PSD TESTING OF LARGE-SCALE STRUCTURES AT ELSA

ELSA LABORATUVARINDA BÜYÜK ÖLÇEKLİ YAPILARIN PSD DENEYLERİ

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ABSTRACT

After a brief description of the pseudo-dynamic test method implemented in the ELSA reaction-wall facility, the paper presents an overview of the testing activity at large scale conducted since the opening of the laboratory in 1992 in the framework of an integrated European programme of pre-normative research in support of Eurocode 8.

1 INTRODUCTION

The Safety Technology Institute of the Joint Research Centre of the European Commission has recently built at Ispra (Italy) a structural assessment laboratory based on a 16m high, 21m wide reaction wall. Designed to resist the forces, typically several hundred tonnes, which are necessary to deform and seriously damage full-scale models of structures, the reaction-wall facility, now named ELSA (European Laboratory for Structural Assessment), is one of the largest facilities of its type in the world. The technical data for the ELSA reaction-wall system are summarized in Fig.1 and Table 1.

In addition to static and cyclic tests on large structures and components, the facility is equipped to perform tests utilizing the pseudo-dynamic (PSD) test method which enables, for instance, the simulation of earthquake loading of full-scale buildings

The paper starts with a brief description of innovative hardware and software aspects related to the implementation of the PSD test method at the ELSA facility. Then, an overview is presented of the testing activity at large scale conducted since the opening of the laboratory in 1992. The tests to be described were performed in close collaboration with a number of research organisations grouped within the PREC8 network under the European Commission's programme on Human Capital and Mobility. They are part of a combined experimental/analytical programme of pre-normative research in support of Eurocode 8, the provisional European standards for the design of structures in seismic areas. The experimental campaign at large scale conducted so far at the ELSA facility includes a 3-storey moment-resisting steel frame, a 4-storey reinforced-concrete frame and a series of irregular bridges. Papers presented during the 10th European Conference

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on Earthquake Engineering (Kakaliagos et al. 1994), (Negro et al. 1994), (Pinto et al. 1994) can be consulted for more detailed information on the above large-scale tests..

Table 1. Characteristics of the ELSA-Reaction Wall Laboratory

LOAD CAPACITY	REACTION WALL	Bending Mom.- 200 MNm
		Base Shear .-- 20 MN
	REACTION FLOOR	Bending Mom.- 240 MNm
	ANCHOR LOAD	Axial Force --- 500 kN
HYDRAULIC CHARACTERIS-TICS	FLOW	1500 l/min.
	PRESSURE	210 bar
	ACTUATORS	Load (MN).....(0.5 - 1.0)) Stroke (m) .(0.25) - (1.0)

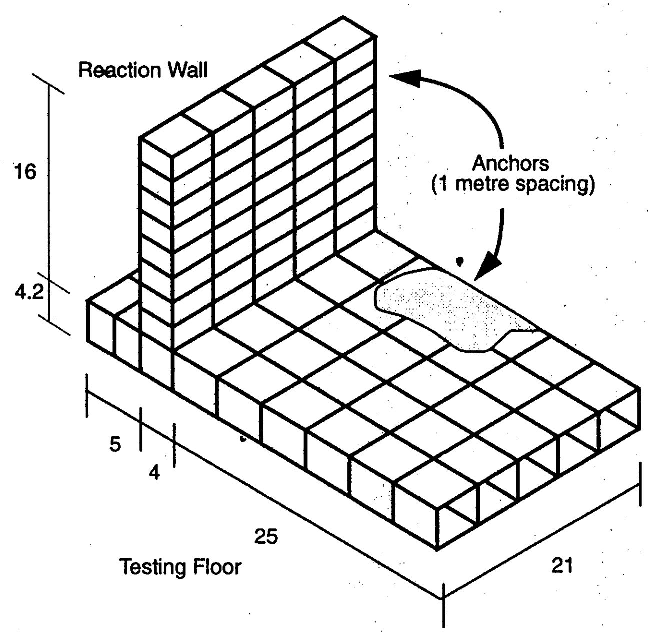


Figure 1. Reaction Wall/Floor system (dimensions in metres)

2 IMPLEMENTATION OF THE PSD TEST METHOD AT ELSA

2.1 PSD testing

A pseudo-dynamic (PSD) test is one which, although carried out quasi-statically, uses on-line computer calculation and control together with experimental measurement of the actual properties of the structure to provide a realistic simulation of the dynamic response. The equations of motion for a discrete parameter model of the test structure are solved on-line using a step-by-step numerical time integration method. Inertial and viscous damping forces are modelled analytically - a relatively straightforward matter compared to the nonlinear structural restoring forces, which are measured experimentally because of the virtual impossibility of modelling them accurately. The process automatically accounts for the hysteretic damping due to inelastic deformation and damage of the structural materials which is the major source of energy dissipation.

For simulating the earthquake response of a structure, a record of an actual or artificially generated earthquake ground acceleration history is given as input data to the computer running the PSD algorithm. The horizontal displacements of the building floors (where the mass of the structure can be considered to be concentrated) are calculated for a small time step using a suitable time integration algorithm. These displacements are then applied to the test structure by servo-controlled hydraulic actuators fixed to the reaction wall. Load cells on the actuators measure the forces necessary to achieve the required storey displacements and these structural restoring forces are returned to the computer for use in the next time-step calculation. Because the inertia forces are modelled there is no need to perform the test on the real time-scale, thus allowing very large models of structures to be tested with only a relatively modest hydraulic power requirement. In this sense, PSD tests are complementary to the more conventional shaking-table tests which are made in real time, but are restricted to components or small-scale models of large structures.

The experience gained so far has shown that it is the attention to the experimental implementation of the PSD method that ultimately leads to good results (Shing & Mahin 1984), (Eberg 1988), (Magonette 1991), (Magonette 1993). Many components in the physical implementation of the PSD test method can, in fact, introduce errors. Measurement and control errors tend to have a cumulative effect and in some cases these have been seen to dominate the response. The ELSA reaction-wall facility is the first to use fully digital servo-control for the applied displacements (see Fig.2), thus allowing a highly accurate test procedure and a versatile use of the various possible algorithms for numerical time integration of the equations of motion.

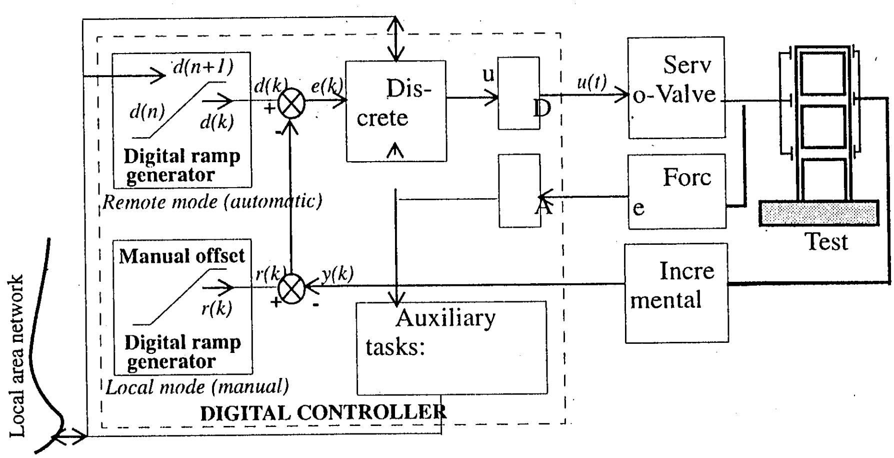


Figure 2. Digital control system implemented at ELSA

3 *LARGE-SCALE PSD TESTS*

The ELSA reaction-wall facility is currently being used for prenormative research in support of Eurocode 8 (EC8), the provisional European standards for the design of civil engineering structures in seismic areas. The research is performed jointly with 18 research organisations in the European Union grouped together in the PREC8 network under the European Commission's programme on Human Capital and Mobility.

The project of prenormative research in support of EC8 covers four major priority topics needing resolution to enlarge the current field of application of the code and improve its reliability. The identified priority topics are:

- *Reinforced concrete frames and walls*: The objective is to clarify the interrelation between a number of design parameters used in EC8 which, in a combined form, influence the nonlinear behaviour of structures subjected to earthquake motion. The parameters under study include regularity classification, values of the behaviour factor, methods of analysis and effects of capacity design procedures. The project also addresses the clarification of the requirements specified in EC8 for reinforcing steel in the light of the new steel production technologies in Europe and accounting for the ductility demands resulting from the design philosophy and quantified prescriptions included in EC8.
- *Infilled frames*: The main objective consists of contributing to the revision of all EC8 clauses which relate to the effect of infills on the seismic design and response of reinforced concrete frames and dual systems.
- *Bridges*: The main objectives for bridges are essentially related to regularity and behaviour factor procedures. Secondary objectives are related to capacity design procedures, second-order effects, asynchronous motion of piers and isolation/dissipation devices.
- *Foundations and retaining walls*: Of concern here are the seismic response and safety verification of direct foundations, deep foundations and retaining walls.

The place of ELSA in this programme is to perform the necessary large-scale confirmatory tests on various types of structures (frames and bridges) studied at small-scale or component level or by analytical methods by the other partners in the PREC8 network. The remainder of the present paper is devoted to a brief presentation of the large-scale pseudodynamic tests recently performed in the ELSA reaction-wall facility.

3.1 *Tests on a Four-Storey R/C Frame*

Fig.3 shows the general layout of a full-scale reinforced concrete frame designed according to Eurocodes 8 and 2 by the working group "R/C Structures" of the European Association of Structural Mechanics Laboratories (EASML) (Carvalho 1993).

It is a four-storey, high-ductility, framed structure. Dimensions in plan are 10m x 10m, interstorey heights are 3.0m, except for the ground storey which is 3.5m high. The structure is symmetric in one direction (that of testing) with two equal spans of 5.0m and slightly irregular in the other direction with span lengths of 6.0 and 4.0m. All columns have a square cross section (40x40cm), except for the interior column which is 45x45cm. All beams have a rectangular cross section with a total height of 45cm and a width of 30cm. A solid slab with a thickness of 15cm has been adopted for all storeys.

The materials used for the test structure are normal-weight concrete C25/30 as specified by Eurocode 2, and B500 Tempcore rebars and welded meshes. The selection of this

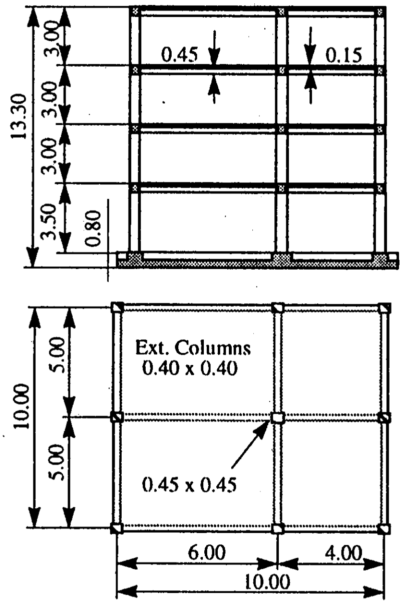


Figure 3. General layout of a full-scale reinforced concrete frame tested in ELSA

kind of steel, which was originally not included in EC8 provisions, is becoming dominant in many European countries, so the importance to assess the adequacy of this steel for earthquake-resistant construction has been recognized.

After the preliminary tests aiming at the dynamic characterization of the structure including the measurement of the structural stiffness, the structure has been tested pseudo-dynamically for two earthquake intensity levels, namely 0.4 (low-level) and 1.5 times (high-level) the accelerogram shown in Fig.4. The same figure, shows the storey displacements for the high-level test. More detailed results are presented in (Negro et al. 1994) and (Pinto et al. 1994).

The structure performed very well; the dissipation mechanism resulting from the capacity design method for frame structures as well as a 'uniform' energy dissipation were evidenced. The only concern is the apparent low damage sustained. In fact, despite the large values of interstorey drift (7 cm) neither spalling of the cover concrete, nor local instability of reinforcement were observed. However, the cracks at the beam-to-column interfaces remained permanently open which is the consequence of an important slippage of the bars in the joint leading to pronounced pinching of the hysteretic loops limiting the dissipation capabilities of the structure.

The structure had initially a natural frequency of 1.8 Hz. After the high-level PSD test a frequency of 0.8 Hz has been measured leading to a global frequency based damage index of about 0.4 which compares well with Park&Ang damage index computed assuming theoretical ultimate deformation capacity of the R/C members.

A definitive assessment of the damage suffered by the structure will be possible only when experimental data about the ultimate strength and ductility of the frame will become available. To this aim, a final test up to failure will be performed after the other tests foreseen for this specimen.

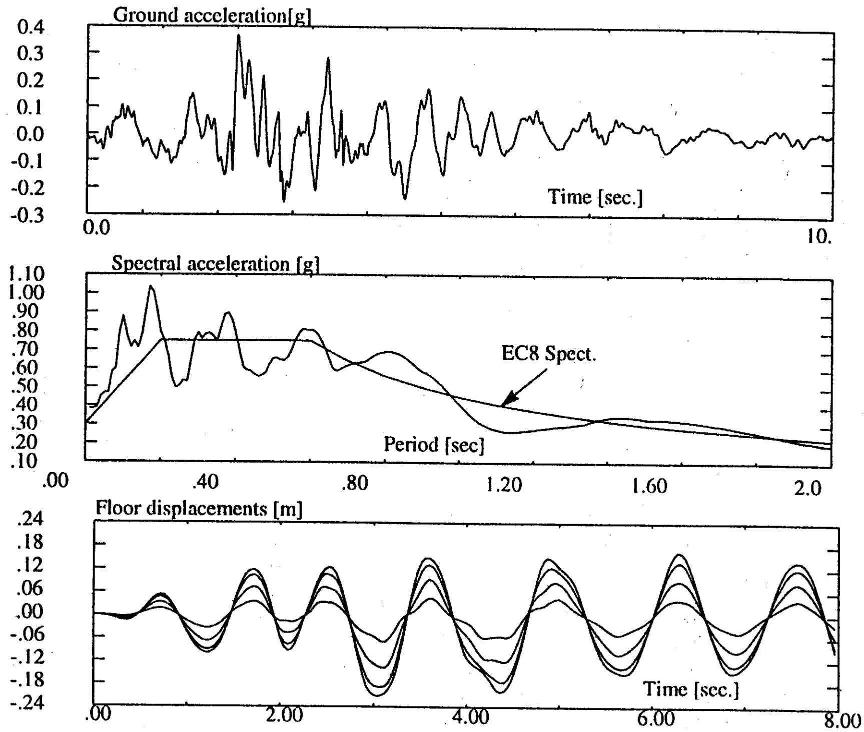


Figure 4. Earthquake signal, corresponding response spectrum and building response (floor displacements) for the high level earthquake.

3.2 Tests on a R/C frame with masonry infills

The exterior frames of the four-storey reinforced concrete building have been infilled with hollow brick masonry (Fig.5). This will allow to conduct pseudodynamic tests on the infilled structure, to improve the understanding of the effects of the masonry panels on the global response.

The modern seismic codes neglect, or take into account to a very limited extent, the effects of nonstructural masonry panels. Indeed, the masonry panels strongly change the behaviour of the main structure. In general, the presence of nonstructural masonry panels has a beneficial effect, because they significantly increase the global strength of the structure. On the other hand, they also increase the initial stiffness, so that the inertial forces may be increased to a large extent. The beneficial effect due to the increase of strength may or may not counterbalance the potentially negative effect due to the global stiffening of the structure.

Computer models are available to conduct parametric studies about the effects of the infill panels. Generally, phenomenological global models are used (Fardis & Calvi, 1994). These models are of the equivalent diagonal strut type. They are simple and robust, however, the calibration of the global properties is rather difficult. The experimental work conducted to-date (generally on simple one-storey one-bay infilled sub-

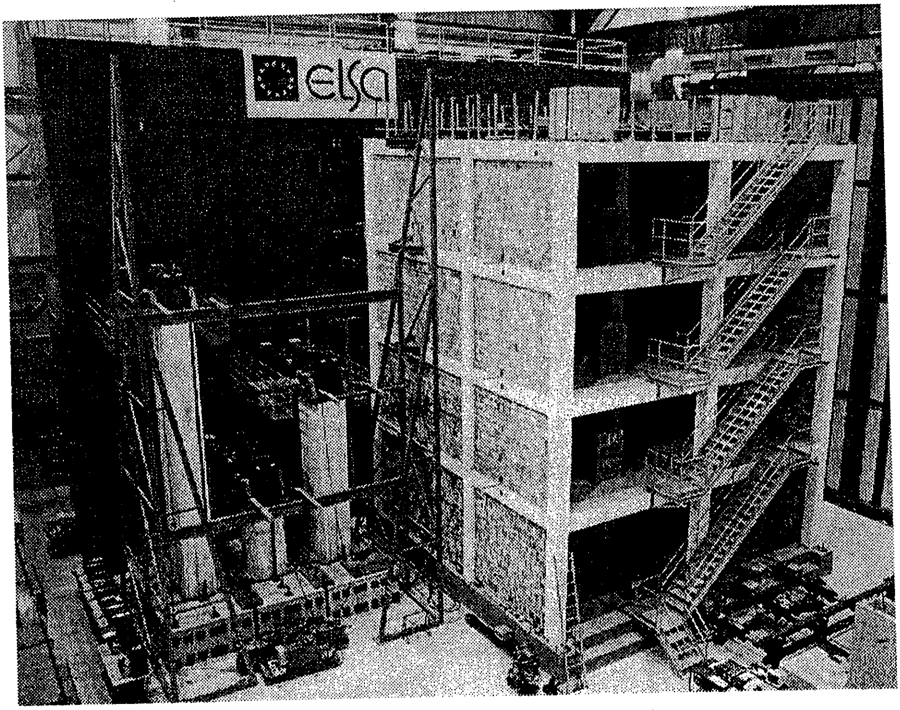


Figure 5. Experimental setup for the Infilled R/C frame and the substructured irregular bridge

assemblages), does not provide data for the calibration of the global models, since the basic properties of the material are generally not available. To fill this gap, a more refined model, is being developed at Ispra (Dellis & Anthoine, 1994). This includes 2D smeared-crack elements for masonry and concrete, and either full-bond or unilateral friction-less condition at the infill-frame interface. By means of a monotonic analysis, it is possible to calibrate the parameters required for the global models, starting from the basic properties of the materials.

Monotonic analyses of the test structure have shown that the results are extremely sensitive to the design assumptions. This confirms the need for the test to be conducted on the infilled frame, as well as the need for continuing the refinement of the computer models, to include effects such as friction at the interface.

An even more important issue about the effects of infills is their distribution. Irregular arrangement in plan and elevation may cause important concentration of damage in the frames, due to torsional effects or to the formation of soft-storey mechanisms. After the first test on the fully infilled structure, a second test will be performed without infills in the first storey, to create a soft-storey effect.

It is believed that this experimental activity will allow to validate and calibrate the available computer models, so that extensive parametric analyses can be carried out. The results of this study will assist in taking into account more realistically the effects of the infills, an issue which is thought to leave room for code improvement.

3.3 PSD Testing of R/C Bridges with Substructuring

3.3.1 General comments

The pseudo-dynamic testing method is a hybrid method combining the numerical integration of equations of motion of complex structures condensed on a reduced number of degrees-of-freedom (d.o.f.), with the experimental measurement of the reaction forces resulting from this motion.

Despite the potential of the PSD technique, direct testing of very large civil engineering structures like bridges would require several controlled d.o.f. that could exceed the experimental capabilities. It is however possible to extend the PSD field of application, at least when the behaviour of a part of the structure is well known, by introducing a substructuring technique (Dermitzakis 1985). This technique takes profit of the hybrid character of the PSD method in combining the numerical simulation of the known part of the structure, the substructure, with the physical testing of the remaining structural part, the tested structure. The method is well suited for bridges since their largest part, the deck, can be assumed linear elastic and then modelled by any finite-element software: only the piers, whose dimensions remain reasonable in many cases and where damage is expected, are tested in the laboratory.

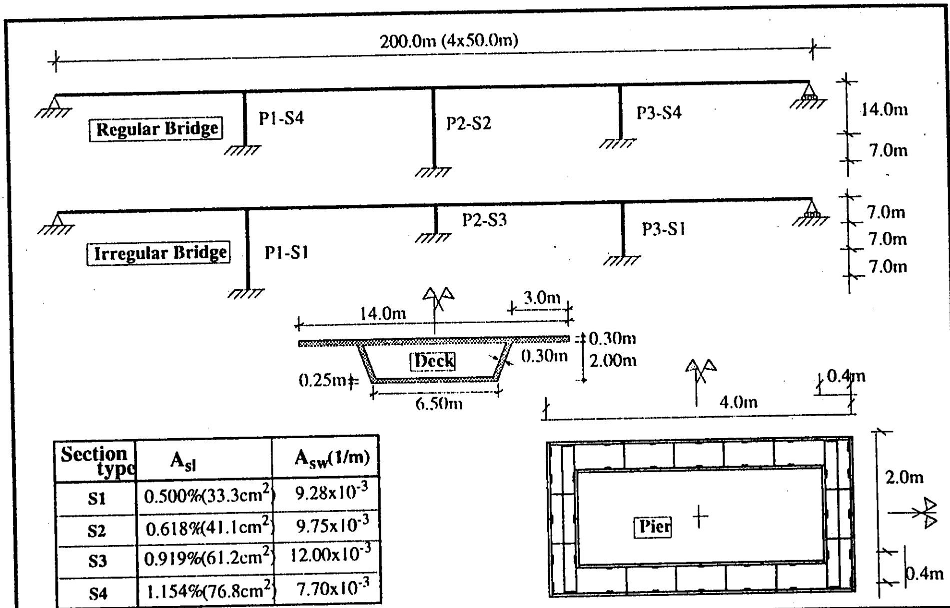
A further advantage, which is again well suited for bridges, is the possibility of dealing with situations where the seismic excitation is asynchronous or presents different amplitudes along the foundation.

The use of substructuring techniques in PSD testing implies, for the substructure, a model and the time integration of its spatially discrete equations of motion. This model may present a number of d.o.f. greater, by some orders of magnitude, than the number of nodes actually controlled by the PSD algorithm. Thus, if the substructure is handled by a PC program the current capabilities of this controller program may easily be exceeded. To overcome this difficulty, the adopted strategy was to have two processes running in parallel: the one responsible for the PSD algorithm running in the PC (controller) and the other, responsible for the substructure, running in a remote workstation and communicating between them using standard network capabilities such as Berkeley sockets. Details of the ELSA implementation of PSD testing with substructuring are given in (Buchet & Pegon 1994).

3.3.2 Testing program

Included in the project of prenormative research in support of EC8-Bridges are the PSD testing of six bridges (1:2.5 scale) in the ELSA laboratory. These tests result from the combination of three different geometric configurations and five pier sections with different detailing (see Fig.6). Isolation devices between the piers and the deck are also to be considered. In addition, a preliminary quasi-static cyclic test with imposed displacement history will be performed on a short pier (modelling calibration). Thus, results from large scale laboratory tests will be available to help us to calibrate and/or improve EC8 design specifications.

The structures under analysis consist of a continuous deck supported by middle span piers and abutments at the extremities. Assuming a linear elastic behaviour for the deck, a substructuring technique can be adopted allowing the piers to be built and tested apart from the deck. In this case, the interaction between both structures, the piers in the laboratory and the numerical deck in the computer, is established through the real structure common points, i.e., the points connecting the piers to the substructure; a numerical step-by-step resolution algorithm finds the displacements to be applied on the top of the piers



Section type	A_{sl}	A_{sw}(1/m)
S1	0.500%(33.3cm^2)	9.28x10^{-3}
S2	0.618%(41.1cm^2)	9.75x10^{-3}
S3	0.919%(61.2cm^2)	12.00x10^{-3}
S4	1.154%(76.8cm^2)	7.70x10^{-3}

Figure 6. General characteristics of the bridges to be tested in ELSA (dimensions of the 1:1 scale)

so that the real reaction forces can be measured and taken in account in the numerical algorithm. Then, new displacements are calculated and applied to the piers closing the cycle. A view of the experimental setup for the irregular bridge of Fig.6 can be found on Fig.5.

Fig. 7 presents the first test results from one irregular bridge (B213A). The force-displacement diagrams of two piers (short and medium) highlight the 'vulnerability' of the short pier. However, the ductility demand, for the considered design seismic loading, is far away from ultimate ductile capacity of the bridge piers.

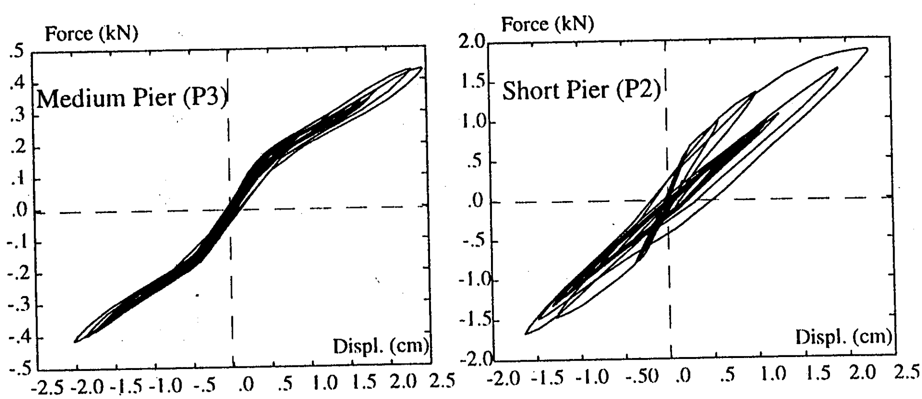


Figure 7. Force-displacement diagrams for the medium and short piersof the irregular bridge B213A

4 CONCLUSION

The general characteristics of the ELSA laboratory have been presented. Aspects related to the implementation of the pseudo-dynamic test method at the ELSA reaction-wall facility have been discussed and an overview of the testing activity at large scale conducted in the framework of an integrated European programme of pre-normative research in support of Eurocode 8 was given.

It is expected that this unique facility will contribute to the updating of the European design codes and subsequently increase the competitiveness of the European construction industry in earthquake prone zones.

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