A passive control methodology for seismic safety enhancement of monumental structures

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ABSTRACT

A passive control methodology to increase the seismic safety of multi-drum columns is presented. The response of a large scale column-model to dynamic excitations is investigated experimentally. A particle damper is used to replace one of the columns' original drums. The influence of the system parameters on the response of the column is also examined. The seismic response of the column can be considerably reduced if a particle damper replaces a drum above the mid-height. Guidelines and a design methodology are proposed to restore and protect monumental structures consisting of multi-drum columns.

Keywords: monument, multi-drum column, passive control, particle damper

1. INTRODUCTION

During the last decades there has been an increasing interest in preserving cultural heritage. Ancient monuments have great historical value and can be damaged from environmental causes. Several historical monuments have suffered from lack of maintenance deteriorating with time. In seismic prone areas their safety in future earthquakes is an additional concern. Anastylosis of ruined structures includes reposition of original architectural elements and replacement of missing parts with new ones resembling the original. Common strengthening techniques cannot be used since they usually modify significantly the form and architectural features of the monument.

This paper examines the increase of seismic safety of ancient monuments consisting of multi-drum columns using particle dampers. Previous research has explored the dynamic response of monuments and their damping mechanisms ([1]-[13]) as well as the effectiveness of particle dampers in reducing the response of common structures and machines ([14]-[31]). The particle damper in the form of a hollow marble drum containing particles can replace an original drum without altering the overall appearance of the monument. The dynamic responses of a large-scale multi-drum column-model with and without the damper are compared and the influence of the system parameters on the response reduction is examined. The results obtained, from the experimental investigation of a small and a large scale column-model provided with a particle damper, are compared. Existing monuments that can benefit with the use of this passive technique are presented and guidelines for preservers are provided.

2. EXPERIMENTAL TESTING

A 3 m tall and 1707 kg marble multi-drum column was used as a model for our experimental testing (Figure 1). This column replica of an ancient column from the Parthenon (scale 1:3.3) consisted of eleven drums of 0.27 m height each, resting on a 0.7x0.9x0.14 m marble plate. The bottom diameter of the lower drum (1st drum) was 0.58 m and the top diameter of the last drum (11th drum) 0.44 m. The particle dampers were hollow marble drums that could substitute the seventh and the top drum. The diameter of the hollow part was 35 cm. Spherical steel particles of 20 and 50 mm were used. The mass ratios (mass of the particles with respect to the mass of the column) used were 0.7%, 1% and 2%. A safety structure was built around the column consisting of a steel frame and loose ropes in order to avoid damage of the drums under high excitation.

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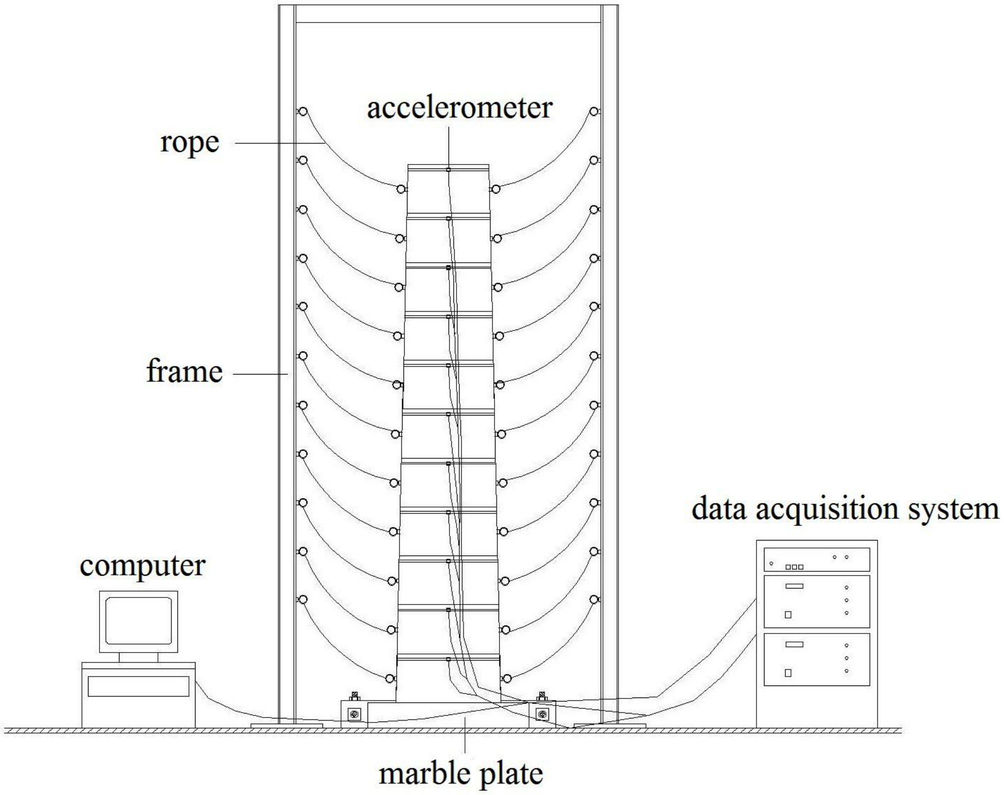

Figure 1: Experimental set-up (drawn by M. Miaoulis).

The whole structure was attached to a 3x5 m shake table. The excitation used was a random signal containing frequencies from 1 to 10 Hz (Figure 2). The motion of the drums and the base were measured with accelerometers. The response acceleration of the drums was converted to displacement by double integration.

3. DYNAMIC RESPONSE OF COLUMN MODEL

The column model was excited and its response at the direction of the excitation as well as the transverse and vertical direction was measured. The drums were mainly rocking and sliding. The highest response occurred at the top drum. The experiments were repeated several times to quantify the experimental variability. Significant changes from experiment to experiment have been observed by other researchers [7]. Figure 3(a) presents the displacement of the top drum for a mid-response of the column. The rms displacement ratio (root mean square of the displacement of the top drum with respect to the root mean square of the displacement of the table) was 5.03. After the 10 seconds of forced vibration the column continued to move for 6 more seconds till it came to a complete rest.

Next, the particle damper replaced the 7th drum. Initially, thirty two steel particles of 50 mm diameter were used corresponding to 1% mass ratio. The particles had enough space to move, hit the walls of the damper and exchange momentum with the primary system. The response was reduced considerably (Figure 3(b)) and the rms displacement ratio was 3.63. After the first 10 sec of the forced vibration the motion of the column continued with smaller amplitude and for less time than when the damper was not used. In additional experiments different number of particles, of 50 mm diameter, was also used corresponding to 0.7 and 2% mass ratio respectively. The particles corresponding to 0.7% mass ratio were less efficient (rms ratio 4.57) than the particles corresponding to 1%. The particles corresponding to 2% mass ratio gave approximately the same reduction as in the 1% case.

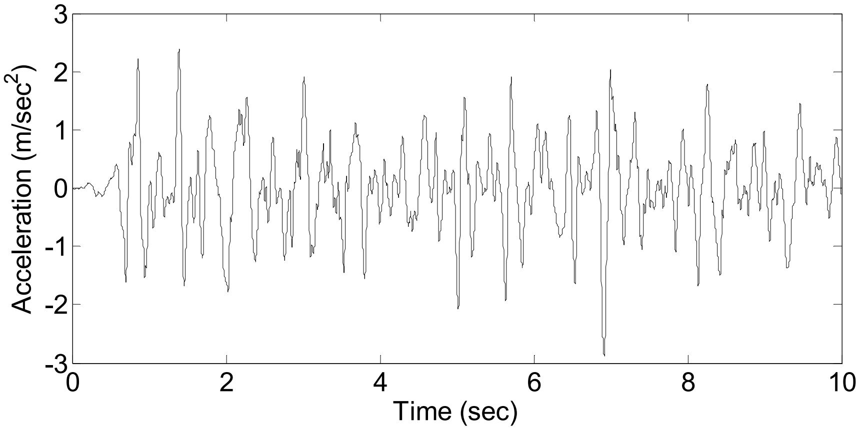

Figure 2: Input signal used in the experiments.

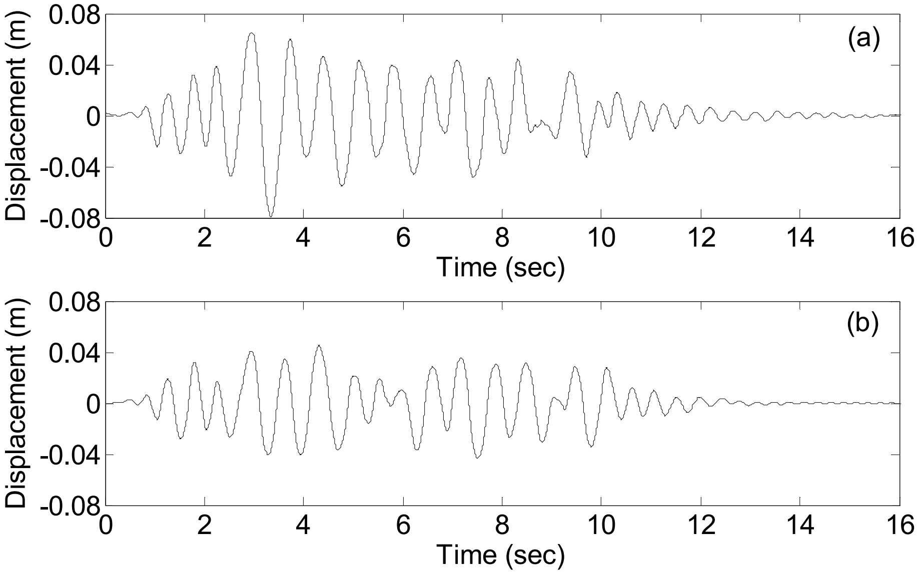

Figure 3: Response of top drum of the column: (a) without damper; (b) with the damper replacing the 7th drum (containing 32 particles of 50 mm diameter).

Smaller size steel particles with 20 mm diameter were also used. Initially, five hundred particles were placed inside the damper (mass ratio 1%). The particles did not reduce the motion of the column considerably but only the free vibration component (Figure 4). The rms displacement ratio was 4.57. Smaller or larger number of particles used did not affect the response of the column. The friction among the particles did not allow them to move much and to exchange momentum with the primary system. Similar results were obtained when the particle damper replaced the top drum.

The results obtained from the experiments with the large scale column were compared with those using a smaller scale column ([32]-[33]). The behavior of the two systems was quite consistent in both cases. The particle damper has to be placed at the top half part of the column where the motion is high. In addition the particles need enough space to move to be able to exchange momentum with the primary system. A mass ratio of 1-3% is sufficient to reduce the motion of the column more than 30% for random excitation.

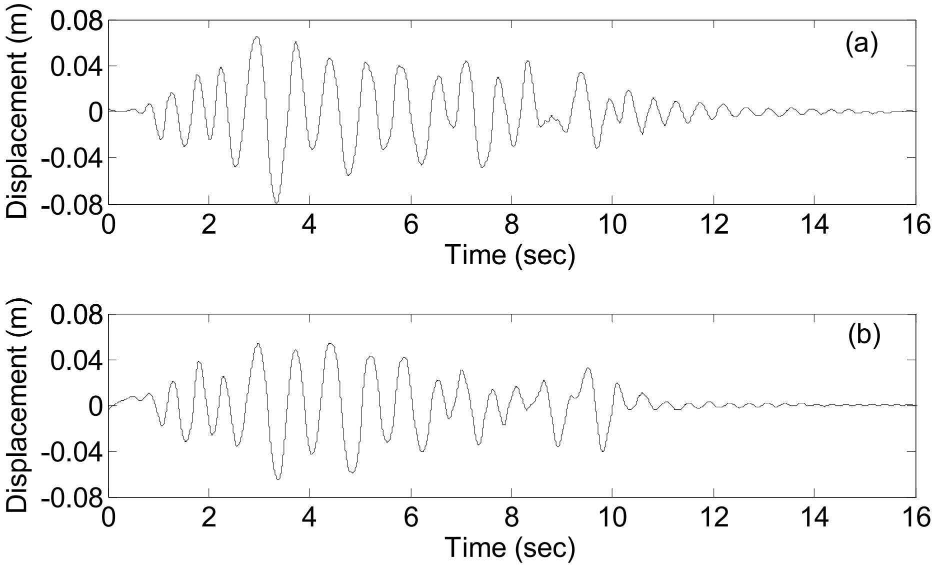

Figure 4: Response of top drum of the column: (a) without damper; (b) with the damper replacing the 7th drum (containing 500 particles of 20 mm diameter).

4. DAMPERS IN ANCIENT MONUMENTAL STRUCTURES

The particle damper can be used in most of the ancient temples consisting of multi-drum columns if proper selection of the system parameters is made. Even though the test performed used only a single column the results are applicable to a series of columns since increasing the stability of an individual column will increase the system stability. The temple of Zeus in Olympia offers a good example for the damper application since it is currently restored (Figure 5).

Figure 5: Ancient temple of Zeus in Olympia (www.archaiologia.gr).

The temple of Zeus in Olympia, the most important building in the Altis (sanctuary), is the largest temple in the Peloponnese. The temple was completed in 456 BC and it is considered a perfect example of Doric architecture. The columns, made of shell-limestone, were 10.43 m high having 2.25 m base diameter. The temple included a pronaos, cella, and opisthodomos. The cella was divided into three naves by two double rows of seven columns. At the far end stood the chryselephantine statue of Zeus, one of the Seven Wonders of the ancient world, created by Pheidias in 430 BC. The temple was burnt by order of Theodosius II in AD 426. Badly damaged by the fire, it finally collapsed by the earthquakes of AD 551 and 552. Excavations at the temple began by the French in 1829, and were completed by the German Archaeological Institute. Conservation and cleaning of the monument are currently in progress.

A great part of the temple's original material is on the ground, found after the removal of the layers of mud that were carried by the two rivers of the site, Alpheus and Kladeus. The quantity of the preserved original material should normally permit the restoration of a great part of the monument. However, the bad quality of the limestone, along with the fact that it remained for so many centuries covered by the mud of the two rivers, has resulted in the deterioration of the external surface of the drums of the columns. In order to place the drums on top of each other, a lot of new material has to be used to complete the missing parts and recreate the smooth contact surfaces. Smooth surfaces are necessary for the good contact of the drums with each other and, for their good behavior in an area which is among the most seismic of Greece. Notwithstanding those problems, the large quantity of original material can permit the restoration of at least some columns. Already one of them has been restored, with a considerable amount of new material used to complete the drums. However, that situation has a positive side in relation to the protection of the restored temple against earthquakes: for the restoration of a column, even if all the original drums are preserved, at least some original drums are in too bad a state to be used and have therefore to be replaced by modern substitutes. That permits the insertion of a damper (Figure 6), replacing the original drum that either is missing or is too deteriorated.

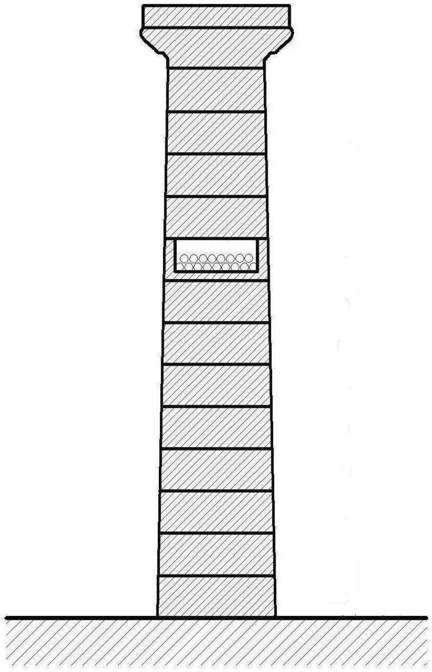

Figure 6: Indicative position of the damper (drawn by M. Miaoulis).

This way, the damper system can be used without reducing the original material that could be used in the case of a conventional restoration. The restriction would be that the damper would have to be placed in every column at a level defined by the state of conservation of the original material. That means that it could not be placed at the same level in all restored columns, but that in every column it would have to be put in the place of an original drum that will not be able to be used at all. Of course, that level will differ in every column. However, that problem could be minimized if it would be decided to choose the right drums to be restored according to their place in the column, in order to leave room for a damper at about the optimum height. It is a fact that today the principle is to put each drum in its original place, in the right column and each column in its right place in the monument. However, taken into account the extremely high seismic character of the specific area, a divergence from that rule could be justified by the monument's safety. Of course, special care would be taken to adapt the system to that situation, in order to minimize the number of drums that would have to be put in the “wrong” place, in order to facilitate the action of the dampers. That decision would combine the best possible protection of the temple against earthquakes with the best possible respect of international conventions of monument protection. In that way, the intervention will contribute to the monument’s preservation for future generations and at the same time will enhance its aesthetic qualities through its structural completion.

5. CONCLUSIONS

This paper examined the use of particle dampers in reducing the dynamic response of multi-drum columns. A large-scale model replica of an ancient column was used for the experimental investigation. A damper in the form of a stone drum replaced an original drum. It was found that proper selection of the system parameters can reduce the dynamic response of the column under random excitation. In particular even a small mass ratio can reduce the motion of the column more than 30% as long as the particles have enough space to move to exchange momentum with the primary system.

Some guidelines for practitioners include the placement of the damper above the mid-height where the motion of the column is high. In addition, the mass ratio must be in the range of 1-3%. Appropriate selection of the mass ratio must be made in consideration of the fact that congested particles cannot give proper operation of the damper. It is better to use a smaller mass ratio leaving space for the particles to obtain enough momentum.

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