Severe loading tests on large-size structures at ELSA laboratory

F. J. Molina, G. Magonette, P. Pegon, P. Negro

ELSA Laboratory, IPSC, JRC, European Commission, 21020 Ispra (Varese), Italy

Abstract

The ELSA laboratory is provided with a large reaction-wall facility and has acquired its best expertise on the development and implementation of innovative experimental techniques mainly related to testing of large-scale specimens by the pseudo-dynamic method. Important examples are represented by the bidirectional tests performed on multi-storey buildings and the tests with non-linear substructuring applied to bridges. Apart from the relevant achievements within the testing techniques, the role of a reference laboratory in Europe has allowed ELSA to rely on the collaboration of many important research institutions that have collaborated to the projects and added maximum scientific value to the results of the tests. The aspects of advanced testing methods and collaboration through extensive use of networking are very important components for the proposed future European facility for seismic testing within project EFAST in which ELSA is also taking part. Such networking should include shared database, telepresence and geographically distributed testing.

Keywords: seismic testing, real size testing, pseudo-dynamic testing

1. INTRODUCTION

The European Laboratory for Structural Assessment (ELSA) was inaugurated in 1992. It belongs to the Joint Research Centre (JRC) of the European Commission with location in Ispra, Italy. Physically, the laboratory is based on a large reaction wall-strong floor system which dimensions and capacities are shown in Fig. 1. The purpose was to provide the European countries with a reference facility with capabilities for large-size testing of structures and particularly as a complement to the already existing shaking tables of several national laboratories. Thanks to a staff team consisting of a combination of experts in experimental mechanics, in control and in numerical modelling, special focus was put on the development and implementation of the pseudo-dynamic (PsD) test method. That method integrates the equations of motion step by step using experimental quasistatic restoring forces measured on line [1] Among other innovations introduced at ELSA, the use of very-high resolution digital transducers for the feedback of the actuators control signal, allowed for a tremendous reduction of the experimental errors in the method, which opened the way to the effective application of it to large

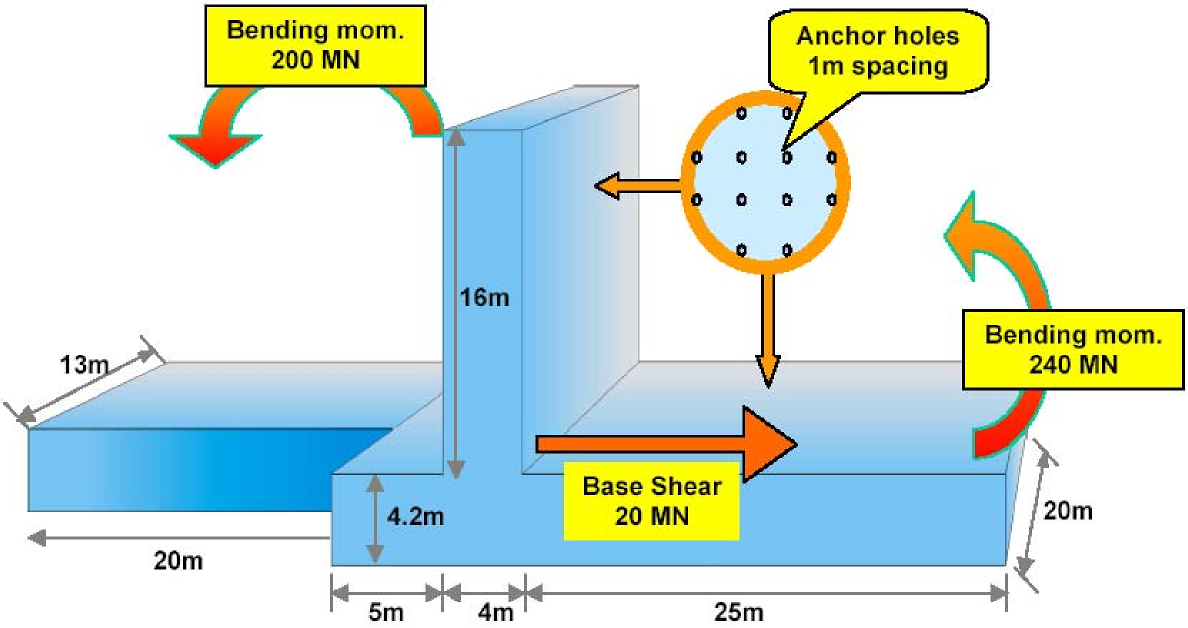

Fig.1 Dimensions and capacities of the reaction wall-strong floor system at ELSA.

systems with a significant number of DoFs [2]

At the same time, the collaboration with other institutions was favoured, especially through the creation of an European association of Structural Mechanics laboratories, and an outstanding role has been played during these years in producing experimental reference data for large models for many kinds of structures. In many cases the experiments were designed for the validation of different chapters of Eurocode 8, the European standard for seismic design of structures. Some other tests have involved advanced materials or devices, at that moment not yet under regulation, but with promising characteristics to be evaluated. Most of the tests performed on large-size structures would not have been possible on the shaking tables existing in Europe because of the dimensions of the specimen. Moreover, the obtained accuracy in the imposition of the input accelerograms and in all the measurements at the transducers would have also been impossible on any shaking table due to the difficulties in control and measurement with a real dynamic experiment. In fact, the great advantage of the PsD method for seismic testing of structures, when feasible, is on the quasistatic application of the displacements [3]

During these years, ELSA has substantially contributed to new developments within the PsD methodology thanks to an exceptional design of hardware and software in which high accuracy sensors and devices are used under flexible architecture with fast intercommunication among the controllers. Two of these pioneering achievements are described in the following sections of this paper.

As a first example, ELSA has performed accurate bi-directional PsD tests on real-size multi-storey building specimens by using up to nine DoFs and twelve actuators. Sophisticated geometric and static on-line transformations of variables between the equation of motion and the controllers was required. The results of this kind of tests are widening the knowledge on the torsional response of plan-wise irregular buildings.

As a second example, substructuring techniques developed within the PsD method have proved to be very useful for obtaining the seismic response of large structures such as a bridge. In such case, a testing set-up is devised in which the reduced part of the structure that suffers the largest damage (some of the piers) is the actual specimen and the rest of the structure (the deck and the rest of the piers) is numerically substructured.

Finally, a short description will be done of project EFAST that concerns the design study of a future seismic testing facility that would include the last advances in the field.

2. BIDIRECTIONAL PsD TESTING (SPEAR PROJECT)

Torsional response can be very significant for non-seismically designed buildings and it could be quite difficult to predict by simplified numerical models. The project SPEAR (Seismic Performance Assessment and Rehabilitation) focused on existing buildings because of the current economic and social relevance of their seismic performance. The experimental campaign at ELSA within SPEAR (see the picture at Fig. 2) included series of seismic tests for the original not retrofitted configuration as well as for two retrofitted configurations of a 3-storey reinforced-concrete (RC) full-scale structure [4]

In order to obtain the bidirectional and torsional response of the building, as shown in Fig. 3, at every floor, the displacement along two horizontal perpendicular axes x and y with origin at the centre of mass (CM), plus the in-plane rotation were considered as DoFs [5] [6] Even though four actuators with associated displacement transducer were attached to every floor, only three of them were used for the imposition of those three DoFs. The fourth piston was controlled following a strategy to optimise the load distribution among the pistons. The equation of motion was formulated and explicitly solved on the 9 DoFs of the structure. Subsequently, at each step, the computed displacements were converted to target displacements at the transducers by a geometrically non-linear transformation and the obtained forces at the piston load cells were statically reduced to the conjugated restoring forces and moments at the DoFs. The seismic equivalent forces were given by the application of two uncorrelated semi-artificial accelerograms following the x and y directions of the ground.

The servo-control units used were MOOG actuators with ±0.5 m stroke and load capacity of 0.5 MN. The control displacement transducers on the structure were optical HEIDENHAIN sensors with ±0.5 m stroke and 2 µm resolution. Every actuator was equipped with a load cell, a TEMPOSONICS internal displacement transducer and a PID controller based on a digital control loop at a sampling period of 2 ms. The four controllers for the four pistons of each floor were governed by a master CPU which was able to transmit and receive the controllers signals at real time (every 2 ms) through a high-speed communication channel based on dual port RAM boards. The three master units for the three floors had a common clock signal for the 2 ms interrupt.

Apart from the load cells and control displacement transducers, additional instrumentation was installed on the specimen. Damage was expected mostly on top and bottom of the columns. Accordingly, clinometers were installed at the columns on up to three levels of each one. Additionally, some potentiometer extensimeters were also installed on some localised areas. Photogrammetry techniques were applied at two locations and a couple of cameras were used in order to record the stereo images and estimate the bidimensional displacements of marked targets.

Fig. 2. View of the SPEAR structure ready for the bidirectional PsD tests

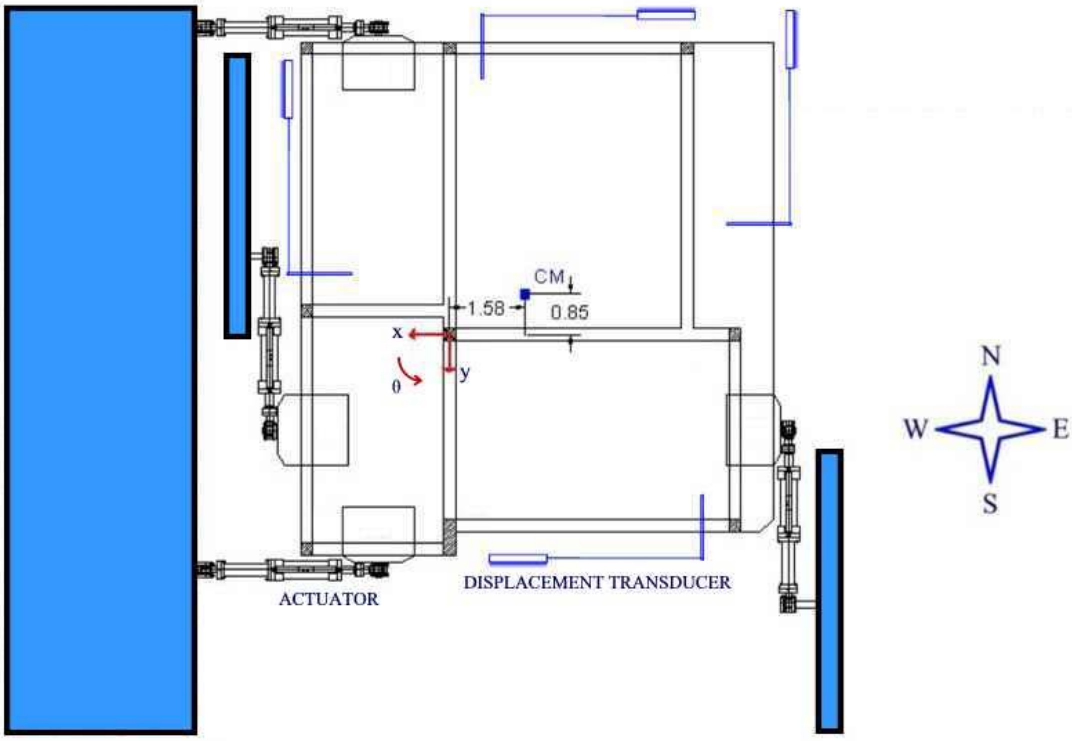

Fig. 3. Floor axes, actuators and displacement transducers for bidirectional test.

storey building and was designed for gravity loads alone using the Greek design code applied from 1954 to 1995. As seen in Fig. 3, it had a doubly unsymmetric plan configuration, but it was regular in elevation. It was made of three 2-bay frames spanning from 3 to 6 m in each direction with a storey height of 3 m.

For practical reasons, the specimen was built outside of the laboratory, starting from a thick RC base slab on which the ground columns were anchored. Afterwards, the base was borne on PVC rolls in order to transport the built specimen up to its final position on the strong floor of the laboratory, where it was clamped with post-tensioning bars.

As shown in Fig. 3, four actuators with four associated control displacement transducers were used for the bidirectional testing of the structure. In principle, these actuators were connected to the floor in positions not too close to the structural joints. Additional RC stiffeners were created in the floor slabs in order to properly distribute the local force applied by the pistons. The clamping of the piston attachments included post-tensioning bars. The piston bodies were supported by the reaction wall or by a supplementary reaction structure while the control displacement transducers were fixed on unloaded reference frames.

The CM, total mass and moment of inertia for the PsD equations were obtained from the theoretical mass distribution for the seismic assessment of the building according to Eurocode 8. Since the corresponding weight of the model was lower, additional water containers (Fig. 2) were set on the floors of the specimen in the laboratory in order to have realistic gravity loads at the members. The input signals for the test were semi-artificial records modulated consistently with Eurocode 8. After some preliminary small tests to verify the testing system and tune the control parameters, two big PsD tests were performed for peak ground acceleration of up to 0.20 g, on the original specimen, and 0.30 g on the two retrofitted configurations. For each test, the intensity of the excitation was equal in the horizontal x and y components but the history of ground acceleration was different.

After the testing campaign on the original model, a second round of tests was run on the first retrofitted configuration which tempted to increase the poor ductility capacity of the original columns and joints by means of the application of uniaxial and multiaxial glass-fibre wraps (Fig. 4). For this configuration, the introduced ground acceleration level arrived up to 0.30g which produced 200mm displacement in the X direction and 120mm in the Y direction. After that, the glass fibre was removed and an alternative retrofitting intervention was introduced by means of RC-jacketing of two of the columns at all the levels. This second kind of intervention was focused to reduce the eccentricity between the CM and the centre of strength in the X and Y direction, without regarding the ductility capacity of the remaining members. For this second retrofitted configuration, the 0.30g earthquake produced displacements of 160mm in the X direction and 130mm in the Y direction.

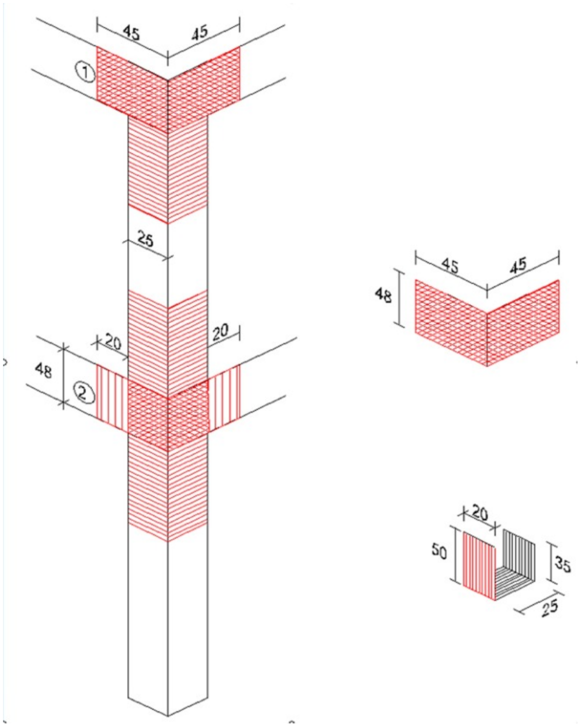

Fig. 4. Adopted FRP retrofitting design on the SPEAR model.

Details on the obtained response and damage at the different configurations are given by Negro and Mola [4] During the different tests, the obtained maximum displacements at the third floor were in the order of 200 mm in the “x” (weak) direction, 150 mm in the “y” direction and 23 mrad of torsion. This level of torsion was higher than the predicted one using regulated methods.

The tests were performed with very low experimental error. For example, the errors produced at the controller loops were always lower than 0.1 mm and those estimated in the generalised displacement at the CM were lower than 0.3 mm. The latter are mostly due to the existing flexibility of the floors since three structural displacements were used for the control while all four of them entered in the estimation of the measured generalised displacement.

3. PsD TESTING WITH NON-LINEAR SUBSTRUCTURING (VAB PROJECT)

The VAB (Vulnerability Assessment of Bridges) project had as an objective the assessment of the Talübergang Warth Bridge in Austria, shown in Fig. 5. The substructuring method was used with two of the bridge piers, namely A40 and A70, represented by physical models in the laboratory (see Fig. 6) and the rest of the piers, as well as the deck and abutments were analytically modelled; non-linear behaviour was adopted for the numerical substructured piers.

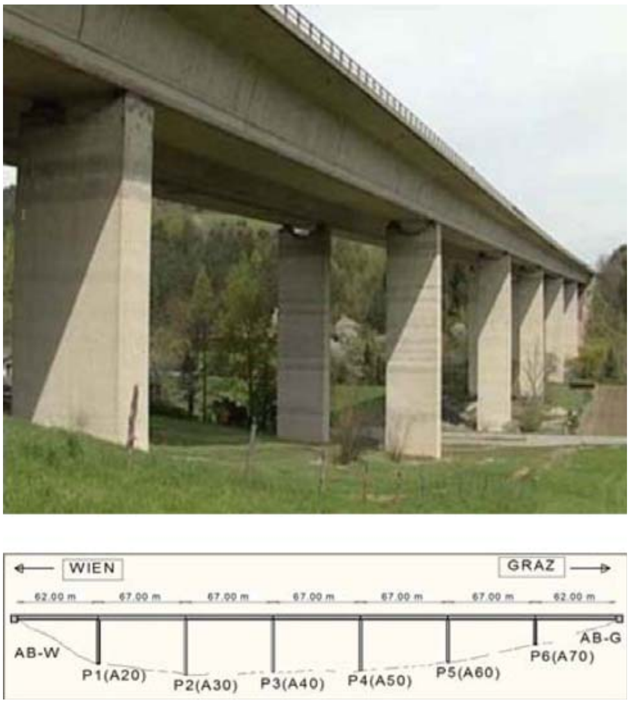

Fig.5 Warth bridge.

Fig.6 VAB test set-up.

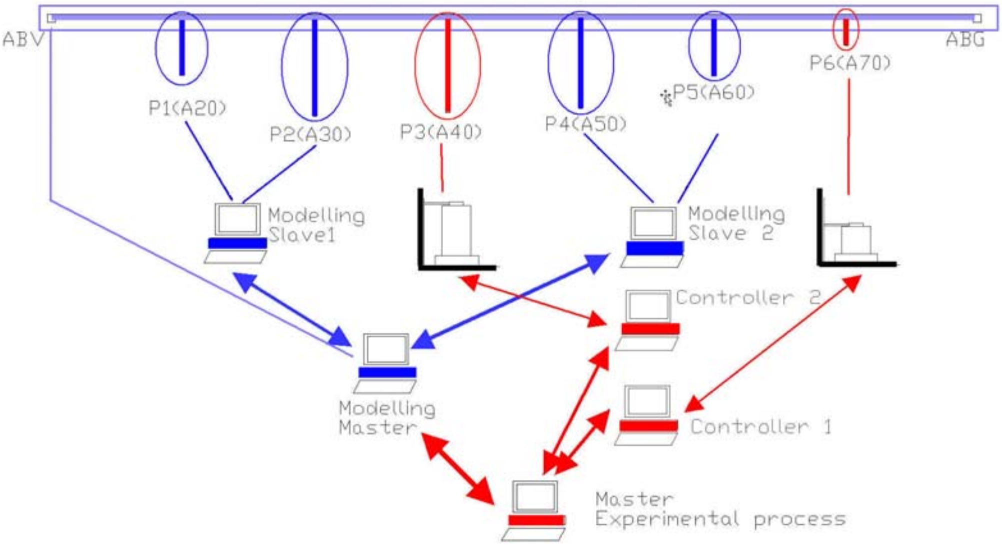

Fig.7 Distributed PsD testing with non-linear substructuring

generated for the bridge site, was considered. Three PsD tests were performed for input motions with increasing amplitude until failure of the bridge. The bridge model adopted for the tests had been scaled by a factor 1:2.5.

The objective of the conducted research was twofold. On the one hand, the aim was the seismic assessment of an existing bridge, that presents characteristics (such as hollow-box cross-section, lapped splices within the potential plastic hinge region, bar cut-off at inaccessible heights, low percentage of longitudinal and transversal reinforcement, short overlapping length, inadequate detailing of horizontal reinforcement and lack of appropriate confinement reinforcement) commonly found in bridges in Europe and Japan. On the other hand, the aim was to develop and implement the non-linear substructuring technique in PsD testing. This innovation in PsD testing at the ELSA laboratory provided simplified, yet accurate, tools allowing the testing of the complete bridge system using the existing laboratory capacity and reducing considerably the costs of the testing campaign and set-up (two piers instead of six).

The substructured test was implemented as follows (see Fig. 7). A main workstation (modelling master), running the linear model of the deck and the lateral DoFs of the piers, statically condensed at the top and bottom is used to perform the time integration of the equations of motion using the α Operator Splitting technique. At each time step, the relative lateral displacement to impose to the piers is computed. The displacements to impose to the experimental piers are sent to the main experimental computer (experimental master), which in turns pilots two controllers by means of an S-shape ramp. The displacements to impose to the analytical piers are sent to two other workstations (modelling slaves) taking care of the non-linear model of the piers and using an iterative process to equilibrate the internal nodes of them. When the analytical piers are equilibrated and the experimental piers reach the target displacement, the force levels reached at the ends of each pier are transmitted back to the modelling master in order to compute the next displacement. The problem was solved by using an intra-field approach (a unique main process delegating all the piers tasks to other processes) rather than an inter-field approach (two processes running in parallel).

Fig. 8 and Fig. 9 present the shear/displacement cycles observed on the experimental and numerical piers, respectively. The different curves correspond to the growing intensities of the loading (0.4, 1.0 and 2.0 * nominal earthquake). Observe in particular that, in this non-regular bridge, the short pier A70 largely enters in the non-linear range only during the 3rd PsD test.

The implemented substructuring technique proved to be representative of an earthquake test. The experimental results were in agreement with pre-test analytical results of dynamic analysis applying two alternative time integration schemes. The control system was reliable and the simplified numerical models guaranteed reasonably short computation time and accurate results. The Internet communications established between the numerical and physical parts of the bridge proved to work fairly well. It is interesting to note that the tested part was completely controlled remotely. The connection between the various processes used standard Internet features. Thus, this campaign of tests shows also that the tele-operation of experimental facilities, further combined with sophisticated numerical algorithms running on decentralised hardware was a working reality at the moment of this experiment.

New PsD tests of bridges with substructuring are foreseen in ELSA in 2012 within project SERIES [8] . In this occasion the continuous PsD algorithm with substructuring developed at ELSA (Pegon et al., 2008) will be used, allowing for a further improvement in the quality of the tests.

4. A FUTURE TESTING FACILITY (EFAST PROJECT)

ELSA is currently participating, together with other four research institutions in project EFAST [9] that consist of the design study of a European Facility for Advanced Seismic Testing. Such facility will be based on a system of at least two powerful 6-DoF shaking tables that may work coupled, combined with a strong floor and a modular reaction system that can also be coupled to the tables for some hybrid experiments (Fig. 10).

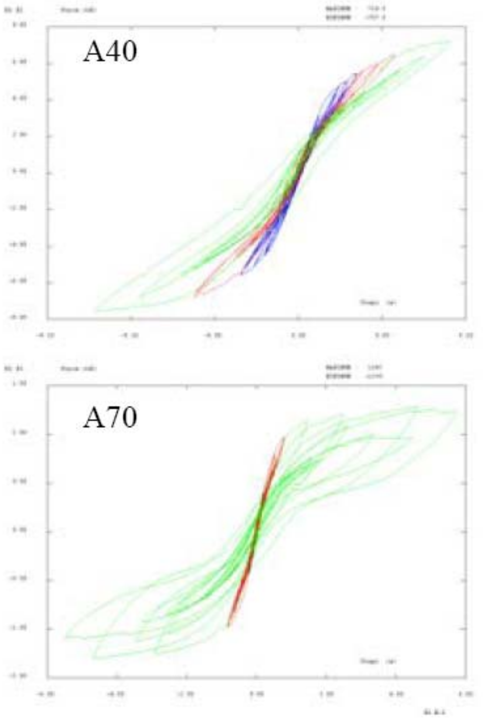

Fig. 8. Experimental piers.

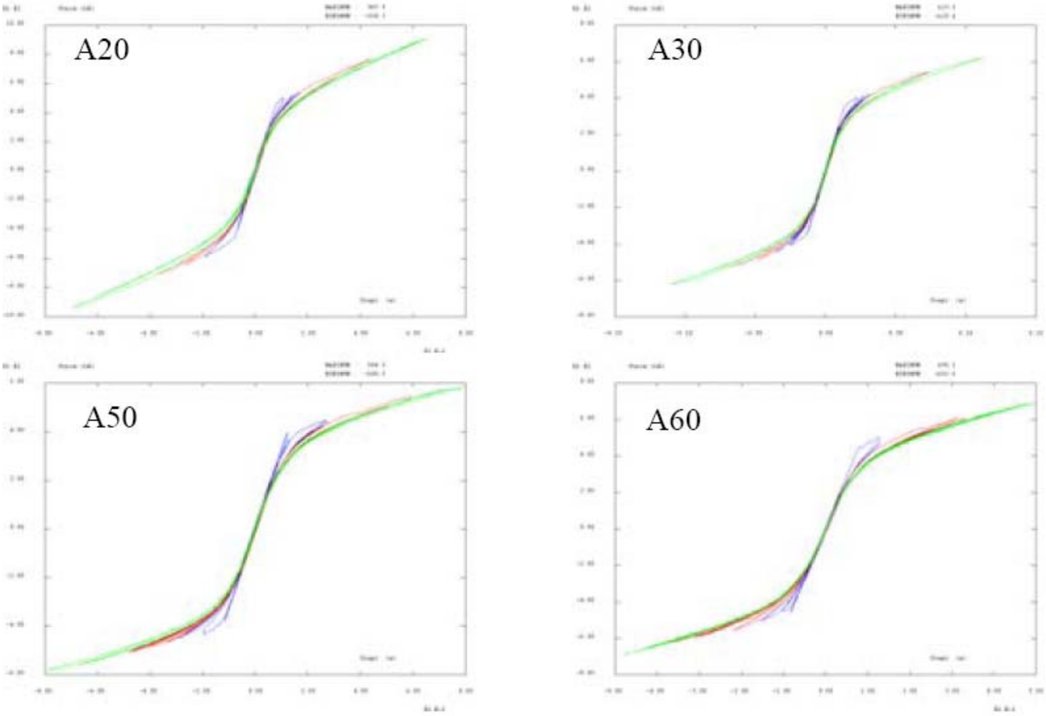

Fig. 9. Analytical piers.

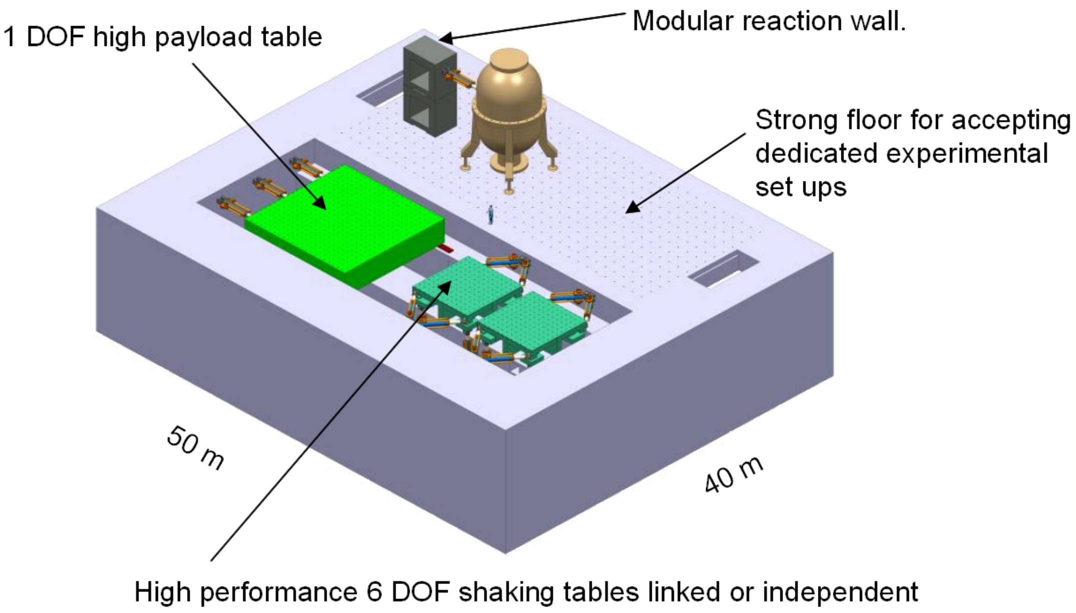

Fig. 10. Schematic lay-out of proposed EFAST facility

operate independently or be linked and operate as a single table. The facility foresees also an additional high-payload (500t) unidirectional shaking table for soil-structure interaction experiments.

The EFAST facility should have capabilities for PsD, substructured and real-time hybrid testing. It should be especially designed for collaboration with other laboratories, including the use of shared database and telepresence, so that the test data can be accessed either after or during the execution of it. Capabilities for geographically distributed testing are also foreseen.

5. CONCLUSIONS

A few of the main capabilities and features in structural testing at the ELSA laboratory have been summarised in this paper. As a complement to other laboratories in Europe, ELSA has specialised itself in tests on large-size models and with sophisticated computer-controlled load-application conditions. Internationally recognized pioneering steps have been achieved for the development of the PsD testing method and its full-scale implementation.

Acknowledgements

The Project SPEAR was funded by the EC under the “Competitive and Sustainable Growth” Programme, Contract N. G6RD-2001-00525 and the access to the experimental facility took place by means of the EC contract ECOLEADER N. HPRI-1999-00059. Project VAB was financed by program Environment & Climate of the EC by contract ENV4-CT97-0574 (DG 12 – EHKN). EFAST project is financed by the EC programme on Capacities (contract n. 212109). Many members of the ELSA staff as well as project partners have contributed with much effort to the success of the activities described in this paper. The authors are grateful to all of them.

References

[1] Takanashi, K., Nakashima, M. (1986), ‘A State of the Art: Japanese Activities on on-Line Computer Test Control Method’, Report of the Institute of Industrial Science, 32, 3, University of Tokyo.

[2] Pegon, P., Molina, F. J. and Magonette, G. (2008) “Continuous pseudo-dynamic testing at ELSA” in Hybrid Simulation; Theory, Implementation and Applications, ed. Saouma V.E. and Sivaselvan M. V. (Taylor & Francis/Balkema) 79-88.

[3] Molina, F. J., Magonette, G., Viaccoz, B. and Geradin, M. (2008) “Apparent damping induced by spurious pitching in shaking-table testing” Earthquake Engineering & Structural Dynamics 37 (1): 103-119. DOI: 10.1002/eqe.747.

[4] Negro, P., Mola, E., Molina, F. J., Magonette, G. E. (2004), “Full-scale PsD testing of a torsionally unbalanced three-storey non-seismic RC frame”, Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Paper N. 968.

[5] Molina, F.J., Verzelletti, G., Magonette, G., Buchet, Ph., Geradin, M. (1999), “Bi-directional pseudodynamic test of a full-size three-storey building”, Earthquake Engineering and Structural Dynamics, 28, 1541-1566.

[6] Molina, F. J., Buchet, Ph., Magonette, G.E., Negro, P. (2004), “Bidirectional pseudodynamic technique for testing a three-storey reinforced concrete building”, Proc. of 13th World Conference on Earthquake Engineering, Paper N. 75, Vancouver.

[7] Pinto, A.V., P. Pegon, G. Magonette, J. Molina, Ph. Buchet, G. Tsionis (2002), “Pseudodynamic tests on a large-scale model of an existing RC bridge using non-linear substructuring and asynchronous motion”, EUR Report No. 20525 EN, 111 pages, Ispra, Italy.

[8] SERIES project (28 September 2010) http://www.series.upatras.gr/

[9] EFAST project (21 September 2010) http://efast.eknowrisk.eu/