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Experimental seismic performance assessment of asymmetric masonry buildings

Leonardo Avila[a,*], Graça Vasconcelos[b], Paulo B. Lourenço[b]

[a] VSL, Singapore

[b] ISISE – Institute for Sustainability and Innovation in Structural Engineering, Department of Civil Engineering, University of Minho, Portugal

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ABSTRACT

This paper presents the experimental validation and analyses of a structural constructive system based on concrete block masonry. The system has been proposed as an innovative solution for the construction of residential buildings. In the present study, an asymmetric configuration for the masonry buildings tested at the shaking table was adopted, being considered two buildings (reinforced and unreinforced). The seismic performance of both buildings is evaluated based on global and relative displacements, global damage patterns and failure mechanisms. Additionally, a comparison of the mechanical performance between the two buildings is also provided. Both structures were tested to "near collapse" condition from which it was found the influence of the geometrical configuration and the presence of steel reinforcement.

The reinforced building attained an input acceleration twice the unreinforced building on the weak direction. The structure developed important in-plane and out-of-plane damage mainly at the first level including detachment of units, structural components (wall to wall) and failure of horizontal reinforcement. On the other hand, the damage observed on the unreinforced building was more distributed along the height of the building, is characterized for lower detachment of units but for a clear sliding mechanism at the second level along the cracks at the bed joints.

1. Introduction

From previous seismic events, it has been seen that unreinforced masonry often presents an inadequate behavior to seismic actions, showing extensive cracking and disintegration due to combined in-plane and out-of-plane loadings. This behavior is due to the low quality of materials, namely of rubble stone masonry, and mainly due to inadequate connection between the structural elements, namely between intersecting walls and between masonry walls and floors [22]. If adequate connection between structural elements exist, the premature out-of-plane collapse of masonry walls can be prevented and walls may develop in-plane shear resisting mechanism, ensuring the global stability of the building (Box behavior) [29]. It should be mentioned that most of those catastrophic unreinforced masonry structures were built with low quality materials and low quality workmanship, empiric procedures and without any earthquake resistance regulation guidance for the designers or masons [18].

The seismic behavior of masonry structures has been systematically studied since 1980s [1,29,32]. In spite of the different experimental methods that can be followed to assess the behavior of masonry structures, namely by using quasi-static monotonic or cyclic tests [7,23,34], focused mostly on structural masonry walls, the experimental approach based on dynamic shaking table testing allows to evaluate the global behavior of masonry buildings, enabling a better understanding of the interaction among the different structural elements. Besides, the shaking table device allows the most accurate simulation of seismic events, becoming the best tool for the earthquake resistance evaluation of buildings. In this scope, the dynamic seismic behavior of several construction systems composed of different materials has been evaluated experimentally by shaking table tests [9,14,19,28]. Bothara et al. [8] studied the seismic performance of a symmetric two story brick masonry house with timber floors and roof. The structure was subjected to incremental input motions on a shaking table and both in-plane and out-of-plane behavior were analyzed and related with the failure mechanisms, being the gable walls recognized as the most vulnerable elements. In addition, the influence of diaphragms and of the masonry bond pattern in the global behavior of the masonry buildings was also analyzed. Benedetti et al. [6] developed an enlarged experimental campaign in order to evaluate the seismic response of symmetric masonry buildings. For this, 12 stone and brick

* Corresponding author.
E-mail address: leonavila@gmail.com (L. Avila).

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masonry buildings were subjected to 58 shaking table tests from which performance indexes were obtained and correlated with the damage. From this work, it was concluded that the damage of spandrel beams produces more significant energy absorption than other types of damage. Concerning the use of steel reinforcement, Zonta et al. [35] evaluated the ductility and seismic performance of symmetric plan reinforced masonry buildings (with distinct reinforcing techniques) in an experimental program including 33 shaking table tests. Behavior factors for this type of construction were also provided.

Modern concepts for open spaces and free areas characterize the present architecture design and result in geometrical setbacks (re-entrant corners or edge recesses) and uneven distribution of openings (doors and windows), and hence in asymmetric configurations of the current residential building constructions. This is an issue, particularly in case of new residential buildings, for which architectural demanding is often required. Codes like Eurocode 8 [12] and Eurocode 6 [13] impose some limitations in terms of geometry plan layouts in order to avoid structural complexity and ensure bi-directional resistance and stiffness, including the resistance to torsional efforts. The asymmetry of buildings has been studied in some works from literature. Juhásová et al. [18] performed shaking table tests on an asymmetric one story stone masonry building reinforced with polymer grids in order to assess the influence of the reinforcing technique in the seismic resistance, ductility and control of damage. The seismic response of the original building was characterized by great out-of-plane deformation of walls. It was found that the response of the repaired model exhibit smaller increments of absolute accelerations and relative displacements in comparison with the response of the original model. Bairrão and Falcão [4] carried out experimental shaking table tests on an asymmetric limestone masonry building. The structure presented considerable damage at the bottom of the walls and at the corners of the openings, and the cracking characterized by a random distribution at the joints. More recently Tomaževič and Gams [31] studied the seismic behavior of two asymmetric confined masonry buildings through shaking table tests, having one of the buildings three stories and the other four stories. In both cases, typical shear behavior was observed, with diagonally oriented cracks in the walls at the first story determining the failure mechanism. Both models exhibit good seismic behavior with adequate resistance and energy dissipation. The authors proposed typical design values for displacement capacity and structural behavior factor.

The experimental approach based on shaking table test was adopted in this work to study the construction solution based on concrete block masonry aiming at validating its seismic behavior. In a first phase, two symmetric buildings, one reinforced and one unreinforced, were analyzed [21]. However, given the need to study more demanding geometrical configuration in the sequence of modern architectures, it was decided to extend the experimental analysis on the shaking table to two asymmetric buildings, with similar reinforcement configurations as the ones adopted in the symmetric buildings. Reduced scale buildings were designed to be representative of housing buildings and further tested at the shaking table by a series of incremental input motions so that the global behavior could be evaluated. The main objective of the present paper is to present and discuss the results of the shaking table tests carried out on two asymmetric masonry buildings built with concrete blocks with and without any reinforcing scheme. From the results, it was attained a better insight on the influence of in plan eccentricities on the resistance and deformation parameters of the masonry buildings under seismic actions.

2. Outline of the research work

The research work addresses the seismic performance of a masonry structural system developed for low to medium rise residential buildings. The idea is the proposal of an earthquake-resistant masonry system that ensures good mechanical performance, compatible with economy and simplicity in terms of construction technology. The use of structural masonry, which can be used in the construction market, requires a deeper insight on the seismic behavior of masonry buildings, as many European countries present medium to high seismic hazard.

The experimental validation of the construction system started with static cyclic tests carried out on walls and beams with distinct reinforcing arrangements at the University of Minho with subsequent numerical analysis and a parametric study [16,17]. Those studies provided useful information about the cyclic behavior of masonry walls but validation of the seismic behavior of masonry buildings built with the proposed masonry system solution was still missing. The interaction within connecting elements (i.e. wall-wall and wall-slab), the distribution of stresses, the combination of in-plane and out-of-plane resisting mechanisms and the interaction between structural components can be evaluated only when an entire building is studied. To have a better insight of these issues, shaking table testing of different typologies of masonry buildings were planned in order to assess: (1) the influence of the geometry configuration on the seismic behavior of the concrete block masonry buildings; (2) the influence of the reinforcing system composed of vertical and horizontal truss type reinforcements. In total four masonry buildings were planned to be tested in the shaking table, namely two with symmetric geometry and two with asymmetric geometry. In both cases, addition of a scheme of vertical and horizontal truss type reinforcement was considered. A detailed analysis of the results of the shaking table tests carried out on the symmetric buildings is available in Lourenço et al. [21]. The present paper focuses on the experimental seismic analysis and discussion of results obtained on the two asymmetric masonry buildings tested on a shaking table under similar conditions as the ones considered for symmetric buildings.

3. Brief description of the masonry constructive system

The constructive system for structural masonry under analysis is based on three-cell concrete block units, truss type steel reinforcement (when applied) and modified general-purpose mortar used for both laying masonry units and filling the vertical hollow cells (when reinforcement is added), see Fig. 1a. Typical concrete block masonry units found in the market only present two cells formed by rectangular molds, most of the time without frogged ends. By using these units, the steel reinforcement must be placed in one of the cells allowing for an interlocking arrangement as traditional masonry bond. For the present research project, an innovative modification to the units is proposed, in order to allow for assembly flexibility during construction stage and at

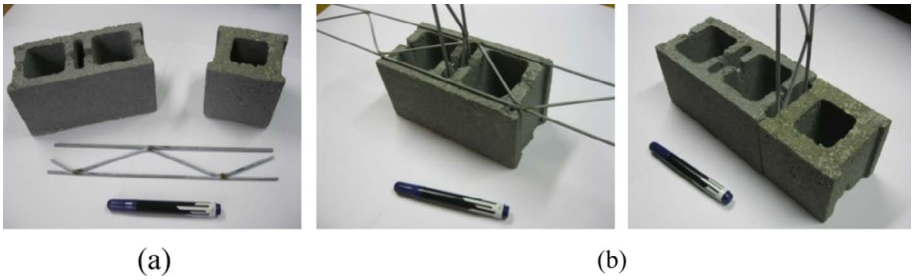

Fig. 1. Details of the constructive system: (a) unit block, half unit block and steel truss type reinforcement, (b) traditional masonry bond and alternative continuous vertical reinforced joints.