Engineering Structures 80 (2014) 501–513

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Numerical study on the performance of improved masonry-to-timber connections in traditional masonry buildings

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A R T I C L E   I N F O

Article history:
Received 3 March 2014
Revised 4 August 2014
Accepted 16 September 2014
Available online 7 October 2014

Keywords:
Masonry
Injection anchors
Tensile strength
Numerical analysis

A B S T R A C T

This paper deals with a numerical study on the structural performance of masonry-to-timber connections in ancient buildings. The work is supported on an experimental campaign carried out at University of Minho, which aims at characterising a strengthening solution based on the use of injected anchors for the improvement of the connection between masonry and timber frame walls. The numerical study resorts to a detailed 3D finite element model, which reproduces the experimental test setup and procedure. The modelling approach adopted allows an accurate characterisation of the behaviour of all structural elements, in terms of stress field and displacement distribution. The 3D model was validated against the available experimental results, which was then used to perform parametric analyses in order to evaluate the influence of key parameters. Finally, simplified analytical approaches to estimate the strength capacity of injected anchors on masonry are presented and discussed.

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1. Introduction

Most Portuguese traditional buildings (in which the Pombalino buildings are included) are made of unreinforced stone masonry walls and flexible timber diaphragms, with the exception of a few cases in which the timber floors and roofs provide efficient in-plane stiffness [1]. Given its widespread presence worldwide, recent seismic events have emphasised the great vulnerability of the majority of these masonry buildings, mostly due to the lack of effective connections between elements [2]. Evidence from the recent 2011 New Zealand earthquake, among many others, confirmed that out-of-plane wall collapse was one of the main collapse mechanisms observed in masonry buildings, which is strongly dependent on the connection quality [3]. When not properly connected to the roof, floors and perpendicular walls, a masonry wall can easily become unstable and collapse out-of-plane, compromising in this manner the global capacity of the structure. When walls are seismically excited in their plane, the excitation has generally a small amplification because of the large stiffness and low natural period. On the contrary, walls subjected out-of-plane present a quite large seismic amplification, due to their low stiffness and high natural period.

Hence, the structural performance of traditional masonry buildings to seismic actions depends on their capability to redistribute the horizontal loads between the vertical elements, which allows exploring in-plane strength of the walls at its maximum and preventing local out-of-plane mechanisms. Assuming that the quality and state of conservation of vertical elements is good and that the horizontal elements have enough stiffness to redistribute horizontal actions, the building global performance is greatly influenced by the effectiveness of the connections between vertical elements and between vertical and horizontal elements. If these connections are ineffective, a box-like behaviour cannot be achieved and the building may collapse under the effect of low seismic excitations by developing local mechanisms.

Bearing in mind the typical structural organisation of traditional masonry buildings, the capability of the structures to redistribute horizontal loads depends on the connection between orthogonal walls, the flexibility of the diaphragms and their connection to the masonry walls [4]. The combination of effective connections and floor diaphragms, stiff enough to redistribute the horizontal actions through in-plane walls, provides the so called "box behaviour" to the building, which usually leads to a good performance of the structure when subjected to horizontal actions [5,6].

The seismic response of masonry buildings to past earthquakes showed that the strengthening of connections between structural components (walls and floors) can enhance the global seismic performance in a significant way. Senaldi et al. [3] present some

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http://dx.doi.org/10.1016/j.engstruct.2014.09.027
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successful examples of retrofitted masonry buildings that survived the recent 2011 NZ earthquake without suffering major damage. It was observed that the strengthening of connections using anchoring systems and the insertion of steel tie rods at floor and roof levels proved to be effective in preventing local out-of-plane collapse of walls under seismic events.

The performance of connections in masonry buildings has been studied by a few authors, either evaluating the behaviour of a single connection or analysing the effect of connections on the global behaviour of a building. For example, the use of steel to strengthen ancient masonry buildings has been observed since the 1920s [7]. On the other hand, a dissipative device to improve the connection of perpendicular walls was recently proposed by D'Ayala and Paganoni [8]. Some examples of traditional and innovative strengthening solutions for connections can be found in [2,9,10].

Injected anchors are well suited to repair and strengthen ancient masonry buildings as they allow for an effective connection between perpendicular walls, thus avoiding overturning of walls excited out-of-plane and activating the relatively stable in-plane behaviour of adjacent walls, without changing the appearance features of the building. Investigations on the behaviour of anchors injected in concrete have been extensively documented and several models have been proposed in the literature for determining the failure load. However, scarce research has been conducted on anchors applied to masonry [7,11–18], and for this reason the knowledge concerning the behaviour of anchors in masonry is very limited. Moreover, field observations made during the recent New Zealand earthquakes revealed inadequate behaviour of anchor connections, mainly attributed to the low strength of masonry, wide anchorage spacing and/or insufficient embedment depth of anchors in some cases [19]. Experimental and numerical studies in this field are required for a clear characterisation of the structural behaviour of these anchoring systems, as well as necessary for the development of standards.

This paper presents a detailed numerical study based on the use of injected anchors for the strengthening of masonry-to-timber connections. In a first step, the numerical model was validated against existing experimental results obtained at University of Minho. Subsequently, parametric analyses were then carried out aiming at evaluating the influence of key influencing parameters on the behaviour of the strengthened connection. Finally, analytical relationships to estimate the maximum force that an injected anchor in a masonry wall is able to carry were revised and compared against the numerical and experimental results.

2. Experimental behaviour of anchoring systems

2.1. Potential failure modes

The anchoring system considered here consists of a steel element inserted in a core made in a masonry wall filled with grout. The load transfer between the steel element and the surrounding masonry comprises two interfaces: the outer interface between masonry and grout, and the inner interface between grout and the steel element. Experimental results indicate that the main factor limiting the capacity of the anchoring system is usually not the failure of steel or the steel/grout interface, but rather the somehow reduced shear and tensile strength of the masonry substrate to which the anchor is injected [17].

Still, the possible failure modes experimentally identified for injected anchors in masonry are similar to the ones found for anchors in concrete [11–15,20]. When subjected to tensile loading, injected anchors in masonry may exhibit the following failure mechanisms (see also Fig. 1):

- Steel tensile failure: the anchor is loaded until the yielding of steel (Fig. 1a).
- Masonry cone failure: shear cone-like surface failure that occurs in the masonry with detachment of a small part of the wall around the anchoring system (see Fig. 1b).
- Sliding failure along the outer interface: sliding of the anchoring system by failure at the masonry–grout interface (outer interface) with the disconnection of the anchoring system from the wall (see Fig. 1c).
- Sliding failure along the inner interface: sliding of the steel anchor along the steel–grout interface (inner interface), involving local failure (see Fig. 1d).

Although the four individual failure mechanisms are possible, steel failure is rarely observed and takes place only in cases when the embedment depth and strength of the masonry are very high. A combination of two different failures was also observed experimentally [15,17]. Usually, the masonry cone failure occurs with the presence of the cone formation simultaneously with sliding (also called bond failure) along the outer interface.

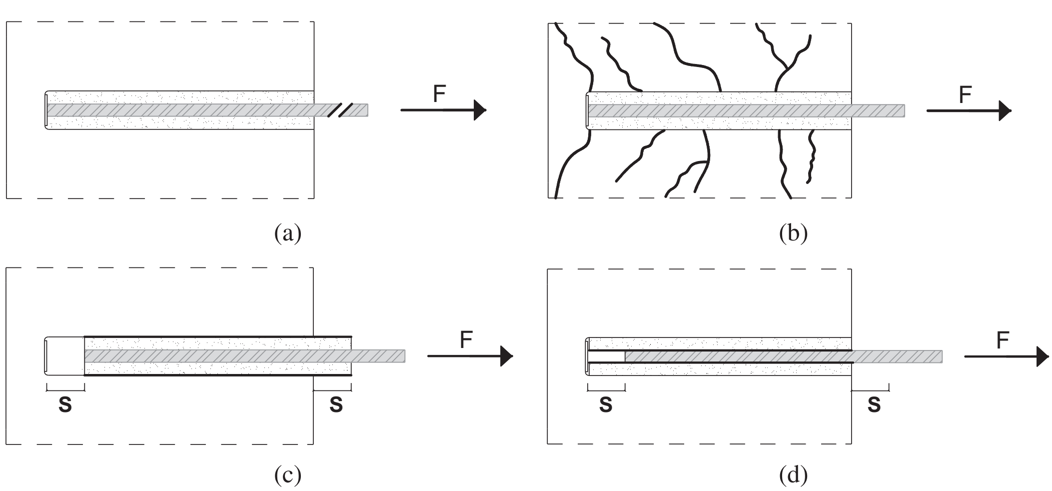

Fig. 1. Possible failure mechanisms in anchoring systems: (a) steel failure; (b) masonry cone failure; (c) sliding failure along the outer interface; (d) sliding failure along the inner interface.

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