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A practice-oriented model for pushover analysis of a class of timber-framed masonry buildings

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ABSTRACT

Timber-Framed (TF) masonry is a structural system characterised by high complexity and diversity. Limited experimental and analytical research has been carried out so far to explore their earthquake response, partly due to the complexity of the problem and partly due to the scarcity of TF buildings across the world. Here, a new practice-oriented non-linear (NL) macro-model is presented for TF masonry structures, based on the familiar diagonal strut approach with NL axial hinges in the struts. The constitutive law for the hinges (axial force vs. axial deformation) is derived on the basis of an extensive parametric analysis of the main factors affecting the response of TF masonry panels subjected to horizontal loading. The parameters studied are related to the geometric features of the panel and the strength of wood as well as the connections of the timber elements. The parametric analysis is performed using a micro-model based on Hill-type plasticity and it is shown that in the studied X-braced walls the masonry infills do not make a significant contribution to the lateral load resistance. Empirical expressions are proposed for the yield and maximum displacement and shear of a horizontally loaded TF panel. The model is verified against available experimental data, and is found to capture well the envelopes of the experimental loops. The model is readily applicable to NL static analysis (pushover) analysis for the assessment of the lateral load capacity of TF masonry buildings, as the number of input parameters for deriving the constitutive law has been limited to only five.

1. Introduction

The last decade has witnessed an increased interest in TF structures, stimulated by reports on their relatively good performance during recent earthquakes. An interesting example are the 1999 Izmit and Ducze earthquakes in Turkey for which it has been argued [1,2] that TF masonry buildings performed better than not only conventional Unreinforced Masonry (URM) buildings, but even Reinforced Concrete (RC) buildings poorly detailed for seismic resistance. Indeed the implementation of a timber truss in the brickwork has its origin in the effort to tackle URM inefficiency against seismic loads. This truss that dates back to the 16th century B.C. in Greece [3] is sometimes so strong that TF structures are more of a timber structure than a URM one [4]. Using an X-bracing in a TF infilled panel (Fig. 1) diminishes the role of masonry infills and lateral loads are carried by the main structural system which is the timber truss. From the ancient construction to contemporary TF systems such as those found in Pombalino buildings [5] a large variety of TF masonry walls is encountered, a key difference being the configuration of the wooden elements; herein the focus is on the bracing that is most effective for lateral load resistance, i.e. the cross-inclined diagonal (X-bracing).

1.1. Overview of available test results

Experimental research on this structural system has been quite limited, characterised by a growing interest in the last few years. It started in Portugal in 1997 [6]; this first experimental campaign involved three specimens extracted from an existing building in the historic centre of Lisbon. These TF walls were one storey high (3.5 m) and consisted of six X-braced panels. All joints between timber members were realised through iron nails and traditional carpentry joints that involved overlapping of the respective members; the diagonals were joined to the surrounding frame solely through nails, without any carpentry configuration. The walls were subjected to horizontal reversed cyclic loading at the top beam

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(without vertical load) and developed considerable ductility and energy dissipation capacity. Another finding of that research was that the initial elastic phase of the response was very brief, its end marked by un-nailing of the diagonals from the surrounding frame. Failure of TF walls was due to degradation of the frame, including partial out-of-plane failure of the masonry infills.

Recently, another series of TF walls were tested, also in Portugal [7]. This experimental research involved three large-scale specimens constructed in the laboratory that were shorter (2.6 m) than the ones taken from the old building. Joints were constructed as close as possible to those found in old buildings. A specific cyclic loading protocol appropriate for timber structures was used [8] involving both horizontal and vertical loading. Failure occurred due to out-of-plane falling of masonry infills and buckling of the diagonals. Test results confirmed the high displacement and energy dissipation capacity of TF walls; they also illustrated the pinching effect due to un-nailing of the diagonals and sliding of the masonry infills. Meireles et al. [7] have also observed early detachment and low influence of masonry infills in the overall response of the TF walls.

Another experimental investigation, also conducted in Portugal, involved seven TF panels (1 m^2) with diagonal braces [9]. Materials and construction techniques were similar to the previous test but with a view to rehabilitation and fast cure of masonry; to this end, cement-based mortar was used. The testing protocol was also similar. That study reconfirmed the key role of the diagonals and the early detachment of the masonry infills from the surrounding frame. Another interesting conclusion was that diagonals in tension separated from the surrounding frame at very small horizontal displacement. The authors suggested that the contribution of the infills should not be taken into account in analytical models.

Again, a cyclic horizontal force was applied and a constant vertical load to three full-scale walls (3 m long and 2.5 m high), each including 16 X-braced TF panels [10], a configuration common in areas of India and Pakistan (where the tests were carried out). However, joints were constructed using a different technique the mortise (groove) and tenon scheme, supplemented with mild steel nails, commonly used in TF structures in these areas, which is highly dependent on the axial load of the columns. The conclusions drawn are generally similar to those of the Portuguese researchers, i.e.: (a) highly NL response of the walls with separation of the connections under tensile stress, (b) minor contribution of the masonry infills to lateral stiffness and strength but rather important contribution to energy dissipation, and (c) rocking response due to the mortise and tenon joints.

1.2. Overview of available analytical models

Simplified models for TF structures have been confined so far mainly to elastic ones. The progressive removal of the failed elements from the model proposed by Cardoso et al. [11] is an approximate procedure, not particularly accurate in the estimate of displacements and not particularly convenient for every-day analysis since multiple runs with changing models are required; however, it has the advantage that there is no need for a proper non-linear model. Masonry infills were ignored in the simulation and diagonal struts were assumed pinned at the connections and carrying compression only.

A similar approach is suggested by Vintzileou et al. [12] focusing on possible variations of the damaged structure and the collapse mechanism; it suffers from the same disadvantages regarding displacements. A distinction is made regarding the connections of timber elements; rigid connections are assumed between timber posts and beams, while the diagonals are taken as pinned to the surrounding timber frame.

Fig. 1. TF panel with two diagonal braces subjected to a horizontal force.

Similarly, Ferreira et al. [9] assumed carpentry joints to be rigid and diagonals to be pinned at the connections. These authors presented a model comprised of beam, strut and plane elements. However, they found rather unrealistic results when they included masonry infills in the model, and decided to finally exclude them. A trial and error modification of the stiffness of the diagonals was deemed necessary to achieve reasonable match with test results. A high modification factor (over 35) was proposed for reducing the axial stiffness; it should be noted that this modification factor applies specifically to the series of specimens considered in the study.

A NL macro-model was proposed by Ahmad et al. [10] for the previously described type of TF that is found in parts of Pakistan and India on the common lumped plasticity beam-column elements. Despite observing in their tests that inelastic deformation occurs mainly in the diagonals, they assigned NL hinges only to timber posts, while beams and diagonals were assumed to behave elastically. The inelastic law of the NL hinges involved both moment-rotation and axial force-axial deformation. The moment-rotation law was based on a bilinear approximation of the flexural strength vs. deformation curve of URM walls. The axial force-axial deformation law was also a bilinear approximation, this time of the axial strength vs. deformation curve of the timber posts. Based on test results they proposed two versions of their macro-model, a bilinear and a trilinear one, whose properties were defined through calibration against experimental results. Therefore, the use of this model is restricted to the type of walls studied in [10].

Another macro-model appropriate for response-history dynamic analysis of historic TF structures consists of a hysteretic model for the joints between posts and beams [13]. This model was initially developed for modern timber shear walls sheathed with plywood board (see for example [14]) and later adopted to traditional TF walls. This model excludes masonry infills and takes them into account indirectly, through the rotational springs that simulate the pinching effect during the reversal of the load direction. A methodology applied in six steps can estimate the maximum PGA that a structure can sustain and the behaviour factor q, provided that experimental results for TF walls are available to calibrate the model. A hysteretic model with exponential ascending and descending branches has been used for the analysis of traditional TF structures [7] although it has been originally developed for modern timber shear wall (see for example [15]). A step-by-step procedure for the calibration of the parameters of the hysteretic model has also been proposed [16].

Masonry infills are considered rigid and a set of elastic springs join the blocks to the timber structure to simulate the friction in an investigation of TF stone masonry walls without diagonals [17]. The mechanical characteristics of the materials are defined