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Numerical modelling of the cyclic behavior of timber-framed structures

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ABSTRACT

The present paper presents a study on the applicability of numerical models in predicting the global response of timber-framed shear walls during earthquake events. Based on previous in-plane cyclic testing of traditional timber frames with and without masonry infill, numerical models were developed to describe the cyclic response of traditional timber frame walls including flexural behavior, pinching and strength degradation. The numerical models were developed in the finite element software OpenSees with calibrated springs representing nailed connectors found in traditional half lap joints. Based on the calibrated models a study was conducted on the timber frame wall with brick infill model by varying wall configuration and analysing cumulative energy dissipation and the effect of slenderness and load capacity with increasing drift. A good correspondence was obtained with the experimental data and future work will include the application of the model to whole buildings.

1. Introduction

Ancient heritage is abundant with timber-framed structures that function as either shear walls within masonry buildings or as independent structural systems, resisting both lateral loads and gravity loads. In earthquake prone areas they have been used as seismic-resistant construction and their good behavior during seismic events has been documented and observed in several countries (e.g. Portugal, Italy, Greece, Turkey, Peru and Haiti) [1–4].

Timber shear wall systems are typically composed of internal braces forming an X-shape called the Cross of St. Andrew and are typically found in seismic countries such as in Italy and Portugal. Portuguese Pombalino buildings, introduced after the 1755 earthquake and subsequent tsunami and fire by the prime minister of the time, the Marquis of Pombal, consist of external load bearing masonry walls and internal timber-framed shear walls (Fig. 1a), called frontal walls [5]. Even though the city has not experienced significant seismic activity since 1755 (the return period is estimated to be 250 years), the seismic effectiveness of these buildings is unknown. However, it is expected that the seismic performance of Pombalino buildings is directly dependent on the timber frame walls and, thus, it is important to understand their mechanical behavior.

In Italy, the so called “casa baraccata”, introduced after the 1783 earthquake by the Borbone house, has a timber frame also embedded in the exterior masonry walls [2]. Timber frame shear walls are encountered in several other countries, especially in the local vernacular architecture, and can be composed of various infill materials, ranging from brick and stone masonry to mud and cane. The timber is not only able to better resist horizontal loads, but it also provides a confining effect on the masonry structure improving its mechanical properties [6]. In Greece and Turkey a variety of timber-framed structures can be found [1,7] and they have proved to resist well to seismic actions when appropriately maintained. The same can be said for other Balkan countries, e.g. Romania and Albania. Timber framed construction (quincha construction) in Peru also proved its efficiency during seismic events [8,9]. In this case, the walls are lighter and are infilled with interwoven bamboo canes. Quincha is used for upper floors, while the ground floor of traditional buildings is usually in adobe.

Timber frame construction systems are also present in typical vernacular architecture in non-seismic regions, such as Germany, France, the UK, and in general all northern European countries [10,11]. There is a great variability in terms of geometry, with bracing elements in the corners. Often, additional timber members are used as decorations, being also rounded (Fig. 1b).

The connections on timber frame construction are a key issue, as they control the in-plane behavior, particularly as regards the dissipative capacity of the timber walls. As there are very different types of connections, it is expected that different dissipative behavior is found, and this justifies the experimental research work that has been carried out in the last years on different timber frame systems [2,9,12–17]. Scarcer works are available from a numerical point of view. Kouris and Kappos [18] performed non-linear numerical analyses on traditional

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Fig. 1. (a) Frontal walls in (a) Pombalino building (© Stellacci) and (b) timber-framed house in York, UK, XVI century (© Poletti).

Portuguese half-timbered walls, first performing a detailed modelling of a wall, considering non-linear properties for the materials and modelling the contacts in timber elements and subsequently creating a simplified model using beam and link elements. Quinn et al. [9] modelled traditional Peruvian timber frame walls adopting semi-rigid spring elements to model the mortise and tenon connections of the wall. The springs were calibrated based on experimental results by using the components method, which is an analytical method that allows to calculate the joint stiffness assuming a semi-rigid model taking into account all the components of the loads (normal, shear and bending) [19]. Ceccotti and Sandhaas [20] used a hysteretic law to analyse the behavior of traditional timber frame walls. In the numerical model, the walls are represented by lumped masses and rotational springs and rigid elements represent the timber elements, being the global cyclic behavior of the wall given only by the behavior of the springs. For modelling a traditional Pombalino wall, Meireles et al. [16] introduced an analytical hysteretic law in a finite element software to describe the connections represented by means of spring elements. A macro-element was then developed to represent the frontal walls inside a masonry building. The hysteretic law was also implemented in an existing finite element model for other timber frame structures [21]. The use of hysteretic models can also be found for modern timber frames [22].

Due to the high computational cost of modelling a full-scale building using detailed nonlinear finite element analysis it is of paramount importance to have calibrated simplified nonlinear beam models to accurately represent structural elements. The advantage of such a model is that nonlinearity is confined to point hinges (lumped plasticity approach) that, once calibrated using plastic axial springs for a wall panel, can then be extrapolated for full-scale analysis of a real structure [18]. This type of model is capable of capturing the nonlinear response of the system, but the calibration of the connections is important to develop more realistic global behavior. A software that can incorporate various material models for the behavior of individual connections is necessary.

Following an experimental research carried out on the in-plane behavior of timber frame walls characteristic of Pombalino buildings [12], it was decided to define a numerical model on OpenSees platform [23] that describes appropriately the experimental results and that after this enables to evaluate the influence of some parameters in the in-plane response of the traditional walls. Open System for Earthquake Engineering Simulation (OpenSees), developed by F. McKenna and G. L. Fenves with many other contributors at the NSF sponsored Pacific Earthquake Engineering (PEER) centre, is an object-oriented framework for simulating applications in earthquake engineering using finite element analysis [23]. It has the capability of performing many types of analysis including static push-over, static reversed-cyclic, dynamic time-series, and uniform or multi-supported excitations for inelastic time-history analysis for both structural and geotechnical systems. There exists a number of uniaxial-material, section and element models available as part of the OpenSees database. The database contains models for typical materials such as steel/reinforcing steel, concrete, elastic and elastic-plastic uni-axial materials, as well as other particular models including *hysteretic* models (Pinching4 model). It has great potential for timber modelling and various works can be found on such field. The OpenSees platform was recently used to analyse CLT wall panels under in-plane cyclic loading [24] and to model CLT mechanical connections under cyclic loading and compare the results with analytical models [25].

In the present work, different numerical approaches with different level of complexity were tested to describe the in-plane cyclic behavior of timber frame walls being their performance evaluated through the comparison with experimental results available. In addition, a study is provided assessing the influence of geometric parameters in the in-plane behavior of timber frame walls.

2. Brief summary of experimental results

To study the seismic response of traditional Portuguese timber frame walls, under quasi-static in-plane cyclic tests were performed on real scale specimens [12]. Half lap joints were used for the connections between the elements of the main frame, while the diagonals were simply nailed to the frame (Fig. 2). The walls were tested under two levels of vertical pre-compression, being it applied on each post (25 kN or 50 kN per each post), representing the condition encountered on site (Fig. 3). Additionally, different infill solutions were tested, namely brick masonry, lath and plaster and no infill. In general, the walls showed a good load capacity and deformation ability. Results greatly varied depending on the level of vertical pre-compression and on the presence of infill, which could alter the response of the wall from a shear to flexure (Fig. 5b).

Furthermore, in-plane cyclic tests and cyclic pull-out test were carried out on traditional joints with and without strengthening [26]. The selected joint was the one at the base of the wall, the half-lap tee-halving joint, since post uplifting had such a great influence on the response of the wall. Diagonal elements were not considered (Fig. 4). For the in-plane cyclic tests, two vertical loads were adopted, as done for the wall tests (Fig. 4). From the results, it was apparent the main factors influencing the capacity of the joint were the presence of gaps and defects in the wood (knots and fissures), as they would constitute preferential paths for failure [12] as well as the type of strengthening and its ductility.

From the experimental campaign on timber frame walls (cyclic testing) [12] and traditional half lap connection (pull-out and cyclic testing) [26], the following observations could be deduced: