Seismic Behaviour Analysis of Dissipation Devices and Assessment of European Shaking Tables and Reaction Walls

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ABSTRACT

The results presented in this paper were achieved within the NEFOREEE research network (New Fields of Research in Earthquake Engineering Experimentation) [1] funded by the European Commission. This network has inherited a big experience from previous consortia of European laboratories working in the field of earthquake and dynamic experimental research and operating paramount European shaking tables and reaction walls.

Benchmark tests were developed on similar specimens at three different facilities (first in Greece, then in Italy and finally in Portugal). A one-degree-of-freedom full-scale steel frame, very easy to put up and to transfer from lab to lab was built. This frame was designed to allow also a relatively smooth assemblage and exchange of two different types of dissipation devices: a shear panel with hysteretic behaviour [2] and a standard industrial shock absorber.

Following a dynamic analysis of the bare frame, a series of tests, for both types of dissipation devices, was performed in each lab. These tests have included an El Centro input, 0.2g peak scaled, sinusoidal excitations for 0.05g and 0.1g, with 80% and 100% of the natural frequency for each specimen configuration and, finally, successive EC8 artificial time histories up to 1g of peak table acceleration.

The last tests concerning this task of the NEFOREEE research network were recently accomplished in Lisbon. So, the main results obtained are included in the present paper thus extending the analysis started in two previous presentations [3,4].

INTRODUCTION

In this experimental program, three of the major European facilities in the earthquake engineering research were involved: JRC (Ispra, Italy), LNEC (Lisbon, Portugal) and NTUA (Athens, Greece).

To perform these benchmarking studies it was necessary to design a single degree of freedom specimen exhibiting a considerable flexibility, to be used in different facilities for a better comparison between shaking table and reaction wall tests. Steel was the main material used to build the model, because it allows a good flexibility and an easy design of the connection details. The specimen had to satisfy some requirements in order to optimise its design and to obtain a better modularity to be used in the different experiments performed in the laboratories that were chosen. The main requirements to be fulfilled were:

1 The dimensions in accordance with the characteristics of the shaking tables and reaction walls to be suitable for both kind of experiments;

2 The total mass not exceeding the maximum capacity of the smallest shaking table involved, in this case 10ton which corresponds to the maximum specimen weight for the NTUA shaking table;

3 The slab, constituted by a metal container filled with concrete and properly connected, designed to achieve the requested mass, not blocking the connections with the frame and allowing future slabs adding to increase the number of the degrees of freedom;

4 The braces with K and X shapes allowing the placement of passive-control devices and a range of natural frequencies convenient for shaking table and pseudo-dynamic tests.

SPECIMEN AND DISSIPATION DEVICES

The main elements of the specimen were designed through an elastic analysis using the finite element program SAP200NL [5] considering two earthquake time history accelerations: one is an earthquake generated to be in accordance with type 1 of the Eurocode 8 [6] and the other is an El Centro earthquake record, both of them with a peak ground acceleration of 0.5g.

According to the design requirements, the frame should present a longitudinal size of 300 cm; a transversal size of 275 cm; a column height of 450 cm; and an inter-storey distance of 300 cm. In what regards the height of the column and the inter-storey distance, the slabs could be spaced with 3m, allowing another steel-concrete composite slab to be added at a height of 6m. Consequently a second degree of freedom can be obtained simply through the use of elements with the same characteristics and details of the basic structure.

A one degree-of-freedom full-scale shear type K-braced steel frame, easily transportable from lab to lab, was conceived [7]. The structure was designed to allow two types of dissipation devices to be inserted: a special shear panel device and a usual industrial device. The model without the energy dissipation devices included presented a very linear behaviour with a very low damping. This should certainly put in evidence the alteration introduced by the testing methods such as control delays in the PsD method or spurious rocking on the shaking table. With non-linear dissipator devices, those deficiencies may be hidden by the large damping developed at the specimen, but an appropriate strain-rate effect compensation technique is necessary within the PsD method. In a similar way, that non linearity may impose limitations as well on the compensation techniques based on linear filtering of the reference signal and traditionally used at the shaking tables [4]. The following figure shows a global view of the specimen just before the experimental program at the LNEC facility:

Fig. 1 – Specimen
on the LNEC 3D shaking table

The structure was equipped with energy dissipation devices in the longitudinal direction. In particular, two dampers have been designed for the purpose. The first one was a steel shear panel [2]; it is inserted into a square steel tube and dissipates energy by means of elastic-plastic shearing. The second type of device tested was a Jarret shock absorber relying on the compression of a viscous-elastic silicone fluid. These devices were applied to the specimen to dissipate a large part of the kinetic energy generated in a seismic event. Both, Dorka and Jarret devices, are shown in Figures 2 and 3.

Fig. 2 - View of the
Dorka shear panel devices

Fig. 3 - View of a
Jarret viscous fluid damper

INSTRUMENTATION

The instrumentation set-up that was used to measure the response of each specimen to earthquake tests on the shaking table is shown in Figures 4 (SPECIMEN I – Bare Frame) and 5 (SPECIMEN II – Frame with Dorka devices and SPECIMEN III – Frame with Jarret devices). In the instrumentation of the specimen were used accelerometers, inductive displacement transducers (LVDTs) and optical displacement transducers (Hamamatsu). The instrumentation used in LNEC was adapted from the instrumentation previously used in JRC and NTUA.

Three accelerometers (A1X, A2X, A3X) were fixed on the top of the specimen in order to measure in and out-of-plane accelerations. Absolute displacements at the top (D3, D4) and at the bottom (D1, D2) level of each specimen were measured with respect to a stiff frame, which was fixed outside the shaking platform. Strain gauges (SG1, SG2) were also used in order to check the strain level at the bottom of steel columns. For the tests performed on SPECIMENS II and III the shear force was measured directly on dissipation devices (LC), while two additional displacement transducers were mounted at the devices as well.

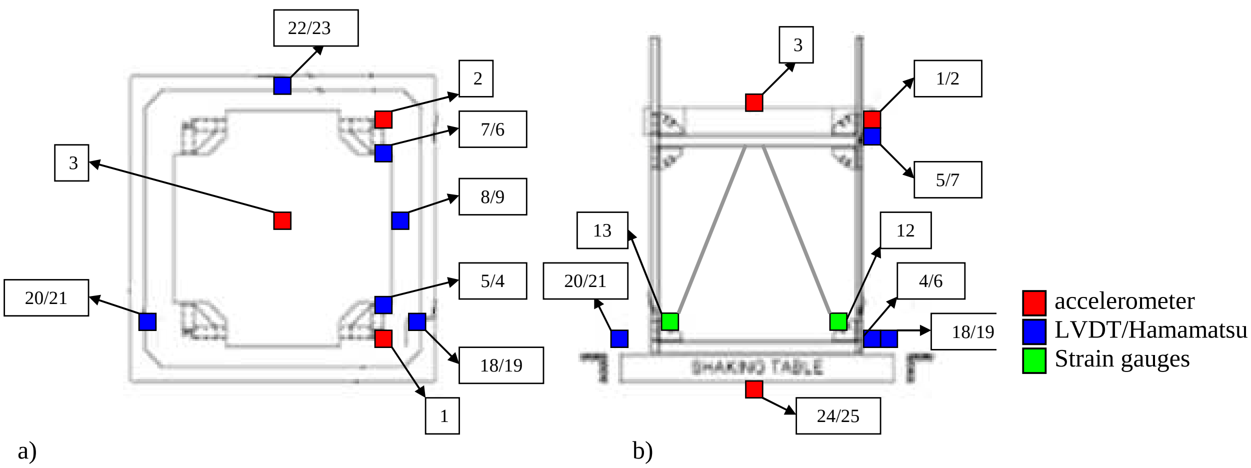

Figure 4 – Instrumentation set-up of SPECIMEN I at LNEC: a) Plan view and b) Elevation.

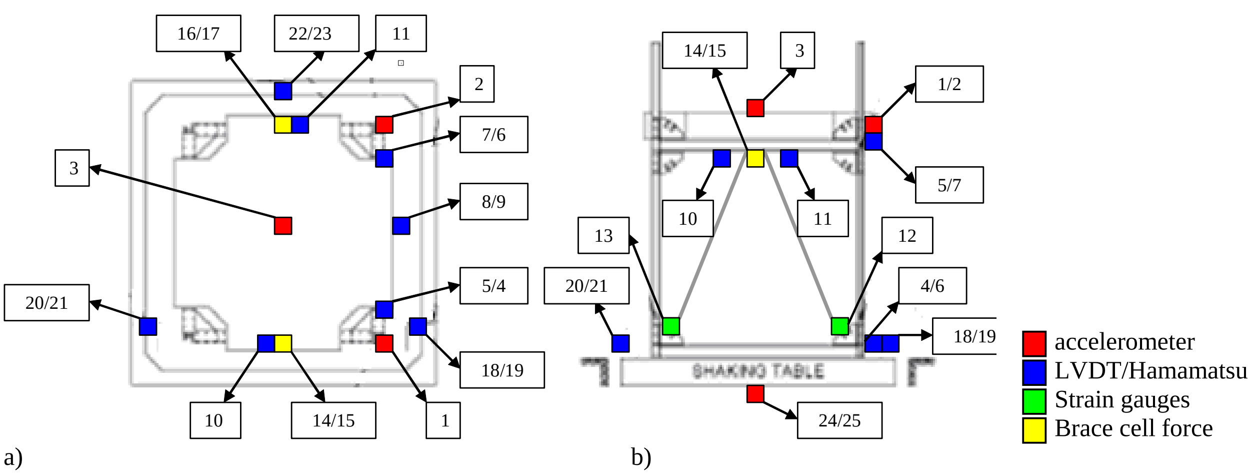

Figure 5 – Instrumentation set-up of SPECIMENS II and III at LNEC: a) Plan view and b) Elevation.

The different sensors were connected to 4 posts corresponding, respectively to: Post 1 – accelerometers, Post 2 – inductive displacement transducers, Post 3 – strain gauges and Post 4 – optical displacement transducers.

EXPERIMENTAL PROGRAM

The loading sequence used in LNEC was very similar to the used in the NTUA tests and was pre-defined for the partners involved in the project. In a similar way to the case of the shaking table tests, the testing campaign at JRC has included some preliminary low-amplitude tests, such as modal tests, by using an instrumented impact hammer, and snap-back tests, at which an initial displacement was introduced after which the structure was left to oscillate freely.

The sequence of tests performed in LNEC tests are presented in the following tables:

Table 1 - **Tests performed on SPECIMEN I (Bare Frame)**

Test	Description
1	Cat00 along EW direction, Table acceleration 0.05g
2	El Centro earthquake along EW direction, Table Acceleration 0.20g
3	Cat01 along EW direction, Table acceleration 0.05g

Table 2 - **Tests performed on SPECIMEN II (Frame with Dorka devices)**

Test	Description
4	Cat02 along EW direction, Table acceleration 0.05g
5	El Centro along EW direction, Table acceleration 0.20g
6	Sinusoidal 10.28 Hz, Table acceleration 0.05g
7	Artificial EC8 time history along EW direction, Table acceleration 0.20g
8	Sinusoidal 8.22 Hz, Table acceleration 0.05g
9	Cat03 along EW direction, Table acceleration 0.05g
10	Artificial EC8 time history along EW direction, Table acceleration 0.60g
11	Cat04 along EW direction, Table acceleration 0.05g
12	Artificial EC8 time history along EW direction, Table acceleration 0.80g
13	Cat05 along EW direction, Table acceleration 0.05g
14	Artificial EC8 time history along EW direction, Table acceleration 1.0g
15	Cat06 along EW direction, Table acceleration 0.05g

Table 3 - **Tests performed on SPECIMEN III (Frame with Jarret devices)**

Test	Description
16	Cat07 along EW direction, Table acceleration 0.05g
17	El Centro along EW direction, Table acceleration 0.20g
18	Sinusoidal 9.48 Hz, Table acceleration 0.05g
19	Artificial EC8 time history along EW direction, Table acceleration 0.20g
20	Sinusoidal 7.58 Hz, Table acceleration 0.05g
21	Cat08 along EW direction, Table acceleration 0.05g
22	Artificial EC8 time history along EW direction, Table acceleration 0.60g
23	Cat09 along EW direction, Table acceleration 0.05g
24	Artificial EC8 time history along EW direction, Table acceleration 0.80g
25	Cat10 along EW direction, Table acceleration 0.05g
26	Artificial EC8 time history along EW direction, Table acceleration 1.0g

The tests performed in LNEC have comprised Stage Tests and Characterisation Tests. The Stage Tests corresponded to main earthquake series with increasing intensities from 0.2 up to 1.0g. These series were uniaxial earthquake records and two different time histories in the main direction (X) were applied. These time histories were, as already referred, a modified component of an El Centro earthquake record and an artificial time history, which was generated to match the elastic response spectrum Type 1 of Eurocode8 [6] with corresponding peak ground acceleration of 0.5g, damping at 5% and a subsoil type A.

The Characterisation Tests have comprised sin-sweeps and “Cat Tests”. The first one corresponded to the performance of a complementary ramp sinusoidal excitation with test frequency 100% and 80% of the natural frequency of the specimen in order to achieve each specimen resonant response. This way just before the earthquake tests the specimen was tested under sine logarithmic sweep excitation along X direction for the determination of its natural frequencies and their damping.

This sine logarithmic sweep signal was in a frequency range of 1 to 35 Hz at a rate of one octave per minute. The tests were executed along global X axis with an amplitude vibration of 0.05g.

There were also performed the “Cat Tests” which preceded every Stage Series and corresponded to low amplitude, broadband base signals with the objective of estimating the specimen’s dynamic characteristics and their evolution during the experimental tests. In Figures 6 and 7 are presented the spectra of the time histories used in LNEC.

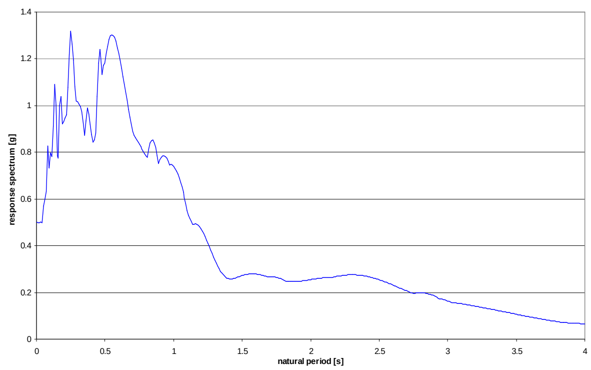

Fig. 6 - Response spectrum for El Centro earthquake (1940) (adapted from [7])

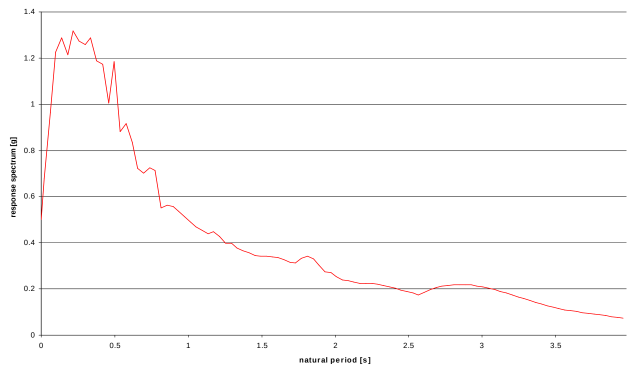

Fig. 7 - Response spectrum for an artificial earthquake according to type 1 of Eurocode 8 (adapted from [7])

TEST RESULTS

The modal frequencies were identified using frequency response functions estimations and the peak picking method. It was identified one translational single mode as a result of the dynamic action imposed for each characterization (cat) series. The evolution of the modal frequencies during the experimental program is presented in Figure 8.

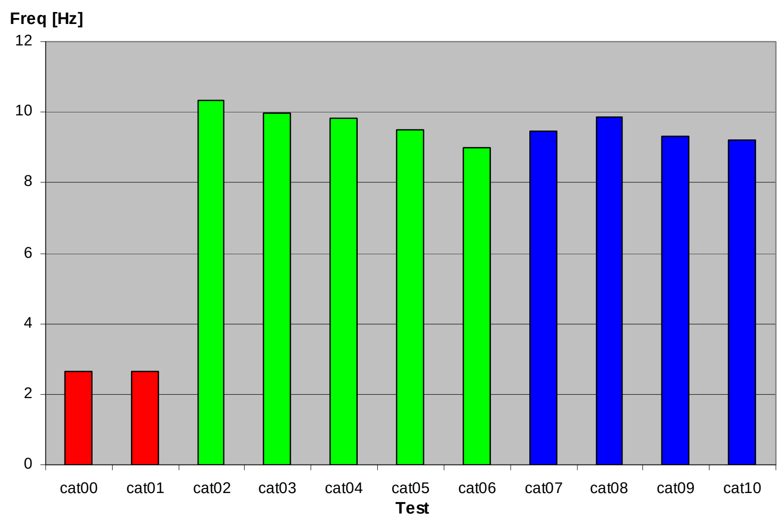

Fig. 8 – Experimental modal frequencies

An example of the identified frequency response functions obtained during the experimental program is presented in Figure 9 for the case of the viscous fluid dampers and after an artificial EC8 input with a shaking table peak acceleration of 0.8g. The damping was estimated for all the specimens, being obtained approximated values of 1.5%, 3% and 7.5% for SPECIMEN I, II and III, respectively.

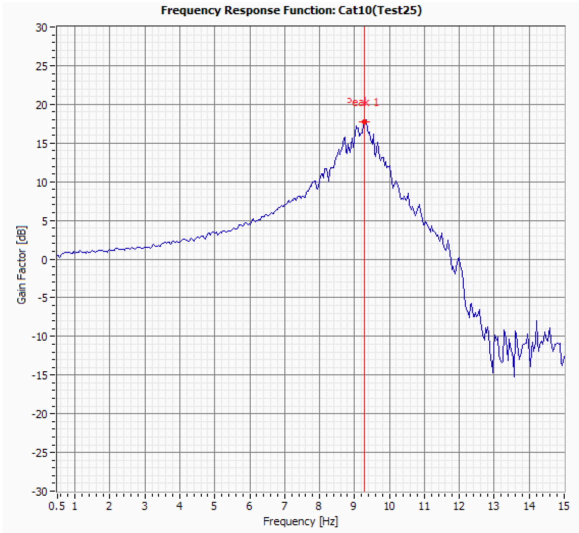

Fig. 9 - FRF peak picking for SPECIMEN III – cat10 (Test25)

During the experimental program all the channels identified in Figures 4 and 5 were recorded. As an example, Figures 10 and 11 show the results obtained for the NW top transverse acceleration and the NW top column displacement during the ElCentro 0.2g input, corresponding to Test2, Test5 and Test17. In these figures Plot 0 corresponds to the results obtained for SPECIMEN I, plot 1 for SPECIMEN II and plot 2 for SPECIMEN III.

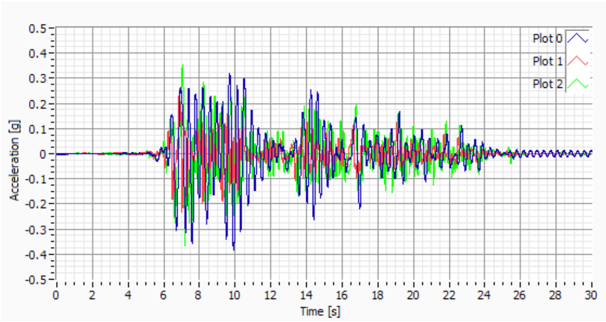

Fig. 10 – Comparison of NW top mass transverse acceleration

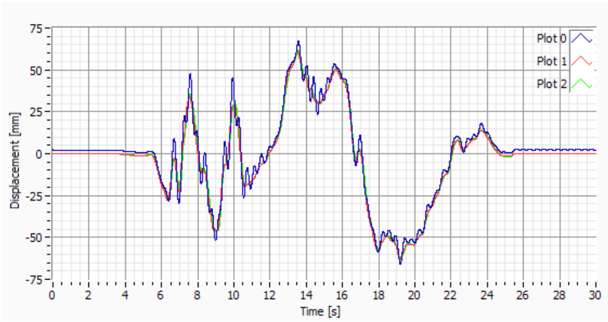

Fig. 11 – Comparison of NW top column transverse displacement

From the observation of these results it can be concluded that concerning accelerations, the SPECIMEN II was the one which has presented the lowest values at the top mass level. Concerning displacements, all the SPECIMENS have presented a similar behaviour.

Table 4 and 5 present the main results obtained for the specimens with dissipation devices. The maxima values recorded at the most representative channels are shown.

Table 4 - **Maxima values for the tests performed on SPECIMEN II (Frame with Dorka devices)**

	ElCentro 0.2g	EC8 0.2g	EC8 0.6g	EC8 0.8g	EC8 1g
NW top accel trans [g]	0.26	0.32	1.02	1.16	1.39
SW top accel trans [g]	0.27	0.37	1.11	1.25	1.51
Vert mass accel (CM) [g]	0.014	0.020	0.47	1.18	1.26
NW top column displ [mm]	63.34	26.23	78.92	104.40	110.20
SW top column displ [mm]	63.45	26.49	80.57	106.69	133.85
FNorth [kN]	10.49	14.47	42.87	49.43	56.98
FSouth [kN]	12.59	17.47	47.41	58.22	60.12
Displ North [mm]	0.27	0.40	1.03	1.75	4.02
Displ South [mm]	0.38	0.36	1.26	2.51	5.49

Table 5 - **Maxima values for the tests performed on SPECIMEN III (Frame with Jarrett devices)**

	ElCentro 0.2g	EC8 0.2g	EC8 0.6g	EC8 0.8g	EC8 1g
NW top accel trans [g]	0.37	0.27	0.89	1.50	1.70
SW top accel trans [g]	0.33	0.30	0.87	1.58	1.74
Vert mass accel (CM) [g]	0.007	0.009	0.05	0.09	0.13
NW top column displ [mm]	63.04	28.27	85.57	107.12	102.23
SW top column displ [mm]	63.35	28.65	86.30	114.06	133.63
FNorth [kN]	6.30	8.21	20.89	35.63	50.54
FSouth [kN]	6.76	8.63	21.63	39.48	54.81
Displ North [mm]	1.96	1.99	10.61	11.71	12.55
Displ South [mm]	1.95	1.89	10.33	12.00	12.48

In what concerns the top accelerations (NW and SW) the values obtained were similar for low and medium intensities while for the two highest levels bigger values for the Jarrett device were achieved. This can be explained by the specific characteristics of the materials used in this device (viscous fluid).

The clearly higher values of vertical mass acceleration obtained for the Dorka devices are due to the plastic behaviour of the steel cubes allowing vertical deformations for all levels of PGA intensity.

In spite of the different behaviour observed for the devices the values of maxima top displacements recorded at both columns were very similar due to the high rigidity of the common V bracing system adopted for both specimens.

Figures 12 and 13 present interaction diagrams of the force-displacement records at the North side Dorka dissipation device (SPECIMEN II), for a medium and the maximum EC8 input accelerations, respectively. Figures 14 and 15 present identical hysteretic loops for the North side Jarrett dissipation device (SPECIMEN III).

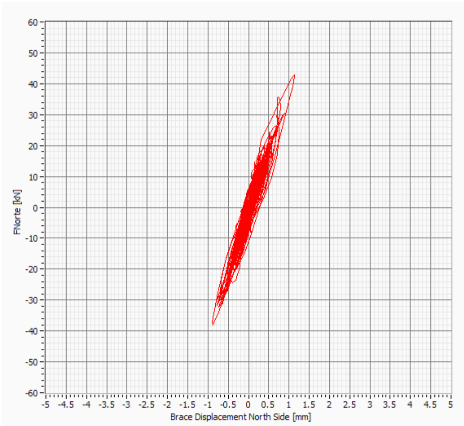

Fig. 12 – Hysteretic loops SPECIMEN II (EC8 0.6g)

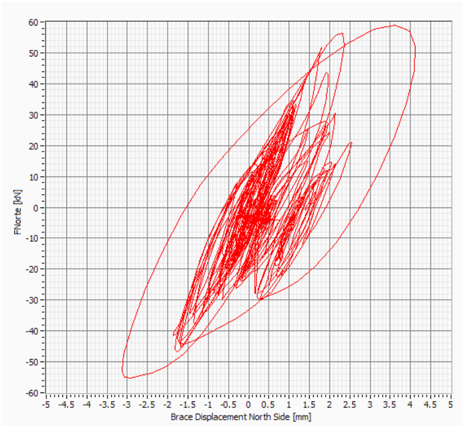

Fig. 13 – Hysteretic loops SPECIMEN II (EC8 1.0g)

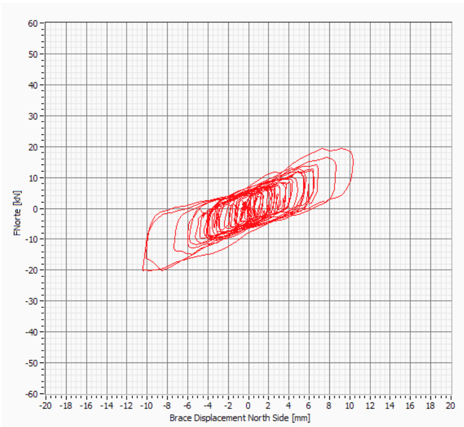

Fig. 14 – Hysteretic loops SPECIMEN III (EC8 0.6g)

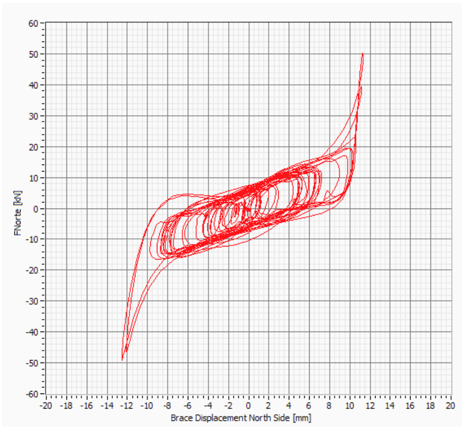

Fig. 15 – Hysteretic loops SPECIMEN III (EC8 1.0g)

From the observation of the previous figures it can be stated that apparently the Jarrett devices present a better dissipation performance with much higher displacements for the same levels of force when compared with the Dorka cubes.

It is also clear that the Jarrett characteristics are kept up to almost the maximum level of input accelerations achieved as it is presented in Figure 15 where it is shown that the changing of the global hysteretic loop shape appears only through final peaks in both directions.

Concerning the displacements recorded for both devices, for the Dorka the values have increased substantially from medium (0.6g) to high (1.0g) PGA values, while for the Jarrett those values were similar under both conditions. Although this fact, the Jarrett deformations were always extremely bigger thus proving their high capability. On the other hand when comparing the hysteretic loops for the Dorka devices from medium to high intensities there is a clear improvement due to the shear behaviour of the steel membrane used.

CONCLUSIONS

The experimental tests presented in this paper are part of a benchmark testing campaign that will analyse experimental results from two shaking table facilities (LNEC and NTUA) that have performed dynamic tests, a reaction wall laboratory (Ispra-JRC) that has performed pseudo-dynamic tests and a high-speed on-line sub-structuring installation (Univ. of Oxford).

All the tests were recently concluded and a global comparison of the results is under progress.

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REFERENCES

[1] New Fields of Research in Earthquake Engineering Experimentation – University of Bristol technical report, U.K., 2001.
[2] Schmidt, K. and Dorka, U., Exp. Verification of Hyde-System, Paper 3163, 13th WCEE, Vancouver, Canada, 2004.
[3] Bairrao, R., Bursi, O., Carydis, P., Magonette, G., Mouzakis, H., Tirelli, D. and Williams, M., Benchmark Testing and Performance Comparison of Shaking Tables and Reaction Walls, 13th WCEE, Paper N. 441, Vancouver, Canada, 2004.
[4] Molina, F.J., Bairrao, R., Blakeborough, T., Bursi, O., Tirelli, D., Magonette, G., Mouzakis, H. and Williams, M.S., Testing performance benchmark for shaking tables and reaction walls within the NEFOREEE Project, 1st ECEES, Paper 303, Geneva, Switzerland, 2006.
[5] SAP200NL, Structural Analysis Program, Computers and Structures Inc., Release 8.2.3, Berkeley, CA, 2003.
[6] prEN 1998-1, Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings, CEN, European Committee for Standardization, Brussels, Belgium, 2002.
[7] Bursi, O., Industrial application of shaking tables and reaction walls, NEFOREEE Project, University of Trento, 2004.