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# Experimental and analytical analysis of a post-tensioned timber connection under gravity loads

F. Wanninger *, A. Frangi

ETH Zurich, Chair of Structural Engineering – Timber Structures, Stefano-Franscini-Platz 5, CH-8093 Zurich, Switzerland

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ABSTRACT

The moment-rotation-behaviour of a post-tensioned beam–column timber joint has been analysed extensively with a series of static bending tests. The timber joint was loaded at the end of the beams in order to apply a moment to the connection. The tests were conducted with various forces in the tendon, from 300 kN up to 700 kN. The bending tests were performed with a controlled load level, so that no failure perpendicular to the grain in the column occurred. The maximal allowable vertical load to be applied was estimated using a simple spring model. A final bending test was conducted in order to study the failure mode of the post-tensioned timber joint. The vertical load on the beams was increased until the tendon elongation got so high that the test had to be aborted. The results of bending tests of the post-tensioned timber joint are presented herein. Attention will be given to the structural behaviour and to the influence of the applied post-tensioning force on the connection stiffness. The experimental results will be compared to the results obtained using a simplified analytical calculation model.



## 1. Introduction

In the past decades precast concrete frames were developed using tendons to connect columns and beams [1–3]. These systems showed favourable seismic behaviour, being able to avoid residual deformations after an earthquake. Furthermore a model, the modified monolithic beam analogy, was developed to describe the connection behaviour [4,5]. A similar system for timber was introduced in New Zealand at the University of Canterbury [6–14]. A timber frame made of laminated veneer lumber was post-tensioned, resulting in a good structural behaviour. Design proposals were published [15–19] and buildings using the post-tensioned timber frames were constructed [20].

An important issue with these systems is the long-term behaviour. Some tests were performed [21,22] and design procedures have been published [23]. When prestressing timber, creep – particularly in the column which is loaded perpendicular to the grain – and also tendon relaxation lead to a loss in post-tensioning force. These losses can be significantly higher than for a post-tensioned concrete structure and have to be accounted for during the design process.

The technology is not just used in combination with concrete and timber, post-tensioned moment resisting steel frames have been developed as well, whereas the focus lies on the seismic design [24–27].

Post-tensioned timber joints are also being studied at the Institute of Structural Engineering at the ETH in Zurich [28]. An innovative post-tensioned beam–column timber joint has been developed using glued laminated timber (spruce) and local strengthening of the joint with hardwood made of ash (fraxinus). No further steel elements are required for the moment-resisting timber joint, only a single straight tendon is placed in the middle of the beam. The system differs from the one developed in New Zealand in two aspects: The material being used is glulam instead of laminated veneer lumber and the column is reinforced with hardwood instead of steel fasteners. The developed post-tensioned beam–column timber joint is characterised by a high degree of pre-fabrication and easy assemblage on site.

The moment-rotation-behaviour of the post-tensioned beam–column timber joint has extensively been analysed with a series of static bending tests. The timber joint was loaded at the ends of the beams in order to apply a moment to the connection. The tests were conducted with different forces in the tendon, from 300 kN up to 700 kN. The bending tests were performed with a controlled load level, so that no compression failure perpendicular to the grain occurred in the column. The maximal allowable vertical load to be applied was estimated using a simple spring

* Corresponding author. Tel.: +41 44 633 31 77; fax: +41 44 633 10 93.
*E-mail addresses:* wanninger@ibk.baug.ethz.ch (F. Wanninger), frangi@ibk.baug.ethz.ch (A. Frangi).

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**Nomenclature**

*Symbols*

| | |
|---|---|
| $b$ | width beam |
| $b_s$ | width column |
| $c$ | spring constant |
| $c_{mod}$ | modified spring constant |
| $d$ | position tendon |
| $e$ | eccentricity |
| $f_{c,0,k}$ | compression strength parallel to grain |
| $f_{c,90,k}$ | compression strength perpendicular to grain |
| $f_{p,k}$ | tension strength tendon |
| $h$ | height beam |
| $w_0$ | mean value for initial compression |
| $x$ | neutral axis depth |
| $y$ | displacement measured with LVDT |
| $r$ | position resulting force |
| $A$ | area cross section beam |
| $A_c$ | area cross section column |
| $A_p$ | cross section area tendon |
| $E_0$ | Young's modulus parallel to grain |
| $E_{90}$ | Young's modulus perpendicular to grain |
| $E_p$ | modulus of elasticity tendon |
| $F$ | force applied on the beam |
| $G$ | shear modulus |
| $I_B$ | moment of inertia beam |
| $K_I$ | initial connection stiffness |
| $L_F$ | distance interface-load application |
| $L_p$ | length tendon |
| $M$ | moment |
| $M_{max}$ | maximal moment for design |
| $N$ | number of strands |
| $P$ | tendon force |
| $P_0$ | initial tendon force |
| $P_{max}$ | applicable design load tendon |
| $R$ | resultant force |
| $W$ | section modulus beam |
| $\Delta L_p$ | elongation tendon |
| $\gamma$ | shear angle |
| $\sigma_1$ | stresses at bottom of the interface |
| $\sigma_2$ | stresses at top of the interface |
| $\sigma_{inf}$ | maximal compressive stress at the interface |
| $\theta$ | rotation |
| $\theta_{GA}$ | rotation due to shear deformation |
| $\theta_{max}$ | maximal rotation for design |

model. The model is an adoption of a simplified approach based on a rigid foundation on elastic springs and is presented as an alternative to the modified monolithic beam analogy. A final bending test was conducted in order to study the failure mode of the post-tensioned timber beam–column joint. The vertical load on the beams was increased until the tendon-elongation got so high that the test had to be aborted due to safety reasons.

In this report the results of the bending tests with a post tensioning force of 550 kN are presented. The results for the entire test series are summarised in a test report [29].

Particular attention will be given to the structural behaviour of the post-tensioned timber connection. Furthermore, an analytical model will be introduced. The experimental results will be compared to the results obtained using the analytical calculation model.

## 2. Specimen and test setup

### 2.1. Specimen

The test specimen consists of two beams and a column made of glulam. The glulam beams are made of spruce GL24h [30] except for the three bottom lamellae, which are made of ash D40 [31] (classification based on density). The strength values are summarised in Table 1. The column is a hybrid element as well, made of spruce and ash. The hardwood is used in the connection area between the column and the beam (darker areas in Fig. 1), where high stresses perpendicular to the grain occur.

A straight tendon (see Table 2 for tendon properties) is inserted in the middle of the beams and attached at each side of the beams. A 50 mm thick steel plate is used at the end of the beams for the load transmission from the tendon into the beams. A hydraulic press is installed between the anchorage of the tendon and the tendon itself, so that the tendon force can be controlled and changed if necessary.

The moment-resistant connection does not require further steel elements. The shear force between beam and column is transferred via friction and through the small supports under the beams, which were manufactured by cutting a notch into the column.

All the tests were performed at the ETH Zurich on a strong floor. A rigid steel frame was built for the tests. Fig. 2 shows the test setup. The frame consists of two columns, which are fastened to the strong floor with high-strength pre-stressed bolts. Two horizontal beams connected to a strong wall provide lateral stability to the testing rig. The test specimen is attached to the columns with stiff steel profiles. The load $F$ on the beams is applied by two cylinders, which are connected to the beams at a distance of 1.24 m from the interface column/beams (see Fig. 1). The cylinders allow applying a load of max. 300 kN on each side of the specimen. The cylinders are connected to a hydraulic pump, which allow to control them separately, so that several load cases can be investigated. It is for example possible to apply the load only on one beam, while the other one is unloaded. One beam can also be loaded to a certain constant force while the second beam is loaded to a different force. The weight of one beam with two cylinders is 480 kg, which has to be accounted for in the analysis.

### 2.2. Instrumentation

To investigate the structural behaviour of the post-tensioned timber connection several types of measuring devices were used (see Table 3):

- linear voltage displacement transducers (LVDTs),
- inclinometers,
- pressure sensors.

**Table 1**
Characteristic strength and stiffness properties in MPa for strength grade GL24h [30] and D40 [31].

| Strength grade | GL24h | D40 |
|---|---|---|
| $f_{c,0,k}$ | 22 | 26 |
| $f_{c,90,k}$ | 3 | 8.3 |
| $E_0$ | 11,000 | 13,000 |
| $E_{90}$ | 300 | 860 |
| $G$ | 500 | 810 |