16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 951 (Abstract ID)

Registration Code: S-L1459930030

COMPARISON BETWEEN DIFFERENT TYPES OF CONNECTIONS AND THEIR INFLUENCE ON TIMBER FRAMES WITH MASONRY INFILL STRUCTURES' SEISMIC BEHAVIOR

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Abstract

Recent tendency in buildings construction emphasizes the use of natural materials. Timber frames with masonry infills (TFM) structure represents one of these types of eco-friendly house. Besides this, latest research studies and earthquakes also proved they are earthquake resistant. TFM structures are still built nowadays, either for aesthetic reasons, seismic resilience, or both. Most important parameters in TFM structures are the timber connections, therefore the paper will present a comparison between five types of connections used for TFM structures and their influence on the main parameters governing the seismic behavior.

Five specimens, each composed of a timber frame infilled with one masonry panel, were tested under static cyclic loading. The bottom connections were different for each specimen: cross-halved, mortise-tenon with a timber dowel, mortise-tenon with "L" shaped metal plates, mortise-tenon with "T" shaped metal plates, and mortise-tenon with hold-down.

Results showed very similar hysteretic behavior for all specimens, the infill being responsible for the stiffness and strength of the structure, but the connections influenced the damage pattern for the masonry. Cracking of the masonry infill dissipates energy, thus the findings of this study give information on how to choose the connection type when building new TFM houses.

Keywords: timber connection; masonry; damage pattern

1. Introduction

Timber framed masonry represents a special structural system because of its higher strength than of a timber structure and higher ductility than of an unreinforced masonry structure. Although timber framed masonry buildings are spread all over the world, in some countries being common residential houses, while in others representing important heritage, there is no design standard or published method that can be used to analytically evaluate the capacity of this type of building.

Therefore, an experimental study was developed in Tokyo Institute of Technology, having the objective to assess the mechanical behavior of these structures based on the Portuguese timber framed masonry heritage buildings type (Pombaline) regarding the construction details, but without the timber diagonals (St. Andrew's cross) [1]. The structure without the diagonals can be found in other countries' timber framed masonry buildings, like Romania, China, etc [2, 3]. The study is based on a previous study developed in Portugal which consisted of experimental analysis of Portuguese type timber framed masonry wall [4].

Fig. 1 – Tımber frame with masonry infill (S2)

The conclusions after the first part of the study in Sakata Laboratory (Fig. 1) highlighted a generally good in-plane behavior [1]. The elements of this building system can become independently deformed while simultaneously collaborating. The connections in the original panels are characterized by the direct wood/wood contact that comes under local compression and is usually never perfect fit, so there are possible displacements without unacceptable states of stress in the timber elements and thus some of the energy is dissipated through friction between the connection elements.

The timber framed masonry system is still built nowadays in seismic prone areas, as it is highly influenced by the availability and the low cost of the construction materials and after past earthquakes most of them showed slight damages, but rarely collapsed. Moreover, for Pakistan and Portugal this structural system was chosen for reconstruction. This may be a reason to encourage building of this system, as it mitigates life loss with low costs.

Additionally, recent tendency in buildings construction emphasizes the use of natural materials and TFM buildings usually respect the eco-friendly tendency. This also explains the growing of interest for the researchers into this system, as it can be seen from the already existing studies [1, 2, 3, 4, 5, 6]. Numerical analysis methods have also been proposed, mainly using FEM software and trying to simplify as much as possible the modelling method so it can be available to the engineers [1, 6]. There is still much research to conduct in order to achieve both simple and comprehensive evaluation method for this type of buildings (TFM).

The proposed research aims to focus on solving the connection problem, as it is more stringent than the out of plane behavior of masonry, as showed in reconnaissance report after the 2013 Lushan earthquake [3], as maybe one leads to another and if some masonry panels fail in out of plane direction, the timber frame can still prevent collapse, but if the bottom connections fail, than even if masonry panels have no damage, the structure collapses.

In this respect, the Japanese timber connections are famous in the world for their seismic resistance and variety, so the plan is to substitute the weak bottom connections (i. e. cross-halved in Portugal, just supported on the ground in China, etc.) of the timber framed masonry system with more resistant type of connection, inspired by the Japanese type.

2. Research methodology

The research plan consisted of two types of experiments. First a static cyclic test on five timber framed masonry walls containing only one masonry panel width confined by a timber frame (Fig. 1a). The masonry panels had the same dimensions as for S2 (Fig. 2b). The first specimen (TFM-CH) had the cross-halving connections. This test also aimed to determine the contribution of one panel in the behavior of the overall wall and to indicate the transfer of the vertical force between the timber frame and the masonry panel.

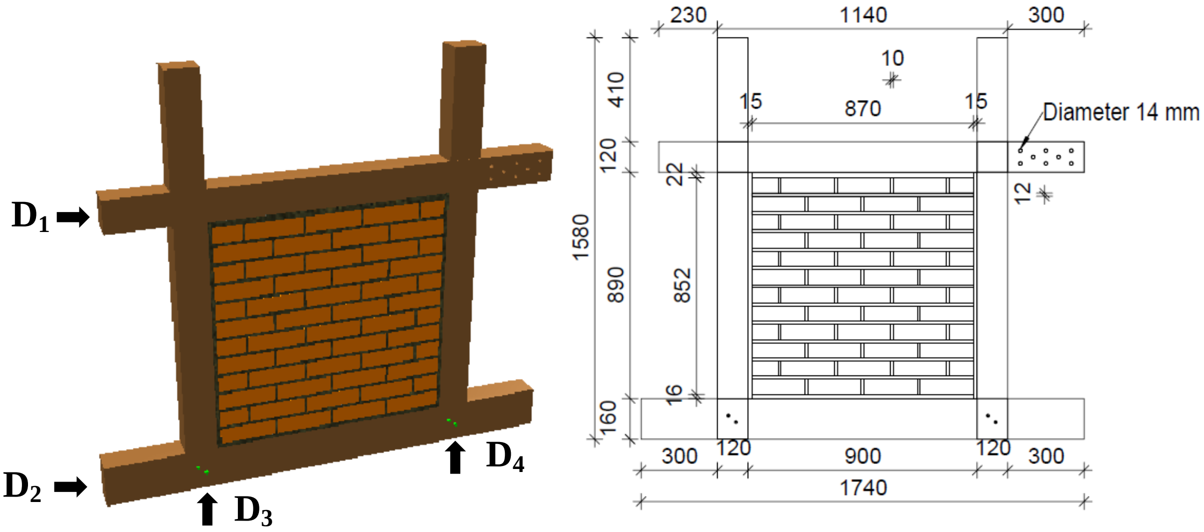


Fig. 2 – TFM-CH specimen layout (left) and dimensions (right)

For the other four specimens the parameter was the mortise-tenon connection with: timber dowel (TFM- MT-TD), L-shaped metal plates (TFM-MT-LMP), T shaped metal plates (TFM-MT-TMP) and hold down (TFM-MT-HD). These connection changes were applied only for the bottom connections. The specimens were subjected to in-plane static cyclic loading (Figure 3, left), thus the influence of the Japanese connection types on the overall behavior of the wall could be observed. For all tests, the CUREE – Caltech standard protocol for wood frames was used [1]. The reference displacement, Δ, was chosen based on previous experimental test observations, as 0.033 rad displacement at the top of the wall [1]. As the input deformation, the shear angle, δ, was used to cancel the rocking and thus to observe the pure shear behavior of the wall, being calculated with the following equation:

$$\delta = \frac{D_1 - D_2}{\text{Height}} - \frac{D_3 - D_4}{\text{Width}} \tag{1}$$

Where D1, D2, D3, D4 are the measured displacements and the positions of the wire displacement transducers is shown in Fig. 2 (left).

The specimen is supported on the steel beam of the reaction frame, by hold-downs on the vertical direction and lateral restrainers on the horizontal direction (Fig. 3). The vertical load was applied by tensioning tie rods, as shown in Fig. 3. On the tie rods, 4 strain gauge/tie rod were used to measure the force applied. The initial force applied was 30 kN.

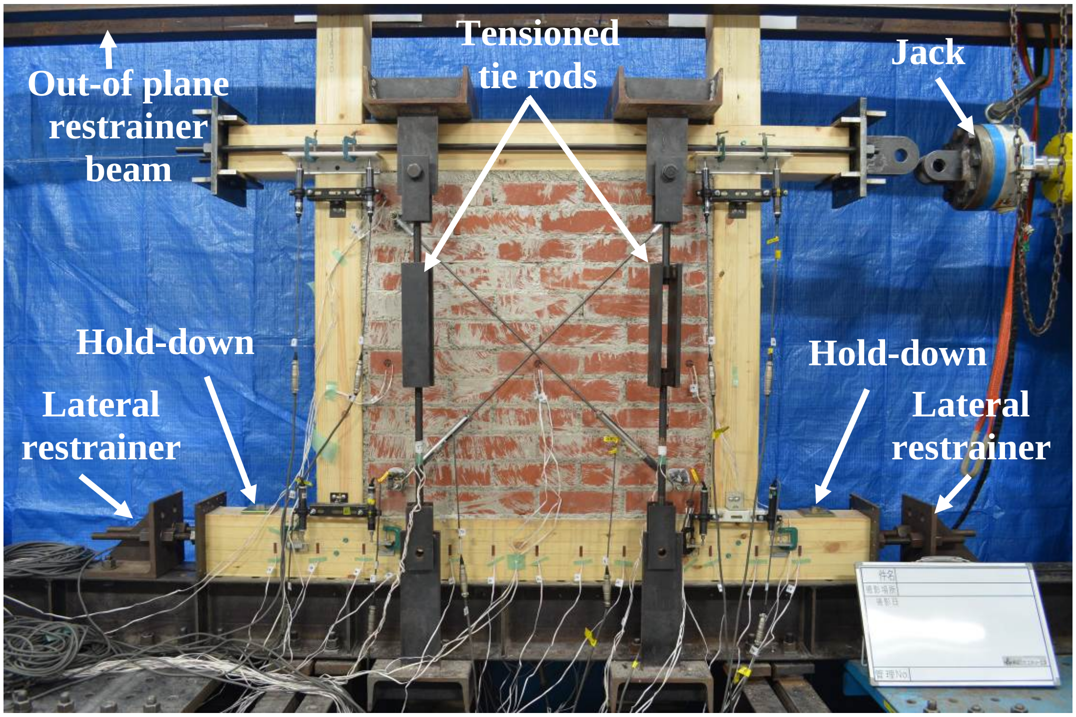
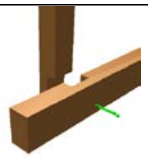
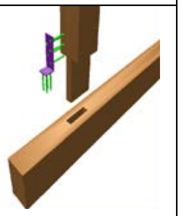
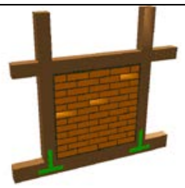
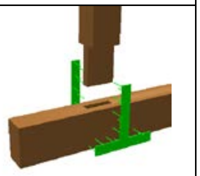
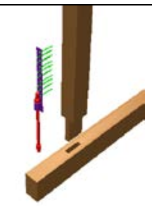
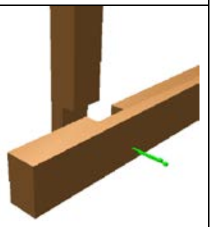
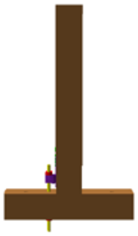
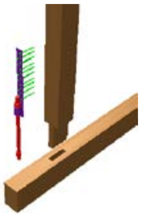


Fig. 3 – Test setup for wall specimen

The experiments are summarized in Table 1, specifying the name, photo of the specimen and the test type.

Table 1 – Summary of the experimental tests conducted

No. of test	**Name of specimen**	**Connection type**	**Test type**	**Specimen Photo**	**Connection photo**
1	TFM-CH	Cross-halved	Cyclic static		
2	TFM-MT-TD	Mortise tenon with timber dowel			
3	TFM-MT-MP1	Mortise tenon with "L" shape metal plates			

No. of test	Name of specimen	Connection type	Test type	Specimen Photo	Connection photo
4	TFM-MT-MP2	Mortise tenon with "T" shape metal plates			
5	TFM-MT-HD	Mortise tenon with hold-down			
6-12	CH-(1-6)	Cross-halved	Bending cyclic static		
12-18	HD-(1-6)	Mortise tenon with hold-down			

3. Experimental results

Fig. 4 shows the envelope curves obtained by static cyclic tests. The results were similar in strength, the difference being the failure mode. Fig. 4 shows the deformation of the specimens at 0.03 rad, on the positive loading and Fig. 5 and 6 present the cracks exhibited by all specimens at the end of the tests.

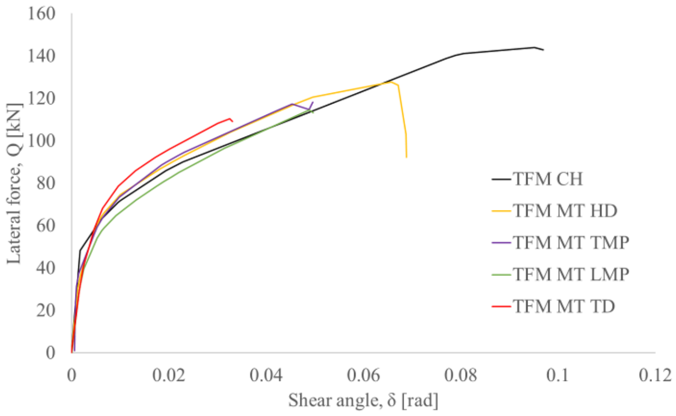
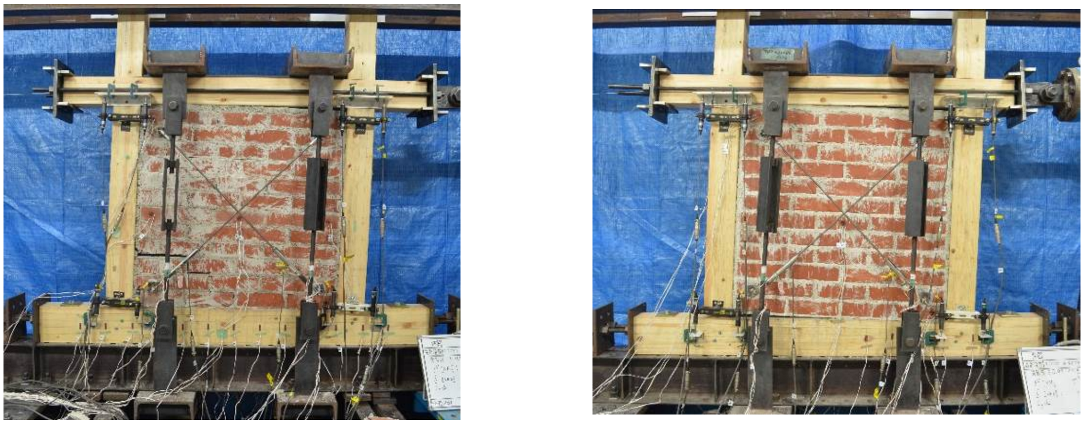


Fig. 4 – Test results comparison

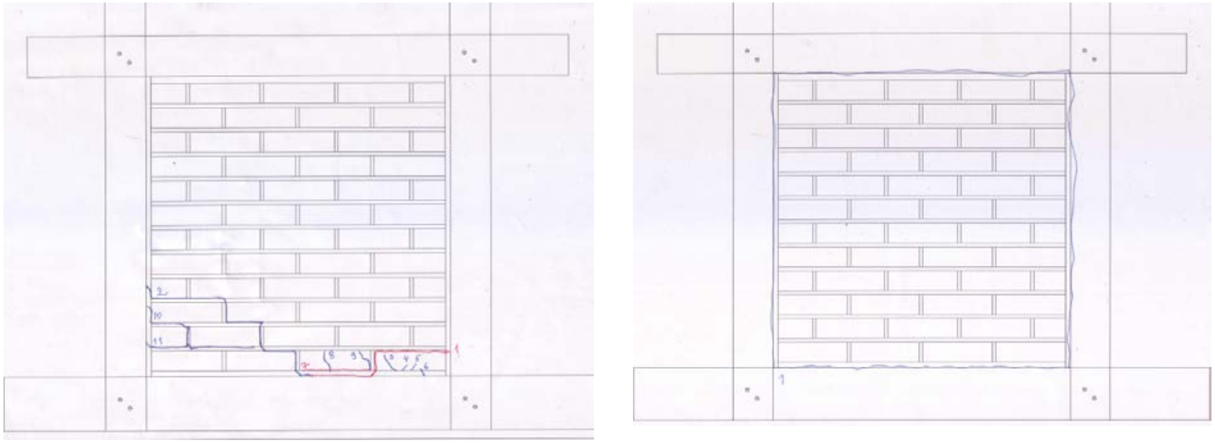


TFM-CH with initial vertical force (1) TFM-CH without initial vertical force (2)

TFM-MT-HD TFM-MT-TD

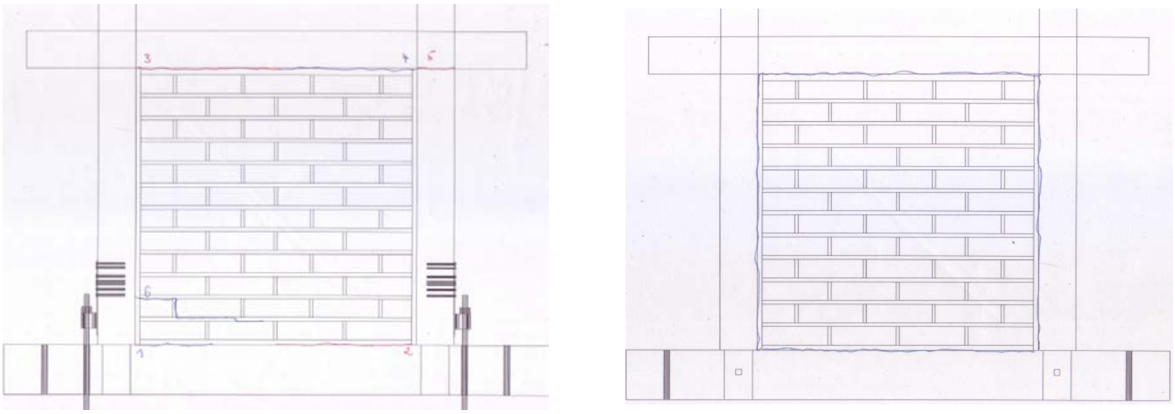
TFM-MT-LMP TFM-MT-TMP

Fig. 5 – Deformation of the specimens at 0.03 rad



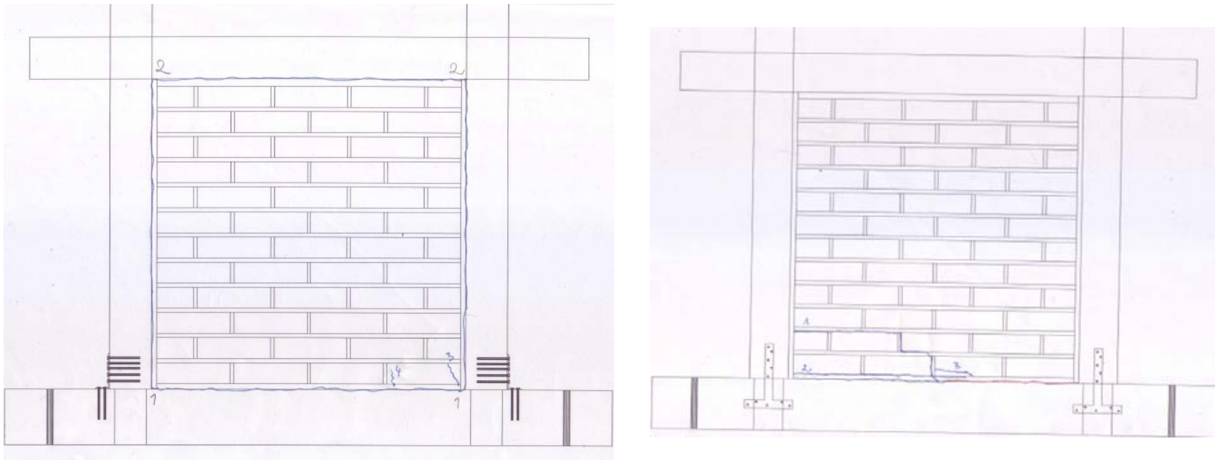
TFM-CH with initial vertical force

TFM-CH without initial vertical force



TFM-MT-HD

TFM-MT-TD



TFM-MT-LMP

TFM-MT-TMP

Fig. 6 – Cracks distribution on the specimens

Sub-assemble tests were conducted on cross-halved and mortise tenon with hold-down connections (Fig. 7, a and b), as it was assumed that they were the weakest and the strongest, respectively, from the studied connections.

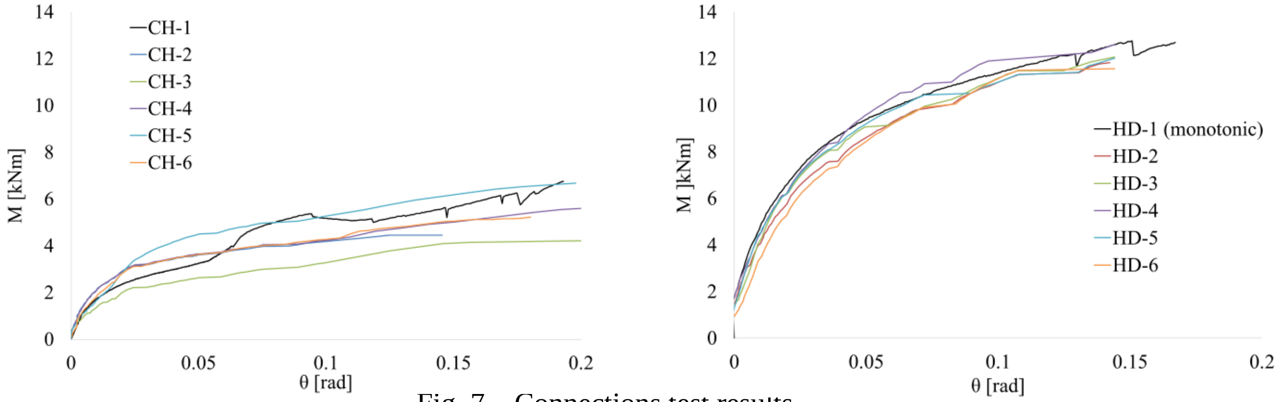


Fig. 7 – Connections test results

The characteristics of the used materials (mortar and glulam timber) were obtained by material tests. Average compression strength for mortar resulted as 17.27 MPa, while the average Young’s modulus was 16.52 GPa. The Young’s modulus was calculated as the ratio between the force and the deformation at 1/3 from the maximum force recorded. For the timber bending test, the average Young’s modulus obtained by calculation according to the Japanese standard [13] was 11 GPa.

Connection tests were also conducted to observe timber connections when subjected to a pure shear test. The results were as expected, only compression perpendicular to grain was observed (Fig. 8), and no shear failure could be obtained.

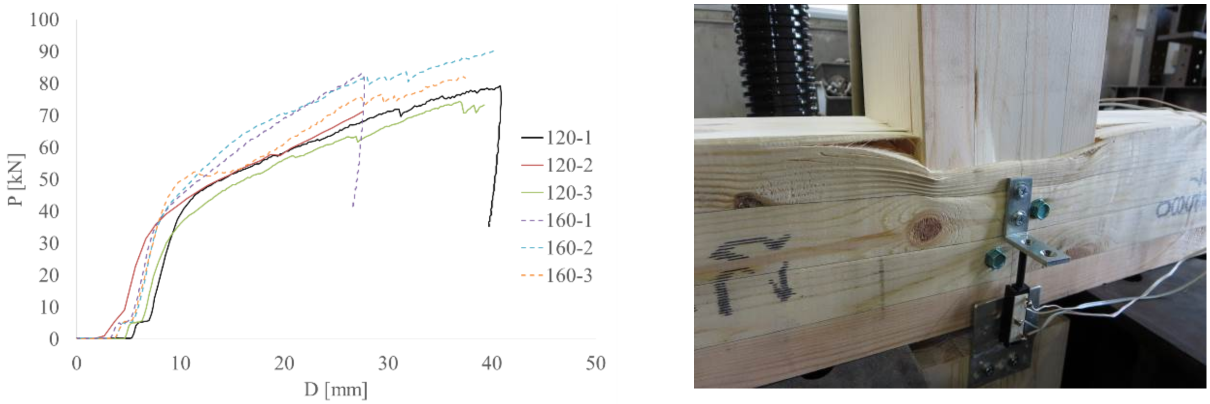


Fig. 8 – Cross-halved connection shear test results and failure mode

The bricks’ average compression strength was 57.6 MPa, and the obtained Young’s modulus was 16.8 GPa [1]. Masonry prisms were also tested in compression and average compression strength was 36.8 MPa, with corresponding Young’s modulus of 1.9 GPa [1].

4. Discussion

Test results confirmed that the masonry panel gives the strength of the specimen and that the timber frame successfully confines the masonry, such as even after masonry cracks, there is still increase in stiffness.

The confinement’s efficiency is due to the timber’s capacity to deform in local compression perpendicular to grain. This phenomenon appears both in the timber connections and in the vicinity of the connection, where masonry panels act on the timber beams. The direct shear forces acting on the timber beams do not cause shear failure, only local compression damages, which are not causing failure of the element, just deformation. This phenomenon is typical for timber and is difficult to measure it precisely, because of the continuously rising stress-strain curve (Fig. 9, left). Under severe loading, deformation continues until the wood substance is fully compressed, about 1/3 of the original volume [10].

On the other hand, due to the vertical force application system specific to timber structures (tensioned vertical tie rods) the uplift of the connections (visible in all tests, except in the one with the hold-down, where the uplift shifted to the upper connections) enhances the increase of the vertical force directly proportional with the displacement at the top. As it is known, the vertical force is beneficial for masonry, thus, from the results comparison (Fig. 4) the continuous increase in strength is visible.

So, although difficult to do a separate identification, both timber frame and masonry have a continuously rising force-deformation curve. S2 test [1] showed that this rise stops when the shear failure of the timber beam occurs. This failure was not obtained in the experiments on just one masonry panel. This is due to the layout of the vertical force introducing system that was the same for both tests. In the one panel test (Fig. 9, left), the vertical load was almost uniformly distributed, due to the reduced dimension of the panel, while for S2 it was closer to concentrated loads (Fig. 9, right), although a steel plate was set to distribute the load from the tie rods.

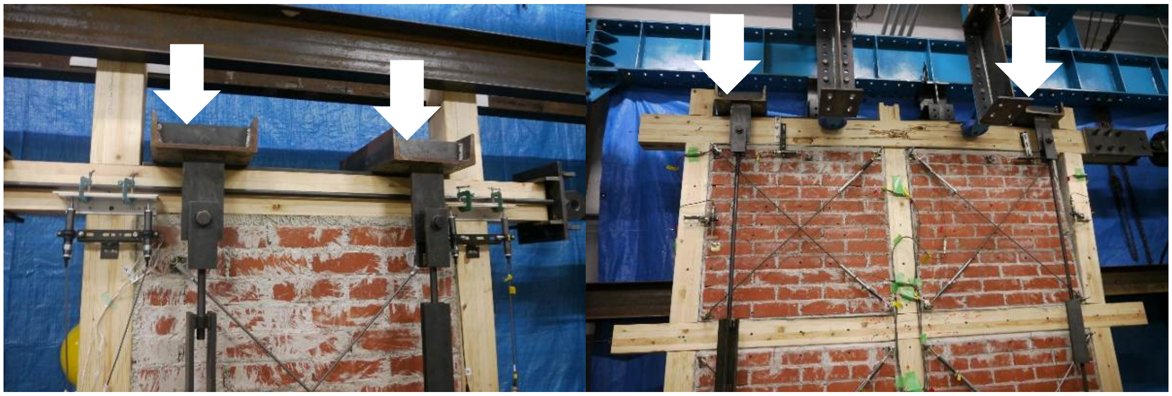


Fig. 9 – Vertical load application on TFM-CH (left) and S2 (right)

The presence of the vertical force for TFM system is necessary, due to the fact that if tested without it, the specimen will just exhibit damage in the connection and the masonry infill does not actually work. Thus, the purpose of the test, to observe the shear behavior when subjected to earthquake would be lost. That's why, although the vertical force introducing system is different than in the real situation, it helps to obtain parameters that were envisaged by the study. This was demonstrated by tests of TFM-CH with and without vertical force (Fig. 10 and 11). In the test with no vertical force (TFM-CH-2), only the beginning of the test was with no vertical force, due to the fact that after a certain amount of uplift (allowed without axial force), the tie-rods started to tension and thus, limiting the uplift. Comparison between the axial load applied on both specimens is shown in Fig. 11.

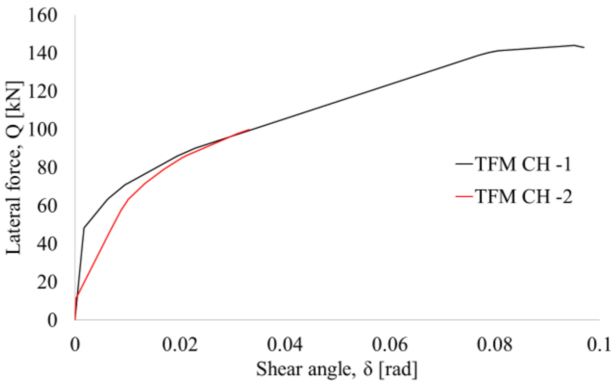


Fig. 10 –Lateral force versus shear angle comparison for TFM-CH with (TFM CH-1) and without initial vertical loading (TFM-CH-2)

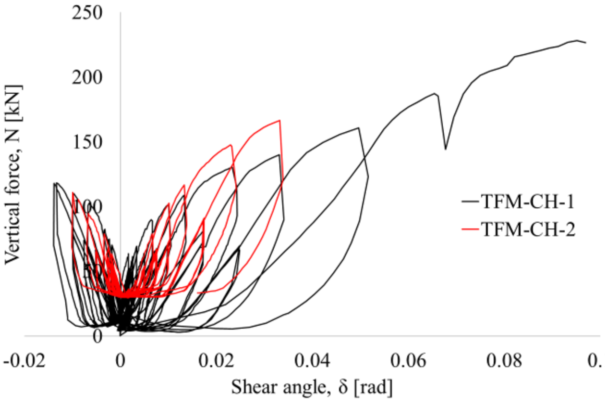


Fig. 11 –Vertical force versus shear angle comparison for TFM-CH with (TFM CH-1) and without initial vertical loading (TFM-CH-2)

The shear angle of the masonry infill (for TFM-CH-1) was calculated with the Mohr's circle and maximum shear strain is obtained starting from the measurement of principal strains on the diagonals of the panels. Fig. 12 shows variation of the masonry infill's shear angle in relation with the corresponding shear angle of the timber frame. The shear angle of the infill is much lower than that of the timber frame. After the crack of the infill (around 0.0017 rad of timber frame's shear angle), the value of the shear angle of the infill is increasing, this meaning that some of the horizontal displacement concentrates in the opening of the cracks.

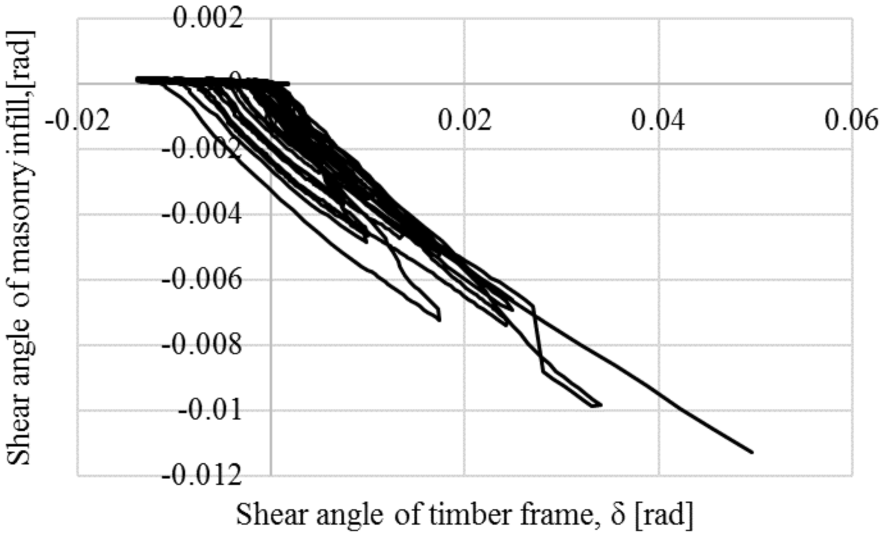


Fig. 12 – Relationship between masonry's shear angle and timber frame's shear angle for TFM-CH-1

Energy dissipation and damping ratio were also compared for all test specimens and Fig. 13 shows the results. It seems that the cross-halved connection gives the highest energy dissipation for the first cycles, and in the end, it is almost equal to the mortise-tenon with timber dowel type. The latter also showed better damping ratio among all the connection types.

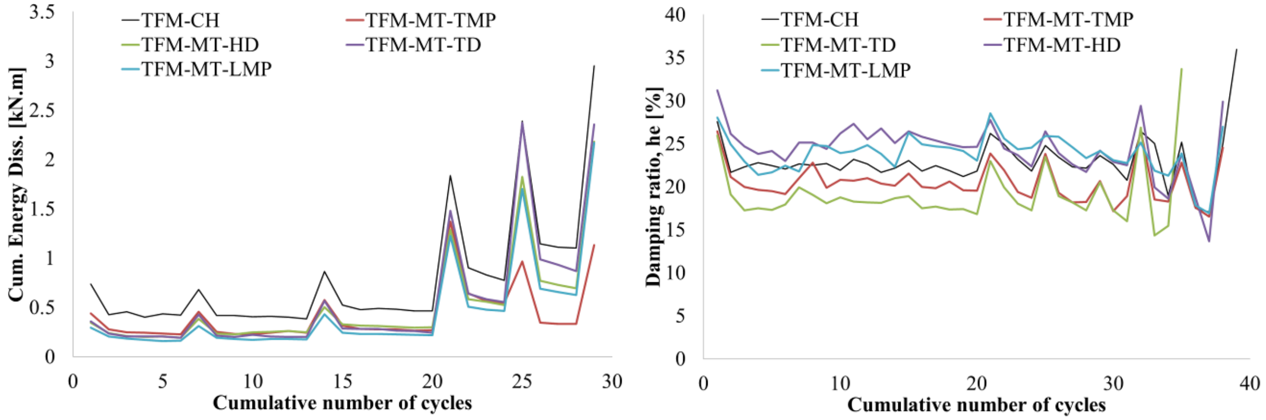


Fig. 13 – Cumulative energy dissipation and damping ratios

The TFM system's flexibility is undoubted given by the timber elements and the connections. In order for it to be resilient in earthquake (to dissipate energy without collapse) it is clear that there are some rules that should be followed:

- The masonry should have a relatively low strength mortar, so it can crack in the joint and thus to dissipate the energy and not to cause the failure of the timber elements;

- The timber should have a good compression perpendicular to grain property in order to absorb the deformation without actual failure;
- Connections must be strong enough not to break and flexible enough to allow the rotation or sliding in the joints of the masonry panel.

From the experimental tests presented hereby (Fig. 4, 5 and 6), the influence of the connection is only on the damage pattern, namely on how the masonry cracks. Considering the above recommendations, it is observed that three of the specimens (TFM-CH, TFM MT-HD and TFM-MT TMP) showed cracks in the masonry, this meaning that energy is dissipated in the infill panel too, and this is beneficial for the overall building assemble.

For the other two specimens, Fig. 6 shows that the infill only separates from the timber frame, since there is no adherence between them [1], and the panel just rotates, causing high uplifts for the connections.

5. Conclusions

Recent tendency in buildings construction emphasizes the use of natural materials. Timber frames with masonry infills (TFM) structure represents one of these types of eco-friendly house. Moreover, latest research studies and earthquakes also proved they are earthquake resistant [1]. Most important parameters in TFM structures are the timber connections, therefore the research presented in this paper showed a comparison between five types of common connections used in Japan, applied for TFM structures, and their influence on the main parameters governing the seismic behavior.

Five specimens, each composed of a timber frame infilled with one masonry panel, were tested under static cyclic loading. The bottom connections were different for each specimen: cross-halved, mortise-tenon with a timber dowel, mortise-tenon with “L” shaped metal plates, mortise-tenon with “T” shaped metal plates, and mortise-tenon with hold-down.

Results showed very similar hysteretic behavior for all specimens, the infill being responsible for the stiffness and strength of the structure, but the connections influenced the damage pattern for the masonry. Cracking of the masonry infill dissipates energy, thus the findings of this study give information on how to choose the connection type when building new TFM houses.

The hold-down connection, as expected, showed the best behavior among all the types, re-directing the damages and uplift in the upper connections. In the same time, they are also the most expensive of all tested types. From the connection test, the difference in terms of maximum moment is very clear when compared to the cross-halved connection.

On the other hand, the eco-friendly version among all types was the mortise tenon with a timber dowel connection, because it doesn’t include any steel part. Although it didn’t produce cracks in the masonry, thus indicating that the energy dissipation level is lower than for the other types of connections, from the test a similar hysteresis with the initial connection type, cross-halved, was obtained. When comparing the moment-rotation capacity given in [12] with the cross-halved connection results, it seems the latter is stronger.

In order to be used for new buildings, the connections should be evaluated according to existing methods. Such methods exist already for most of the connections studied in this paper [11, 12] and for the others, they are under development as ongoing research. Also, when considering the type of connection used in a new building, locally available materials should be considered and also the easy manufacture.

6. Acknowledgements

The authors acknowledge the kind cooperation and support of FIBEX and ASAHI BOND companies.

The financial support of the Japan Society for Promotions of Science (JSPS) for the postdoctoral research grant no. PE 13092 is acknowledged.

The authors also acknowledge the financial support of the Romanian National Authority for Scientific Research and Innovation, CNCS – UEFISCDI, project number PN-II-RU-TE-2014-4-2169”.

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