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Dynamic response of reinforced masonry columns in classical monuments

Ioannis Stefanou [a,*], Ioannis Psycharis [b], Ioannis-Orestis Georgopoulos [a]

[a] School of Applied Mathematics and Physics, Section of Mechanics, National Technical University of Athens, 9 Heroon Polytechniou Str., Polytechnic Campus, Athens, Greece
[b] Laboratory for Earthquake Engineering, School of Civil Engineering, National Technical University of Athens, 9 Heroon Polytechniou Str., Polytechnic Campus, Athens, Greece

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ABSTRACT

From the mechanical point of view, the particularity of masonry structures stems from the fact that the structural system is hard to be modeled by the classical Continuum Mechanics approach. The problem gets more complicated when imperfections, such as cracks are present. An example of a single multi-drum column, with fractured drums, is studied herein, using the Distinct Element Method (DEM). The purpose of the research is the investigation of the impact of the fractures to the overall stability of the structure. The 3D DEM numerical results are explained on the basis of simple 2D analytical considerations. The shear and normal crack deformation is monitored and the minimum required strength of the crack interface is quantified. An experimental program of direct shear tests is set in order to estimate the strength of the marble–cement interface. The experimental values are compared to the minimum required from the numerical analysis.

1. Introduction

During the last decades an increased interest in the dynamic response of ancient classic monuments has arisen. Typical examples of such cultural heritage assets are the classical Hellenistic, Greek and early Roman temples (Fig. 1). In certain cases this kind of structures may undergo intense earthquake actions without collapsing. The particularity of these classical monuments is that they are constituted by many discrete bulgy stone blocks, which form dry masonry walls and multi-drum columns. The various bulgy discrete blocks were not systematically connected together in ancient times, and when they were, special metal or wooden connectors were used. A special element of these structures is the multi-drum column which is made of (sometimes astoundingly) perfectly fitted stone drums placed on top of each other avoiding the use of cement (mortar) [1]. It is worth noticing that the seismic response of these articulated discrete structures has very little in common with the dynamic response of modern structures, which exhibit 'tensegrity' (tension + integrity) in the sense that they can bear tensile stresses and keep their integrity. The stability and resistance of modern structures subjected to axial lateral loads and moments is attributed to the development of internal tensile forces, while the stability and resistance of classical structures is attributed primarily to friction and is affected by their geometric characteristics [3,2]. This fundamental difference makes inapplicable most of the available structural theories and classical computational tools.

Despite the lack of inter-connection among the stone elements, classical monuments are not, in general, vulnerable to 'typical' earthquake motions, if they are in their intact condition [4]. Their large 'apparent' period and large dimensions make them vulnerable only to earthquakes that are characterized by increased values of spectral acceleration in the long period regime. The energy dissipation, caused by wobbling, rocking and sliding, has also a beneficial effect. This good seismic behavior has been proved in practice, since many classical monuments are standing for more than 2000 years, although they are located in regions of extensive seismic activity, as Greece and Italy.

The vulnerability of classical monuments to earthquakes depends on two main parameters: the predominant period of the ground motion and the size of the structure [4]. The former significantly affects the response and the possibility of collapse with low-frequency earthquakes being much more dangerous than high-frequency ones. In the first case, the response is characterized by intensive rocking; in the latter, significant sliding of the drums occurs, especially close to the upper part of the structure, while rocking is usually restricted to small values. This good seismic behavior may be attributed to their large 'apparent' period, which

* Corresponding author. Address: School of Applied Mathematics and Physics, Section of Mechanics, National Technical University of Athens, 9 Heroon Polytechniou Str., P.O. BOX GR15780, Athens, Greece. Tel.: +30 697 7 212 890; fax: +30 210 67 22 873.

E-mail addresses: istefanou@mechan.ntua.gr (I. Stefanou), ipsych@central.ntua.gr (I. Psycharis), I.Georgopoulos@mechan.ntua.gr (I.-O. Georgopoulos).

URLs: http://lee.civil.ntua.gr/ (I. Psycharis), http://geolab.mechan.ntua.gr/ (I. Stefanou, I.-O. Georgopoulos).

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Fig. 1. Poseidon's temple at Cape Sounion, Greece.

increases with the amount of rocking. The size of the structure is another important parameter, with bulkier structures being much more stable than smaller ones of dimensions with the same aspect ratio.

Unfortunately, imperfections are present in many monuments. They are caused by various factors as previous earthquake events, foundation failure, material deterioration or man interventions, as fire and vandalism. The most common imperfections are cut-off drum corners, displaced drums, inclined columns and broken element stones (Fig. 2). Previous analyses [4,5] show that such imperfections reduce significantly the stability of the structure and can lead to collapse even for middle-size earthquakes. An example of the significant reduction of the stability, produced by imperfections, is shown in Fig. 3. In restoration practice, when broken pieces are missing, new pieces are usually constructed by new material to complete the ancient member. These new additions from new material have to respect the geometry of the authentic member and to fit 'exactly' to the failure surface. In this way the intervention at the ancient member is minimal. In order to join the additions with the ancient member, dowels and cement paste are used, as for example, at the Acropolis of Athens and the Epidaurus restoration sites [6], where dowels made of titanium and white cement are used to join the additions with the ancient members. The number of reinforcing dowels used, has to be as small as possible in order to preserve and not destroy the ancient member with excessive drilling, while at the same time has to be strong enough to bear the external actions exerted to the ancient member. The design of the reinforcement has to account for shear, tension, compression, bending and torsion of the addition to the failure

Fig. 2. Photo of the bottom cracked drum of a column at Olympieion temple in Athens.

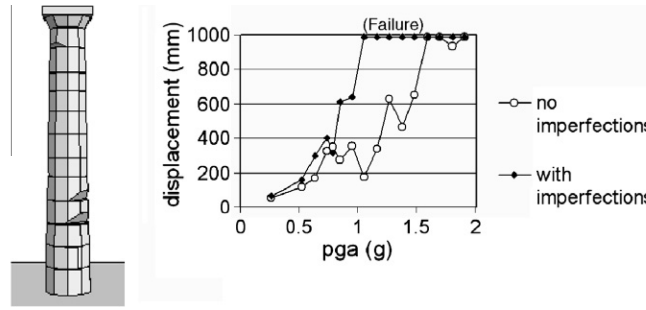

Fig. 3. Top displacement of a model of the Parthenon Pronaos column with and without imperfections, for the Aigion, Greece, 1995 earthquake, scaled to several values of PGA (numerical results, Psycharis et al. [5]).

surface of the ancient member. This problem is a complex contact problem, which has not been yet systematically addressed.

In the present paper we deal with the seismic response of a multi-drum column considering several cases of fractured stone drums. The aforementioned cases are simplified representations of flaws that are often displayed in classical monuments. The advance of the present work on previous approaches is that it focuses mainly on the developed stresses at the crack interfaces and that it correlates the strength of the latter to the global stability of the system. In particular, the objective of the current analysis is the investigation of the effect of several parameters to the possibility of failure of the system, such as the mechanical properties of the failure surfaces and the position and the inclination of the cracks. More specifically, in Section 2, we firstly highlight the three dimensional dynamic behavior of masonry multi-drum columns, when subjected to seismic actions. The Distinct Element Method (DEM) is a keen and powerful tool which may, when critically used, provide useful results in the understanding of the behavior of such structures. Further, in Section 3, the numerical analysis of a cracked multi-drum column is presented in detail, focusing on the effect of different crack types to the stability of the system. A simplified 2D analytical model is presented in order to approximate the internal stresses developed in the cracked drums and the results from the numerical and the analytical models are critically compared. Numerical analyses allow for the monitoring of the shear and normal crack deformation. Moreover, they make possible to derive a rough estimate of the minimum required cohesion and tensile strength of the crack interface. If these minimum required values are not assured then the structure may become unstable and collapse. The various failure modes of the structure are critically discussed in the same section and connected to the orientation and the position of the cracks. Finally, in Section 4, an experimental program of direct shear tests is set, in order to estimate the strength of the marble–cement interface. The experimental results for the mechanical properties of the marble–cement interface are used to qualitatively and quantitatively validate the required calculated values of cohesion and tensile strength provided by the DEM analyses.

2. Modeling of multi-drum columns

2.1. Three dimensional dynamic response

The complexity of the dynamic behavior of multi-drum columns originates from the fact that the structure continuously moves from one 'mode' of vibration to another; different joints are opened and different poles of rotation apply for each mode. The term 'mode' is used here to denote different patterns of the response (for an example we refer to Fig. 4) and does not refer to the