Engineering Structures 80 (2014) 137–146

Contents lists available at ScienceDirect

Engineering Structures

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

Sensitivity analysis of the seismic performance of existing masonry buildings

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ARTICLE INFO

Article history:
Received 2 June 2013
Revised 21 July 2014
Accepted 1 September 2014
Available online 18 September 2014

Keywords:
Seismic performance
Masonry
Existing buildings
Numerical analysis

ABSTRACT

This paper presents a sensitivity analysis taking into account possible variations on the features of masonry buildings. The main objective of the analysis is to compare the seismic performance of a typology of buildings in Lisbon as a function of the changes of its properties with respect to a reference model calibrated from experimental tests. The sensitivity analysis was carried out using non-linear dynamic analysis with time integration and using pushover analysis with distribution of forces proportional to the inertial forces of the structure. The deviations on the seismic response were mainly analysed in terms of maximum load capacity and collapse mechanisms. The results show that the Young's modulus of the masonry walls, the Young's modulus of the timber floors and the compressive non-linear properties are the parameters that most influence the seismic performance of this type of tall and weak existing masonry structures. Furthermore, it is concluded that the stiffness of the timber floors significantly influence the strength capacity of the building and the type of collapse mechanism.

1. Introduction

The seismic behaviour of existing masonry buildings is particularly difficult to characterize and depends on several factors, such as the material properties, the geometry, the foundations, the connections between walls and floors, the connections between walls and roof, the stiffness of the horizontal diaphragms or the building condition. Furthermore, "non-structural" elements (partition walls) and their connection to the load-bearing walls can also contribute to the performance of these buildings.

Masonry is a composite material that consists of units and mortar, which had been used for construction of housing and many important monuments around the world. Units can be bricks, blocks, ashlars, irregular stones and others. Mortar can be clay, bitumen, chalk, lime/cement based mortar, glue or other. The huge number of possible combinations generated by the geometry, nature and arrangement of units as well as the characteristics of the joints raises doubts about the accuracy of the term masonry to identify a single structural material.

The strength of masonry depends on the unit and mortar properties as well as on the construction technique. As an example, the compressive strength of stone units may range from values such as 5 MPa (low quality limestone), and even less for tuff, to over 130 MPa (good quality limestone), and even more for granite or marble. The strength of the mortar also presents large variations and depends on the proportion of its components (cement, lime, sand, soil and water) used in the mix [1]. The compressive strength of the mortar of existing masonry buildings can be about 1.5–3.5 MPa [2,3], even if weaker and stronger mortars can be found. Furthermore, the strength and failure modes of masonry are dependent on the loading direction and combination of the loads [4]. Nevertheless, the mechanical behaviour of different types of masonry has some common features: high specific mass, low tensile strength, low to moderate shear strength and low ductility (quasi-brittle behaviour). The specific mass of stone masonry can range between 1700 kg/m^3 to 2200 kg/m^3 [5].

The characteristics of masonry make it a material mainly suitable for structural elements subjected to compressive stresses caused by vertical static loads, such as walls, arches, vaults and columns subject to the self-weight. Masonry properties have a direct influence on the seismic performance of unreinforced masonry buildings and massive damages have been observed in strong seismic events. The inertial forces induce tensile and shear stresses which may lead to the failure of masonry elements and, consequently, to local or global collapse of the building. Detailed information on the mechanical behaviour of the masonry is given in [1,4,6].

The geometrical regularity in plan and in elevation as well as the structural simplicity (well distributed of mass and stiffness)

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http://dx.doi.org/10.1016/j.engstruct.2014.09.005
0141-0296/

improve the seismic performance of masonry structures, preventing local damage and decreasing torsional effects. These criteria, together with requirements for material properties in terms of strength and robustness, and rules for design and detailing are present in modern codes [7–9], aiming at a good seismic performance of masonry buildings in terms of strength capacity and adequate collapse mechanisms. But, existing masonry buildings often present geometric and material properties, which may lead to brittle or non-proportionated collapse mechanisms. The damage generally occurring in unreinforced masonry buildings due to the seismic action are cracks between walls and floors, cracks at the corners and at wall intersections, out-of-plane collapse of the perimetral walls, cracks in spandrels beams and/or parapets, diagonal cracks in structural walls, partial disintegration or collapse of structural walls and partial or complete collapse of the buildings [6]. For more information about the damage occurring in unreinforced masonry buildings, see e.g. [10,11].

The present work presents a sensitivity analysis taking into account variations of the features in existing masonry buildings. The main objective of the sensitivity analysis is to compare the response of the structure, as a function of the change of its properties with respect to the response of a reference numerical model, which was calibrated with an experimental test. The sensitivity analysis was carried out using non-linear dynamic analysis with time integration and pushover analysis proportional with distribution of forces proportional to the mass. The comparison of the response of structure is mainly based on the maximum load capacity and type of damage.

2. Seismic performance of masonry walls and timber floors

Although the seismic performance of unreinforced masonry buildings depends on several aspects, only the seismic behaviour of the masonry walls and of the floors are discussed here. The in-plane behaviour of masonry walls depends on the geometry of piers, spandrels and openings. In what concerns the seismic behaviour of piers, the typical in-plane collapse mechanisms (Fig. 1) are [12–14]:

- Rocking induced by bending, which causes horizontal cracks at the top and at the bottom of the pier. The failure of the pier occurs by overturning of the wall. The failure by in-plane overturning, which occurs rarely, is associated to very slender and slightly loaded piers.
- Sliding associated with horizontal forces at the piers that are larger than the shear strength of the bed joints (low vertical load and low friction coefficient), which is characterized by single full pier width horizontal cracks.
- Diagonal tension, in which the principal tensile stress caused by the seismic action exceeds the strength of masonry and diagonal cracks arise. The cracks can propagate along the bed and head joints or go through the units, depending on the strength of the mortar, mortar-unit interface and unit.
- Toe crushing, which can appear in combination with rocking or diagonal tension. The toes of the piers are usually zones of high compressive stresses and when the principal compressive stress caused by the seismic action exceeds the strength of the masonry, compressive failure (crushing) can occur.

The behaviour of spandrels is similar to the behaviour of piers. However, two aspects have to be taken into account: (a) the axis of the spandrel is horizontal and not vertical as in the piers; (b) the normal stress existing in the spandrels, caused by vertical loads, is much lower than the one in the piers. The first aspect is important for regular masonry, due to the orthotropic behaviour, while the behaviour of irregular masonry is more independent from the load direction. The second aspect has consequences in all types of masonry, as the normal stress has a strong influence on strength. Fig. 2a presents the in-plane behaviour of spandrels subjected to a seismic action, in which shear stresses occur and can lead to them to collapse (Fig. 2b). In masonry buildings with elements that prevent such collapse mechanisms (Fig. 2c), diagonal compression occurs and these elements increases the bending strength of the spandrels. Under these conditions, the spandrels present two possible collapse mechanisms [15,16]:

- Collapse due to high compression of diagonal struts (similar to the collapse of piers subjected to combined axial and bending forces).
- Collapse due to diagonal tension (shear failure).

The out-of-plane behaviour of unreinforced walls is rather complex and depends on the connection between walls and floors/roof, the connection between transverse and longitudinal walls, and the in-plane stiffness of the floors. When the floors are rigid and are adequately connected, masonry walls have local effects. On the

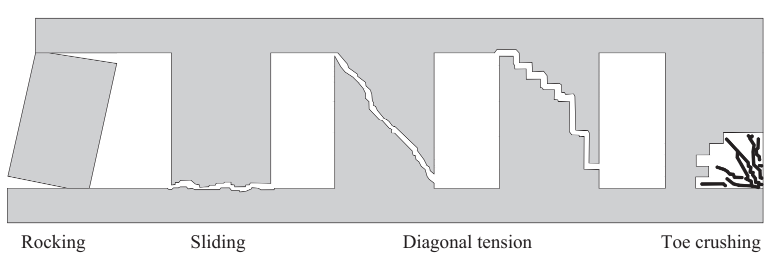

Fig. 1. In-plane collapse mechanisms of the piers (adapted from [14]).

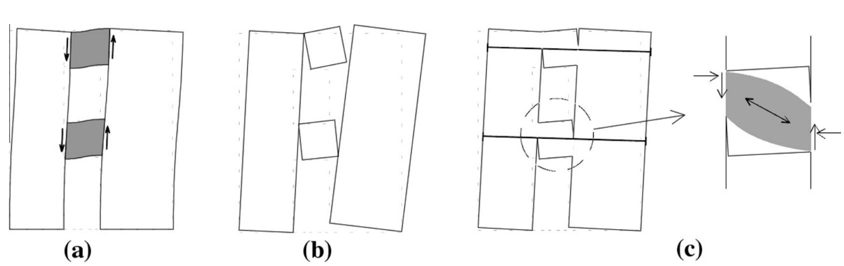

Fig. 2. In-plane behaviour of the spandrels [17].