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STUDY OF THE DYNAMIC AND EARTHQUAKE BEHAVIOR OF ANCIENT COLUMNS AND COLONNADES WITH AND WITHOUT THE INCLUSION OF WIRES WITH ENERGY DISSIPATION CHARACTERISTICS

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SUMMARY

Ancient Greek and Roman structures 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 colonnade (including free-standing monolithic columns or columns with drums) is the typical structural form of ancient Greek or Roman temples. The columns are connected at the top with the epistyle (entablature), also composed of monolithic orthogonal blocks, spanning the distance between two columns. The seismic response mechanisms that develop on this solid block structural system during strong ground motions can include sliding and rocking, thus dissipating the seismic energy in a different way from that of conventional contemporary buildings. This paper presents results and conclusions from an experimental study that examines the dynamic response of rigid bodies, representing simple models of ancient columns or colonnades. The rigid bodies employed in this study were made of steel and are assumed to be models of prototype structures 20 times larger. These models are subjected to various types of horizontal base motions (including sinusoidal as well as earthquake base motions), reproduced by the Earthquake Simulator Facility of Aristotle University. It also studies the influence on the response of the examined models arising from the inclusion of wires having energy dissipation characteristics. Summary results and conclusions from the observed dynamic performance are presented and discussed. 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 scheme of insertion of certain SMA wires with energy dissipation characteristics 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.

STUDIED STRUCTURAL CONFIGURATIONS

The rigid bodies employed in this study for forming these models were made of steel and are assumed to be models of prototype structures 20 times larger. Certain models that were also examined were made of marble but their response is not included in this paper. 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 1 and 2. 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

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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.

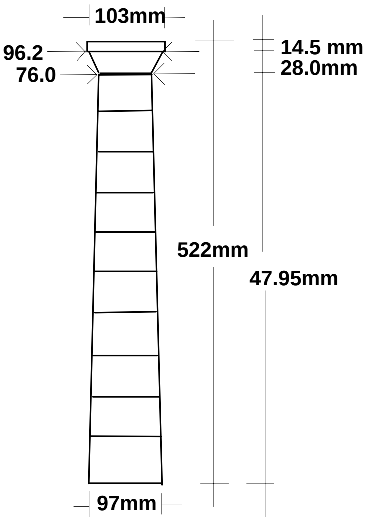


Figure 1. Geometry of the single steel column

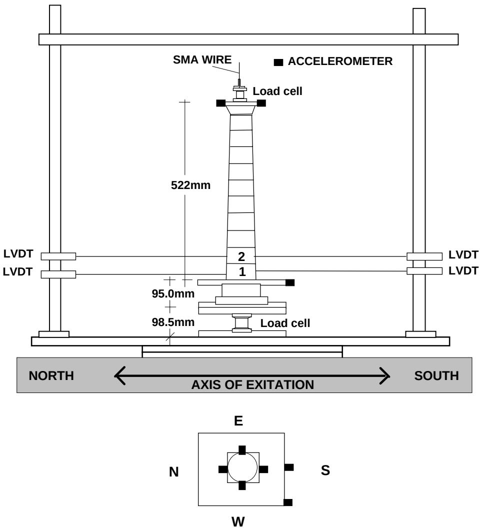


Figure 2. Single steel column on the shaking table

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. In a number of experiments with the model single column or with the models of the two-column colonnade a special supporting platform for these models was constructed on top of the shaking table platform in order to measure the forces transferred during the excitation sequence from the excited structures to the base. However, as this testing arrangement was rather complex, it was used in a limited number of tests; for most tests the moving platform of the shaking table provided the foundation base for the model structures.

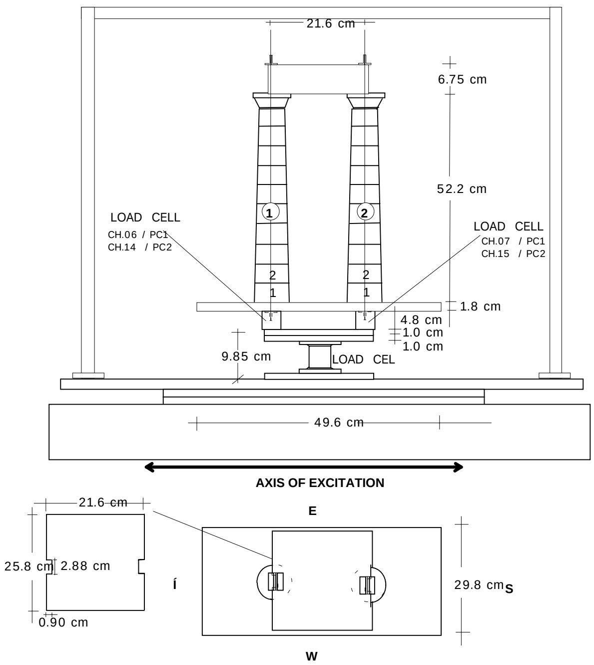
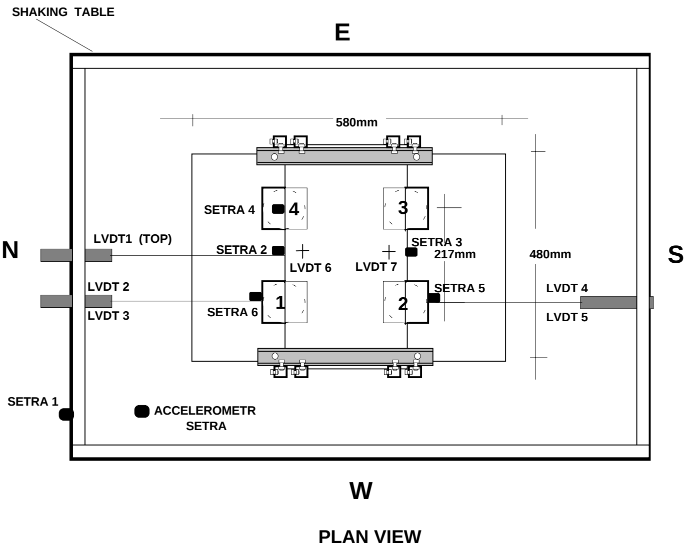


Figure 3. Two-steel column model colonnade

Four-Steel Column Model Colonnade.

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 4a, 4c and 4d was placed at the top of these identical four steel columns in a perfect fit condition. This model structural formation is depicted in figure 4a 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 this figure 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. Moreover, as can be seen in figures 4a, 4c and 4d 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 model is also depicted in figures 4a to 4d.



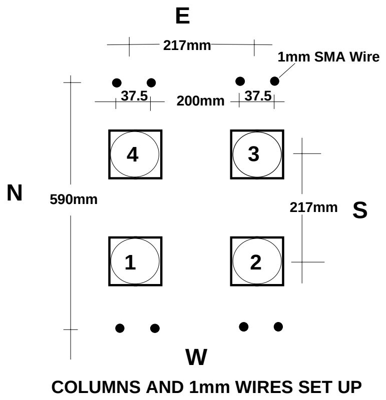


Figure 4b Location of theSMA wires

Figure 4a. Four-column colonnade (Plan View)

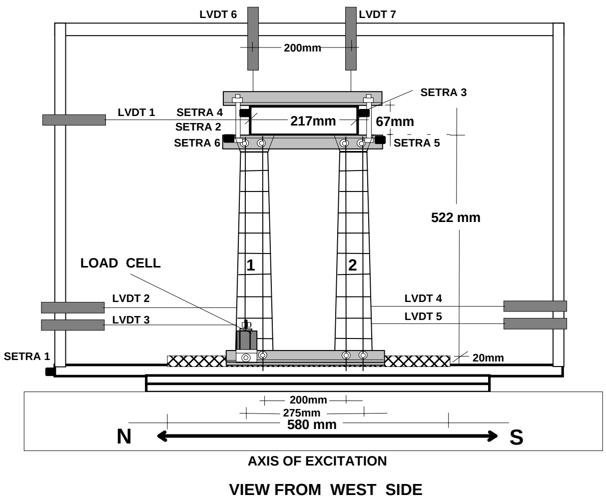


Figure 4c Four column colonnade. Testing arrangement along the axis of the horizontal base motion.

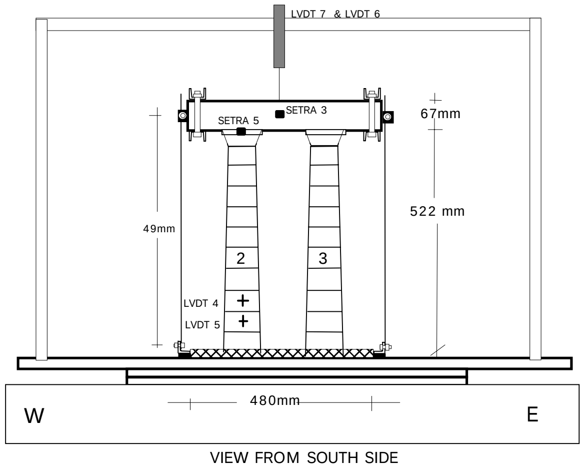


Figure 4d Four column colonnade. Testing arrangement transverse to the axis of the horizontal base motion.

Configurations of Columns and Colonnades with Wires.

The experimental investigation was supplemented by an additional study that aimed to examine influences on the dynamic response arising from a certain intervention technique with wires having energy dissipation characteristics. These wires were applied at critical locations and aimed to provide an increased resistance as well as energy dissipation capacity. The wires that are used throughout were 1mm in diameter and were provided by FIP Industriale of Padova, Italy, in the framework of a cooperative research project supported by the European Union (Manos, 1998). Their mechanical properties were fully investigated by a special testing campaign conducted at the Joint Research Center of the European Union at Ispra, Italy. A limited number of basic tests were also conducted at the Laboratory of Strength of Materials of Aristotle University with the wires that were directly employed in the present investigation.

For this purpose a fully dynamic uniaxial tensile testing machine was utilized whereby specimens of the wires could be tested in a fully cyclic manner with the desired amplitude and frequency. Figure 5 depicts the stress-strain plot from such a test with the frequency of the cyclic loading sequence being equal to 0.1Hz. As can be seen from this figure the loading cyclic behavior is characterized by almost plastic upper and lower plateaus with a recovery of the plastic strain due to the basic material properties that lead to the name shape memory alloy; for this reason these wires are designated in this paper as SMA wires. SMA wires with 1mm diameter were used in all the studied model structures mentioned in 1.1, 1.2 and 1.3 before.

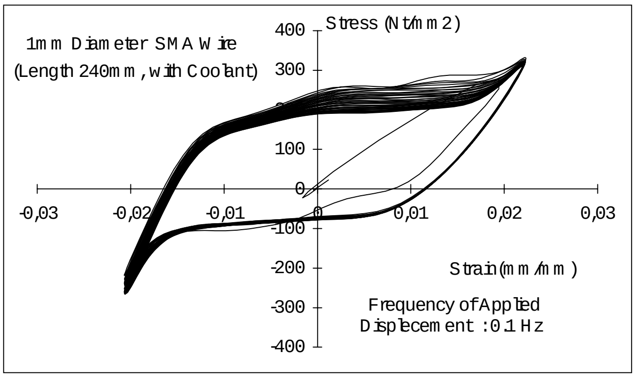


Figure 5. Mechanical properties of the used SMA wires

In the single steel column and the two-steel column colonnade the SMA wires were positioned through the centers of the columns and were anchored at the base and the top, as shown in figures 2 and 3, respectively. For the colonnade with the four steel columns the position of the wires is depicted in figure 4b as well as in figures 4c and 4d. A special anchoring case was firmly attached at the epistyle and the SMA wires were anchored there as well as at the moving platform of the shaking table. The number of wires employed here was either four or eight. The arrangement shown in figure 4b is for the eight wires. The removal of the four wires located the furthest from the center of this model colonnade resulted in the four wire arrangement.

EXPERIMENTAL INVESTIGATION.

During this experimental sequence the model structures 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 wires. 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 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 6a. 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 base motion amplitude results in excessive rocking response, which after certain buildup leads to the overturning of the specimen. Large rocking response is also accompanied by significant sliding at the base and 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 6a. 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 increase.

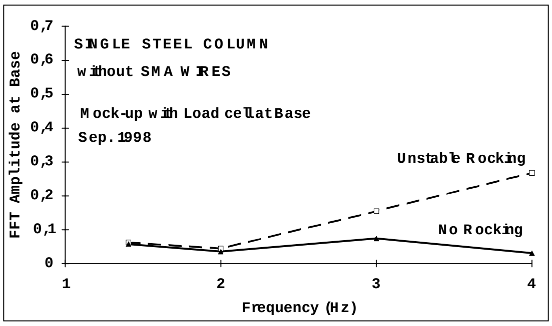


Figure 6a Single column dynamic response with SMA wires

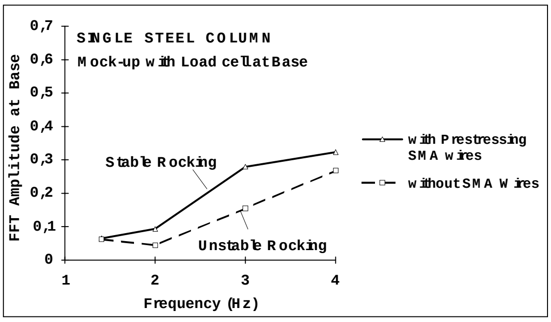


Figure 6b Single column dynamic response with SMA wires

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 6b 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 6a, 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 model 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 6b for the model single steel column with the SMA wire with the stable-unstable boundary for the same structure without the SMA wire 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 7a; figure 7b 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 7a and 7b 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 5). This observation is also true for the overturning moment response; in this way the overturning moment transmitted from the model structure to the foundation is limited by the observed upper plastic plateau.

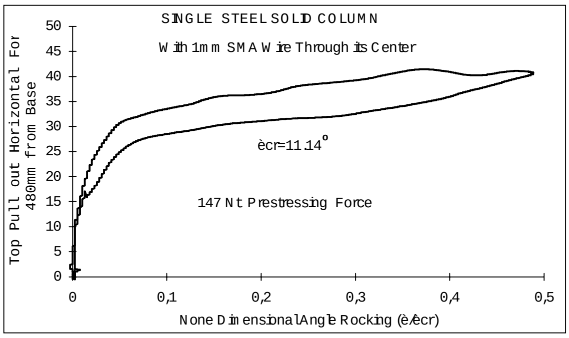


Figure 7a. **Static pull-out response of single steel column with SMA wire**

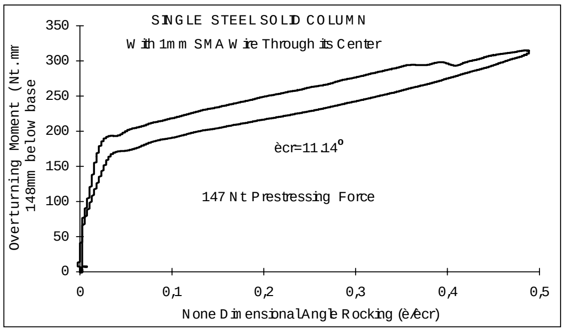


Figure 7b. Static pull-out response of single steel column with SMA wire

Model colonnade with two-steel columns without and with SMA wires.

Sinusoidal base motions.

The testing sequence, based on the sinusoidal excitation which was described in 3.1.1. before, is repeated here. This was done once with the two columns supporting an epistyle with 286Nt weight and was repeated with an epistyle of 605Nt weight.

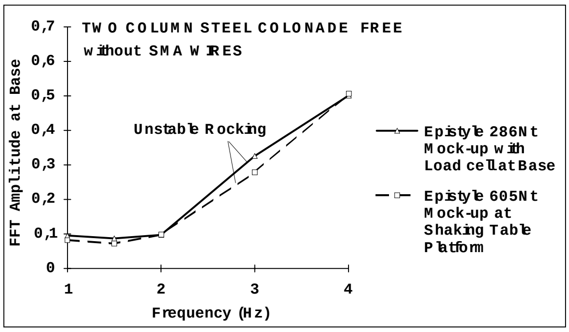


Figure 8a. Two column colonnade dynamic response without SMA wires

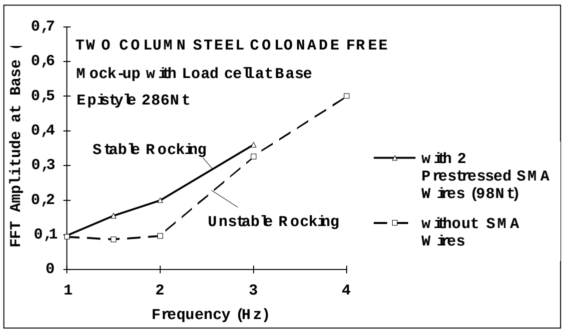


Figure 8b Two column colonnade dynamic response with SMA wires

Discussion of the Observed Performance :

- The behavior of the examined model colonnade with two steel columns without the SMA wires, being subjected to sinusoidal base excitations, exhibits similar trends to those observed for the individual steel column without the SMA wire, with regard to the influence that the excitation frequency exerts on the rocking amplitude. That is, for higher frequency of excitation larger excitation amplitude is required to cause the overturning of the structure; this can be seen in both figures 8a and 6a.

- For medium rocking angles, the observed response of the model colonnade with the two steel columns tends to remain in-plane. This observation is valid for both the sinusoidal as well as the simulated earthquake excitations.

- There are no noticeable variations on the stability of this model colonnade without the SMA wires that result from the increase of the weight of the epistyle during the sinusoidal dynamic excitation test sequence. This can be seen from the plot of the measured response during this experimental sequence as expressed through the stable-unstable boundary curves in figure 8a, whereby the boundary curves for the two epistyle weight cases almost coincide. This confirms such an expected performance to dynamic excitations whereby the stabilizing influence of the increase of the weight of the epistyle is offset by a corresponding increase in the inertia horizontal forces.

- By comparing the stable rocking response curve in figure 8b for the model colonnade with the two steel columns with the SMA wire with the stable-unstable boundary for the same structure without the SMA wire, the favourable influence of the insertion of the SMA wire on the stability of the dynamic sinusoidal response can be clearly identified.

Simulated Earthquake Tests

The shaking table tests were performed with the model two-steel column colonnade with the epistyle having 286Nt weight (see figure 2). The earthquake simulated tests were based on the prototype recordings of the horizontal ground motion during the El Centro 1940 and the Kern County 1953 (Taft) Californian earthquakes. The horizontal acceleration as recorded at the shaking table moving platform is a measure of the intensity of the simulated earthquake motion. This is depicted in figure 9a and it is a simulated earthquake motion. This excitation was used in two tests with the two-column model colonnade; the first without the SMA wires and the second with the SMA wires.

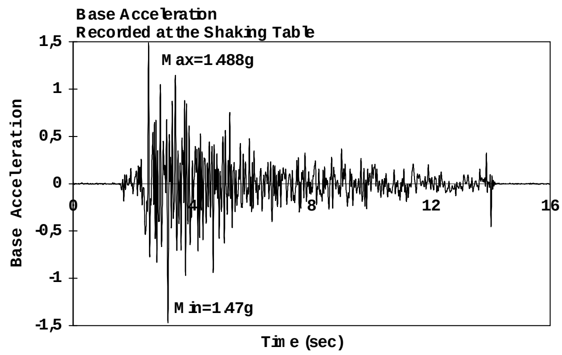


Figure 9a. Acceleration recorded on the shaking Table

The rocking response for the model colonnade with the SMA wires is depicted in figure 9b whereas the corresponding response without the SMA wires for the same simulated excitation is depicted in figure 9c. The plotted parameter is that of the ratio of the rocking angle (θ) by the critical rocking angle (θcr); values of this ratio larger than 1 indicates overturning, which is evident for the case without the SMA wires but not in the case of with the SMA wires (figures 9b and 9c). Thus the favourable influence of the insertion of the SMA wire on the stability of the model structure could also be observed during the earthquake simulated tests with the two-steel column colonnade on the shaking table.

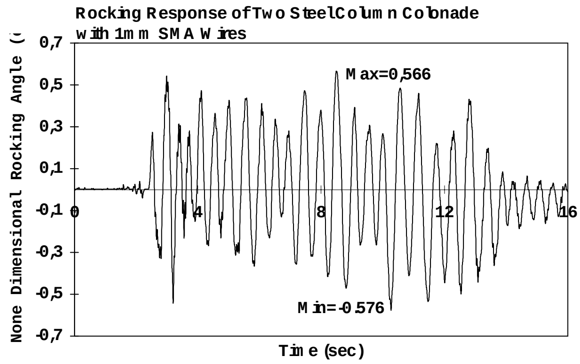


Figure 9b Rocking response of the model colonnade with the SMA wires

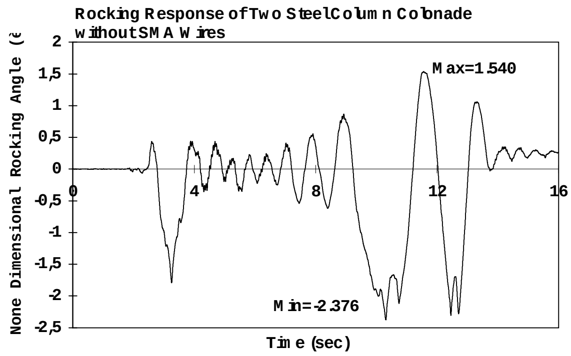


Figure 9c Rocking response of the model colonnade without the SMA wires

Model colonnade with four steel columns with and without SMA wires.

Sinusoidal base motions and Simulated Earthquake Tests.

The testing sequence based on the sinusoidal excitation which was described in 3.1.1 is repeated again here. This was done once with the four columns supporting an epistyle with 649Nt weight; the anchoring fixtures for the SMA wires were present during the tests for the model with and without the SMA wires. The weight of the epistyle together with the weight of these anchoring fixtures was 706Nt. As already mentioned in paragraph 1.4, two arrangements for the SMA wires were tried here; the first with 8 SMA wires and the second with 4 SMA wires.

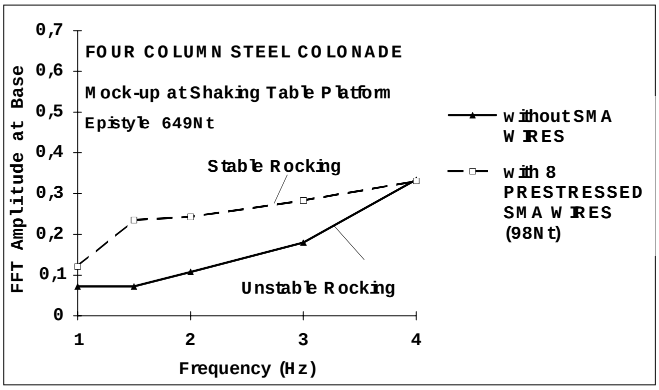


Figure 10. Dynamic response of four column colonnade with and without SMA wires

The observed dynamic performance of the configuration with the 8 SMA wires is depicted in figure 10 together with the same configuration without any SMA wires.

- The observed performance of the model colonnade with two columns without the SMA wires (figures 8a) can also be observed here with a typical stable-unstable response boundary (figure 10).

- Due to the presence of four columns in this model colonnade the observed rocking response remains mainly in plane even for large rocking angles, without exhibiting tendencies for significant out-of-plane response.

- By comparing the stable rocking response curve in figure 10 for the model with the SMA wires with the stable-unstable boundary for the same structure without the SMA wires the favourable influence of the insertion of the SMA wires can again be clearly identified.

CONCLUSIONS

1. The dynamic performance, in terms of stability, of the examined model structures, that is of the single column, of the model colonnade with two columns and finally of the model colonnade with four columns, exhibited similar trends with regard to the influence that the excitation frequency and amplitude exert on the rocking amplitude and the subsequent overturning of these structural formations.

2. 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 the SMA wires had already overturned. This is more apparent for relatively lower frequencies.

ACKNOWLEDGMENTS

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