Description of the main S&T results

Literature survey and identification of needs

A literature survey both on the design procedures for precast structures followed by the European countries of the current consortium as well as on the connection typologies between precast members applied among these countries was carried out at the beginning of the project.
The survey "typologies of connections" had the purpose to study the different typologies of connections mostly used in the Countries involved in the project, in order to extrapolate the most common connections used and then study their seismic behavior. In order to do this many associations of precast producers and universities have been involved in presenting material regarding the most common connections used in their Countries so as to have a general view on the argument.
The purpose "General survey and design procedures" of the survey was to obtain a general vision of the typologies of systems existent all over the world and in particular in the Countries involved in SAFECAST project, in order to focus the points that need to be developed. In particular, special attention is given to the design procedure of precast concrete structures.

Experimental activity on new and existing connections

The main aim of this activity, was the experimental investigation of the seismic behaviour of existing, new and improved connections. Two types of tests on simple units, joints and subassemblies were carried out: (a) monotonic and cyclic tests in order to characterize their mechanical behaviour; (b) shaking table tests in order to investigate the effects of the dynamic excitation to their response and to evaluate the influence of the vertical component of the seismic action. The results of these tests were also used to calibrate the analytical models.
The behaviour of connections in real-size elements were tested by performing tests on subassemblies. These tests were performed in order to analyse possible effects of member's deformability, shear and pre-stressing on the behaviour of the connection and investigate the ductility of different typologies of connections. Monotonic and cyclic tests on adequate numbers of connections were carried out.

Floor-to-beam connections

Tests on single connections installed between two over-designed members under the main component of the expected action in the structural system have been performed. 3 types of steel mechanical dry connections between floor and beam members have been tested and characterized, starting from the classical hot rolled angle widely available on Italian precast market and developing two similar connections, improving steel type and shape for a better response to cyclic loads.
Monotonic and cyclic tests on subassemblies have been also performed. A great number of results have been collected, representing the pushover and the cyclic behaviour of each type of connection. Ductile and dissipating behaviours have been reported for the improved connections, while very stiff connectors showed a fragile rupture in the concrete members.
Considering the concrete "side", eight pull-out tests have been performed, investigating the influence of additional stirrups, fiber reinforcing and post-tensioned tendons on the pull-out resistance of a traditional double-tee concrete member. The different configurations aimed at investigating the possible contribution in terms of resistance or general behavior of such reinforcements.

Figure 1 - Floor-to-beam connections: local tests and tests on subassemblies

Column-to-foundation connections

The tests carried out to compare different connection systems: wet joints with expansive grouted mortar connecting the rebar protruding from the column and two industrialized mechanical connections with different improvements.

A total amount of ten tests on column-foundation connections were performed, as well as characterization tests on materials used in test set-up. The tests results were evaluated in terms of strength, ductility and dissipated energy, comparison of results obtained for each type of analysed connection was performed and the non linear moment-curvature diagrams were calculated. Cyclic tests were performed on full scale sub-assemblies to assess the hysteretic behaviour of the connections at large displacements.

Figure 2 - Tests set-up

Beam-to-column connections

The primary objective of the testing programme was the investigation of the behaviour of mechanical beam-to-column connections in precast building structures in pure shear, under monotonic and cyclic excitation. The typology concerns a dry pinned beam-to-column connection with one or two dowels. This type of connection represents a common solution in precast construction practice in S. Europe and elsewhere, mainly for single-storey industrial buildings.

The dowels were grouted in the beam side and fastened on top, while the beam sits on a rubber pad. In total, 20 experiments of this type were performed.

Four improvements of existing connections were investigated during the experimental course: (a): the increase in the distance *d* of the axis of the dowels from the edge of the beam, (b): the placement

of a steel fully anchored plate on the front of the beam, in front of the dowels, (c): .the use of fibre-reinforced concrete instead of normal concrete and (d): the increase of the strength of the grouting that fills the ducts of the dowels.
Based on the results of the experimental investigation, a new formula for the estimation of the resistance of pinned connections under cyclic loading was derived.

(a) (b) (c)

Figure 3 - (a) and (b) Damage observed at monotonic pull test 2D25-d15-PLL; (c) damage observed at the end of the cyclic test 2D25-d15-CY

Tests were also performed in order to obtain the strength and deformation capacity of such connections considering large relative rotations between the beam and the column. 16 experiments were planned and executed. The specimen was tested with the cyclic loading according to the prescribed protocol.
Additional, improved connections were also examined. The improvements have been made so that the connection could resist a certain amount of the bending moment. This was assured by connecting the beam and the column with the additional reinforcement bars.

Figure 4 - Test set-up

In order to evaluate the effect of the dynamic loads on the behaviour of the pinned beam-to-column joints, the results obtained during the shaking table tests that concern the joint response were compared to the corresponding results that were obtained from the corresponding cyclic tests on pure shear excitation. In general, the nonlinear response of the connections was similar to that for cyclic loading but the observed damage was different.

Wet beam-to-column connections

The specimens concerned beam-column joints of multistory buildings, in which the flanges of the T-beam were made of hollow core slabs topped with in situ poured concrete. In this way, beam-to-column connections, column-to-column connections and hollow core slab-to-beam connections were tested. Four ½ scale specimens for Industrial Type (IT) beam to column connections and four 1/1 scale specimens for Residential Type (RT) beam to column connections, totally eight specimens, were tested. Additionally, two more specimens of each type, in which proposed improvements from the manufacturers were implemented, were also tested.

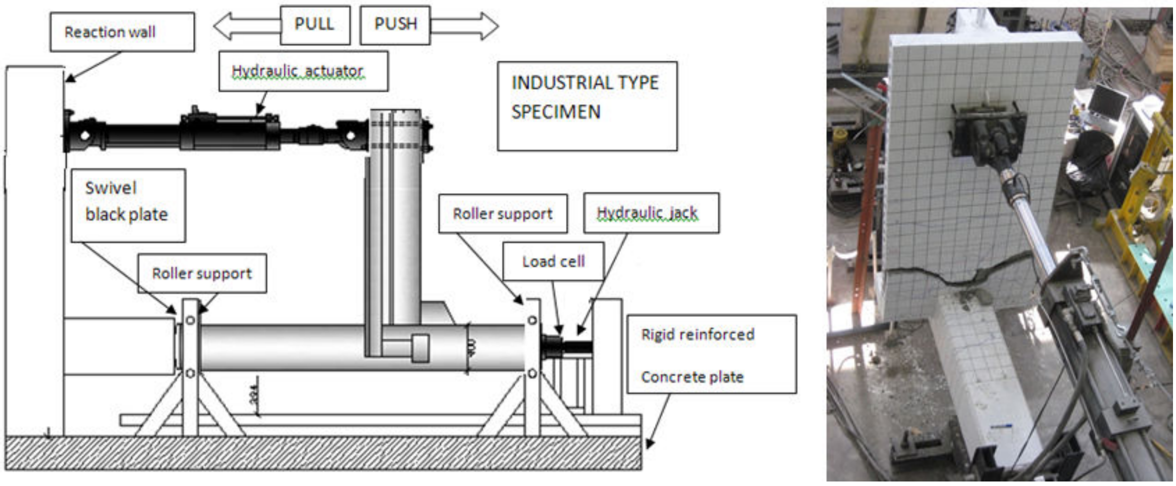

Figure 5 - General lay-out of testing set-up

Panel-to-column connections

A regular three dimensional frame structure, composed by four columns and four beams, was tested with horizontal cladding panels (three per wall) tied to the columns with connectors.

Two different panel configurations were experimentally studied. In the first one three cladding panels were placed only on one side of the frame structure, either North or South. This configuration intends to simulate the behavior of façade walls.

In the second panel configuration, where the same portal frame was used, two sets of three panels were placed on two sides of the mock-up, respectively South and East. This particular configuration simulates the behavior of a corner of a building.

These models were tested under two different input conditions: longitudinal motions, for testing out of plane behavior in the case of the first panel configuration, and longitudinal and transversal motions, in the second panel configuration for testing eventual corner interaction.

Figure 6 - General experimental set-up

Development of analytical models

The main aim of this activity was the development of analytical models for the seismic behaviour of the connections in precast systems. The proposed analytical models should be able to generalize the experimentally observed response of the tested elements to a whole range of realistic connections and to provide reliable information to define design procedures and tools needed in addition to the experimental results.

Since the goal of the SAFECAST project was very ambitious (seismic performance evaluation of a broad variety of different structural systems using very different /innovative/ connections applied in large scale prototypes of realistic structures) it was believed that such extensive task could be fulfilled only using macro-elements. Such elements could provide proper balance of practical applicability as well as reliability provided by their robustness.

However, macro-elements are by definition empirically calibrated. It is not realistic and feasible to perform adequate number of experiments to provide large enough empirical database. In addition to this a proper analysis of the complex behaviour of the connections is needed to define the proper components of the macro model. Therefore, in addition to the extensive experimental support, detailed FEM analyses were carried out to develop and calibrate the macro models.

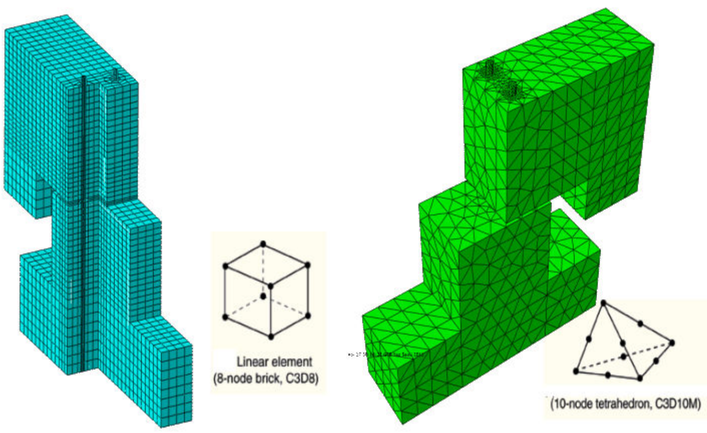

Figure 7 - Example of two FEM models

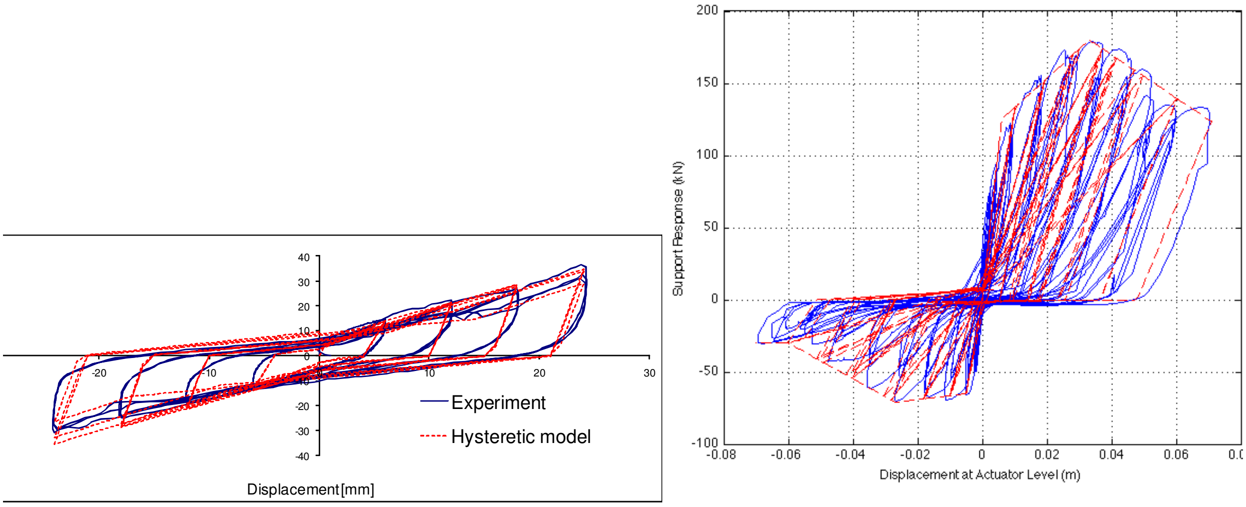

Figure 8 - Examples of the good match between experimental and numerical hysteresis loops

Very good agreement with the experimental results was obtained, even when the relative rotation between the beam and the column was large.

A complex FE model was able to demonstrate large hardening behaviour of the connection observed in the experiments which could not be modelled with a simple system of springs. It was demonstrated that the hardening behaviour is resulting from the eccentricity of the horizontal force which is causing the bending moment in the connection. Bending moment is transmitted by a contact pressure between the beam and the column and the tensile force in the dowel. Due to the bending moment (which resists the horizontal force) the “horizontal stiffness” of the connection is increased which is displayed as hardening of the force-displacement curve.

SAFECAST project is focused on the seismic behaviour of connections. Very little has been known and published regarding this topic. Therefore the design practice relies on “engineering feeling” and very crude approximations. Therefore all results regarding reliable and robust numerical models are quite important. However one result can be in particular classified as the breakthrough result. To our knowledge dowel connections have never been tested and analysed at large relative rotations. Yet this is a realistic and common situation during strong earthquakes when the columns yield. Therefore any realistic seismic analysis can not be done without the model considering this effect. In this study such (efficient) model was proposed for the first time.

Experimental assessment on real structures

The structure tested in the EC-DG JRC was a three-storey precast building in real scale. The structure had been defined by the consortium as to test, on a single mock-up, different structural typologies. For this reason it has been designed in a way that permits the structure to be tested in four different alternative configurations

Before the final design of the specimen, predictive analyses with simplified models of the structure were carried out in order to give a rough prediction of the expected behaviour of the structure, verifying the possibility to test the same mock-up in different configurations and making a first check of the feasibility of the test according to the limits imposed by the equipment available in the laboratory.

The continuous PsD method developed at the ELSA laboratory of the European Commission JRC was employed for testing the mock-up.

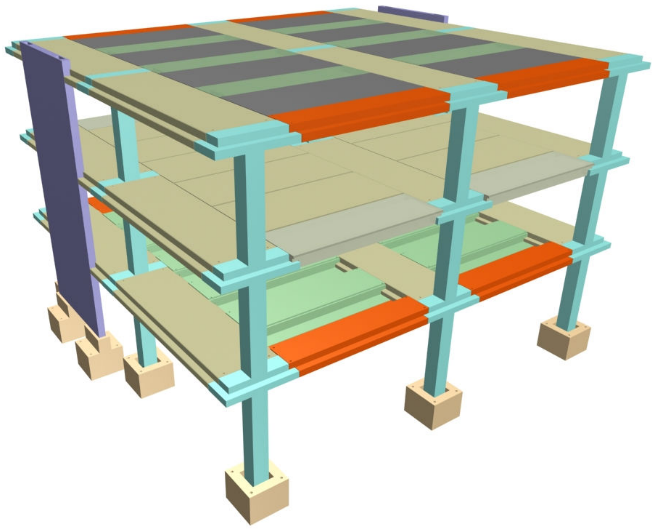

Figure 9 - Model of the prototype

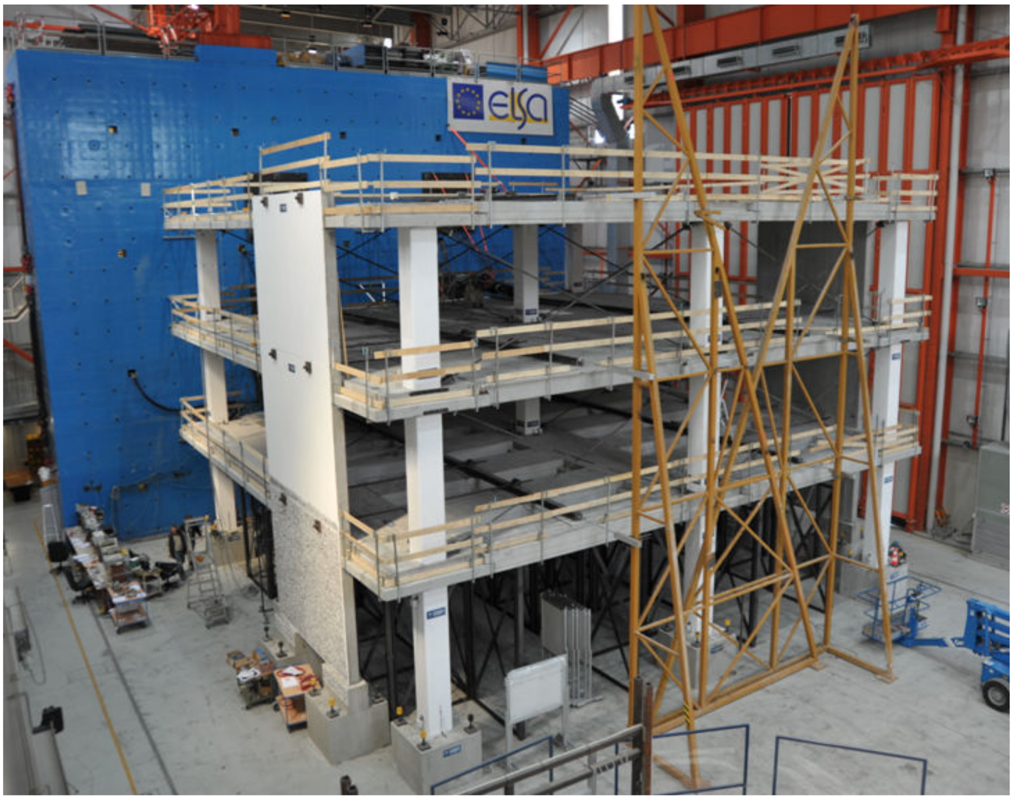

Figure 10 - General view of the experimental set up

The first configuration tested is a dual frame. Prototype 1 was PsD tested under two input motions scaled to a PGA of 0.15g and 0.30g. This dual wall-frame precast system was as expected stiff, with a fundamental natural vibration period of T= 0.30 sec for the 0.15g PGA. At the higher intensity earthquake, namely 0.30g PGA, the response curves were characterised by lower frequencies due to the partial loss of tension stiffening in the vertical precast elements cause by the 0.15g test. The first test structure sustained the maximum earthquake for which it had been designed (0.3 g peak ground acceleration) 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-to-column connections by means of dowel bars (shear connectors). Prototype 2 was also PsD tested under two input motions scaled to a PGA of

0.15g and 0.30g. This configuration, which represents the most common connection system in the construction practice of European countries, was quite flexible and suffered large deformations under the design level earthquake.
This much more flexible structural system, with a natural vibration period of 1.40 sec, led to lower inertia forces and higher storey drifts. The vibration of the structure is sensibly affected by the higher modes. The behavior of this structural configuration with hinged beam-to-column connections was in general satisfactory. Despite the limited stiffness of this structural configuration, Prototype 2 did not suffer significant damage in its structural members during the 0.30g PsD test.
The possibility of achieving emulative moment resisting frames by means of a new connection system with dry connections was investigated in the third and fourth structural configurations. With the target of providing continuity to the longitudinal reinforcement crossing the joint, an innovative connection system, embedded in the precast elements, was then activated by means of bolts connecting the steel devices in the column and beam. A special mortar was placed to fill the small gaps between beams and columns. In particular, the solution examined first was oriented to reduce flexibility of such structures with hinged beam-to-column joints by restraining just the last floor of multi-storey buildings; and thus, in the third layout (Prototypes 3) the connectors of the new connection system were restrained only at the third floor. Prototype 3 was PsD tested under the higher intensity input motion of 0.30g.
In the last fourth layout (Prototype 4) the mechanical connection system was activated in all beam-column joints with the aim of creating emulative moment-resisting frames. Prototype 4 was PsD tested under two input motions scaled to 0.30g and 0.45g.
Peak ground accelerations of 0.30g or 0.45g could be interpreted as the intensity for the no-collapse limit state of a high seismicity zone. However all these pseudodynamic tests did not lead to heavy damages. To approach the ultimate capacity of the structure, a final "funeral" sequence of cyclic tests has been performed, controlling the top displacement of the structure and constraining the floor forces to an inverted triangular distribution.

Table 1 Sequence of PsD and cyclic tests

Model \ Test	PGA of 0.15 g	PGA of 0.30 g	PGA of 0.45 g	Cyclic
Prototype 1	X	X	--	--
Prototype 2	X	X	--	--
Prototype 3	--	X	--	--
Prototype 4	--	X	X	X

An extensive monitoring activity was also carried out. A measurement was done to evaluate the shear stress acting an the joints using the connection dowels as traducers. The dowel has been instrumented with strain gauges. The measurement of shear stress upon junction dowels has been performed using the instrumented dowel. The first implementation was designed applying four full bridges into the dowels. This transducer should be first calibrated in laboratory applying a controlled shear deformation.
The time history measurement of pre-stress force in prestressed beams have been carried out using customized fiber optic deformation transducers based on FBG (Fiber Bragg Grating). This solution has been selected among others because in this case it is required to insert the sensors inside the concrete. The embedding process requires a very reliable sensor because of faults in the sensors can't

be fixed if embedded in concrete. FBG have good time stability and the selected devices are also temperature compensated from -40°C to +40°. The sensor is designed to be embedded in concrete and it has a mechanical support with two bolted disks . The FBG is protected by a thick plastic cylinder.
The long term monitoring started at the factory were the beam was manufactured after the casting, on 13/12/2010. The sensor vas mounted close to the tendons before casting and a first measurement was recorded . then after casting and the cutting of the tendons a second measurement was done .
After the beam has been delivered in JRC (Ispra), it has been mounted on two supports placed under its extremities. This boundary condition was the same of the previous one were the first measurement has been performed. The next measurement point took place on 10/03/2011 and the new relative deformation was -330 us , showing a precompression loss of 4% the same day the following four operations have been carried out:

- Cutting of the 4 upper sacrifice tendons
- Loading with distributed tanks filled with water until regaining the initial camber
- Temporary load test with concentrated weight in the central section
- Impulse load (jump) in the central section

The Long-term prestress loss has been monitored with others four measurements on 17/03/2011, 27/03/2011, 25/05/2011, 15/11/2011.

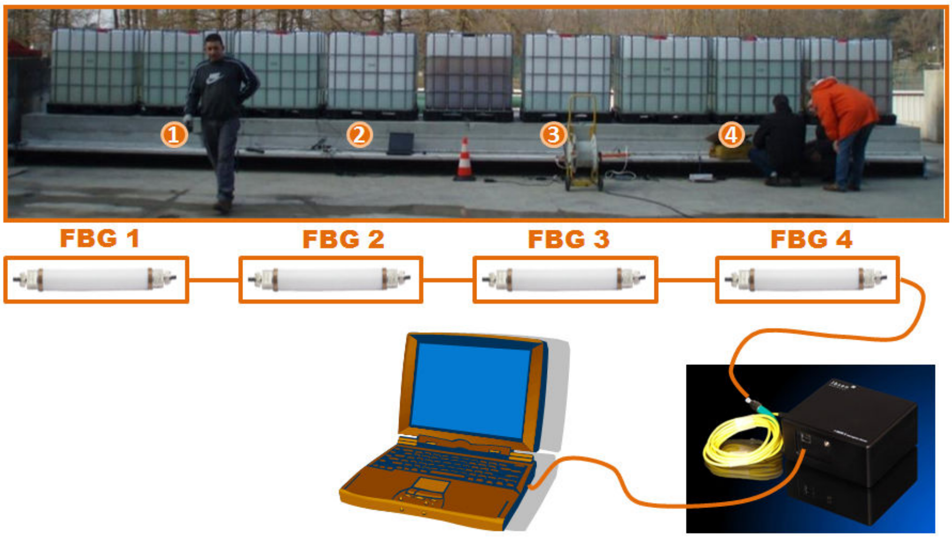

Figure 11 – Lay-out of the instrumentation system

<u>Numerical model validation</u>

The main goal of this activity was the seismic performance evaluation of a broad variety of different types of RC precast buildings with different types of innovative dissipative as well as no-dissipative connections. Beside different types of connections, which were quite poorly investigated in the past, precast buildings typically includes several structural elements that can have significant influence to the overall response, but in spite of that there is a substantial lack of data about their seismic response and importance to the overall safety of the RC precast structures.
It was believed that the most efficient way to perform the extensive parametric studies is to use macro-models. Based on the available results of experiments performed within the project, an appropriate macro-model for the different types of key connections has been proposed. The proposed model was also calibrated using more refined FEM analyses.
In line with the set objectives 3 computer codes were chosen: Open Sees, SAP2000 and ABAQUS.
OpenSees platform was selected due to its numerous distinctive advantages:

- It comprises a large set of the numerical models, starting from very simple 1D link elements to very sophisticated 3D finite elements, for which a very large variety of response types are available,
- The programme system is "open-source" software; which means that the programme source is fully available, free of charge and possible to modify and extend. It can be used free of charge unless it is used for commercial purposes.
- The platform has been developed and supported by the largest earthquake engineering network system in the world – NEES (the US Network for Earthquake Engineering Simulations)
- It was successfully used within the PRECAST EC8 project. Within this project several models for precast elements (precast columns with large shear-span ratios and for L steel angle connections) have been already incorporated.

For most of the analyzed connections the "Hysteretic" model (defined as uniaxial material Hysteretic in Opensees) was found to be the most appropriate. "Hysteretic" model was able to describe the strain hardening as well as the strength degradation between cycles of different amplitudes. It was also capable to model the distinctive asymmetric cyclic response of some of the connections (e.g. two eccentrically positioned dowels, which were used to connect columns and beams in the intermediate stories). Moreover, the great versatility of the model was demonstrated when it was successfully used to model the response where the energy dissipation was considerable, as well as the origin oriented response, where the energy dissipation was considerably smaller.
Since the OpenSees cannot be used for the commercial purposes, the appropriate numerical models of the connections were also calibrated in a typical commercial programme. The programme SAP 2000 was chosen because:

- It comprises a similar versatile type of the macro-element as OpenSees platform,
- SAP 2000 is widely spread among different design offices in the world, and was successfully used for the design of the most complex structures,
- It has been developed and supported by distinguish company, which constantly modernize and extend the programme, based on the recent theoretical achievements in various fields of the structural design.

The "Hysteretic" element, similar to "Hysteretic" material in OpenSees was used to model the response of connections in SAP 2000.

For each connection and for both programmes the input parameters were calibrated based on the experimental results. The envelopes of the hysteretic response as well as the individual hysteretic loops were compared. In some cases also the total amount of dissipated energy was checked. The match with the experiment depended on the type of the connections, but it was in general very good for all types of the connections. On average the energy dissipation differed not more than 5% (note that this comparison was not made for all connections). The visual inspection of all hysteretic loops also confirmed that the difference between the analytical and experimental results was small.

The robust macro-models (incorporated in the OpenSees and SAP 2000 programs) providing appropriate efficiency in the inelastic analyses of structures have been the first choice for the use in the design and assessment. Nevertheless the complex nature of the precast structures frequently calls for the use of more refined FEM models in the development work. This is in particularly true for the in-depth studies of structural details. For such purposes the models in the well-known ABAQUS program were studied and calibrated.

An extensive parametric study of the whole set of multi-storey structures with hinge beam-to-column connection was made. First, a survey was made to determine a range of multi-storey precast structures most frequently used in the Slovenian practice, which adequately represents the European practice in general. In addition to the systems most commonly used in the design practice also some limit examples (still tolerated by EC8 requirements, but less likely to occur in the real life) were included in the study to analyse the trends in the results as influenced by the key parameters. The structures were designed according to Eurocode 8 (DCM, ag = 1.2x0.3 g) considering all minimum requirements.

It was found that these structures, when designed according to DCM (by considering minimum reinforcement requirements), have large overstrength (in case of DCH the overstrength is typically even larger). This is due to the fact that these structures are very flexible. Due to the large flexibility, drift limitations and P-delta effects are decisive in the design. In order to increase the stiffness and reduce the damage, large column cross-sections have to be used. Large column cross-section combined with the minimum amount of reinforcement in columns (1%) lead to large column resistance and hence, large overstrength of the structures. The parametric study demonstrated that minimum reinforcement (1 %) is applicable to all columns in the analysed (regular) multi-story precast structures. In this aspect, the ductility design and the size of the behaviour factor are irrelevant. Therefore, some additional studies not considering the minimum requirements were made to analyse the (large) influence of the overstrength generated by these requirements.

The inelastic dynamic analyses revealed important problem regarding the amplifications of forces in multi-story cantilever structures (as multi-storey cantilever columns in precast structures with hinged beams). The actual shear forces and storey forces obtained from the inelastic dynamic analysis were much larger than those predicted by traditional design procedures (i.e. equivalent lateral force or modal response spectrum analysis). The storey forces are the seismic forces acting on the mass of a structure and are calculated as the difference between the total shear force above and below each floor. In precast structures storey forces are particularly important because they determine the design of the beam-to-column connections. The magnification of shear forces and story forces could cause shear failure both in the column and in the connections, seriously impairing or even destroying the energy dissipation capacity of the structure. Hence, the inelastic amplification of shear forces and storey forces was studied in detail for the whole set of multi-storey structures. The final objective was to propose the procedure and the equations for calculating the seismic (shear) demand in columns and the connections.

In the past, similar problem has been addressed with the reference to the RC (cantilever) walls. The amplification of shear forces at the base of the walls was mainly studied. It was demonstrated that the magnification occurs due to flexural overstrength, amplified effect of the higher modes, and period shift of the structure entering the inelastic range. Contrary to the RC walls, this problem in multi-storey precast columns has never been addressed yet. In particular the storey forces have never been discussed, related to any kind of a structural system. Consequently, there are no provisions for the design of precast columns and joints specified in the current version of the Eurocode 8. Therefore, a designer has no instructions how to apply capacity design principles in the case of the shear forces in the multi-storey columns and in particular seismic forces in the case of the design of connections. Therefore, important objective of this research was to investigate the magnification of shear forces and storey forces in multi-story precast structures, and to propose the magnification factors similar to those determined for the RC walls.

A specific procedure has been suggested.

A life cycle assessment has been carried out to provide an estimate of the environmental impacts of a commercial office building in Italy. The system studied the entire life cycle of the office building, including manufacturing of precast concrete elements, construction, use and dismantling phases.

Derivation of design rules

Within Work Package 6 the design rules regarding the connections that have been subjected to test have been collected.

The document refers to connections in precast frame systems, either for one-storey or multistory buildings. Large wall panel and three dimensional cell systems are not considered.

The types of connections described in this document are the following:

FLOOR-TO-FLOOR CONNECTIONS

- Cast-in-situ topping
- Cast-in-situ joints
- Welded steel connections
- Bolted steel connections

FLOOR-TO-BEAM CONNECTIONS

- Cast-in-situ joints
- Supports with steel angles
- Supports with steel shoes
- Welded supports
- Hybrid connections

BEAM-TO-COLUMN CONNECTIONS

- Cast-in-situ connections
- Connections with dowels
- Connections with mechanical couplers
- Hybrid connections

COLUMN-TO-FOUNDATION CONNECTIONS

- Pocket foundations
- Foundations with protruding bars
- Connections with bolted sockets
- Connections with bolted flanges
- Connections with mechanical couplers

CALCULATION OF ACTIONS

Furthermore, criteria regarding the calculation of actions for higher modes sensitive buildings such as the typical precast have been inserted, with particular reference to simplified tools for evaluating correct seismic storey and shear forces, critical for the definition of the design actions to which the connections and the members will be subjected and dangerously underestimated by the common present design approach.

The capacity design procedure has been addressed within the specificity of precast structures.

In the introduction it is stated that any type of connection shall be experimented with an initial type testing in order to quantify its strength and possibly the other properties that affect its seismic behaviour, from this experimentation a design model may be deducted, by means of which a verification by calculation can be applied on the different connections of the same type.

For a specific application one can refer to the available results of previous experimentations like those provided in the document clauses or in other reliable documents such as official regulations (Eurocodes, CEN product standards and Technical specifications, …).

A proper test protocol is suggested and collected in the Annex.