Moment Connection with Frictional Damping for Timber Post and Beam Construction in Earthquake-Prone Areas

Intelligente Momentenverbinder für Holzhäuser in offener Skelettbauweise

Les assemblages instantanés destinés à la construction de maisons en bois en poteau-poutre

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1. Introduction

Moment connections for timber post and beam constructions (PBC) can be designed as a building's lateral load resisting system. While such connections need to behave stiffly during wind loads and moderate earthquakes for limiting the inter-storey drift and maintaining the serviceability of the building, they also require certain ductility and energy dissipation capacity for preventing structural members from critical stresses during strong and extreme seismic events.

Different beam-to-column connections (BCC) for wood moment resisting frames (MRF) have been investigated in recent decades, but for most of them, the ductility was provided via plastic deformation of mechanical fasteners and wood (dowel bearing and yielding). In addition, the energy dissipation was based on the degradation of the strength and stiffness after a seismic event. This approach causes the inconvenience that both, the plastic ductility and resulting stiffness and strength degradation, are irreversible processes.

However, the research regarding low damage concepts of timber BCCs for MRF under seismic performance is rather rare [1]. A simple version of a low damage concept is a passive damping devices with frictional characteristics. The main advantage of these damping device is that the structure returns to a quasi-reversible state after the seismic event while controlling the energy dissipation demands on the structural members [2]. Frictional devices have been already investigated and implemented in many steel structures.

Although timber structures withstand much larger deflections than steel structures in elastic range, and thus there is plenty of potential of using frictional energy as damping mechanism, the research of frictional devices in timber frame structures is rather rare too. There is a particular lack of research regarding 3-D BCC connecting for timber PBC with the use of frictional damping devices (FDD). Application of a slotted bolted connection for a braced timber frame was researched by Tjahyadi [3]. Research of a 3-D BCC for timber PBC with frictional characteristics was done by Kasal et al. [4, 5].

Within this project, a 3-D BCC with adjustable and controlled frictional characteristics was proposed and investigated based on previous tests of a 3-D frictional BCC by Kasal et al. [4]. The distinctive feature of that BCC is its high energy dissipation capability by reversible frictional damping, which can be adjusted to the specific requirements of each building, and to allow a 3-D PBC. In addition, the proposed connection was tested in a 1:3 scaled three story frame on a shaking table, and the results showed that the elastic energy stored in structural members was enough for the frame to overcome the frictional moment and achieve self-aligning capabilities.

The presented BCC has been designed for timber buildings in a 3-D PBC of more than five storeys, and according to the following requirements: (i) the mechanical performance needs to remain quasi-unchanged after ten loading repetitions into the range of yield moment; (ii) the performance of the BCC should not be affected by the transport conditions, installation on the construction-site, and should remain constant during the life of the building.

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2. The Frictional Connection

The targeted response of the desired BCC under monotonic loading should match with that shown in Figure 1, i.e. to behave relatively stiffly under wind loading and moderate earthquakes, to response in frictional manner (reversible) and dissipate energy under strong earthquake, and provide plastic deformation (irreversible) under extreme earthquakes. In order to obtain such a mechanical performance, a damping device with frictional characteristics and shear bolts was designed.

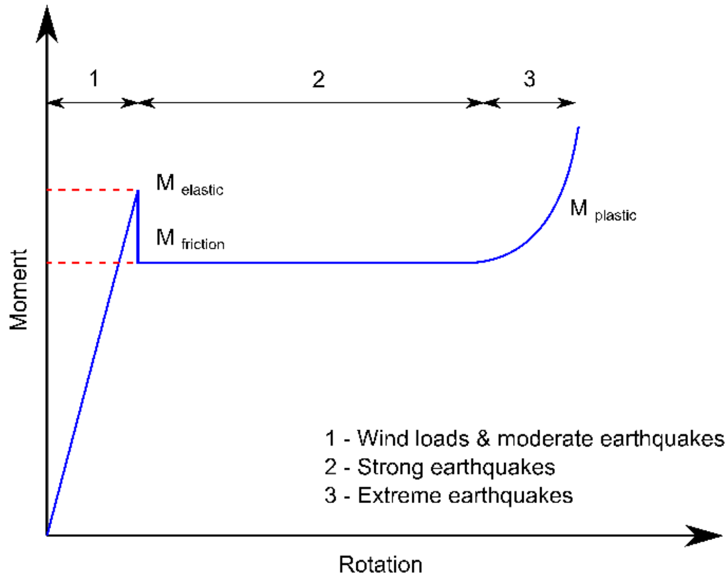


Figure 1: Schematic description of the moment-rotation characteristics for the frictional damping device

Figure 2 shows the parts and assemble of the scaled FDD. The FDD consisted of three metallic plates, eight pre-stressed bolts and two shear planes with additional friction plates. The inner plate had slotted holes to allow slippage. The maximum allowed slippage was constrained by the size of the slot for free slippage and the pre-stressed bolts On each side of the inner plate four frictional plates were placed and tightened by four small bolts for each attached to the inner plate. The frictional plates and the three steel parts were held together by eight high strength pre-stressed bolts. At the pivot point of the FDD a dowel pin was placed in order to fix the rotation point and carry vertical loads.
Additionally, four holes were drilled in the corners of each steel plate to place the shear bolts. Figure 3 shows a shear bolt for the scaled and full scale specimen. The shear bolts can increase the stiffness and the energy dissipation capacity of the connection and allow the adjustment of the characteristics of the connection.
Figure 4 shows in detail an intersection of one pre-stressed bolt in the connection. At each side two conical spring washers (according to DIN 6796 [6]) were placed to ensure a constant pressure. Hardened washers prevented the cutting of the conical spring washer edges into the outer steel parts.
The preload of the bolts was controlled by turning the nut, and conical spring washers. The tightening of the bolt was done in two steps according to VDI guideline 2230 [7]: (1) torque controlled for preload of the connection to ensure that all the interfaces were completely closed and (2) angle controlled after the threshold torque were exceeded. This method has the advantage of a reduced effect of the friction on the preload scatter compared with torque-controlled tightening. However, the precision is still influenced by angle errors, except for the case when bolts are loaded beyond plastic range.

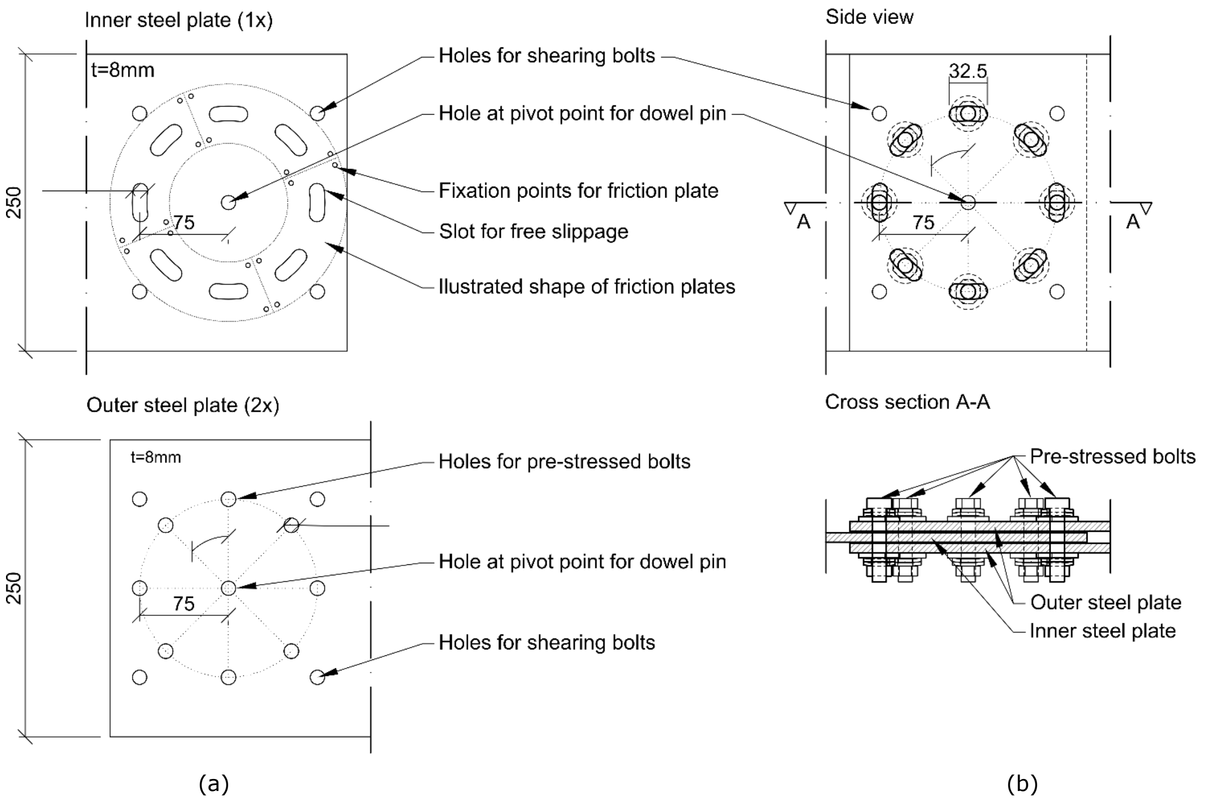


Figure 2: The three steel parts of the frictional damping device (a) and the assemble in side view and cross section (b)

Before testing, the theoretical slip force was calculated based on the determined preload and the friction coefficient. The calculation of the preload was done according to the VDI guideline 2230 part 1 [7]. The calculation considers the loss of preload as result of embedding, the resilience of the bolt, the resilience of superimposed clamped parts as illustrated in Figure 4 (steel parts, washer and friction plates) and the load-deflection characteristics of the conical spring washers. The load-deflection characteristics were directly determined from conical spring washers by testing.

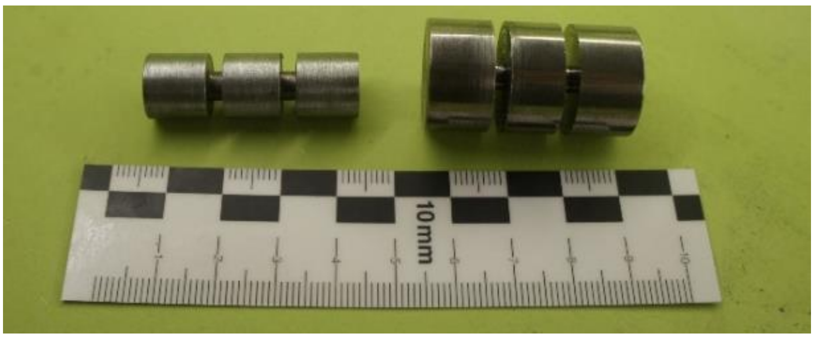


Figure 3: Shear bolt for the scaled and full scale specimens with reduction of the cross section at the shear planes for a defined failure of the bolts

For the first tests, friction plates made of aluminum were chosen, because they can offer a moderately stable dynamic friction force [16], and at the same time are cost effective and simple to produce. For further optimization hardened steel plates were used as proposed by Golondrino et al. [8].

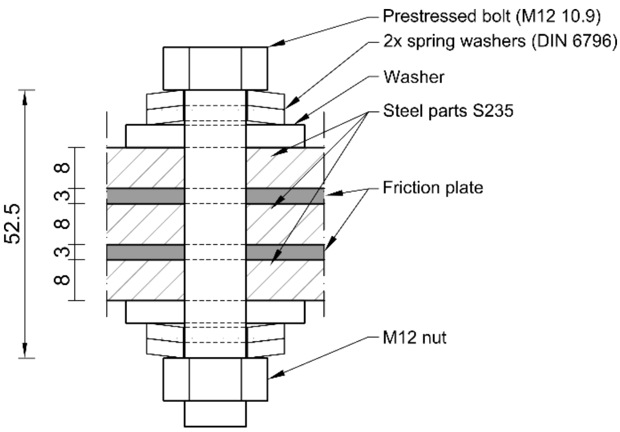


Figure 4: System of the pre-stressed bolt

3. Experiments

The FDD was assessed by performing several scaled and full scale displacement controlled tests.

First, a scaled (Spec01) and full-scale (Spec02) single pre-stressed bolt connection was tested to evaluate the tightening method and the influence of the different material properties, as well as to adjust the frictional behaviour of the FDD, and combine friction and shear forces for the stiffness control of the scaled and full scale design. Figure 5 shows Spec01 with shear bolt and pre-stressed bolt in the testing machine.

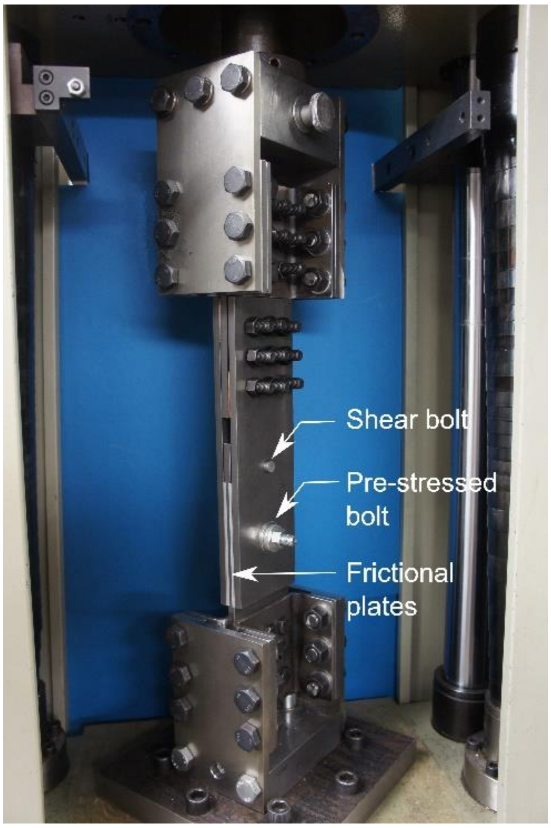


Figure 5: Spec01 with a simple slotted bolted connection in the testing machine

Second, quasi-static cyclic loading tests were conducted to evaluate the FDD in a BCC replacing wood beam and column by steel parts for a scaled (Spec03) and full scale (Spec04) specimen. The three plates were welded to rectangular steel section. Through holes at the end of the section the specimen was fixed with a pin at each side to the test machine allowing free rotation. Figure 6 shows the setup for the scaled Spec03.

The scaled damping device was also tested being connected to a wooden beam and column (Spec05). Figure 7 shows the top view and side view of Spec05 as well as a picture of the

FDD connected to beam and column. The inner plate was welded together with a second plate to a T-shaped steel part, which was connected to four glued in rods at the end grain of the beam. Each outer plate was welded together with a second steel part to an L-shaped steel part, which were connected to the columns face.

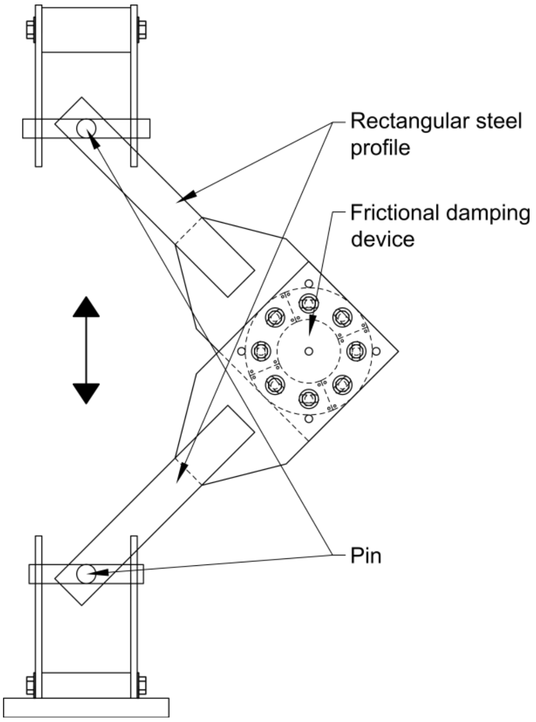
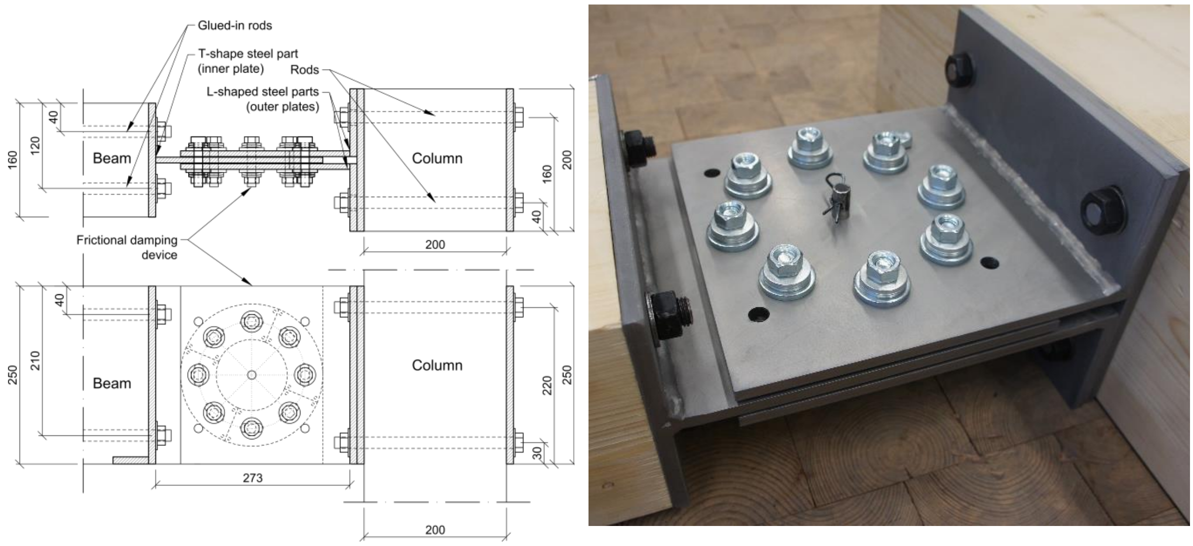


Figure 6: Setup of the scaled and full scale specimen Speco03 and Spec04 for testing the frictional damping device in a moment connection without wooden beam and column

The cyclic tests followed the testing protocol based on DIN EN 12512 [9]. Additional control cycles were added between each cycle sequence to proof the degradation from one amplitude to the next higher one – see an illustration in Figure 8. To test the tightening method, five cycles with the same amplitudes were chosen to simplify the testing procedure.



(a) (b)

Figure 7: Top view and side view of the beam-to-column connection with the frictional damping device (Spec05) connected to beam and column with bolts to glued-in rods (a) and picture of the assemble (b)

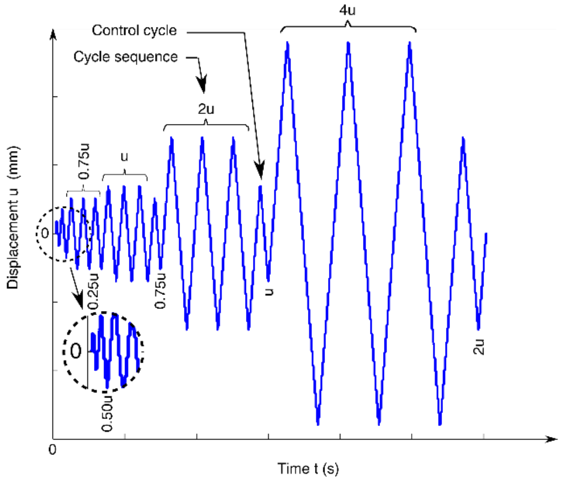


Figure 8: Testing protocol for the cyclic loaded tests based on DIN EN 12512:2001+A1:2005 with additional control cycles

4. Results

Figure 9 shows the histogram of the median friction force of the tested Spec01 with aluminum friction plates and an applied preload by a torque of 5 Nm and a nut turning angle of 4/8. The tests were repeated 25 times and each time the friction plate and the bolts were replaced. The frequency distribution of the medians is normally distributed. The median of the friction force with 28.23 kN is closed to the calculated friction force for of the connection of 26.05 kN. A dynamic friction coefficient of 0.47 [10] was used for calculation. It can be concluded, that the tightening method allows a reproducible friction force. However, the range of the friction force between 5%- and 95%-quantile is still 10.16 kN.

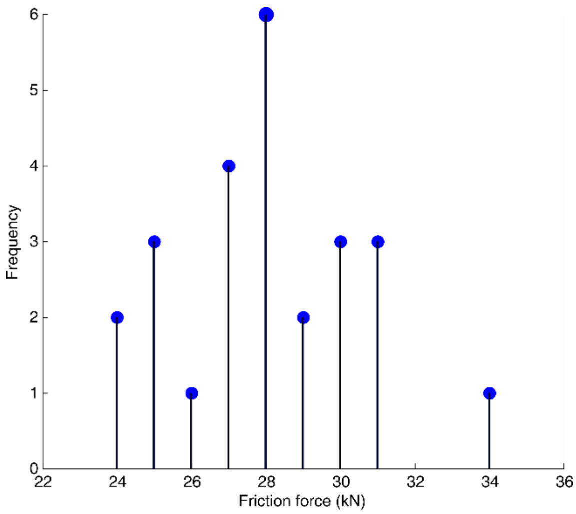


Figure 9: Frequency distribution of the median friction force of 25 tests of Spec01 with five cycles of each test

Figure 10 shows the load-displacement curve of Spec01 under cyclic loading with and without an additional shear bolt. Both curves show a high energy dissipation as expected from frictional behaviour. The shear bolt increases the load and energy dissipation capacity of the connection. After shearing of the bolt, the friction force is similar to the one without the bolt. The increase of the force for larger displacement can be explained by the contact of shear bolt to the outer steel plates. By changing the setup, this can be avoided. Figure 10 shows the result of a quasi-static pull test of Spec02 for the combination of shear force and friction force. The curve is qualitatively similar to the desired characteristics presented in

Figure 1. The second peak between 12 and 15 mm displacement was caused by the contact of the shear bolt to one of the steel parts.

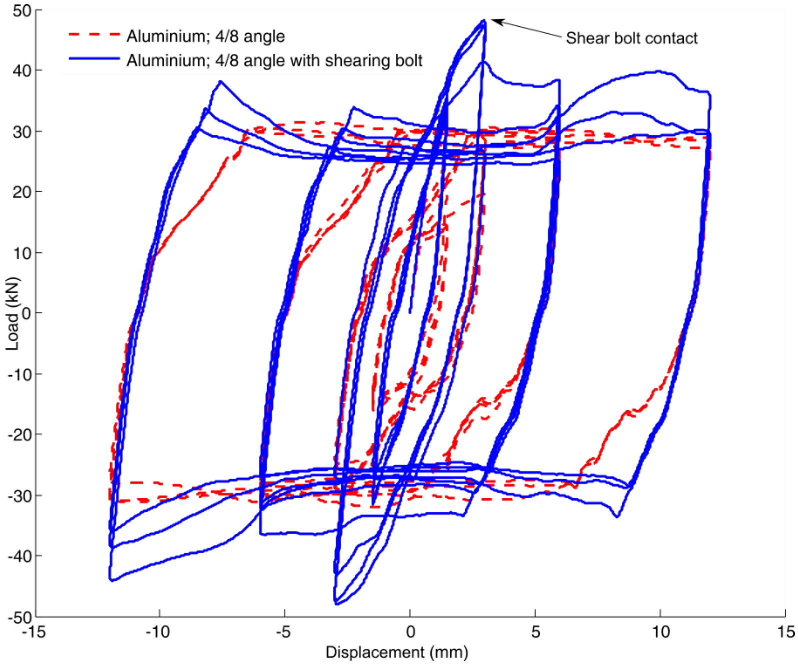


Figure 10: Comparison of two load-deflection curve of Spec01 under cyclic loading with (continuous line) and without (dashed line) additional shear bolt beside friction force applied with 4/8 angle nut turning

The results of the scaled and full-scale BCC without wood beam and column showed high energy dissipation capabilities, see the hysteretic curve in Figure 12 for the full scale specimen Spec04 with moments up to 60 kNm. In addition, the BCC underwent almost no degradation, i.e. the curves were very comparable in consecutive cycles. According to these results, the BCC shows a great potential for being used in the practice.

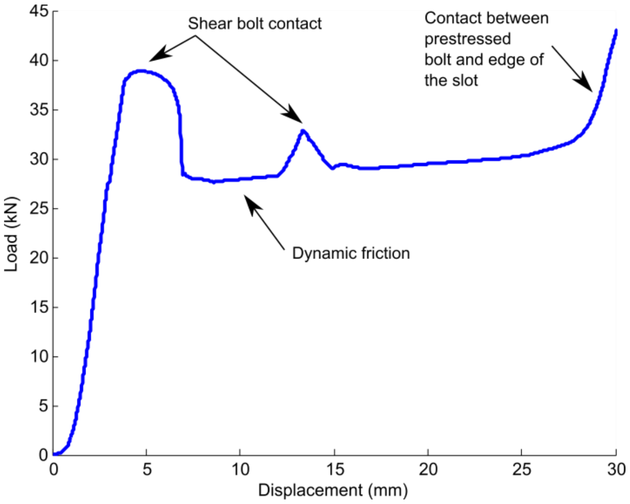


Figure 11: Load-displacement curve of a quasi-static pull test for Spec02 (5 Nm torque; 4/8 nut turning angle)

Figure 13 shows the hysteretic curve of the mock up testing of Spec05. The rotation is calculated from a potentiometer attached directly to the FDD.
As expected from the testing of Spec03 and Spec04 the BCC showed high energy dissipation capacity without degradation of the connection to the wooden beam and column.

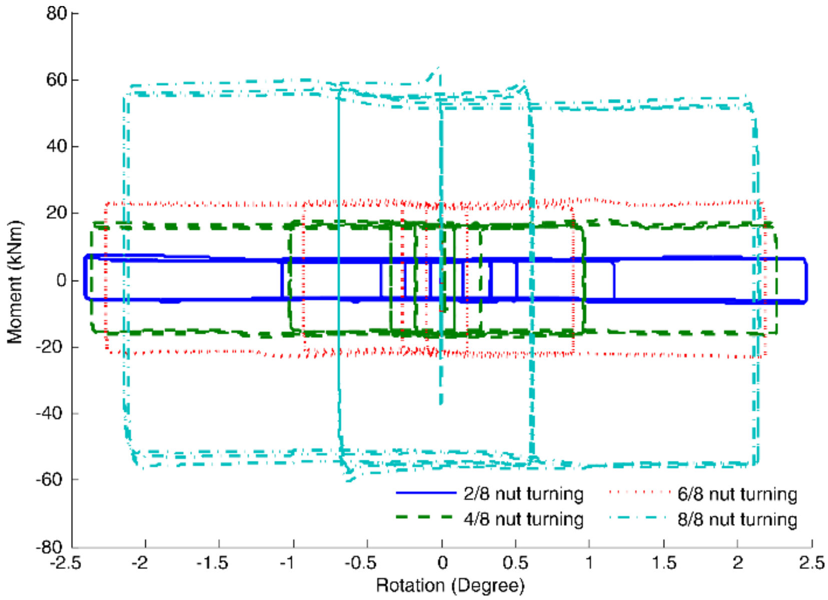


Figure 12: Results of the frictional connection in full scale without the influence of the connection to the timber beams and column depending on different nut turning

The performance of the connection under various environmental conditions must be proven to verify that the surfaces and resulting frictional behaviour remain unchanged after climate exposure. The climate exposure will be simulated with a climate chamber and tests before and after the simulation to proof the frictional behaviour.

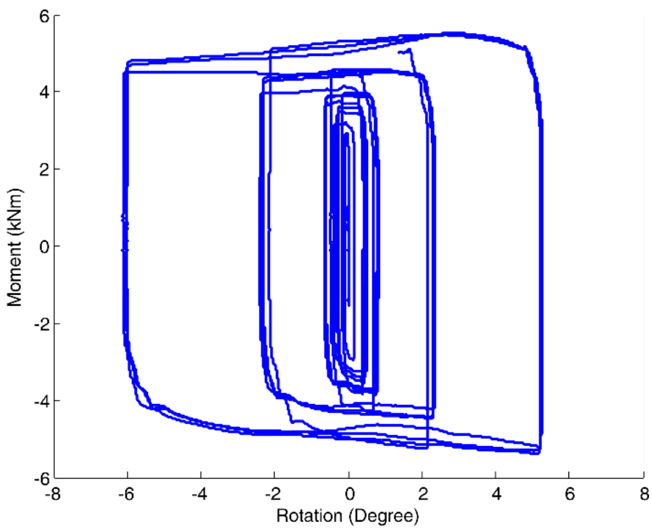


Figure 13: Hysteretic curve of Spec05 – frictional damping device attached to wooden beam and column by nuts to glued-in rods.

5. Conclusion

Moment connections with friction offer a great potential for high-rise wooden buildings in earthquake-prone areas because the relatively high drifts can be used to considerably improve the energy dissipation capabilities in a reversible manner.
The proposed BCC can be used as a 3-D BCC, connecting up to 4 beams to each column. Additionally, the design is feasible for industrial production and can be adjusted according to FDD. From the constructional standpoint, the FDD can be directly connected to beams and columns. Also, the shear bolts offer an additional possibility to control the characteristics of the BCC and further adjust the BCC to the needs of the desired PBC.
There still however some aspects that need to be further investigated and additional tests with the specimens Spec03, Spec04 and Spec05 are currently ongoing. For further optimization, piezo resistive thin film sensor systems [11] are planned to monitor and control the pre-stressing force, displacement and temperature during the tests, as well as to proof

the usability for long term monitoring of the BCC during building life cycle. The recorded characteristics of the tested BCCs will be implemented in a 2-D and 3-D numerical model of a multi-storey timber building for predicting the seismic behavior and derive the necessary characteristics of the BCC.

6. References

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