18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)
Beijing, China, August 7-12, 2005
SMiRT18- K12-3

TESTS WITH THE SAME NON-LINEAR SPECIMEN TO EVALUATE THE PERFORMANCE OF THE EUROPEAN SHAKING TABLES

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ABSTRACT

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 behavior, 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 behavior 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 first tests are presented.
Keywords: Shaking tables - Controllers.

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. That is to say, the fidelity with which a specified input could actually be applied to a test-specimen, bearing in mind the mechanical and control imperfections.

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 Refs. [1,2].

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 a 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) and 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 behavior.

In this paper are presented the first 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 take into account the performances and dimensions of this three representative shaking tables. The specimen will be tested successively on each table (the same specimen will be transported by truck among the laboratories), under uniaxial input signals, and the results will be compared.

This test specimen was designed to reproduce the global non-linear behavior 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 behavior.

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 allows a comparison of the earthquake simulators behavior concerning the change of the control conditions and the influence of the intrinsic characteristics of each specific facility.

2. TESTING PROGRAM

A testing program has been defined by the three laboratories. This program consists in seismic tests performed in each laboratory on a model where the characteristics can change very fast during the excitation to simulate for example the collapse of a building during an earthquake. The model was dimensioned in order to be able to be tested on the three shaking table of the CEA, LNEC, and LTUA having characteristics very different the ones from the others and with repetitive testing conditions. The model is tested in its plan.

3. TESTING FACILITIES

3.1 CEA testing facility

The CEA testing facility, TAMARIS infrastructure, includes the **AZALEE** 6m x 6 m shaking table. It allows testing of specimen with a mass up to 100 tons in 3 directions and has 6 degrees of freedom (translations and rotations). Independent excitations of any kind: (sinusoidal, random, shock, seismic...with a 0 -100 Hz frequency range) may be applied. Three other tables (**VESUVE, TOURNESOL and MIMOSA**), each having about 10 tons capacity, optimize the use of the facility. The tables are completed by a pit (**IRIS**) which allows testing of specimen up to 25m long with a diameter of about 4m;
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 (Europe, Japan,..) programs related to the seismic behavior of equipment, components and structures.
Main activities are devoted to
- Industrial and nuclear equipment such as electrical cabinets, tanks, storage racks, piping systems, to understand and codify their seismic behavior, and to evaluate the margins of current design methodologies.
- Civil engineering structures: analysis and testing of structural element (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 slip, lap splices,..) and soil structure interaction

The tests are carried out on the triaxial shaking table (Horizontal + Vertical) Azalée of laboratory EMSI. This table, 6 m X 6 m, can support specimens of a mass being able to reach 100 Tons.

It is actuated by 8 electro hydraulic jacks of 1000 kN each one (4 jacks into horizontal and 4 into vertical). Four pneumatic static supports placed under the table make it possible to take again a part of the actual weight (model + table) during the tests. The figure N° ** presents a view of the table

The shaking table is controlled by a bay of control associated with a PC with piloting DELL Precision 410, i. 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 table is calculated starting from the acceleration measured on the table. It is 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 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).

Table 1 – Characteristics of the Saclay testing facility (AZALEE shaking table)

Parameters		Characteristics
Table size		6m x 6m
Table mass		25 tons
Maximum specimen mass		100 tons
Concrete reaction mass		2500 tons on springs and dampers
Hydraulic flow		2200 liter/min + 12 accumulators (12x250 liters)
Controlled degrees of freedom		6 (3 Translations and 3 rotations)
Longitudinal	Displacement max	125 mm
	Velocity max	1 m/s
	Acceleration max	4.5 g
	Number of actuator	2 of 1000 kN
Transversal	Displacement max	125 mm
	Velocity max	>1 m/s
	Acceleration max	>4.5 g
	Number of actuator	2 of 1000 kN
Vertical	Displacement max	100 mm
	Velocity max	> 1 m/s
	Acceleration max	> 4.5 g
	Number of actuator	4 of 1000 kN

3.2 LNEC testing facility

The infrastructure is constituted by the seismic testing facilities installed at the LNEC (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 recently accomplished, by means of an additional bank of nitrogen accumulators and replacement of the existing servo-valves by higher capacity ones in order to enable the table to reach peak velocities of 70 cm/s.

The shaking tables are located in a large testing hall with floor to ceiling height of 10 m enabling the testing of tall structures. Furthermore, around the triaxial shaking table there are 3 moderate capacity reaction walls that increase the ability of the facility to support diversified testing set-up.

It should also be referred that an overhead crane with 400 kN 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 three specifically dedicated rooms, two 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.

Table 2 – Characteristics of the LNEC testing facility

Parameters		Characteristics
Table size		5.6 m x 4.6 m
Table mass		40 tons
Maximum specimen mass		40 tons
Concrete reaction mass		
Controlled degrees of freedom		3 (Translation X, Y, Z)
Hydraulic flow		690 liter/min
Longitudinal	Displacement max	175 mm
	Velocity max	0.2 m/s
	Acceleration max	1.8 g
	Number of actuator	1 of 1000 kN
Transversal	Displacement max	175 mm
	Velocity max	0.2 m/s
	Acceleration max	1.1 g
	Number of actuator	2 of 300 kN
Vertical	Displacement max	175 mm
	Velocity max	0.2 m/s
	Acceleration max	0.6 g
	Number of actuator	1 of 300 kN

3.3 NTUA testing facility

A mechanical shaking table was existing at Athens' National Technical University 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 realized 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 may be summarized as follows:

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, quadrangular, signals with specified spectra or other characteristics created at the Laboratory, etc vibrations 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

Table 3 – Characteristics of the NTUA testing facility

Parameters		Characteristics
Table size		4m x 4m
Table mass		10 tons
Maximum specimen mass		10 tons
Concrete reaction mass		2500 tons on the ground
Controlled degrees of freedom		6 (3 Translations and 3 rotations)
Hydraulic flow		1248 liter/min
Longitudinal	Displacement	100 mm
	Velocity	1 m/s
	Acceleration	2 g
	Number of actuator	2 of 160 kN
Transversal	Displacement	100 mm
	Velocity	1 m/s
	Acceleration	2 g
	Number of actuator	2 of 160 kN
Vertical	Displacement	100 mm
	Velocity	1 m/s
	Acceleration	4 g
	Number of actuator	4 of 160 kN

3.4 Comparison between the testing facilities

The table below shows the principal characteristics of the shaking tables.

Table 4: Comparison on the size of the shaking tables

Site of the test facility	Dimensions of the shaking table	Degrees of freedom	Empty mass of the table (tons)	Maximum payload (tons)	Electronic controller
CEA/Saclay	6 m x 6 m	6	25 (aluminum alloy)	100	MTS
LNEC	4.5 m x 5.3 m	3	(steel)	30	INSTRON
NTUA	4 m x 4 m	6	10 (steel)	10 à 15	MTS

Table 5 - Controller of the shaking table and signal conditioner

		Type	**Company**	**Name**
CEA AZALEE	Table	6 DDL 6m x 6m	SEREME	AZALEE-
	actuators	8 electro hydraulic	MTS	244
	controllers	PID 6 DDL	MTS	469
	Control computer	Seismic test	Signalstar	I_PSCn
LNEC	Table	3 DDL 4.5m x 5.3m		
	actuators	3 electro hydraulic		
	controllers	PID 3 DDL	Instron	8580
	Control computer		Instron	SPiDAD
NTUA	Table	6 DDL 4m x 4m	MTS/NTUA	
	actuators	8 electro hydraulic	MTS	204
	controllers	PID 6 DDL	MTS	469
	Control computer			

4. TESTED MOCK-UP

4.1 Characteristics of the mockup

The model consists of a frame with an oscillating mass wedged between inflatable cushions (see figure #**). This oscillating mass is characterized by stiffness and damping in order to simulate the response of a model equivalent at a building. It is possible to change the characteristics into a more or less long time in order to simulate degradation due to a seismic test. The frequency is adjusted by the pressure in the cushions and damping is ensured by the Gerb shock absorbers. The change of frequency is done by a partial depressurization through gauged diaphragms.

After dialogue between the three laboratories, the characteristics of the model were defined as follows:

- Lower maximum mass: 14 tons,
- Mass of the oscillating part approximately 6 to 7 tons,
- Initial frequency about 7 Hz,
- Final frequency about 3 Hz,
- Duration to pass from 7 to 3 Hz between 5 and 0.1secondes,
- All the configurations must be reproducible several times on the same table and in different laboratories.

Two diaphragms of larger (60 mm) and smaller (10 mm) opening are tested for validation of the durations of discharges. The diaphragm of 60 mm diameter of opening lasts one discharge of 0.1second and that of 10 mm of diameter lasts 5 second.

4.2 Instrumentation of the mockup and shaking tables

The instrumentation on the table and the mock-up consists in:

- Accelerometers (3) to measure accelerations on the level, table, masses additional and frame.
- Displacement sensors to measure the displacement of the additional masses.

Different signals from the shaking table controller and the position of the valves are also recorded:

- Velocity, force and displacement of the table along the excited axis
- Displacement and force from roll and pitch degrees of freedom
- Displacement, intensity and delta Pressure on the level of a servo valve of one actuator
- Driver signal send to the servo valve
- Opening and closing commands of the valves.
- Opening or closing Response of the valves.

5. SEISMIC TESTS

Preliminary tests have been performed to calibrate the pressure in the airbag to obtain the required frequencies. With pressurized airbags the frequency of the steel mass in the frame is 6.73 Hz. Without pressure, the minimum frequency of the mass is measured at 3.4 Hz.

5.1 SEISMIC TESTS IN CEA-Saclay

Several series of seismic tests were carried out with increasing level of acceleration 0.1g, 0.4g and 0.6g. For each series of tests, the durations of variation of the characteristics of the model were changed (diaphragms): 5 seconds and 0.1 second.

For some tests, the piloting of the table is made in acceleration and/or displacement with one or three variables. The table below gathers the whole of the seismic tests carried out on Azalée shaking table

In order to see whether the table behave in the same way with tests with or without depressurization one compares the response of the sensor of table "axtab" with a test with and without depressurization of the model, under the same condition of configuration of the table and on the same level of excitation.

Our results are first of all based on the response of the sensor "axtab" because it measures the acceleration of the table, and because it is placed at the bottom of model.

We can notice, that, the Azalée table answers in acceleration (figures #1 to 3) at very similar with and without depressurization for all test levels and especially for high level. There is effect, due to the variation of stiffness on the response of the table.

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Table 6 - List of the seismic tests realized on AZALEE shaking table

		diaphragm 0 mm without discharge		diaphragm 10 mm discharge in 5 seconds		diaphragm 60 mm discharge in 0.1 seconds	
		Correct° RRS	Temporal Correct°	Correct° RRS	Temporal Correct°	Correct° RRS	Temporal Correct
3 variables control (acceleration) (acceleration signal)	0.1 g	**X**	**X**		**X**	**X**	**X**
	0.4 g	**X**	**X**		**X**	**X**	**X**
	0.6 g	**X**	**X**		**X**	**X**	**X**
3 variables control (direct) (displacement signal)	0.48 g	**X**				**X**	
	1.13 g	**X**				**X**	
1 variable control (direct) (acceleration signal)	0.1 g		**X**		**X**		
	0.4 g				**X**		
	0.6 g				**X**		
1 variable control (direct) (displacement signal)	0.55 g	**X**				**X**	
	1.19 g	**X**				**X**	

From the acceleration signals, the response spectra of the shaking table have been calculated (figure # 4). The comparison of the response spectra shows, for tests with and without depressurization, there is not a great difference, which still proves that the Azalée shaking table controller ins not affected by the behavior of the non linear model.

5.2 SEISMIC TESTS IN LNEC

The same tests (as Saclay) have been performed with the same initial conditions for the mock-up. The base signal was filtered to a frequency band ranging from 0.1 to 33 Hz and adapted to achieve 0.6G in the table.

During tests the adapted base signal was scaled to achieve the desired peak acceleration level. In all tests applicable the trigger action to open the relief valves occurred 5s after signal start.

The slow discharge (approximately 5s) was obtained by using the plate with a 10mm aperture; while the fast discharge (approximately 0.1 s) was obtained by using the plate with a 60 mm aperture.

The following table gives the list of the tests.

The figures #5 and 6 show the comparison to the required signals for displacements and acceleration measured at 0.6 g for the three configurations without discharge and with 5s and 0.1 s discharge. No significant effect can be observed.

Table 7 - List of the seismic tests realized at LNEC

Peak level (G)	Configuration
0.1	diaphragm 0 mm without discharge
0.4	diaphragm 0 mm without discharge
0.6	diaphragm 0 mm without discharge
0.8	diaphragm 0 mm without discharge
0.1	diaphragm 10 mm discharge in 5 seconds
0.4	diaphragm 10 mm discharge in 5 seconds
0.6	diaphragm 10 mm discharge in 5 seconds
0.8	diaphragm 10 mm discharge in 5 seconds
0.1	diaphragm 60 mm discharge in 0.1 seconds
0.4	diaphragm 60 mm discharge in 0.1 seconds
0.6	diaphragm 60 mm discharge in 0.1 seconds
0.8	diaphragm 60 mm discharge in 0.1 seconds
1.0	diaphragm 60 mm discharge in 0.1 seconds
1.2	diaphragm 60 mm discharge in 0.1 seconds

5.3 SEISMIC TESTS IN NTUA

The tests in NTUA have been performed during the spring. The tests results are not available today.

6. CONCLUSION

The tests carried out on the LNEC and CEA shaking table and the analysis of the results, show that the control of the tables is not affected by the fast decrease of stiffness of the mock-up.

For the tests performed in Saclay and Lisbon, the mock-up is relatively small by comparison with the masses of the shaking tables.

It is not the same case for the tests performed in Athens. Probably, some effects will be measured. The last series of tests will be presented and explained in a future article.

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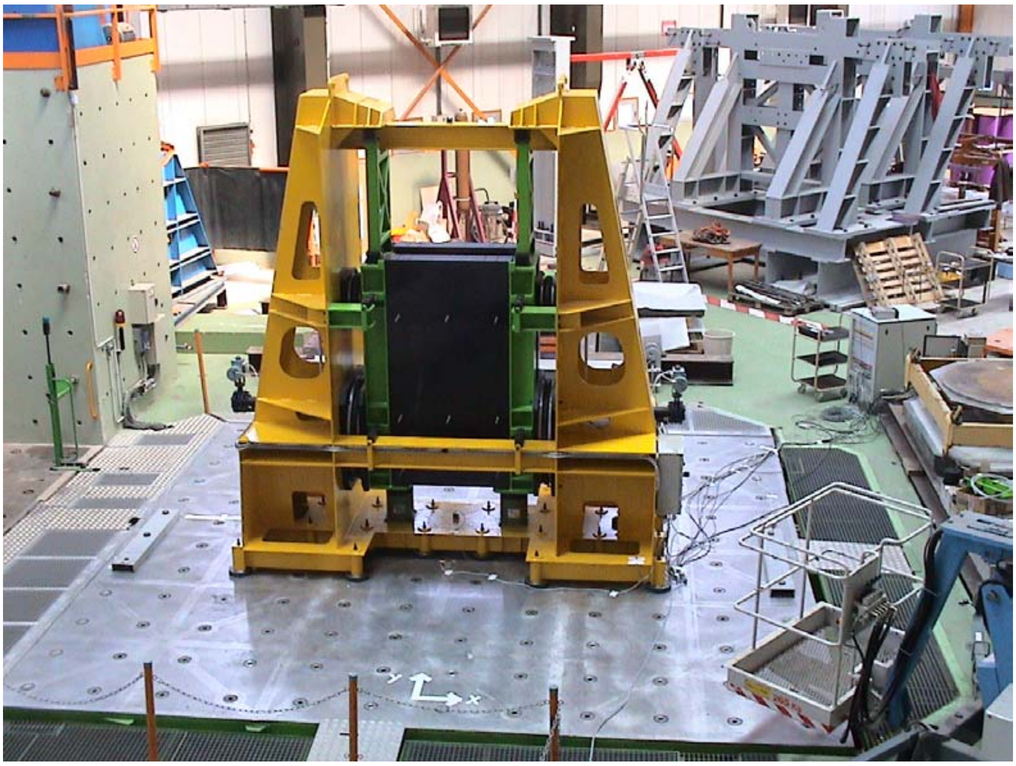

Photography 1 – View of the mock-up on the AZALEE shaking table

Photography 2 – View of the mock-up on the LNEC shaking table

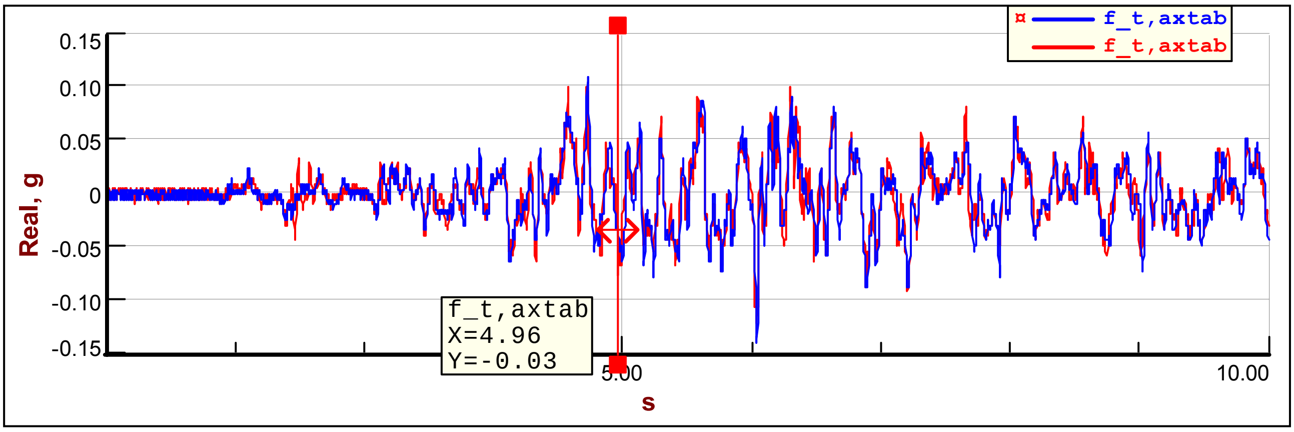

Figure # 1 - CEA-Saclay – test at 0.1 g

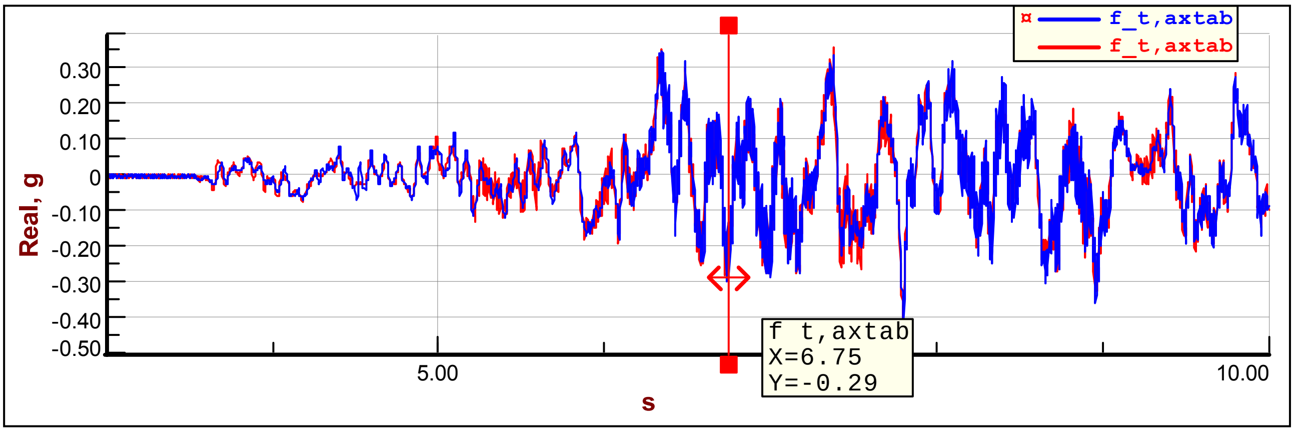

Figure # 2 - CEA-Saclay – test at 0.4 g

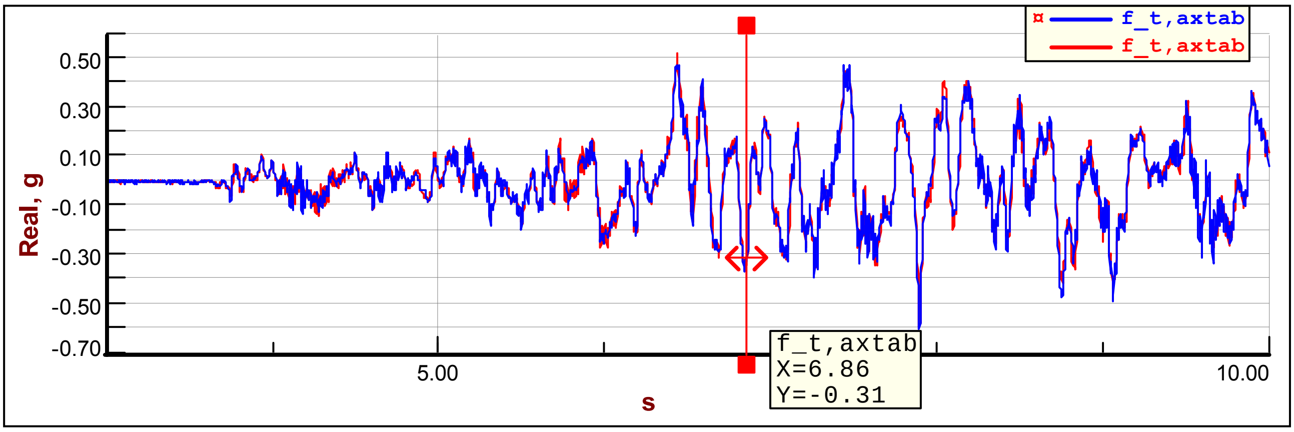

Figure # 3 - CEA-Saclay – test at 0.6 g

Test on AZALEE shaking table - Comparison for three level of 0.1 g, 0.4 g 0.6 g, with and without discharge

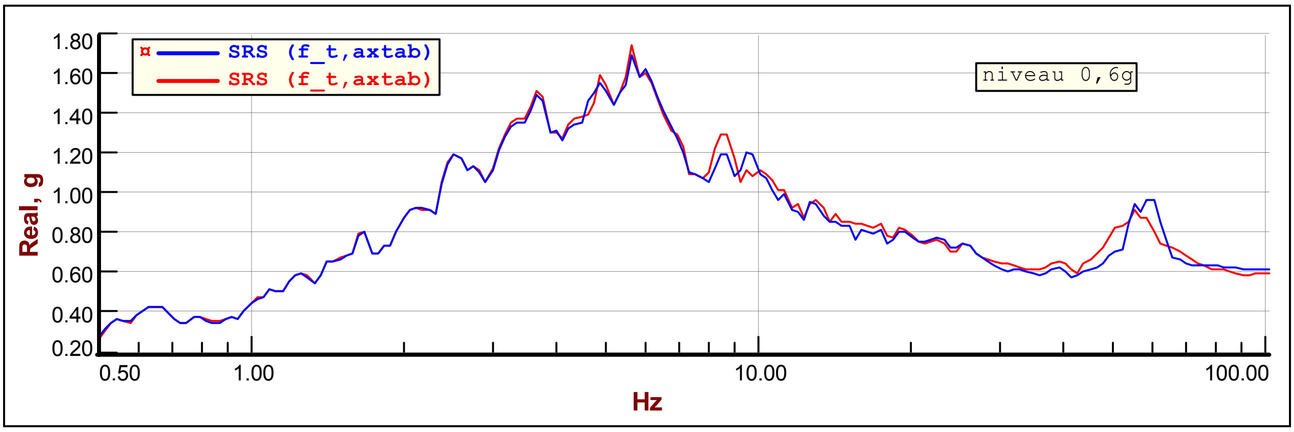

Figure # 4 - CEA-Saclay – Spectrums – Comparison with and without discharge at 0.6 g

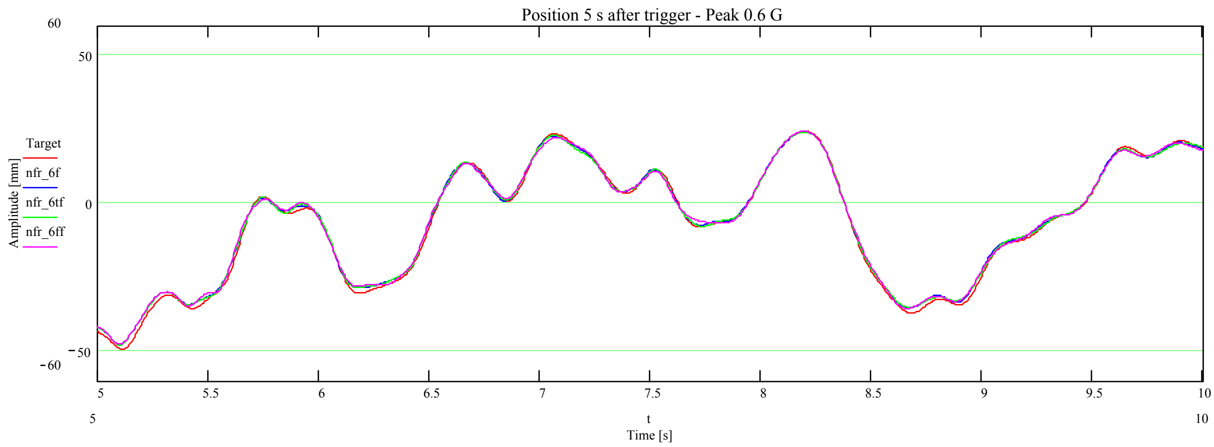

Figure # 5 - LNEC - Displacement of the shaking table – Comparison with and without discharge at 0.6 g (Discharge performed at time 5s at the beginning of the curve)

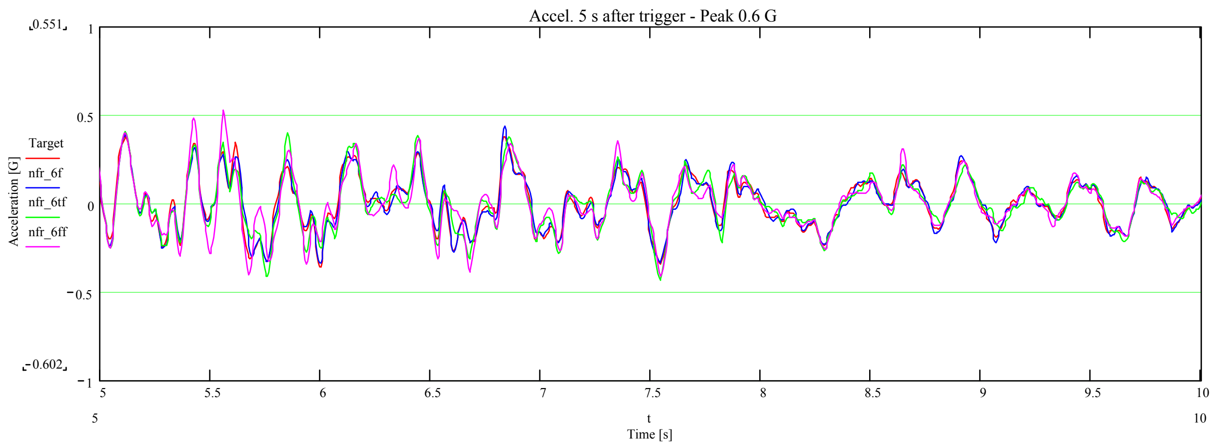

Figure # 6 - LNEC - Acceleration of the shaking table – Comparison with and without discharge at 0.6 g (Discharge performed at time 5s at the beginning of the curve)