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EXPERIMENTAL DYNAMIC TESTING OF PROTOTYPE AND MODEL OF THE ANTONINA COLUMN IN ROMA

KRSTEVSKA Lidija*, MIHAILOV Vladimir*, BOSCHI Enzo**, ROVELLI Antonio**

* Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje, Macedonia
** Istituto Nazionale di Geofisica, Rome, Italy

ABSTRACT

Presented in the paper are the results obtained by experimental dynamic testing of the prototype and the model of the Antonina column in Rome, which was performed within the frame of the cooperative project "Analysis of the Seismic Risk of Existing Column Monuments in Rome by Seismic Shaking Table Testing of a Model", between IZIIS - Skopje and Istituto Nazionale di Geofisica - Rome. Based on the experimental data obtained from the site testing of the prototype, a model in scale 1:6 was designed according to similarity laws. With the performed seismic testing of the model on the shaking table, the phenomenon of seismic behaviour and the resistance of the Antonina column became more clear.

KEYWORDS: vibrations, frequencies, mode shapes, model testing, seismic response, failure mechanism

INTRODUCTION

The column of Marcus Aurelius (Antonina column) is one of the oldest monuments of Ancient Rome, located on Piazza Collona in the historical center of Rome. Built in the year 198 and honored to the great emperor Marcus Aurelius this column has withstand for many centuries. Even several restorations have been performed in the past, significant local damages are still evident manifesting by cracks and dislocations particularly in the upper part of the column. One of the explanations is that the damage was caused by happened earthquakes in the past centuries and because of the soft soil conditions at the site of the column. To evaluate the seismic stability and behaviour of the column, the cooperative project was performed between the Institute of Earthquake Engineering and Engineering Seismology, University St. Cyril and Methodius, Skopje, Republic of Macedonia and Istituto Nazionale di Geofisica, Rome, Italy. Within the scope of the project, detailed in situ investigation of dynamic characteristics of the column and behaviour of the column model under actual earthquake conditions has been performed. In situ experimental testing of the column was performed to obtain its dynamic characteristics: resonant frequencies, mode shapes of vibration, damping capacity and soil-structure interaction, while the main objective of the shaking table testing of 1/6 scaled model of this column performed at the Dynamic Testing Laboratory of IZIIS was to find out the reason of existing damage, as well as to define the seismic resistance and intensity of earthquake motion which could cause developing of failure mechanism of the column.

FULL SCALE DYNAMIC TESTING OF THE COLUMN PROTOTYPE

The column of Marcus Aurelius is a tall and impressive structure. Its main cylindrical part is built by superimposing seventeen blocks of white Carrara marble. The blocks have been placed one on another with no mortar, but they were originally doweled by metal pins driven into the holes drilled in the marble and subsequently sealed in place with fused lead. Dowels and lead were stolen during the Middle Ages, so now there is no connection pinning the blocks. The principal diameter of the column is 360 cm and it is approximately 43 m high from the base to the top of the Apostles' statue, Fig. 1.

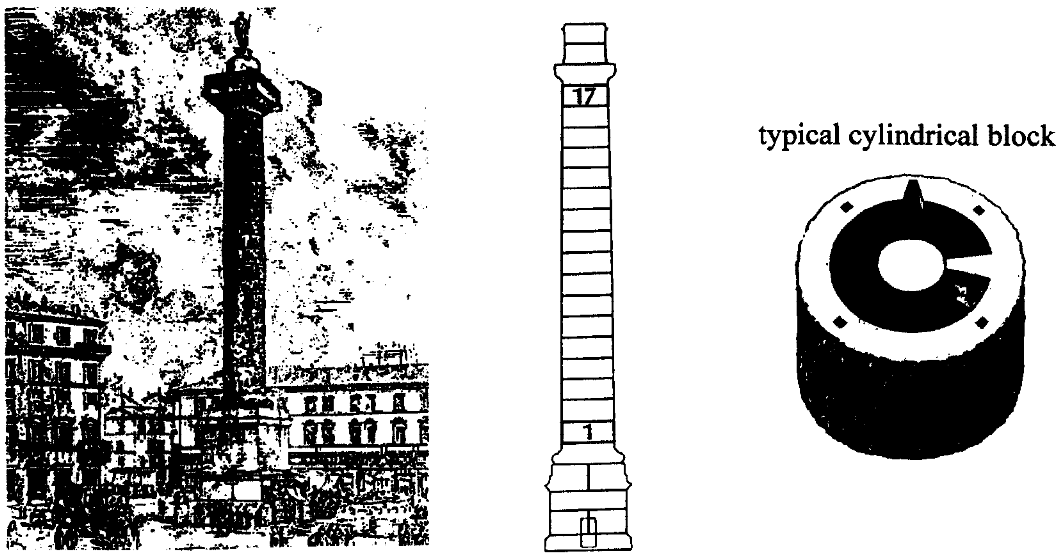

Fig. 1. The Antonina column in Rome

Full scale experimental testing of the column was performed applying two different testing methods-ambient and forced vibration testing method. During ambient vibration measurements Ranger type SS-1 model seismometers, Kinemetrics USA product were used for measuring the column vibrations at selected points and the signals were processed by Spectrum Analyzer HP product, applying digital Fast Fourier Transform technique. Natural frequencies were clearly selected on the obtained spectra, Fig. 2.

Forced vibration measurements were performed applying harmonic excitation force at the level of the column capitol, produced by a small electrodynamic shaker ELECTRO-SEIS type 113. Accelerations at selected points of the column were measured with Statham accelerometers type A4-0.25 (USA). The frequency response curve obtained during the forced vibration measurements is presented in Fig. 3.

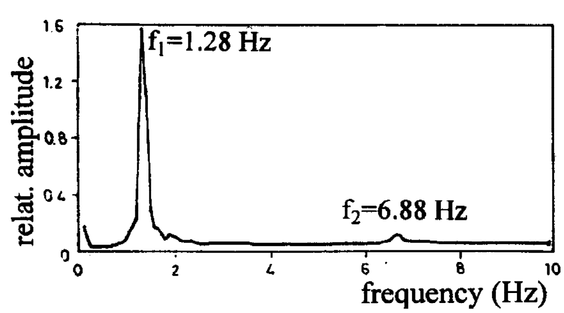

Fig. 2. Fourier amplitude spectrum

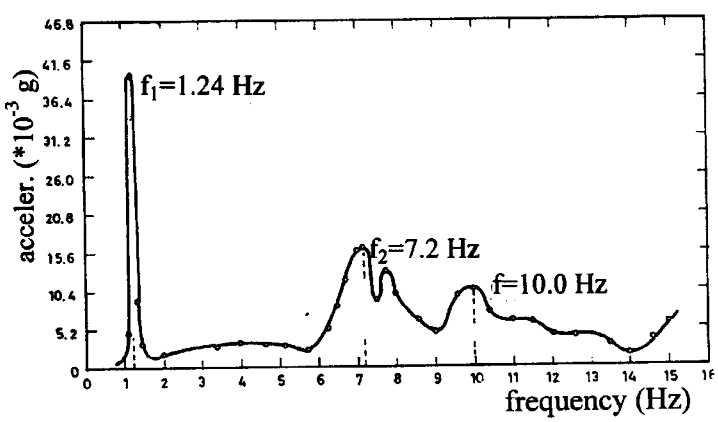

Fig. 3. Frequency response curve

The obtained results from full scale dynamic testing of the Antonina column define its dynamic characteristics. Resonant frequency of the first mode which is predominant in the vibrations of the column is

1.24 Hz. Mode shapes of vibration obtained by both testing methods by normalizing the amplitude of each level to the amplitude of the reference level (point T1 on the capitol), are very similar, as presented in Fig. 4. Damping coefficients are obtained from the spectra, i. e. from the resonant frequency curves, applying the "half power method". Damping coefficients for the first mode are also obtained from the free vibrations of the columns after the shaker has been switched off. Considering the obtained damping coefficients, it is obvious that damping capacity of the column is very low. Table 1 presents the natural frequencies and damping coefficients for the column. Soil structure interaction is insignificant, taking into account the measured amplitudes of acceleration at the ground level near the column during its vibration in resonance.

Table 1. Resonant frequencies and damping coefficients for the column

testing method	frequency (Hz)		damping coeff. (%)	
	f_1	f_2	β_1	β_2
ambient vibrations	1.28	6.88	3.9	-
forced vibrations	1.24	6.96 (7.20)	0.8 (resp. curve) (0.6) (free vibr.)	7.2

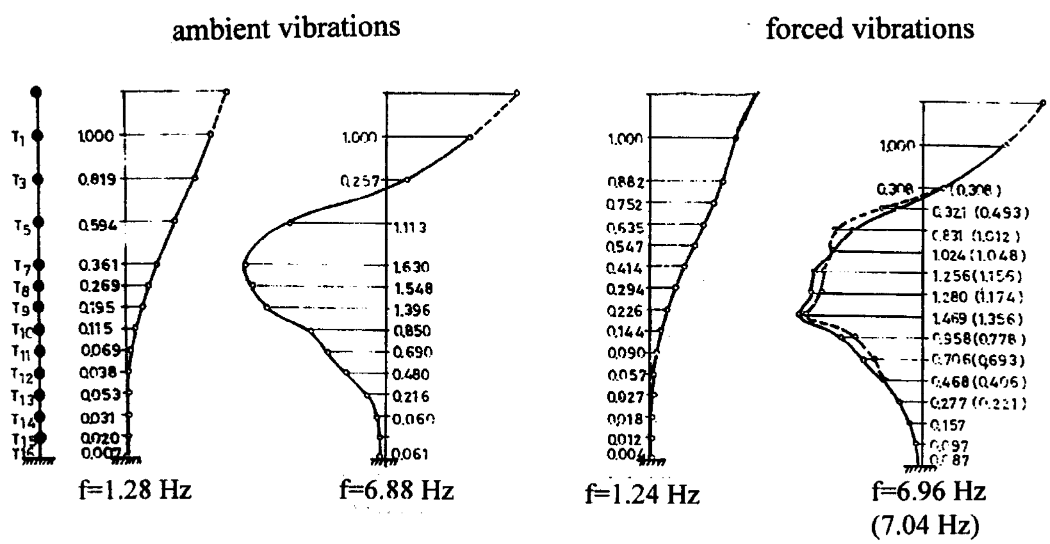

Fig. 4. Mode shapes of vibrations for the column

SHAKING TABLE TESTING OF THE COLUMN MODEL

For shaking table test a model of the column in scale 1/6 was designed and constructed according to the modeling principles. True replica modeling technique was applied. In Table 2 presented are the scaling factors model - prototype. The model was 6.5 m high, with total weight of 3.95 t and it consisted of 25 segments which were placed one over the other without any connection between them, Fig. 5. The material for model construction was water-cement mixture which enabled proper simulation of the ratio of moduli of elasticity E_m/E_p.

Dynamic characteristics of the model were measured applying the same testing methods as for the prototype - ambient and forced vibrations. Fig. 6 presents the Fourier spectrum obtained during ambient vibration measurements and the frequency response curves obtained by forced vibration measurements of the model. The first two natural frequencies of the model are f_1=2.08 Hz and f_2=11.0 Hz. Mode shapes of the model are presented comparatively with the mode shapes of the prototype in Fig. 7.

Table 2. Scaling factors model - prototype

parameter	required scaling factor	achieved scaling factor
length, displacement (l_r)	1/6	1/6
time (t_r)	$(1/6)^{1/2}$	$(1/6)^{1/2}$
frequency (f_r)	$(1/6)^{-1/2}$	$(1/6)^{-1/3}$
mass density (ρ_r)	1	0.67
inertial force (F_r)	$(1/6)^3$	$(1/6)^3$
Young's modulus (E_r)	1/6	1/6.82
strain (ε_r)	1	1
stress (σ_r)	1/6	1/6.82
acceleration (a_r)	1	1
additional mass	0.34	0
E/σ ratio	300-400	352

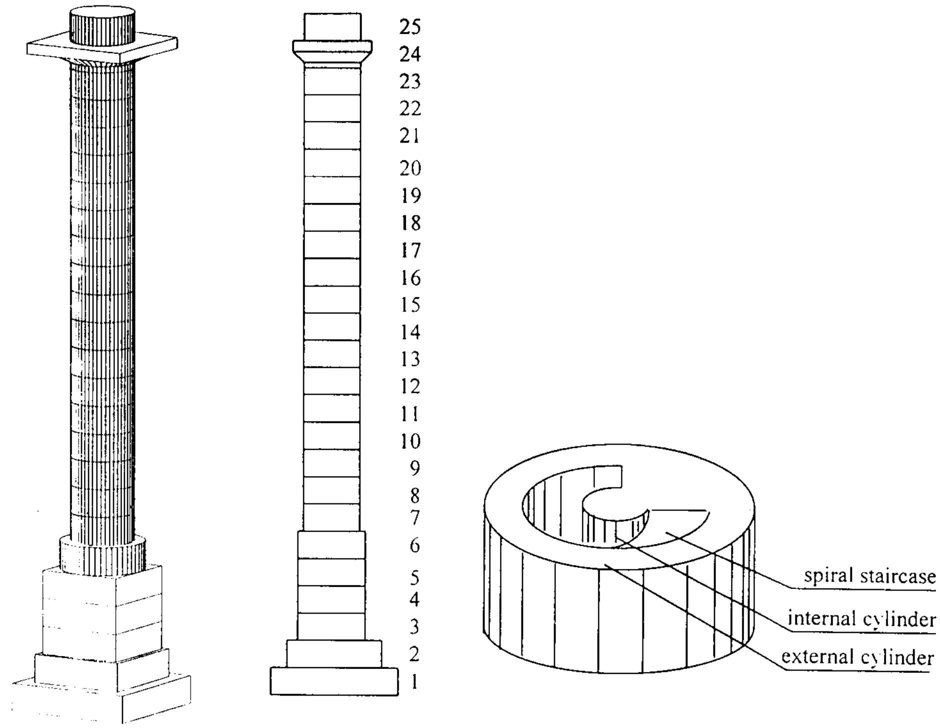

Fig. 5. The model of the Antonina column

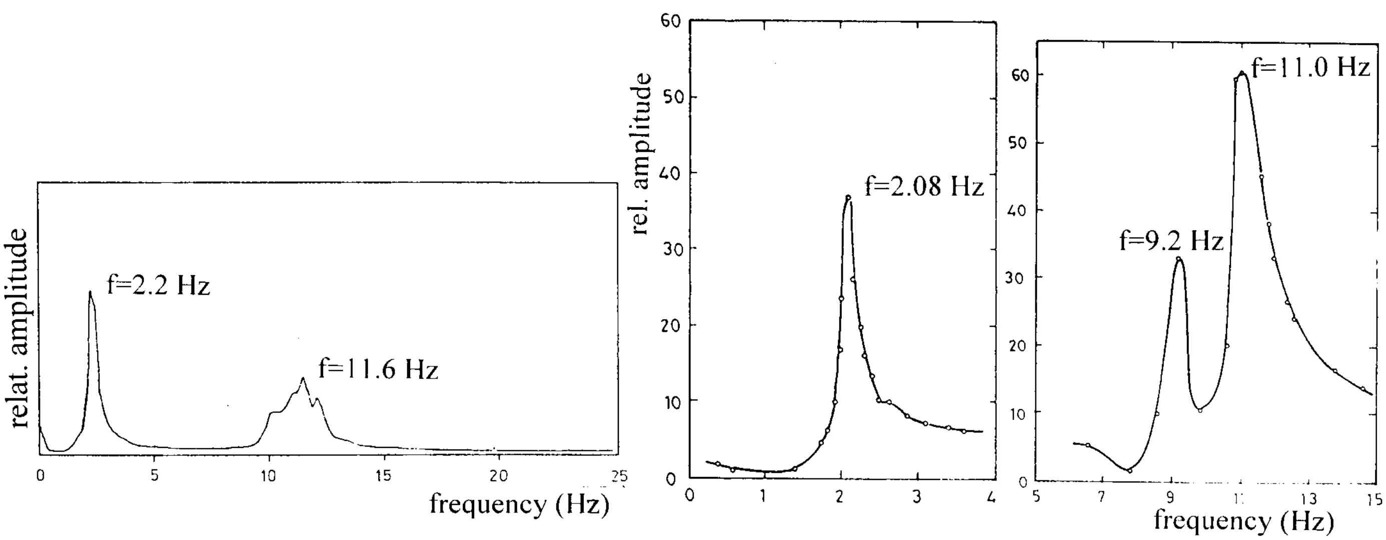

Fig. 6. Fourier amplitude spectrum and frequency response curves for the model

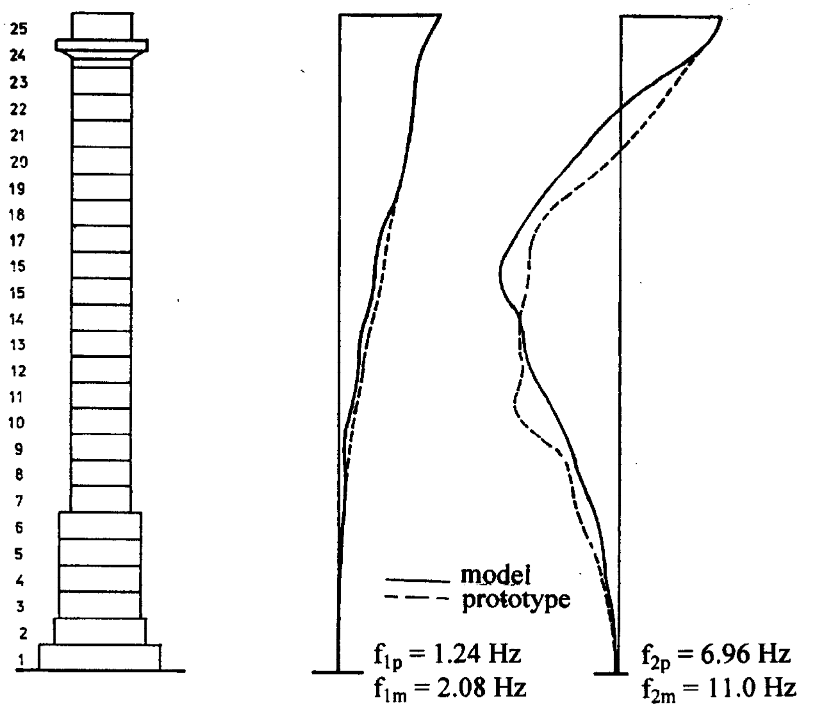

Fig. 7. Comparative presentation of the mode shapes of vibration prototype - model

Shaking table testing of the model, i. e. its linear and nonlinear behavior was investigated applying the accelerogram of the Irpinia earthquake (M 6.8, Southern Italy) recorded at Mercato San Severino, as the most suitable for magnitude and site response (60 m thick Holocene sediments). For measuring of all parameters of interest, the model was instrumented as shown in Fig. 8. Accelerations, displacements and relative displacements (uplifting of the elements) were measured at characteristic points of the model.

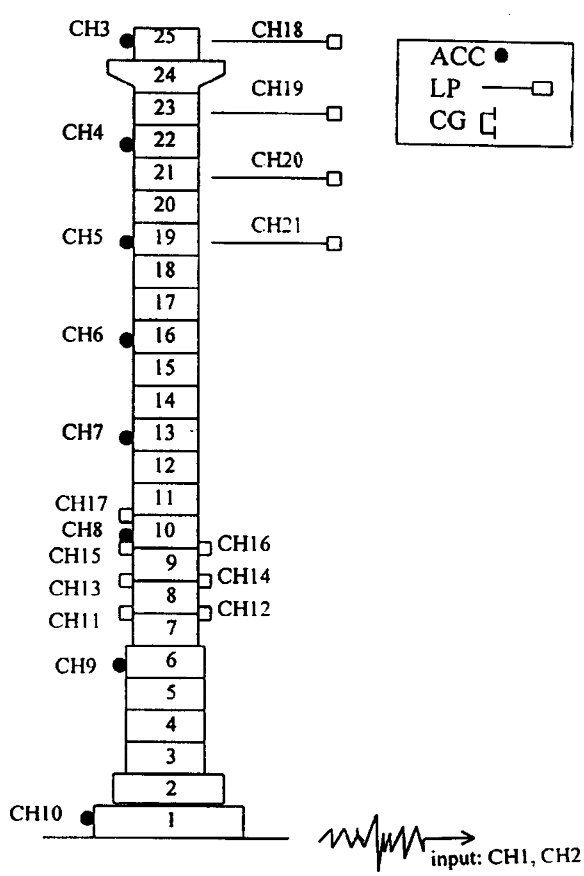

Fig. 8. Instrumentation of the model

The dynamic testing procedure was performed in two steps:

- First, the original record was scaled 1.5 times to correspond to the estimated resonant frequency of the model. The intensity of the input excitation was increased in steps up to 0.15 g.
- During the second testing phase, until failure of the model, the time scaling factor was changed from 1.5 to 0.87, but the peak acceleration was kept constant, 0.15 g. This approach was applied in order to provoke the model response near resonance, since the response frequency of the model for higher input intensities had a tendency to shift to a lower value than the predominant frequency of the input. So, the resonant conditions could be avoided and response parameters could have reduced values. Decreasing the predominant input frequency by changing the scaling factor intensive response was provoked. Applying this approach the input parameter overestimated the reality (predominant frequency and intensity of input motion), but it was the most proper way to investigate the intensive response of the model and to define its failure mechanism.

During the dynamic tests performed with low intensities, the behaviour of the model was linear. For higher intensities (0.10 and 0.15 g) the response of the model increased. So, for input acceleration of 0.15 g the maximum acceleration on the top was 0.25 g and the maximum absolute displacement was 28.1 mm. Uplifting between blocks 8 and 9 was 0.46 mm and cracks in particular blocks occurred as a consequence of stress concentration due to compression.. The response frequency decreased from 2.2 to 1.2 Hz.

The first test of the second series with constant input intensity of 0.15 g was performed with the time scaling factor of 1.3 (predominant input frequency 1.5 Hz), and further development of cracks was observed on the model. During the last test with input frequency 1.0 Hz, time scaling factor 0.87, the maximum acceleration on the top was 0.40 g and top displacement was 136 mm. Uplifting of the contact 7 - 8 reached the value of 7.4 mm and dislocation (sliding) of the contact 17 - 18 and 18 - 19 was 8 mm and 4 mm, respectively. Considering the intensive response of the model it could be concluded that the model was near collapse.

Time histories and Fourier spectra of these parameters are presented in Fig. 9 and the distribution of the maximum response quantities during this test are given in Fig. 10. The final damaged state of the model is presented in Fig. 11.

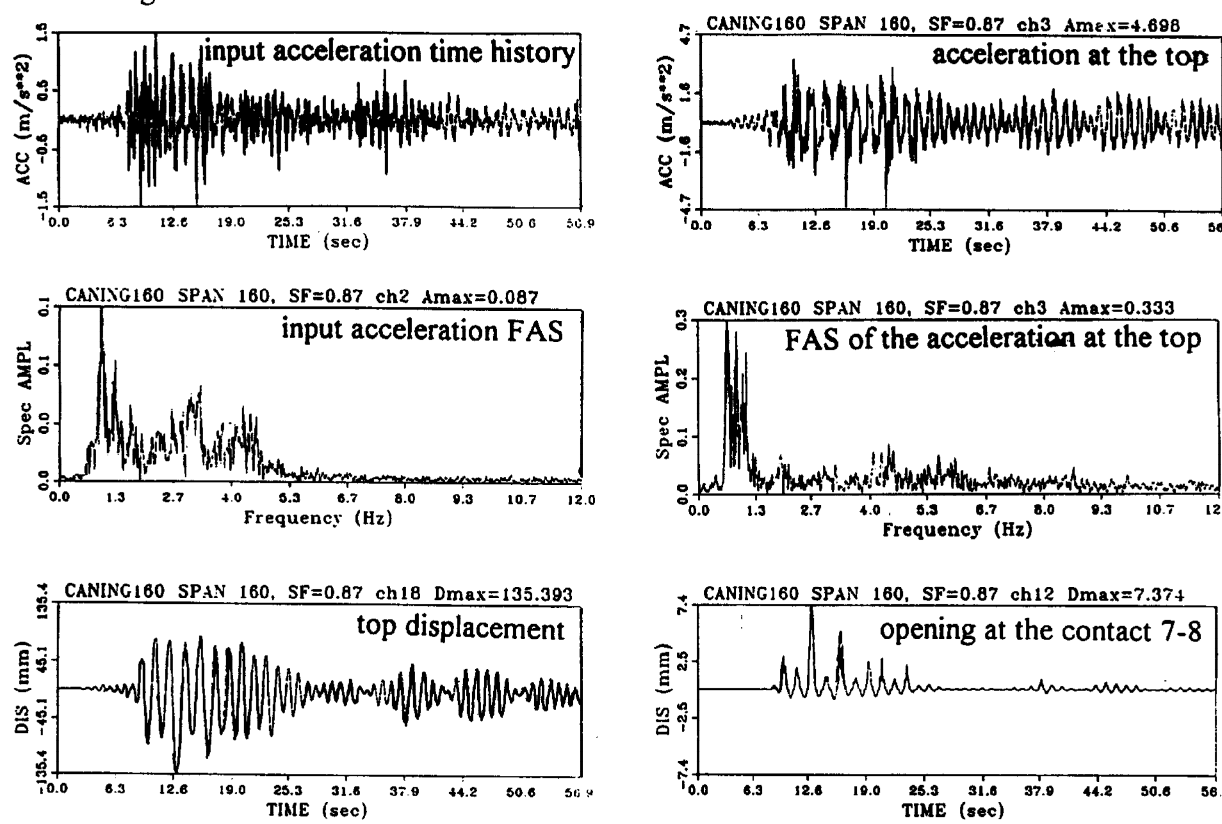

Fig. 9. Time histories and Fourier spectra of important parameters during the last seismic test

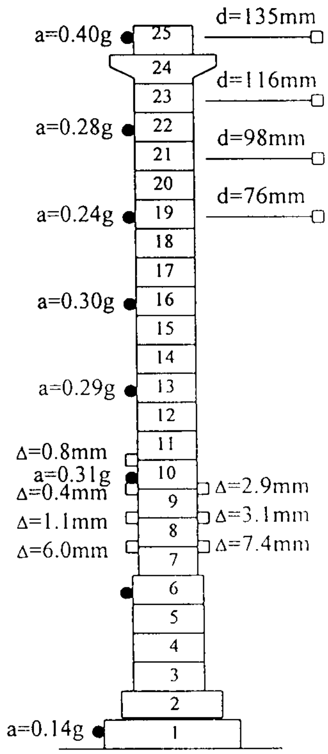

Fig. 10. Response parameters obtained during the last seismic test

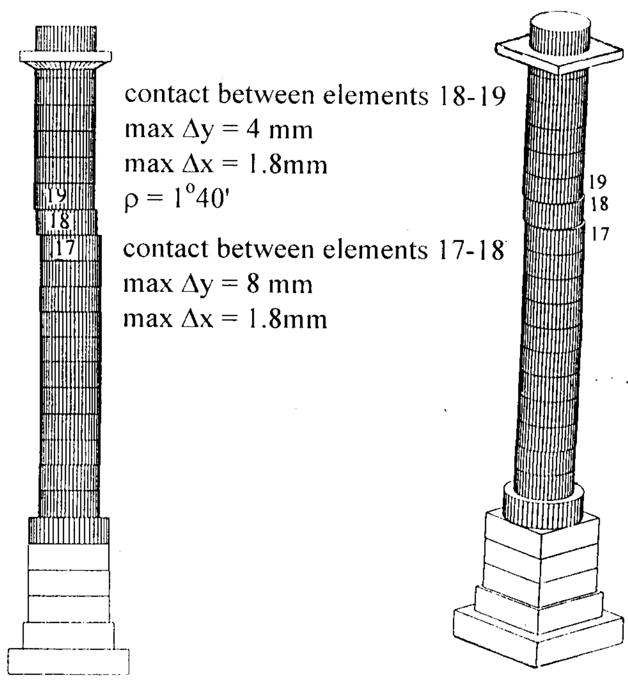

Fig. 11. Final damaged state of the model

SIMILARITY OF SEISMIC BEHAVIOUR OF THE MODEL AND EXISTING STATE OF THE ANTONINA COLUMN

Seismic shaking table testing of the Antonina column model was performed applying an original earthquake record which was considered as the most characteristic for the monument site. During the shaking table testing of the model the development of failure mechanism was a result from the critical opening of the contacts (uplifting) between the cylindrical blocks above the foundation and sliding of blocks at the upper third. Instability of the model was mainly caused by the lack of connecting elements between the blocks.

Comparing the existing damaged state of the Antonina column in Rome and the damage of the 1/6 scaled model , it could be said that there is a great similarity in the crack pattern, as well as in the deformed state. Namely, the dislocation of the blocks of the column model occurred at the same part like in the prototype. This leads to the conclusion that the damage of the Antonina column can be explained by the occurrence of earthquakes in the past and that low frequency content earthquakes might cause serious damage on the column. The vicinity of the first natural frequency of the column and the predominant frequency of the seismic motion could be the reason for intensive vibrating of the column under resonance conditions, which are unfavorable for its stability, especially considering the fact that there are not connections between the marble blocks of the column.

CONCLUSIONS

The results obtained by full scale experimental testing of the prototype of Antonina column and shaking table testing of its model allows evaluation of the seismic behaviour and stability of this structure of Ancient Rome. The shaking table test of the model of Column of Marcus Aurelius was designed based on the true replica modeling technique. The cement-water mixture reproduced properly the Young's modulus ratio, but not the mass density ratio, which required additional mass to be introduced in the model. Besides this distortion, the model properly reproduced the dynamic behavior of the actual structure. The designed and constructed model reproduced properly the dynamic behaviour of the prototype structure, which was approved by comparison of the model and prototype dynamic characteristics. The difference in the values of the natural frequencies of the column and the frequencies of its model is most likely caused by the free contact between the model elements, which might be not very close to the reality (possible existence of some connections between the blocks or due to natural process of calcification that might have changed the contacts between the blocks during centuries making them monolithic). Mode shapes of vibration of the prototype and the model are quite similar, which proves that geometry and mass distribution are properly simulated.

The crack pattern as well as the dislocation of the blocks at the upper third of the column model, obtained after the seismic test, are very similar to those existing on the Column of Marcus Aurelius in Rome. Once again it confirmed the realistic design and construction of the model.
Concerning the structural stability, the column consisting of 25 blocks superimposed without any connections, represents a seismically unstable system. The mechanism of failure is manifested through the blocks dislocation, joint opening and uplifting of the edges due to overturning moment during the seismic action. These effects are present even for moderate earthquakes. The general conclusion from the shaking table testing is that low frequency content earthquakes may cause serious damage to the column.

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