17^{th} *World Conference on Earthquake Engineering, 17WCEE*
Sendai, Japan - September 13th to 18th 2020

INNOVATIVE STRATEGIES FOR STATIC RESTORATION OF COLUMNS MADE UP OF RIGID BLOCKS

L. Petti[(1)], D. Greco[(2)], F. Nuccio[(3)]

[(1)] *Professor, University of Salerno, petti@unisa.it*
[(2)] *Researcher, University of Salerno, dgreco@unisa.it*
[(3)] *Young researcher, University of Salerno, filomena.nuccio@gmail.com*

Abstract

Greek and Roman constructions represent an extraordinary heritage on which the Mediterranean culture is founded, describing among all the traditions and evolution and the complex development of knowledge. Although, some typologies of ancient constructions have shown in many cases a high capacity towards aging and extreme natural phenomena, the ordinary degradation and/or human induced damages require, in any case, a particular caution in defining a management plan for preservation and conservation, compatible with the principles underlined by the Venice Chart. In this context, some monuments made up of stone blocks, such as slender structures, present an intrinsic appeal and represents a challenge for civil engineering.

The work investigates innovative strategies to preserve columns made up of rigid blocks by means of simplified analysis methods carried out by a wide experimental campaign aimed to investigate the behaviour of such structures. To the scope, simplified equivalent non-linear models are developed by investigating the overall dynamic behaviour through the fundamental parameters such as the vibration period, the restitution ratio and the equivalent damping factor.

The proposed approach permits to study innovative static restoration technique based on a suitable alteration of the interface mechanical proprieties between stone blocks by means of neoprene sheets. The described strategies produce an improvement of the damping capacity and the control of the contact phenomena among blocks only slightly modifying the natural vibration period and the static behaviour of columns. For the purpose, examples of models of the columns of the temple of Neptune in Paestum (Southern Italy) are considered in case of expected seismic demand for large return period.

Keywords: rigid body dynamics, column restoration, seismic response.

1. Introduction

The study of the dynamic behaviour of monumental buildings, such as the Greek temples, is one of the most critical issues in the field of conservation and protection of Cultural Heritage, especially in earthquake-prone areas (UNESCO, 2013).

Housner described the behaviour of a rigid body (Housner, 1963), trying to explain the limited damage to some structures at the Chilean earthquake of 1960 and other examples of columns and other parts of monumental structures that still stand after disastrous seismic events. The model of Housner (Fig. 2), considered in numerous studies (bibliography reported in Giannini 1980 and Sorrentino 2003), defines the motion of a non-deformable body in rigid contact interface conditions. At present, different approaches are available in the literature considering different contact types at the interface (Giannini, 1991) between the blocks in both rigid and elastic contact hypothesis. Normally, rigid contact models assume the non-deformable joints, infinite compression strength, non-tensile strength and not sliding effects (Heyman, 1997). In the case of elastic contact models, it is hypothesized to concentrate the deformability of the section where the impact occurs, introducing a suitable link (Giannini, 1991) to describe the constitutive laws.

Other recent studies seem to show the impossibility of modeling the phenomenon of rocking in multi-block columns with a single rigid system (Minafò et al., 2016). Some research studies on the seismic response of this type of structures were also carried out (Konstantinidis et al., 2005), with the aim of determining the level of seismic shaking in conditions of incipient collapse. Moreover, in the literature, there are experimental tests on shaking table of a portal made by two columns formed by different rigid blocks (Drosos et al., 2014) and release tests to assess main dynamic parameters (Petti et al., 2017, 2018, 2019).

Fig. 1 – The Neptune temple of Paestum (Southern Italy).

The paper shows a deeper study of the dynamic behaviour of ancient rigid block structures through experimental tests on several configurations of Greek temples, such as the Neptune temple in Paestum (Fig. 1), located in the Southern Italy not far from the Sannio and Irpinia Appennini faults system. Even though the valley of the temples in Paestum suffered in several earthquakes in the past (La Greca, 2007), the ancient monuments did not undergo particular damages, highlighting a low seismic vulnerability. Nevertheless, damages caused by other natural (wind, thunderstorm, etc..) and human-induce hazards, underline the need to evaluate the safety evolution of the dynamic behaviour of such constructions. Moreover, the built-up damage, could be caused local fragilities, such as partial crushing of blocks and local breaks at the drum interfaces.

With the aim of assessing the static and seismic safety of the temples in Paestum, the validity range of the main dynamical parameters (restitution coefficient, vibration period and damping factors) has been evaluated to describe their relationship with the response amplitude.

Based on the assessment of the overall dynamic response, the study presents new restoration strategy that entails a favorably improvement of columns static and seismic behaviour by means of neoprene sheets interposed among drums. In such a way, it possible to improve the overall response of ancient structures by increasing damping ratios and lowering local stresses, slightly affecting the global behaviour in terms of

© The 17th World Conference on Earthquake Engineering - 3d-0009 -

vibration period. Moreover, the interposition of neoprene sheets brings about an easy substitution of one or more damaged drums when needed by avoiding punctual contact effects. At the end, this kind of restoration strategy could be very efficient and non-invasive for the structure only having the need of maintenance with the replacement of the neoprene sheets when required and, especially, the intervention is completely reversible.

2. Rigid block behaviour

The model of Housner is represented by a homogeneous parallelepiped block on a not deformed ground and no sliding at the base: the motion is described by a single Lagrangian coordinate, represented by the rotation θ.

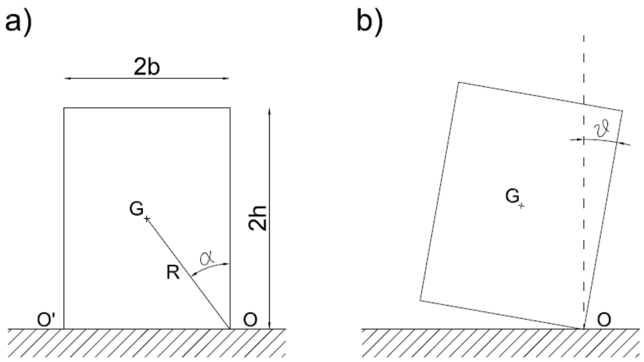

Fig. 2 – The model of Housner (1963).

In the above described model, G represents the centre of gravity, R is the semi-diagonal, h the semi-height, b the semi-base, m the overall mass and W=mg the weight of the block. The geometry of the block is described by the semi-diagonal R and the angle α, which provides a block slenderness ratio. The angle θ is the rotation with which the block oscillates alternately around its two lower vertices O and O '.

The fundamental equation of the motion can be written as:

$$\ddot{\theta} = -\mathrm{sgn}(\theta) \cdot p^2 \cdot \mathrm{sen}(\alpha - |\theta|) \quad (1)$$

The mathematical problem (1) is characterized by a double nonlinearity for the presence of trigonometric terms and the sign function which describes the alternation of the rotation point at the base due to the collisions. In the case of small rotations and slender blocks (α≤20°) the problem can be simplified (2) as follow:

$$\ddot{\theta} = -p^2 \cdot \alpha + p^2 \cdot \theta \quad (2)$$

where p is the frequency parameter and I_O the mass moment of inertia concerning the pole O:

$$p = \sqrt{\frac{mgR}{I_0}}; \qquad I_0 = \frac{4}{3} m \cdot R^2$$

In addition, in the hypothesis of null initial angular velocity, the relation (3) allows to evaluate the natural vibration period as follows, showing that the oscillation period depends on the initial rotation:

© The 17th World Conference on Earthquake Engineering

$$T = \frac{4}{p}\cosh^{-1}\left(\frac{1}{1-\theta_0/\alpha}\right) \tag{3}$$

In the case of two drums, the energy dissipation due to the collisions at the base can be described using the restitution coefficient (*e*) (Yim and Chopra, 1980) which depend on the kinetic energy variation (*r*). For rigid conditions the following apply (Petti et al., 2017):

$$r = \frac{\frac{1}{2}\cdot I_0 \cdot \dot{\theta}_2^{\ 2}}{\frac{1}{2}\cdot I_0 \cdot \dot{\theta}_1^{\ 2}} = (\frac{\dot{\theta}_2}{\dot{\theta}_1})^2 = e^2 \tag{4}$$

$\dot{\theta}_1$ and $\dot{\theta}_2$ respectively represent the velocities at the time immediately before and after the collision. By setting the angular momentum to the rotation pole O, it is possible to evaluate the restitution coefficient as:

$$e = \frac{\dot{\theta}_2}{\dot{\theta}_1} = \sqrt{r} = \frac{1}{4} + \frac{3}{4}\cdot\cos(2\alpha) \tag{5}$$

The relation (5) shows that the restitution coefficient (*e*) is function of the geometry of the block, and in particular of the slenderness.

In the following figures, some examples of experimental release tests (T_1-T_{10}), carried out to validate the previous theoretical formulations and assessing the fundamental vibration period, the restitution coefficient and the damping factor, in function of the initial rotation angle θ, are shown. With regard to the equivalent viscous damping ξ, it is possible to consider the following relation (Claugh et.al., 1975):

$$\eta = e^{-\frac{2\pi\xi}{\sqrt{1-\xi^2}}} \tag{6}$$

since η is the reduction ratio obtained by considering two consecutive maximum response values.

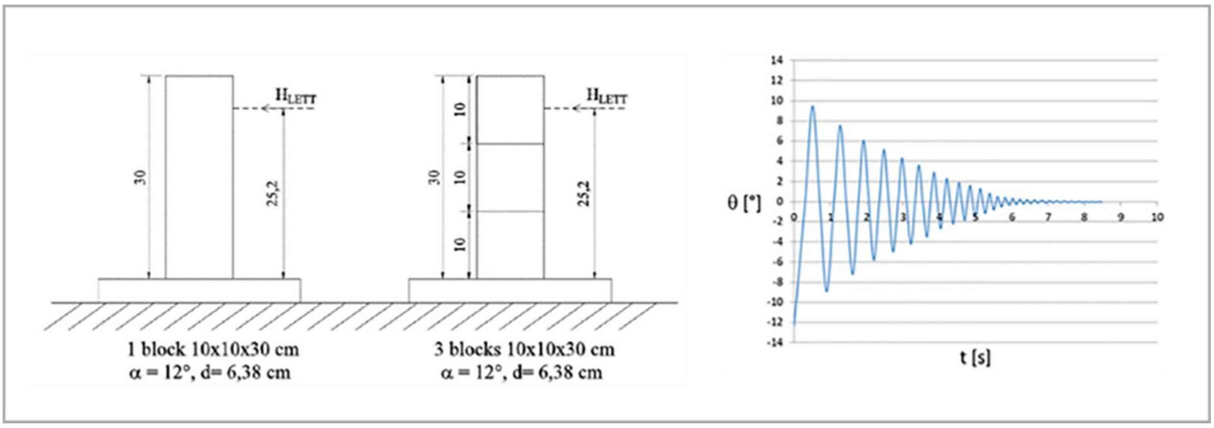

Fig. 3 – Experimental test: example of single and multi-block set-up configurations with an example of free response time history.

© The 17th World Conference on Earthquake Engineering

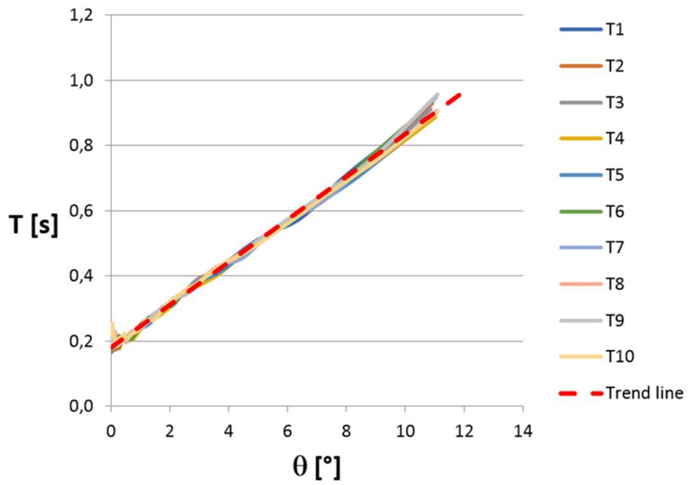

Fig. 4 – Experimental overall vibration period trends of the single-block column configuration.

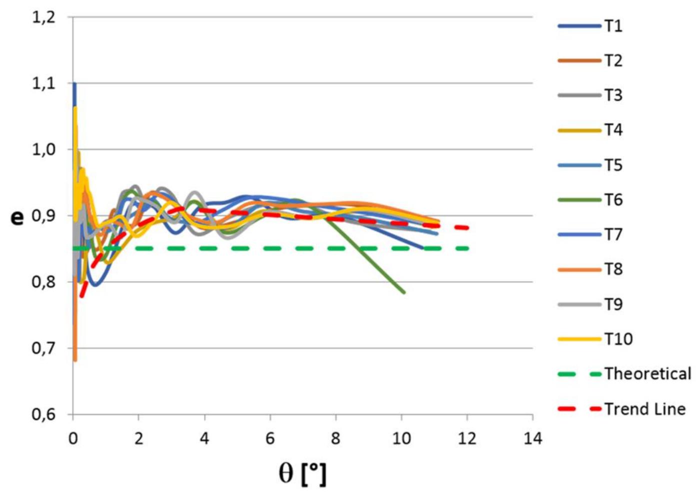

Fig. 5 – Experimental restitution coefficient of the single-block column configuration.

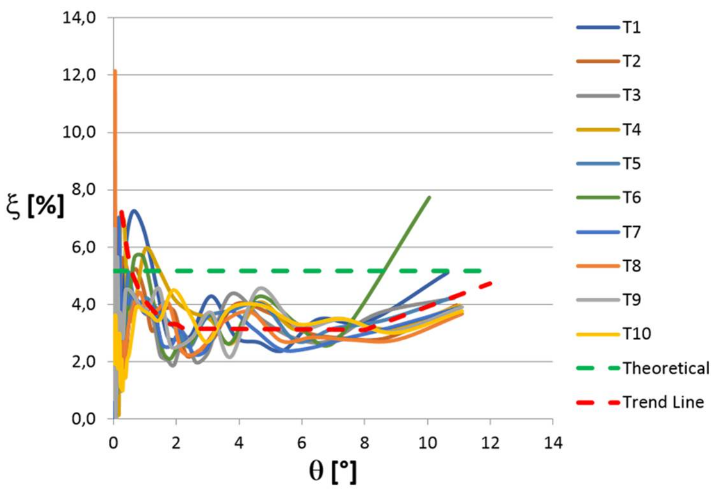

Fig. 6 – Experimental equivalent damping factor of the single-block column configuration.

© The 17th World Conference on Earthquake Engineering

3. Experimentation of multi-block column scale models

As described before, the paper presents an innovative restoration strategy with the aim to reduce the continuous degradation of the blocks occurring at each impact by placing at the interface of each drum and only at the base of multi-block column configurations investigated some neoprene sheets.

Two different types of column configurations, with neoprene sheets among every drum interface and only one at the base interface, were tested, considering three, four and five-block configurations. The blocks are made up of cellular cement (siporex, “S”).

The dynamic motion assessment of the columns was performed by using Micro-Epsilon interferometric laser sensors (Opto ILD 1420-200), where the data acquisition system was designed to describe the position of the specimens at each instant of the tests. The initial angle α used to carry out the tests for each different configuration is equal to 12°. Through simple trigonometric relations, it was possible to determine, for each instant of time, the principal descriptive parameters of the dynamic behaviour of the single block have been evaluated, i.e. the vibration period, the restitution coefficient and the damping factor.

The following figures show the results of the release tests conducted for the four-block configuration. In the details, ten experimental tests (T_1-T_{10}) were performed and the trend lines were evaluated for each configuration.

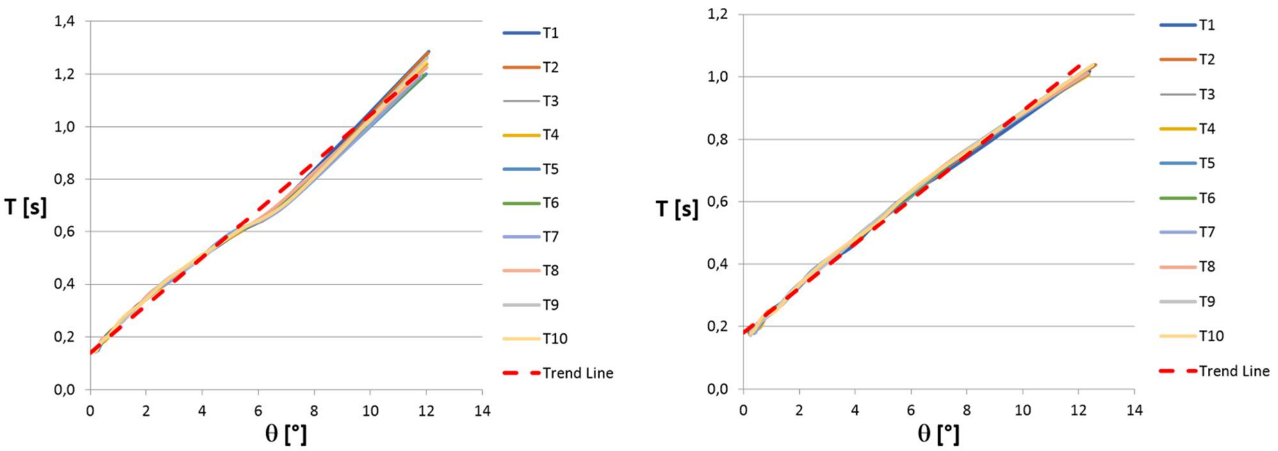

Fig. 7 – Experimental overall vibration period trends of the four-block column configuration: one neoprene sheet at the base interface (left), neoprene sheets at every drum interfaces (right).

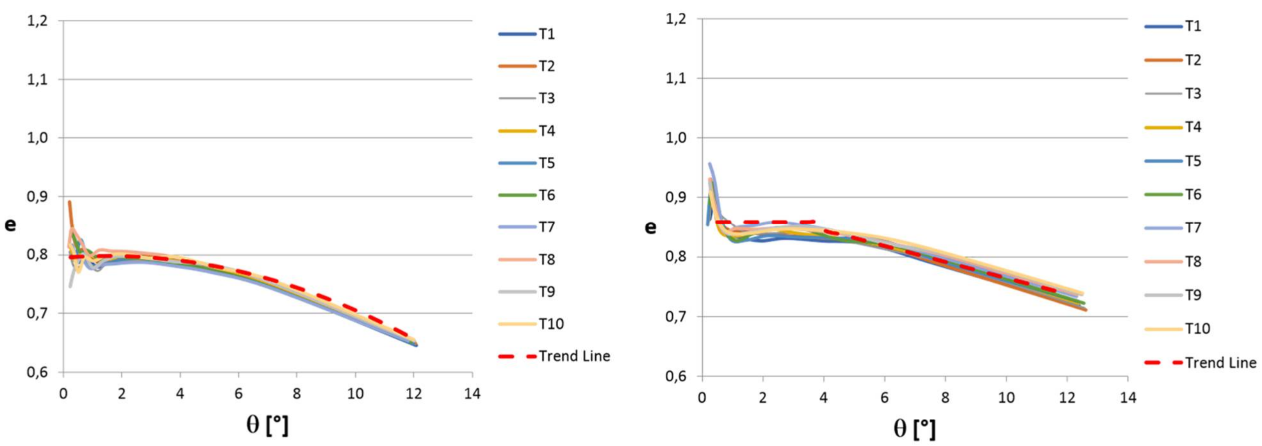

Fig. 8 – Experimental restitution coefficient of the four-block column configuration: one neoprene sheet at the base interface (left), neoprene sheets at every drum interfaces (right).

© The 17th World Conference on Earthquake Engineering - 3d-0009 -

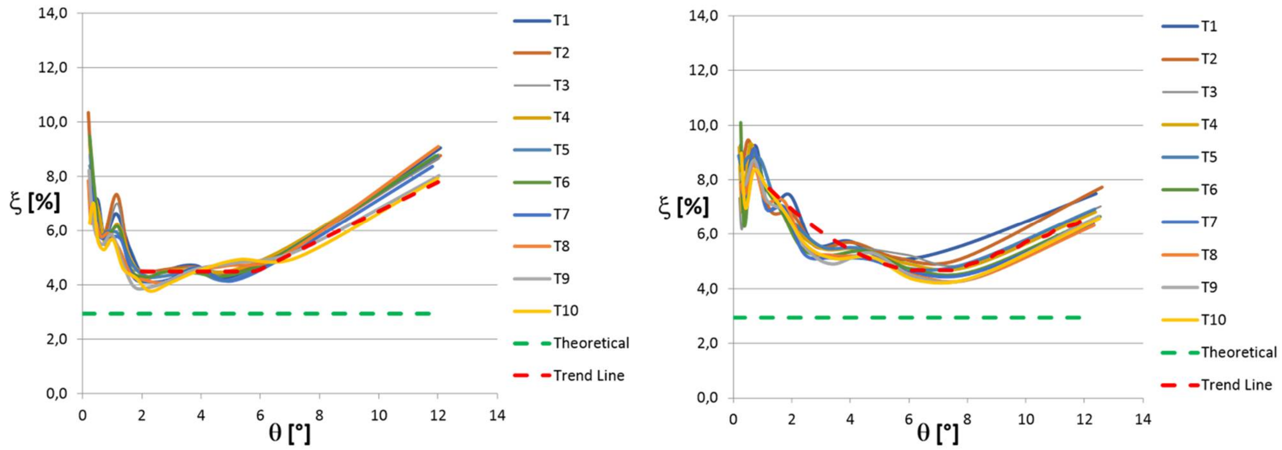

Fig. 9 – Experimental equivalent damping factor of the four-block column configuration: one neoprene sheet at the base interface (left), neoprene sheets at every drum interfaces (right).

The following figures describe the overall comparison of the obtained results in term of vibration period, restitution coefficient and damping factor for all the considered configurations, with and without neoprene sheets. In the details, the three-drum (blue), the four-drum (green) and the five-drum (red) configurations are shown.

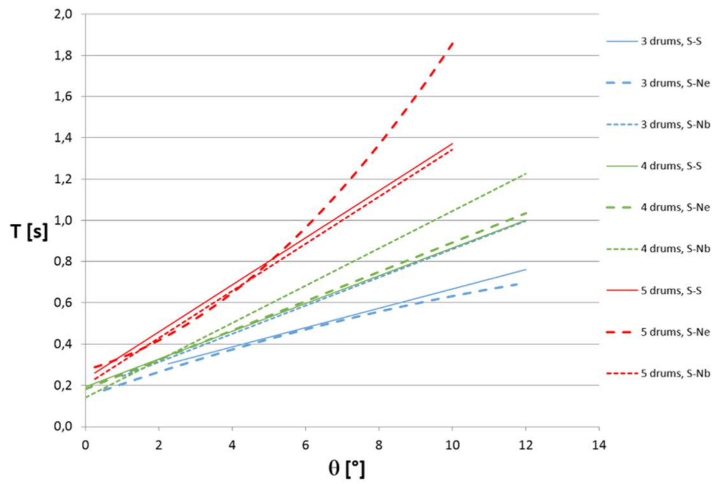

Fig. 10 – Experimental overall vibration period trends of multi-block configurations: three, four and five-drums configurations (S= without neoprene, N_b= neoprene at the base, N_e= neoprene everywhere).

The previous figure shows that the interposition of neoprene sheets among all the drums affects the vibration period trends only in the case of configurations with a higher number of drums and for initial rotation angles values greater than about 6°. Instead, the placing of a neoprene sheet only at the base of the column affects the vibration period trends only for columns made up of three and four drums. In any case, experimental results show a generally increasing of the fundamental vibration period trends, which permits to have an improvement of the response in the case of seismic demand.

Figure 11 shows that with the interposition of neoprene sheets, the more the number of drums increase, the less the restitution coefficient trends decrease, due to the impacts that occur at the interfaces. In addition, the more the initial rotation angle θ grow, the more observed differences increase. Moreover, columns have a more homogeneous behaviour for a higher number of drums configurations.

© The 17th World Conference on Earthquake Engineering

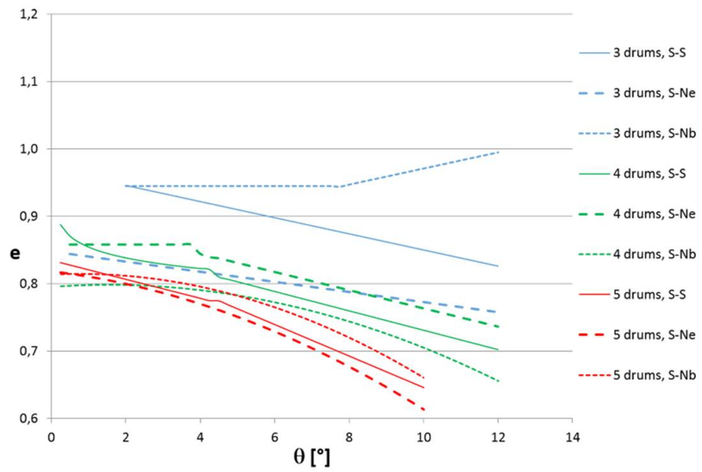

Fig. 11 – Experimental restitution coefficient of multi-block configurations: three, four and five-drums configurations (S= without neoprene, N_b= neoprene at the base, N_e= neoprene everywhere).

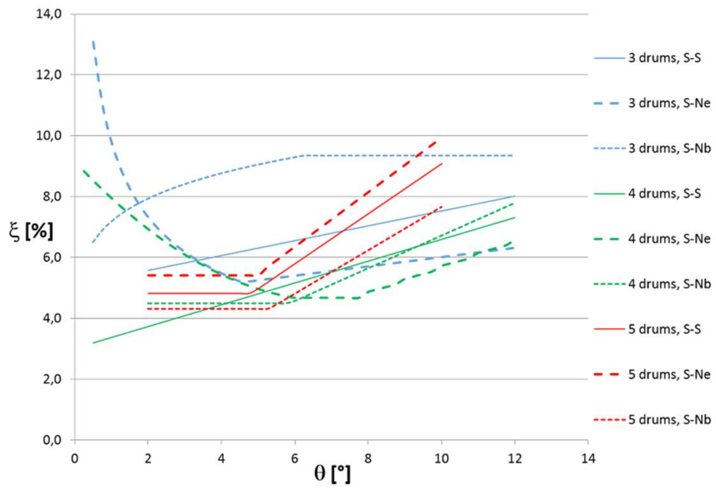

Fig. 12 – Experimental equivalent damping factor of multi-block configurations: three, four and five-drums configurations (S= without neoprene, N_b= neoprene at the base, N_e= neoprene everywhere).

Figure 12 highlights that the difference between multi-block column configurations with and without the interposition of neoprene sheets among all the drums, in terms of equivalent damping, grows for low values of the initial rotation angle, where the damping factor assumes the maximum value. The interposition of neoprene sheets improves the column damping capacity for low load conditions. On the other hand, the presence of a neoprene sheet only at the base of the column leads to: an improvement of the overall response regardless of the value of the angle θ in the case of three-drum configurations; it does not determine significant changes of the response in the case of four-drum configurations; it is slightly worse for five-drum column configurations.

These observations highlight that, from a global point of view, neoprene sheets permit, in any case, the reduction of contact effects by avoiding local stress peaks at the interface among blocks.

In the following tables the comparisons between the case without neoprene and the configurations with neoprene sheets at every drum interfaces (N_e) or only at the base (N_b) are highlighted. In the details, the up arrow "↑", the down arrow "↓" and the symbol of equivalence "=" mean respectively an increasing, a decreasing and an equivalence of the trends compared to the configuration without neoprene sheets.

© The 17th World Conference on Earthquake Engineering

Table 1 – Vibration period (*T*)

	3 drums configuration	**4 drums configuration**	**5 drums configuration**
N_b	↓	=	↑
N_e	↑	↑	=

Table 2 – Restitution coefficient (*e*)

	3 drums configuration	**4 drums configuration**	**5 drums configuration**
N_b	↓	↑	↓
N_e	↑	↓	↑

Table 3 – Damping factor (ξ)

	3 drums configuration	**4 drums configuration**	**5 drums configuration**
N_b	↓	↓	↑
N_e	↑	↓	↓

3. Conclusions

The paper investigated the choice of using innovative restoration technique for ancient columns, such as the ones of the Neptune temple in the Archaeological Park of Paestum (Southern Italy), by interposing neoprene sheets among drums. To this scope, the study of behaviour of rigid blocks motion was conducted, by comparing analytical and experimental results for columns made up of rigid blocks.

The obtained experimental results leaded to evaluate the principal dynamic parameters such as the fundamental vibration period, the restitution coefficient and the equivalent damping factor for single and multi-block configurations by also using neoprene sheets at every drum interface and a sheet only at the base of the column.

The experimental results of the conducted research confirm that restoration interventions by placing synthetic material among drum interfaces of ancient columns can lead to improve the dynamic response of structures such as Greek temple, whose columns have a rigid body behaviour. In fact, with this strategy, it is possible to avoid local stress peaks, improving the local dynamic behaviour, by increasing the damping ratio for low initial rotation angles, slightly affecting the global behaviour in terms of vibration period.

Moreover, this kind of intervention could be very efficient and non-invasive for the structure only having the need of maintenance with the replacement of the synthetic sheets when damaged and, most of all, the rubber sheets lead to avoid contact effects.

4. Acknowledgements

The activity presented in the paper has been carried out with the support of Archeological Site of Paestum in Italy (Gabriel Zuchtriegel, Director; Antonella Manzo, Architect) and PRIN2015 National Research Project "Protecting the cultural heritage from water-soil interaction related threats" n. prot. 2015EAM9S5.

© The 17th World Conference on Earthquake Engineering

5. References

[1] UNESCO (2013). Managing Cultural World Heritage. ISBN 978-92-3-001223-6.

[2] Applied technology Council (1996). ATC-40. Seismic Evaluation and Retrofit of Concrete Buildings. Report No. SSC 96-01 November 1996.

[3] NTC – 2018, New Regulations for Constructions.

[4] Hart, R., Cundall, P. A. (1988). Formulation of a Three-dimensional Distinct Element Model – Part II. *Mechanical Calculations for Motion and Interaction of a System Composed of Many Polyhedral Blocks.*

[5] Petti, L., Barone, F., Mammone, A. , Giordano, G., Di Buono A. (2016). Advanced Methodologies and Techniques for Monuments Preservation: the Trajan Arch in Benevento as a Case of Study. *In 1st International Conference on Natural Hazard & Infrastructure, EACS 2016 – 6th European Conference on Structural Control Sheffield, England: 11-13 July 2016.*

[6] Housner, G. W. (1963). The behavior of inverted pendulum structures during earthquakes. Bulletin of the Seismological Society of America. Vol. 53, No. 2, pp. 403-417, February 1963.

[7] Minafo', G., Amato, G., Stella, L. (2016). Rocking behaviour of multi-block columns subjected to pulse-type ground motion acceleration. *The Open Construction and Building Technology Journal, 2016, 10, (Suppl 1: M9) 150-157.*

[8] Clough, R. W., Penzien, J. (1975). Dynamic of structures. Mc Grow-Hill Inc. ,US. ISBN-10:0070850984.

[9] Dromos, V., Anastasopoulos, I. (2014). Shaking table testing of multidrum column and portals. *Earthquake Engineering & Structural Dynamics, 2014, 43:1703-1723.*

[10] Yim, C.S., Chopra, A.K. and Penzien, J. (1980). Rocking response of rigid blocks to earthquakes. *Earthquake Engineering & Structural Dynamics, 1980, vol. 8, 565-587.*

[11] Konstantinidis, D. and Makris, N. (2005). Seismic response analysis of multidrum classical columns. *Earthquake Engineering & Structural Dynamics, 2005, 34: 1243-1270.*

[12] Petti L, Sicignano F, Greco D. (2017). Dynamic behaviour assessment of ancient columns through experimental analysis. *In: XVII Convegno ANIDIS "L'Ingegneria Sismica in Italia", 17-21 Settembre, Pistoia, pp. 2534-2541.*

[13] Obón Santacana F., Dorka U. E., Nguyen C. K. L, Petti L. (2017). Behaviour of Greek columns during earthquakes with and without tendon system. *Lisbon, Portugal.*

[14] Petti, L., Sicignano F., Greco D. (2018). Seismic and dynamic assessment of monumental structures made up of rigid blocks: Neptune temple. *In 16th European Conference on Earthquake Engineering, Thessaloniki, 2018.*

[15] Petti L, Greco D, Nuccio F, (2019). Seismic behaviour assessment of columns made up of rigid blocks. *XVIII Convegno ANIDIS, 15-19 Settembre 2019, Ascoli Piceno.*

[16] Petti, L., Barone, F., Greco D., Zuchtriegel, G. (2019). Innovative structural monitoring as tool of preservation and valorisation of monumental architectures: the case of Neptune Temple in Paestum. In: *Sustainable conservation of UNESCO and other heritage sites through proactive geosciences, Egypt, 10-12 December 2019.*

[17] Petti L, Sicignano F, Greco D, (2018). Valutazione della risposta dinamica e sismica del tempio di Nettuno: risultati preliminari. L'emblema dell'eternità. *Edizioni ETS, Paestum. ISBN-13: 978-8846754639, 177-189 pag.*

[18] Petti L, Grelle G, Greco D, (2019). Procedure innovative pe l'analisi della risposta sismica delle costruzioni monumentali realizzate a blocchi rigidi. Il caso del tempio di Nettuno. Zuchtriegel, Carter, Oddo. *Paestum. POSEIDONIA E L'ACQUA. Archeologia e cambiamenti climatici; ISBN: 978-88-87744-86-6, 123-133 pag.*

Baratta I, Corbi O, Corbi L, De Andreis L, Marchetti L, Greco D, Petti L, (2019). Heritage Preservation: Challenges and Perspective, *STC 2019 International Conference, Salerno.*

© The 17th World Conference on Earthquake Engineering