SIMPLIFIED SEISMIC EVALUATION METHOD FOR TIMBER FRAMES WITH MASONRY INFILLS

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ABSTRACT

Masonry infilled timber frames (TFM) are widely used for residential houses in many countries in the world. Recent seismic events around the world showed that this typology is resilient for earthquakes, and even though it exhibits damages, it rarely collapses. For developing countries, TFM can be a real contribution for life protection of the inhabitants, in mitigation of seismic risk, but also as a reconstruction solution after the disaster, because it uses local materials and the construction method is easy to be applied even for non-engineered persons.

This study proposes a simplified seismic evaluation method for timber framed masonry walls, based on a shear spring model calibrated with experimental results on timber framed masonry walls with different dimensions and also material testing. The resulting envelope curve simulates satisfactorily the initial stiffness and maximum strength.

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Simplified seismic evaluation method for timber frames with masonry infills

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Masonry infilled timber frames (TFM) are widely used for residential houses in many countries in the world. Recent seismic events around the world showed that this typology is resilient for earthquakes, and even though it exhibits damages, it rarely collapses. For developing countries, TFM can be a real contribution for life protection of the inhabitants, in mitigation of seismic risk, but also as a reconstruction solution after the disaster, because it uses local materials and the construction method is easy to be applied even for non-engineered persons. This study proposes a simplified seismic evaluation method for timber framed masonry walls, based on a shear spring model calibrated with experimental results on timber framed masonry walls with different dimensions and also material testing. The resulting envelope curve simulates satisfactorily the initial stiffness and maximum strength.

Introduction

The seismic performance of masonry infilled timber frames has been reported after several major earthquakes. In the 1999 M7.4 Kocaeli earthquake in Turkey, the houses with this type of structure sustained less damage in comparison with poorly constructed reinforced concrete ones with masonry infills [1,2]. In [3] it was reported the survival of timber framed houses in Greece during the 2003 M6.2 Lefkada earthquake, even when not properly maintained. In the 2010 M7.0 Haiti earthquake, the local traditional timber frames with masonry infills, referred to as Gingerbread houses, sustained significant damage but very few collapsed [4]. In [5], based on the comparison between the statistics of their damage levels after 2013 Lushan earthquake masonry infilled timber houses sustained much less damage during the earthquake than the URM ones, while the confined masonry ones exhibited better seismic performance in general. Detailed and simplified numerical models were also developed for TFM, such as those [6] and [7].

This paper proposes an evaluation method based on a shear spring model which simulates monotonic lateral loading of a timber frame wall with masonry infills. Each component spring is defined empirically, and their arrangement in series or in parallel was decided based on the experimental test of a wall specimen described in detail in [8], but also considering engineering judgment. In this first phase of this model, empirical definition of the springs aims to use experimental tests as simple as possible (only monotonic loading), in order to be able to be reproduced easily by engineers. In order to adapt it for other timber frames with infills, the configuration of the shear spring model can be changed, since it involves many materials properties, based on the construction details of the target wall. This is an important feature, due to the variation of the type of connections and infill arrangements existing even in the same country.
Experimental test

The dimensions of the timber frame and masonry infill are shown in Figure 5, having four masonry panels with the same characteristics [8]. Figure 6 presents the cross-halved connections of the timber frame, reinforced with screw nails having a 6 mm (~0.24 in.) diameter and 90 mm (~3.55 in.) length, chosen based on the available materials in Japan and on the fact that the nails shear capacity was previously determined by [9].

A vertical force of 60 kN was initially introduced through steel tie rods and uniformly distributed on the top of the specimen using steel plates connected to the upper beam with screw nails [8].

Figure 1. Dimensions of the wall specimen considered for calibration of the shear spring model [8]

Figure 2. Hysteretic curve of the wall test

The specimen with a timber frame having masonry infills showed a maximum shear capacity of 118 kN (~26600 lb) and an initial stiffness of 9034 kN.rad (~14015 lb/in.), calculated as the secant of the shear force versus lateral displacement relationship passing through the yielding point. Figure 2 shows the hysteretic behavior of the timber framed masonry panel (S2), represented in terms of lateral force and shear angle (rad). The details of the test are presented in [8].

Shear spring model

The springs are placed in the model in series or in parallel (Figure 3), based on the observed mechanical behavior during the experiments described above and also from previous studies [10]. For each branch of the model, the equivalent stiffness is given by the weakest spring.
For each component of the shear spring model, the force-displacement relationship will be obtained, either by experiments (adherence between mortar and timber, adherence between mortar and brick, masonry strut and timber connection – timber frame) or analytically (column flexure). Based on the experimental results, the elements of the shear spring model were identified and for each of them a force-displacement relationship was defined, calibrated with materials or sub-assemblies’ experiments, or, if not available, using mechanics’ and strength of materials’ theory. The elements with corresponding force-displacement curves that were used for the analysis will be presented further.

**Timber frame ($k_{\text{joint}}$)**

The bare timber frame’s force-displacement curve was calculated based on connection experiments (Figure 4) from which moment-rotation was obtained for a cross-halved connection. With the values of the moments from bottom and middle connection, which was considered also as the bottom one, for simplicity, shear forces in the columns were calculated and summed into the total shear force depending on the rotation, which was transformed to displacement, $D$.

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**Figure 3.** Shear spring model for a timber framed masonry wall

**Figure 4.** Setup of the cross-halved connection bending test

**Figure 5.** Envelope curve determined from connection tests vs. frame test experimental results
Due to the fact that the rotation in the joint is directly responsible for the displacement at the top, by multiplying with the height, it gives the displacement due to the connections (which is considered the same for all three bottom connections).

**Timber-mortar (k\text{m-t})**

The relationship between mortar and timber (adherence) (Figure 12) was also included in the shear spring model, and was defined by material tests presented in [8]. Given the assumption that the masonry panel rotates as a rigid body (Figure 6), the displacement resulting from timber-mortar sliding in the vertical direction was considered equal to the displacement on the horizontal direction, thus directly included in the total displacement at the top of the wall.

![Figure 6. Assumption that the masonry panel rotates as a rigid body, and thus vertical displacement, \( \delta_y \), is assumed equal to the horizontal displacement, \( \delta_x \)](image)

**Brick-mortar (k\text{b-m})**

The mortar-brick relationship was also included and determined by material tests presented in [8]. The displacement resulting from the brick-mortar sliding is directly influencing the total top displacement, and thus, the relationship determined within the material tests is used as global relationship, for the wall. Considering that the axial force distribution is not known within the wall, in the model two levels of constant normal stress were considered, corresponding with the data obtained in the material tests, of 0.16 MPa and 0.30 MPa (Figure 10). The number of mortar layers was not taken into account in the model, assuming that a panel is as strong as its weakest leak in the chain, in this situation, one joint.
**Column flexure (k\text{flexure})**

Although for the construction details of the tested wall the column flexure was negligible, in order to increase the versatility of the model, it is included in the shear spring model. To simplify the calculation, a virtual model to identify the rigidity of the frame was used in SAP2000 software, assuming all rigid connections. The columns were considered fixed at the bottom and the wall was subjected to a lateral concentrated load at one end (Figure 7). The result of the static elastic analysis is shown in Figure 8 and the resulting stiffness directly corresponds to the one used in the model.

![Figure 7. Simplified model with rigid connections used to determine the flexural stiffness of the frame](image)

![Figure 8. The force-displacement relationship used in the shear spring model](image)

**Masonry panel’s strut (k\text{strut})**

The diagonal compression tests presented in [12] were used to define the spring corresponding to the masonry panel’s strut evaluation. Based on the results obtained, a bi-linear curve was proposed for the masonry panel in diagonal direction. Transforming to global relationship for the wall, the force was multiplied by \cos 45 and displacement was divided by \sqrt{2}, and result is shown in Figure 13 to be used in the spring model.

**Compression perpendicular to grain of timber (k\text{emb})**

The full compression test results on timber prisms were used to define the embedment of timber perpendicular to grain presented in more detail in [8]. This phenomenon is observed as predominant within the total behavior of the wall, due to the load transfer through the masonry strut to the timber elements, by compressing them perpendicular to grain.

The contact area is very important and was considered 10 mm*100 mm at each corner of the masonry panel’s diagonal. However, two panels were considered, as the diagonal of the whole wall, thus 4 corner areas. The yielding strain obtained by experiment was used, and was multiplied by a 2.4 coefficient, in order to consider the contribution of surrounding timber area (partial
compression) in the behavior during compression perpendicular to grain [13]. The stiffness after yielding was considered between 1/6 and 1/8 of the initial stiffness [14]. Knowing that this property of timber is characterized with hardening even until large displacements are reached, after reaching the 110 kN value of the force (maximum strength of the masonry strut), stiffness was considered 0.

Given the assumptions considered on the rotation of the masonry panel as a rigid body described in Figure 6, its embedment in the timber in the vertical direction was summed with the embedment in the horizontal direction and the total embedment was included in the total displacement at the top of the wall. Resulting force-displacement curve is shown in Figure 9.

![Figure 9](image)

Figure 9. Model used in the shear spring model for compression perpendicular to grain of timber

**Testing the shear spring model**

Starting from the shear spring model configuration (Figure 3) and considering each spring force-displacement curve, 4 events were obtained in the total behavior of the panel. Each branch relationship was calculated as combination of the two springs which composed the branch, and being in series, the weakest spring gives the maximum force. Then, with the maximum force, the displacement is calculated as the sum between the 2 springs, for the same level of force. For the mortar-timber spring a pre-compression level of 0.30 MPa was considered.

![Figure 10](image)  
Figure 10. Brick – mortar relationship

![Figure 11](image)  
Figure 11. Timber – mortar relationship
Figure 12. Brick–mortar combined with timber–mortar relationship (1st branch of the shear spring model – F3)

Figure 13. Masonry strut relationship

Figure 14. Compression perpendicular to grain relationship

Figure 15. Masonry strut combined with compression perpendicular to grain relationship (2nd branch of the shear spring model – F1)
In the end, the three branches are in parallel, so starting from the first event’s displacement (when overlapped on the same graph), the force is summed and the resulting curve is presented in Figure 19.

Figure 16. Timber frame relationship

Figure 17. Column flexure relationship

Figure 18. Timber frame combined with flexure relationship (3rd branch of the shear spring model – F2)

Figure 19. Four masonry panel shear spring model
The model shows reasonable result also for the four masonry panels wall, although initial stiffness is not matching perfectly. This difference in accuracy can be explain by the more complicated behavior of the four panels, when compared to the simpler one panel wall. It can easily be observed that for both models, the strut and compression perpendicular to grain are the key parameters governing the curve, which matches also the real situation.

**Summary**

The model shows reasonable result in terms of force-displacement of the wall. Initial stiffness is given by the timber-mortar spring, and after quick cracking, the compression perpendicular to grain property is activated, together with the strut in the masonry. Due to the consideration of separate springs for masonry strut and adherence between mortar and brick, respectively, model does not simulate combined behavior, such as in real situation when after the first crack of the panel and reconfiguration of the strut, there is joint shear sliding in the masonry and stiffness is actually maintained and still increasing. The model does not simulate cyclic loading in this form, but for simple and initial seismic evaluation the shear spring model can be used. Although especially the masonry is sensitive to the cyclic loading, the presence of the timber frame as a confinement for masonry can make the use of the model acceptable even for only monotonic loading. Moreover, the model was calibrated to the positive loading envelope of the experiment, in which the stiffness degradation is included. The results presented in this paper for the model are only applicable to the wall configuration tested and described in [8]. In order to adapt it for other timber frames with infills, the configuration of the shear spring model can be changed, since it involves many materials properties, based on the construction details of the target wall. This is an important feature, due to the variation of the type of connections and infill arrangements existing even in the same country. Of course, the model can be improved in the future researches, by including cyclic loading, non-linearity or combined behavior of multiple elements.

**Acknowledgments**

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS – UEFISCDI, project number PN-II-RU-TE-2014-4-2169”. The conference participation was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS – UEFISCDI, project number PN-III-P2-2.1-PED-2016-1073, within PNCDI III” The Japan Society for Promotions of Science (JSPS) is also acknowledged for the financial support through the postdoctoral research grant no. PE 13092 for experimental tests in Tokyo Institute of Technology.

**References**

system of the island of Lefkada, Greece, Construction and Building Materials, 21(1): 225-236.


