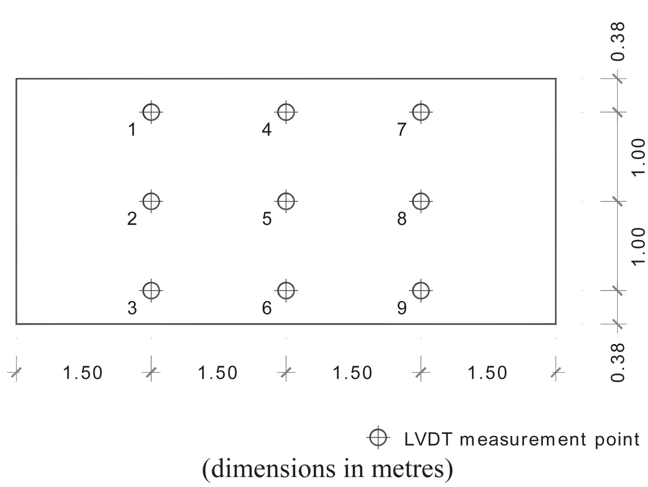

Figure 9.— Linear variable differential transformers grid.

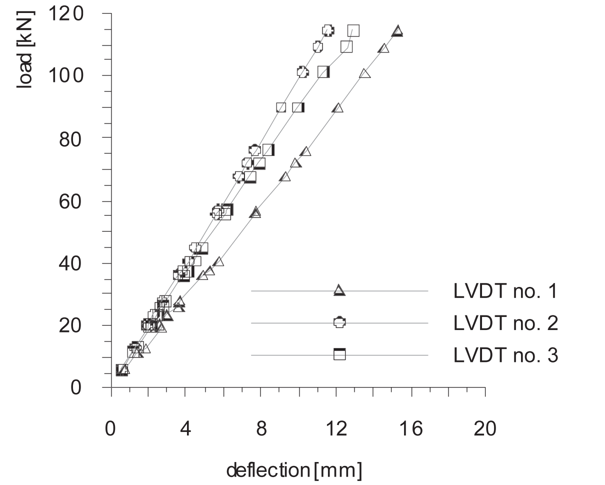

Figure 10.—Vertical displacements at locations 1, 2, and 3 (high prestress level).

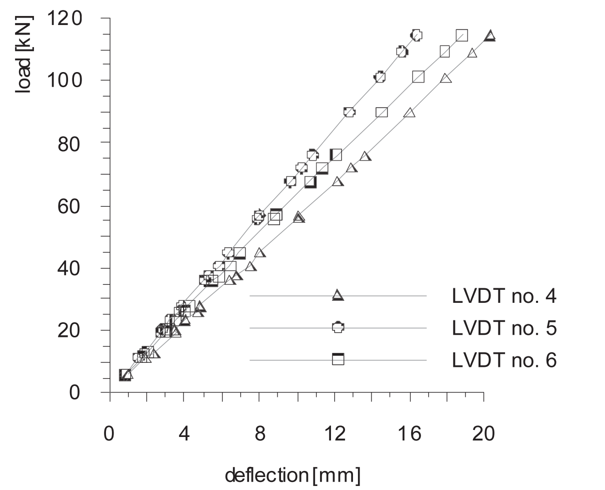

Figure 11.—Vertical displacements at locations 4, 5, and 6 (high prestress level).

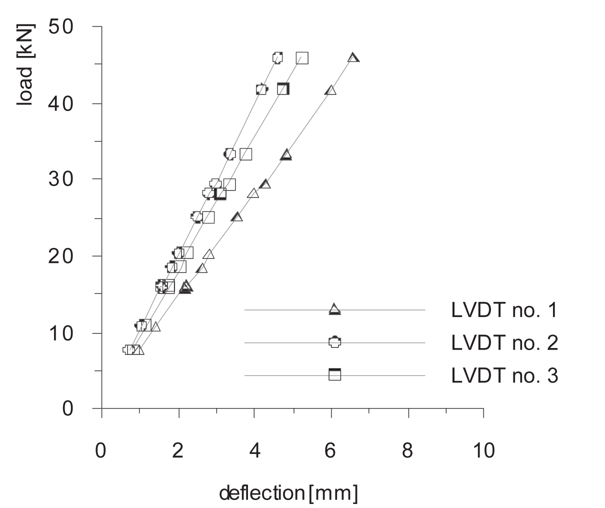

Figure 12.—Vertical displacements at locations 1, 2, and 3 (low prestress level).

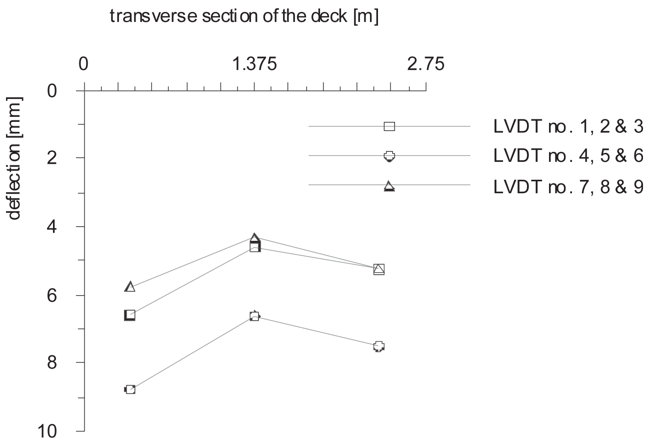

Figure 13.—Transversal deformations of the bridge deck.

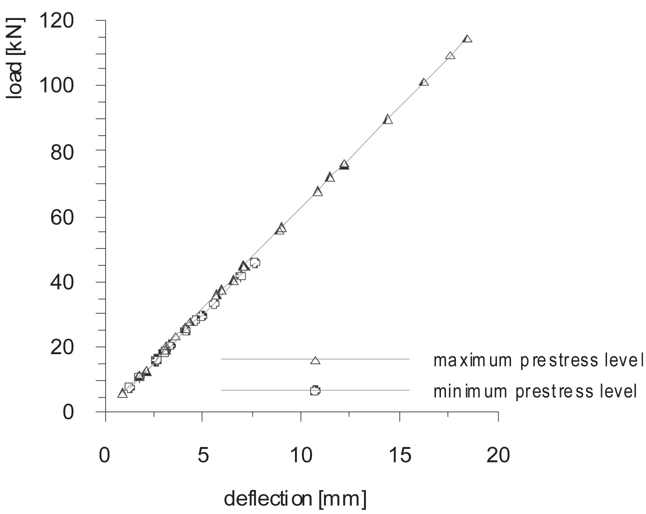

Figure 14.—Deflections at centre of bridge deck.

asymmetry in point loads location, but they are almost symmetrical along the longitudinal lines (1-4-7, 2-5-8, and 3-6-9), suggesting that the asymmetry of prestressing is not conditioning deflections.

4. The maximum deflections take place along the transversal line 4-5-6, as would be expected since that line defines the midspan of the slab.

For the second flexural test, the level of prestress of the transversal bars was reduced to the minimum value that had occurred during the first phase of the research program. The deflections were monitored, and the calculated stiffness was compared with that obtained in the first flexural test. The values were almost coincident. Figure 14 shows the load–deflection relationship at the center of the slab for the two flexural tests (LVDT 5). The minimum prestress level is approximately 65 percent lower than the maximum prestress level. Such reduction in prestress resulted in an increase in deformations of nearly 3.5 percent. Such difference is not even noticeable in Figure 14 and can be considered negligible, proving that the efficiency of the bridge deck is not compromised by the natural loss in prestress within certain limits. It should be emphasized that this comment is valid only for SLS, which corresponds to the level of loading that was applied in this phase.

Final Remarks

This work had a limited time to be implemented, and the authors decided to allocate 6 months for the stabilization of the prestress losses. This decision was based on recommendations found in the literature (Ritter 1990, Sarisley and Accorsi 1990, Ritter et al. 1991). During the rest period, the bars were restressed twice to compensate for the long-term losses simulating the recommended procedure in place. The flexural tests were carried out after this 6-month rest period. After the completion of this research work, the authors felt that the rest period should have been longer because the prestress forces in the transverse bars were not completely stabilized after 6 months.

For the flexural tests, the authors considered two extreme cases: the level of prestress forces in the transverse bars at its high value and the level of prestress in the transverse bars at its low value. However, the deflections of the two cases were approximately similar, showing that prestressing level within the tested prestress loads range has little influence on the bridge deck stiffness for service loads.

The use of a different type of wood (with a higher density) can be considered for the outer single timber planks of the laminated structure. This would likely give a higher strength to the slab and would help it to withstand the high level of concentrated stresses applied by the prestressing anchors.

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