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Experimental and analytical analysis of a post-tensioned timber frame under horizontal loads

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ABSTRACT

Post-tensioned timber frames are investigated at ETH Zurich in the context of the development and promotion of efficient hybrid timber structures made of hardwood. These structures can be prefabricated and are quickly assembled on site, making them suitable for multi-storey buildings.

A post-tensioned timber frame with hardwood reinforcement was analysed with a series of static pushover-tests. The frame was loaded with a horizontal force while the displacement was recorded. The results of these pushover-tests are presented herein and will be compared with pushover-curves obtained from an analytical spring model. Attention will be given to the behaviour of the beam–column connections, where several LEDs were attached to analyse the connection behaviour and the influence of the tendon force on the lateral stiffness of the frame. All tests were performed with a controlled load level, which was estimated using a simple analytical spring model.

The test verified the analytical spring model and showed the self-centring behaviour of such structures.

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 called the monolithic beam analogy was developed to describe the connection behaviour [4]. A similar system for timber was developed in New Zealand at the University of Canterbury [5,6]. Research included section analyses [7,8], experimental campaigns on frame structures designed for seismic loads [9–11], as well as investigations on frames designed for gravity loads [12]. Design proposals were published [13–15] and buildings using the post-tensioned timber frames were constructed [16–18].

The technology is not just used in combination with concrete and timber, post-tensioned moment resisting steel frames have been developed as well [19–21].

Post-tensioned timber joints are also studied at the Institute of Structural Engineering at the ETH Zurich within the framework of promoting the use of hardwood as a construction material. The amount of hardwood in the Swiss forests has been increasing in the past decade due to climate change and a change in silviculture. However, approximately 60% of the harvested hardwood is used directly for energetic purposes instead of using it for other applications – for example as a construction material – first [22]. A post-tensioned beam–column timber joint was developed using glued laminated timber (Norway spruce, *Picea abies*) and local strengthening of the joint with hardwood (European ash, *Fraxinus excelsior*). No further steel reinforcement is required for the moment-resisting timber joint, only a single straight tendon is placed in the middle of the beam. The developed post-tensioned beam–column timber joint is characterised by a high degree of pre-fabrication and easy assemblage on site. Moreover, frame structures lead to a good amount of flexibility for the user. Short construction time and large open floor spaces without walls are the main advantages for such structures in countries with low seismicity.

The moment rotation behaviour of the proposed joint was studied extensively in the past. The focus lied on vertical loads, only some tests were conducted with an asymmetrical loading so that shear deformations occurred in the column [23]. These loads were closer to horizontal load cases (wind, earthquakes), but were never intended to check the performance of such structures under horizontal loading. In order to study the behaviour of a post-tensioned timber structure under horizontal loading more accurately and validate the developed spring model for horizontal loads [24], a three bay post-tensioned timber frame was investigated performing several static pushover-tests. Since the main objective is the validation of the model, the tests were performed with

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Nomenclature

A_c	cross section area column	N	number of strands
A_p	cross section area tendon	M	moment
D	diagonal of the shear panel	P_{max}	applicable design load tendon
E_0	modulus of elasticity parallel to the grain	R	resulting force
E_{90}	modulus of elasticity perpendicular to the grain	b_b	width of the beam
E_b	modulus of elasticity of the beam	c	modulus of subgrade reaction, spring constant
E_c	modulus of elasticity of the column	$f_{c,0,k}$	compressive strength parallel to the grain
E_p	modulus of elasticity of the tendon	$f_{c,90,k}$	compressive strength perpendicular to the grain
F	horizontal force	$f_{p,k}$	tensile strength tendon
G	shear modulus	h_b	beam height
G_c	shear modulus of the column	h_c	column height
I_b	moment of inertia of the beam	u	horizontal displacement of the frame
I_c	moment of inertia of the column	θ	rotation due to moment
K	spring constant for the rotational spring	$\theta_{col,el}$	elastic rotation of the column
K_{hor}	horizontal stiffness of the frame	θ_{GA}	rotation due to shear deformation
K_i	spring constant at the inner column	θ_{tot}	total rotation in the beam–column interface
K_o	spring constant at the outer column		

pinned column bases in order to have clear boundary conditions, i.e. all the lateral resistance was provided by the connections.

2. Specimen and test setup

2.1. Specimen

The test frame was assembled with three beams and four columns all made of glulam as shown in Fig. 1. The thickness of the lamellae was 40 mm. The glulam beams were made of spruce except four lamellae at the beam–column interface, which were made of ash (see Fig. 2). The properties of the two kinds of timber are summarised in Table 1. The beams had a dimension of 6.12 × 0.72 × 0.28 m. The columns were made entirely of ash and had a dimension of 3.54 × 0.38 × 0.38 m.

The hardwood was required in areas where high stresses perpendicular to the grain occurred, namely in the connection between the columns and the beams (see Fig. 2). The additional brackets under the beams were for safety reasons and for the construction phase, where no tendon force had yet been applied to the specimen and the beams were therefore not connected to the columns.

The values for strength and stiffness of the materials are summarised in Table 1. The properties of the tendon are summarised in Table 2. The frame specimen was similar to the frame that was used for the construction of the ETH House of Natural Resources [25].

The tendon was anchored with a steel plate at either end of the specimen for the load transmission from the tendon to the frame.

The shear force between beam and column was transferred via friction.

2.2. Test setup

All the tests were performed at ETH Zurich on a strong floor as shown in Fig. 3. The force was applied by two cylinders, which allowed to apply a force of 300 kN in total on the specimen.

The columns were connected to the strong floor using steel profiles. The column bases were constructed in a way that allowed the columns to rotate. The pushover tests were therefore performed with pinned columns.

Six large steel columns were connected to the strong floor and positioned between the timber columns (see Fig. 3). These columns were necessary to avoid out of plane movement, allowing the specimen to move in direction of the load application but not perpendicular to that.

2.3. Measuring instrumentation

To investigate the structural behaviour of the post-tensioned timber frame under horizontal loading several types of measuring devices were used:

- inclinometers
- optical 3D measurement system

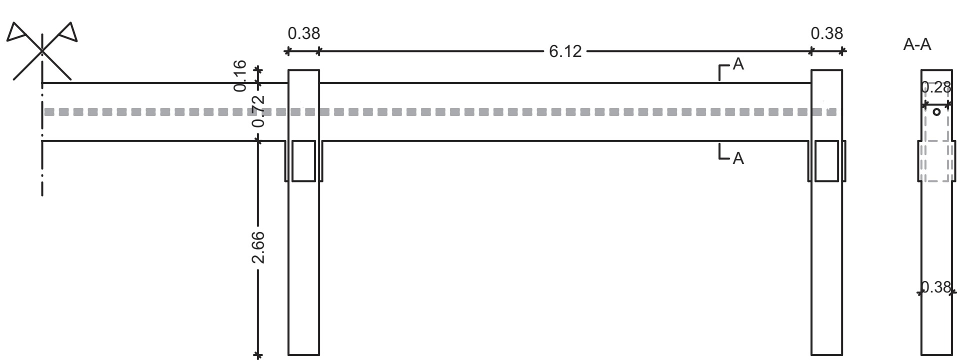

Fig. 1. Test specimen with all dimensions in [m].