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RESEARCH ARTICLE

Control of the Dynamic Response of Classical Columns with Defects

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Abstract

This paper investigates the protection of classical columns in areas of seismic activity using passive control techniques. Small scale multi-drum column-models with a damaged bottom drum or inclined base are considered under random excitation. Their response without any protection is measured and compared with their response when an impact damper is attached to them. The damper takes the form of a drum that looks exactly like the rest of the drums but is hollow and contains particles. It is found that the damper, if it is properly designed, can reduce effectively the motion of classical columns (reaching levels up to 40%) without altering their overall appearance.

Keywords

Passive control · impact damper · particle damper · monuments

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1 Introduction

Monuments are historical structures that need to be protected and preserved. Multi-drum columns can be found mostly in monuments around the Mediterranean and are often exposed to dynamic loads. During anastylosis of monuments, missing or damaged parts are replaced with new materials resembling the old ones. The increase of seismic safety of historical monuments is challenging because conventional methods of strengthening and repair alter their appearance something not acceptable by the principles of Charter of Venice.

Researchers have studied the response of multi-drum columns to dynamic loads [1–10] providing insights in the behaviour of these structures. Further research is needed to increase their seismic safety respecting simultaneously their historic appearance. One of the non-conventional methods that can be utilized to increase the seismic safety of classical columns is the application of impact dampers. Impact dampers have been used for many years to attenuate the response of structures and machines [11–36]. They consist of a container with particles which can move inside the enclosure. When the structure starts to move, the particles hit the walls of the container exchanging momentum with the structure (primary system) and dissipating energy, reducing its response. Impact dampers can be used to reduce the response of classical columns without altering their overall appearance by taking the form of a drum that looks like the rest of the drums but is hollow containing particles. The damper can replace an original damaged drum something very common in anastylosis of monuments.

This paper examines the effectiveness of impact dampers in reducing the motion of multi-drum columns. Since most of monuments have experienced damage due to earthquake loads or other environmental causes, this paper focuses on the worst case scenario by investigating the response of columns with defects under dynamic loads. Initially, the response of a column-model without defects under dynamic load is examined. Next, two column-models with defects are considered: a) one that rests on an inclined base and b) one with a broken base drum. The influence of the system parameters on the behaviour of the damper is investigated.

2 Experimental description

The column-model (primary structure) was designed based on multi-drum columns of ancient monuments having the drum diameter larger than its height. A small scale model (scale 1:8) of an ancient column from the temple of Hephaestus in Athens was chosen. In order to perform the experimental work with ease, a small scale model (scale 1:8) was chosen. The total height of the marble column-model was 651 mm and its weight 19.8 kg. All drums had the same diameter (120 mm) and height (93 mm). The constant size of the drums facilitated the investigation of the best placement of the damper in the column. The drums were placed one above the other without any connection between them. The base of the column was a marble plate with dimensions of 140 x 140 x 20 mm. The marble plate was glued on a larger steel plate attached on a 3 x 5 m shake table capable of moving in one direction. A safety structure consisting of threaded rods and fishing lines was built around the column to prevent damage of the drums (Fig. 1).

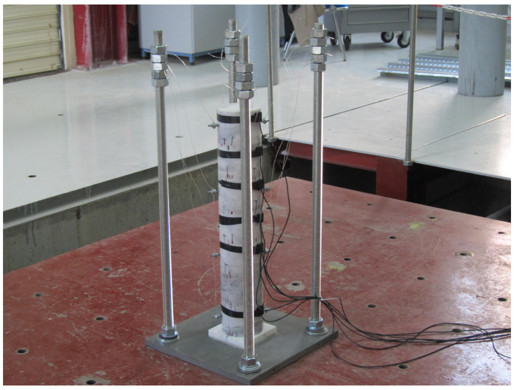

Fig. 1. Experimental set-up of column-model

The response of the column was measured with accelerometers attached on the drums. A built-in accelerometer measured the base motion. A data acquisition system collected the data that were transferred to a computer for analysis. Two dampers were used with diameter of their hollow part 9 cm and 8 cm respectively. The walls of the damper were selected to be thick enough to sustain the impacts of the particles but leaving enough space for the particles to move. One spherical steel particle was placed inside the damper having 50 mm diameter. Some experiments were performed with a larger number of particles having 20 mm diameter. The mass of the single particle of 50 mm diameter with respect to the mass of the column (mass ratio) was 2.6%. This mass ratio is small and in the range of the ones that has been used in other studies ([15, 35]). A random signal was used for the excitation (Fig. 2) containing frequencies in the range of 1 - 10 Hz, including all natural frequencies of the primary structure.

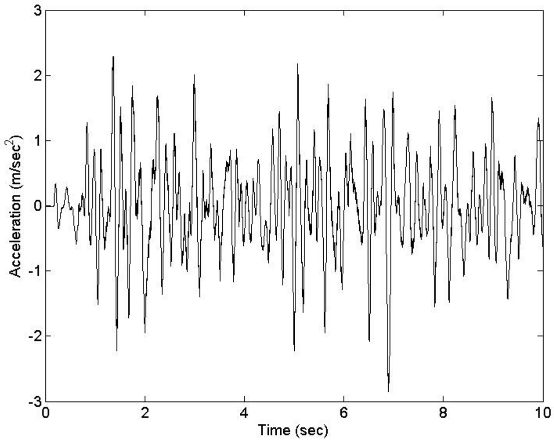

Fig. 2. Input motion (random signal)

3 Results and discussion

3.1 Column without defects

The column-model without the damper was excited by the random signal. The drums were sliding, rotating and rocking. It was noticed that small imperfections affected the response of the column. To increase the robustness of the results the experiments were repeated several times. A good measure of the response of the vibrating structure is the root mean square (rms) of the displacement of the structure with respect to the root mean square of the displacement of the base (rms response ratio). Thus, the acceleration signals were integrated twice to obtain the displacements. The average rms response ratio of the top drum for the series of tests performed without damper was 5.5. Fig. 3a presents the relative displacement of the top drum in the direction of excitation for a representative experiment with mid-response (rms response ratio 5.13).

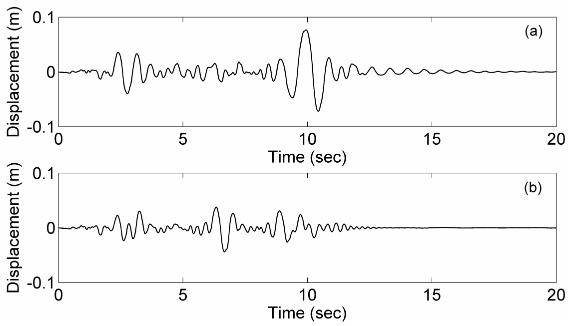

Fig. 3. Displacement of top drum: (a) without damper; (b) with damper

Next, the damper replaced one of the drums above the mid-height of the column where the motion was larger. One particle of 50 mm diameter was used (Fig. 4). Initially, the damper with the large hollow part replaced the 5th drum in order to affect the response of the top and bottom drums. The average rms response ratio of the top drum was 2.92. Fig. 3b presents the displacement of the top drum in the direction of excitation for a representative experiment with mid-response (rms response ratio 3.22). The response was reduced considerably (more than 40%). The free-vibration of the column, which occurred after 10 sec when the forced vibration stopped, died out much faster.

The single particle inside the damper was replaced with particles of 20 mm diameter. The response was similar to the response of one particle (even with smaller mass ratio) when there

Fig. 4. Damper with one particle of 50 mm diameter

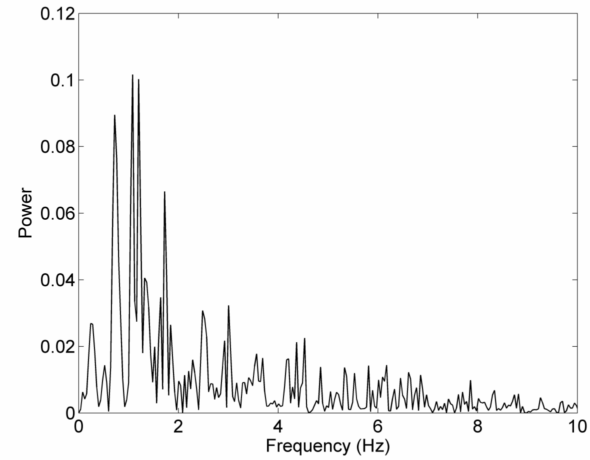

Fig. 6. Frequency spectrum of absolute acceleration of column's top drum (without damper)

was enough space for the particles to move and exchange momentum with the primary system [37].

3.2 Column with defects

3.2.1 Inclined column

The column was raised from one side inserting a wooden plate under the steel plate achieving a 2.5% slope. Tests were performed with and without damper for the same input random signal used earlier. The results are presented for the top drum of the column where the motion was larger.

The column moved considerably loosing its balance in half of the experiments (Fig. 5). The peak values of the frequency spectrum of the absolute acceleration of the column's top drum in the direction of motion (Fig. 6) were below 2 Hz. The average rms response ratio for the series of experiments conducted was 8.93, excluding the ones in which the column lost its balance. The displacement of the top drum relative to the base in the direction of the motion is shown in Fig. 7 for a representative experiment that the column did not loose its balance (rms response ratio 8.30). Close to the end of the experiment the column exhibited out of plane motion which was smaller than the motion in the direction of excitation.

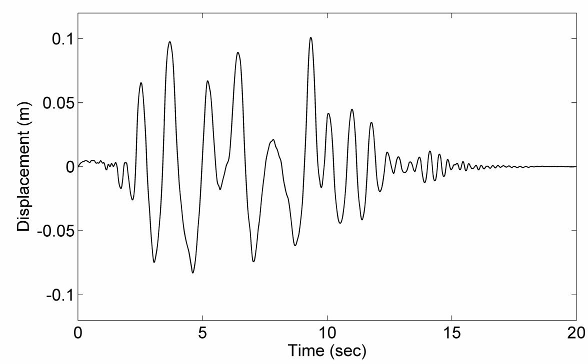

Fig. 7. Displacement of top drum in the direction of motion (without damper)

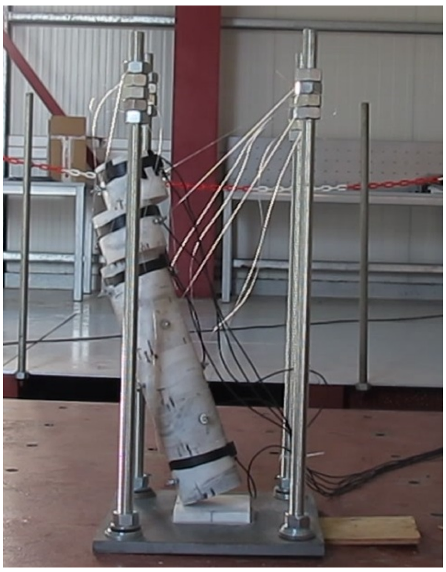

Fig. 5. Response of column without damper under random excitation

The damper with the large hollow part replaced the 5th drum containing one particle of 50 mm diameter. The mass of the particle with respect to the mass of the column was 2.60%. The particle of the 50 mm diameter occupied about 30% of the area of the hollow part of the (9 cm diameter of hollow part) damper. The presence of the damper reduced the motion of the column at the beginning of the experiment but towards the end the motion became large and the column became unstable. A steel plate was inserted inside the large damper creating internal slope close to the slope of the column but at opposite direction. In this experiment the motion was reduced in all directions (average rms response ratio 4.50) increasing the stability of the column. Fig. 8 presents the frequency spectrum of the absolute acceleration of the column's top drum. The peak values below 2 Hz were reduced but those above 2 Hz increased. The high frequencies have a small effect in the overall motion of the column. The displacement of the top drum relative to the base is shown in Fig. 9. The motion was reduced considerably (close to 35%).

The damper with the 8 cm diameter of the hollow part (the particle occupied 40% of the area of the hollow part) was effective even without tilting its base (Figs. 10 - 11). The small distance between the walls reduced the effect of the column's inclination on the damper. Similar results were obtained when one of the dampers replaced the top drum.

Steel spherical particles of smaller diameter (20 mm) were also used. They were not as effective in reducing the motion of the column as the single steel particle of 50 mm diameter. Due to the inclination of the column the small spherical particles gathered close to the one side of the container unable sometimes to reach the opposite wall of the container. Tilting the base of the damper did not improve consistently the performance of the damper with this size of particles, resulting in small reduction of the column's response.

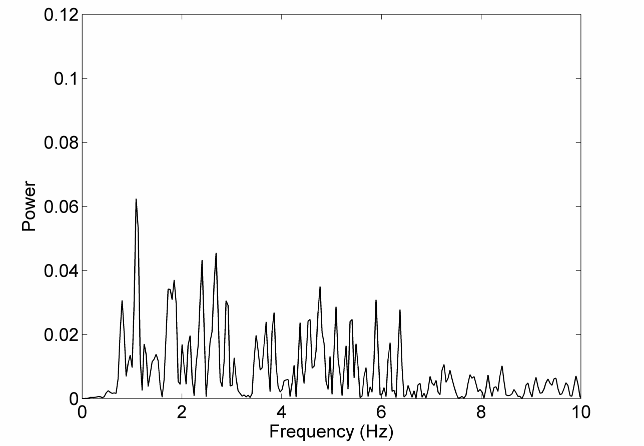

Fig. 8. Frequency response of absolute acceleration of column's top drum (with large damper replacing the 5^{th} drum)

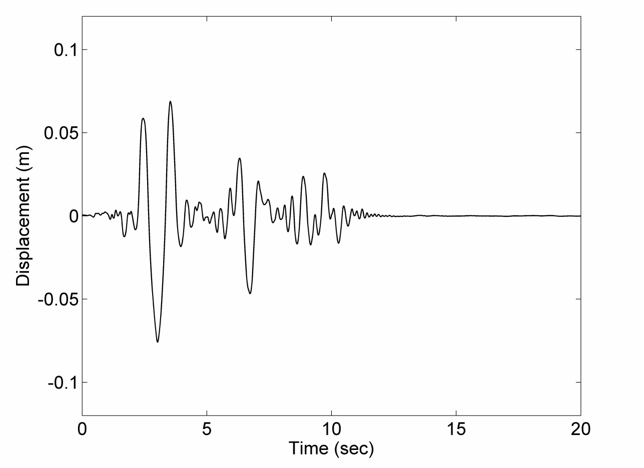

Fig. 9. Displacement of top drum (with large damper and one particle of 50 mm diameter)

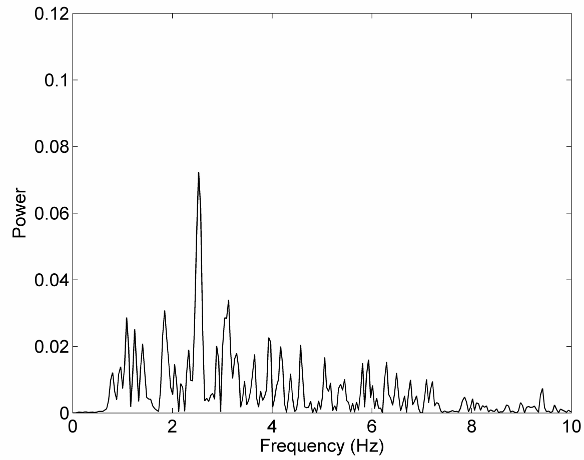

Fig. 10. Frequency spectrum of absolute acceleration of column's top drum (with damper replacing the 5^{th} drum)

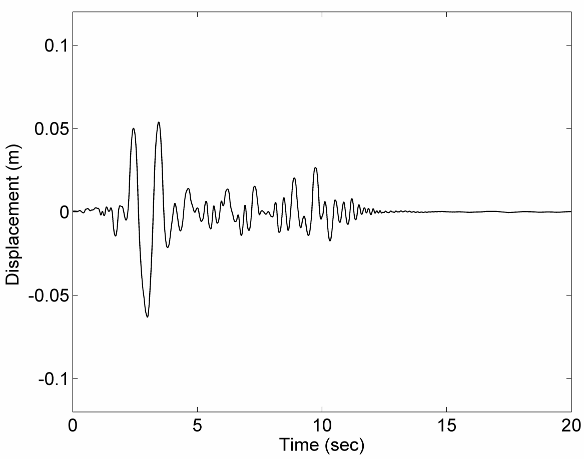

Fig. 11. Displacement of top drum in the direction of motion (with damper)

3.2.2 Column with broken base-drum

In this case the base was levelled and the first drum of the column was replaced by a drum broken in one side. The broken part was at the bottom of the drum and oriented in the direction of motion creating this way the worst case scenario that can be encountered in practice (Fig. 12). The column was excited by the same random signal used earlier.

The column moved considerably loosing its balance in four out of the seven experiments conducted. Fig. 13a shows the displacement of the top drum of the column for a representative experiment in which the column lost its balance about 10 sec after the excitation started, that is towards the end of the forced vibration. When the motion became large the column due to the defect at the bottom could not return to its initial position loosing its balance and falling (Fig. 14).

In the first tests, the damper with the large hollow part replaced the 5^{th} drum. One steel particle of 50 mm diameter was placed inside the damper. The response of the column to the random excitation was reduced during the last seconds and the column return to its initial position without loosing its balance (Fig. 13b). After the forced vibration stopped the column vibrated freely for a few seconds till the motion completely stopped.

Similar response was observed when the damper with the small hollow part replaced the damper with the large one. The column was stable without loosing its balance in any of the experiments but a small increase of the amplitude response was observed compared with the response of the column with the damper with the large hollow part.

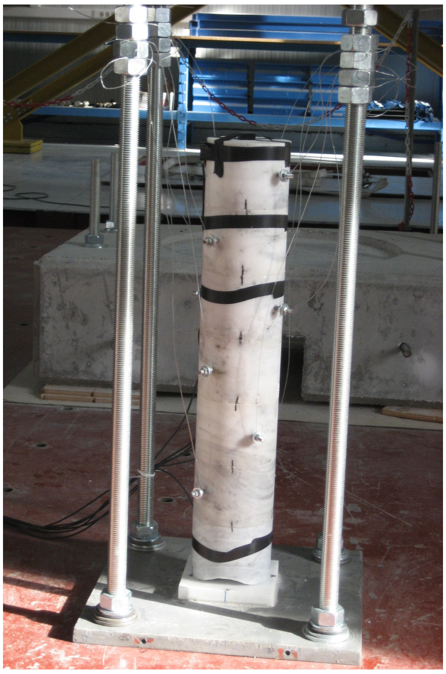

Fig. 12. Experimental set-up of colum model with a broken base-drum

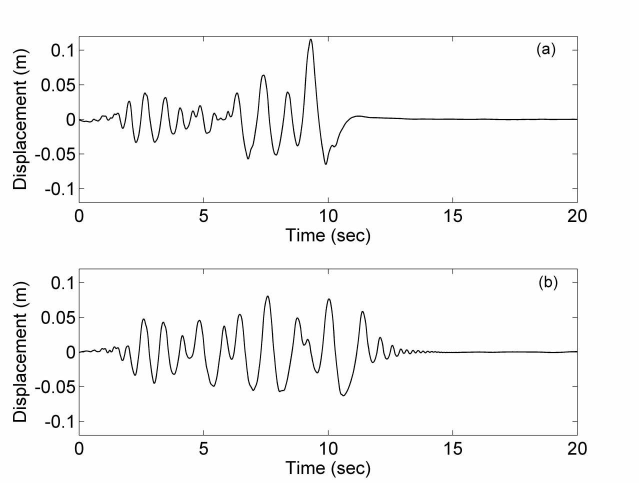

Fig. 13. Dispalcement of top drum of column with a broken base-drum: (a) without damper (b) with damper

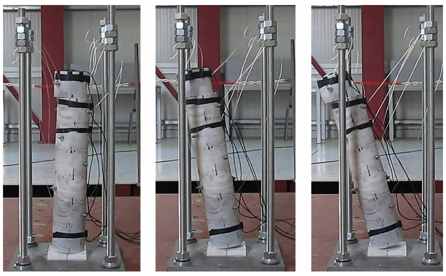

Fig. 14. Response of column without damper under random excitation

In addition, eight steel spherical particles of 20 mm diameter were also used (mass ratio 1.33%) occupying 50% of the area of the hollow part of the large damper. This number of particles was selected so that they had the space needed to move and exchange momentum with the primary system. They were less effective (approximately 15%) in reducing the motion of the column compared to the results obtained with the single steel particle of 50 mm diameter. Experiments were also conducted replacing the top drum with a damper. The motion of the column was large in some experiments but the column did not loose its balance.

In general, classical columns with defects including broken drums or inclination of the base can be less vulnerable to seismic action if one of their drums below the top one is replaced by a hollow drum containing one particle. The mass ratio (mass of particle with respect to mass of the column) must be approximately 2 - 2.5%. In addition, the area that the particle occupies with respect to the area of the hollow part must be 35 - 40%. As an example, a common classical column of 10 m height and average drums diameter of 1.7 m will need a 0.70 m diameter particle to move in a hollow part of 1.1 m diameter.

4 Conclusions

The effectiveness of an impact damper in reducing the response of ancient monuments consisting of multi-drum columns that have been damaged or lying on inclined surfaces was investigated. A damper, in the form of a regular drum looking outside exactly like the rest of the drums but being hollow containing particles, replaced an original drum. It was found that if the damper is located above the mid-height of the column, where the motion is larger, but below the top drum it can effectively reduce the response when a single particle (mass of particle with respect to mass of column in the range of 2.5%) is used. The particle needs to have enough space to move to exchange momentum with the primary system performing well for ratios of area the particle occupies with respect to the area of the hollow part of the damper in the range of 35 - 40%. When the ground has an inclination special care needs to be taken creating either internal slope inside the damper opposite to the slope of the ground or reducing the distance that the particle has to move alleviating the effect of the slope of the ground. Properly designed dampers can give a good solution in increasing the seismic safety of monuments without altering their overall appearance.

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References

1 **Psycharis I, Papastamatiou D, Alexandris A**, *Parametric investigation of the stability of classical columns under harmonic and earthquake excitations*, Earthquake Engineering and Structural Dynamics, **29**, (2000), 1093–1109, DOI 10.1002/1096-9845(200008)29:8<1093::AID-EQE953>3.0.CO;2-S .

2 **Psycharis I, Lemos J, Papastamatiou D, Zambas C, Papantonopoulos C**, *Numerical study of the seismic behaviour of a part of the Parthenon Pronaos*, Earthquake Engineering and Structural Dynamics, **32**, (2003), 2063–2084, DOI 10.1002/eqe.315.

3 **Mouzakis H, Psycharis I, Papastamatiou D, Carydis P, Papantonopoulos C, Zambas C**, *Experimental investigation of the earthquake response of a model of a marble classical column*, Earthquake Engineering and Structural Dynamics, **31**, (2002), 1681–1698, DOI 10.1002/eqe.184.

4 **Papantonopoulos C, Psycharis I, Papastamatiou D, Lemos J, Mouzakis H**, *Numerical prediction of the earthquake response of classical columns using the distinct element method*, Earthquake Engineering and Structural Dynamics, **31**, (2002), 1699 –1717, DOI 10.1002/eqe.185.

5 **Konstantinidis D, Makris N**, *Seismic response analysis of multidrum classical column*, Earthquake Engineering and Structural Dynamics, **34**, (2005), 1243–1270, DOI 10.1002/eqe.478.

6 **Argyriou N, Ktenidou O-J, Manakou M, Apostolidis P, Chavez-Garcia F-J, Pitilakis K**, *Seismic response analysis of ancient columns*, In: 8th International Conference on Earthquake Geotechnical Engineering; Thessaloniki, Greece, 2007.

7 **Dassios M, Psycharis I, Vayias I**, *Analysis of seismic behaviour of columns and series of columns of ancient temples*, In: 3rd Greek Conference in Seismic Mechanics and Technical Seismology; Athens, Greece, 2008. (in Greek).

8 **Papadopoulos K, Vintzileou E**, *The seismic response of the columns of Epikouriou Apollo's*, In: 3rd Greek Conference in Seismic Mechanics and Technical Seismology; Athens, Greece, 2008. (in Greek).

9 **Papaloizou L, Komodromos P**, *Planar investigation of the seismic response of ancient columns and colonnades with epistyles using a custom-made software*, Soil-Dynamics and Earthquake Engineering, **29**, (2009), 1437–1454, DOI 10.1016/j.soildyn.2009.06.001.

10 **Pitilakis K, Tavouktsi E**, *Seismic response of the columns of two ancient Greek temples in Rhodes and Lindos*, In: 8th International Symposium on the Conservation of Monuments in the Mediterranean Basin; Patra, Greece, 2010. (in Greek).

11 **Araki Y, Yuhki Y, Yokomichi I, Jinnouchi Y**, *Impact damper with granular materials*, Bulletin of JSME, **28**, (1986), 1121–1217, DOI 10.1299/jsme1958.29.4334.

12 **Araki Y, Yuhki Y, Yokomichi I, Jinnouchi Y**, *Impact damper with granular materials*, Bulletin of JSME, **28**, (1986), 1121–1217, DOI 10.1299/jsme1958.29.4334.

13 **Bapat C, Sankar S**, *Multi unit impact damper—re-examined*, Journal of Sound and Vibration, **103**, (1985), 457–469, DOI 10.1016/S0022-460X(85)80015-8.

14 **Popplewell W, Semercigil S**, *Performance the bean bag impact damper for a sinusoidal external force*, Journal of Sound and Vibration, **133**(2), (1989), 193–223, DOI 10.1016/0022-460X(89)90922-X.

15 **Papalou A, Masri SF**, *Performance of particle dampers under random excitation*, ASME Journal of Vibration and Acoustics, **118**, (1996), 614–621, DOI 10.1115/1.2888343.

16 **Papalou A, Masri SF**, *Response of impact dampers with granular materials under random excitation*, International Journal of Earthquake Engineering and Structural Dynamics, **25**, (1996), 253–267, DOI 10.1002/(SICI)1096-9845(199603)25:3<253::AID-EQE553>3.0.CO;2-4.

17 **Papalou A, Masri SF**, *An experimental investigation of particle dampers under harmonic excitation*, Journal of Vibration and Control, **4**, (1998), 361–379, DOI 10.1177/107754639800400402.

18 **Papalou A, Masri SF**, *Experimental Studies of Particle Dampers under Random Excitation*, In: First World Conference on Structural Control; Los Angeles, California, 1994, DOI 10.1002/eqe.4290241210.

19 **Friend R, Kinra VK**, *Particle impact damping*, Journal of Sound and Vibration, **233**(1), (2000), 93–118, DOI 10.1006/jsvi.1999.2795.

20 **Olson S**, *An analytical particle damping model*, Journal of Sound and Vibration, **264**(5), (2003), 1155–1166, DOI 10.1016/S0022-460X(02)01388-3.

21 **Saeki M**, *Impact damping with granular materials in a horizontally vibrating system*, Journal of Sound and Vibration, **251**(1), (2002), 153–161, DOI 10.1006/jsvi.2001.3985.

22 **Mao K, Wang M, Xu Z, Chen T**, *DEM simulation of particle damping*, Powder Technology, **142**(2-3), (2004), 154–165, DOI 10.1016/j.powtec.2004.04.031.

23 **Xu Z, Chan K, Liao W**, *An empirical method for particle damping design*, Shock and Vibration, **11**, (2004), 647–664.

24 **Xu Z, Chen M, Chen T**, *Particle damping for passive vibration suppression: numerical modelling and experimental investigation*, Journal of Sound and Vibration, **279**(3–5), (2005), 1097–1120, DOI 10.1016/j.jsv.2003.11.023.

25 **Marhadi K, Kinra V**, *Particle impact damping: effect of mass ratio, material and shape*, Journal of Sound and Vibration, **283**(1), (2005), 433–448, DOI 10.1016/j.jsv.2004.04.013.

26 **Liu W, Tomlinson G, Rongong J**, *The dynamic characterisation of disk geometry particle dampers*, Journal of Sound and Vibration, **280**(3-5), (2005), 849–861, DOI 10.1016/j.jsv.2003.12.047.

27 **Yang M, Lesieutre G, Hambric S, Koopmann G**, *Development of a design curve for particle impact dampers*, Noise Control Engineering Journal, **53**(1), (2005), 5–13, DOI 10.3397/1.2839240.

28 **Fang X, Tang J**, *Granular damping in forced vibration: qualitative and quantitative analyses*, Journal of Vibration and Acoustics, **128**(4), (2006), 489–500, DOI 10.1115/1.2203339.

29 **Li K, Darby A**, *Experiments on the effect of an impact damper on a multiple-degree-of-freedom system*, Journal of Vibration and Control, **12**(5), (2006), 445–464, DOI 10.1177/1077546306063504.

30 **Hu L, Huang Q, Liu Z**, *A non-obstructive particle damping model of DEM*, International Journal of Mechanics and Materials in Design, **4**(1), (2008), 45–51, DOI 10.1007/s10999-007-9053-z.

31 **Wong C, Daniel M, Rongong J**, *Energy dissipation prediction of particle dampers*, Journal of Sound and Vibration, **319**(1-2), (2008), 91–118, DOI 10.1016/j.jsv.2008.06.027.

32 **Lu Z, Masri S, Lu X**, *Parametric studies of the performance of particle damper under harmonic excitation*, Structural Control and Health Monitoring, **18**(1), (2011), 79–98, DOI 10.1002/stc.359.

33 **Lu Z, Lu X, Masri S**, *Studies of the performance of particle dampers under dynamic loads*, Journal of Sound and Vibration, **329**(26), (2010), 5415–5433, DOI 10.1016/j.jsv.2010.06.027.

34 **Lu Z, Masri S, Lu X**, *Studies of the performance of particle dampers attached to a two-degree-of-freedom system under random excitation*, Journal of Vibration Control, **17**(10), (2011), 1454–1471.

35 **Lu Z, Lu X, Lu W, Masri S**, *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, **331**, (2012), 2007–2022, DOI 10.1016/j.jsv.2011.12.022.

36 **Naeim F, Lew M, Carpenter L, Youssef N, Rojas F, Saragoni G, Adaros M**, *Performance of tall buildings in Santiago, Chile during the February 2010 off shore Maule, Chile earthquake*, The Structural Design of Tall and Special Buildings, **20**(1), (2011), 1–16, DOI 10.1002/tal.674.

37 **Papalou A, Strepelias E**, *Effectiveness of Particle Dampers in Reducing the Monuments' Response under Dynamic Loads*, Mechanics of Advanced Materials and Structures, (2014), DOI 10.1080/15376494.2014.943913.