Engineering Structures 61 (2014) 195–208

Contents lists available at ScienceDirect

Engineering Structures

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

Comparative analysis on the seismic behaviour of unreinforced masonry buildings with flexible diaphragms

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ARTICLE INFO

Article history:
Received 20 July 2013
Revised 25 December 2013
Accepted 30 December 2013
Available online 11 February 2014

Keywords:
Unreinforced masonry buildings
FE modelling
Macro-element model
Static nonlinear analysis
Inelastic dynamic analysis (IDA)
Seismic loading

ABSTRACT

The paper reports a comparison among different methods of analysis and different numerical models to estimate the seismic behaviour of unreinforced masonry buildings with flexible diaphragms through the investigation of a reference masonry prototype. The prototype was a two-storey building tested on shaking table at the CNR-ENEA research centre of Casaccia (Roma, Italy) under increasing natural ground motions in order to analyse its seismic response from initial elastic conditions until moderate to extensive damage. A first numerical model was built with the finite element technique, and was employed to perform nonlinear static analyses (pushover). A second one was built based on the simplified macro-element approach and, being less computation demanding, was adopted to perform nonlinear dynamic analyses. The main results of all analyses are critically compared and discussed in order to investigate the effectiveness of both simplified models and analysis methodologies. Eventually, numerical results are compared with the available experimental data. The FE model is able to predict the damaged areas and the incipient collapse mechanism, as well as the collapse load. The macro-element model is able to predict the collapse load but, due to some limitations of the approach, a satisfactory reconstruction of the actual collapse mechanism was not obtained. Nevertheless, the simplified model is able to fairly accurately estimate the accelerations at the top floor measured in the tests.

1. Introduction

Prediction of the seismic behaviour of masonry buildings is a wide-ranging and basic topic of earthquake engineering. The investigation of the response of a masonry building under earthquake loads involves many different questions, which need to be properly assessed. Under moderate earthquakes, absolute accelerations are significant to predict the damage suffered by facilities and equipments, together with the possible discomfort suffered by users. Therefore, the prediction of peaks of absolute accelerations and their spectral decomposition is essential to evaluate the immediate-occupancy (IO) or life-safety (LS) performance limit states. For earthquakes with medium-to-high seismic intensity masonry buildings generally suffer a large amount of damages (such as shear or flexural cracking of in-plane walls, loss of anchorage between walls and floors or between wall and wall, and local out-of-plane collapse of walls) and the global collapse can also occur. Hence, the assessment of the seismic capacity of a building is crucial to evaluate the collapse-prevention limit state (CP), either for the design of a new construction and for the retrofitting of an existing one. The concept of seismic capacity can be defined in many different conventional ways. If the seismic loading is represented by a set of equivalent static horizontal forces, the maximum base shear and the ultimate horizontal drift can be used as basic response parameters. Alternatively, since earthquake induces a dynamic loading in the constructions, for a given seismic shock the level of the peak ground accelerations (PGA) corresponding to the CP limit state can be used.

The largest part of the analysis methods employed to investigate the seismic behaviour of a masonry building can be divided into three main categories: (i) the modal analysis, usually based on linear models and combined with the concept of structural behaviour factor q to account for the energy dissipation effects that occur in the structure during the earthquake ground motion, (ii) the nonlinear static analysis (pushover) and (iii) the nonlinear dynamic analysis [1–4]. Procedures of the first type are commonly employed in a professional context, to verify the compliance of the performance level with the standards. Anyway, these methods are not fully appropriate for a reliable prediction of the amount and the type of damage occurred in the building under the earthquake loading. The pushover analysis is a procedure used to obtain the so called "capacity diagram" of a structure (to be compared with the seismic demand), which represents a basic datum to predict the strength

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http://dx.doi.org/10.1016/j.engstruct.2013.12.038

and the ductility. In recent times, the method is quite widespread also in the engineering practice. Yet, since it is based on a static nonlinear procedure where the external loads monotonically increase up to failure, it neglects many significant aspects of the actual structural response, like the damage produced by reversal loads. The nonlinear dynamic analysis method foresees a direct step-by-step integration in the time domain of the motion equations. The method, provided that both a reliable nonlinear numerical model of the building and a proper modelling of the seismic input are achieved, can cover the drawbacks of the first two procedures, being able to follow the full seismic loading process (from the initial state, through the weakly nonlinear behaviour under service loading, up to the strongly nonlinear behaviour leading to collapse). However, since the building response can be very sensitive to the selected individual seismic input, many nonlinear analyses with different ground records are required to obtain a reliable estimation of the actual structural behaviour. In this respect the incremental dynamic analysis (IDA) procedure [3] seems an attractive alternative approach able to reduce the computational effort.

Irrespective of the used method, a further main difficulty consists in the proper definition of the mechanical parameters of the masonry material, depending on the specific requirements of the numerical model employed to perform the analysis. Given the wide variety of masonry building typologies (both for materials and for constructive techniques) and the complex nature of the masonry material (a nonlinear, anisotropic and inhomogeneous medium) several modelling approaches have been proposed in last decades which resort in different levels of complexity. In addition to the simplified methods proposed in the eighties (such as POR [5], POR-FLEX [6], VEM [7] and RAN [8]), procedures based on the macro-element approach (such as MASS3D [9], PEFV [10] and 3DMACRO [11]), on the equivalent frame schematization (SAM [12] and TREMURI [13] [14]), on the hybrid multiscale continuum-discrete methodology ([15]) and on the non-smooth contact dynamics method (NSCD [16]) are now available and are able to cover all the analysis methods, both in static and dynamic field. Alongside the above approaches, the finite element modelling technique (FEM) still represents an effective tool for the analysis of masonry buildings. However, a specific attention must be paid to properly characterize the masonry, especially if a macro-modelling approach is adopted where a distinction between individual units and joints is not made [17]. Several successful studies were presented in which the method is employed, with different levels of complexity, to simulate the behaviour of masonry structures for seismic assessment. These studies demonstrate that the FE method can accurately reproduce the key features of both in-plane and out-of-plane masonry buildings response however, due to the high computational effort, the use of the FE approach is mainly justified in case of analysis of historic masonry structures [18–21].

Within this framework the paper presents the results of a numerical investigation performed through two different, both for capability and facility, three-dimensional (3D) numerical models of a simple scaled unreinforced masonry building (URM) tested by shaking table at the CNR-ENEA research centre of Casaccia near Roma, in Italy. The first model refers to the finite element technique, and was built with the commercial code ANSYS [22]. The second one was built based on the macro-element approach through the implementation of simplified nonlinear models for masonry in MATLAB. An identification procedure was used to define the most important masonry constitutive parameters required by the two models. Available results of laboratory tests performed at the CNR-ENEA centre on units, mortar and diagonal compression tests on masonry wallets were used to this aim. After identification, the FE model was used to predict the capacity diagrams of the building and the type of suffered damage, by static pushover analysis. The macro-element model, which is less computationally expensive, was used to perform nonlinear dynamic analyses of the building under natural records. The time histories analyses were aimed to: (i) evaluate the envelope of the dynamic response base-shear vs drift and comparisons with the FE model pushover results, and (ii) predict the seismic capacity of the building through the IDA procedure. Eventually, the macro-element model was used to reproduce some of the physical shaking table tests, those characterized by low-to-medium seismic intensity. Attention was focused on the comparison between experimental and numerical maximums values of absolute accelerations measured at the higher level, together with their spectral decomposition. The main results of all analyses are presented and critically discussed with the aim to deepen the effectiveness of simplified models and analysis methodologies to assess the seismic behaviour of unreinforced masonry buildings with flexible diaphragms.

2. The analysed masonry building

The building herein investigated is one of the two masonry prototypes built at the CNR-ENEA research centre of Casaccia, near Roma (Italy). The two buildings, tested through an extensive experimental investigation on shaking table, were built within a research project partially funded by the Italian Ministry for Research [23]. The project aimed to assess the seismic performance of masonry elements and scaled structures made with both the typical materials and the constructive techniques employed in old masonry buildings in Central Italy. Within the project the effectiveness of innovative retrofitting techniques with the CAM (Active Confinement of Masonry) system were also evaluated by comparing the results on the two prototypes [24,25]. The first prototype (RM) was built and strengthened with the CAM system, then was tested to verify the effectiveness of the reinforcement; the second one (URM) was tested until collapse without any strengthening. The prototype herein analysed is the unreinforced one.

Tests on shaking table were carried out through the application of a normalized natural seismic input applied with increasing intensity. The reference input used was the accelerogram of Colfiorito (Perugia, Italy), recorded during the Umbria-Marche earthquake of September 26, 1997 (Richter magnitude of 6.1, epicenter in Annifo-Colfiorito). To be consistent with the reduced scale of the structure the original record was time-compressed (i.e. the records were scaled along the time axis by a factor equal to the square root of the geometric scale of the model: $\sqrt{3/2} = 1.225$ [25]) and both the North–South (NS) and the East–West (EW) components were applied simultaneously during the tests.

2.1. Geometry of the prototype

The prototype is a 1:1.5 scaled two-storey building (Fig. 1), with walls constructed with chaotic masonry texture and low quality mortar with the aim to reproduce some of the typical masonry structures existing in Central Italy areas. The plan layout was constituted by a single cell with outer dimensions of $3.5\ \text{m} \times 3\ \text{m}$ (Fig. 2) and the interstorey heights measured approximately 2.2 m. A further masonry board 0.15 m high was present at the top of the building over the second floor level, so the total height of the prototype was 4.55 m. Masonry walls, constructed with calcareous tuff stones and lime-cement mortar, had a constant thickness of 0.25 m and were composed by two vertical faces without any transversal connection (Fig. 3). The horizontal structures were made with flexible timber floors. Each floor was built using 5 wooden joists (with section $0.10\ \text{m} \times 0.18\ \text{m}$) and wooden boards with a thickness of about 20 mm nailed to the wooden beams. To reproduce the poor constructive technique typical of