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The Open Construction and Building Technology Journal, **2014,** ***8,*** **351-356** **351**

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Structural Control of Monuments' Response under Sinusoidal Excitation Using Particle Dampers

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Abstract: The effects of particle dampers attached on a classical column under dynamical loadings are investigated. A number of tests were performed to evaluate the ability of particle dampers to control the vibration of a small scale multi-drum column under a swept-frequency sinusoidal signal. The particle damper can reduce considerably the response of the column to sinusoidal excitation when the size of the container, the mass ratio, the particle size and the placement of the damper are properly selected.

Keywords: Monuments, multi-drum column, particle damper, passive control, sinusoidal excitation.

INTRODUCTION

In the last decades, countries have made an effort to restore and protect their historical heritage from natural hazards [1-4]. Restoration and preservation of historical structures and monuments is a challenging task. Interventions used to restore damaged historical structures must respect their architectural features and be reversible according to Charter of Venice [5]. Common restoration techniques replace damaged parts and increase the seismic safety of structures but usually alter their architectural features.

Passive control and health monitoring systems have been used for many years to control the vibration of structures under dynamic excitations [6, 7]. Their successful use has been attributed to their simplicity, low cost and zero for power requirements. Dampers and base isolation systems have been used successfully to increase the strength and seismic safety of historical structures.

Particle dampers are passive control systems that have been used for many years to reduce the motion of machine tools, turbine blades, flexible structures, etc. [8-25]. They consist of particles that can move freely inside a container colliding with its walls. After the collisions the particles reverse direction while the primary system decelerates. The reduction of motion of the system occurs due to the exchange of the particles' momentum with the primary system when they hit the walls of the container and the energy dissipation during the collisions. Particle dampers are highly nonlinear devices with several system parameters influencing their behavior. The main system parameters that influence the damper's performance include the mass ratio (mass of particles with respect to mass of the column), size of hollow part of damper, particles' size and amplitude of excitation [8-10].

Particle dampers can also be applied to monuments to increase their seismic safety. Many ancient temples consist of multi-drum columns that have been restored by adding new material when their drums were damaged or missing. These damaged or missing drums can be replaced with particle dampers. The dampers will look outside like the rest of the drums but inside will be hollow containing particles.

Several researchers have investigated the response of ancient monuments under dynamic loads considering multi-drum columns either in the form of rigid blocks or by examining the seismic response of marble column models [26-39]. The dynamic response of multi-drum columns is influenced by small perturbations of the base excitation and various system parameters. The highly nonlinear behavior of the column and damper makes the theoretical study quite challenging. Experimental investigation seems more appropriate for these complex problems.

This paper investigates experimentally the performance of particle dampers added to classical columns under sinusoidal excitation. The parameters that influence the response of the structure are examined using a small scale model.

EXPERIMENTAL DETAILS

A small marble column model of 651 mm height consisting of seven drums of 120 mm diameter and 93 mm height was used for the experimental investigation (Fig. **1**). The drums were not connected to each other resembling ancient columns that have lost their wooden connection parts due to environmental causes. The column was placed on a 140 mm x 140 mm x 20 mm marble plate which was glued to a steel plate. The whole arrangement was attached to a 3 m x 5 m shake table. A safety structure was built around the column (Fig. **1**). The column was excited in one direction and its motion was measured by accelerometers that were attached on the drums. The accelerometers were measuring the vertical and out of plane motion as well. A built in accelerometer was measuring the acceleration of the shake table.

Two different size particle dampers were used. The diameter of the hollow part of these dampers was 9 cm and 8 cm respectively. Steel spherical particles of 20, 30 and 50 mm diameter were used (Fig. **2**).

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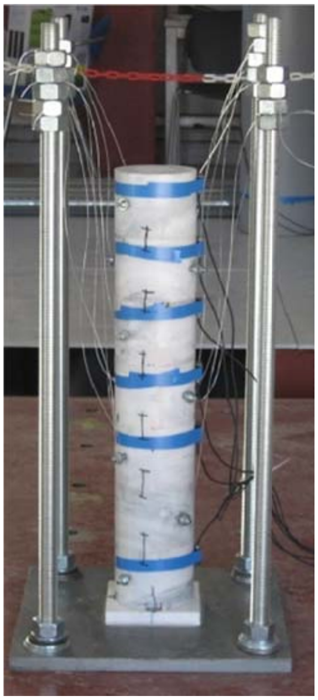

Fig. (1). Column-model used for the experimental investigation.

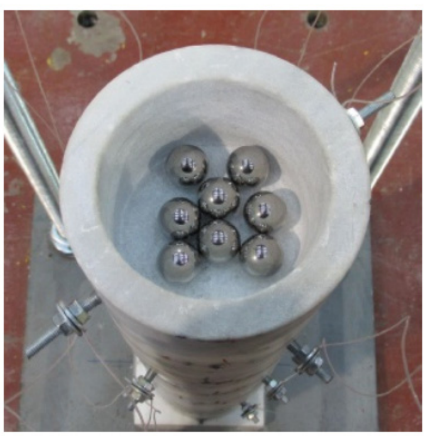

Fig. (2). Particle damper containing spherical particles.

The main natural frequencies of the column were expected to be below 5 Hz thus the excitation used as an input was a sine-sweep signal containing frequencies from 1-7 Hz (Fig. **3**). This signal could invoke the main natural frequencies of the column giving large motion of the drums.

RESPONSE OF COLUMN UNDER SINUSOIDAL EXCITATION

Response of Column without Damper

The column (without damper) was excited with a swept-frequency sinusoidal signal containing frequencies from 1-7 Hz and its response was measured. Rocking, sliding and rotation of the drums were observed. The highest motion occurred in the direction of the excitation but some out of plane motion was also observed. The results will be presented for the top drum of the column where the motion was the highest. The response of the other drums was similar but smaller.

After a few experiments it was observed that the response of the column was not the same under the same excitation. Small imperfections of the set-up could invoke different response under the same initial conditions. To ensure the robusteness of the results, experiments under the same conditions were repeated several times. If two consecutive experiments under the same initial conditions gave similar response, the experiment was not repeated for a third time.

The frequency response of the absolute acceleration of the top drum of the column is presented in Fig. (**4**) for the highest response obtained in the repeated experiments. The main natural frequencies of the column were 1.05, 1.50, 2.10, 2.50, 2.80, 3.0, 3.50, 3.99, 4.20 and 4.5 Hz.

The displacement of the drums was obtained with double integration of the acceleration and removal of the trend. The root mean square of the response dispalcement was calculated with respect to the root mean square (rms) of the dispalcement of the base. Since the experiments were repeated several times, the average response was calculated. The average rms of the response displacement with respect to the base (average rms response) of the top drum in the direction of the motion was 3.75 and the standard deviation 1.02. The highest response obtained from these experiments without the damper was 6.21. Fig. (**5**) presents the displacement of the top drum in the direction of motion (light line) for the experiment with the highest response.

Response of Column with Damper

The location of the damper is one of the important parameters of its efficiensy. Two positions were considered: the damper replaced the fifth drum and the damper replaced the top drum. The higher motion of the top drums will increase the momentum of the particles a necessary condition for the effectiveness of the particle damper.

Initially the larger damper (9 cm diameter) replaced the fifth drum. Eight particles of 20 mm diameter were placed inside the container. The mass of the particles with respect to the mass of the column (mass ratio) was 1.33%. As the column was moving the particles hit the walls of the container exchanging momentum with the column (primary system) and dissipating energy.

The frequency response of the absolute acceleration of the top drum of the column is presented in Fig. (**4**). The amplitude for the low frequencies is smaller than without the damper. For some of the high frequencies the amplitude increases but these frequencies have a small contribution to displacement of the drums. The response displacement was the same for the first second since the particles needed time to reach the walls of the container and exchange momentum with the primary system (Fig. **5**). Then the amplitude was reduced considerably and in some cycles more than 50%. In addition, the motion of the column with the damper at the end died faster. The average rms response of all experiments performed with the same conditions was 2.95 with standard deviation 0.80.

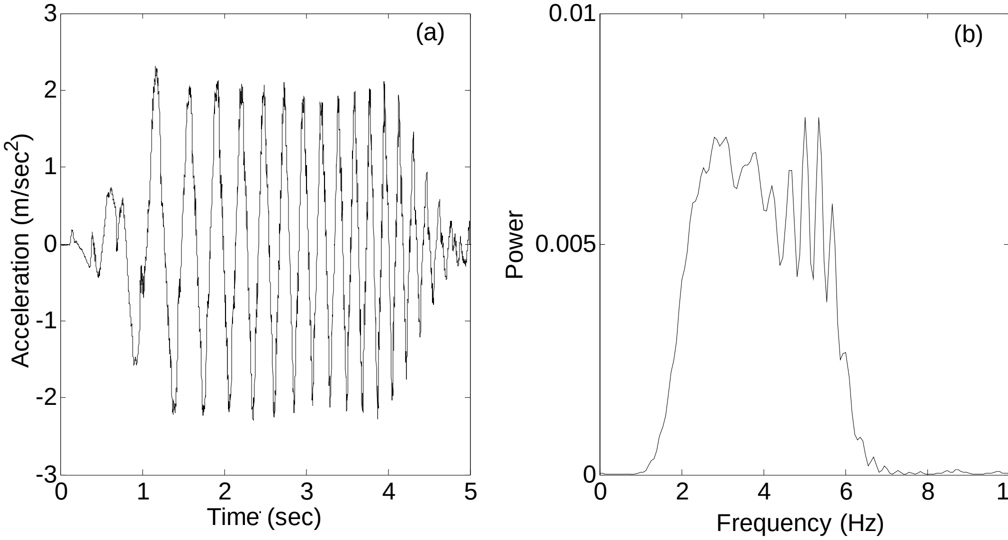

Fig. (3). Sinusoidal sweep signal containing frequencies in the range of 1-7 Hz: (**a**) time history; (**b**) frequency spectrum.

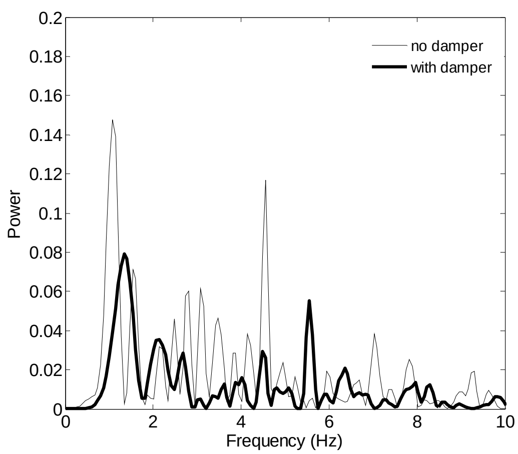

Fig. (4). Frequency response of the absolute acceleration of the top drum of the column without and with the damper with the larger diameter replacing the fifth drum containing eight particles of 20 mm diameter.

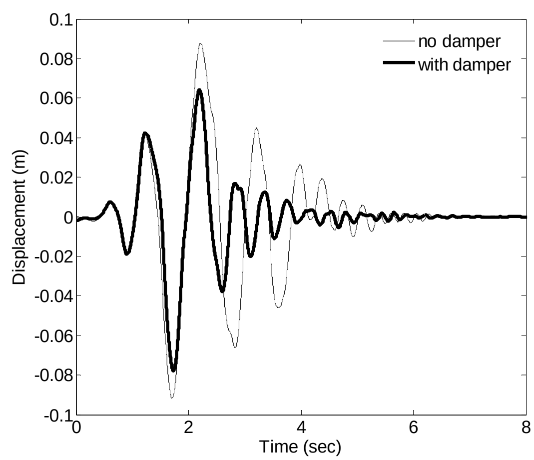

Fig. (5). Response displacement of top drum without and with damper (highest response) without and with the damper with the larger diameter replacing the fifth drum containing eight particles of 20 mm diameter.

In the next set of experiments the 20-mm diameter particles were replaced by three particles of 30 mm diameter corresponding to mass ratio of 1.67%. The average rms response was 4.37 with standard deviation of 0.11. Even though the average response ratio was higher than the average response ratio of the previous experiments performed, the highest response was considerably smaller (rms displacement ratio 4.44) than the highest response occurred without damper (rms displacement ratio 6.21) corresponding to a 28% reduction. Then, one particle of 50 mm diameter (mass ratio of 2.6%) replaced the three particles of 30 mm diameter. The average rms response was 3.75 with standard deviation of 0.35. The highest response was considerably smaller (rms dispalcement ratio 4.0) than the highest response occurred without damper (rms dispalcement ratio 6.21) corresponding to a 36% reduction.

The effect of the damper size was investigated by replacing the large damper with a smaller size one (medium damper with inner diameter = 8 cm) and repeating the experiments under the same excitation. Initially, the eight particles were placed inside the damper. The average rms response was 3.88 with standard deviation of 0.17. The highest response was considerably smaller (rms displacement ratio 4.0) than the highest response without a damper (rms dispalcement ratio 6.21) corresponding to a 36% reduction. Similar results were obtained with the use of other size particles. The average rms response with the three particles of the 30 mm diameter was 3.66 with standard deviation 0.35 and the average rms response with the one particle of the 50 mm diameter was 3.54 with standard deviation 0.27.

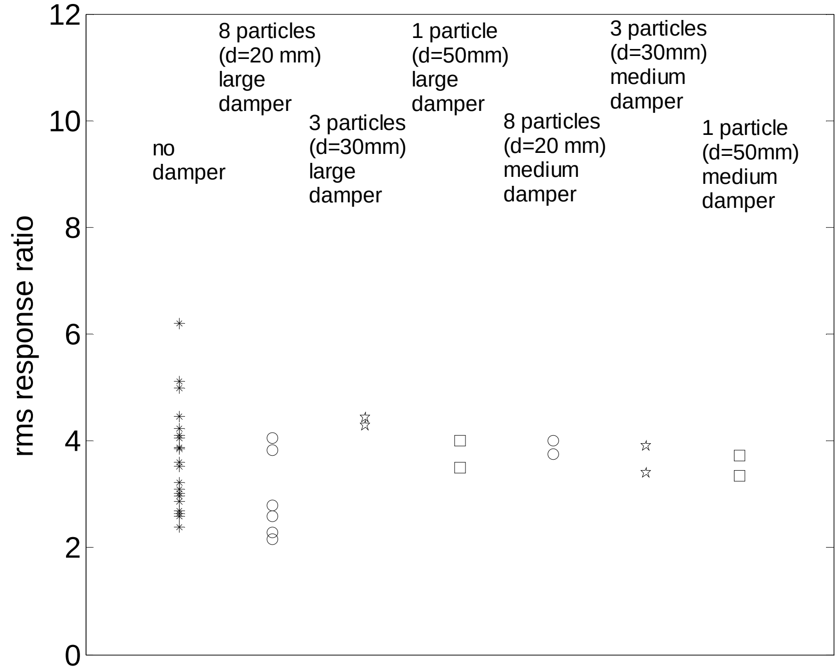

Fig. (6). Root mean square of the response displacement using different size dampers and particles.

For the eight particles the response was better with the large damper since the particles had enough space to move to hit the walls of the container exchanging momentum with the primary system. For the rest of the cases the size of the damper did not influence considerably the response of the column. Sixteen and thirty two of 20-mm diameter particles were also used but the column's response was not influenced by the existence of the damper.

(Fig. (**6**)) presents the rms displacement ratio of all the experiments performed under different initial conditions. When the response of the column obtained from two consecutive experiments under the same initial conditions (excitation, placement of damper, number and size of particles) was similar, no more experiments for this case were performed in order to avoid further material degradation. The damper influences the response of the column. The response is more stable, with less variation from one experiment to the next under the same excitation when the damper is added. The large damper is more effective when the smaller size particles are used since the extra space increases the momentum exchange with the primary system but the response was more variable from experiment to experiment. The smaller size damper would give stability and predictability of the results without being so much influenced from the mass ratio or size of particles.

The damper was placed on the top drum and similar experiments were performed. The response was quite variable and in some cases the damper would slide excessively reducing its effectiveness. The small weight of the damper and the non existence of other drums on the top of the damper reduced the necessary friction needed to avoid the extra sliding. Conclusively, the replacement of the top drum with a damper was not effective in reducing the response of the rest of the drums under sinusoidal excitation.

The particle damper can be effective when it is properly designed. It should be placed above the mid-height but below the top and the mass ratio must be greater or equal to 1% to get the highest efficiency. The particles need enough space to move to be able to exchange momentum with the primary system. The area the particles occupy with respect to the area of the hollow part must be between 30-50% in order to have satisfactory results.

Even though the specimen used was a small scale model of a real column, our experiments still provide useful insight about the influence of particle dampers on the dynamic behavior of multi-drum columns. The damper reduced the sensitivity of the column's dynamic response to small variation of the system parameters and also the column's motion. Preliminary tests with a 3 m model gave similar results. Since the connection of columns with architraves stabilizes the behavior of the individual columns [28] it seems reasonable to conclude that the particle damper will influence positively the response of a series of columns.

Overall, the dynamic response of classical columns can be reduced with the use of particle dampers reaching levels more than 30%. The damage of the drums caused by the pounding of one with the other during their rocking action will be reduced since the overall motion will be reduced.

CONCLUSION

Restoration and preservation of historic structures and monuments is an important issue that many countries with historical heritage face. Common restoration techniques usually are either difficult to implement or alter considerably the historical features of the structure. Particle dampers have been used for many years to reduce the motion of mechanical and small structural systems. The effectiveness of particle dampers in reducing the response of classical columns considering a small column-model under a sweep sinusoidal signal was investigated. A particle damper made of marble resembling the rest of the drums but being hollow containing particles replaced one of the top drums. The influence of different system parameters on the effectiveness of the damper, including mass ratio, particle and damper size were also considered. It was found that the motion of the column can be considerably reduced by replacing the fifth drum with a particle damper. The replacement of the top drum with a damper was not effective in reducing the response of the column under sinusoidal excitation thus this position is not recommended. The large size damper was more effective in reducing the response of the column when the smaller size particles (20 mm diameter) were used. The smaller size damper gave stability and less variation of the response but higher amplitude for the smaller size particles. In addition, congestion of the smaller particles reduced the efficiency of the damper since the particles need space to move to obtain enough momentum. A small number of particles corresponding to mass ratio 1-2% can be sufficient to reduce the motion of a classical column by more than 30% as long as there is sufficient space for the particles to move.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

This research has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: ARCHIMEDES III. Investing in knowledge society through the European Social Fund.

The authors would like to thank Pr. S. Bousias, Pr. T. Triantafillou, Pr. D. Roubien for their useful comments and suggestions as well as the undergraduate student M. Miaoulis for his help. The testing campaign was realized at the Seismic Simulator of the Department of Civil Engineering at the University of Patras under the supervision of Prof. S. Bousias.

REFERENCES

[1] P.G. Asteris, M.P. Chronopoulos, C.Z. Chrysostomou, H. Varum, V. Plevris, N. Kyriakides, V. Silva, "Seismic vulnerability assessment of historical masonry structural systems," *Engineering Structures*, vol. 62-63, pp. 118-134, 2014.

[2] P.G. Asteris, A.D. Tzamtzis, P.P. Vouthouni, D.S. Sophianopoulos, "Earthquake resistant and rehabilitation of masonry historical structures," *Practice Periodical on Structural Design and Construction*, vol. 10, no. 1, pp. 49-55, 2005.

[3] P.G. Asteris, "On the structural analysis and seismic protection of historical masonry structures," *Open Construction and Building Technology Journal*, vol. 2, pp. 124-133, 2008.

[4] M.E. Stavroulaki, A. Papalou, "Parametric analysis of multi-leaf masonry walls," *International Journal of Conservation Science*, vol. 5, no. 4, pp. 435-446, 2014.

[5] "Charter of Venice," Decisions and resolutions, In: *Proceedings of the 2nd International Congress of Architects and Technicians of Historical Monuments*, Venezia, 1964, vol. 5, pp. 25-31 [in French].

[6] S. Russo, "On the monitoring of historic Anime Sante Church damaged by earthquake in L' Aquila," *Structural Control Health Monitoring,* vol. 20, no. 9, pp. 1226-1239, 2013.

[7] G. Boscato, M. Pizzolato, S. Russo, A. Tralli, "Seismic behaviour of a complex historical church in L' Aquila," *International Journal of Historical Heritage*, vol. 8, no. 5, pp. 718-757, 2014.

[8] A. Papalou, S.F. Masri, "Performance of particle dampers under random excitation," *ASME Journal of Vibration and Acoustics,* vol. 118, pp. 614-621, 1996.

[9] A. Papalou, S.F. Masri, "Response of impact dampers with granular materials under random excitation," *International Journal of Earthquake Engineering and Structural Dynamics*, vol. 25, pp. 253-267, 1996.

[10] A. Papalou, S.F. Masri, "An experimental investigation of particle dampers under harmonic excitation," *Journal of Vibration and Control*, vol. 4, pp. 361-379, 1998.

[11] C.N. Bapat, S. Sankar, Multi unit impact damper re-examined, *Journal of Sound and Vibration*, vol. 103, pp. 457-469, 1985.

[12] N. Popplewell, S.E. Semercigil, "Performance the bean bag impact damper for a sinusoidal external force," *Journal of Sound and Vibration*, vol. 133, no. 2, 193-223, 1989.

[13] Y. Araki, Y. Yuhki, I. Yokomichi, Y. Jinnouchi, "Impact damper with granular materials," *Bulletin of JSME,* vol. 28, no. 240, pp. 1121-1217, 1986.

[14] M.Y. Yang, G.A. Lesieutre, S.A. Hambric, G.H. Koopmann, "Development of a design curve for particle impact dampers," *Noise Control Engineering Journal*, vol. 53, no. 1, pp. 5-13, 2005.

[15] Z. Xu, K. Chan, W. Liao, "An empirical method for particle damping design," *Shock and Vibration,* vol. 11, pp. 647-664, 2004.

[16] M. Saeki, "Impact damping with granular materials in a horizontally vibrating system," *Journal of Sound and Vibration*, vol. 251, no. 1, pp. 153-161, 2002.

[17] K. Mao, M.Y. Wang, Z. Xu, T. Chen, "DEM simulation of particle damping," *Powder Technology*, vol. 142, no. 2-3, pp. 154-165, 2004.

[18] L. Hu, Q. Huang, Z. Liu, "A non-obstructive particle damping model of DEM," *International Journal of Mechanics and Materials Design*, vol. 4, no. 1, pp. 45-51, 2008.

[19] C. Wong, M.C. Daniel, J.A. Rongong, "Energy dissipation prediction of particle dampers," *Journal of Sound and Vibration*, vol. 319, no. 1-2, pp. 91-118, 2009.

[20] Z. Lu, S.F. Masri, X. Lu, "Parametric studies of the performance of particle damper under harmonic excitation," *Sturctural Control and Health Monitoring*, vol. 18, no. 1, pp. 79-98, 2011.

[21] R.D. Friend, V.K. Kinra, "Particle impacting damping," *Journal of Sound and Vibration*, vol. 233, no. 1, pp. 93-118, 2000.

[22] K.S. Marhadi, V.K. Kinra, "Particle impact damping: Effect of mass ratio ratio, material and shape," *Journal of Sound and Vibration*, vol. 283, no. 1, pp. 433–448, 2005.

[23] Z. Xu, M.Y. Chen, T. Chen, "Particle damping for passive vibration suppression: Numerical modelling and experimental investigation," *Journal of Sound and Vibration*, vol. 279, no. 3-5, pp. 1097-1120, 2005.

[24] Z. Lu, X. Lu, S.F. Masri, "Studies of the performance of particle dampers under dynamic loads," *Journal of Sound and Vibration*, vol. 329, no. 26, pp. 5415-5433, 2010.

[25] Z. Lu, X. Lu, W. Lu, S.F. Masri, "Experimental studies of the effects of buffered particle dampers attached to a multi-degree-of-freedom system under dynamic loads," *Journal of Sound and Vibration*, vol. 331, pp. 2007-2022, 2012.

[26] N. Argyriou, K. Pitilakis, A. Sextos, "Numerical study of the seismic behavior of drum structures," *1st Greek National Conference of Anastylosis*, ETPAM, Thessaloniki, June 14-17, 2006, pp. 14-16 [in Greek].

[27] N. Argyriou, O-J. Ktenidou, M. Manakou, P. Apostolidis, F.-J Chavez-Garcia, K. Pitilakis, "Seismic response analysis of ancient columns," *4th International Conference on Earthquake Geotechnical Engineering*, Thessaloniki, June 25-28, 2007.

[28] M.E. Dassios, I. Psyxaris, I. Vayias, "Experimental investigation of columns and their assemblages of ancient temples," *3rd Greek Conference in Seismic Mechanics and Technical Seismology*, 5-7 November, 2007 [in Greek].

[29] H.P. Mouzakis, I.N. Psycharis, D.Y. Papastamatiou, P.G. Carydis, C. Papantonopoulos, C. Zambas, "Experimental investigation of the earthquake response of a model of a marble classical column,"

Journal of Earthquake Engineering and Structural Dynamics, vol. 31, pp. 1681-1698, 2002.

[30] M.E. Dassios, X. Mouzakis, I. Psyxaris, K. Papantonopoulos, I. Vayias, "Experimental Investigation of columns and series of columns", *3rd Greek Conference in Seismic Mechanics and Technical Seismology*, 5-7 November, 2008 [in Greek].

[31] D. Konstantinidis, N. Makris, "Seismic response analysis of multidrum classical columns," *Earthquake Engineering and Structural Dynamics*, vol. 34, pp. 1243-1270, 2005.

[32] H.P. Mouzakis, I.N. Psycharis, D.Y. Papastamatiou, P.G. Carydis, C. Papantonopoulos, C. Zambas, "Experimental investigation of the earthquake response of the model of a marble classical column," *Earthquake Engineering and Structural Dynamics*, vol. 31, pp. 1681-1698, 2002.

[33] K. Papadopoulos, E. Vintzileou, "The seismic response of the columns of Epikouriou Apollo's," *3rd Greek Conference in Seismic Mechanics and Technical Seismology*, 5-7 November, 2008 [in Greek].

[34] L. Papaloizou, P. Komodromos, "Planar investigation of the seismic response of ancient columns and colonnades with epistyles using a custom-made software," *Soil-Dynamics and Earthquake Engineering*, vol. 29, pp. 1437-1454, 2009.

[35] C. Papantonopoulos, I.N. Psycharis, D.Y. Papastamatiou, J.V. Lemos, H. Mouzakis, "Numerical prediction of the earthquake response of classical columns using the distinct element method," *Earthquake Engineering and Structural Dynamics*, vol. 31, pp. 1699-1717, 2002.

[36] K. Pitilakis, E. Tavouktsi, "Seismic response of the columns of two ancient Greek temples in Rhodes and Lindos," *8th International Symposium on the Conservation of Monuments in the Mediterranean Basin*, Patra, 31 May-2 June, 2010.

[37] I.N. Psycharis, D.Y. Papastamatiou, A.P. Alexandris, "Parametric investigation of the stability of classical columns under harmonic and earthquake excitations," *Earthquake Engineering and Structural Dynamics*, vol. 29, pp. 1093-1109, 2000.

[38] I. Psycharis, J. Lemos, D. Papastamatiou, C. Zambas, C. Papantonopoulos, "Numerical study of the seismic behaviour of a part of the Parthenon Pronaos," *Earthquake Engineering and Structural Dynamics*, vol. 32, pp. 2063-2084, 2003.

[39] G.C. Manos, "The dynamic performance of ancient columns and colonnades with and without the insertion of wires made of shape memory alloy," *International Conference Structural Studies, Repairs and Maintenance of Historical Buildings,* Dresden, Allemagne, 1999.

Received: September 09, 2014 Revised: December 23, 2014 Accepted: December 29, 2014