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Seismic protection of monuments using particle dampers in multi-drum columns

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ABSTRACT

This paper investigates the use of innovative, cost-effective techniques to protect ancient monuments consisting of multi-drum columns from seismic excitations. The proposed approach includes the use of particle dampers in the form of classical drums, with a hollow part containing particles. These can substitute damaged or missing drums. Their effectiveness in reducing the seismic response of classical columns is examined by exciting a marble multi-drum column-model of 3 m height by dynamic loads. The influence of the system parameters such as mass ratio (mass of particles with respect to mass of the column), placement of damper, particle and damper size on the effectiveness of the particle damper is also investigated. The experimental results showed that particle dampers, if properly designed, can reduce the monument's dynamic response by more than 30%. Finally, some brief design guidelines are given for benefiting from the use of such dampers in monumental sites.

1. Introduction

There are a lot of historical sites that need to be preserved from environmental factors and earthquakes. Countries prone to earthquake hazard need to invest a lot of effort and resources to restore and preserve their historical heritage. Common restoration efforts include substitution of damaged or missing parts of the historical monuments with new material similar to the old one. This new material does not usually increase the seismic safety of the monument especially if it consists of ancient marble parts that have deteriorated through the years.

Research efforts have focused on finding the dynamic characteristics of multi-drum classical columns [1–16]. Several studies have examined analytically or numerically, the behavior of rigid blocks while few of them have considered the experimental investigation, especially on large size column-models. Some of the more important findings of the previous research on the dynamic response of a multi-drum (or multi-block) column include the following:

a) The primary dynamic response of the blocks involves rocking and sliding. Sliding of the blocks increases the stability of multi-block column even more than a monolithic one [1];
b) The dynamic response of a multi-drum column is highly nonlinear and sensitive to small changes of geometric characteristics or of the excitation [3];
c) The structure during vibration changes modes. Planar excitation can produce out of plane motion of the drums due to imperfections [4];
d) A series of columns connected with each other are more stable than individual ones [5];
e) The wooden poles (pole-empolium) that were used in ancient times had minimal effect on the dynamic response of the column. The metallic shear links that have been employed in restorations (substituting the wooden poles) to connect the drums may have undesirable effects on the dynamic response of the column ([1,3]), but may be beneficial between capital and architraves in a colonnade [3];
f) Imperfections of the column including reduced section of the drums, inclination of the column etc. can reduce the seismic safety of the column [3];
g) Multi-drum columns are more in danger of collapsing at low-frequency excitations than high-frequency ones [3].

Even though the dynamic response of multi-drum columns has been investigated extensively, not much attention has been given in exploring ways to increase their seismic safety. Restoration and strengthening techniques used in monumental structures have to respect the architectural features of the monument, according to the principles of Charter of Venice. Usual strengthening techniques

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are intrusive and alter the appearance of the monument and innovative techniques [17] have been given minimal attention.

Innovative techniques that have been developed to reduce the dynamic response of structures include mainly passive and active control techniques and their combination. Passive control techniques are more widely used due to their simplicity, low cost and inherent stability. Particle dampers are passive devices that have been used for many years to reduce the dynamic response of small structures and mechanical systems [18–42]. Lately, they have been employed to reduce the vibrations of large structures including high-rise buildings and bridges [42]. Particle dampers consist of a container with particles, embedded in or attached to a structure. As the particles move freely inside the container they collide with each other and the walls of the container exchanging momentum with the primary system and dissipating energy. Past research has examined theoretically or experimentally the behavior of these nonlinear devices [18–42].

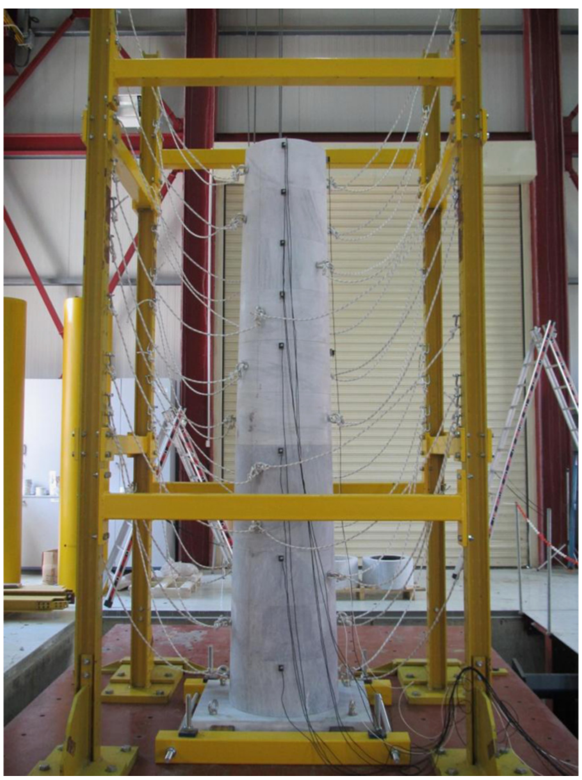

Fig. 1. Experimental setup.

This work investigates the performance of particle dampers in reducing dynamic vibrations of monumental structures such as multi-drum classical columns. The particle damper can, in this case, take the form of a hollow drum containing freely-moving particles. Since the outer part of the drum will look exactly like the rest of the drums, the overall appearance of the column will not be affected. The damper can thus substitute an original drum that is missing or has been damaged. Measurements using a small column-model provided promising results [43–45]. In this paper a large size multi-drum column-model is exited dynamically, with and without the damper. The influence of several system parameters such as the mass ratio, the size of the damper and particles on the effectiveness of the particle damper are also investigated. The results are compared to those of the small size column-model. A design methodology is proposed and monumental sites that can benefit from this new technique are discussed.

2. Experimental setup and procedure

A large marble column-model was used for the experimental investigation (Fig. 1) with its geometry derived from that of a column from the temple of Parthenon. The scale used was 1:3.3 with a model of 2992 mm in height and 1707 kg of weight. The column consisted of eleven drums with varying diameter simulating the tapped form of actual columns. The top-drum diameter was 445 mm and that of the bottom was 584 mm. The drums were of the same height (272 mm) while the characteristic flutters of ancient column were omitted for cost effectiveness and considering their minor influence to the results of this investigation. The drums were not connected to each other by any means -the wooden parts that used to connect the ancient drums usually were not preserved through the years and past studies shown that they have minor effect on the dynamic response of the column [1–3]. The consecutive drums were laid in full contact with each other all around a 50 mm-wide, smoothly polished, peripheral ring that was manufactured on the top of each drum – the rest of the area had a slight recess (to resemble the type of contact area of ancient drums). A solid marble plate of $900 \times 700 \times 140$ mm was used as the base for the simply supported column. The specimen was placed on the 3×5 m platen of a uniaxially seismic simulator. The marble plate was secured from sliding through steel beams attached on the table and in tight contact with the marble plate. A steel safety structure was built around the column with loosely hanging ropes connecting each drum to the frame, to prevent accidental fall of the drums.

Two dampers were used for the experimental investigation, one assumed to replace the seventh drum (Fig. 2) and another to

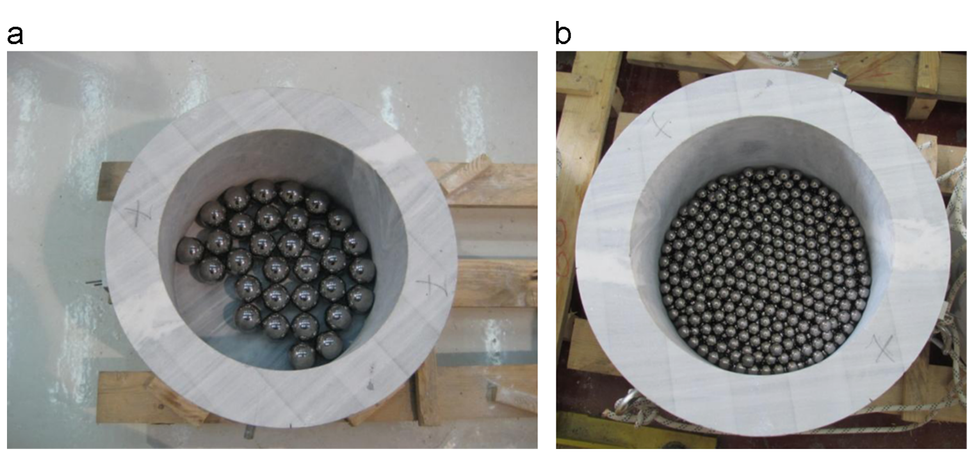

Fig. 2. Damper containing particles of diameter: (a) 50 mm and (b) 20 mm.