Fast assembled post-tensioned timber frames

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1. Introduction

Post-tensioned timber frames have its origin in concrete structures. In the 90ies, precast concrete frames were developed using tendons to connect columns and beams within the framework of a program to investigate the performance of precast concrete buildings called the "Precast Seismic Structural Systems Research Program" (PRESSS) [1,2]. Different connection types were used and tested for the developed precast concrete frames. One of these connections was realised with unbonded tendons. This system showed favourable seismic behaviour, being able to avoid residual deformations and experience only minor damage after an earthquake (see Figure 1).
The system was introduced to timber engineering by the University of Canterbury in New Zealand [3]. The developed system - called Pres-Lam® - uses laminated veneer lumber (LVL) as an alternative to concrete for post-tensioned frame and wall structures. Several tests on a post-tensioned beam-column joint as well as on a frame system showed a favourable seismic behaviour [4]. Energy dissipation is easily possible by adding dissipators or by yielding of mild steel within the specimen making the system suitable for areas with high seismic activity [5]. The scope of the research in Canterbury also includes frames designed of gravity loads [6] as well as the interaction between the frame and the floor system [7].
Another post-tensioned timber frame system called Flexframe® has been developed at ETH Zurich [8]. The system differs from the one developed in New Zealand in the timber species used and in the reinforcement of the column. The Flexframe® connection is built with glulam made from Norway spruce (picea abies). The column and the beams' bottom side are reinforced using European ash (fraxinus excelsior). The reinforcement is needed in areas where high stresses perpendicular to the grain occur as indicated in Figure 1 (the darker parts are made of ash). Moreover, using ash as reinforcement leads to a higher stiffness in the connection. The tendon is placed in a cavity in the middle of the specimen and anchored at the end grain faces of the beams with steel plates. The steel plates transfer the force from the tendon to the specimen leading to a compression of the connection itself, which leads to a semi-rigid moment resistant connection.

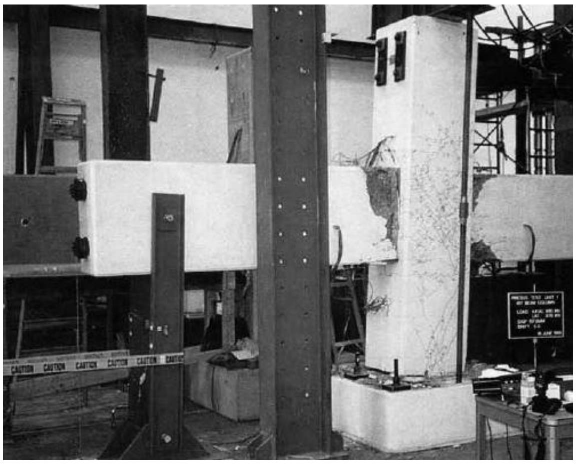
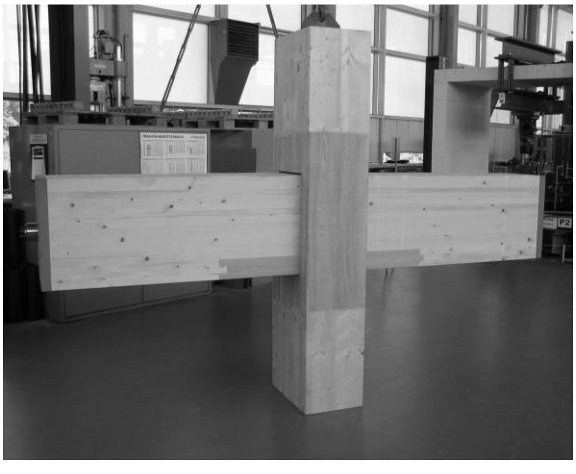

Figure 1: Post-tensioned concrete connection developed for the PRESSS-Program (left) [2] and the post-tensioned timber connection made of glulam developed at ETH Zurich [8]

2. Analytical modelling of the connection

The tendon force presses the beams against the columns. The column, which is loaded perpendicular to the grain, is much softer than the beams, which are loaded parallel to the grain. The column is therefore modelled as springs that embed the rigid beams. This spring-based model was introduced by the author and is described in more detail in Wanninger and Frangi [9]. The model allows for calculating the connection behaviour with simple equations that can be derived using equilibrium conditions (all equations and its derivation can be found in Wanninger and Frangi [9,10]).
Since there are no steel elements apart from the tendon in the connection area, a gap occurs as soon as there is no compression at either the top or bottom edge of the connection. This has to be accounted for in the modelling process; there are 4 stages (see Figure 2):

- Stage 1: Before decompression; the beam is in full contact with the column.
- Stage 2: After decompression; a gap occurs at the edge of the beam.
- Stage 3: Tendon elongation; if the gap reaches the tendon, the latter gets elongated, resulting in an increase in tendon force.
- Special case: Asymmetrical load case; if the column is not loaded equally from both sides, shear deformations occur in the column. This can be modelled with a shear spring. More details can be found in Wanninger [10].

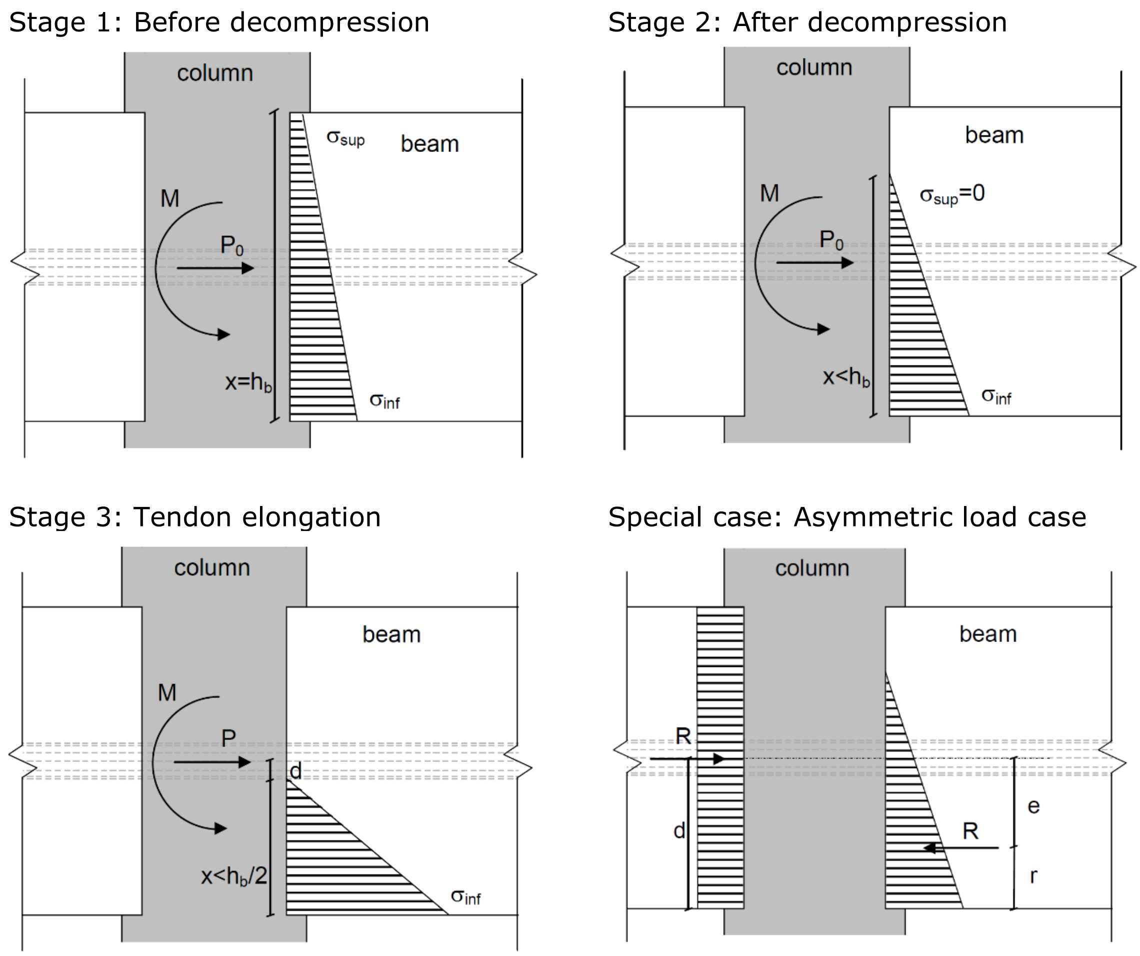

Figure 2: Beam-column interface for different stages and for the asymmetrical load case (i.e. frame under horizontal loading)

The analytical model allows to replace each connection with a rotational spring, as it allows to calculate the rotation θ in the connection for any given moment M. This makes the numerical modelling very easy, as rotational springs can be modelled with most commercial engineering software (as indicated in Figure 3). A preliminary calculation will be given in the chapter "Design of an optimised post-tensioned frame structure".

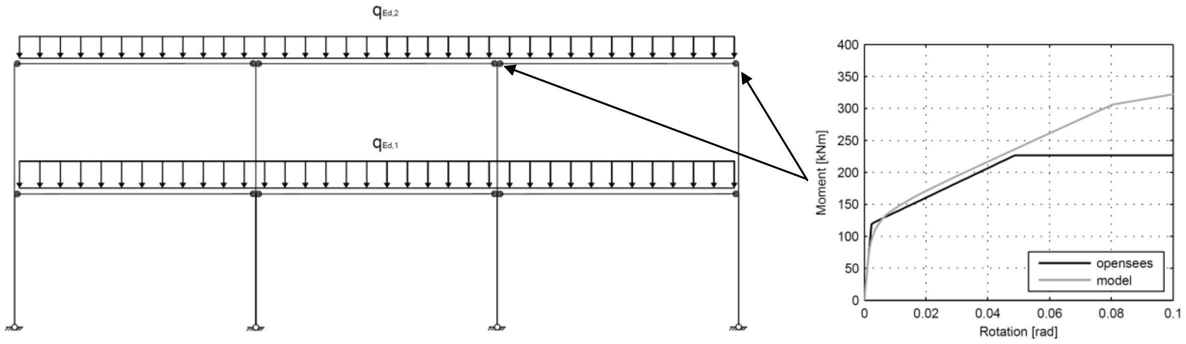

Figure 3: Modelled frame with rotational springs in the beam column interface. The springs replace the connection and can be modelled with several commercial software (here Opensees)

3. Experimental campaigns

3.1. Post-tensioned timber connection under gravity loads

A post-tensioned timber connection was tested at ETH Zurich under gravity loads in 2012. The load was applied with cylinders, as can also be seen in Figure 4. The specimen was fixed using a steel frame in order to prevent it from moving.
The main goal of the tests was the estimation of the structural behaviour of the post-tensioned timber connection and the validation of the analytical model described in the previous chapter.

During the test series, several parameters were measured or calculated:

- The rotation θ
- Height of the compressed zone x
- Maximal stresses at the interface σ
- The moment M at the interface due to the applied force F

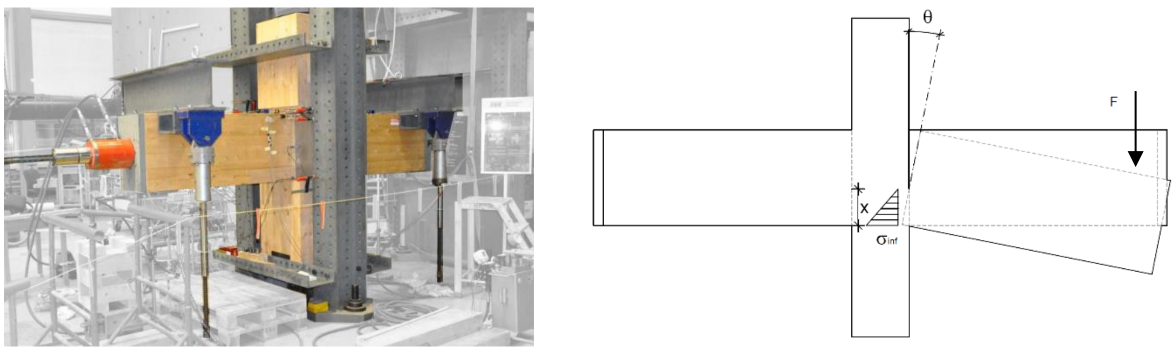

Figure 4: Test specimen in the lab (left). Both beams were loaded under gravity loads as illustrated on the right

The results for a test are shown in the following figure in grey with the prediction from the analytical model (black):

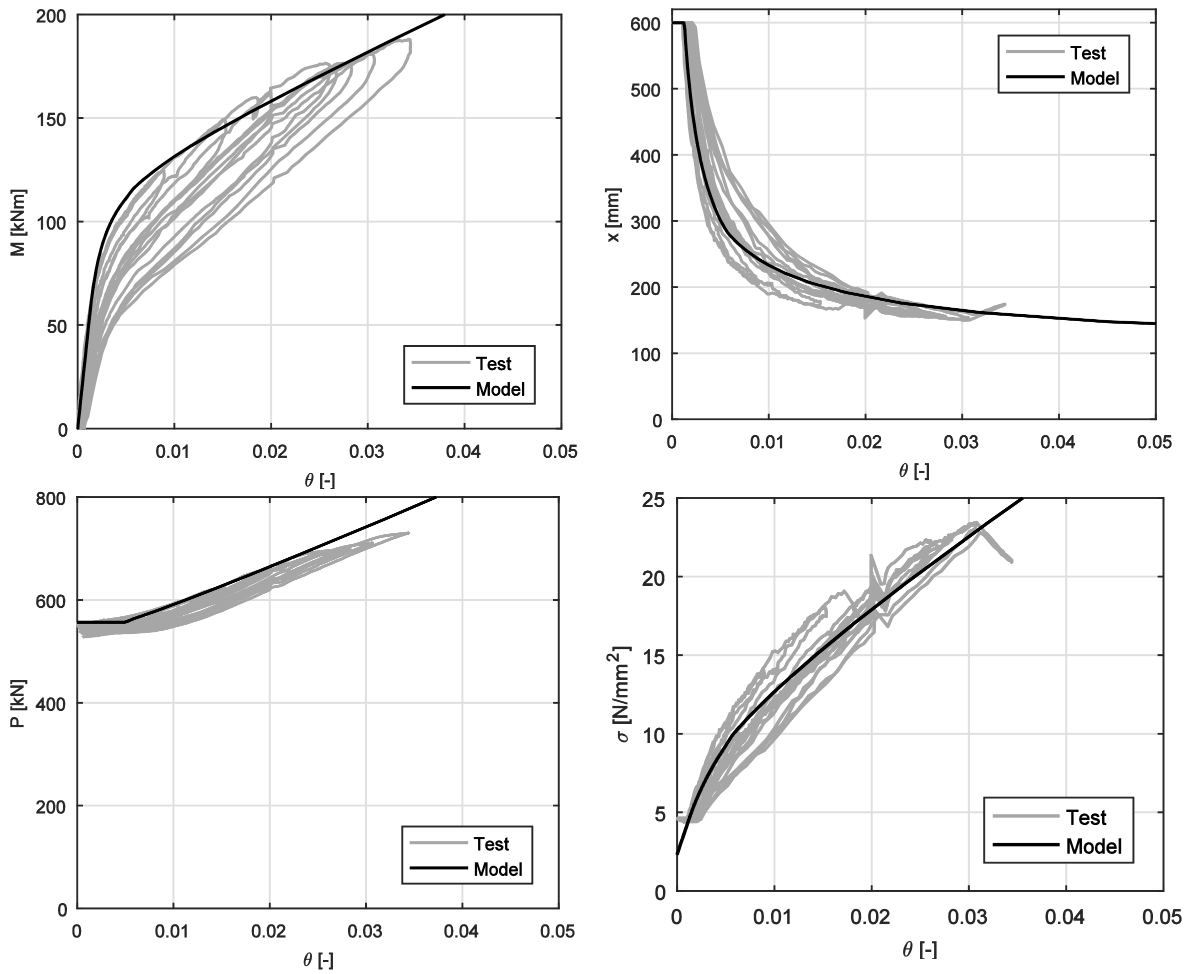

Figure 5: Test results (grey line) and analytical prediction (black line) for: Moment-rotation (top left), neutral axis depth-rotation (top right), tendon force-rotation (bottom left) and maximal stresses-rotation (bottom right)

The moment-rotation diagram is needed for the design process, i.e. this graph represents the rotational spring that needs to be implemented for modelling the connection of a post-tensioned timber frame.

The height of the compressed zone x decreases as soon as the gap opens. For this specimen, the height of the beam is 600 mm, which corresponds to the initial value for x. The tendon is positioned in the middle of the beam, i.e. at x = 300 mm. Since x got smaller than 300 mm, tendon elongation was the cause, as can also be seen in the plot for the tendon force P. The tendon force increases for rotations over 0.006 rad.

The stresses at the interface were calculated from the other values based on linear-elastic theory. The stresses reach values that are much higher than the strength of the column perpendicular to the grain (approximately 12-14 MPa [11]). It is recommended to choose a maximal allowable stress in the connection and reduce the moment in the connection according to the chosen stress level. I.e. for a chosen stress level of approximately 14 MPa the moment should not exceed 150 kNm.

The tests also showed another characteristic of any post-tensioned timber connection; the self-centering behaviour. As soon as the load is reduced, the rotations go back to zero, i.e. the rotations are reversible.

The prediction given by the analytical model is also accurate for moment, rotation, stresses as well as height of the compressed zone and the tendon force.

3.2. Post-tensioned timber frame under horizontal loads

A frame specimen was tested under horizontal loading in order to investigate the behaviour of a post-tensioned timber frame under wind and seismic loading. The frame was fully scaled, i.e. it had a total length of approximately 20 m and a height of 3 m. The test setup is shown in Figure 6.

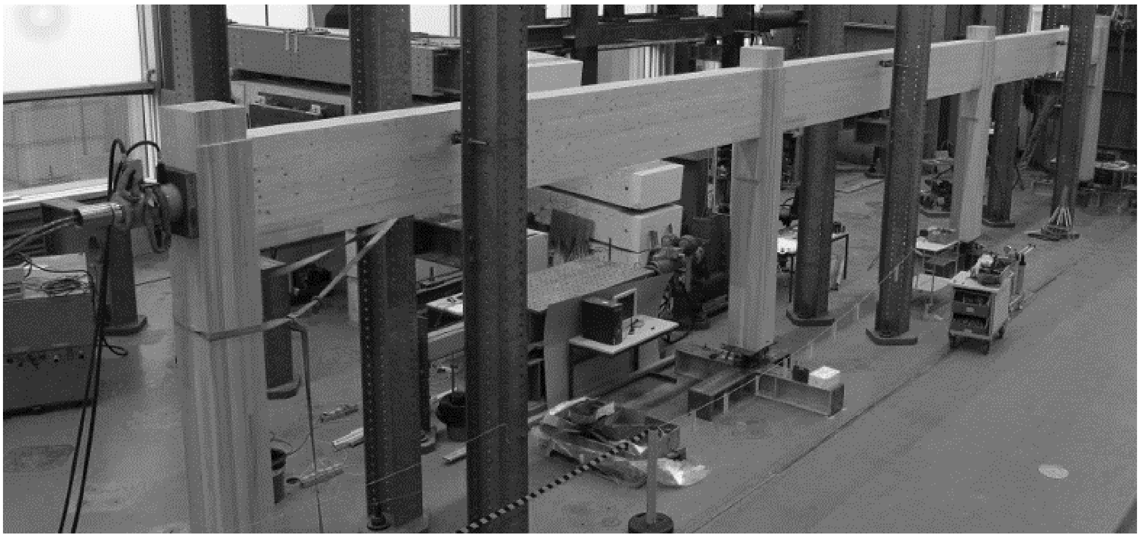

Figure 6: Test setup with a post-tensioned timber frame

The tests were conducted with quasi-static loading. The main measurements included the applied horizontal force F and the horizontal displacement u of the frame specimen, i.e. the characteristics needed to describe the pushover-curve of the post-tensioned timber frame.

The measured pushover-curve is plotted in Figure 7 as a grey line. The curve shows two loading and unloading cycles. The frame moves laterally as the load is applied and goes back to its initial position as soon as the load is removed. This self-centering behaviour is beneficial in order to resist earthquakes undamaged. The frame moves with the earthquake and goes back to its initial position after the shock is over. The structure remains intact without suffering from residual deformations. The capability to move laterally during an earthquake is are reason for naming the system Flexframe®.

The prediction made with the analytical model is plotted as well. The model predicts a stiffer pushover-curve. However, the model is a simplification and easy to use. More details regarding the calculation of the analytical pushover curve can be found in Wanninger [10].

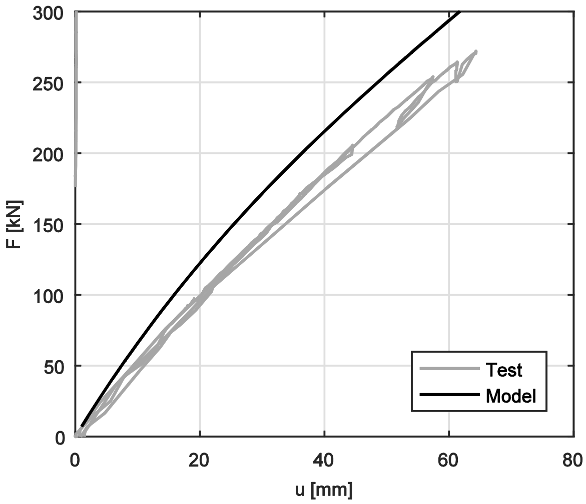

Figure 7: Pushover-curve for the tested post-tensioned timber frame (grey) and the prediction calculated with the analytical model (black)

3.3. Tendon force losses

The tendon force will deteriorate over time, leading to a decrease in connection stiffness. It is therefore important to estimate the losses during the lifetime of the building. Two post-tensioned timber frames and a post tensioned beam specimen have been monitored at ETH Zurich for over four years up to date [10].
The tendon force P over time is shown in Figure 8 for frame and beam specimens that were post-tensioned. The frames suffer from more losses than the beam, which is due to their larger size and due to the column, that is loaded perpendicular to the grain. The tendon force increases and decreases in cycles, which correspond well with the relative humidity in the testing environment (Figure 8, right graph). An increase of the relative humidity leads to an increase of the moisture content in the specimen, leading to swelling and therefore to an increase of the tendon force. The opposite happens if the relative humidity drops; the specimen shrinks due to a dropping moisture content and therefore the tendon force drops as well.

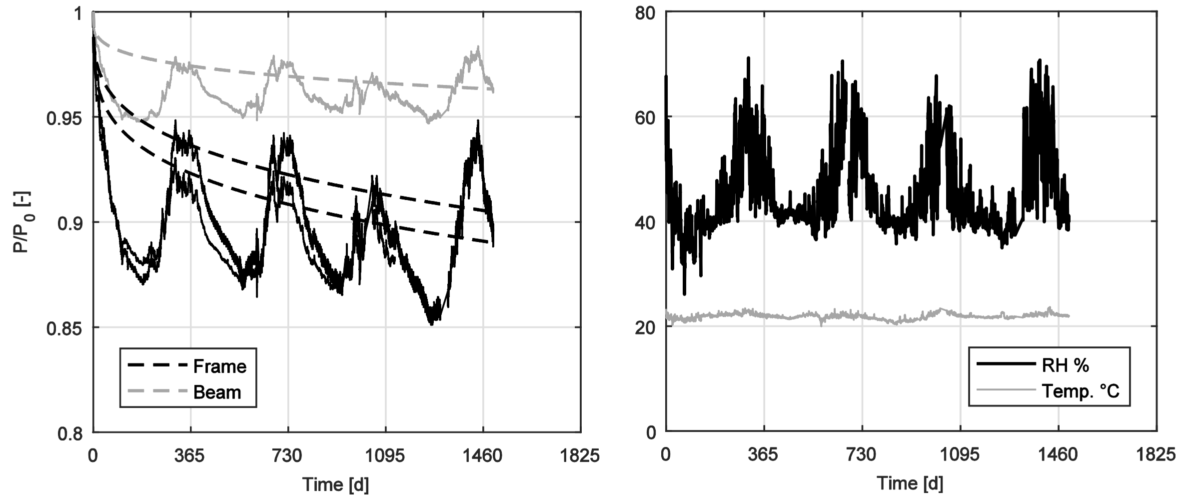

Figure 8: Tendon force P normalized with the initial tendon force P_0 (left) and relative humidity with temperature in the test environment (right)

The losses can be extrapolated as shown in the left plot in Figure 8 with the dashed lines. The extrapolated values are summarised in Table 1.

Table 1: Extrapolated tendon force losses for the beam and the frame specimens

Tendon force losses in %	**10 years**	**50 years**
Beam specimen	5%	7%
Frame specimen (3 years)	14%	21%
Frame specimen (4 years)	12%	19%

The losses for the beam specimen add up to 7% after 50 years, the ones for the frame specimens add up to 19% and 21%. These losses have to be accounted for during the design of a structure. It is therefore recommended to add approximately 30% of losses to the initial tendon force, which should lead to an initial compression of approximately 2.5 MPa [10].

4. Prototype building: ETH House of Natural Resources

The post-tensioned timber frame presented in this paper was implemented in a building for the first time in 2015. The building is called "ETH House of Natural Resources" and is shown in Figure 9. The four storey building is situated on the campus site "ETH Hönggerberg". The basement as well as the ground floor were built conventionally with reinforced concrete. The top two storeys were constructed with the post-tensioned timber frame and different kind of timber-concrete composite slabs, which were also developed as part of a PhD-thesis [12]. Moreover, the building is being monitored and data has been collected since the beginning of the construction process [13-15].

Figure 9: ETH „House of Natural Resources. Building from the outside (left) and office with post-tensioned timber frame (right)

The upper two storeys, which are used as office space, are composed of a post-tensioned timber frame, which carries the gravity as well as the horizontal loads. This means that all walls as well as the staircase are not load-bearing. The walls are drywalls that can be removed if the layout of the building needs to be changed due to altering requirements from the owner of the building. The frame allows for flexible floor plans, which is the second reason for naming the system Flexframe®.

Another advantage of the frame is the quick assembly process of the frame, which is shown in Figure 10. The frame was set up by a workforce of two within a few days. The frame can be loaded as soon as the tendon force is applied.

Figure 10: Post-tensioned timber frame during its construction process: Installation of the columns (left), followed by the positioning of the beams (top right) and application of the tendon-force (bottom right)

5. Design of an optimised post-tensioned frame structure

This chapter describes the design of an optimized structure; i.e. the frame will be the same as for the House of Natural Resources, however, the slab systems will be altered. The slab systems used for the House of Natural Resources are very heavy, which is a major drawback for a seismic region.

5.1. Structural elements

The structural system of the building consists of a post-tensioned timber frame and two different slab systems. The frame has a height of 6 m (2 times 3 m storeys and 3 times 6.5 m span bays in both directions (Figure 11). The beams have a cross section of 720 × 280 mm and are made of glulam GL24h [16]. The hardwood columns have a cross section of 380 × 380 mm and are of the strength grade GL48h [17]. A tendon force of 500 kN was chosen to achieve the building design objectives. This force has to be guaranteed over the lifetime of a building, thus, the initial tendon force was set to 700 kN, i.e. aproximately 30 % tendon force losses are accounted for.
For simplicity reasons, the symmetry is accounted for and the frame is reduced to a 2D-frame-model that is loaded uniformly (as shown in Figure 11 on the right side). The connection between each column and the beam is modelled with a rotational spring with the characteristics shown in Figure 5.

Figure 11: Two storey post-tensioned timber frame

The slab systems are chosen from a catalogue provided by Lignum [18], which is suited for an office space (acoustics) and is light at the same time. The slab systems for the floor and roof are shown in the following figure:

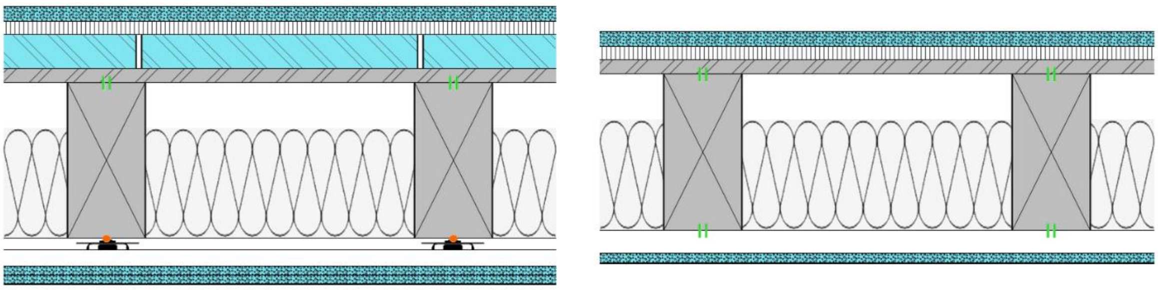

Figure 12: Slab systems: Floor (left) and roof (right) [18]

The resulting dead and live loads are summarised in Table 2:

Table 2: Loads on the building

	Office floor	Roof
Dead loads	8.1 kN/m (2.5 kN/m^2)	6.5 kN/m (2 kN/m^2)
Live loads (office space)	9.8 kN/m (3 kN/m^2)	3.3 kN/m (1 kN/m^2)

The column base is made with glued in rods as shown in Figure 13 and the moment-rotation behaviour is modelled according to test results which were performed at ETH in 2016 [19]. These column bases add lateral stiffness to the frame and re-distribute the moments from the connections in the first storey to the column bases.

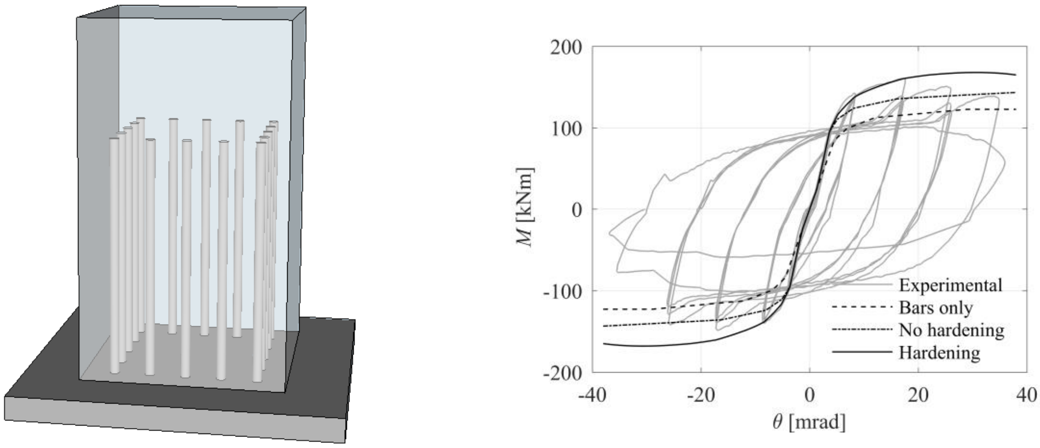

Figure 13: Column base (left) and moment rotation behaviour of the column base [19].

5.2. Design for seismic loads

The design is done for a two storey frame as described previously and for a three storey frame. The design in done for three seismic zones in Europe, whereas Europe is divided into three zones with three different ground accelerations; 1.6, 2.4 and 3.6 m/s^2 [20].

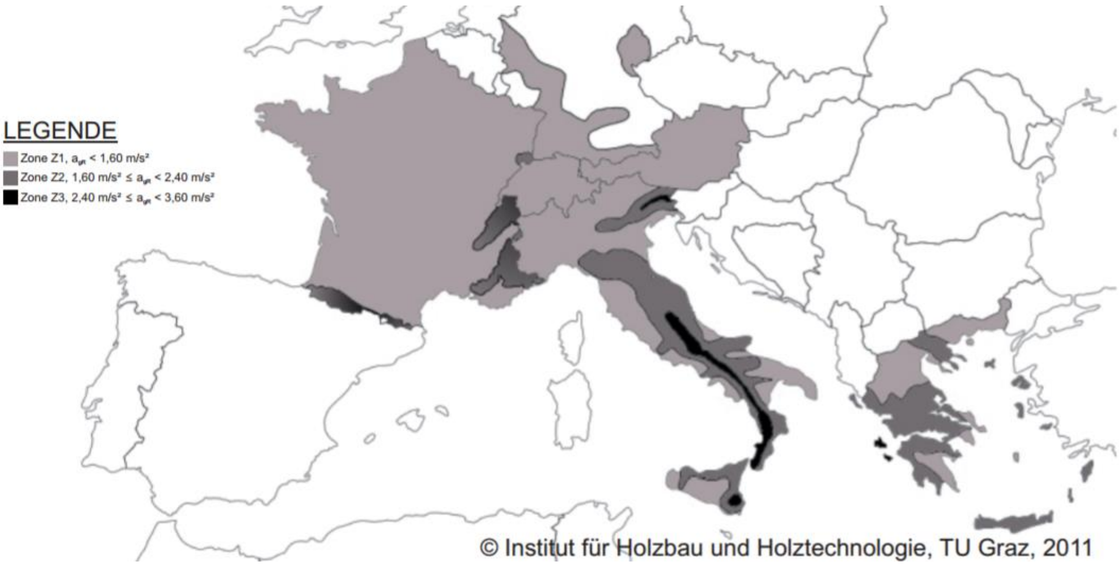

Figure 14: Seismic zones for Germany, Switzerland, Austria, Italy and Greece according to Ringhofer and Schickhofer [20].

The design for the proposed post-tensioned timber frame has to be done displacement based rather than force based, since there is currently no behaviour factor q available. Therefore, acceleration (S_a) – displacement (S_d) – spectra are used for the seismic design. The elastic spectra were generated according the Eurocode 8 [21] for a ground class C and are shown in Figure 15 on the left. Two recorded earthquakes are shown in Figure 15 in the right graph, the recordings are for the following earthquakes:

- Amatrice 24.08.2016, M_W = 6, measured in Amatrice (station code AMT), site classification EC8 B*
- Aquila 06.04.2009, M_W = 6.1, measured in Aquila (station code AQV), site classification EC8 B

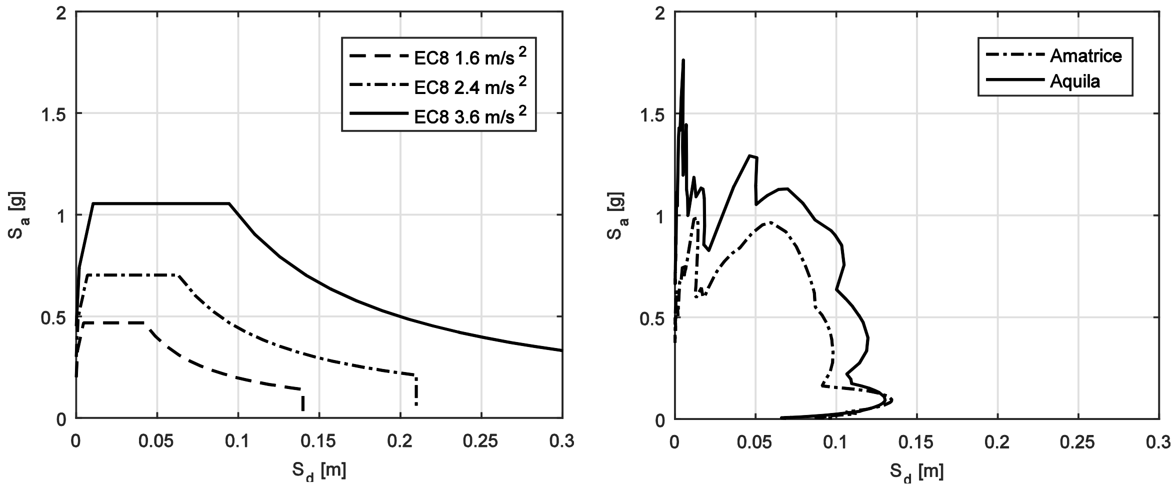

Figure 15: Elastic spectra according to EC8 for three ground accelerations and ground class C (left) and recordings from earthquakes in Aquila and Amatrice (right)

The pushover curve for the building is generated with a numerical model using rotational springs for the connecting (according to Figure 3). The gravity loads were added to account for the P-Delta-effect. The pushover curve for the two and three storey frame were transformed into a pushover-curve for an equivalent SDOF-system [22] and are plotted in Figure 16 for a two storey and a three storey building for the design earthquakes (left figure) as well as for the recorded earthquakes in Aquila and Amatrice (right figure). The pushover-analysis was stopped as soon as a connection between beam and column reached a value of approximately 150 kNm. This is the value that was chosen according to Figure 5 and it also represents a value that was reached during the pushover tests on the post-tensioned timber frame and is therefore considered safe [10].

Based on the data in Figure 16, the building should withstand the design earthquake for a ground acceleration of 1.6 as well as 2.4 m/s^2, as the demand from the earthquakes corresponds to a displacement of 0.05 and 0.08 m for the three storey building and 0.03 and 0.04 m for the two storey building, which behaves stiffer than its counterpart with three storeys. Both buildings do not have the capacity to withstand the design earthquake for a ground acceleration of 3.6 m/s^2, as the pushover-curve ends within the envelope defined by the earthquake.

The recorded values suggest that the two as well as the three storey building could have withstood the Amatrice earthquake. However, the two storey building would not have withstood the Aquila earthquake, whereas the three storey building could have survived that earthquake as well.

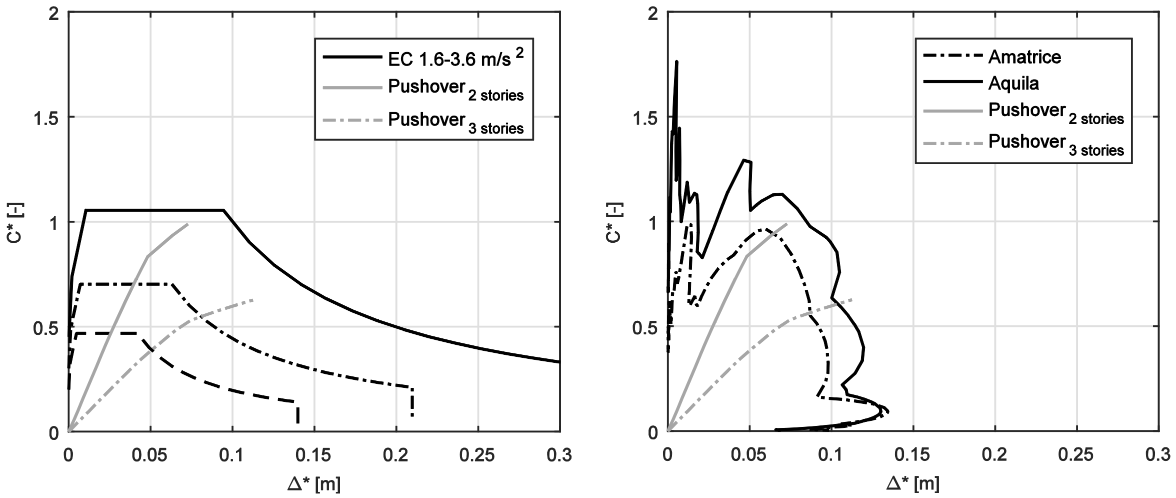

Figure 16: Capacity spectra with pushover curves for the EC8 elastic design earthquakes for a ground class C (left) and capacity spectra for the recorded earthquakes with the pushover curves (right)

6. Conclusions and outlook

The construction of the "ETH House of Natural Resources" showed that timber frame structures can be built in a short time due to pre-fabrication and the very simple connection by a small workforce. The flexible floorplans allow for flexible use and re-arrangement of non-bearing walls within the building. This allows the owner of the building to act if an alternative floorplan is needed, for example if the tenant of a building needs a different layout of the floor plan.
The second interesting characteristic is the lateral deformation capacity. This allows the building to be constructed in seismic areas, increasing the potential market for such a construction substantially. The behaviour of the Flexframe® helps it to move with an earthquake and prevent damage, rather than being fixed on a spot and face an earthquake with stiffness and resistance.
Further research focuses on different materials for the column, different column bases as well as the seismic design in general. The aim of the research is to optimize the performance of the Flexframe®. Further large scale tests on a two storey post-tensioned timber frame under horizontal loading are planned to start in autumn 2017.

7. Nomenclature

[1] M.N. Priestley, "Overview of PRESSS research program", PCI Journal, Vol. 36, pp. 50-57, 1991

[2] M.N. Priestley, "The PRESSS Program – Current Status and Proposed Plans for Phase III", PCI Journal, Vol. 41, pp. 22-40, 1996

[3] A. Palermo et al., "Seismic Design of multi-storey buildings using laminated veneer lumber (LVL)", Proceedings of the 2005 NZSEE conference, Taupo, New Zealand, 2005

[4] A. Palermo, S. Pampanin and A. Buchanan, "Experimental investigations on LVL seismic resistant wall and frame subassemblies", Proceedings of the first European conference on earthquake engineering and seismology, Geneva, Switzerland, 2006.

[5] M. Newcombe et al., "Section analysis and cyclic behavior of post-tensioned jointed ductile connections for multi-story timber buildings", Journal of Earthquake Engineering, Vol. 12, pp. 80-110, 2008

[6] W. van Beerschoten, "Structural performance of post-tensioned timber frames under gravity loading". Doctoral dissertation, University of Canterbury, 2013

[7] D. Moroder et al. "Design of Floor Diaphragms in Multi-Storey Timber Buildings", International Network on Timber Engineering Research, Bath, England, 2014

[8] R. Schneider, "Tragverhalten von vorgespannten Holzkonstruktionen [Structural behaviour of post-tensioned timber structures]". Master thesis, ETH Zurich, 2010

[9] F. Wanninger and A. Frangi, "Experimental and analytical analysis of a post-tensioned timber connection under gravity loads", Engineering Structures, Vol. 70, pp. 117-129, 2014

[10] F. Wanninger, "Post-tensioned timber frame structures", Phd thesis, Institute for structural engineering, ETH Zurich, 2015, http://e-collection.library.ethz.ch/view/eth:48610

[11] F. Wanninger, A. Frangi and R. Steiger. "Bearing stiffness in wood-to-wood compression joints." Engineering Structures, Vol. 101, pp. 631-640, 2015

[12] L. Boccadoro and A.Frangi, "Experimental analysis on the structural behaviour of timber-concrete composite slabs made of beech-laminated veneer lumber", Journal of Performance of Constructed Facilities, Vol. 28, 2013

[13] ETH House of Natural Resources, English, ETH Zurich [Online]. Available: www.honr.ethz.ch/en http://www.honr.ethz.ch/en

[14] C. Leyder et al., "Dynamic response of an innovative hybrid structure in hardwood", Proceedings of Institution of Civil Engineers: Construction Materials, Vol. 168, No. 3, pp. 132-143, 2015

[15] C. Leyder, A. Frangi, and E. Chatzi, "Modal vibration testing of an innovative timber structure". Proceedings of the World Conference on Timber Engineering (WCTE 2016), Vienna: TU Verlag, 2016

[16] Swiss Standards Association, "SIA 265: Timber structures". Swiss Society of Engineers and Architects, Zurich, Switzerland, 2003

[17] T. Strahm, "Esche und Buche im Ingenieurholzbau", 2. Forum Holzbau, Beaune, Frankreich, 2012

[18] Schallschutz-Bauteilkatalog, Lignum, http://bauteilkatalog.lignum.ch/

[19] J. Ogrizovic et al., "Experimental and analytical analysis of moment-resisting connections with glued in rods, Engineering Structures, submitted (2017)

[20] R. Ringhofer, G. Schickhofer, „Erdbebennormung in Europa und deren nationale Auslegungen", TU Graz, 9. Grazer Holzbau-Fachtagung, Graz, 2011.
Online: https://pure.tugraz.at/portal/files/3008025/02_RINGHOFER.pdf

[21] EN 1998-1: 2004; Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings

[22] A. K. Chopra, "Dynamics of structures: theory and applications to earthquake engineering". New Jersey: Prentice Hall, 2007