Engineering Structures 126 (2016) 224–236

Contents lists available at ScienceDirect

Engineering Structures

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

Discrete element modeling of a scaled masonry structure and its validation

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ARTICLE INFO

Article history:
Received 30 May 2015
Revised 22 July 2016
Accepted 23 July 2016

Keywords:
Discrete element modeling
Nonlinear dynamic analysis
Masonry
Shake table experiment
Scale models of historical structures

ABSTRACT

The 1:10 scale model of the 15th century Mustafa Pasha Mosque in Skopje, that underwent a comprehensive shake table program, is modeled by the discrete elements approach. A rigid block model with nonlinear behavior concentrated at the joints was developed and calibrated by comparison with the observed response. Time domain analyses of the discrete model were performed under the various levels of dynamic excitation used in the shake table test. Under the lower levels of input, the time and frequency domain characteristics of the shake table experimental response were fairly well simulated by the numerical model. This model also predicted well the zones and the level of damages. For the higher input levels, the comparison was less satisfactory. Overall, the discrete element approach showed the capability to handle the dynamic nonlinear modeling of relatively complex masonry structures.

1. Introduction

Determination of the safety of masonry structures against earthquakes is a complex challenge. Several investigations have been carried out in recent years concerning masonry structures geared towards their earthquake safety assessment [1–9].

In dealing with the problem of global analysis of masonry structures, linear and nonlinear methods are used in common practice. Regarding the modeling, finite element method is the most well-known methodology based on elements that behave quite connected under static and dynamic loading conditions. However, masonry structures have a natural complexity due to the heterogeneity of materials (stone, brick, mortar, etc.), discontinuities and different elastic-plastic behavior characteristics of these materials under static and seismic loading. The aim of this study is to enhance our modeling and structural analysis capabilities of masonry structures, which display a highly complex behavior due to their material characteristics, structural and architectural configuration and damage history.

Available numerical modeling methods such as finite element, boundary element and finite difference techniques are based on the continuum assumption. Although they have been proved as capable to solve complicated problems in various fields of science and engineering and within the context of civil engineering to satisfactorily represent the global structural behavior, the continuum based methods have limitations in solving problems which involve complex discontinuity such as masonry [10–12].

Among the numerical approaches available, the discrete element method is particularly suited to simulate failure modes involving crack propagation along joints or discontinuities between blocks. It has been used very successfully by various authors for the study of masonry structures under seismic loading. De Felice [3] employed it to model the out-of-plane failure of masonry walls. Psycharis et al. [2] applied the method to study the walls of the Parthenon under earthquake action. Çaktı et al. [9] analyzed the seismic response of historical minarets in Istanbul with discrete element models. De Lorenzis et al. [13] applied the method to the analysis of arches under dynamic impulses, validating the numerical results against analytical solutions. Dimitri et al. [14] employed similar models for other types of masonry structures, such as arches supported by buttresses. Reference should also be made to alternative numerical approaches which share many underlying assumptions with discrete element models, such as rigid body and spring methods, e.g. Milani et al. [15], or models

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http://dx.doi.org/10.1016/j.engstruct.2016.07.044
0141-0296/

Fig. 1. Image of Mustafa Pasha Mosque in Skopje, Macedonia [17] on the left; 1:10 scale shake table model of the mosque on the right.

based on rigid elements and nonlinear interfaces, e.g. Milani and Lourenço [16].

Within the scope of a bilateral project between the Department of Earthquake Engineering of Boğaziçi University, Kandilli Observatory and Earthquake Research Institute in Istanbul, Turkey, and the Institute of Earthquake Engineering and Engineering Seismology in Skopje, Macedonia, a reduced-scale model of the Skopje Mustafa Pasha Mosque was constructed in Istanbul, and was subjected to the shake table testing. The aim of this project was to compare the performance of models of different scales: the 1:6 scale model previously built and tested in Skopje; and the 1:10 scale model tested in Istanbul [17,18].

The Mustafa Pasha Mosque is a masonry building constructed in 1492 during the Ottoman era (Fig. 1). It has a square plan and is topped by a monumental dome supported by a polygonal drum and four pendentives. The dimensions of the main square area are 20 m × 20 m. The diameter of the dome is about 16 m. The main structure is about 22 m high. The massive walls and the drum are composed of two exterior layers of natural stone, brick and mortar combination with an inner core of stone and brick rubble set in lime mortar. The dome is of brick masonry. The minaret of the Mustafa Pasha Mosque is 42 m high and is constructed of cut-stone masonry [19].

The 1:10 scale model of the Mustafa Pasha Mosque constructed in Istanbul and the experimental data obtained during its testing on the shake table (fixed base model) are the starting point of this study. Our aim is to develop a 3D discrete element model that represents the linear and nonlinear behavior of the shake table model as closely as possible. It is expected that the experience gained from this exercise is transferable to modeling of real-life masonry buildings.

2. Description of the shake table model and experimental program

The overall dimensions of the shake table model are 2.0 m × 2.0 m in plan and 2.2 m in height. The minaret is 4.0 m high. The walls of the body were built in three layers through their thickness. The two exterior layers, 6 cm thick each, are made of stone, brick and lime mortar. The 6 cm thick interior layer is an infill of mortar, brick and stone fragments. The pendentives are made of masonry in brick and lime mortar. The drum is made of stone, brick and lime mortar and is 0.23 m high. The outer diameter of the drum is 1.88 m; that of the dome is 1.74 m. The outer diameter of the minaret is 30 cm. The shake table model can be seen in Fig. 1. The model was designed and built according to similitude laws in terms of geometry and material characteristics.

The shake table model was instrumented with accelerometers. Altogether ten uniaxial accelerometers and seven tri-axial accelerometers were employed. Eight uniaxial accelerometers were utilized in the instrumentation of the minaret, placed as orthogonal pairs at 1.75 m, 2.45 m, 3.25 m and 3.90 m heights. Two uniaxial accelerometers were installed directly onto the shake table in orthogonal directions. Four out of seven tri-axial accelerometers were installed on the top four corners of the walls; one was placed on top of the dome; one on the drum; and one was fixed to the shake tabletop.

The north-south component of the Montenegro earthquake (15.4.1979, M_w 6.9) recorded at the Petrovac station with a peak acceleration of 4.45 m/s^2 was used as unidirectional horizontal motion. The tests on the 1:6 scale model in Skopje had been executed using the same record as input. The ground motion records were compressed in time to satisfy the similitude requirements and to account for the reduced scale of the shake table model.

A total of 26 tests were performed using the Montenegro earthquake record that was sequentially increased from 5% to 250%, taking peak acceleration of the original record as reference. The first crack was observed in the minaret right after the 155% Montenegro input. The minaret is adjacent to the body up to the base of the drum that supports the dome. From this level on, the minaret rises as a free-standing structural element. The crack initiated just at this level. At higher amplitude input motions the part of the minaret above the crack started to rock. Also, cracks started to develop in the body of the shake table model. Preliminarily they were observed at the corners of the openings in the drum and in the walls. The cracks in the drum preceded those in the walls. They slowly started to propagate down through the walls and up to the dome. In the walls they jumped from opening to opening following a diagonal path. Stones were displaced. Some of them fell. In the dome both horizontal and vertical cracks developed. The vertical cracks were mostly continuation of those that started in the drum. A horizontal crack between the dome base and the drum was also observed.

3. Discrete element model

Analytical models are created in search of the best representation of the response of a structure to static and dynamic actions.