

# IMPROVED MOMENT-RESISTING TIMBER FRAMES FOR EARTHQUAKE-PRONE AREAS PART I: STRUCTURAL CONNECTIONS

## MEJORA DE PÓRTICOS DE MOMENTO DE MADERA PARA ZONAS SÍSMICAS PARTE II: ENSAYOS EN MESA VIBRADORA

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#### Abstract

This investigation comprises the development of innovative timber multi-story buildings based on post-beam moment-resisting frames that can withstand moderate to intense earthquake loads. This is the first paper of a two-series and covers the design, testing and modelling of 6 typologies of structural connections under static monotonic and pseudo-dynamic cyclic loading. The studied designs covered many of the typical connecting devices used in beam-post timber frames ranging from self-tapping screws and bolts, thru in-glued steel rods, polymer concrete or hardwood-blocks. All the connections were cyclically tested up to failure in order to determine the load capacity, stiffness, hysteretic behavior and energy dissipation capacity. Overall, results showed that perpendicular loading of the column is a critical aspect for the design of these type of connections. Out of the 6 connections, a connection based on hardwood blocks was found to provide an outstanding load capacity and stiffness being significantly cost effective so it could be applied in low demanding seismic scenarios where drift control is the main limiting criterion. Conversely, a connection based on frictional damping showed high energy dissipation capability and low degradation, even after extreme cyclic loading. This last connection could be a promising approach for future timber structures subjected to demanding earthquakes.

**Keywords:** structural connection; earthquake; post-beam frame; damping device; energy dissipation; cyclic loading

#### Resumen

*Esta investigación comprende el desarrollo de edificios de varias plantas de madera innovadores basados en pórticos de momento tipo poste-viga de modo que éstos puedan resistir cargas sísmicas de alta y moderada intensidad. Esta es la primera parte de una serie de dos artículos, la cual comprende el ensayo y modelización de 6 tipologías de unión bajo carga monotónica y cíclica. Los diseños estudiados cubren muchos de los tipos de conexión empleados en estructuras tipo poste-viga, como por ejemplo tornillos auto-perforantes, barras de acero encoladas, polímero de concreto y bloques de madera de frondosa. Todas las conexiones fueron ensayadas cíclicamente hasta la rotura con el fin de determinar la capacidad de carga, rigidez, histéresis y disipación de energía. En general, los resultados indican que las solicitaciones perpendiculares a la dirección de la fibra en la columna son un aspecto crítico de diseño. De entre las 6 conexiones, la unión basada en el uso de bloques de madera de frondosa mostró una gran capacidad de carga y rigidez a un precio muy reducido lo cual podría ser de interés en zonas de baja demanda sísmica en las cuales el control del drift puede ser el aspecto más limitante. En contraposición, una unión basada en amortiguamiento por fricción mostró capacidad para disipar una gran cantidad de energía preservando su integridad incluso tras carga cíclica extrema. Esta última conexión podría suponer un enfoque prometedor en el futuro de cara a mejorar el desempeño de estructuras de madera sujetas a sismos de alta intensidad.*

**Palabras clave:** conexión estructural; sismo; estructura poste-viga; amortiguador; disipación de energía; carga cíclica

## 1. INTRODUCTION

Laminated wood utilization in medium-rise buildings is increasing due to ease of manipulation and construction, light-weight, transportation and low ecological footprint. Also the high strength-to-weight and stiffness-to-weight ratios placed the timber in a very competitive position with regards to seismic performance in comparison to other classical construction materials. The deformation capacity of the timber on the elastic range is also much larger than that of other materials so that the development of damping devices that dissipate energy during seismic loading is a very promising field. However, nowadays most civil construction standards in the world still base drift limitations on concrete or steel investigations so that the deformation is most often the limiting engineering design parameter (EDP) for mid to high rise timber buildings on seismic prone areas.

The beam to column connection (BTC) is typically the least stiff part of post-beam timber frames and relatively small rotations between beams and columns may cause large drifts in the system. It appears that developing a stiff BTC can reduce excessive drift but still is far from fulfilling with current standard drift limitations. In addition, the design of stiff BTC is challenging since local over-stresses are difficult to avoid.

Most previous investigations of dynamically resistant BTC based the energy dissipation mechanism on the plastic deformations of the steel fasteners, which is characterized by a non-reversible, non-conservative and non-linear response with pinching [1]. When designed properly, such a dissipative system can release a high amount of elastic energy out of the system and distance the response from resonant frequencies to prevent collapse. Another important challenge on the design of these connections is however to find a balance of the stored and dissipated energy for the structure to shape back to the original position and show self-aligning capabilities. In this context, previous researches investigated the optimal ductility of BTC connections [2], while others confirmed the necessity of very stiff timber BTC to satisfy current limitations of deformation [3-7] as well as the aptitude of timber for large energy dissipation while self-aligning maintaining its integrity [8-11].

This paper describes the outputs of an experimental investigation in where a wide range of distinct connections was designed and tested in views of seismic performance. The investigation involved the design and testing of 6 different connection typologies. The connections were tested under monotonic and cyclic loading up to failure which served to assess the moment capacity, stiffness, ductility, hysteretic behavior and energy dissipation capacity of each connection. These results served to select, along with the applicability and cost-effectivity, two connections out of the 6 typologies in order to test its seismic performance on a shaking table. This first paper describes briefly the design and performance of the six connections. The results of the seismic tests are presented in the subsequent part of this series.

## 2. MATERIALS AND METHODS

All BTC were made of laminated spruce (*Picea abies*) in accordance to the standard manufacturing process (DIN 1052) at HESS TIMBER GmbH & Co. KG, located in Kleinheubach, Germany. The assembly of the beams and columns was performed in the Institute of Theoretical and Applied Mechanics (ITAM) laboratory, Prague, Czech Republic. The various metallic connectors were manufactured by SFS Holding AG, Heerbrug, Switzerland. The experimentals of each connection involved two stages. First, the BTC was tested with a static monotonic load in order to determine the amplitude of the displacements of the subsequent test. Second, the connection was tested under cyclic pseudo-static loading with increasing displacement amplitude as stated in EN 12512. The load is applied by a controlled hydraulic actuator until the connection fails. Records of loading and displacement of the piston are combined with string potentiometers and linear variable differential transducers as shown in Figure 1, which serves to determine the moment and rotation during the entire testing.

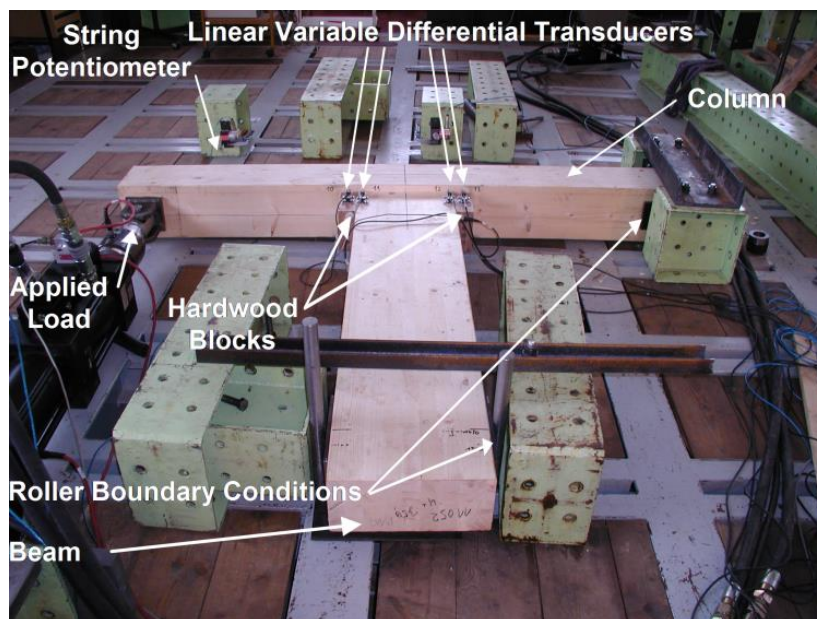


Figure 1: Typical testing layout of the BTC, based on [12]

### 3. DESIGN AND RESULTS OF PLASTICITY BASED BTC

The first series of connections based the energy based dissipation mechanism mainly on the plastic yielding of steel connections. This section presents the main results of these types of BTC.

#### 3.1 Polymer concrete and glued-in steel bars

The first BTC consisted of two beams with dimensions of 36 cm x 12 cm and a column of 22 cm x 22 cm. At each beam, two threaded bars (M20 4.6) were glued-in in the longitudinal direction up to a depth of 500 mm. The remaining length of the rods was introduced in the column via coupling nuts pf M20 x 60. In addition, a shear key was located at the interface between column and beams bear the shear forces. The perforation holes for the bars, connecting nuts and shear key were realized with milling cutting and the clearance holes and openings where filled up with polymer concrete. The connection was designed so that most of axial forces were supported by the steel rods while shear forces were provided by the shear key. The design and testing of the connection is shown in the Figure 2.

It was found that the rigidity of the connection mainly on the stiffness of the wood across the grain and the yielding of the threaded bars. The connection was quite stiff at the beginning of the test and provided a capacity of about 40 kNm, however the stiffness was clearly degraded after each cycle so that relatively large rotations were measured at the end of the test. The stiffness degradation was not associated to high yielding of the steel so that the energy dissipation was relatively low. The failure was produced at the column in the direction perpendicular to the grain.

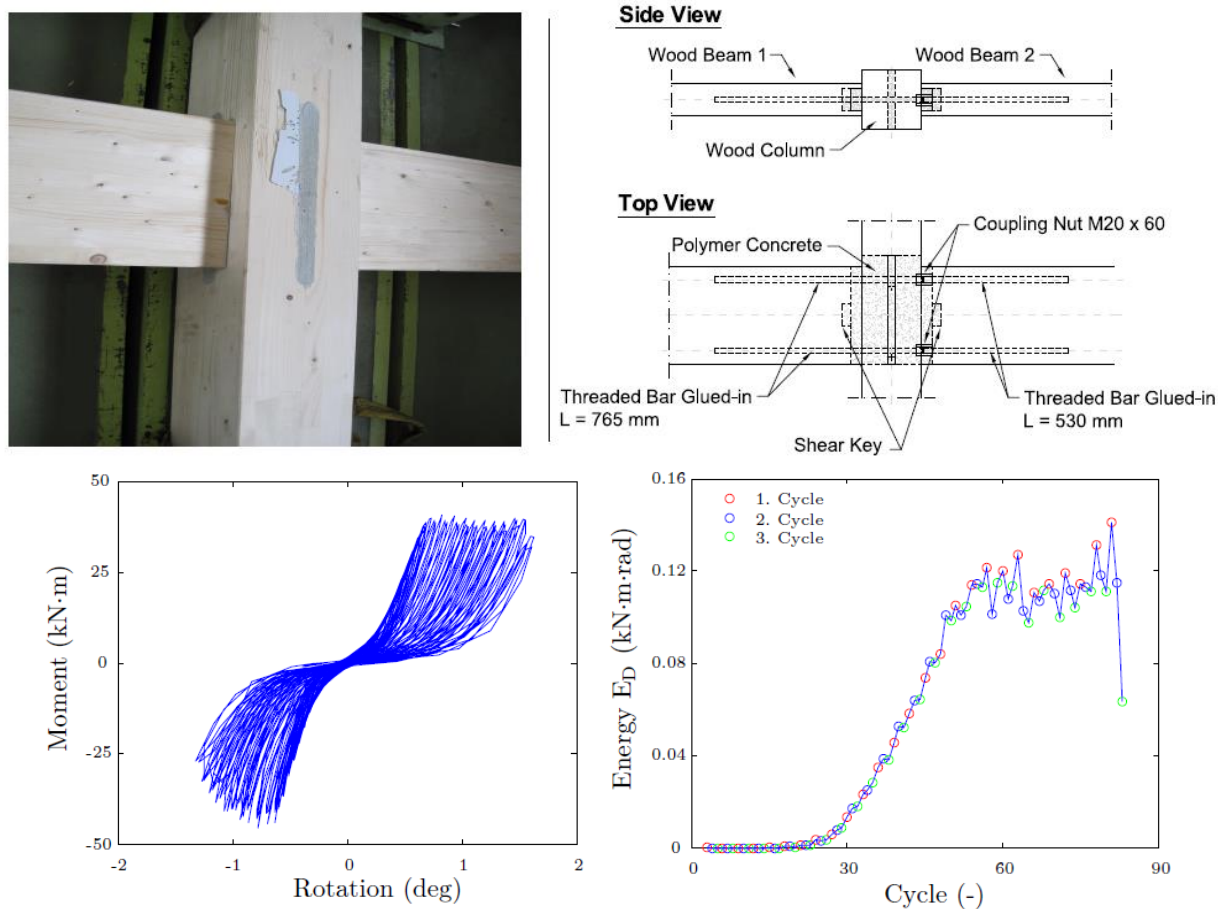


Figure 2: Design (up), hysteretic curve (down left) and dissipated energy (down right) of the glued-in steel bars and polymer concrete BTC, based on [13]

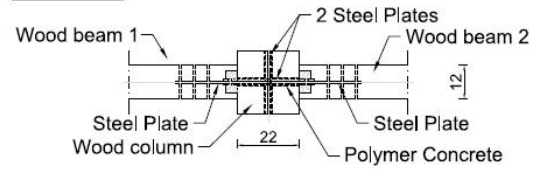
### 3.2 Polymer concrete and steel plates

The second BTC consisted of two beams and one column with the same dimensions of the previous connection, but rather than glued-in steel bars, the beams connected with the column using kerf (steel) plates. One kerf plate sized in 215mm x 400mm and thickness of 8 mm was embedded at the middle of each beam being connected with 23 drift pins with a diameter of 10 mm, see the orientation of the pins in Figure 3. Two parallel additional steel plates were slotted in the column so to connect with the kerf plates of the beams with six bolts M12 8.8. The openings between the steel plates at the column were refilled with polymer concrete to hold the steel plates in place inside the column. The hysteresis curve and dissipated energy for this connection is shown in the Figure 3.

For this connection, the stiffness was mainly dictated by the small pins at the beams as well as the deformations of the steel plates inside the column, which are intended to supply the resistance perpendicular to the grain of the column. The moment capacity, rotations and stiffness degradation were similar to those measured for the first connection but the energy dissipation capacity was much higher and it was not observed any failure in the column. The superior energy dissipation can be attributed to more and better yielding mechanisms arising from the yield of pins, steel plates and wood plastic deformation.



**Side View**



**Top View**

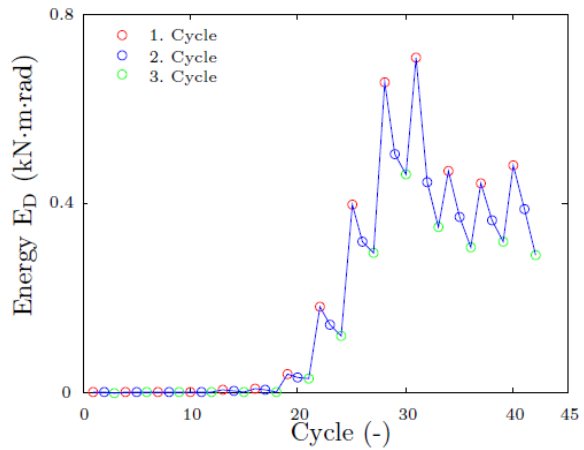
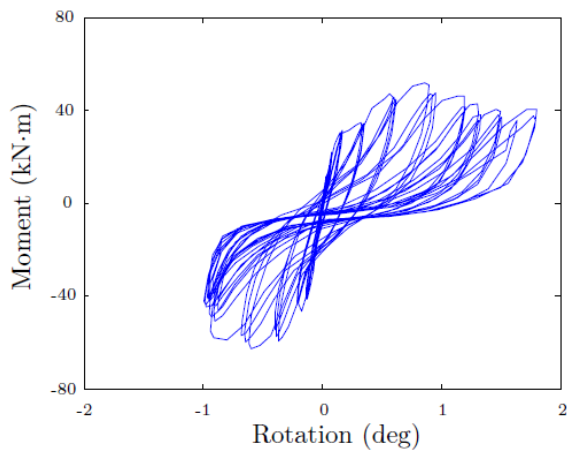
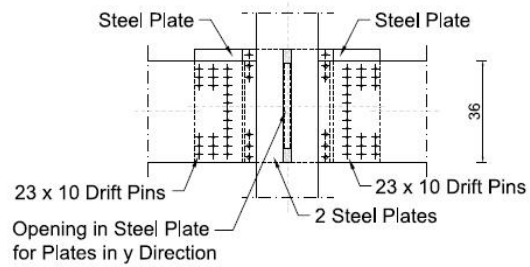


Figure 3: Design (up), hysteretic curve (down left) and dissipated energy (down right) of the steel plates and polymer concrete BTC, based on [13]

### 3.3 Steel plates

As for the previous connection, this BTC was based on kerf plates embedded on the beams except that they were connected to the column via conventional T-shape steel plates rather than two embedded plates. The kerf plates sized 120mm x 400mm and had a thickness of 12 mm. The connection kerf plate-beams was also realized with 23 small drift pins. In contrast to Specimen 03, the kerf-plate was welded perpendicular to a steel face plate. The two T-shaped steel plates connected with the column with four M16 5.5 bolts, see the Figure 4.

In this case the stiffness of the BTC does not only depend mainly on the drift pins of the kerf plate but also on the perpendicular to the grain stiffness of the column timber in contact with the T-shaped steel plates, so that the overall stiffness of the connection was much lower than the previous one. However, this flexibility did not positively increase the energy dissipation capacity, as it was approximately half of that from the previous BTC.

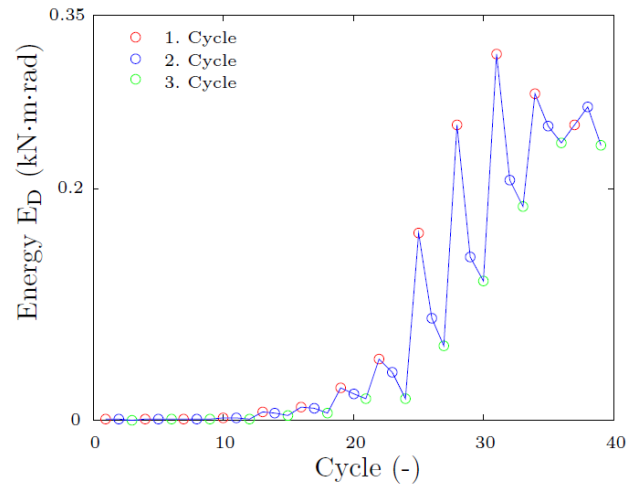
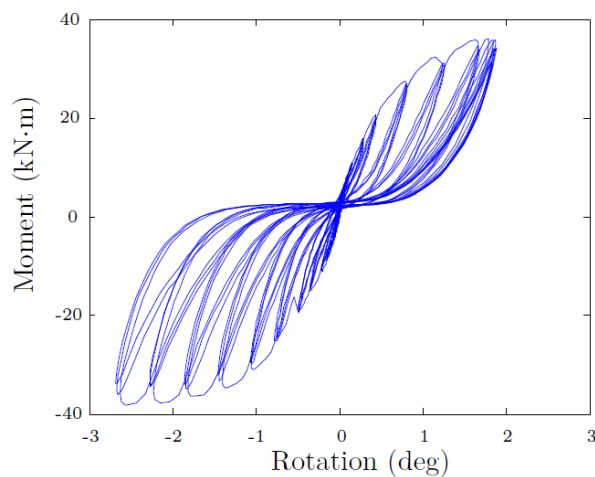
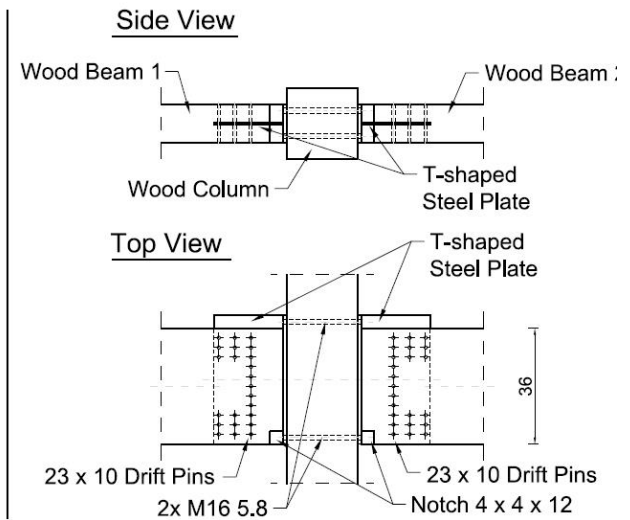
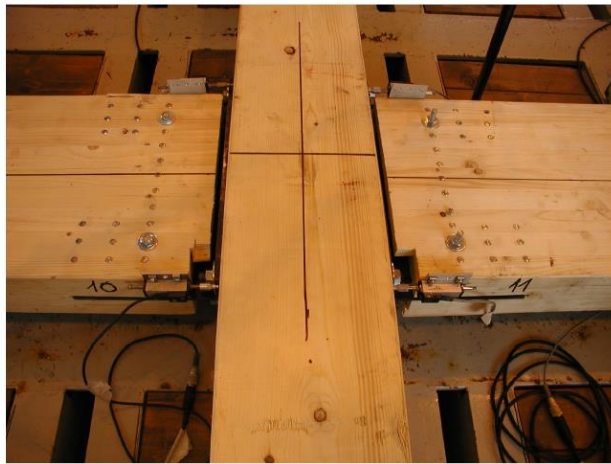


Figure 4: Design (up), hysteretic curve (down left) and dissipated energy (down right) of the steel plates BTC, based on [13]

### 3.4 Hardwood blocks

The fourth BTC was a T-Shaped connection in where the beam connected with the column with a 12 of self-tapping screws that were inserted with distinct orientations into two beech hardwood blocks of 65mm x 160mm x 170 mm, see Figure 5. The self-tapping screws are effective wood connectors with a high pull out strength.

As shown in the Figure 5, this BTC was very good in preventing the drift and showed a very high moment resisting capacity. This can be attributed to self-tapping screws that are oriented at 45 degrees and thus prevent the column from high perpendicular to the grain stresses. Also the BTC can offer several advantages such as inexpensiveness, ease of construction and fire resistance. However, the energy dissipation capacity was rather small due to the small yielding of the steel connectors and low transversal loading of the wood.

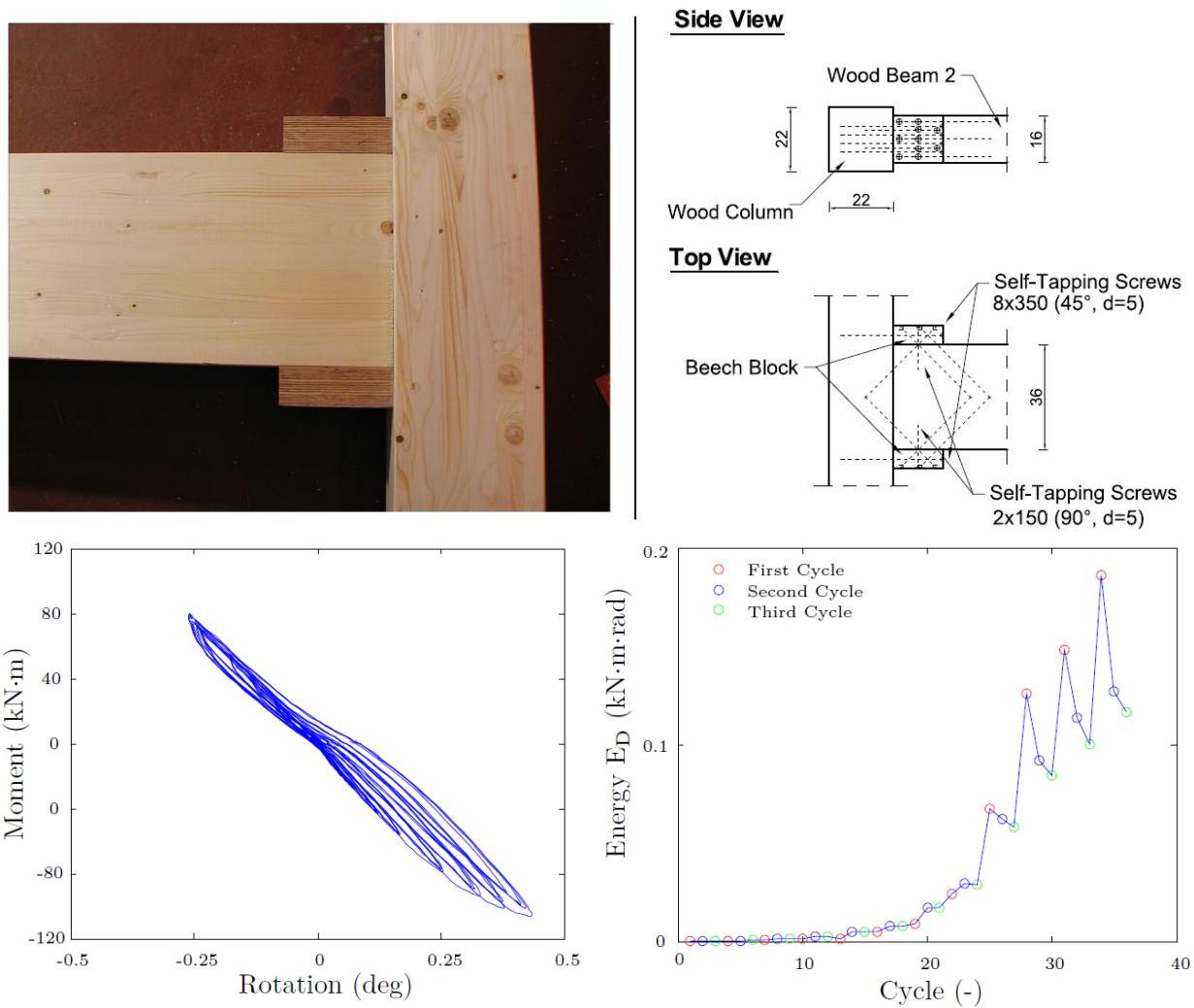


Figure 5: Design (up), hysteretic curve (down left) and dissipated energy (down right) of the hardwood blocks BTC, based on [13]

### 3.5 Polymer concrete blocks

The last plastic-yielding based BTC was similar to the previous except that the blocks were manufactured with polymer concrete and was not a T- but cross-shaped connection, see Figure 6. The mechanical behavior of this BTC was similar to the previous, which proves the insignificant plasticity on the wood blocks, but the stiffness degradation was higher and over all the moment capacity was about half of the previous connection. The failure was observed at multiple small cracks at the column so that the difference of the moment capacity could be attributed to the reduced cross section of the column caused by the increased number of screws.

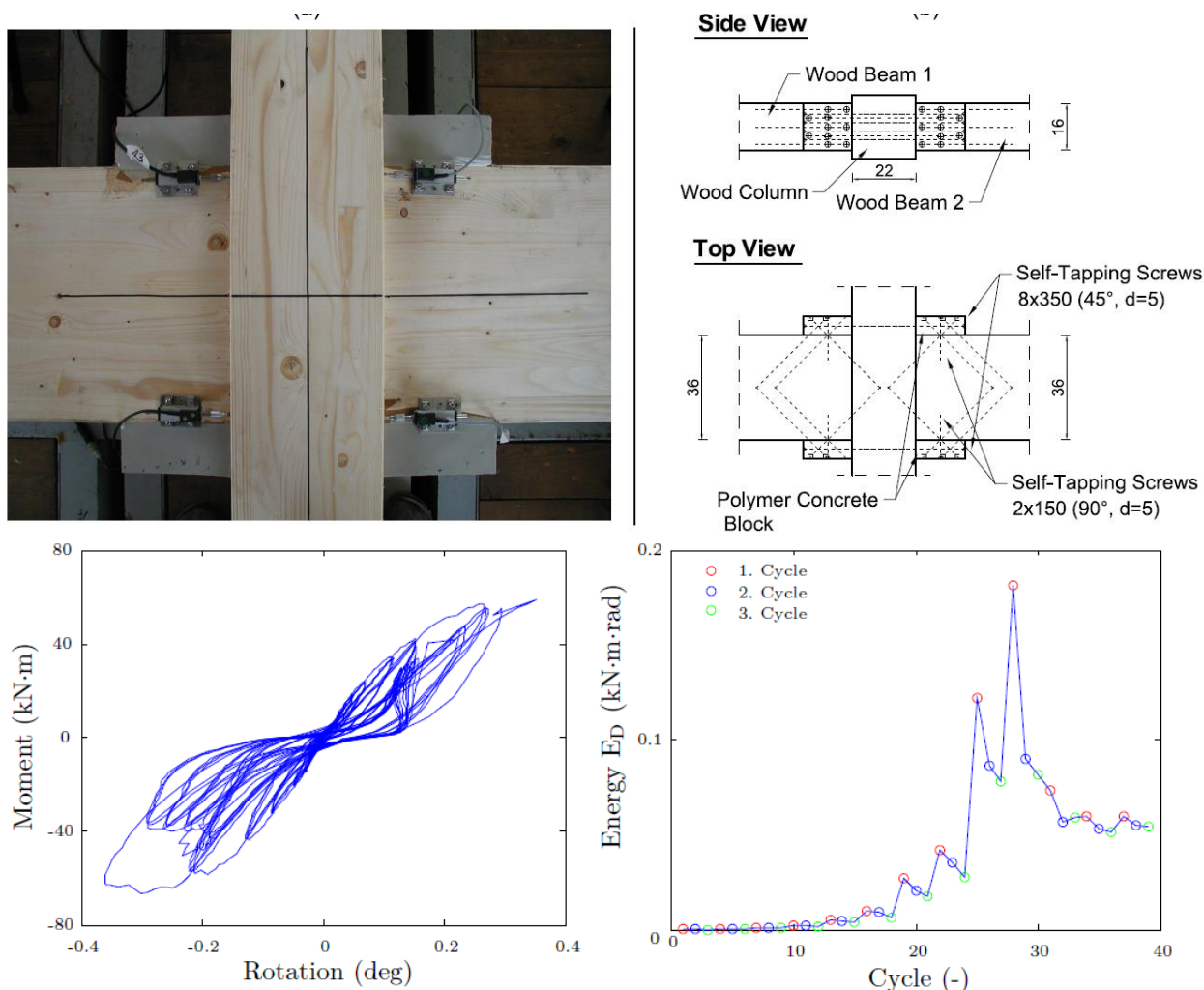
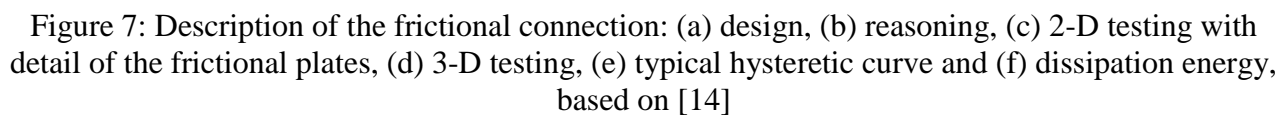


Figure 6: Design (up), hysteric curve (down left) and dissipated energy (down right) of the polymer concrete blocks BTC, based on [13]

#### 4. DESIGN AND RESULTS OF FRICTION BASED BTC

This connection is different from the previous BTC in that the main energy dissipation mechanism is provided by friction between steel plates and not by the plastic yielding of the steel itself. The design, reasoning, 2- and 3-D testing as well as the testing results are shown on the Figure 7. As shown in Figure 7a, the connection design is similar to the third connection, i.e. a kerf plate embedded on the beams connects to a T-shaped steel plate bolted on the column, but the connection of the kerf to the T-shaped steel plate is not completely fixed - the bolts are tightened to a selected moment so that beyond a defined frictional moment the BTC no longer behaves rigidly and the kerf plate frictions with the T-shaped plate. This frictional motion of the bolts is achieved thanks to increased clearance holes on the steel plates. In addition, as seen in the detail of Figure 7c, there are two additional small steel plates connected to the bolts located over the kerf and T-shaped plates so to increase the friction of the connection.

The reasoning behind this design is illustrated in the Figure 7b. There are three differentiated mechanical behaviors of the connections that correspond to three different loading scenarios. First, when the connection is loaded with relatively small moments due to the wind or moderate earthquakes, the moment is not enough for the BTC to friction and thus the connection behaves rigidly preventing from drifts. Second, at high seismic intensities, when the moment of the connection



approaches the frictional moment (which needs to be tuned up close to the elastic limit of the column) the friction of the BTC starts so that the rotation increases but also the amount of dissipated energy due to friction. Third, in extreme loading scenario the bolts reach the boundaries of the clearance holes, and deform plastically providing more stiffness and increased energy dissipation via plastic yielding.

The connection was tested in 2D and 3D configuration as shown in the Figure 7c and 7d, respectively, and the typical test results are presented in Figure 7e and 7f. Note the connection was tightened in this case to have a small capacity of about 15 kNm and the rotation was similar to the initial connections presented on the last section, however the energy dissipation capacity was about 8-10 times higher than the previous BTC while remaining undamaged. In addition, the monotonic static tests showed that the frictional moment is consisting with the tightening of the bolts showing a linear relation.

## 5. CONCLUSION

A series of 6 different connection typologies were designed, tested and assessed under monotonic static and pseudodynamic cyclic loading in order to find suitable connections for construction of mid-rise post-beam timber buildings in seismic prone areas. The connections used a wide variety of timber connectors such as in-glued rods, screws, bolts, or steel plates and other relatively novel materials such as hardwoods and polymer concrete.

The results showed in overall that the transverse stress at the column is a critical issue for the design of these connections. This is especially critical when embedding steel plates, or using thick steel connectors in the column. Also, when using small connectors, the reduced cross section could be an issue. The wide variety of timber connectors also reflects on the drift control, moment capacity, hysteretic behavior as well as the energy dissipation capacity of the joining systems.

Out of the designed connections, one based on hardwood blocks showed a very high capacity to bear loading and control the drift while keeping ease of construction and cost-effectiveness. This connection may be a solution for post-beam timber structures with high drift limitations and therefore was selected for being tested in a real structure on a shaking table, which is presented on the next part of this series.

On the other hand, an original connection based on frictional yield rather than steel plasticity was designed to dissipate high amounts of energy while keeping integrity against relatively intense dynamic loading. This second connection could be useful for guaranteeing the structural integrity of timber buildings during extreme seismic scenarios and was also selected for shaking table testing, which is also shown in the following paper.

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