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# COLUMN LOSS ANALYSES FOR POST-AND-BEAM STRUCTURES

Katharina Sroka[1], Pedro Palma[2]

**ABSTRACT:** As the size and complexity of timber buildings grow, so do the consequences of a collapse, making robustness a key requirement in the structural design. However, the response of timber buildings to initial local damage, i.e., their robustness, is not yet well understood. To investigate the ability of timber post-and-beam buildings to develop alternative load paths in a column removal scenario, a campaign of large-scale quasi-static pushdown experiments was planned. The investigation focuses on beam-to-column connections with laterally-loaded dowels and continuous slotted-in steel plates. An experimental setup was designed that can apply combined shear, bending, and tensile loading on the connection. The setup enables the implementation of different values of horizontal restraint stiffness. First results show that dowelled beam-to-column connections with continuous steel plates through the damaged column can reach high displacements and rotations and enable load redistribution through catenary action if the surrounding structure has some horizontal flexibility. Further experiments with different horizontal restraint stiffness and validation of the numerical model are ongoing.

**KEYWORDS:** robustness, column removal, experiments, LVL, steel-to-timber connections

## 1 – INTRODUCTION

Structures for which the consequences of structural failure are high, including taller timber buildings, must be able to withstand adverse events without suffering damage disproportionate to the original cause [1]. Resistance to disproportional collapse can be achieved by reducing the exposure of the building to hazardous events (protective measures); reducing the vulnerability to local damage (overdesign); or increasing robustness, i.e., reducing the probability of damage propagation given an initial damage [2]. Measures to increase robustness are segmentation and redundancy. The latter is the focus of this project, which investigates the development of alternative load paths in timber post-and-beam structures after a column loss. The notional removal of a supporting column is a common approach to verify the robustness of buildings of high consequence class [3].

Previous research in this field has mainly been conducted for steel and concrete buildings, but with the growing complexity of modern timber buildings robustness is becoming more important also in timber design. Timber structures are expected to respond differently to initial damage scenarios due to the anisotropy and brittle failure modes of timber members, complex behaviour of timber connections, high natural variability of mechanical properties, and the low weight of the material. Previous column removal experiments have shown that the connections are critical for ductility and deformation capacity in timber structures and that continuous connections perform better in column removal scenarios [4, 5].

[1]Empa - Swiss Federal Laboratories for Materials Science and Technology, Structural Engineering Research Laboratory, Dübendorf; and ETH Zurich, Institute of Structural Engineering, Switzerland, katharina.sroka@empa.ch
ORCID:0000-0003-4721-6661

[2]Empa - Swiss Federal Laboratories for Materials Science and Technology, Structural Engineering Research Laboratory, Dübendorf, Switzerland, pedro.palma@empa.ch
ORCID:0000-0003-3253-646X

This project investigates steel-to-timber connections with laterally-loaded dowels and multiple slotted-in steel plates under sudden column loss scenarios. The objective is to demonstrate load redistribution at high displacements through bending and catenary action, i.e., beams and connections acting in tension. The accidental loading scenario of a sudden column removal combines multiple topics on which research for timber structures is scarce to date. First, a column loss can lead to large displacements involving material and geometrical nonlinearities, as well as combined shear, bending and tensile loading. A numerical model was developed and a large-scale experimental campaign is currently ongoing to study the steel-to-timber connections under this combined loading and to validate the numerical model under quasi-static loading. Second, the sudden loss of a column due to, for example, a vehicle impact or an explosion leads to dynamic effects. Numerical and experimental investigation of these effects is planned for a later stage of the project.

## 2 – COLUMN REMOVAL EXPERIMENTS

### 2.1 CONCEPT DEVELOPMENT

The focus of this project is on the investigation of load redistribution in beam-to-column connections of timber post-and-beam structures. The initial damage scenario caused by an accidental or extreme event is assumed as the loss of an interior column (Figure 1a). All floors above the removed column are considered to contribute to the load redistribution, i.e., carry their own weight instead of being supported by a strong floor. It is assumed that the beam-to-column connections are the same at all columns. The response of the beam-to-column connection at the removed column was investigated numerically and will be validated through large-scale quasi-static pushdown experiments, ongoing at the time of writing this paper.

The experimental setup was designed to investigate com-

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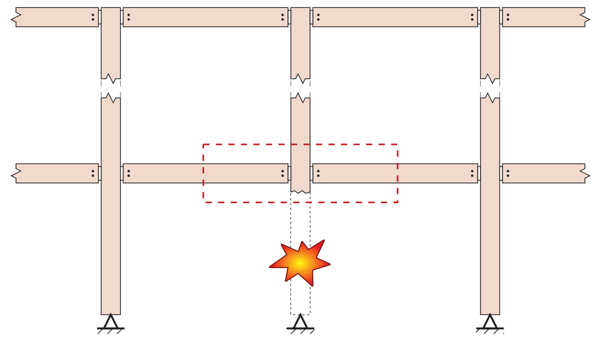
monly used connections at realistic dimensions to avoid the influence of size effects. As a compromise between feasibility and realistic member size, the experimental setup does not include the full two bays, but utilises the symmetry of the system and only consists of an unsupported middle column and a part of each beam (Figure 1b). This approach was chosen to focus on the behaviour of the connections and to allow more experimental parameters to be studied.

The stiffness of the horizontal restraint in the subassembly (Figure 1b) is a key influencing parameter for the ability of the internal beam-to-column connection to reach large displacements and rotations and to develop catenary action, i.e., tensile forces in the beams [6]. In reality, this stiffness depends on the connections between the beams and the outer columns, on the floor system, and on the global horizontal stiffness of the adjacent bays or the structure. Previous studies have incorporated horizontal restraints in column removal experiments in different ways. Lyu et al. [4] tested a two-bay system with horizontal supports at the outer columns at smaller scale with beam cross-sections of 150x63 mm$^2$. Results obtained from these small timber volumes in combination with scaled down connection dimensions and material properties may be influenced by size effects. Przystup et al. [7] conducted experiments on floor-to-floor connections in cross laminated timber with active application of a constant horizontal tension force. For the experimental setup presented in this paper, the objective was to investigate the influence of different magnitudes of horizontal restraint stiffness on the beam-to-column connection. For this purpose, a horizontal support was implemented in a first step through threaded rods that resulted in a constant stiffness of around 50 kN/mm (see Figure 7c), which is below the elastic axial stiffness of the beam-to-column connection. A second variation of the experimental setup is planned with hydraulic cylinders at the horizontal supports to allow implementing different values of constant horizontal restraint stiffness.

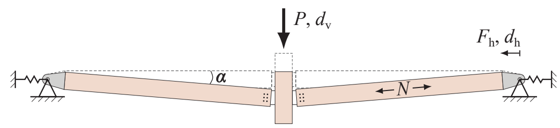
Previous experiments on different timber connections under quasi-static pushdown have shown that continuity of the connections through the damaged column is critical for achieving load redistribution at large displacements and rotations [4, 5]. The focus of this study was on laterally-loaded dowelled connections with slotted-in steel plates, which are commonly used in Europe. The connection to the column is typically implemented through a nailed or screwed T-section, but this was considered to have insufficient tensile capacity to achieve large displacements and load redistribution through catenary action. Instead, it was decided to investigate a continuous connection through the column, expected to offer high potential for load redistribution after column removal. The chosen connection with continuous slotted-in steel plates is shown in Figure 1c. Alternatively, a continuous connection based on T-sections could be implemented with multiple bolts connecting the T-sections on either side of the column.

## 2.2 MATERIALS

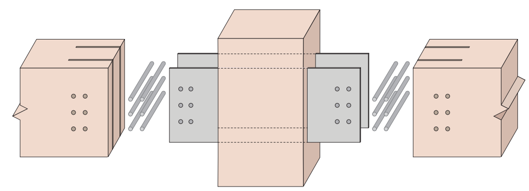
The 1.6 m long beams are block glued from spruce (*Picea abies* (L.) H. Karst.) and fir (*Abies alba* Mill.) laminated veneer lumber (LVL) with only parallel veneers [8]. In



*(a) Investigated column removal scenario and focus area.*




*(b) Schematic experimental setup.*



*(c) Investigated connection with continous steel plates.*

*Figure 1: Experimental concept.*

addition, a few specimens made of spruce glued laminated timber (GLT) will be tested. The beam cross-section was chosen as 280x160 mm$^2$, based on minimum requirements for fire resistance R30 [9]. The internal beam-side connection contains six S235 steel dowels of 10 mm diameter and two 5 mm thick slotted-in plates of S355 steel that are continuous through both beam connections. The connections were designed for ductile failure with multiple plastic hinges developing in the dowels [10]. The LVL beams of the specimen presented in this paper had a mean density of 576 kg/m$^3$ and were stored at 20 °C and a relative humidity of 30%.

A series of experiments will be carried out with reinforcement of the internal beam-to-column connection perpendicular to the grain through fully threaded screws against splitting and horizontal confinement against opening. It is expected that this will delay cracking and brittle failure modes, as well as increase the connection ductility and load-carrying capacity [11–13]. An overview of the planned experiments is given in Table 1.

## 2.3 EXPERIMENTAL SETUP

The experiments are being conducted at Empa in Switzerland. The setup consists of a 7.2 m wide steel frame on a strong floor, with additional diagonals and supports on either side to increase the moment resistance and thus the capacity for tensile forces in the specimen (Figure 2). Two steel columns with teflon lining are placed on either side of each beam to guide the vertical displacement and prevent out-of-plane movements.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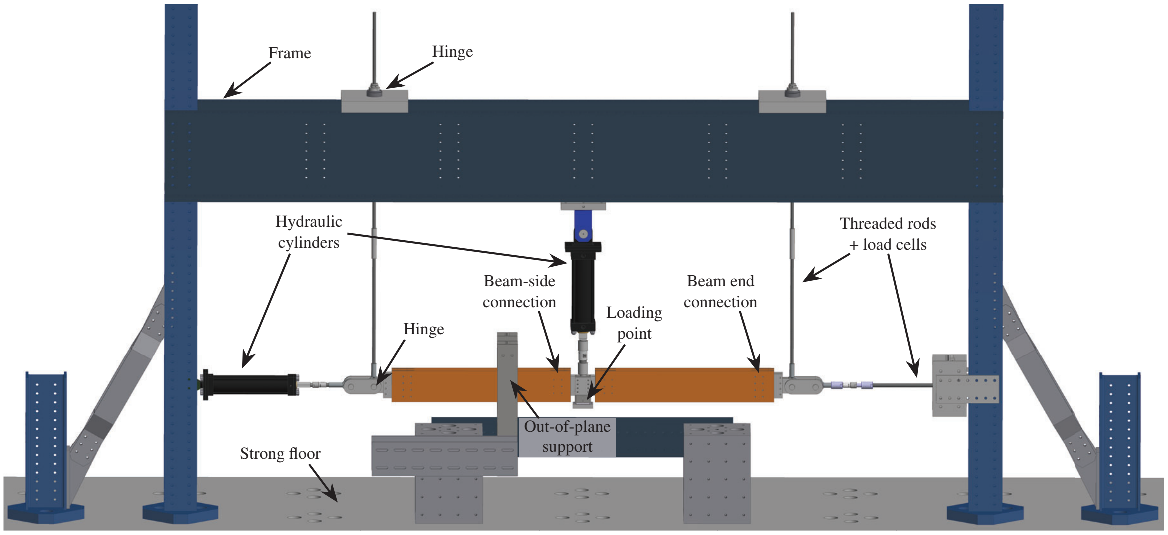
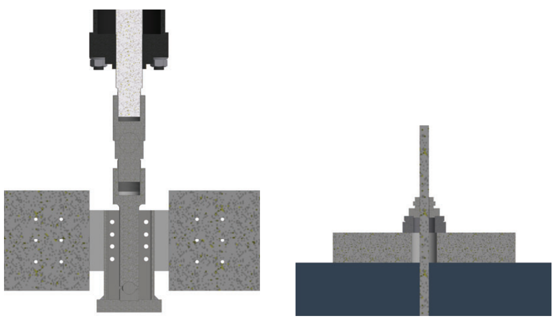


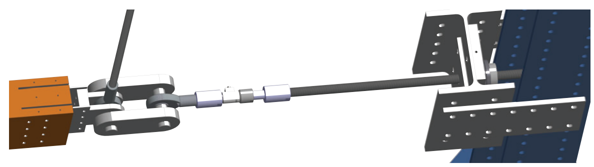

*Figure 2: Experimental setup. Out-of-plane displacement of the beams is prevented through steel columns on both sides of the beams (only shown on the left). Different horizontal support options are shown on either side.*



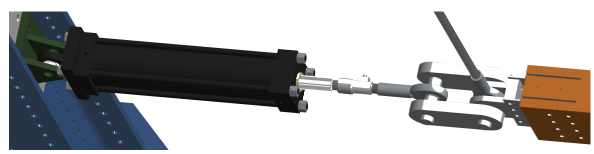
*(a) Vertical load application below the beam centreline to avoid instability.*

*(b) Hinge support for the vertical hangers with a load cell at the top of the frame.*

*Figure 3: Load application and vertical support in the experimental setup.*



*(a) Threaded rod as horizontal restraint with a constant stiffness of 50 kN/mm, including a load cell.*



*(b) Hydraulic cylinder with load cell for implementing a horizontal support of arbitrary constant stiffness.*

*Figure 4: Hinges and horizontal support options in the experimental setup.*

A steel box profile is attached centrally between the two continuous slotted-in steel plates of the timber connection to allow load application and prevent buckling of the thin plates. The vertical pushdown load is applied through a hydraulic cylinder under displacement control at a displacement rate of 0.2 mm/s. The load introduction point is at the bottom of the steel profile below the beam centreline to avoid lateral instability (Figure 3a). The clear spacing between the top edge of the steel profile and the beam edges allows the beam to rotate by 25° before contact causes crushing in the beams. This approach was taken to enable investigation of the behaviour of the beam-side connection and minimise the influence of additional effects, thereby facilitating validation of the numerical model. A few experiments will be conducted with timber parts attached to the middle column to estimate the influence of crushing against a timber column.

*Table 1: Planned experiments.*

| Beams | Column | Connection | Horizontal restraint stiffness (kN/mm) | No. |
|---|---|---|---|---|
| LVL | steel | unreinforced | 50 | 3 |
| LVL | steel | reinforced | 50 | 3 |
| GLT | steel | reinforced | 50 | 3 |
| LVL | timber | unreinforced | 50 | 3 |
| LVL | steel | unreinforced | cylinder | 3 |
| LVL | steel | reinforced | cylinder | 3 |

Custom-made hinges are implemented at the beam ends to allow free rotation, reproducing a point of contraflexure in the full structural system (Figure 4). The hinges and their connection to the beams were overdesigned for the expected tensile forces in the specimen to avoid plastic deformation in these parts. The beam end connection consists of eight S235 steel dowels of 14 mm diameter and two 5 mm thick slotted-in steel plates. These thin plates are made of high-strength steel with yield strengths of 850 MPa to enable the transfer of the expected tensile forces to the hinge.

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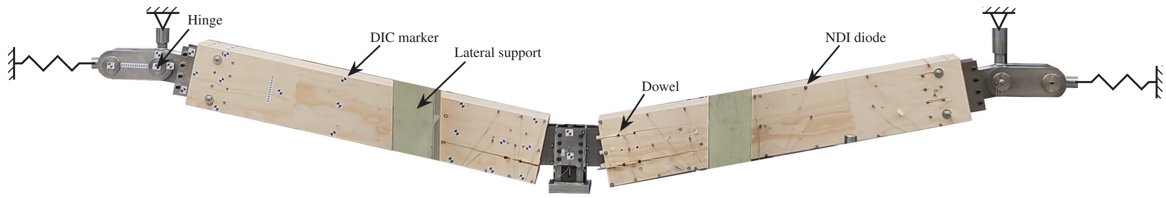


*Figure 5: Specimen after failure, also showing DIC markers and NDI diodes (photo by Jonathan Wilp).*

The hinges hang from vertical threaded rods that are supported on top of the frame, where rotation but no lateral motion is allowed (Figure 3b). This ensures that the hinge at the beam end can move laterally according to the stiffness of the horizontal restraint. In the first set of experiments, a horizontal restraint is implemented through threaded rods (Figure 4a), resulting in a maximum horizontal movement of the hinge of around 5 mm.

Both the horizontal and vertical support reactions are measured through four load cells on the threaded rods on either side of the specimen. The vertical force and displacement of the central hydraulic cylinder are also measured. In addition, a laser measures the vertical displacement of the steel column at the height of the beam centreline. Local displacements on the beam, column, and hinge surfaces are measured through optical measurement systems. The main system is the Optotrak Certus System by Northern Digital Inc. (NDI) [14] which tracks the 3-dimensional position of infrared light emitting diodes. These diodes are attached to the surface of the central beam-to-column connection, of the right beam, and of the right hinge. To capture the full length of the specimen, markers for digital image correlation (DIC) are placed on the left hinge and beam. The 2-dimensional position of these markers is tracked by an additional camera. The NDI diodes and DIC markers can be seen in Figure 5.

## 3 – RESULTS

As the experimental campaign is still ongoing, the results of only one experiment are presented in this paper. Ductile connection failure was achieved, with very pronounced hinges especially in the two dowels on the beam centerline (Figure 6).

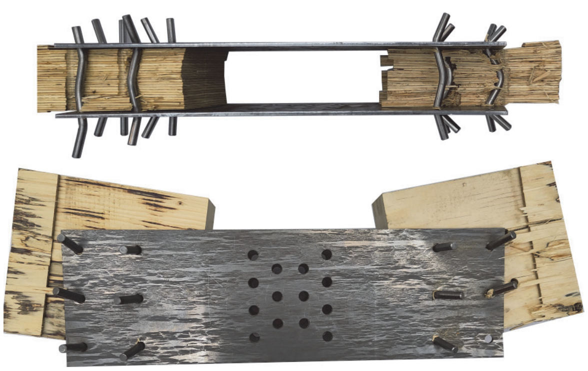

*Figure 6: Connection after failure and removing the outer timber layers, view from bottom and front (photos by Jonathan Wilp).*

The first specimen with horizontal restraint of 50 kN/mm reached a maximum pushdown force of 83 kN and a maximum vertical displacement of 315 mm (Figures 5 and 7). This corresponds to a maximum rotation of 11°. The maximum tensile force reached in the beams was 224 kN. These values exclude the initial loading and displacement due to self-weight of the specimen. The vertical and horizontal load cells on either side of the specimen showed very similar values, demonstrating the symmetric behaviour of the specimen. The positional data from the NDI diode placed at the rotation point of the right hinge confirms that the stiffness in the horizontal restraint was approximately constant at 50 kN/mm throughout the experiment (Figure 7c).

The load-displacement (Figure 7a) and moment-rotation (Figure 7b) curves show the initial elastic-plastic bending phase up to a displacement of around 100 mm. As the maximum bending moment was reached, both the moment and the vertical pushdown force exhibited a plateau. At this point, a distinct splitting crack formed at the bottom dowel row, such that the loading redistributed to the two upper dowel rows and the moment resistance reduced. The transition to catenary action began at around 100 mm vertical displacement, as the axial tension force in the beams increased while the bending moment in the connection reduced. From around 120 mm vertical displacement, catenary action dominated and the vertical pushdown force increased linearly until the connection failed. At high displacements, splitting also occurred in the top dowel row, as well as row shear failure (Figure 5).

## 4 – NUMERICAL MODEL

A nonlinear numerical model was developed using *OpenSeesPy* to conduct quasi-static pushdown and dynamic analyses. The connection is modelled with rigid elements for the continuous steel plates and a parallel combination of beam-on-springs models to capture the dowel behaviour, developed by Wydler [15] and Cao et al. [16]. The model was validated against quasi-static column removal experiments on GLT subassemblies without horizontal restraint by Petrycki and Salem [11]. A further validation with horizontal restraints will follow once the experimental campaign of this project is completed.

## 5 – CONCLUSION

This study investigated the load redistribution capacity of laterally-loaded dowel connections with continuous slotted-in steel plates under large displacements caused by a column removal. A large-scale experimental setup was developed that enables the application of combined shear, bending, and tensile loading on the connection to simulate a quasi-static column removal. The ongoing exper-


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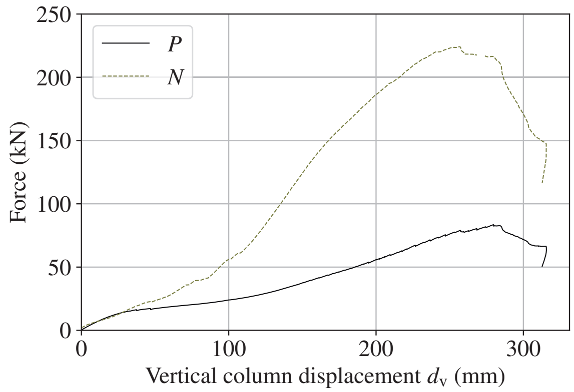
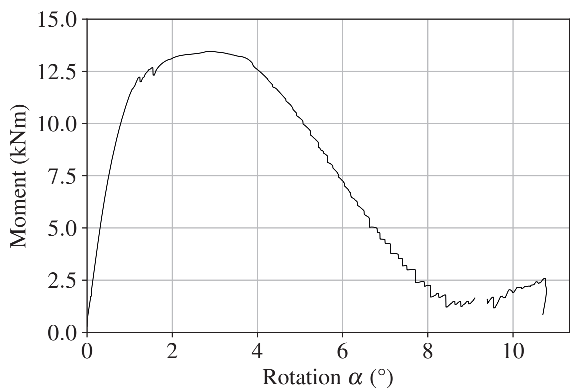
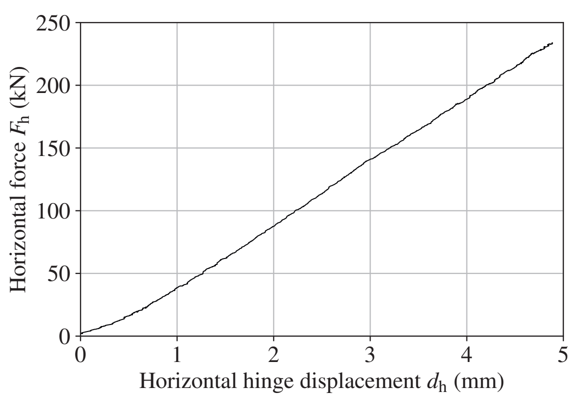



*(a) Vertical pushdown force P and axial tension N in the beams plotted against the vertical pushdown displacement $d_v$.*




*(b) Moment-rotation diagram of the right beam-side connection.*




*(c) Force in the horizontal restraint $F_h$ plotted against the horizontal displacement of the right hinge $d_h$.*

*Figure 7: Results for first LVL specimen with unreinforced connection and horizontal restraint of 50 kN/mm.*

imental campaign and results of a first experiment with unreinforced connections in LVL and a constant horizontal support stiffness of 50 kN/mm were presented. The results show that load redistribution through catenary action is possible if the beam-to-column connections are designed to transfer sufficient tensile forces through the column, e.g. via continuous slotted-in steel plates through the damaged column. These preliminary results demonstrate the potential for alternative load paths through load redistribution within steel-to-timber connections at large vertical displacements.

The ongoing experimental campaign will further investigate the influence of connection reinforcement and of the horizontal restraint stiffness. A numerical model has been developed and will be validated against the generated large-scale experimental data.

## 6 – ACKNOWLEDGEMENT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