RECENT COLLABORATIVE RESEARCH ACTIVITIES BETWEEN EUROPE AND CHINA ON THE SEISMIC BEHAVIOUR OF PRECAST STRUCTURES

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ABSTRACT :

With the support from both European Commission and Chinese Government, a series of collaborative research activities on the seismic behaviour of precast reinforced concrete structures have been carried out between the European Laboratory for Structural Assessment (ELSA), Joint Research Centre, European Commission, and the State Key Laboratory for Disaster Reduction in Civil Engineering (SKLDRCE), Tongji University, Shanghai, P.R. China. The seismic behaviour of this worldwide used structural system is discussed, based on the outcomes of the experimental activity. It is concluded that well-conceived and designed precast reinforced concrete structures have almost the same seismic capacities as the cast-in-situ reinforced concrete structures. The motivations for further ongoing activities are discussed.

KEYWORDS: Precast structures, testing, connections

1. 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.

ELSA and SKLDRCE have a long tradition of scientific collaboration on the subject of the seismic behaviour of precast structures.

ELSA, along with ASSOBETON, has been involved in the study of the seismic behaviour of precast structures elements since 1994 (Saisi and Toniolo, 1998). After the qualification of the seismic behaviour of single elements, a research programme aimed at demonstrating the equivalence between the behaviour factor of precast and cast-in-situ one-storey industrial buildings was launched. 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) participated to the project. Politecnico of Milan, the University of Ljubljana and two industrial precast producers were also involved in the research programme. 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 derived 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 producers 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 document reports 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 (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.
The main achievements of the above mentioned projects are described in the paper.

2. 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 this purpose, two prototypes, a precast one and a cast-in-place one, have been designed and built and submitted to a series of pseudodynamic tests to assess their seismic behaviour.

2.1. Description of the specimens

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 1.

Figure 1: 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.

2.2. Test set-up and testing procedure

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 2 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, may be probably called as a partial explanation for this (Dimova and Negro, 2005).

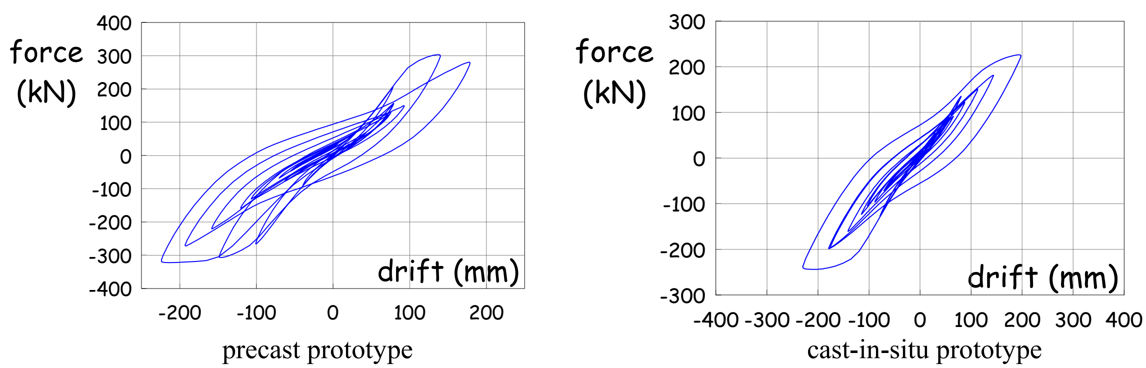


Figure 2: Force-displacement evolutions for a peak ground acceleration corresponding to 2/3 of the maximum

3. THE PRECAST STRUCTURES EC8 PROJECT

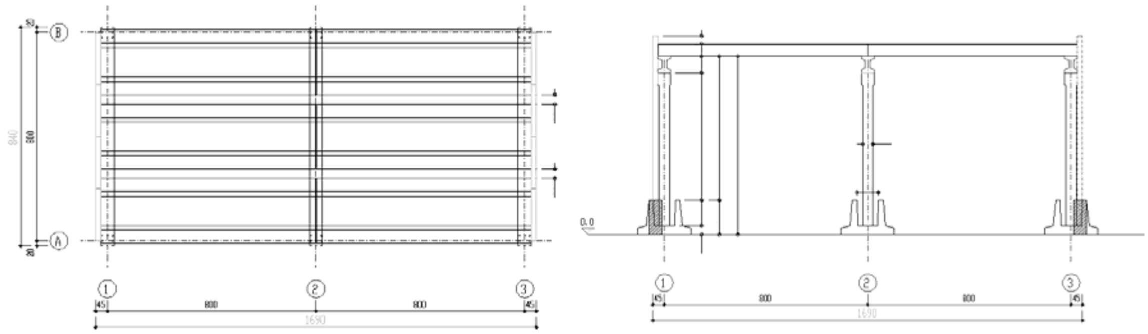
The co-normative research programme "Seismic behaviour of precast concrete structures with respect to EC8" (PRECAST STRUCTURES EC8) was aimed at assessing and possibly calibrating, by means of experimental and numerical investigation, the design rules provided by Eurocode 8 with reference to precast 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.
For logistical reasons, the work was distributed to four National Groups (Greek Group, Italian-Slovenian Group, Portuguese Group and Chinese Group) with the three competencies of production, testing and research. The main results obtained by the Italian-Slovenian and the Chinese Group are reported here.

3.1. Activities of the Italian-Slovenian Group: PsD tests on one storey industrial buildings

3.1.1 Description of the prototypes and input

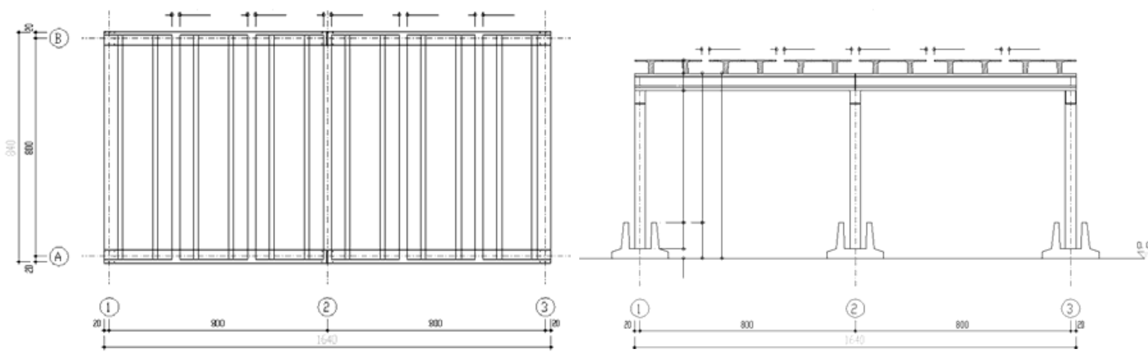
As the core activity of the Italian-Slovenian group, the design and construction of two full-scale structure prototypes were carried out. The prototypes have been designed according to EC8 in order to be submitted to pseudodynamic and cyclic tests. They consisted (figure 3) either of two beam spans-one 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 4).



plan view – roof level   front view

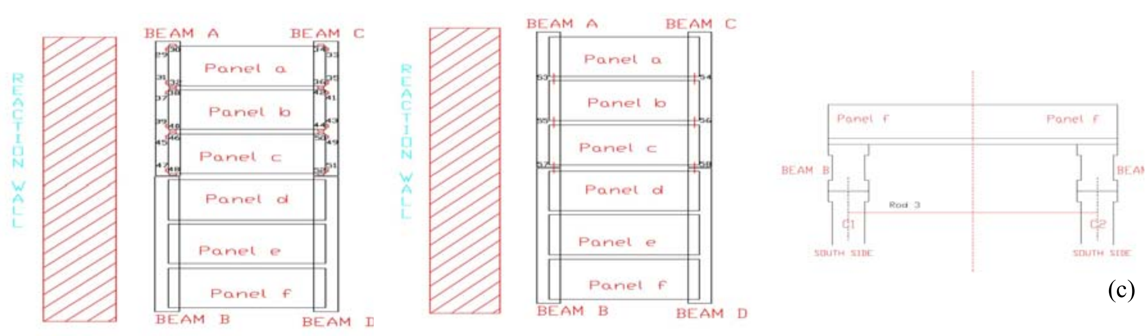
Prototype A with roof elements at a right angle to the earthquake



plan view – roof level   front view

Prototype B with roof elements parallel to the earthquake

Figure 3: Prototypes tested by the Italian-Slovenian Group



(a)   (b)   (c)

Figure 4: 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)

3.1.2 Test results

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 5), confirmed the adequacy of the proposed 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 confirmed that the “worst” roof element was the one closest to the edge frame, and was not negligible. 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.

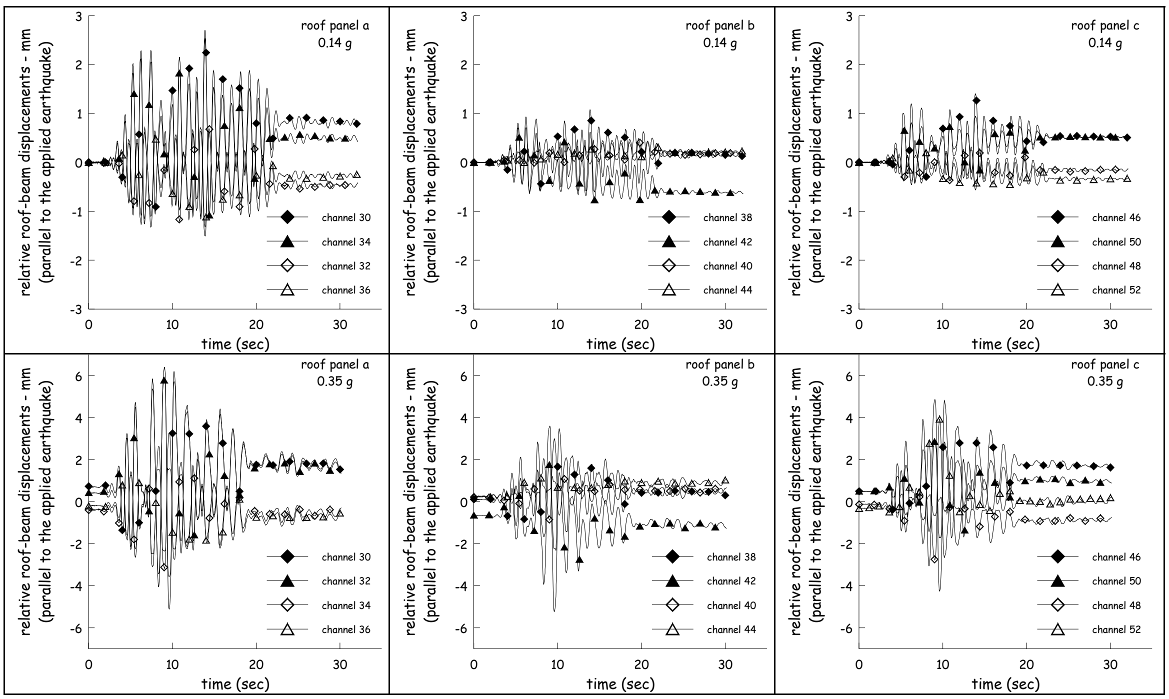


Figure 5: Relative roof-beam displacements in the direction of the earthquake

3.2. Activities of the Chinese Group: Shaking table test of Multi-storey Precast Reinforced Concrete Frame

3.2.1 Description of the test model and input

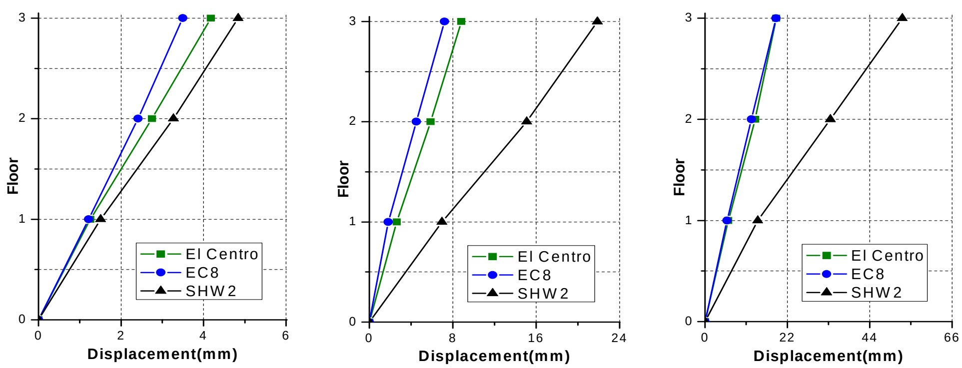
The shaking table test of the multi-storey precast concrete frame model was one important part of the research work in the framework of “Precast Structure-EC8” performed by Tongji University. Based on the full-scale two-bay-two-span-three-storey precast concrete frame prototype designed by the Italian-Slovenian Group, a reduced-scale specimen was designed. The design of the precast concrete frame model structure was carried out based on the similarity rules in order to effectively simulate the seismic behaviour of the prototype. The plane size of the prototype was 20m×20m, so the length similarity coefficient was fixed as 1/5 to make best use of the shaking table space. Following the connection design of the prototype structure, bolts were used for the connections of beams with columns and beams with slabs. Since there is no similarity rule for the connection design, and the performance of the bolt connection under earthquake action is not sufficiently known, the strength of bolts was checked for the extreme condition.

Figure 6: Construction process of the model structure and final prototype on the shaking table

The input table excitations were obtained by modifying the amplitude and duration of actual seismic waves according to the dynamic similarity coefficients. The amplitudes of input excitations were increased gradually during the test to simulate different intensities. El Centro, EC8 Semi-artificial Tolmezzo and SHW2 signals were chosen as the input earthquake waves. The semi-artificial Tolmezzo corresponds to the response spectrum of Subsoil type 1B in Eurocode 8, whereas SHW2 is an artificial seismic wave defined by the Shanghai local seismic design code. The whole test procedure was divided into 3 groups: frequent earthquake, reference earthquake and rare earthquake tests. In each test group, the El Centro, EC8 Tolmezzo, and SHW2 signals were applied in sequence.

3.2.2 Test results

The maximum storey drifts of the model structure are shown as figure 7. The main phenomena affecting the test results are summarized in table 1 and the typical final failure patterns for the connections are shown as figure 8.



(1) Frequent earthquake (2) Reference earthquake (3) Rare earthquake

Figure 7: Maximum storey drifts of the model structure

Table 1: Description of the test phenomena

Locations	*frequent earthquake*	*reference earthquake*	*rare earthquake*
Beam-column connections	Slight cracks in the erection joints. Bolts and angles in contact.	Cracks become clearer and wider. Bolts and angles in good conditions.	The width of cracks becomes larger. Bolts and angles in good conditions.
Beam-slab connections	Slight cracks in the erection joints. Bolts and angles in contact.	Cracks become clear. Crack number increases very fast. Bolts in good conditions.	Maximum width of cracks about 5mm. Bolts in good conditions.
Columns	No cracks	No cracks	Cracks close to the beam ends
Beams	No cracks	No cracks	Slight 45^0-inclined cracks on some flanks of beam ends.
Slabs	No cracks	No cracks	No cracks

Figure 8: Final failure patterns of the connections

4. 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 harmonizedly 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 17 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 5 enterprises (DLC srl, Truzzi Prefabbricati, 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 fruitful collaboration is foreseen with the Tongji University.
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. The tests will be carried out both on the one-storey typical industrial building and on the multi-storey one, since each of the two typologies brings about peculiar issues. With specific reference to multi-storey structures, the investigation will be extended to the interaction between cast-in-situ and precast structural parts. A scheme of the specimen, that will be tested with and without the cast-in-situ core, is reported in figure 9.

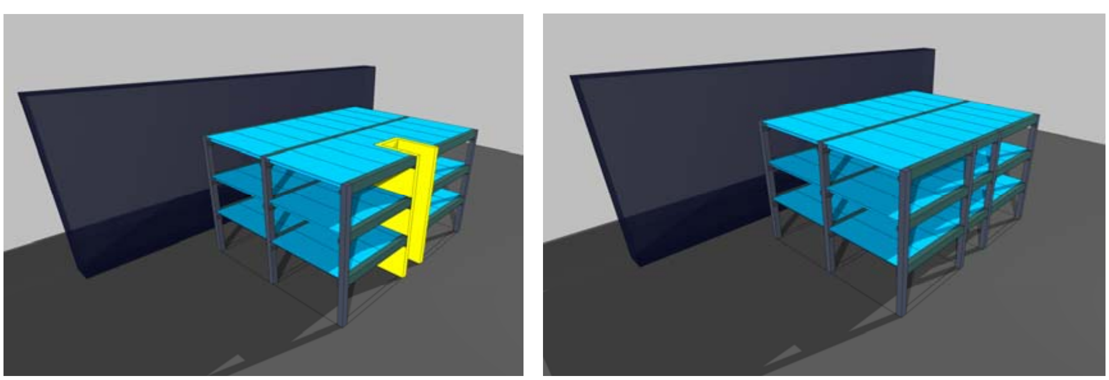


Figure 9: Scheme of the specimens to be tested

5. CONCLUSIONS

The motivations and means of execution of a series of research activities on the seismic behaviour of precast concrete structures, jointly conducted by the European and Chinese research groups, have been described.
A first 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 conducted at ELSA and at SKLDRCE. 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 conducted at ELSA and shaking-table tests conducted at SKLDRCE. 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, which will be conducted in close contact with the Tongji University.

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