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Studies of building components and structures and parts of industrial facilities with laboratory models and prototype structures in-situ (Earthquake Simulator Facility)

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INTRODUCTION - RESEARCH OBJECTIVES

This paper presents in a brief form some of the research activity of the earthquake simulator facility of Aristotle University of Thessaloniki Greece, which has been active in teaching and research in the field of Earthquake Engineering since 1983. The main activity is experimental either at the laboratory or in-situ, utilizing a two degree of freedom shaking table, a strong reaction frame as well as expertise in dynamic measurements for in-situ testing, complemented by numerical simulations. The experimental research includes studies on models of building structures and components, models of parts of industrial facilities and models of structures of cultural heritage (Part A). The in-situ studies focus on the dynamic or earthquake response of structures which include among others buildings, bridges and industrial facilities (Part B). In the framework of the in-situ studies the European Test Site at Volvi is also utilized, whereby the dynamic and earthquake response of relatively large model structures is monitored under realistic ground motion and soil-foundation conditions. The laboratory capabilities are seen as being complemented by the in-situ investigations as will be outlined by this presentation. The objectives of this research for the last 15 years have been to obtain confidence in the capabilities of the earthquake simulator facility of Aristotle University, by reproducing (in small-scale) certain aspects of the dynamic response and earthquake behavior of structures observed elsewhere during the testing of *"similar"* structures of much larger dimensions (near prototype); at the same time to establish the limitations of investigating problems of this nature in small-scale. Moreover, to extend this confidence and overcome the limitations by complementing the laboratory tests with in-situ research, as is briefly described in this paper.

PART A. LABORATORY INVESTIGATIONS.

The earthquake simulator facility includes a two degree of freedom shaking table(one-horizontal and one vertical) shown in figure 1. The size of the moving platform is 1.2m by 1.2m and the maximum velocity that can be obtained with a model of 1ton dead weight is 0.6m/sec in the frequency range from 1 to 25 Hz for the horizontal component and 1-45Hz for the vertical component. The facility is operated in conjunction with a computer system that can reproduce, from a data-base, prototype earthquake recordings. The facility also includes a strong reaction frame with the capacity of simultaneous vertical and horizontal loading on the tested specimens. Currently, partially reinforced masonry walls, depicted in figure 2, are tested in this facility in the framework of an extensive program for the Greek Ministry of Development. The vertical loading component is static with the ability to be stabilized at a desired level up to 20tons, whereas the horizontal component is fully dynamic with a capacity of 20tons in the frequency range from 0.1 to 45Hz. The following represent a brief description of the research activity in the laboratory.

Two-story model R.C. frame (Manos 1990).

A scaled model of a two-story R.C. frame structure was constructed and tested (figure 3). This model had a geometric scale 1 / 7.32 and was geometrically similar to a larger structure with a geometric scale 1 / 1.4 that was extensively tested at the Earthquake Engineering Research Center of the University of California at Berkeley. The main conclusion drawn from this study was that the overall performance and the damage patterns observed when the Thessaloniki specimen sustained considerable inelastic deformations were in general similar to those observed in the much larger Berkeley model (figures 3 and 4). s

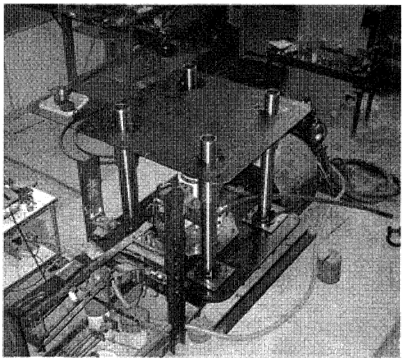


Fig. 1. The Shaking Table

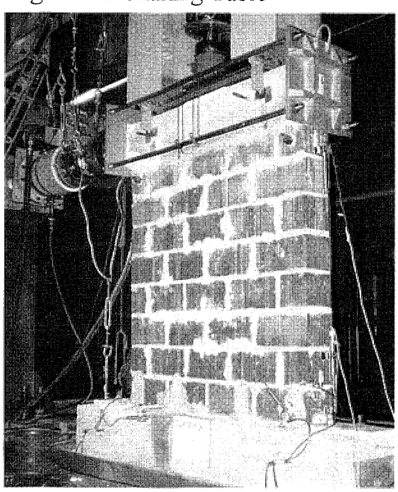


Fig. 2. The Strong Reaction Frame

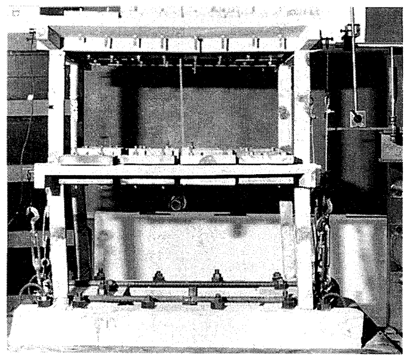


Fig. 3. The two story RC model on the Shaking Table.

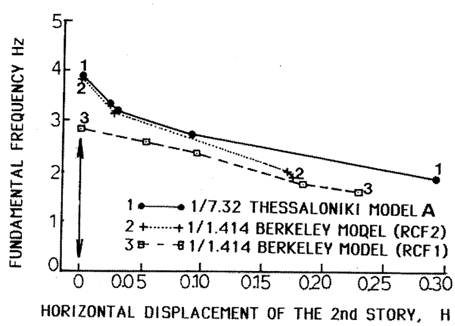


Fig. 4. Frequency variation through the simulated earthquake test sequence

One-story model R.C. frame with masonry infills (Manos 1995).

Specimens of one-bay one-story R.C. frames, with or without masonry infills, were studied representing 1/9 scaled models of prototype structural configurations. The target structures for comparison purposes were *"similar"* frames three times larger, built with prototype materials. The applied cyclic displacement was of the same nature with progressively increasing intensity. This study focused on the influence of the level of axial compression of the columns together with the existence of masonry infills. Figures 5 and 6 depict selected cyclic test results indicating the influence of the masonry infills and the axial load level of the columns. It was concluded that the inelastic cyclic behavior observed in similar structural configurations near prototype scale can be successfully simulated by the studied models.

Two-story model R.C. frame building with masonry infills (Manos 1995).
The investigation performed before was repeated for more complex structural formations involving the 3-D two-story R.C. frame models, presented briefly before; however, this time included masonry infills (figures 7 and 8). This investigation, which was conducted on the shaking table, aimed to establish the influence of the masonry infills on the dynamic response parameters of the structure, especially when the symmetry of the structure could not be safeguarded with the construction of the infills. From the study of the fundamental eigen-modes it was concluded that the presence of these infills on a perfectly symmetric framed structure may introduce eccentricities that would result in a complex - mode dynamic response.

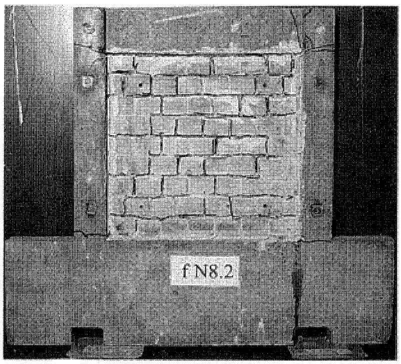


Fig. 5. The one story RC frame with masonry infills.

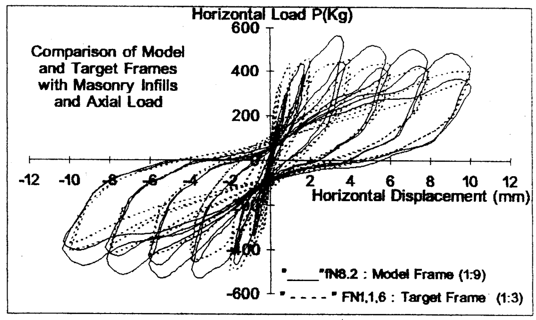


Fig. 6. Comparison of 1/3 Model and Target Frames with Masonry and with axial load

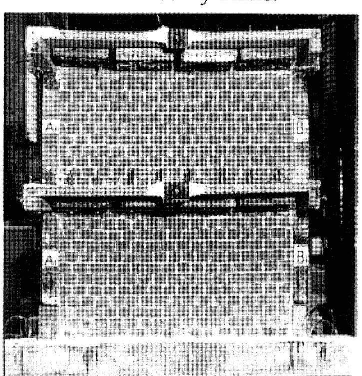


Fig. 7 The two story RC frame with masonry infills.

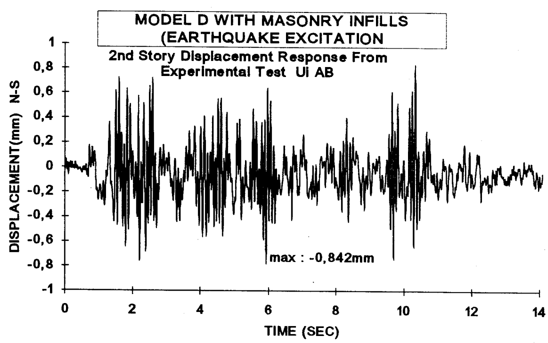
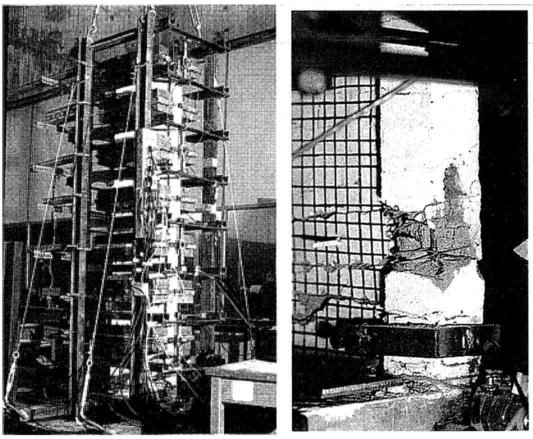


Fig. 8. Time history of the 2nd story displacement

The Shear Wall Model:
This structure is a 1 : 12.5 small-scale model of a 7-story shear-wall (figure 9). The prototype corresponds to the central shear, which was part of a 7-story prototype 3-D building formation that was examined extensively under pseudo-dynamic horizontal loads at the testing facility of Tsukuba-Japan, in the framework of the USA - Japan cooperative program; it included in addition a shaking table testing sequence with a 1:5 scaled-model of the prototype 3-D building formation as well as a pseudo-dynamic sequence with 1:12.5 free-standing scaled planar parts of this building, that contained the central shear-wall.



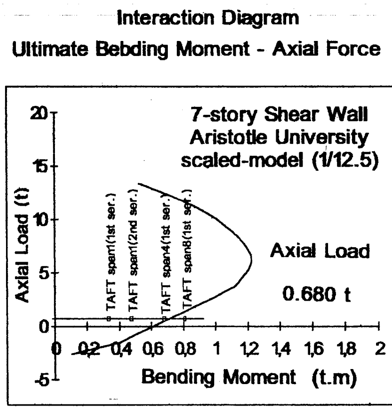


Fig. 9. Model Structure Aristotle University and damages at the 1st story

Fig. 10. Evaluation of observed flexural behavior

The 1:5 3-D structural model was investigated at the earthquake simulator facility of the University of California at Berkeley whereas the 1:12.5 planar parts were tested at the University of Stanford. The free standing shear-wall model that was examined here is a physical replica in dimensions of the corresponding planar structural system which was examined at the University of Stanford. However, whereas the testing sequence at Stanford used pseudo-dynamic horizontal loads, the examination at Aristotle University subjected the 7-story shear-wall model to simulated earthquake motions. The earthquake simulated tests were based on the horizontal ground acceleration recorded at Taft during the Kern county earthquake of 1953. Extensive damage developed on the first-story level of the shear-wall model, as depicted in figures 9a,b.

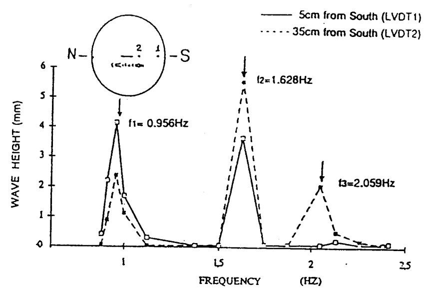
Evaluation of the Observed Shear Wall Performance : Figure 10 depicts this bending moment - axial load interaction diagram for the Aristotle University shear-wall cross-section. The values for the various parameters, such as the geometry of the section and the reinforcement as well as the various elastic and inelastic mechanical parameters of the micro-concrete and the reinforcement, were as they have been measured. The observed dominant flexural damage of the model shear-wall at Aristotle University is in agreement with both the model tests performed at the University of Stanford and Berkeley as well with the observed prototype building performance. However, because the tested at Aristotle University structure was a free-standing single shear wall without any coupling with frames in either the longitudinal or the transverse sense, the important interaction effects from these connections that were observed in these complex tests could not be observed here.

Cylindrical Liquid Storage Tank Models (Manos 1986, 1993).

The seismic behavior of ground supported metal cylindrical model tanks as parts of industrial facilities is examined when they are based on a relative stiff foundation and are left unanchored at their base. These experiments aimed to investigate the sloshing response as well as the earthquake behavior of these structures when they develop uplift response at their base during the seismic excitation. As a result of this type of response and the resulting axial stress concentration at the cylindrical shell near the base various forms of buckling of the tank shell could develop. Moreover the experimental investigation aimed to establish the dynamic parameters of the response during these complex modes of uplifting base displacement. One of the first models, studied at Aristotle University was made of thin bronze alloy sheets (Thessaloniki Bronze Tank), to form a cylindrical tank model 500mm in diameter and 600mm height, was filled with water during the experimental sequence at a depth of 500mm. One other model tank was made of thin copper sheets that formed a cylindrical tank (Thessaloniki Copper Tank) 1000mm in diameter and 1100mm height, which was filled with water during the experimental sequence at a depth of 1000mm.

Dynamic Response Characteristics. The displacement and acceleration response of the shell or the free liquid surface displacement (sloshing) response was monitored during the simulated earthquake tests in order to get an insight into the influence of the base support conditions on these base response quantities. Figure 11a depicts a comparison between the observed and predicted sloshing response for the Thessaloniki Copper Tank whereas figure 11b depicts one of the many distortional response measurements, of the bronze tank's mid-height cross-section.

OBSERVED AND PREDICTED SLOSHING MODES
THESSALONIKI COPPER TANK



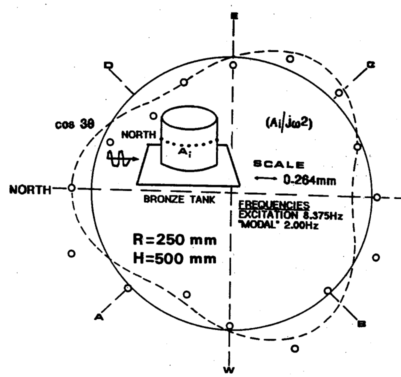


Fig. 11a, b. Results from the experimental investigation of the Thessaloniki Model Tanks

Observed Shell Buckling Behavior : The observed buckling behavior of two metal model tanks is briefly described here. The experimental sequence utilized a tilt-base rotating platform as well as the shaking table of the earthquake simulator facility. It has been established for some time that *"the abrupt loss of axial membrane compression for the shell coincided with a sharp increase in the bending response, believed to be typical phenomena for the transition to post-buckling deformations"*. Figure 12 depicts the observed buckling patterns (diamond shape) of the bronze tank that developed when the tilting exceeded 13 degrees. However, the first visible buckles appeared for tilt angles nearing 12 degrees tilt. Figure 13 depicts the observed buckling patterns of the copper tank that were observed when the tilting exceeding 6 degrees. This time the observed damage is of the distinct "elephant's foot bulge" at the portion of the shell near the tank bottom. This type of buckling that developed during the tilt-base sequence was also reproduced on a replica of the Thessaloniki Copper Tank subjected to horizontal simulated earthquake excitations on the shaking table.

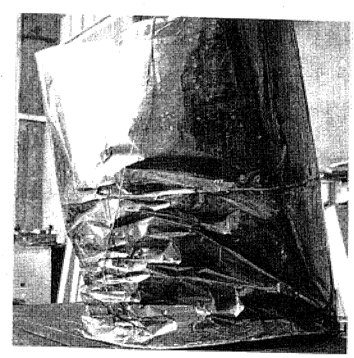


Fig. 12. "Diamond Shape Buckling"
Bronze Tank

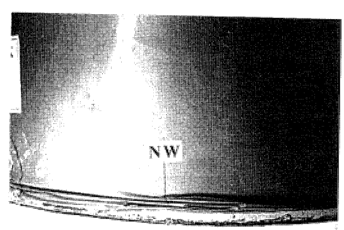


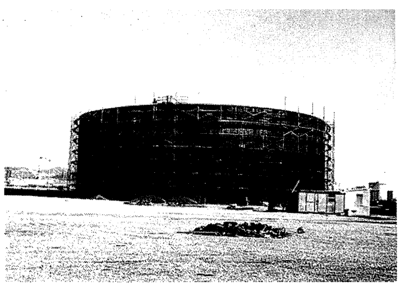
Fig. 13. "Elephant's Foot Bulge"
Copper Tank

Comparison of Observed and Predicted Shell Buckling. One of the objectives of this extensive investigation, apart from simulating, in the laboratory, shell buckling behavior similar to that observed in prototype tanks during strong earthquake excitations, was also to correlate the observed buckling shell response in these test structures with predictions based on an empirical approach developed by the author (Manos, 1986). The limit critical shell compressive axial stress was predicted according to the Manos empirical approach. Good correlation could be observed between predicted and observed shell buckling

PART B. IN-SITU INVESTIGATIONS

Measured Response of a Prototype Liquid Storage Tank.

The displacement and strain response of a prototype steel tank for storing crude oil was measured in-situ immediately upon the completion of its construction during the water-filling test. The diameter of this tank was 45.7m and the height 14.65m. Despite the difficulties imposed by the dimensions of the structure and the variable in-situ conditions this test was quite successful in measuring the strain response variation during the water filling process. Figure 14 depicts a view of this structure and the measured strain response is depicted in figure 15. It was concluded from this study that the strain response measured in this way exhibited reasonably good agreement with analytical predictions.



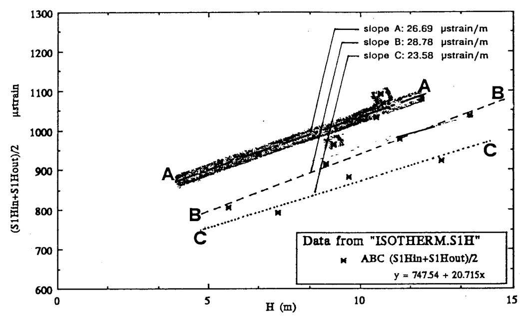
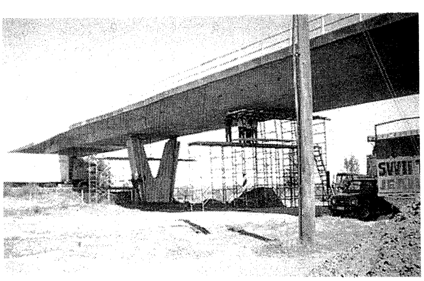


Fig. 14. Prototype Liquid Storage Tank Fig. 15. Measured Strain Response of the Tank



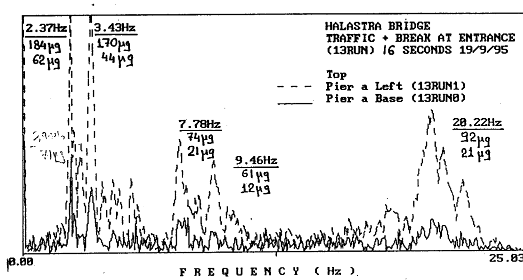


Fig. 16. Prototype Bridge Structure Fig. 17. Measured Dynamic Response of the Bridge

Measured Response of a Prototype Bridge Structure.

In-situ dynamic measurements of the acceleration response of a prototype bridge were carried out in order to obtain the dominant dynamic response characteristics (eigen-modes and eigen-frequencies) of this structure. The excitation was provided by a moving load of 20t. The total length of this bridge is 160m and its width 7.5m. The deck was supported on 5 piers and two external abutments. Figure 16 depicts the tested structure whereas figure 17 depicts typical response measurements. From the correlation of the measured response with a numerical simulation model of this structure it was observed that the resistance to the horizontal earthquake forces up to a level would not be provided only by Pier 3, as designed, but also by the other supports due to restrains imposed in-situ that were not anticipated in design. **In-Situ Tests at the European Test Site in Volvi** (Manos 1996).

The test site is located at Volvi near Thessaloniki, Greece, in an area of high seismicity. A 5-story reinforced concrete building was constructed and instrumented at this site in order to monitor its dynamic response under prototype earthquake conditions. Despite the disadvantage of being unable to produce in-situ significant levels of ground motion, when desired, as can be generated by an earthquake simulator at the laboratory, the advantage here is the presence of realistic conditions for both the foundation support and of course the earthquake ground motion. Already, one earthquake, of moderate intensity, subjected the model structure to seismic loads and excited the permanent instrumentation system. This work has been partially supported by the European Union, Projects ENV.5V-CT93-0281 and ENV.4-CT.96-0255 (DIR XII). Figure 18 shows a transverse cross-section of the valley at its narrowest part.

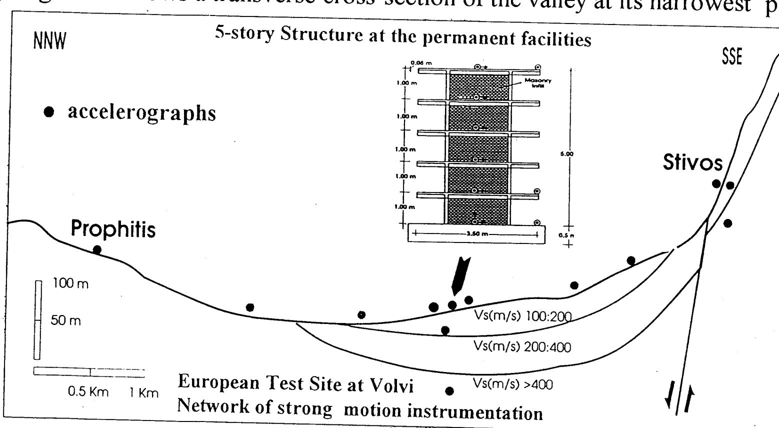
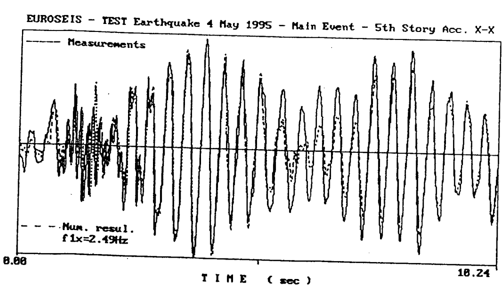


Fig. 18. The 5-story Structure at the European Test - Site

At the central part the permanent facilities of the European test site are also established, and it is here that the 5-story reinforced concrete structure has been built. More than 10 instruments monitor the ground motion across the valley and sixteen sensors record the dynamic response of the 5-story structure (figure 18). All the material properties for the concrete and the reinforcement have been monitored by tests performed with samples taken during construction.

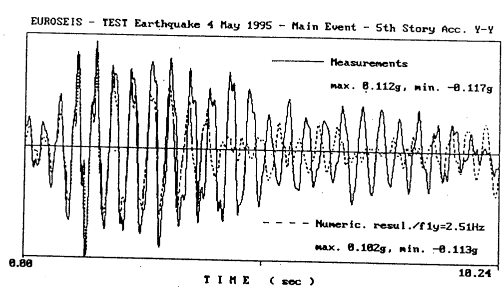


f x = 2.49Hz

---- Numerical Results, max 0.093g, min -0.094g

____ Measurements, max 0.090g, min -0.094g

Figure 19a. 5-story Structure at Volvi,



f y = 2.51Hz

---- Numerical Results, max 0.102g, min -0.113g

____ Measurements, max 0.112g, min -0.117g

Figure 19b. 5-story Structure at Volvi,

CONCLUSIONS

1. By reproducing, in small-scale, certain aspects of the dynamic response and earthquake behavior of structures observed elsewhere during the testing of *"similar"* structures of much larger dimensions (near prototype); it was possible to obtain simulations with a good degree of consistency in the field of structural dynamics and earthquake engineering. Although this facility cannot be used for performance tests of actual structures, or of large components and devices it can realistically reproduce behavioral patterns, that extend to the non-linear domain; it is believed that they can be used to test relevant computer code or to draw important qualitative conclusions. This holds for the global behavior of metal as well as reinforced concrete structures with or without masonry elements. However, certain limitations exist with regard to the simulation of local damage patterns for R.C. structures.

2. For contemporary building structures, the consistency in the simulations of the earthquake simulator facility includes their main components such as frames, shear walls and masonry infills. This, apart from expertise in structural dynamics it also requires extensive experience and skill with materials and small-scale modeling techniques for post-elastic dynamic load investigations. Moreover, the existence of well documented test-structures with dimensions near prototype conditions is of utmost importance. It is the strong belief of the author of this paper that only through these type of comparisons can the consistency of the results be verified. Thus, studies on the earthquake behavior of structures and components that extend to the non-linear range and use models deviating in dimensions and material terms from prototype conditions should verify their experimental processes in ways similar to the one described in order to gain confidence in their results.

3. The reaction frame at the Laboratory of Strength of Materials of Aristotle University, briefly described in the introduction, is intended to be used to study the earthquake performance of structural components near prototype, thus further complementing the knowledge, which can be subsequently utilized by the Earthquake Simulator.

4. With the complementary in-situ research activity, especially that at the European test site at Volvi a successful effort has been made to bridge the laboratory experience and observations on the earthquake behavior of structures with those under prototype conditions, without the limitations imposed by small-scale. In addition, the actual in-situ behavior has the advantage of including, among other things, influences arising from the prototype support conditions at the foundation level as well as those of the earthquake excitations.

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