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EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF THE EARTHQUAKE RESPONSE OF CLASSICAL MONUMENTS

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ABSTRACT

This paper presents the first results of an on-going research project on the earthquake response of classical monuments. The project has involved so far the calibration and validation of the numerical tool with experimental results. The analysis employs the Distinct Element Method and the experiments involve marble specimens on the Shaking Table facility. The experiments have confirmed the complexity of the phenomenon. However, the gross experimental features are captured by the numerical model. Contrasting the experimental with the numerical results is building-up confidence for the use of the numerical codes in more realistic full scale structural configurations under a variety of ground motion conditions.

KEYWORDS

Classical monuments, dynamic response, shaking table, distinct element method.

INTRODUCTION

Very little is known about the earthquake behaviour of classical monuments. Such monuments have been continually subjected to earthquakes, but their response to suvh events is very poorly documented. Few of them are still standing, like the Parthenon on the Acropolis of Athens (Fig. 1).

A project is undertaken, within the European Research Programme Environment, to investigate various aspects of the response of classical monuments subjected to earthquake motions. Our participation to the overall project consists of experimental and analytical work. The experiments were conducted primarily on the Shaking Table, on marble models, whereas the analysis was performed with Distinct Element numerical codes.

Classical monuments behave as assemblies of stone blocks in dry perfect contact and, therefore, are not covered by methods of continium mechanics. In a previous study (Papastamatiou and Psycharis, 1993) the two-dimensional Distict Element Code UDEC (Cundall and Hart, 1983), was applied within the context of the response of classical monuments in Greece, an earthquake country. This application demonstrated the capabilities of available numerical codes but also the lack of experimental data. The current project was planed on this experience as an integrated experimental and analytical research effort. The project is focused at the dynamic response of a column, the basic external supporting element of a classical monument.

The dynamic behaviour of a column is not fully understood. Analytical and experimental investigations are restricted to single prismatic blocks (e.g. Aslam et al, 1980, Ishiyama, 1982, Psycharis and Jennings, 1982,

Fig. 1. View of the Parthenon in Athens.

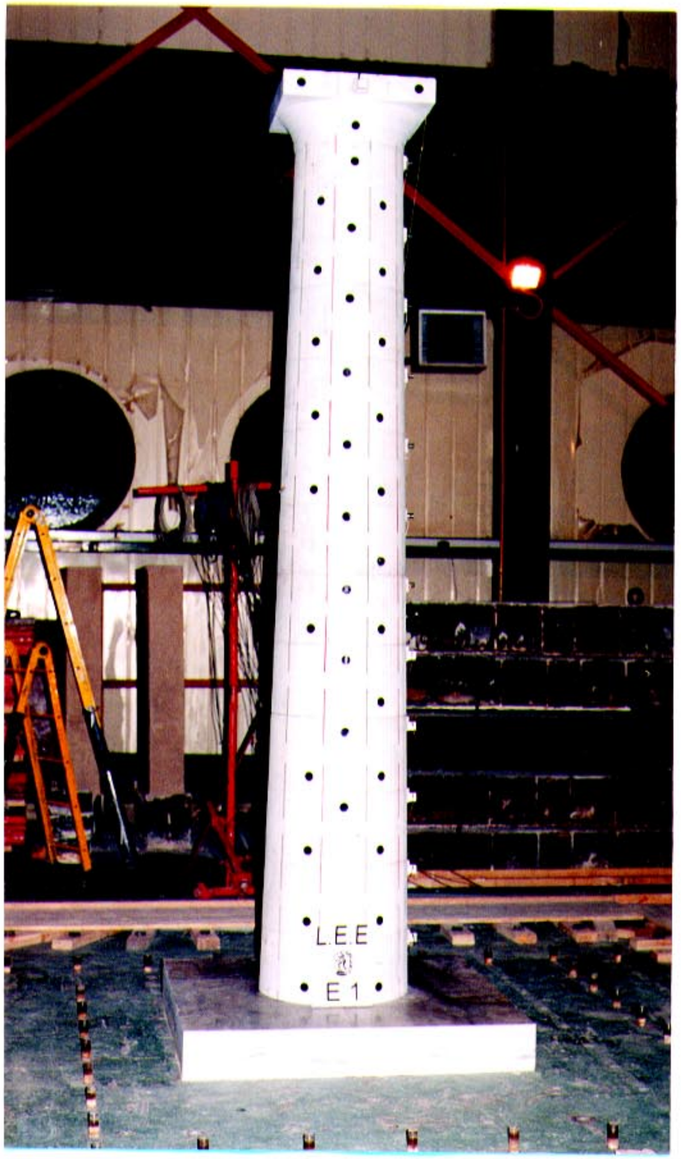


Fig. 2. Model of a column of the Parthenon at a scale 1:3 on the Shaking Table.

Yim et al, 1980) and two-block systems (Psycharis, 1990). Small multidrum steel columns were tested recently under one-directional horizontal excitation (Manos and Demosthenous, 1991). Large specimens of multidrum marble columns have been tested at ISMES, Italy, but only preliminary results have been reported (Giuffre, 1986).

The experimental program concentrated on Shaking Table tests of a 1:3 marble model of a typical Parthenon column. The tests were conducted primarily under real earthquake motions. Tests were also performed for a single 16x19x76 cm prismatic marble block, in order to calibrate the dynamic parameters of the numerical codes. The single block was subjected to free vibrations, sinusoidal excitations and real earthquake motions.

The analysis was inevitably conducted in three dimensions with the program 3DEC, a 3-D extension of UDEC. So far, numerical analysis was planned at a pre-experiment and a post-experiment stage. In the pre-experiment stage the analysis predicted the test and thus fascilitated the preparation of the experiment. In the post-experiment stage the analysis duplicated, as closely as possible, the experimental conditions and aimed at a validation of the numerical predictions with the experimental results. The numerical codes were adjusted to the modeling requirements of the project.

The project is in the final third year. At this stage the experimental program has been completed but the experimental results have not yet been fully analysed and contrasted to numerical predictions. Here we report on the experimental program and an early analysis of the experiments.

EXPERIMENTS

The experiments were conducted on the Shaking Table of the Earthquake Engineering Laboratory, NTUA and involved three different models: a single block, a 1:20 miniature and 1:3 model of a multidrum column of the Parthenon (Fig. 2). Experimental techniques were tested on the single block (Fig. 5) that also provided the basis for the calibration of the numerical model. The 1:20 miniature model is an exact replica of the ancient column and was included in the experimental scheme to study scaling effects.

The model material was obtained from a quarry in the Pentelikon Mountain, north of Athens, that has provided the building material of the classical monuments in the ancient city. The model column was prepared following strict specifications on the geometry and the preparation of the joints. The geometry followed the diametre attenuation towards the top (termed "miossis" by the ancient Greeks) of the original column. The whole length of the column was initially formed from a selected piece of marble and then cut into 12 drums. The marble piece was selected with bedding planes perpendicular to its longitudinal axis, to achieve maximum compressive strength. Special care was given to the formation of the joints. A 0.5 mm gap was created along the perimeter of the joint to avoid concentration of stresses there. The original position of the drums was marked and restored whenever the drums were reassembled in the Laboratory. The column was completed with the capital (Fig. 2). Repositioning of the column was effectively done with a specially designed mechanical system.

Recording of the response of the model was organised along traditional lines (accelerometers, displacement meters and video recordings) and a remote monitoring technique. The latter is described elsewhere (Georgopoulos et al, 1995) and consists of an inovative photogrammetric technique based on stereoscopic video recordings. The targets used in the stereoscopic recordings are the black dots shown on Fig. 2. The Figure also shows the accelerometers attached to each drum. The accelerometer arrangement consisted of the same horizontal component on each drum; only in the capital accelerations were also recorded in the transverse direction. Displacements were measured with Celesco PT8101 position transducers (recording capacity 1283 mm) in space at three different points of the capital. Each point was connected with three transducers in arbitrary directions. The recordings were then decomposed to three orthogonal directions. Experiments were routinely recorded by video cameras in two orthogonal directions.

The single block was subjected to a variety of motions: free vibrations and Shaking Table experiments. The Shaking Table experiments included sinusoidal excitations and actual accelerograms in all three directions. The experiments were guided successfully by numerical predictions. The block performed complicated and intense motions. In some cases, large rotations around a base corner were recorded and the block returned to a final position surprisingly close to the original.

The miniature column was tested on the Shaking Table with sinusoidal constant amplitude acceleration trains and frequencies 2-20 Hz. Tests were not recorded but showed significant response at 7 Hz. This characteristic frequency should not be seen as a resonant frequency in the classical sense, but as a natural frequency of vibrations associated with joint imperfections. Base accelerations in excess of 0.10 g caused sliding of the drums, starting from the top of the column. Although base accelerations reached 0.40 g, rocking motion was not noticeable. The model was ultimately forced to collapse due to excessive slip at the joints.

The 1:3 large multidrum model was subjected to actual earthquake accelerograms in eighteen tests. Three short duration records generated in Greece by moderate size (Ms around 6) earthquakes at short epicentral distances were selected to sample the broad variation of the frequency content of earthquake strong motions: the 1986 Kalamata record on stiff soil, with a predominant period of 0.35 sec, the 1983 Argostoli high frequency record on rock, with a predominant period of 0.15 sec and the 1990 Griva accelerogram, recorded on soft soil, dominated by a persistent long period horizontal motion of about 0.7 sec. Accelerations were scaled (amplified or deamplified) in order to obtain substantial response without approaching collapse conditions. The scaling was controlled by pre-experiment numerical analysis. In general, the numerical predictions of the model deformation were very satisfactory, thus providing a first order validation of the numerical code. The recorded response depended strongly on the input motions. The Kalamata record induced large rotations and very little sliding. The rocking mode of deformation was emphasised by the long period Griva record. The high frequency Argostoli input excited small rotation angles but significant sliding. This aspect is still under investigation.

The experimental program included duplication of tests and a variety of space configurations: in-plane excitations (one vertical and one horizontal) and 3-dimensional input motions. In the duplicate tests initial conditions were carefully restored. Nevertheless, the response showed substantial differences. Fig. 3 documents a 30% increase of the maximum response in two such "identical" experiments. In-plane excitations showed substantial out-of-plane response. Residual slips were also recorded at an angle to the plane of excitation. In general, the residual deformed shapes were not at all indicative of the intensity of the dynamic response of the column. Also, rocking was generaly initiated at base accelerations significantly less than the ones required for rigid blocks (diametre/height in g). There were, however, cases of high frequency base motions where the oposite was observed: although the base acceleration was much higher than the diametre to height ratio, no rocking was noticeable. Such a case is shown in Fig. 4; in this experiment the maximum base acceleration was double the one required for rocking and the top acceleration reached 4 times that value during the experiment. However, no visible deformation of the column was observed; the acceleration amplification was probably caused by small amplitude vibrations due to joint imperfections.

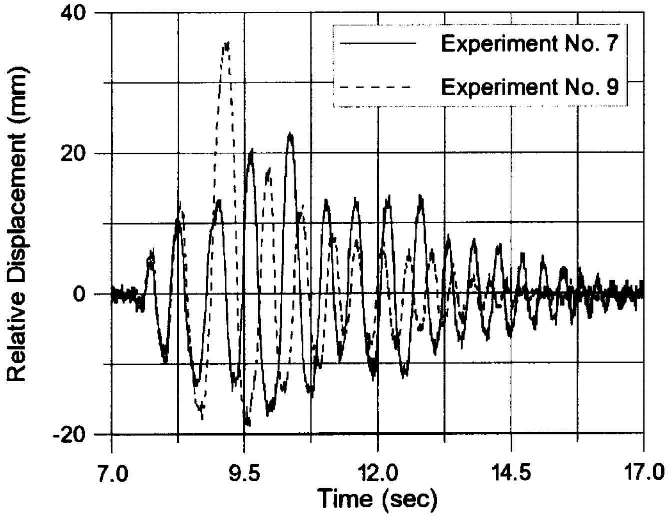


Fig. 3. Comparison of the relative displacement of the top of the column for two "identical" experiments.

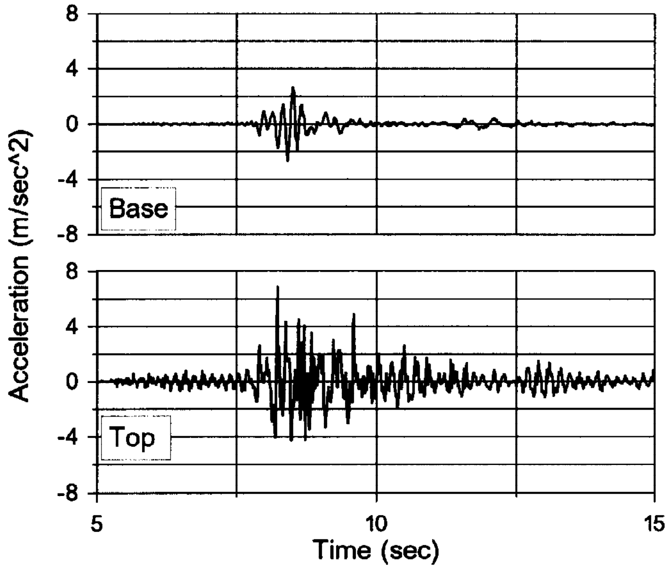


Fig. 4. Base and top acceleration of the multidrum column for the Argostoli earthquake record.

NUMERICAL ANALYSIS

The experiments were repeated numerically using the Distinct Element Method. For this purpose, the programs UDEC (2-dimensional) and 3DEC (3-dimensional) were employed after the necessary adjustments and modifications to the modeling requirements of the project. The experimental specimens were modeled by rigid blocks.

The numerical codes use springs and dashpots at the points of contact of blocks. In order to determine the most appropriate values for these constants, the results of the experiments with the single block column were used. A parametric investigation performed showed that the stiffness constant should be in the range of 10^9 to 10^{10} KPa/m; variations of K within this range do not affect the results significantly. On the contrary, the response of the block is sensitive to the value of damping. In some cases, very small changes of the damping coefficient changed the response drastically. This investigation is still in progress, but first results seem to lead to the conclusion that no damping should be used during the strong shaking, whereas some damping is necessary towards the end of the excitation and during free vibrations.

It should be noted that the sensitivity of the response to even small changes of the parameters is characteristic of the phenomenon of block rocking and it is not due to any numerical instabilities of the computer codes. For example, such a sensitivity appears in the theoretical solution of the rocking of a rigid block on a rigid foundation (Housner, 1963), if the coefficient of restitution during impact is changed slightly.

COMPARISON OF THE NUMERICAL WITH THE EXPERIMENTAL RESULTS

The analysis of the experimental data obtained is still in progress, and thus, only a limited number of comparisons between the numerical and the experimental results are available at this time.

Figure 6shows a comparison for the single block model (Fig. 5); in this case, the Kalamata, 1986, earthquake record, compressed in time by a factor of two, and amplified 1.5 times, was used as the excitation. The time compression was necessary, since, otherwise, the column was overturning soon after uplift because of its relatively small size. The results of 3DEC were obtained using zero damping. It is evident that the agreement achieved in both the amplitude and the frequency content of the response is satisfactory, especially during the strong shaking.

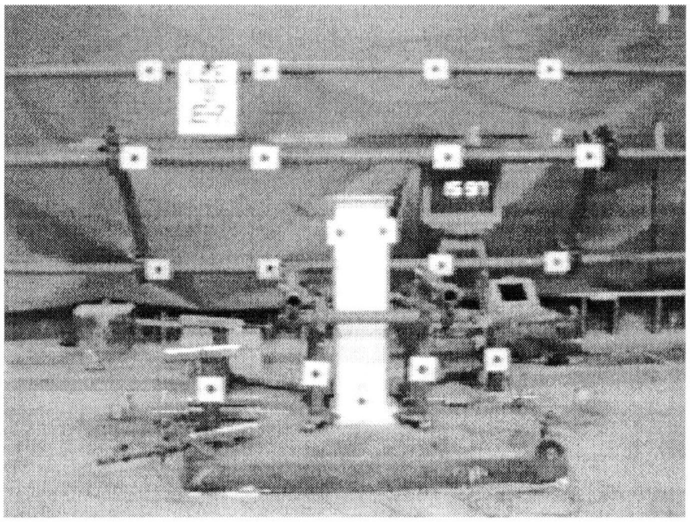


Fig.. 5. Single block marble column model.

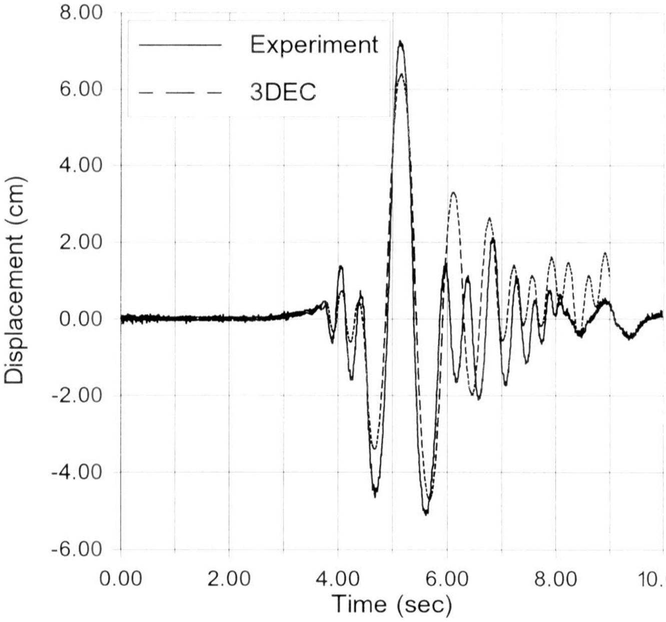


Fig. 6. Comparison of experimental and numerical results for the single block column.

Figures 8 to 10 show a comparison of the results for the multidram column. The Kalamata record, reduced to half its amplitude (Fig. 7), was used as the excitation. Again, the agreement is very good, in all directions. A permanent displacement of the top, which is evident in the experimental data and is due to relative slippage between the drums, was predicted by the numerical analysis, but with a higher value. Only towards the end of the excitation, the numerical results for zero damping do not show the expected amplitude decay. Adding damping to the model improves this behaviour, as can be seen at the bottom plots of Figures 9 and 10, where the results with slight mass damping are presented. Addition of damping, however, affects the response during the strong shaking by reducing the amplitudes and increasing the response frequencies. Since the results during the strong ground excitation are of more importance, it appears that the use of zero damping, as a single value choice, is preferable.

Good agreement between the experimental and numerical results was also achieved in the deformed shapes of the column during shaking (Fig. 11). Although joint openings are not clearly shown on the particular plot in Fig. 11 (b), numerical predictions show, in general, similar patterns of rocking and sliding between drums.

It should be noted that the agreement between the experimental and the numerical results, shown in Figures 6 and 8 to 11, is very satisfactory if one takes into account that the phenomenon is very sensitive to even small perturbations of the parameters. This sensitivity affects the repeatability of the experiments as illustrated on Fig. 3.

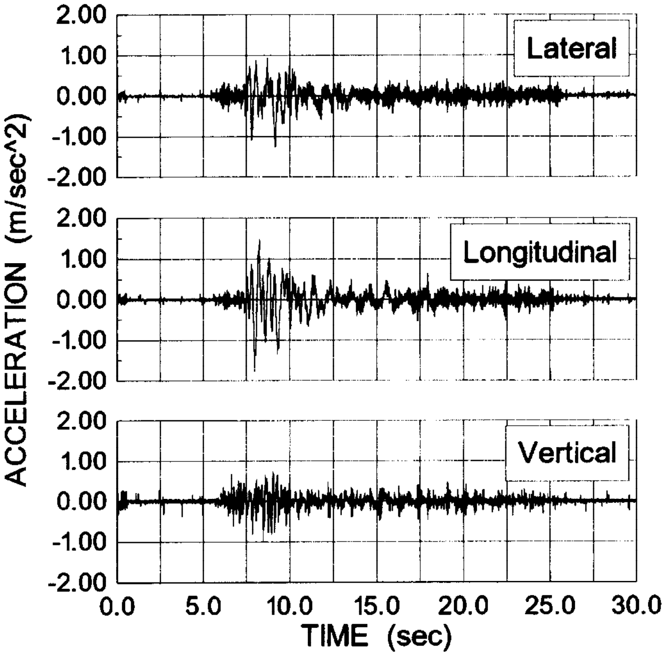


Fig. 7. Kalamata, 1986, accelerogram reduced to half the amplitude.

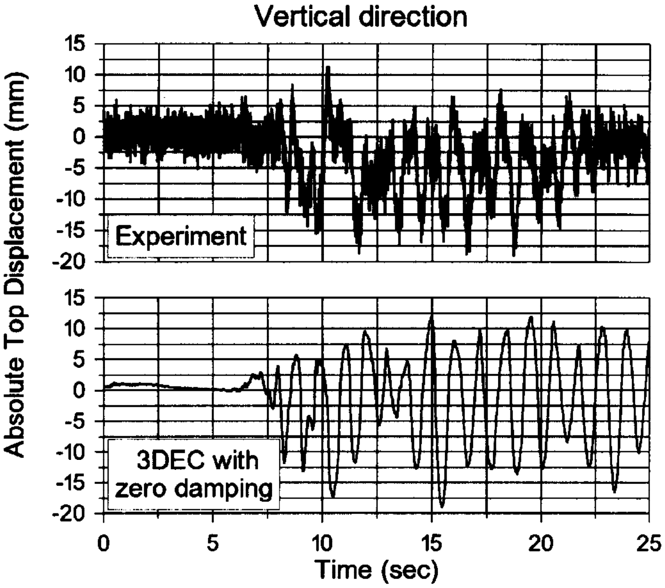


Fig. 8. Comparison of experimental with numerical results at the top of the multidrum column: absolute displacement in the vertical direction.

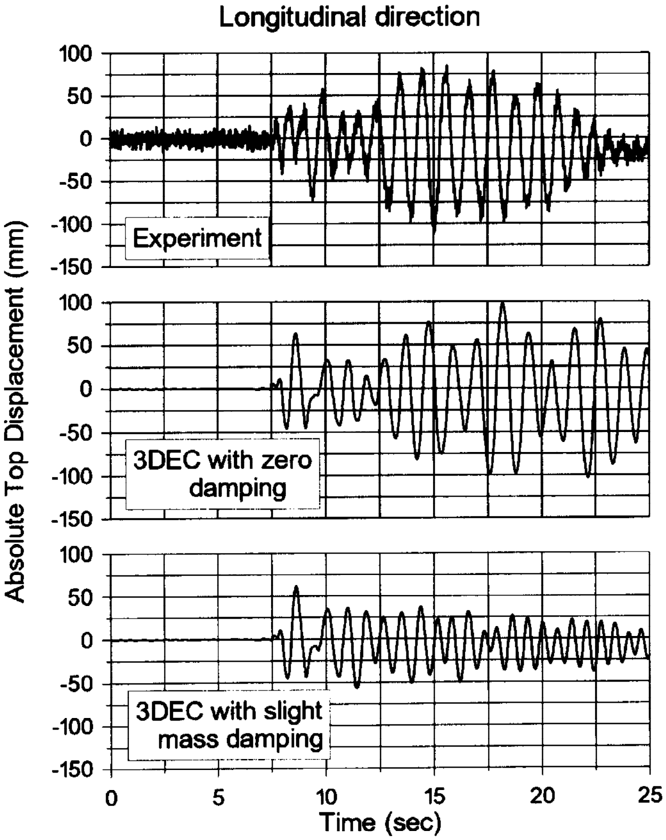


Fig. 9. Comparison of experimental with numerical results at the top of the multidrum column: absolute displacement in the longitudinal direction.

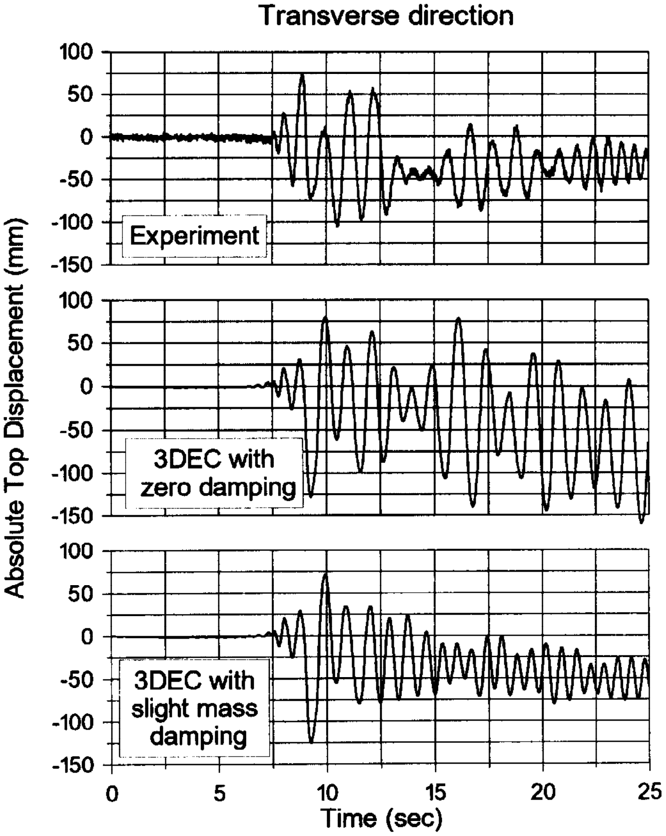
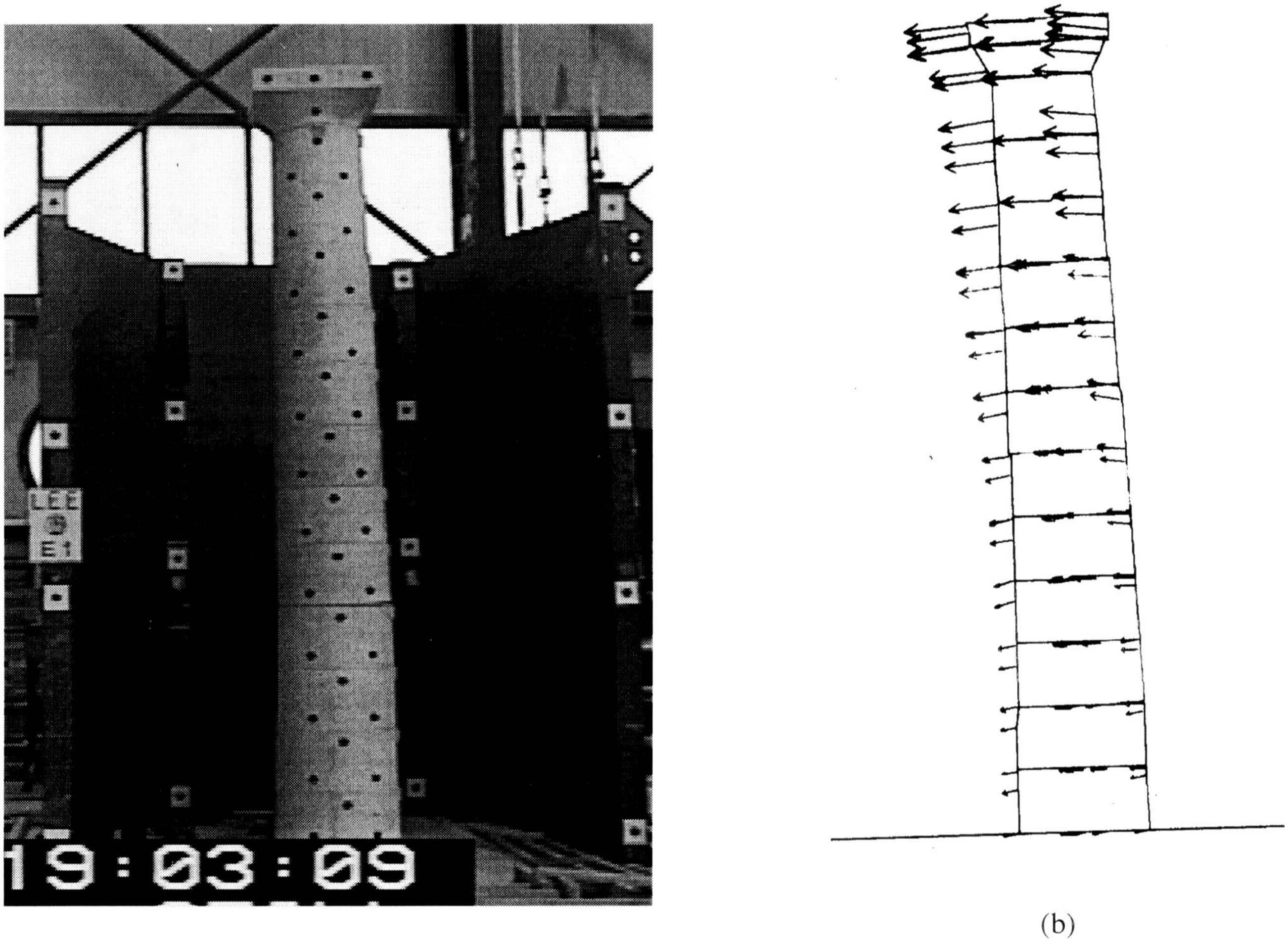


Fig. 10. Comparison of experimental with numerical results at the top of the multidrum column: absolute displacement in the transverse direction.



(a) (b)

Fig. 11. Deformed shape of column at maximum response: (a) digitized video picture (number identifies the frame) and (b) 3DEC analysis (vectors show displacements magnified by 2).

CONCLUSIONS

The analysis of the experimental results has not been completed yet. However, first results document some interesting aspects:

1. The experiments showed substantial sensitivity to small perturbations as expected. Although the details of the response cannot be accounted by the numerical model, the gross behaviour can be predicted numerically.

2. It appears that different mechanisms dominate small and large amplitude response. This situation can be handled numerically by adjusting the details of the joint parameters.

3. The response depends strongly on the ground motion input. In general, long period ground motions excited large angles of rotation whereas short period input produced small angle rotations and sliding.

4. Substantial differences were also observed on different size models. The much smaller, 1:20 marble miniature model, when tested on the Shaking Table with sinusoidal motions responded with a sliding mode.

5. The rocking response of the column is initiated at base accelerations significantly less than the ones indicated for rigid blocks by the ratio diametre/height. This phenomenon is due to the amplification of accelerations along the height of the column caused by the imperfections of the joints. This mechanism is handled by the joint model employed in the numerical code.

6. The experimental model responded to in-plane excitations with substantial out-of-plane motion. These tests also showed a significant out-of-plane permanent deformation.

7. The permanent set were not representative of the intensity of the response. In many experiments the column responded with large displacements, but the final deformation was surprisingly little.

Admittedly, comparisons have been restricted to a single column and stable conditions. However, the parallel run of physical and numerical experiments so far has shown the complexity of the phenomenon but has also built-up confidence on the potential of the numerical model to predict the gross features of the earthquake response. This is important, since the experimental results cannot be extrapolated to the full scale structure because of scaling effects, known from the theory and also confirmed by the experiments. More realistic structural configurations under severe earthquake motions can only be tested numerically.

ACKNOWLEDGEMENTS

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