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Pseudodynamic tests on a full-scale 3-storey precast concrete building: Global response

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ABSTRACT

In the framework of the SAFECAST Project, a full-scale three-storey precast building was subjected to a series of pseudodynamic (PsD) tests in the European Laboratory for Structural Assessment (ELSA). The mock-up was constructed in such a way that four different structural configurations could be investigated experimentally. Therefore, the behaviour of various parameters like the types of mechanical connections (traditional as well as innovative) and the presence or absence of shear walls along with the framed structure were investigated. The first PsD tests were conducted on a dual frame-wall precast system, where two precast shear wall units were connected to the mock up. The first test structure sustained the maximum earthquake for which it had been designed with small horizontal deformations. In the second layout, the shear walls were disconnected from the structure, to test the building in its most typical configuration, namely with hinged beam–column connections by means of dowel bars (shear connectors). This configuration was quite flexible and suffered large deformations under the design level earthquake. An innovative connection system, embedded in the precast elements, was then activated to create emulative beam–column connections in the last two structural configurations. In particular, in the third layout the connectors were restrained only at the top floor, whereas in the fourth layout the connection system was activated in all beam–column joints. The PsD test results showed that, when activated at all the floors, the proposed connection system is quite effective as a means of implementing dry precast (quasi) emulative moment-resisting frames.

1. Introduction and background

A collaborative three-year research project called SAFECAST was undertaken by European national associations of precast concrete producers, along with universities and research centres, to study the behaviour of precast concrete structures under earthquake loading. The main objective of the project was to fill the gap in the knowledge of seismic behaviour of precast concrete structures, with emphasis on the connections between precast members. A major part of the experimental phase of this programme consisted of the pseudodynamic tests on a full-scale 3-storey precast concrete building, carried out at the European Laboratory for Structural Assessment (ELSA), Joint Research Centre (JRC) of the European Commission in Ispra.

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 (the Italian association of precast producers) and the ELSA Laboratory of the Joint Research Centre 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 [1]. After the identification 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 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 was performed at the ELSA Laboratory. The results of the tests demonstrated the excellent capacity of precast buildings to withstand earthquakes without suffering important damage [2]. The data obtained within the two mentioned research projects provided the starting point for the PRECAST EC8 project [3]. This project was successfully carried out

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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 modelling of such precast buildings, was 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 [4–6]. 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 [7], the 1979 Montenegro earthquake [8] and the Northridge earthquake [9]. Failures of welded and poorly constructed connections were also the main cause of extensive collapses in Armenia [10] and during the 1976 Tangshan earthquake in China. These bad experiences have generated mistrust to precast systems in general. In some countries this practically preclude the use of precast structures 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 among precast concrete elements is addressed within the SAFECAST project. The major part of the experimental phase of this programme comprises the pseudodynamic tests on full-scale 3-storey precast concrete prototypes. The paper presents the global test results related to the overall pseudodynamic response of the prototypes.

2. Design of the prototype according to Eurocode 8

The prototype was designed with the aim of providing experimental validation about the seismic behaviour of multi-storey precast concrete buildings, through large-scale reference testing. The aim of this campaign was to provide proper experimental evidences about the seismic behaviour of precast multi-storey buildings with both hinged and moment-resisting beam-to-column connections. The building was representative of a large-scale three-storey building with a 7 m by 7 m structural grid with and without structural walls. Its portion that was (initially) selected to be tested had 2 by 3 spans/bays (14 by 21 m). However, the dynamic non-linear analyses conducted [11,12] revealed the possible effects of the higher vibration modes on this type of relatively-"flexible"-structure. In particular, the storey forces obtained from these analyses exceeded the force capacity of the available actuators in some of the floors. Thus, the prototype that was finally decided to be constructed and tested comprised a 2 by 2 spans/bays structure as presented in next section.

3. Test structures

3.1. The mock-up

The specimen structure was a three-storey full-scale precast residential building, with two 7 m bays in each horizontal direction as shown in Fig. 1a. The structure was 15×16.25 m in plan and had a height of 10.9 m (9.9 m above the foundation level) with floor-to-floor heights equal to 3.5 m, 3.2 m and 3.2 m for the 1st, 2nd and 3rd level, respectively. Whereas the storey height is typically larger in single-storey industrial or commercial precast buildings, those of the specimen well represent the typical configuration for a residential or office building in Europe.

The floor systems which were of high interest in this research, were carefully selected to gather the largest possible useful information. To accomplish this, three different pretopped floor systems were adopted. As shown in Fig. 1b and c, the 1st floor at 3.5 m was constructed with box-type elements put side by side and welded to each other; similarly the 2nd floor at 6.7 m comprised double-tee elements put side by side welded to each other; and finally the 3rd floor at 9.9 m was realized with the same box slab elements of the 1st floor, but spaced to simulate diaphragms with openings. Detailed description of the three floor systems and their connections is given in the companion paper by Bournas et al. [13].

The precast three-storey columns had a cross-section of 0.5×0.5 m (Fig. 2a) which was kept constant along their height and were embedded by 0.75 m into 1-m-deep 1.3×1.3 m in plan, pocket foundations (Fig. 2b). All the columns were constructed with wide capitals at the level of each floor, with widths of 0.90 m and 2.25 m in the loading and transverse direction, respectively (Fig. 2c), in order to allow for the mechanical beam-to-column connection, the details of which are presented in a companion paper. The capitals of the columns were designed as cantilevers fixed at the axis of the columns with flexure and shear reinforcement. Fig. 2d illustrates the erection phase of a column with capitals before its positioning into the pocket foundation.

The longitudinal beams connected to the columns' capitals were precast box-type hollow core elements, with a cross-section 0.4×2.25 m and a length of 6.38 m. The cross section and dimensions of a typical beam spanning in the direction of loading are illustrated in Fig. 3. Such type of beam has similar weight with respect to its equivalent inverted T or I-shaped beam in terms of stiffness but with clear economical advantages over it associated with the increase in the floor area.

As it can be seen in Fig. 1b, two 4.05-m-long $\times$ 9.6-m-tall $\times$ 0.25-m-thick ($4.05 \text{ m} \times 9.6 \text{ m} \times 250$ mm) precast concrete walls were connected to the mock-up in order to compose with the columns a dual frame-wall precast system. Each wall comprised three wall hollow-core precast elements 3.2-m-tall (Fig. 4a) which were joined among themselves by means of vertical reinforcement crossing their gaps at the level of each floor. Concrete was cast only at the two edge cores of the section, where the wall vertical reinforcement was concentrated in "boundary elements". The confinement of the concrete was also limited there (Fig. 4b and c). Thus, the wall's moment resistance was assigned to the "flanges" at the edges of its section and its shear resistance to the "web" in-between them. The nonlinear behaviour of such pre-fabricated walls was expected to differ from the one of normal cast in situ walls, however, this aspect was not considered in the research, since the walls were expected to suffer limited yielding during the test. The longitudinal reinforcement was lap-spliced at the mid-height of the second floor. The walls-to-foundation connection was realized through two pocket foundations in which only the walls' longitudinal reinforcement protruding from the pockets was anchored (Fig. 4d). The connection between the walls and the frame was conceived having in mind the need to easily disconnect the walls at the end of the first round of tests and consisted into over-reinforced blocks of concrete, with steel surfaces, placed at each storey and to be simply cut at the end. This arrangement was neither typical, nor code-compliant; however, in this case the objective was to study the behaviour of the frame as connected to a wall system, rather than studying the behaviour of the wall itself or the connection between the wall and the frame.

All precast elements (columns, walls, beams, slabs) were cast using the same concrete class, namely C45/55, which turned out to havea 28-day strength, measured on 150×150 mm cubes,