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PERFORMANCE BENCHMARK OF THREE MAJOR EUROPEAN SHAKING TABLES

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SUMMARY

Previous studies within former European Consortia of Earthquake Shaking Tables, have investigated and compared how well the different shaking tables of these consortia could execute the same task using identical elastic test pieces. It has resulted in a control enhancement at all the facilities. Being then necessary that similar comparison tests be developed with extension to non-linear behaviour, the largest possible specimen, specifically designed for that purpose, was built and tested on three very different shaking tables. This test specimen was designed to reproduce the global non-linear behaviour of a concrete building while being damaged during an earthquake, concerning a typical global stiffness reduction. This system, being able to simulate a sudden collapse or a progressive degradation, can reproduce, in a repetitive and accurate way, the same non-linear conditions. In the present paper the design of the test specimen is discussed and the results of the tests are presented.

1. INTRODUCTION

A concerted effort has been made, since the beginning of the nineties, by the main partners of the NEFOREEE project (New Fields of Research in Earthquake Engineering Experimentation) to study the way in which shaking tables, and later reaction walls, really behaved. In fact, several studies concluded in the framework of previous European Consortia of Earthquake Shaking Tables (ECOEST) have investigated and compared the performances of the main European shaking tables and how well they could execute the same task using identical elastic test specimens. The partners of these consortia were the Laboratory for Earthquake Engineering of the National Technical University of Athens (NTUA), Greece, the Earthquake Engineering Research Center of the University of Bristol, U.K., the Laboratorio Nacional de Engenharia Civil (LNEC), in Lisbon, Portugal, the Commissariat à l'Energie Atomique (CEA), in Saclay, France and Enel.Hydro s.p.a., in Seriate, Italy. Later, the former ECOEST partners have created a new consortium named ECOLEADER (European Consortium of Laboratories for Earthquake and Dynamic Experimental Research) then including the new reaction wall facility constructed at the Ispra Joint Research Centre, in Italy. These activities have induced an enhanced control at all the facilities of the consortia but have also highlighted the need to carry out a new project in view of further benchmark tests with extension to non-linear behaviour.

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In this paper are presented the tests of a particular task of this new project consisting on the comparison of the performances of three shaking tables (CEA, LNEC and NTUA) of the consortium ECOLEADER. These three laboratories are running important European shaking tables, from 4x4 m to 6x6 m platform, from a dead-weight of 10 tons to 40 tons and allowing horizontal dynamic forces between 300 kN and 2000 kN, thus comprising a wide spread of seismic experimental activities. The characteristics of a common specimen being able to be tested by these three laboratories were defined. These characteristics were taken into account in the performances and dimensions of the three representative shaking tables. The specimen was tested successively on each table, being transported by truck and ship among the laboratories, under uniaxial input signals and the results were compared.

The test specimen was designed to reproduce the global non-linear behaviour of a concrete building while being damaged during an earthquake, concerning a typical global stiffness reduction. It is important to highlight that it was conceived in order to allow consecutive similar tests in spite of its non-linear behaviour. This system, being able to simulate a sudden collapse or a progressive degradation, can reproduce, in a repetitive and accurate way, the same non-linear conditions. It is possible to change its stiffness during the seismic tests whenever it is wanted and for an adjustable duration. Consequently, it also permits a comparison of the earthquake simulators behaviour concerning the change of the control conditions and the influence of the intrinsic characteristics of each specific facility.

2. TESTING FACILITIES

2.1 CEA – Saclay

The CEA testing facility, TAMARIS infrastructure, includes the AZALEE 6m x 6 m shaking table, which allows testing of specimens with a mass up to 100 tons in three directions and has six degrees of freedom (3 translations and 3 rotations). Independent excitations of any kind: (sinusoidal, random, shock, seismic with a 0 -100 Hz frequency range) may be applied. In CEA there are three other tables (VESUVE, TOURNESOL and MIMOSA), each one having about 10 tons capacity, which optimize the use of the facility. The tables are completed by a pit (IRIS), with a diameter of about 4m, which allows the testing of specimens up to 25m long. All equipments are connected to the acquisition system for recording and processing of 142 channels.

The Laboratory is connected to a scientific computing system with finite element code (Cast3M). The Laboratory is working on different national and international programs (Europe, Japan) related to the seismic behaviour of equipment, components and structures. Main activities are devoted to: a) Industrial and nuclear equipment such as electrical cabinets, tanks, storage racks, piping systems, in order to understand and codify their seismic behaviour, and to evaluate the margins of current design methodologies, b) Civil engineering structures with analysis and testing of structural elements (shear walls, frames…) or full structures in order to evaluate the margins of design methods or to improve them and to quantify the effect of construction details (joints, bond slips, lap splices,..) and soil structure interaction.

The AZALEE table is actuated by eight electro hydraulic jacks of 1000kN each (four into horizontal and the other four into vertical directions). Four pneumatic static supports placed under the table make possible to take a part of the actual weight (model + table) during the tests. The left picture on Figure 1 shows the general aspect of the AZALEE shaking table, on which were performed the NEFOREEE tests. In the referred figure is also shown the NEFOREEE specimen.

The shaking table is controlled by a bay of control associated with a PC with piloting DELL Precision 410. For seismic tests, the program of piloting I_PSCn Version 4.5.1.2 developed by the company DATA PHYSICS is used. It allows the control from 1 to 6 degrees of freedom according to the table used. It makes it possible to determine the transfer functions of the testing facility according to all degrees' of freedom and corrects the signals of control sent in loop open on each axis of the table. A Spectrum of Response of Oscillators (SRO) of the table was calculated starting from the acceleration measured on the table and it was compared during the preliminary tests with the spectrum of reference. Corrections on the transfer functions can be carried out if necessary to approach as well as possible the actual acceleration and the desired spectrum. For the controller, the sampling rate is equal to 200 Hz. All the signals are filtered to 50 Hz. For the other acquisition channels, the sampling rate of the signals is 200 Hz (PC DELL Dimension V400).

2.2 LNEC– Lisbon

The infrastructure is constituted by the seismic testing facilities installed at the LNEC (Portuguese National Laboratory for Civil Engineering). It is operated by the NESDE (Seismic Engineering and Structural Dynamics

Division) of the LNEC Structures Department. Its main equipment is a triaxial shaking table that has started its activity in 1993. Two smaller, uniaxial, shaking tables are also available.

The main table has three independent translation degrees of freedom, with the rotational degrees of freedom minimized by torque tube systems. Under the horizontal cranks it can be inserted either passive gas actuators, to cope with the dead weights of the shaking table and of the testing specimen, or rigid blocks eliminating the vertical motion of the table. An important upgrade of its hydraulic performance was accomplished, by means of an additional bank of nitrogen accumulators and replacement of the previous servo-valves by higher capacity ones in order to enable the table to reach peak velocities of about 70 cm/s. The shaking tables are located in a large testing hall with a floor to ceiling height of 10 m enabling the testing of tall structures. Furthermore, around the triaxial shaking table there are three moderate capacity reaction walls that increase the ability of the facility to support diversified testing set-ups. The central picture on Figure 1 shows the NEFOREEE specimen on the LNEC-3D shaking table.

It should also be referred that an overhead crane with 400kN capacity and very low speed control allows the construction, installation and removal of large specimens from the table. The equipment is operated by the NESDE, which provides a strong scientific environment, both in experimental and analytical terms, related to research in Earthquake Engineering. Besides the shaking tables themselves and their power stations this infrastructure includes also two specifically dedicated rooms, one devoted to control and one devoted to data acquisition and processing. An informatic network is established within NESDE providing immediate access from all office rooms to the data acquisition systems. Command and control of the shaking table is fully digital with capability to simulate specific motions expressed either as a response spectra or a time-history of motion. The acquisition system, a state of the art proprietary program, allows up to 154 channels for measuring pressures, forces, accelerations, displacements (LVDTs and optical), strains, etc

2.3 NTUA – Athens

A mechanical shaking table exists at the National Technical University of Athens since 1965. Based on this experience, and by the destructive earthquakes that occurred in the major cities of Greece during the period 1978-1981, a new shaking table was constructed in 1985. This 6 DOF shaking table with its control system was unique in the word, at that time. The steel table was constructed in Athens, as well as other minor items of the facility. The main characteristics of the earthquake simulator are summarized as follows in Tables 1 and 2.

A specific analogue unit with which the user has the possibility of independent or simultaneous performance of each degree of freedom is controlled the shaking simulator. The unit can produce and combine sinusoidal or quadrangular, for instance, signals with specified spectra or other characteristics created at the Laboratory. Vibrations can be generated for each direction independently or simultaneously. External recordings of other receivers can be used to provide input to the analogue unit. Special procedure is performed in order to minimize the deviation between the desired and achieved input signal. The recorded data are stored in the computer, through D/A converters. Recently, and as a result of the CESTADS project the control has been tremendously ameliorated, bringing up the whole fidelity of the facility to the top in world class.

2.4 Main characteristics of the facilities

In Figure 1 are presented the three shaking tables described in the above subsections.

Figure 1: General view of the three shaking tables with the NEFOREEE specimen on them: a) CEA - AZALEE, b) LNEC-3D and c) NTUA

The following tables show the main characteristics of the shaking tables, of the controllers and of the signal conditioners.

Table 1: Characteristics of the shaking tables of the three testing facilities

		CEA - Saclay	LNEC - Lisbon	NTUA – Athens
Table size		6 m x 6 m	5.6 m x 4.6 m	4 m x 4 m
Table mass (material)		25 tons (alluminium alloy)	40 tons (steel)	10 tons (steel)
Maximum specimen mass		100 tons	40 tons	10 tons
Controlled degrees of freedom		6 (3 Translations and 3 rotations)	3 (Translations)	6 (3Translations and 3 rotations)
Hydraulic flow		2200 liter/min and 12 accumulators (12x250 liter)	690 liter/min and a set of accumulators	1248 liter/min
L	Max. Displacement	125mm	150 mm	100mm
	Max. Velocity	1m/s	0.74 m/s	1m/s
	Max. Acceleration	4.5g	2.5 g	2g
	Number of actuators	2 a 1000kN	1 of 1000kN	2 a 160kN
T	Max. Displacement	125mm	150 mm	100 mm
	Max. Velocity	>1m/s	1.21 m/s	1 m/s
	Max. Acceleration	>4.5g	1.9 g	2 g
	Number of actuators	2 a 1000kN	2 of 300kN	2 a 160kN
V	Max. Displacement	100mm	150 mm	100 mm
	Max. Velocity	>1m/s	0.73 m/s	1m/s
	Max. Acceleration	>4.5g	3.2 g	4 g
	Number of actuators	4 of 1000kN	1 of 300kN	4 of 160kN

Table 2: Characteristics of the controllers and signal conditioners of the three shaking tables

		Type	Company	Name
CEA	Table	6 DOF 6mx6m	SEREME	AZALEE
	Actuators	8 electro hydraulic	MTS	244
	Controllers	PID 6 DOF	MTS	469
	Control computer	Seismic test	Signalstar	I_PSCn
LNEC	Table	3 DOF 4.6mx5.6m	LNEC/INSTRON	LNEC – 3D
	Actuators	4 electro hydraulic	INSTRON	3x375/1x1250
	Controllers	PID 3 DOF	INSTRON	8580
	Control computer	INSTRON 8580 – Control tower	INSTRON	SPiDAR
NTUA	Table	6 DOF 4mx4m	MTS/NTUA	-
	Actuators	8 electro hydraulic	MTS	204
	Controllers	PID 6 DOF	MTS	469
	Control computer	Seismic test	MTS (USA/Italy) MCS (UK)	-

3. DESCIPTION OF THE SPECIMEN TESTED

In general the specimen tested is composed by: a) footing plate which allows the perfect connection to CEA, LNEC and NTUA shaking tables, b) rigid steel frame, c) oscillation mass attached with more or less rigidity to the steel frame for corresponding to an initial excitation frequency of about 7Hz, d) system of four pressurized airbags which allow the modification of the frequency during any seismic test. In Figures 2 and 3 are presented, respectively, the front and the lateral view of the model.

The oscillation mass, above referred, is characterized by stiffness and damping, which roughly allows the simulation of the response of a model equivalent to a building. The main characteristics are able to change in a controlled way, whenever wanted and during an adjustable duration, in order to simulate the degradation due to seismic inputs. The mobile mass of the specimen corresponds to an important percentage of the shaking tables masses, particularly for the smallest table (NTUA) in which corresponds to 70%. The mass, composed by a set of several identical plates has a maximum of 7ton and allows the use of a smaller number of plates if convenient. Transversely the mass is guided in order not to disturb the longitudinal motion during the tests. Vertically the mass is maintained by a bearing device that was designed to have a vertical frequency higher than 20Hz.

Figure 2: Front view of the model

Figure 3: Lateral view of the model

The frequency was able to be adjusted by the air bags pressure and the damping was ensured by a set of Gerb shock absorbers. The changing of frequency, from about 7Hz to 3Hz during the tests, was obtained by a partial depressurization through specific gauged diaphragms. Two diaphragms of larger (60mm) and smaller (10mm) openings were tested for validation of the discharges duration.

4. INSTRUMENTATION OF THE SPECIMEN AND SHAKING TABLES

The instrumentation on the table and the specimen consisted only in one displacement transducer to measure the displacement of the additional masses and five accelerometers to measure the accelerations on the bottom and top of the specimen, on the centre of the additional masses and at two different points of the shaking table platform to check the level of rotations that were generated. In Figure 4 is presented the instrumentation plan.

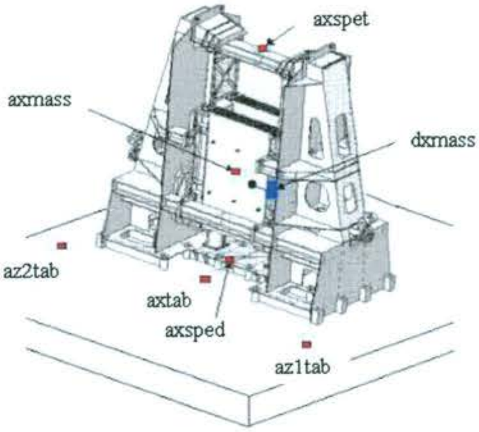


Figure 4: Instrumentation plan of the specimen and shaking table

The different input signals and the condition of the valves were also recorded: a) velocity, force and displacement of the table, b) displacement and force from roll and pitch degrees of freedom, c) displacement, intensity and delta pressure on the level of a servo valve of one actuator, d) driver signal sent to the servo valve, e) opening and closing commands of the valves and e) opening and closing response of the valves.

5. EXPERIMENTAL PROGRAM

Preliminary tests have been performed to calibrate the pressure in each pair of airbags to obtain the required frequencies. With the referred pressurized airbags the frequency of the moving mass is 6.73Hz while without pressure the minimum frequency measured was 3.4Hz.

5.1 Experimental Program in CEA – Saclay

Several series of seismic tests were carried out with increasing levels of acceleration. When changing the dynamic characteristics of the specimen, different durations were adopted by substituting the diaphragms (with different diameters) thus generating this from 5s to 0.1s. For some tests, the piloting of the table was made in acceleration and/or displacement with one or three variables. The table below gathers the whole of the seismic tests carried out on AZALEE shaking table.

Table 3: List of the seismic tests performed on AZALEE shaking table

		Diaphragm 0mm without discharge		Diaphragm 10mm discharge in 5s		Diaphragm 60mm discharge in 0.1s	
		Correct Spectra	Correct Accel.	Correct Spectra	Correct Accel	Correct Spectra	Correct Accel
3 variables control (accel. signal)	0.1g	x	x		x	x	x
	0.4g	x	x		x	x	x
	0.6g	x	x		x	x	x
3 variables control (displ. signal)	0.48g	x				x	
	1.13g	x				x	
1 variable control disp (accel. signal)	0.1g		x		x		
	0.4g				x		
	0.6g				x		
1 variable control disp. (displ. signal)	0.55g	x				x	
	1.19g	x				x	

In order to check the shaking table behaviour and the influence of the depressurization, the response of the sensor on the platform "axtab" is compared with and without depressurization of the specimen, under the same condition of the control system and for the same input levels. The sensor "axtab" was chosen for this purpose because it is placed simultaneously on the platform and at the centre and bottom of the specimen. It should be noticed that AZALEE table has a very good response, particularly in high level in acceleration and almost no changes when a depressurization is imposed, as it can be observed from figures 5 and 6.

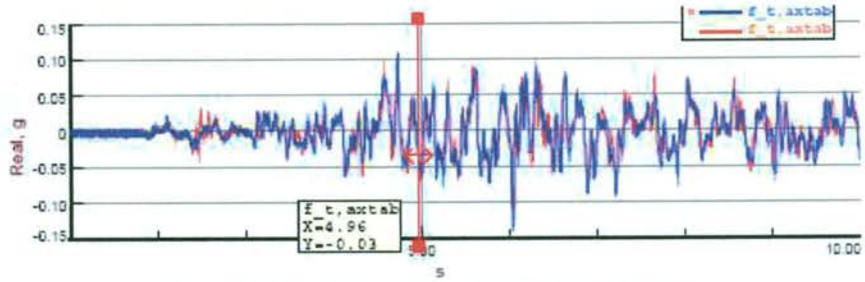


Figure 5: Test at 0.1g – CEA AZALEE shaking table

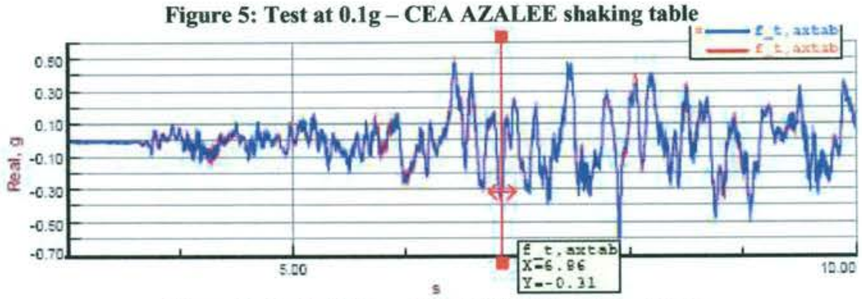


Figure 6: Test at 0.6g – CEA AZALEE shaking table

From the acceleration signals, the response spectra of the shaking table have been calculated (Figure 7). The comparison of the response spectra shows, for tests with and without depressurization, there is not a great difference, which still proves that the AZALEE shaking table controller is not affected by the behaviour of the non linear model.

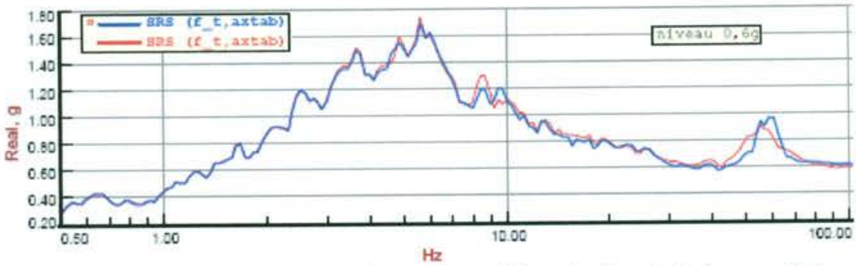


Figure 7: CEA-Saclay Spectra – Comparison with and without discharge at 0.6 g

5.2 Experimental Program in LNEC– Lisbon

Similar tests have been performed in LNEC, considering the same initial conditions for the specimen. The base signal was filtered for a frequency band ranging from 0.1 to 33 Hz and adapted to achieve a table acceleration of 0.6g. During the tests this signal was scaled to achieve the desired peak acceleration level.

In all tests the trigger action to open the relief valves has occurred 5s after the start of the input signal. As in Saclay, the slow discharges (approximately 5s) were obtained by using a diaphragm with a 10mm opening; while the fast discharges (approximately 0.1 s) were obtained by using a diaphragm with a 60 mm opening. The following table resumes the experimental program performed at LNEC.

Table 4: Experimental program performed on LNEC-3D shaking table

PGA [g]	Description
0.1	without discharge
	with discharge in 5 seconds (10mm diaphragm)
	with discharge in 0.1 seconds (60mm diaphragm)
0.4	without discharge
	with discharge in 5 seconds (10mm diaphragm)
	with discharge in 0.1 seconds (60mm diaphragm)
0.6	without discharge
	with discharge in 5 seconds (10mm diaphragm)
	with discharge in 0.1 seconds (60mm diaphragm)
0.8	without discharge
	with discharge in 5 seconds (10mm diaphragm)
	with discharge in 0.1 seconds (60mm diaphragm)
1.0	with discharge in 0.1 seconds (60mm diaphragm)
1.2	with discharge in 0.1 seconds (60mm diaphragm)

The shaking table acceleration and displacement were recorded during the experimental program. For each test, the acceleration time histories and the corresponding response spectrum are plotted, as well as the hysteretic loops of the force-displacement relations. In Figures 8 to 10 are presented the results, in terms of acceleration, obtained for the 0.1g and 0.6 g tests and also the response spectra for the 0.6g test.

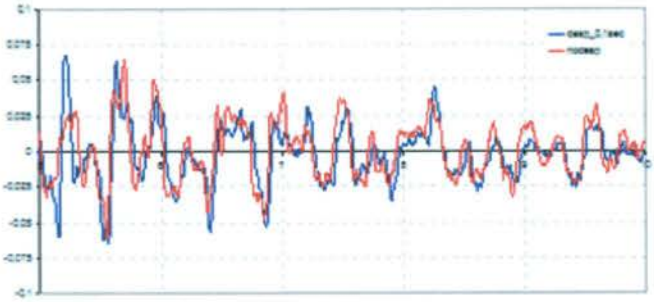


Figure 8: 0.1g test from 5s to 10s– LNEC-3D shaking table

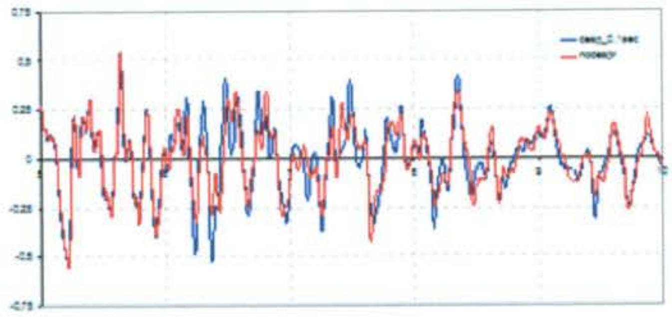


Figure 9: 0.6g test from 5s to 10s– LNEC-3D shaking table

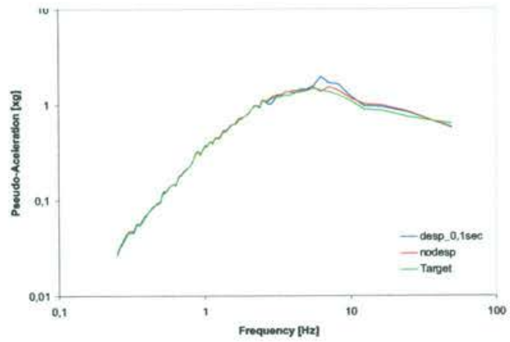
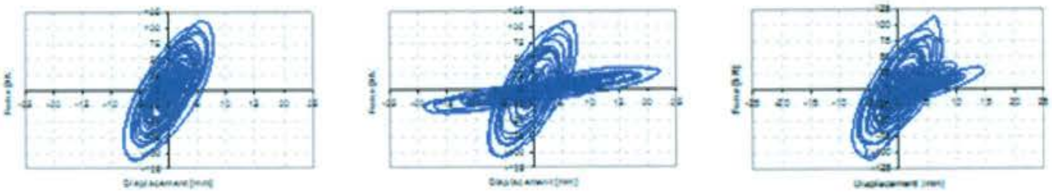


Figure 10: LNEC Spectra – Comparison with and without discharge at 0.6 g

The Figure 11 corresponds to the hysteretic loops obtained for the 0.6g test, considering the different discharges. From the results it can be observed the stiffness reduction from the situation without discharge to the situations with discharge (0.1s and 5s). The reduction is larger for the faster discharge (0.1s).



a) **b)** **c)**

Figure 11: Hysteretic loops a) without discharge, b) 0.1s discharge and c) 5s discharge

5.3 Experimental Program in NTUA – Athens

The test programme in NTUA/LEE was divided into two phases. In the first phase the test specimen had a total mass of 7ton while in the second one the mass of the specimen was 10.60 ton (10 movable plates were fixed on the specimen, each plate had a mass of 306Kg). For each phase, several tests were performed with the input motion to be scaled to achieve the required peak acceleration. During testing, the stiffness of the specimen has decreased 5 seconds after the signal had been started by slow or fast discharges of the airbags. The tests were carried out in the main X direction of the shaking table and the control software was run in acceleration control mode. A general view of the specimen on the shaking table is shown in Figure 1c).

The base motion chosen was filtered band pass in the range 0.1 to 33Hz, while the peak acceleration was 3.40m/sec^2. A random signal was applied at the beginning of each phase in order to allow the transfer function of the whole shaking table – specimen system to be measured. Then the inverse transfer function was measured and used to modify the given signal in an iterative manner until a satisfactory match was obtained between the required and achieved motions. For every discharge test, the frequency change of the specimen was always triggered 5 seconds from the beginning of the seismic time history. In the case of slow discharges, the change of the frequency took place within 5 seconds, while in the case of fast discharges the change of the frequency was completed within 0.10 seconds. Totally, 19 tests were performed, 9 of them were carried out in phase I and the other 10 were carried out in phase II.

During the tests, the achieved shaking table acceleration and displacement were recorded. For each test, the required and achieved acceleration time histories and the corresponding response spectrum were plotted, as well as an overplot of time histories and response spectrum, which highlighted any difference in signals. The amplitude plot of the transfer function between achieved and required time histories is also given.

In Figure 12, the overplot of required and achieved time histories are presented for test 19, where the mass of specimen was 10.60 ton and a fast discharge was occurred 5 seconds after the beginning of input signal. In the same figure, the comparison of the achieved and required signal is given for the next 5 seconds after the fast discharge.

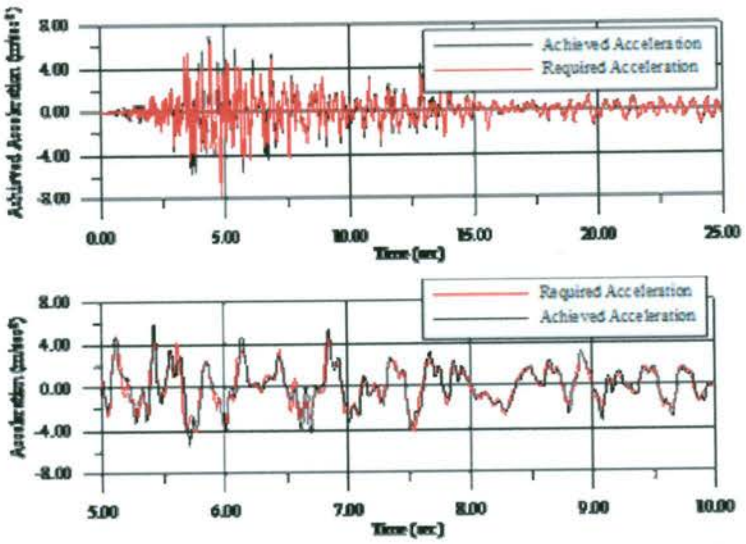


Figure 12: Overplot of achieved and required time histories; achieved and required time histories, 5 seconds after the trigger (test 19)

In Figure 13 is also presented the comparison between the required and achieved spectra for the last test of phase II (test 19)

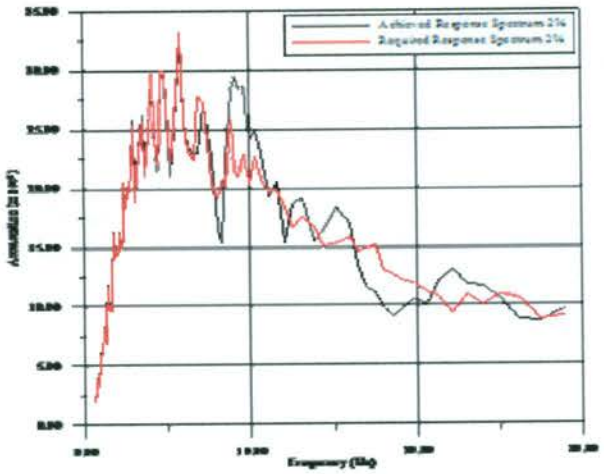


Figure 13: Required and achieved response spectra for test 19

6. CONCLUSIONS

The tests carried out on the CEA and LNEC shaking tables, and the analysis of their results, showed that the control of these tables is not affected by the fast decrease of stiffness of the mock-up. For these two laboratories, the mass of the mock-up is relatively small when compared with the masses of the shaking tables (100 ton and 40 ton, respectively). It is not the same case for the tests performed in Athens, where the weight of the shaking table is 10 ton and so it was decided to set the specimen for a global mass of about 10 ton instead of the 14 ton used in France and Portugal. The tests performed in Athens have demonstrated an excellent performance achieved by the control system of the shaking table when the frequency of the specimen remains constant during the performance of the tests. In the case of slow or fast changes of frequency the response of this NTUA shaking table from DC to 12 Hz remains excellent, while for higher frequencies the response was not excellent but still good. This indicates that there is a need of upgrading the program that controls this shaking table in order to improve the tuning and calibration of the system when nonlinearities of the test specimen appear.

7. ACKNOWLEDGMENTS

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