TAILORING EXPERIMENTAL STRATEGY AND SETUP: THE LONG STORY OF THE SEISMIC BEHAVIOUR OF PRECAST STRUCTURES

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ABSTRACT

Devising the most appropriate testing strategy and conceiving a mock-up "as simple as possible, but not simpler" is the challenge which has to be taken whenever a research programme does involve experiments. Optimizing the experimental programme reduces the risk of either wasting time and resources or missing some of the fundamental ingredients of the structural behaviour because of oversimplification or inclusion of too many elements at the same time. The European Laboratory for Structural Assessment and ASSOBETON have been involved in many research programmes aimed at studying the seismic behaviour of precast concrete structures, with different goals and different levels of complexity. A first programme was aimed at obtaining information about the cyclic behaviour of precast concrete columns. This apparently simple task resulted into an innovative experimental setup because of the need to properly allow for the elongation of the rebars in the region above the pocket foundation. A second programme was aimed at comparing the behaviour of precast and cast in situ frames, and involved the cyclic and pseudodynamic testing of two different mock-ups. Another programme focused on the global behaviour of single-storey precast industrial buildings. In this case the mock-up reproduced in nearly full scale a portion of the building, including foundations, columns, main and secondary beams as well as claddings. The decisions about how to deal with such a flexible structure in a pseudodynamic context had to be made with much care. The paper provides a description of the experimental programmes, highlighting the strategies which were adopted in each case to meet the research requirements. Finally, a description of the recently started EU-funded research programme SAFECAST is provided. This programme focuses on the seismic behaviour of connections in precast structures and will involve pseudodynamic testing of a multi-storey precast structure, with and without cast in situ core.

BACKGROUND

Precast concrete construction represents a viable alternative to construction methods utilizing cast-in-place concrete. Advantages related to the use of precast techniques include higher quality control that can be obtained in the precast plants, speed of erection, and freedom in the architectural shape of the members. Despite these well-recognized advantages, the use and development of precast concrete structures in seismic areas have been typically limited, by the lack of confidence and knowledge about their seismic performance.

ASSOBETON and ELSA have a long tradition of scientific collaboration on the subject of the seismic behaviour of precast structures. The two institutions have been involved in the study of the seismic behaviour of precast structures elements since 1994 (Saisi and Toniolo, 1998). After the identification of the seismic behaviour of single elements, a research programme aimed at

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demonstrating the equivalence between the behaviour factor of precast and cast-in-situ single-storey industrial buildings was activated. This research project, named “Seismic behaviour of precast R/C industrial buildings”, partially financed within the European “Ecoleader” research programme (contract HPRI-CT-1999-00059), was performed at the ELSA Laboratory. Together with ASSOBETON, two other Associations interested in the field (ANDECE and ANIPB, from Spain and Portugal respectively) were involved in the project, together with Politecnico of Milan, the University of Ljubljana and two industrial precast manufacturers. The results of the tests demonstrated the excellent capacity of precast buildings to withstand earthquakes without suffering important damage (Ferrara and Negro, 2003a-b; Ferrara et al., 2004).

The data obtained within the two mentioned research projects provided the starting point for the PRECAST EC8 project (contract G6RD–CT–2002-00857). A number of European and overseas Partners, from academia and other research institutions as well as from the precast construction industry, were involved in the project: the Politecnico of Milan, the University of Ljubljana, the National Technical University of Athens, the Joint Research Centre of the European Commission, the National Laboratory for Civil Engineering of Lisbon, the Tongji University of Shanghai, and the precast elements manufacturers Gecofin and Magnetti Buildings from Italy, Civibral from Portugal and Proet from Greece. The project PRECAST STRUCTURES EC8 was successfully carried out and concluded in early 2007, after 4 years of activity. As a result of the project, a calibration of the global behaviour factor (q factor) for precast frame structures was carried out with a combined experimental and numerical approach. The research pointed out the very good behaviour of precast structures under earthquake conditions and their substantial equality to traditional cast-in-situ ones as for the safety under earthquake excitation, even without monolithic joints.

The only, but crucial missing link in the modeling of such precast buildings, is the adequate knowledge about the behaviour of connections. The empirical evidence from the past earthquakes is sparse, incomplete, non-quantified and first of all controversial. Some reports show excellent behaviour of precast systems and connections (Moguruma et al, 1995; EERI, 2000; Saatcioglu et al, 2001). On the other hand, the same documents report some catastrophic collapses. This is not surprising, since seismic response clearly depends on the specific structural system, type of connections and quality of the design and construction. Some collapses were also reported during the 1977 Vrancea earthquake (Tzenov et al, 1978), the 1979 Montenegro earthquake (Fajfar et al, 1981) and the Northridge earthquake (EERI, 1994). Failures of welded and poorly constructed connections were also the main cause of extensive collapses in Armenia (EERI, 1989) and during the 1976 Tangshan earthquake in China (Anicic et al, 1982). These bad experiences have generated mistrust to precast systems in general. In some countries this practically preclude the use of precast structures (i.e. Chile; Park et al, 2003) and in many codes all precast systems were penalized with high seismic forces related to the reduced competitiveness in the market.

The problem of investigating the seismic behaviour of connection devices will be addressed within the SAFECAST project (Grant agreement no.218417-2), recently financed by the European Commission within the Seventh Framework Program.
Many of the mentioned activities have been conducted in close collaboration with the State Key Laboratory for Disaster Reduction in Civil Engineering (SKLDRCE), Tongji University, Shanghai, P.R. China.

The main achievements of the past projects are described in the paper, along with activities being defined as a part of the newly activated project SAFECAST.

CYCLIC BEHAVIOUR OF PRECAST COLUMNS

The study of the seismic behaviour of precast structures started in 1994 with the collaboration of ASSOBETON, the ELSA Laboratory and Politecnico of Milan. As a part of the research project, the aim of which was the investigation of the ductility capacity of precast cantilever columns with pocket foundation, twenty columns, characterised by different reinforcement arrangements and axial load, were subjected to cyclic loads of increasing amplitude. In order to test the specimens under real restraint conditions (i.e., maintaining the constant axial load while allowing for the progressive elongation of the column as a result of the plastic elongation of the rebars) the special set-up shown in Figure 1 was designed to the specific purpose. The loading system is based upon a vertical actuator which is eccentrically positioned with respect to the column, and steel swivel-jointed bars on the opposite side. As a result, the vertical load is hardly affected by the elongation of the column. The vertical load is indeed acting along the axis of the column, therefore the second order effects were accounted for by means of the control algorithm.

The results of the experimental campaign demonstrated that precast columns are able to dissipate a large amount of energy up to significant ductility (>>5) with stable loops (figure 1). A large number of displacement transducers were placed to measure axial and shear strains above as well as inside the pocket foundation, thus demonstrating that the connection between the precast column and the plinth is at least as rigid as a cast in situ foundation.

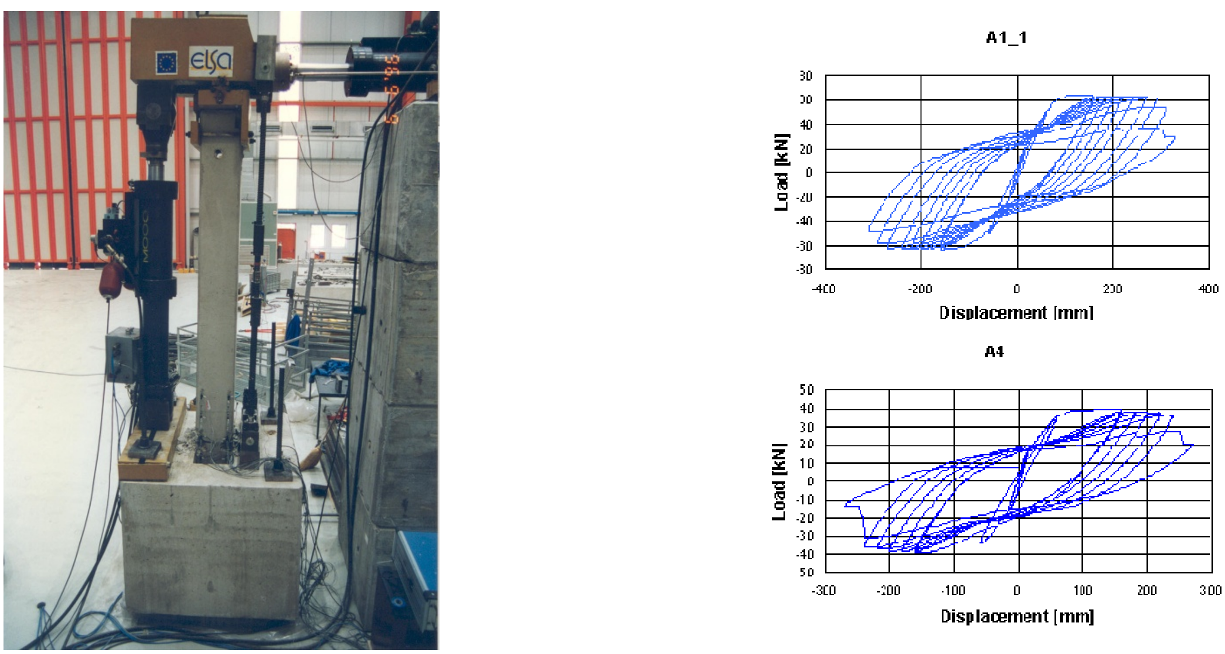


Fig. 1. set up for the pseudodynamic testing of precast columns and examples of measured loops.

THE ECOLEADER PROJECT

As a natural prosecution of the experimental research focused on the behaviour of single precast concrete columns funded by ASSOBETON in 1994, the research project “Seismic behaviour of reinforced concrete industrial buildings” was approved in July 2001 for an Ecoleader funding (European Consortium of Laboratories for Earthquake and Dynamic Experimental Research). The project was aimed at demonstrating the equivalence between the behaviour factor of precast and cast-in-situ one-storey industrial buildings. To derive data to be used to this purpose, two prototypes, a precast one and a cast-in-place one, have been designed, built and submitted to a series of pseudodynamic tests to assess their seismic behaviour.

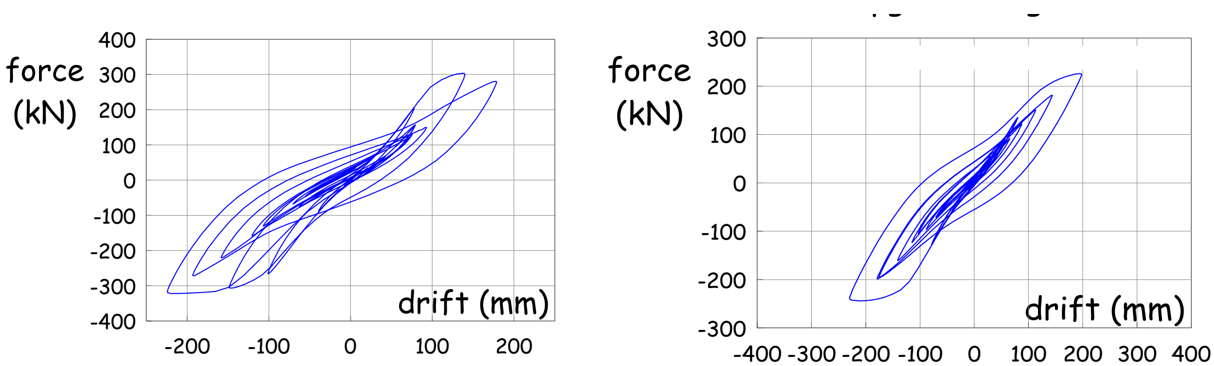
Both prototypes consisted of two two-bay frames, each bay spanning 4 m, connected by an interposed hollow core slab, spanning 3 m. The clear height of columns measured 5.05 m from the edge of the footing socket. Precast foundation sockets were used in both cases, tied by means of Diwidag bars to the floor of the laboratory. The two prototypes are shown in figure 2.

Fig. 2. Precast and cast-in-situ prototypes during the tests.

The design of the prototypes has been performed in accordance with prescriptions of Eurocode 8 (draft May 2001) so that both structures were able to withstand the same base shear force.

The seismic ground motion has been assigned through an artificial accelerogram, the spectrum of which was consistent with the one given by Eurocode 8 for ground type B. The seismic intensity was calibrated on the computed seismic resistant capacity of the structures. Three pseudodynamic tests have been performed for each type of structure, fixing the value of the peak ground acceleration respectively to 1/3, 2/3 and 3/3 of the theoretical maximum one.

A synoptic view of the experimental behaviour of the two prototypes is given in figure 3 through the force-displacement evolutions. The moment-curvature diagrams show in both cases several cycles with significant hysteresis, denoting the full yielding of steel and an appreciable capacity of dissipating energy by the structures, either precast or cast-in-situ, taking profit of the material resources beyond the elastic limits. Some residual displacements were observed in both cases after load removal, as well as some fairly visible cracks in critical zones of columns, as a witness of the irreversible effects of the yielding of steel, cracking of concrete and non-linear behaviour of compressed concrete, as also confirmed by local measurements. The maximum attained value of the shear force was consistent with theoretical predictions for the cast-in-place prototype, whereas a significantly higher (+20%) value was recorded for the precast one. The differences in casting of columns (horizontal for the latter, obviously vertical for the former) as well as the higher degree of quality control which features the production of prefabricated structural elements, mainly in the detailing of reinforcement, might be probably called as a partial explanation for this (Dimova and Negro, 2005).



precast prototype cast-in-situ prototype

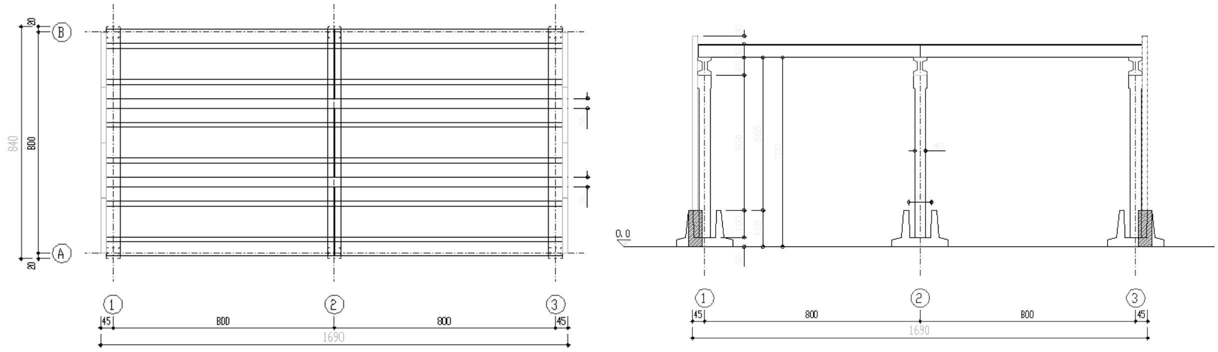
Fig. 3. Force-displacement evolutions for a peak ground acceleration corresponding to 2/3 of the maximum.

THE PRECAST STRUCTURES EC8 PROJECT

The co-normative research programme "Seismic behaviour of precast concrete structures with respect to EC8" (PRECAST STRUCTURES EC8) was aimed at assessing and possibly calibrating, by means of experimental and numerical investigation, the design rules provided by Eurocode 8 with reference to precast reinforced concrete structures. The results of the project were meant to be used to support the European Commission policy in the field of standardization, both for the Eurocode programme and for the revision and completion of the harmonized product standards issued by CEN/TC 229, under Construction Product Directive provisions and mandate M100 Precast Concrete Products.

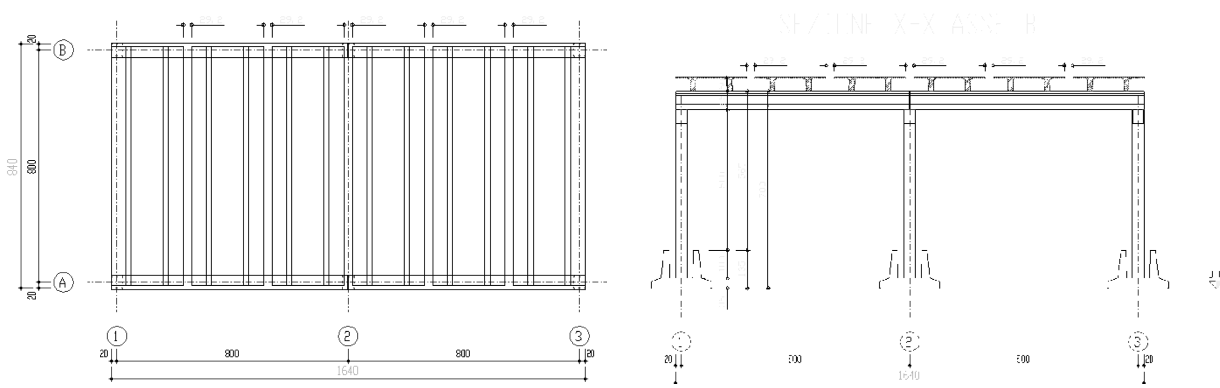
The design and construction of two full-scale structure prototypes were carried out. The prototypes have been designed according to EC8 in order to be submitted to pseudodynamic and cyclic tests. They consisted (figure 4) either of two beam spans-one roof bay or two roof bays-one beam span (with beams and roof elements spanning 8 m each), supported by six 5 m high columns. The experimental campaign foreseen in the project included both pseudodynamic and cyclic tests on both prototypes. The seismic ground motion in pseudodynamic tests was imposed by means of a real signal, modified to fit with the spectrum given by Eurocode 8 for ground type B. The seismic intensity was calibrated on the computed seismic resistant capacity of the structures. Four tests have been performed for each type of structure, fixing the value of the peak ground acceleration respectively to 0.05g, 0.14g, 0.35g and 0.525g. As for the cyclic test, the semi-amplitude of the initial displacement cycles was chosen to be the yield displacement estimated from simplified calculations, taking into account the response obtained in the PsD tests. Each increment in the imposed displacements up to failure was also chosen as equal to the half the yield displacement. Three cycles at each displacement level were designed, in order to explore the stability of the response in terms of global structural parameters at each increasing level of displacement.

The local instrumentation consisted of displacement transducers and inclinometers (see figure 5).



plan view – roof level front view

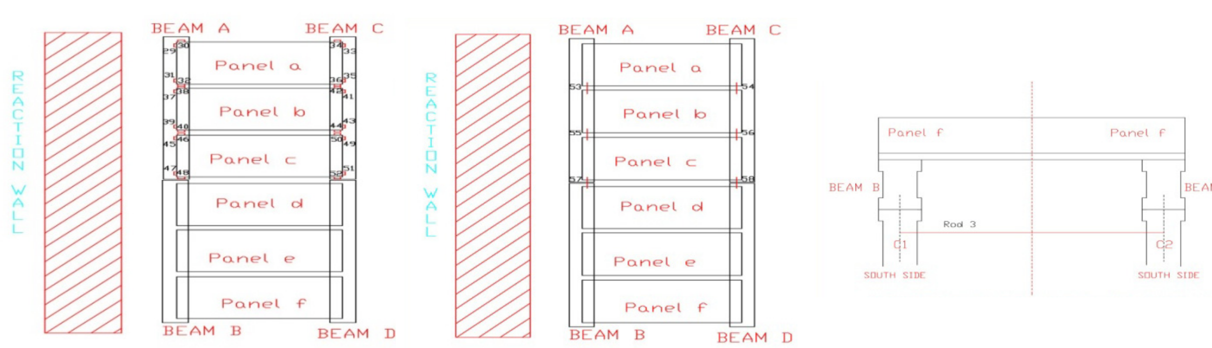
Prototype A with roof elements at a right angle to the earthquake



plan view – roof level front view

Prototype B with roof elements parallel to the earthquake

Fig. 4. Layout of the prototypes.



(a) (b) (c)

Fig. 5. Local instrumentation for measurement of: relative beam-roof element displacements (a); relative displacements between roof elements (b); relative displacements between pairs of aligned column (c).

The possibly most important insight was about the remarkably effective diaphragm action which was developed in the prefabricated roof. Interesting results came out from the analysis of the behaviour of prototype A. The crucial role played by the diaphragm action on the overall behaviour of the structure was highlighted by the PsD results. A first insight into it can be got through the measured relative roof-panel vs. beam displacements. The phase coincidence or opposition of the signals measured on different stems of roof elements (figure 6), confirmed the adequacy of the design scheme. The lower magnitude of relative displacements measured with reference to panel b confirmed its functioning as for the restoring of compatibility. The magnitude of measured displacements turned out to be definitely not negligible, and the "worst" roof element was the one closest to the edge frame. Some unrecoverable damage in the connections took place from the 0.14 PGA test and became far more significant at the end of the 0.35 PGA one, thus possibly explaining the degradation of diaphragm action observed from the ratio of the measured central/edge column displacements.

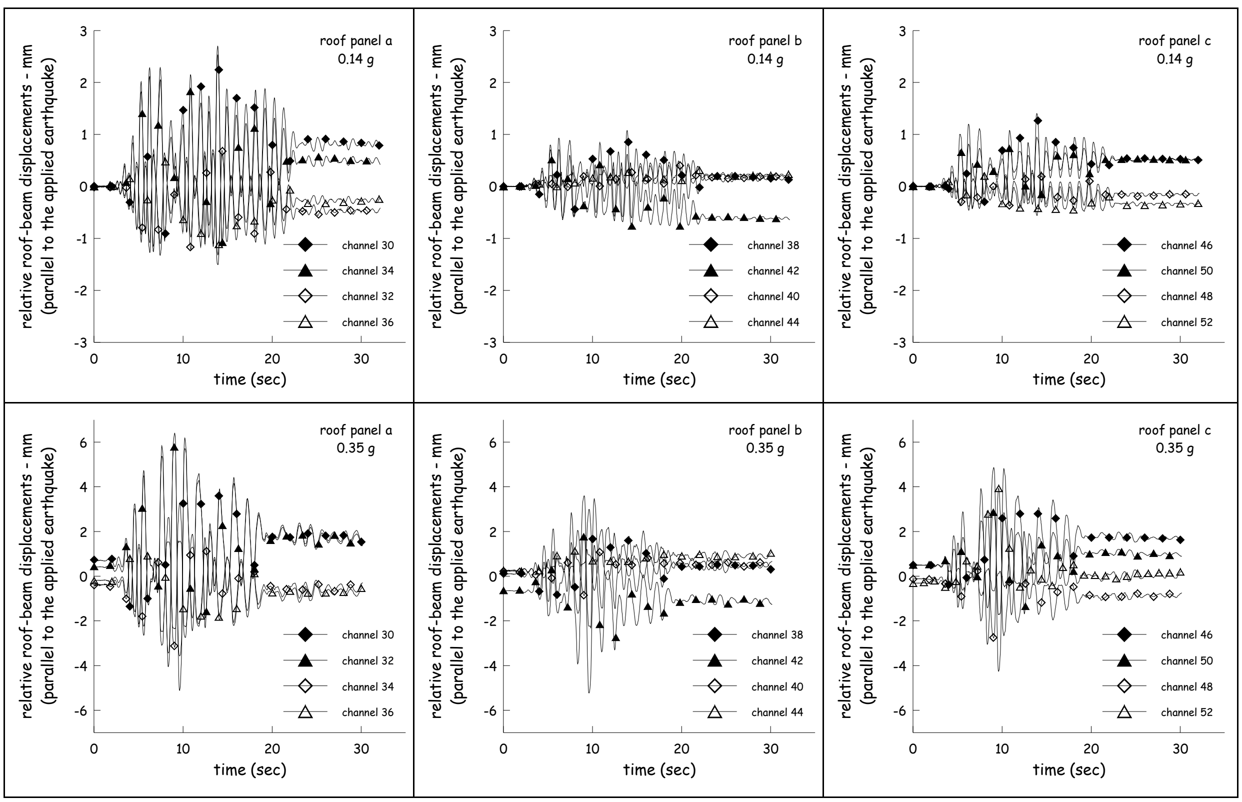


Fig. 6. Relative roof-beam displacements in the direction of the earthquake.

MORE TO COME: THE SAFECAST PROJECT

The seismic behaviour of connections in precast construction systems has been largely recognized as a crucial matter to be addressed both by the industry sector and by the related research community. In spite of this situation, the complexity of the problem and the variety of inherent issues to be harmonized dealt with in proposing design procedures for connections and precast structures as a whole, have made it difficult so far to conceive self-sufficient solutions and approaches of general validity. Scope of the SAFECAST project is to give effective answers to this need for self-sufficient, harmonized solutions of the problems of correct seismic design of

joints and connections in precast structures. The final outcome of the project is thus expected to consist of methods and tools for the seismic design of connections in precast systems, achieved by means of a balanced combination of experimental and analytical activity.
The funding scheme is dedicated to the support of small and medium enterprises associations. For this reason, among the 16 partners involved into the project 5 national associations of precast concrete producers (ASSOBETON, ANDECE from Spain, ANIPB from Portugal, SEVIPS from Greece and TPCA from Turkey) will play a fundamental role fixing priorities and needs. The extensive research effort planned will be subdivided into 7 different RDT performers (Joint Research Centre - ELSA Laboratory, Politecnico of Milan, National Technical University of Athens, Istanbul Technical University, Laboratorio Nacional de Engenharia Civil, University of Ljubljana and Labor srl), according to their peculiar facilities and capabilities. The presence of a number of industrial firms (DLC srl, Prelosar, LU.GE.A Progetti Costruzione Gestione Spa and HALFEN GmbH) guarantees constant feedback on the results and their applicability and also an open door to issues and possible topics of interests for further research that might come along based on the findings of tests or analyses. A key role in the project will be played by the tests on full-scale prototypes of complete structures. This part of the experimental activity is focused on the investigation of open issues related to the global features of the seismic response of precast structures, as affected by the local behaviour of its connection devices.

Two main experimental programmes are envisaged, and are currently being defined.

The first programme will again concentrate on the adequacy of connections in single-storey industrial buildings. The conclusions obtained from the previous research project seemed to indicate that the roofing system is indeed much stiffer than expected, and that it can to some extent act as a rigid diaphragm. Those conclusions, however, were limited by the size of the specimen. In particular, the length of the double-tee secondary beams (which indeed plays an important role in the functioning of the roofing system as a diaphragm) was far from being representative of typical constructions, for which spans of about 20-25 meters are common.
The new setup will most probably consist of elements of such size; however, the mock up will be limited to a single bay of the roofing system, whereas the rest of the structure will be modeled numerically by means of the nonlinear hybrid testing capabilities available at the ELSA laboratory.

The second experimental programme will address the behavior of multi-storey precast buildings, a typology which is becoming more and more common in the construction practice, for which the behavior of connections is expected to play an even more important role.

In addition, it has to be considered that in many multi-storey precast buildings there are one or more rigid vertical elements (such as stairway cases or elevator shafts, typically cast in situ), which end up attracting a large portion of the base shear. This is typically assumed to much improve the global structural behavior; however, the transfer of forces between the stiff vertical elements and the precast frames is far from being understood, and the ability of the connections to accommodate the large deformation has to be demonstrated.
For this reasons, a mock up representative of a three-storey building is being designed, and this will be tested with and without a cast in situ core, as shown in figure 7.

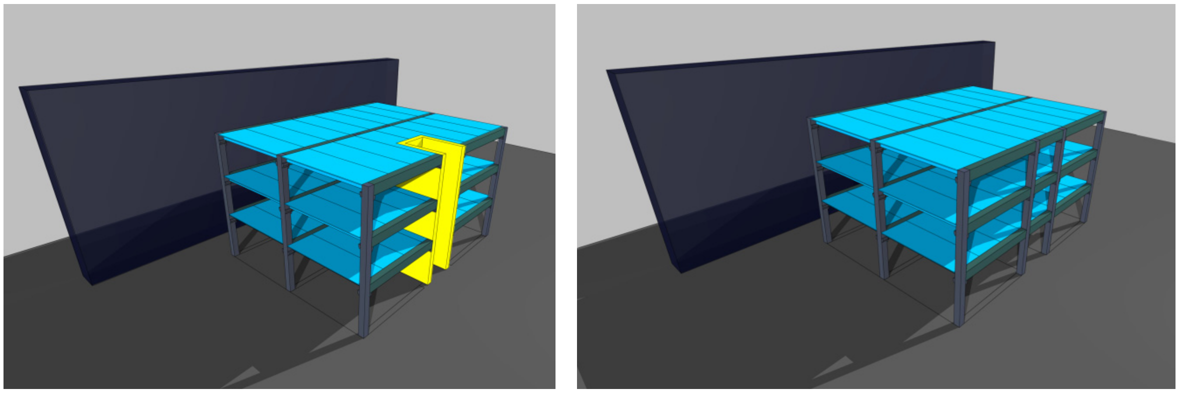


Fig. 7. Scheme of the multi-storey specimens to be tested.

CONCLUSIONS

The motivations and means of execution of a series of research activities on the seismic behaviour of precast concrete structures have been described, focusing on the experimental part of each project.

A first research activity was aimed at demonstrating the substantially equivalent behaviour of precast columns with respect to cast in situ ones, and the satisfactory performance of pocket foundations.

A more ambitious research project was aimed at comparing the global ductility supplies of cast-in-situ and precast equivalent structures, and was based on a series of full-scale pseudodynamic tests. It was concluded that the ductility capacities of precast structures can be comparable to those of ordinary constructions.

Another research programme was aimed at investigating the global behaviour of single and multi-storey precast structures, and was based on pseudodynamic full-scale tests. The structural systems proved to be much more efficient than it was assumed in distributing the horizontal forces, as long as connections are adequately designed.

The design of connections and the contribution of connections to the global behaviour is the main focus of the recently activated research programme SAFECAST, funded by the European Commission. The experimental activities will be aimed at a deeper understanding of the behaviour of the roofing system in single-storey buildings and at the study of the dynamic response of precast multi-storey buildings.

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