STUDY OF THE DYNAMIC AND EARTHQUAKE BEHAVIOR OF ANCIENT COLUMNS AND COLONNADES WITH OR WITHOUT THE INSERTION OF SMA-WIRE DEVICES

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ABSTRACT

Results and conclusions are presented from an experimental and numerical study that examines the response of simple models of ancient columns or colonnades. The influence on the response arising from the inclusion of devices based on wires having energy dissipation characteristics (SMA wires) is also studied. The excessive rocking and sliding and subsequent collapse of the epistyle is an additional form of unstable response in addition to the excessive rocking, rotation and sliding of the individual columns. The insertion of the SMA devices seems to inhibit, up to a point, unstable modes of response, whereas these identical model structures without the wires developed certain types of unstable response at lower excitation amplitudes. The numerical simulation used to predict the pull-out test response of the colonnade structural formation with or without SMA devices seems to reproduce the most significant aspects of the observed response.

Key words: Ancient Masonry, Monuments, Dynamic and Earthquake Behavior, Shape Memory Alloy Devices

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INTRODUCTION

Studied Structural Configurations

Ancient Greek peripheral temples composed of large heavy members that simply lie on top of each other in a perfect-fit construction without the use of connecting mortar, are distinctly different from relatively flexible contemporary structures. The dynamic and earthquake behavior of this type of structural systems is simulated in the present study by utilizing specimens that are relatively rigid and are developing deformations mainly by rocking and sliding response at their supporting boundaries. The employed rigid bodies for forming these models were made of steel and are assumed to be models of prototype structures 20 times larger. Three basic configurations are examined here, as outlined in the following:

Model Single Steel Column

The first studied structural configuration is that of a model single steel truncate cone assumed to be a model of a monolithic free-standing column, as shown in figures 1a and 1b. As reported elsewhere by Manos and Demosthenous (1991, 1997), these model columns, as all steel columns which were employed in the formation of model colonnades that are described next, were manufactured in such a way that they could represent prototype columns either sliced in drums or monolithic columns. For the tests reported here, for the single steel column or for the steel column colonnades, all model columns are monolithic.

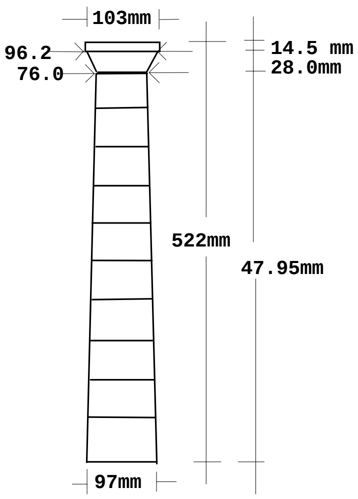

Figure 1a. Geometry of the single steel column

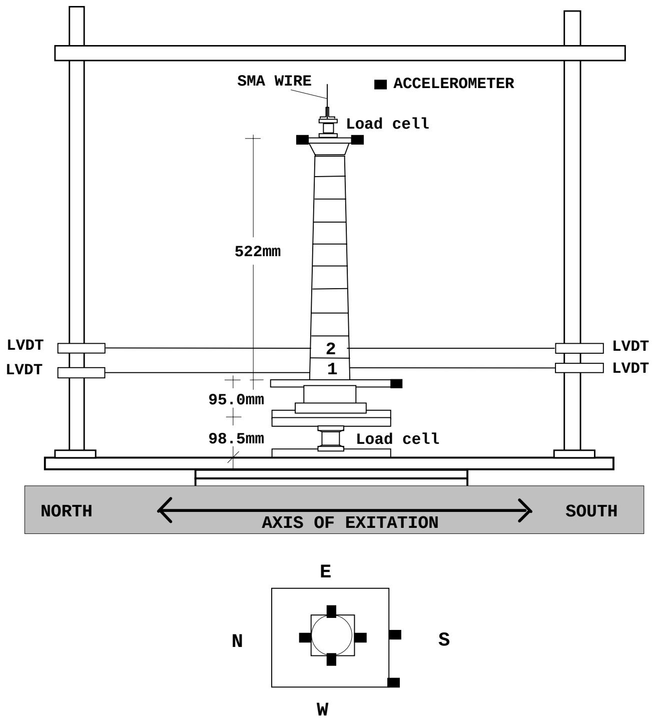

Figure 1b Single steel column on the shaking table

Two-Steel Column Model Colonnade

The second studied structural configuration is formed by two steel truncate cones, of the same geometry as the model of the individual column described in 1.1 before, but supporting a rectangle of solid steel at the top, representing in this way the simplest unit of a colonnade; this is shown in figure 2. In this second configuration the weight of the epistyle was varied. This variation of the weight of the epistyle results in numerous sub-formations from which two distinct cases are reported here; one with this weight of the epistyle being equal to 286Nt whereas the second had the weight of 605Nt. The centers of this two-steel column model colonnade coincided with the axis of the horizontal base motion.

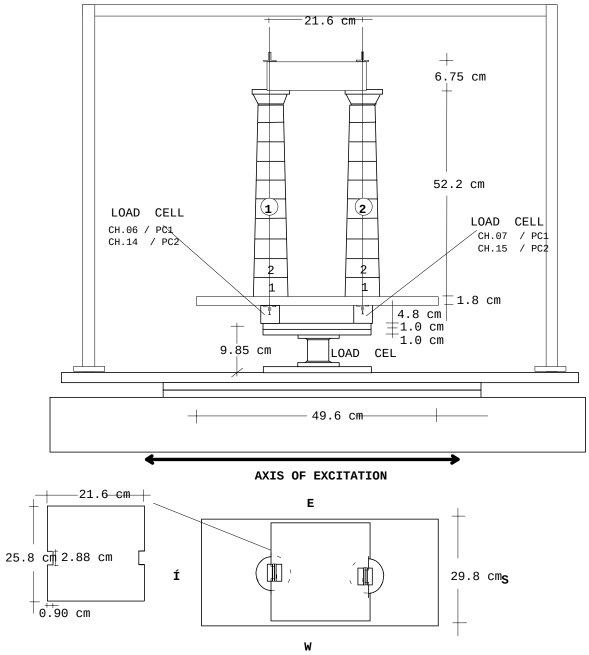

Figure 2. Two-steel column model colonnade

Four-Steel Column Model Colonnade

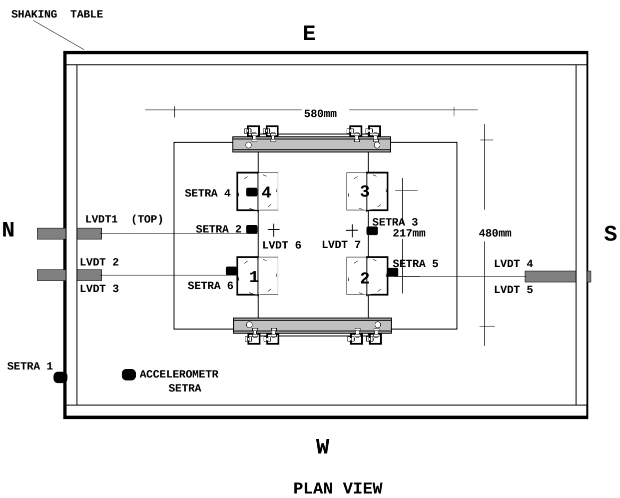

Figure 3a. Four-column colonnade (Plan View)

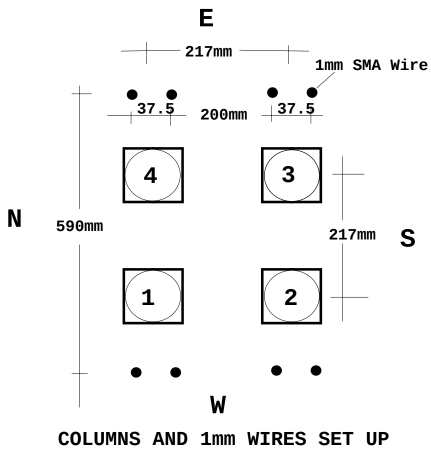

Figure 3b Location of the SMA wires

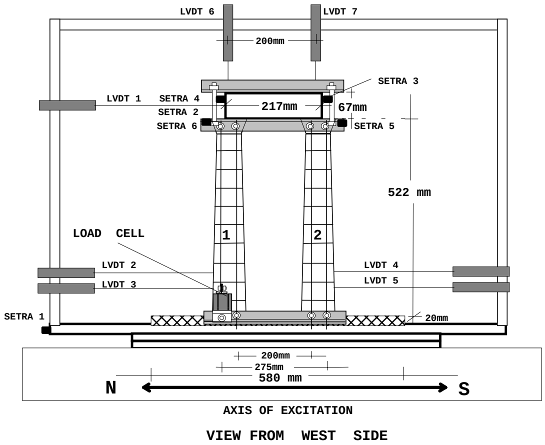

Figure 3c Four column colonnade. Testing arrangement along the axis of the horizontal base motion.

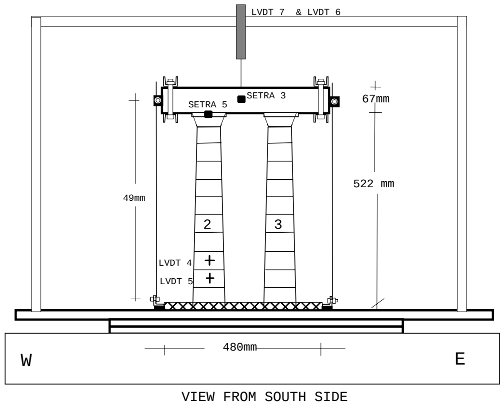

Figure 3d Four column colonnade. Testing arrangement transverse to the axis of the horizontal base motion.

The third configuration is again a model colonnade formed by four steel truncate cones with identical geometry to the ones used before. A monolithic rectangular steel epistyle with dimensions shown in figures 3a, 3c and 3d was placed at the top of these identical four steel columns in a perfect fit condition. This model structural formation is depicted in figure 3a showing the four column assembly looked at from the top of the epistyle as it is resting on the shaking table moving platform. Indicated in figure 3a is the relevant orientation of this model formation with the North (N) - South (S) direction coinciding with the direction of the horizontal motion of the shaking table. As can be seen in figures 3a, 3c and 3d the four-steel column model colonnade is symmetric with respect to this N-S axis of horizontal excitation. It can also be considered as a twin of the two-steel column model colonnade described in 1.2 before, because of the identical geometry and the weight of the epistyle on the four-column formation which is approximately twice as much of the weight of the epistyle for the two-column formation. Some details on the geometry and the instrumentation that was employed in this testing arrangement with the four-column formation is also depicted in figures 3a to 3d.

<u>Configurations of Columns and Colonnades with SMA Wire Devices</u>

As already mentioned, the focus of the study was to examine influences on the dynamic and earthquake response arising from the inclusion of shape memory alloy devices (SMAD's). These devices were based on 1mm or 1.5mm diameter shape memory alloy wires. The SMAD's were applied at critical locations and aimed to provide an increased resistance as well as energy dissipation capacity.

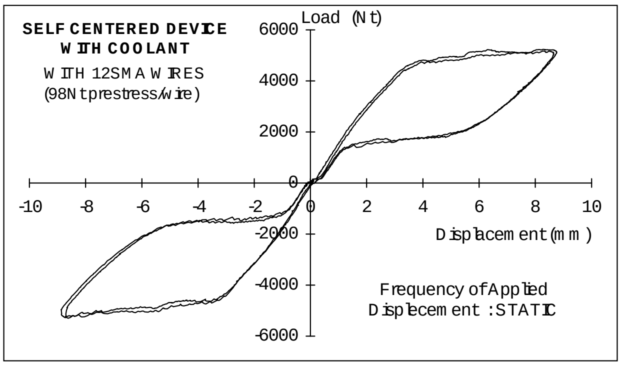

Fig. 4a. SMA Device under "Static" displacement

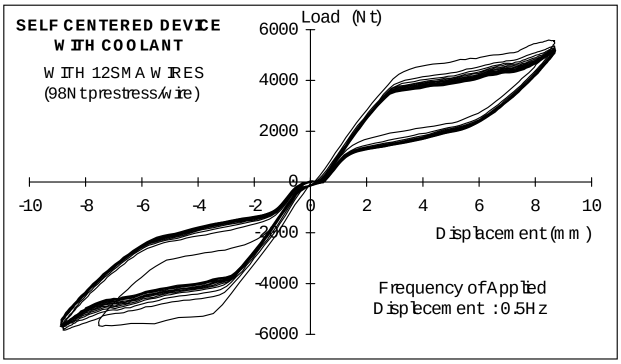

Fig. 4a. SMA Device under "Dynamic" displacement

The SMA wires that were used throughout were provided by FIP Industriale of Padova, Italy, in the framework of a co-operative research project (ISTECH) supported by the European Union (Manos, 1998, 1999, 2000).

Their mechanical properties were fully investigated in the framework of this project by a special testing campaign conducted at the Joint Research Center of the European Union at Ispra, Italy.

A number of basic tests were also conducted at the Laboratory of Strength of Materials of Aristotle University with the SMA wires that were directly employed in the present investigation. Moreover, a self centering device using the same wires was manufactured at Aristotle University and was utilised in a special investigation focusing on the sliding problem of the marble top block.

This device was wholly designed, constructed and tested at Aristotle University. In order to attain the mechanic characteristics of the SMA wires a fully dynamic uni-axial tensil e testing machine was utilised whereby specimens of the wires could be tested in a fully cyclic manner with the desired amplitude and frequency. The cyclic response of the self-centered SMA device, measured at the laboratory, is depicted in figures 4a and 4b. The SMA device response in figure 4a is for a very slow application of the imposed displacement, which is named for this reason as "static", whereas figure 4b depicts the cyclic response of the same SMA device for the imposed cyclic displacement varied with a frequency of 0.5Hz. As can be seen from these figures, the dissipative nature of the cyclic response is present for both the "static" as well as the dynamic imposition of the displacement of this self-centered SMA device.

<u>Single Steel Column</u>

Here, the SMAD was composed of a single 1mm wire, which was positioned through the center of the column and was anchored at the base and the top, as shown in figure 1b. This wire penetrated the steel column through its center. Special anchoring devices were used for the 1mm SMAD both at the bottom and at the top of this steel column. This was achieved by supporting the column on the shaking table with an additional cylindrical steel foundation, so that the anchoring fixture at the bottom of the column could be accommodated.

Two-Steel Column Model

The SMAD's were again composed of single 1mm SMA wires. These devices were again positioned through the centers of the columns and were anchored at the base and the top, as shown in figure 2. The SMAD's penetrated the steel columns through their center. The same special anchoring devices that were used for the single column were employed again for the 1mm SMAD's for both columns at the top and bottom of each.

Four-Steel Column Model.

For the colonnade with the four steel columns, various arrangements for employing the SMAD's were tried. The two most prominent were:

a. Four or Eight 1mm SMA devices.

The number of devices employed here was either four or eight. The removal of the four devices located the furthest from the center of this model colonnade resulted in the four SMAD arrangement (figures 3a to 3d).

b. Sixteen 1mm and four 1.5mm SMA devices.

The special anchoring light frame at the top block was again used; this time in order to anchor four 1.5mm single wire SMA devices at the four corners of the top steel block. Moreover, similar light metal cups were also fixed at the top of each column head in order to anchor there four SMAD's (with 1mm single wire) at the four corners of each column.

EXPERIMENTAL INVESTIGATION

During this experimental sequence the models described in 1.1, 1.2 and 1.3 are subjected to a variety of base motions before and after the intervention technique with the SMA wire devices. During testing, acceleration and displacement measurements were recorded in order to identify sliding and rocking modes of response. A very stiff, light metal frame was built around the studied model structure in order to carry the displacement transducers that measured the rocking angle; this metal frame also provided temporary support to the specimen during excessive rocking displacements indicating overturning. The sequence of tests included a series of sinusoidal base excitations as well as earthquake simulated tests. Moreover, through a series of relatively strong intensity base motions, the stability of the model formations was studied together with the resulting collapse modes at certain stages, focusing on the influence that the inclusion of the SMA wires has on such collapse modes. Finally, the dynamic and simulated earthquake base motions were supplemented with tests named 'Pull Out Static Tests'. During these tests a well controlled horizontal displacement was imposed at the top of the studied model formation at a slow rate. The displacement response of the model was monitored together with the horizontal load that resulted at the top from the gradually imposed horizontal displacement.

OBTAINED EXPERIMENTAL MEASUREMENTS

Model single steel column without SMA wires

Sinusoidal Tests During these tests the frequency of motion was varied from 1.5Hz to 4Hz. This resulted in groups of tests with constant frequency for the horizontal sinusoidal motion for each test. In the various tests belonging to the same group of constant frequency, the amplitude of the excitation was varied progressively from test to test. Summary maximum response results from such tests are depicted in plots such as these of figure 5a. The following points can be made from the observed behavior during these tests:

- For small amplitude tests the rocking behavior is not present; the motion of the specimen in this case follows that of the base.
- As the horizontal base motion is increased in amplitude, rocking is initiated. This rocking appears to be sub-harmonic in the initial stages and becomes harmonic at the later stages.
- Further increase in the amplitude of the base motion results in excessive rocking response, which, after certain buildup, leads to the overturning of the specimen. At this stage the rocking response is also accompanied by some significant sliding at the base as well as by rotation and rocking response out-of-plane of the excitation axis.

Summary results for the single steel column without any wires are depicted in the plot of figure 5a. The ordinates in this plot represent the amplitude of the base acceleration whereas the absiscae represent the frequency of the base horizontal dynamic excitation. The following observations summarize the main points as they can be deduced from this plot:

- The stable-unstable limit rocking amplitude increases rapidly with the excitation frequency.
- For small values of the excitation frequency the transition stage from no-rocking to overturning, in terms of amplitude, is very small and it occurs with minor amplitude increases.

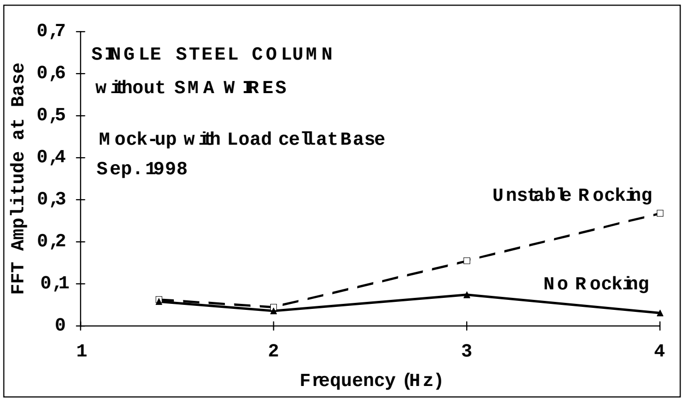

Figure 5a Single column response without SMA wires

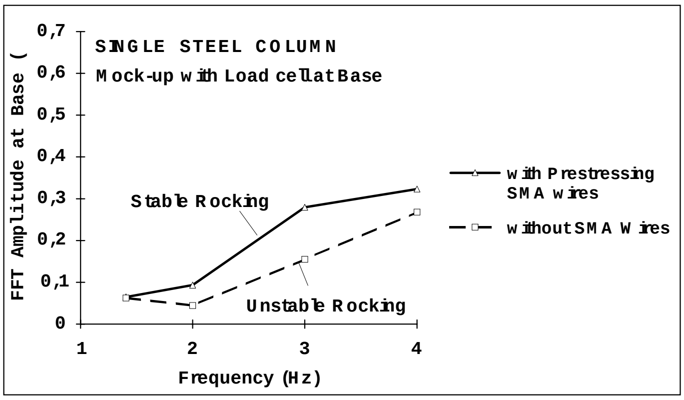

Figure 5b   Single column response with and without SMA wires

Simulated Earthquake tests : A number of tests were performed during this sequence with progressively increasing intensity. The principal objective of these tests was to observe again the stable-unstable behavior of the model which exhibited similar trends to the ones discussed in 3.1.1.

Model single steel column with SMA wires

Sinusoidal and Simulated Earthquake Tests. Tests similar to the ones described above were performed for the single column with one SMA wire passing through the center of the column (figure 2). Due to space limitations only summary results are presented here from the testing sequence with the sinusoidal horizontal base motions. The response curve obtained from these tests for the single steel column with the SMA wire is depicted in figure 5b together with the corresponding response curve of the single steel column without the SMA wire. As already mentioned, when discussing the response curve of the single steel column without the SMA wire of figure 5a, this curve represents in this case a boundary between stable-unstable rocking response. When this boundary is exceeded, because of an increase of the amplitude of the base motion of constant frequency, it leads to the overturning of the model structure (instability). In contrast, the plotted response curve for the mode structure with the SMA wire does not represent a stable-unstable boundary. Because of certain limitations in the capacity of the shaking table and in order to protect the SMA wires and their anchoring fixtures from repeated damage from overturning, the stable-unstable boundary was not established in this case. Instead, the plotted curve indicates amplitudes of the base motion with the model structure fitted with the SMA wire still exhibiting stable rocking response. Obviously, the stable-unstable boundary for the model structure with the SMA wire is expected to occur at higher amplitudes of the base excitation than those represented by the plotted curve, which in this case is designated as stable rocking response.

By comparing the stable rocking response curve in figure 5b for the model single steel column with the SMA wire with the stable-unstable boundary for the same structure without the SMA wire (figures 5a and 5b), the favourable influence of the insertion of the SMA wire on the stability of the dynamic sinusoidal response can be clearly identified. Similar favourable influence of the insertion of the SMA wire on the stability of the model structure was observed during the earthquake simulated tests.

Pull Out Static Tests This testing arrangement was described in paragraph 2 before. The obtained response in terms of non-dimensional rocking angle (ordinates) and applied horizontal load at the top of the single steel column with the SMA wire (absiscae) is depicted in figure 6a; figure 6b shows the measured response for this model structure in terms of non-dimensional rocking angle (ordinates) and overturning moment (absiscae).
As can be seen from figures 6a and 6b the insertion of the SMA wire leads to an almost elastoplastic force-displacement response; moreover the unloading path is accompanied by a lower plateau and a recovery of the plastic strain similar to the one observed during the uniaxial tests of the individual SMA wire.

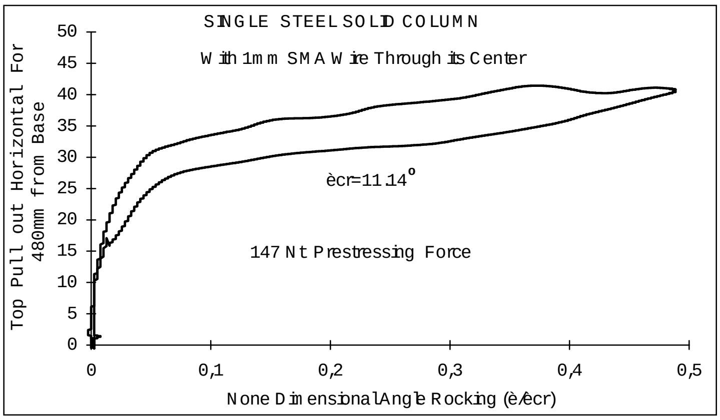

Figure 6a. Static pull-out response of single steel column with SMA wire

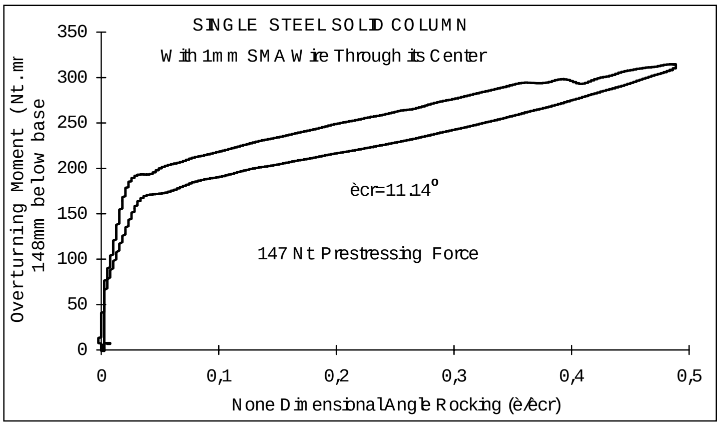

Figure 6b. Static pull-out response of single steel column with SMA wire

<u>Model colonnade with two or four-steel columns and with or without SMA wires</u>

<u>Sinusoidal base motions and Simulated Earthquake Tests</u> The testing sequence based on the sinusoidal and simulated earthquake excitations which was described in 3.1.1. and 3.2.1. before is also repeated here. As can be seen from the results obtained so far the performance of the model colonnades, exhibit similar stability trends with that observed for the individual column. The excessive rocking and sliding and subsequent collapse of the epistyle is an additional form of unstable response in addition to the excessive rocking, rotation and sliding of the individual columns. Moreover, the favourable influence of the insertion of the SMA wires on the stability of the dynamic sinusoidal response can be clearly identified. However, due to space limitations none of the results are presented.

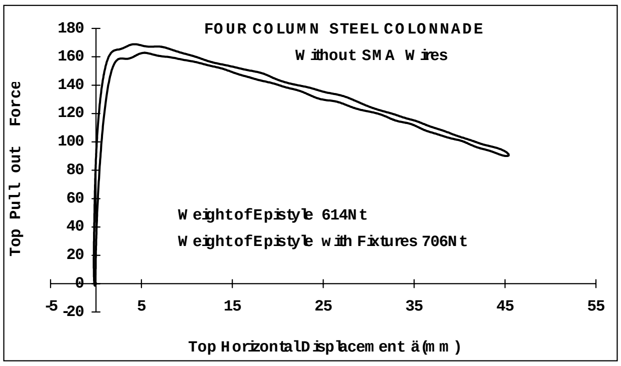

Figure 7a. Static pull-out response of four-steel column without SMA wires

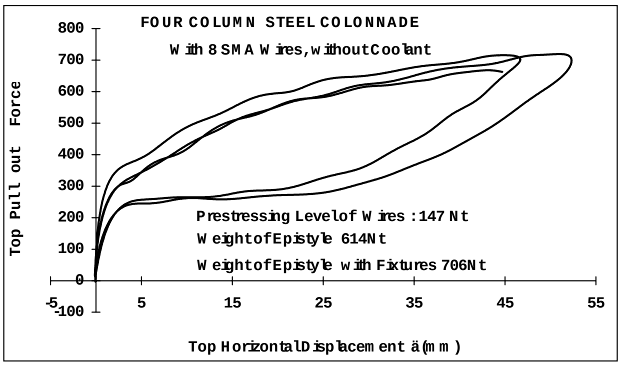

Figure 7b. Static pull-out response of four-steel column with 8 SMA wires

<u>Pull-out static tests</u> As mentioned in 3.2.2. before, this testing arrangement (described also in paragraph 2) was utilized in subjecting colonnades of various configurations to static pull-out horizontal force, which was applied at the center of the epistyle. Figure 7a depicts the measured response for a four-steel-column formation without any SMA wires whereas figure 7b shows the corresponding measured response of the same formation when eight (8) SMA wires were added.

By comparing the measured behavior of the four-column colonnade with and without the inclusion of the SMA wires in these two figures the following points can be made.

- The addition of the SMA wires increased the capacity in terms of horizontal force.
- The formation without the SMA wires exhibits a descending branch after the maximum horizontal load is reached. In contrast, the formation with the SMA wires demonstrates that a post-yielding type of behavior is initiated for displacements exceeding the initial elastic-type behavior. This post-yielding type of behavior is accompanied by continuously increasing horizontal load.

- Finally, the loading - unloading cyclic measured behavior of the four-column colonnade with the SMA wires, demonstrates clearly its dissipative nature, which is of course due to the fact that, for this level of deformation, the corresponding mechanical characteristics of the used SMA wires are mobilized.

NUMERICAL SIMULATION OF THE STATIC PULL-OUT RESPONSE

In this paragraph are presented some of the results obtained by an extensive numerical study which aims to predict the behavior of the single steel column and the various colonnade formations when they are subjected to horizontal static pull-out force, as described in sections 3.2.2. and 3.3.2., respectively. The interface between the columns and the top block as well as the columns and the ground support was approximated by frictional contact-elements, which are part of a specific software package. These elements could only sustain compression together with friction forces whereas no tensile forces could develop. For the configurations including SMA wires the former contact elements were combined with elasto-plastic springs approximating the measured mechanical properties of the SMA wires. The columns and the epistyle were approximated with 2-D quadrilateral plane-stress elements. Figure 8 shows the mesh employed for the two-column colonnade. The latter can also be used to approximate the four-column colonnade, which, due to symmetry, can be considered as a twin two-column colonnade (see figures 4a to 4d and section 1.3). The numerical analyses were performed by applying the desired level of imposed displacement to the same location that was used in the experimental sequence. Due to the geometric and material non-linearities of the contact elements and the elasto-plastic springs the solution, nonlinear in nature, followed many steps whereby the level of horizontal deformation was increased gradually in each step, with a considerable number of iterations per step.

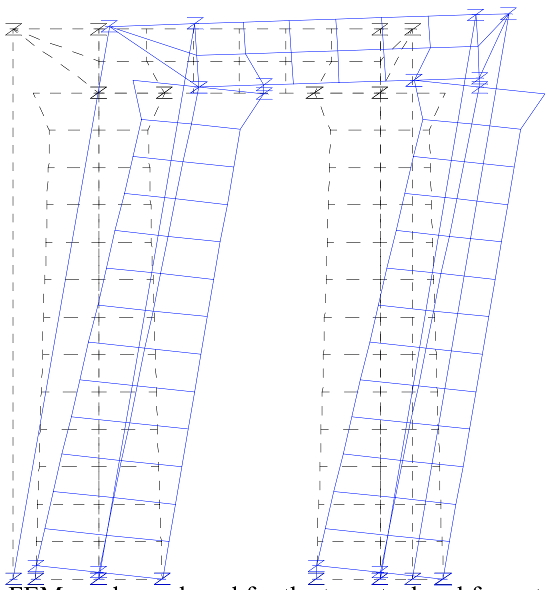

Figure 8. FEM mesh employed for the two steel and four-steel column colonnade

In this way, a simple attempt was made to numerically simulate both the contact problem that is inherent in the behavior of the studied structural formations as well as the presence of the SMA wires, which were installed in the way described for these structural formations. The objective here was to be able to check if such a relatively simple numerical simulation could yield realistic results so that then it can be utilized in the framework of our research effort. Parametric studies were also performed in order to check the sensitivity of the solution to various parameters. However, space limitations do not allow its inclusion here. The numerical results that are presented here belong to the numerical simulation of the behavior of the four-steel column colonnade with and without SMA wires. The horizontal load - horizontal deformation predicted response is depicted below together with the corresponding measurements in figure 9a and 9b.

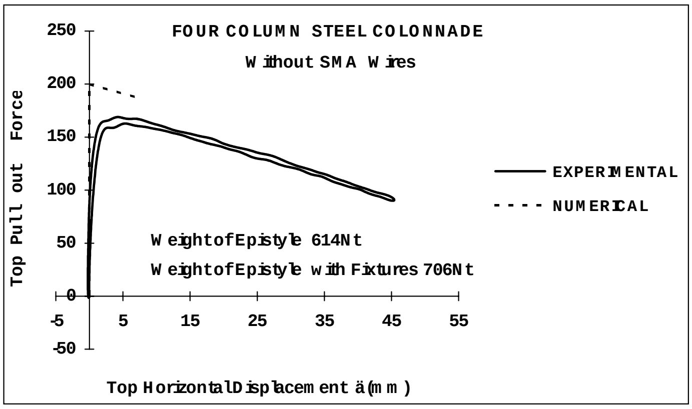

Figure 9a. Measured and predicted static pull-out response of four-steel column colonnade without SMA wires

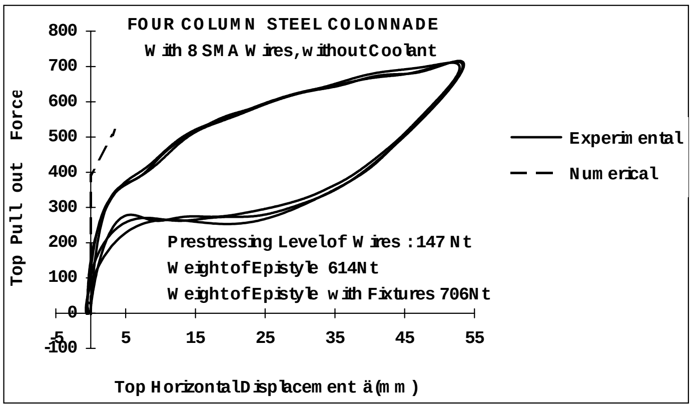

Figure 9b. Measured and predicted static pull-out response of four-steel column colonnade with eight (8) SMA wires

- The predicted response of the four-column formation without the SMA wires appears to reproduce in a satisfactory manner both the peak horizontal load as well as the descending branch of the response.
- Given the simplicity of the numerical approximation for the four-column formation with the SMA wires, the obtained numerical response reproduces in a realistic manner qualitatively if not quantitatively the most significant aspects of the response with the SMA wires in terms of maximum horizontal load values and ascending load path. However, no attempt has yet been

made in order to predict numerically the observed cyclic dissipative behavior.

CONCLUSIONS

- The insertion of the SMA wires as described had a noticeable favourable influence on the stability of the studied model formations. The model structures with the insertion of the SMA wires developed stable response at amplitudes higher than those at which the model structures without SMA wires had already overturned. This is more apparent for relatively lower frequencies.
- The dissipative behavior of the structural formations with the inclusion of the SMA wires was clearly demonstrated with the static pull-out tests.
- The numerical predictions of the four-steel column colonnade with or without SMA wires reproduces in a realistic manner the most significant aspects of the observed response.

ACKNOWLEDGEMENTS

The partial support of the European Commission (DIR XII , ENV.4-CT.96-0106, ISTECH), is gratefully acknowledged.

REFERENCES

Spanos, P.D. and Koh A.S., 1984. Rocking of rigid blocks due to harmonic shaking. J. of Engin. Mech., ASCE 110 (11), pp. 1627-1642.
Koh H.M., Kim J.K. and Park J.H. , "Dynamics of infinitely long 3-D rectangular tanks with submerged objects stored in periodic pattern" 14th SMIRT, Volume 8, Division K part 2, pp 181-188, Lyon, France, 1997.
Manos G.C. and Demosthenous M. , "Dynamic Response of Sliced Rigid Bodies Subjected to Harmonic Base Excitations", *SMIRT-12,* Vol. K1, K11/3, pp. 313-318*, 1993 Elsevier.*
Manos, G.C., and Demosthenous, M. 1991. Comparative study of the dynamic response of solid and sliced rigid bodies, Proc., Florence Modal Analysis Confer., pp.443-449.
Manos, G.C. and Demosthenous, M. 1997. "Models of Ancient Columns and Colonnades Subjected to Horizontal Base Motions - Study of their Dynamic and Earthquake Behavior" STREMA V, pp 289-298.
Manos G.C. and Demosthenous M., "The dynamic response of a simple rigid formation including two rigid columns and a top rigid block", 14th SMIRT, Volume 8, Division K part 2, pp 399-406, Lyon, France, 1997.
Manos G.C., Reports on Task 1, Task 2 and Task 8, 1998. ISTECH project, Program Environment and Climate, European Commission, Contract No. ENV4-CT95-0106.
Manos G.C., "The dynamic performance of models of ancient columns and colonnades with and without the insertion of wires made of shape memory alloy", STREMAH 99, pp. 281-290, Dresden, Germany, 1999.
Manos G.C., Demosthenous M. and Hatzigeorgiou, A., "Experimental and numerical study of the response of models of ancient columns and colonnades subjected to lateral loads", 3rd Greek National Congress on Computational Mechanics, Vol. II, pp. 463-470, Volos, Greece, 1999.
Manos G.C., Demosthenous M., Hatzigeorgiou A., Manou-Evison J. "Study of the dynamic and earthquake behavior of models of ancient columns and colonnades with and without the inclusion of wires with energy dissipation characteristics", presented at the 12th WCEE, Auckland, New Zealand, 2000.