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Experimental behavior of masonry wall-to-timber elements connections strengthened with injection anchors

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ABSTRACT

Out-of-plane failure mechanisms observed in stone masonry buildings subjected to seismic action are often a direct result of poor connections between structural elements. During a seismic event these weak connections become incapable of assuring proper load transmission. Therefore, the need to prevent these phenomena is of critical importance in understanding the behavior of unstrengthened masonry buildings along with the necessity of developing effective strengthening solutions. This paper presents injection anchors as a viable option to improve anchorage between masonry and timber elements on historical buildings, as for example wall-to-timber framed wall or wall-to-timber diaphragm connections. The experimental campaign consisted of quasi-static monotonic and cyclic pullout tests performed on real scale specimens, representative of wall-to-timber framed wall connections found in late 19th century buildings of downtown Lisbon, Portugal. Combined cone-bond failure was obtained in all 7 tests. Boundary conditions of the specimens greatly affected the results in terms of maximum pullout force, dissipated energy, and strength degradation. Displacement ductility of the strengthened connections is high. The force–displacement curves clearly pointed out the influence on the results of the wall's compressive stress state and the contribution of friction in the grout/masonry interface.

1. Introduction

Since the late 1970s, several seismic tests have been carried out to understand the dynamic behavior of unreinforced masonry buildings [1,2]. A limited number of experimental campaigns have also been performed to investigate various strengthening techniques [3]. However, little research has been carried out in the past decades to characterize the behavior of connections between masonry walls and timber walls or floors [4,5]. Post-earthquake surveys of recent events—e.g. Azores 1998, L'Aquila 2009, and Christchurch 2011—show that out-of-plane collapse failures are the most common failure mechanisms in masonry buildings [6]. Although being a local mechanism, it can cause irreparable damage to culturally significant buildings or even compromise the overall stability of a structure. The absence of appropriate structural connections is known to be one of the main factors contributing to the activation of this type of failure mechanism [6]. Thus, there is a need to understand the unstrengthened behavior of these connections so that the characteristics of a strengthening solution can be determined to prevent the formation of out-of-plane mechanisms.

In spite of the fact that it provides a contribution to the behavior of steel anchors in traditional stone masonry walls, this study focuses on masonry wall to timber framed wall connections, specifically those found in buildings constructed after the 1755 earthquake that severely damaged the city of Lisbon, Portugal. From the immediate reconstruction period until 1930, several types of masonry and timber buildings were erected. The quality of materials and construction techniques decreased considerably over time, declining in quality from the so-called 'Pombalino' buildings to the 'Gaioleiro' buildings [7,8].

Initially, the so-called 'Pombalino' buildings had half-timbered walls that were part of a flexible three-dimensional timber frame (called 'gaiola' or 'cage'), which was an engineering innovation designed to decrease seismic vulnerability [1]. The timber frame of the half-timbered walls—consisting of vertical, horizontal, and diagonal members in a St. Andrews cross pattern—increased resistance to horizontal loading and effectively dissipated energy. The frames were completed with brick or rubble masonry infill, which increased their mass. For the 'Gaioleiro' buildings, the half-timbered walls disappeared giving place to simplified timber framed walls or even just lath and plaster walls.

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The external and party walls of the first 'Pombalino' buildings were of limestone rubble masonry with constant thickness between 0.50 m and 0.70 m, while the ones from the 'Gaioleiro' buildings varied in thickness along the height of the building. These walls were built stone by stone, arranged in the best way possible with all voids filled with mortar. The mortar was a mixture of air lime and sand, usually in the proportion of 1:2, but other ratios like 1:2.5, 1:3 or 5:9 were used as well [9]. Existing historic material descriptions specify that the sand should be of good quality and from a specific place of pine trees, probably referring to the Leiria region, in the central part of Portugal. They also prescribed that the stone should be soft (like limestone), of good quality, and should come from Monsanto or Sacavém, as described in records found in the Municipal Archive of Lisbon. Several authors suggest that the compressive strength of irregular masonry with a poor mortar, with the ratios suggested before, should be in the ranges from 0.8 MPa to 1.5 MPa [10] or 0.5 MPa to 1.0 MPa [8]. The elastic modulus should be in the range from 700 MPa to 900 MPa [10].

Different types of wall-to-timber framed wall connections have been described in literature, as shown in Fig. 1. The connection varies according to the amount of timber elements inside the wall and their anchorage length, relying mainly on friction to ensure the connection. Connection types C1 to C5 are common in 'Pombalino' and Late 'Pombalino' buildings, where the three-dimensional timber cage was the main concern. In 'Gaioleiro' buildings, where timber framed walls (or a degraded version) still exist, connection type C6 is commonly found. In this type of connection, the timber framed wall leans against the masonry wall, leaving only the floor joists to maintain the continuity of force distribution [11].

Silva [12] describes some *in situ* pullout tests carried out on connections from type C1 to C5 in a 'Pombalino' building. No information is provided about anchorage length, the story where the connection was found, or any other significant details. However, the pullout horizontal forces obtained in the tests ranged from 1.5 kN to 6 kN. Such a limited capacity contrasts with the resistant capacity of the masonry and half-timbered walls, suggesting the necessity of strengthening solutions to improve load transfer between both structural elements. This is critical since this type of connection connects elements with very different stiffnesses, strengths, and therefore behaviors. The masonry wall, with a much larger stiffness and mass, dictates the out-of-plane behavior. Thus, it is necessary to anchor the flexible timber frame to the masonry in order to expect effective resistance to out-of-plane failures during a seismic event.

In the design and analysis of masonry structures, connections are usually considered to describe one of the two extremes conditions of rigidity: fully constrained (fixed) or pinned. Elements can be mechanically connected in so many ways that often these simplifications do not reflect the true structural response. Recent studies conducted in 'Pombalino' and 'Gaioleiro' buildings have shown that the consideration of these two extremes has a significant impact on the numerical results and, consequently, on the assessment of buildings' seismic vulnerability [5,13].

Most strengthening solutions for connections between timber elements and masonry walls are force designed and rely on anchoring systems like tie rods with anchor plates bolted to the timber elements by means of steel angles, as shown in Fig. 2a [14]. Pinho [8] and Mascarenhas [7] refer the use of similar anchor systems in 'Pombalino' buildings on connections between masonry walls and floor joists. Another possible anchor system is injection anchors, which have been applied in masonry since the 1920s in Germany [15]. The installation of injection anchors is advantageous in comparison to tie rods and anchor plates since injection anchors require access from only one side of a wall, which facilitates interventions on façade and party walls.

The present study focuses on the solution proposed by Silva [12], which consists of a pair of injection anchors placed in pre-drilled holes in a masonry wall. The timber framed wall goes between the parallel injection anchors so that a symmetrical behavior can be explored (see Fig. 2b). The injection anchor itself is a steel rod inside a woven polyester based tubular sleeve, provided by the company Cintec®. It is placed in a pre-drilled hole and injected, under low pressure, with a cementitious grout. The sleeve can expand to suit the diameter of the borehole, which can vary according to the steel bar diameter, and control the flow of grout into voids. The distance between anchors can vary according to the thickness of the half-timbered wall and the steel gusset plates. These plates are bolted to both sides of the half-timbered wall, usually at the intersection of the different timber elements of the cross (vertical, horizontal and diagonal), so that they work as a double shear connection. This strengthening application tries to respect the concept of "minimum intervention" required for historical interventions. Although focus is given here to the

Fig. 1. Different type of wall-to-half-timbered wall connections (adapted from Cardoso [11]).

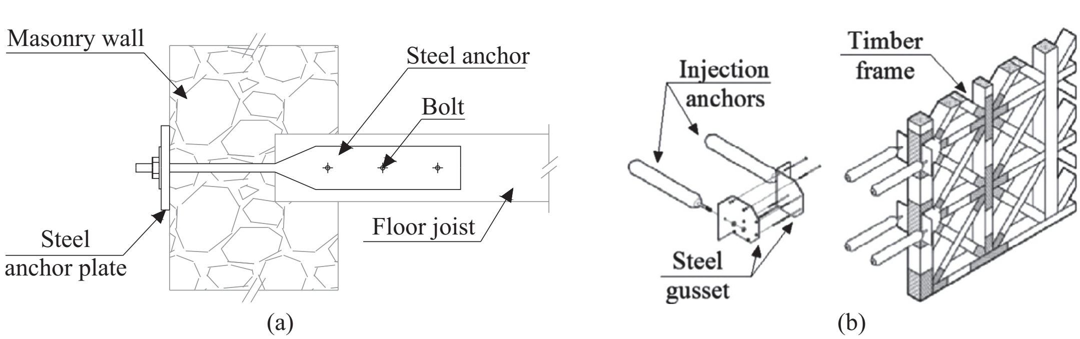

Fig. 2. Strengthening solutions: (a) anchoring floor joists to masonry walls with steel ties with anchor plates (adapted from [14]); (b) anchoring half-timbered walls to masonry walls through injection anchors [12].