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Original article

Detailed and simplified non-linear models for timber-framed masonry structures

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ABSTRACT

The need for improved methodologies to describe the post-elastic behaviour of existing structures in the framework of seismic vulnerability assessment has long been recognised. The study presented herein deals with the non-linear seismic response of timber-framed (T-F) masonry structures, such as those found in traditional edifices of cultural heritage. T-F masonry generally consists of masonry walls reinforced with timber elements, including horizontal and vertical elements, as well as X-type diagonal braces. Since the Bronze Age T-F buildings were common in regions where moderate-to-strong earthquakes were frequent. There is ample historical evidence that the embodiment of timber elements in masonry walls is closely related to earthquakes. The paper focuses on the description of the seismic response of T-F structures by means of a detailed analytical model. Although elastic analysis can adequately identify regions with high stresses, it fails to capture the redistribution of stresses and the ensuing failure mechanism. The simulation of T-F masonry is made here using a plasticity model. Non-linear laws for the materials, such as a trilinear stress-strain curve for monotonic loading of timber and a Mohr-Coulomb contact law for wooden members, are used to express their behaviour under moderate and high stress levels. An associated flow rule is assumed and Hill's yield criterion is adopted with isotropic work-hardening. Masonry infills are not included in the model due to their insignificant contribution after the initial elastic stage of the response. The proposed finite element model is intended for a detailed non-linear static analysis of parts of a building. A simplified model using beam and link elements with non-linear axial springs is also developed, which is appropriate for 2D non-linear analysis of common buildings. Both models are validated using experimental results of three T-F masonry walls obtained from the literature. Finally a non-linear static analysis of the façade of an existing building situated in the island of Lefkas, Greece is performed.

1. Introduction

The current trend in seismic risk analysis and loss estimation involves the use of fragility curves derived from non-linear static or dynamic analysis of representative structures. For many kinds of structures, such as reinforced concrete or steel buildings, modelling is rather straightforward, whereas for others like unreinforced masonry structures, it presents more of a challenge. For some structures like the T-F masonry buildings studied herein, very little progress has been made so far with regard to the modelling of their non-linear response. However, there have been several studies using elastic models for the static and/or dynamic analysis of these structures. Some of them assume that diagonal timber elements are capable of resisting bending moments [1,2], while others consider timber diagonals as axially loaded bars pinned at their ends [3,4], or a combination of these [5]. Elastic analysis is a useful tool for identifying regions with high stresses, but often fails to capture the final failure mechanism, that may be substantially affected by stress redistribution. The work presented here involves a plasticity-based finite element model for the analysis of T-F masonry structures. The proposed model is applied to the analysis of three T-F masonry walls for which experimental data are available.

Unreinforced masonry suffers from low tensile strength and low ductility. Strengthening of masonry structures against earthquakes dates from the ancient times. A technique put forward was the use of T-F masonry, which has been utilised even in the Bronze Age in Greece [6–8] and in the early Roman Times [9] in regions of high seismicity. Their presence and development is closely related to earthquakes.

Buildings of timber-framed masonry display quite varied typologies with regard to the timber elements. Although a historical overview of several common T-F masonry typologies is given in the next section, this paper focuses specifically on timber-framed masonry structures situated in earthquake-prone areas, whose main feature is the presence of lateral-load-resisting diagonal

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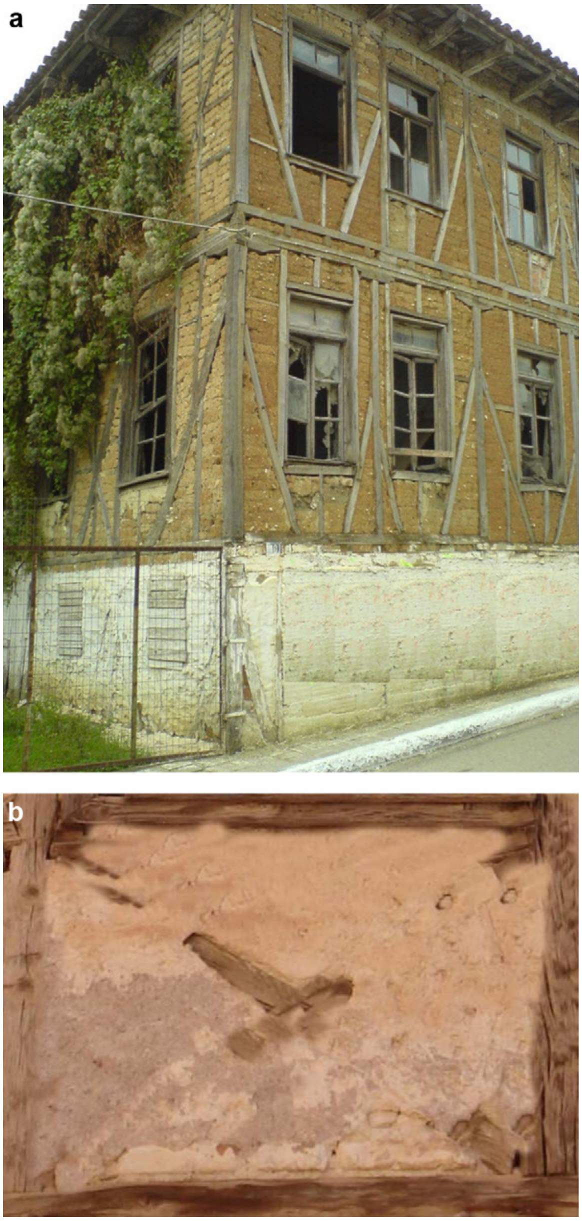

Fig. 1. Examples of T-F structures: a: building situated in Macedonia, Greece; b: a regular plane frame of T-F masonry including diagonal bracing.

members (Fig. 1a). A common building of this type is composed of a spatial (3D) timber frame and the infilled masonry. The 3D timber frame consists of horizontal and vertical elements, and X-type diagonals. The structural system is formed of panels of timber-framed masonry with strong connections to each other in both directions and to the horizontal diaphragm. The two diagonals of such a panel form an X-type brace (Fig. 1b). Sometimes there is a more complex configuration of the basic panel with more diagonal braces (Fig. 1a). Timber connections are made by means of iron nails and ties; however, these elements are usually very deficient due to their rather low resistance to corrosion.

The developed planar finite element model of T-F masonry is intended for panels and walls. An important factor in the performance of the walls is the presence of weak, rather than strong, mortar. This compensates for the incompatibility between rigid masonry panels and the flexible timber frame. The low-stiffness mortar can accommodate deformation along the bed/head joints, leading to sliding instead of cracking through the masonry units when the masonry panels are subjected to horizontal displacements. This behaviour is quite different from that of masonry infills effectively connected to the surrounding frame (a rather common case in masonry-infilled reinforced concrete frames) which would initially attract a substantial amount of the lateral (seismic) force and dissipate significant energy, but subsequently suffer significant strength and stiffness degradation due to their low deformability. Thus, T-F masonry buildings can effectively resist moderate-to-strong earthquakes, albeit with some cracking; this performance during an earthquake is manifested by the cracks at the interface between bricks and wooden frame that could lead to crushing of the brick infill at the corners of the wooden frame. This type of failure has often occurred in these buildings during recent earthquakes. Detailed descriptions of damage in T-F masonry structures during earthquakes that occurred in the past decade are given in the literature [2,10–14].

Weak masonry infills are not directly included (except for their weight) in the model presented in the following, since, as discussed previously, their contribution in carrying seismic loads is of minor importance in the post-elastic range, particularly with regard to the stiffness and the ultimate strength and deformation of the T-F panel. Nevertheless, their effect is indirectly taken into account by assuming that they prevent timber braces from buckling. This treatment of masonry infills is in line with previous studies [3] and its main ramification is that it leads to lower stiffness during the elastic range of the response when all structural components are in some form of contact. As the lateral loading increases, and given the low efficiency of the metal joints, the infills gradually separate from the surrounding timber members and their contribution to the lateral load capacity becomes negligible. Masonry infills could be included in the analysis through proper interface models [4], but given that the present study focuses on the post-elastic behaviour of T-F masonry structures, wherein disengagement from the timber frame has already occurred, the accuracy resulting from this refinement of the model is not deemed to counterbalance the substantial increase in complexity and computational cost.

Due to their directional properties, the wooden elements can be accurately modelled as an orthotropic material. In traditional structures their mechanical parameters are difficult to determine and have a significant variability, mainly due to varying degrees of deterioration. The values adopted in the examples presented here refer to pine timber according to EN338 [15]. An appropriate interface model is adopted for the description of contact between timber braces and posts; an asymmetric contact element is chosen for the modelling of the interface. The proposed model is validated against the results of laboratory tests performed at LNEC, Lisbon [16]. These specimens are modelled using the ANSYS finite element package [17] according to the proposed method.

2. Brief overview of the history of timber-framed masonry

Remains of timber-framed masonry buildings date back to the Bronze Age. Remains of T-F masonry in Greece from that era consist of one timber framework on each face of the thick masonry wall, the two of them sometimes being linked together. This type of structure was occasionally used (as a rule, not throughout the building) in Minoan Crete [6], Mycenae [8] and the island of Thera [7]. All these areas are of high seismicity, moreover the island of Thera was an active volcano at that time. Wooden framework techniques often have simple technology and are more commonly used in multistorey structures. A few horizontal and/or vertical timber members were embodied into rubble-stone walls (Fig. 2). Timber reinforcements within masonry walls are only found in critical parts of the building. Sometimes, horizontal timber components