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THE INFLUENCE OF CLADDINGS ON THE SEISMIC RESPONSE OF PRECAST STRUCTURES: THE SAFECLADDING PROJECT

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ABSTRACT

The current design practice of precast buildings is based on a frame model where the peripheral cladding panels enter only as masses without any stiffness. The panels are then connected to the structure with fastenings dimensioned with a local calculation on the base of their mass for anchorage forces orthogonal to the plane of the panels.

This design approach does not work, as it was dramatically shown by several recent earthquakes, like L'Aquila in 2009, Grenada in 2011 and Emilia in 2012. New technological solutions for connectors with proper design approaches are therefore urgently required.

All those aspects are being investigated, by means of a balanced combination of experimental and analytical activity, within the research project SAFECLADDING. This research has received funding from the European Union's Seventh Framework Programme managed by REA-Research Executive Agency: http://ec.europa.eu/research/rea (FP7/2007-2013) under grant agreement n° FP7-SME-2012-314122 "SAFECLADDING.

The main contribution of this Research Project is to propose design solutions able to improve the safety of the people living or working in precast building structures in case of hazardous natural events such as earthquakes. The outcomes of the research are also meant to be directly reflected into normative documents, like EC8.

INTRODUCTION

The reinforced concrete precast constructions have been in use for more than half of the century and their seismic safety has been recognized as one of the most important issues. Surprisingly so, only limited research results related to seismic safety of precast structures are available, in particular in the field of efficient and reliable analytical models and tools. This situation can be partly explained by the fact that the predominant mechanisms of the seismic response of the connections in precast structures (i.e. dowel action, shear slip, interlock shear, gap opening and closing, shear-bending interaction) are very difficult to model. Moreover, diversity of structural and technological solutions makes generalisation of the research results even more difficult.

Caused by the slow development of new knowledge through limited research in comparison with the cast-in-situ systems, related standards for earthquake resistant design and construction of precast systems are still under development.

At present, even in the countries with the most developed earthquake engineering, codes in general regulated only the seismic design of the equivalent monolithic precast systems. The latest version of the European design standard, Eurocode 8 (EC8 - CEN, 2004), recognizes that precast

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structures could be designed with the energy dissipation capacity comparable to that of the cast-in-situ structures. EC8 incorporates capacity design for strong connections as well as non-emulative approach. However, without knowing the actual behaviour of the connections in the specific system and without having appropriate analytical and design tools, EC8 is impossible to apply.

Prof. M. Fardis, former chairman of the CEN Subcommittee for EC 8, in its document "Pre- and Co-Normative Research Needs for Eurocode 8" (Pinto et al., 2007) lists seismic rules for prestressed concrete elements and systems as one of the topics not- or partially- covered in the present version of EC8.

Even if the issue has been largely recognized as a crucial matter to be addressed, both by the industry sector and by the related research community, 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. Moreover, the above recalled complexity of the issues specifically related to precast constructions is reflected in the codification and normative approach to the matter lagging behind with respect to the needs of designers and producers for sound guidelines and prescriptions purposely conceived for precast structures.

As previously mentioned, design approaches codified in EC8 are mainly transposed from those conceived for cast-in-situ structures, based on the concepts of capacity design. Still, the inherent features of precast structural systems (i.e. non-monolithic connections) call for a thorough validation of the basic assumptions of said approaches, i.e., that joints have larger capacity than elements, or that dissipative joints, when devised in design, do possess the necessary ductility resources.

During the last years an extensive experimental and theoretical research activity has been carried out at European scale with the aim to investigate the seismic behaviour of precast structures. The attention has been addressed to frame systems for one-storey industrial buildings and multi-storey low-rise commercial buildings that have a very large diffusion in most European countries. The research campaign is still going on with a "co-normative" aim for next updating and revision of the same Eurocode.

An excellent outline of the research activity above mentioned can be found in Toniolo (2012). In the following paragraphs the main results of the SAFECAST project, ended at the beginning of 2012, are summarised. More details are reported about the on going SAFECLADDING project.

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 EU-funded project SAFECAST (contract FP7-SME-2007-2 Grant agreement n. 218417 (2009-2012)) was to give effective answers to this need of self-sufficient, harmonized solution of the problems of correct seismic design of joints and connections in precast structures.

The innovative aspect of the project was the unified performance-based perspective in which the problem of the characterization of the seismic behaviour of connections was dealt with. Such complex problem, in fact, needs to be dealt with in a unified performance-based framework, since when dimensioning and designing the system for an optimum performance under earthquake loading, all the other basic performance requirements, i.e. durability, deformability limits, energy dissipation…, are also to be taken into account and complied with.

The research was focused on the categories of mainly dry connections, consisting of mechanical devices, which is the most common type in modern precast buildings. The advantages of dry connections, in terms of quick erection, maintenance, re-use, make them even more appealing in an environmentally friendly, life-cycle performance oriented perspective.

Each category of connection among the different structural elements creating the structural body brings about peculiar issues to be investigated, in relation to their role and function in the structure itself: in view of this, the experimental and numerical activities devoted to each category of connections was concluded "package-by-package", each of them adding up knowledge to more ample themes.

Many of the key-aspects mentioned in the previous section were successfully addressed within the SAFECAST project.

An extensive experimental and numerical campaign was carried out within the project. Based on the gathered experimental data it was possible to define adequate numerical models. Different macro and FE models for commercial as well as research-oriented software were developed (e.g. Fischinger et al., 2012a and Karadogan et al. 2012). They were calibrated using the experimental results.

One important piece of result obtained within the SAFECAST project was the gathered knowledge about the response of multi-storey precast structures. The basis for this research was the PsD tests of multi-storey structures in 1:1 scale (see Fig. 1), performed at European Laboratory for Structural Assessment (ELSA) of the European Commission in Ispra (Negro et al., 2012). The results of these tests were in a good correlation with the results of the analytical studies (Fischinger et al., 2012b and Biondini et al., 2012). One of the main findings was that higher modes of vibration importantly influence the storey forces as well as the demand in joints (connections). The amplifications turn out to be very large because the response is dominated by the higher modes, whereas the energy dissipation is only associated to the first mode of vibration, the one which corresponds to the plastic hinges to form at the columns bases (Bournas and Negro, 2012). The results of the experiments performed in ELSA were used to calibrate numerical models. Using the developed numerical models extensive studies of the multi-storey buildings were performed (Fischinger et al. 2012b). As a final result a capacity design procedure for more accurate estimation of the shear and joint forces in multi-storey structures was proposed, taking into account all important parameters which affect the magnification of these forces.

Figure 1. Multi-storey building that was tested in ELSA laboratory

One of the most important outcomes of the project is the final document "Design Guidelines for Connections of Precast Structures under the Seismic Action" (Negro and Toniolo, 2012), which is the practical implementation of the knowledge gathered within the project. This guidelines include the directions and descriptions of proper design procedures for those types of precast structures and their connections, which were addressed within the SAFECAST project.

Among the beam-to-column joints studied, the pinned connection using steel dowels is the most commonly used in typical European industrial buildings. Possible failure mechanisms of these connections are two: (a) local failure characterized by the simultaneous yielding of the dowel and crushing of the surrounding concrete and (b) global failure, characterized by spalling of the concrete between the dowel and the edge of the column or the beam. Local failure mechanism normally occurs if the dowel is placed relatively far from the concrete edge. The global failure is more likely to occur if the dowel is placed closer to the edge of the column or the beam (e.g. about six diameters of the dowel or less), due to the spalling of the concrete between the dowel and the edge. When there are no stirrups in the region, this failure is brittle, since the capacity of the connection is governed by the tensile failure of the concrete between the dowel and the edge of the column or the beam. A new procedure for estimation of the strength, which explicitly takes into account the contribution of the stirrups in the critical region around the dowel, is proposed in Zoubek et al. (2014).

THE SAFECLADDING PROJECT

As mentioned in the previous paragraphs, the SAFECAST project was devoted to the study of the seismic behaviour of connections in precast buildings. The project started at the beginning of March 2009. Few days after, the area of L'Aquila, South of Italy, was shaken by an earthquake that caused a lot of damages and victims. A number of precast panels collapsed, underlining a weakness in the seismic behaviour of precast structures. Due to the dramatic potential effects of the collapse of precast panels, the SAFECLADDING project was drafted and submitted to the EU for possible funding. The proposal was accepted and the SAFECLADDING project (SAFECLADDING - Improved Fastening Systems of Cladding Wall Panels of Precast Buildings in Seismic Zones, Contract FP7-SME-2012 Grant agreement n. 314122 (2012-on going)) started officially in August 2012, just few months after the end of the SAFECAST project.

To understand the problem, it is important to remember that the latest version of EC8 recognizes that precast frame structures can be designed with an energy dissipation capacity comparable to that of the corresponding cast-in-situ structures. Based on this view, the current design practice of precast buildings is based on a bare frame model where the peripheral cladding panels enter only as masses without any stiffness. Furthermore some designers introduce only the mass of the walls orthogonal to the direction of the seismic action, assuming that the walls parallel to that direction provide by themselves for their resistance. The panels are then connected to the structure with fastenings dimensioned with a local calculation on the base of their mass for anchorage forces orthogonal to the plane of the panels.

This approach does not work, as it was dramatically shown by several recent earthquakes, like L'Aquila in 2009, Grenada in 2011 and Emilia in 2012. The panels, fixed in this way to the structure, come to be integral part of the resisting system conditioning its seismic response. The high stiffness of this resisting system leads to forces much higher than those calculated from the frame model. These forces are related to the global mass of the floors and are primarily directed in the plane of the walls.

Furthermore, the seismic force reduction in the type of precast structures of concern relies on energy dissipation in plastic hinges formed in the columns. Very large drifts of the columns are needed to activate this energy dissipation foreseen in design. However, the capacity of the connections between cladding and structure is typically exhausted well before such large drifts can develop. As a consequence, the design of these connections cannot rely on the seismic reduction factor used for design of the bare structure.

The unforeseen intensity and direction of the forces and the lower energy dissipation drove many fastenings to failure, leaving the frame of columns and beams practically undamaged. Fig. 2 shows an emblematic image: a building of recent construction in L'Aquila (Fig. 2a) of which the structure (columns, beams, roof elements) kept substantially their integrity; a whole wall of vertical panels, on the contrary, has collapsed. The same situation occurred in Grenada (Fig. 2b). The cause of the collapses is shown in Fig. 3: the fastenings of the panels failed under forces for which they were not designed.

The forces developed under the earthquake have been much higher than those calculated in the design stage on the base of a local behaviour. In fact, the wall system provides the construction with a stiffness much higher than that of the bare frame made of columns and beams represented in the model for structural analysis. The actual seismic response has been therefore characterised by a high acceleration that brought strong distortion forces on the fastenings in the plane of the walls.

Failures did not regard only channel bars but also other types of fastenings, as shown in Fig. 4. It has been not a question of product inadequacy, but of inadequate design of the connection. In fact the design followed the specific rules of the code, quantifying the forces with a local analysis on the base of the mass of the single panel considered as a non structural element. Actually the panels received much higher forces and in the direction not considered in design. This because their fixed connection to the structure made them integral part of the resisting structural system, taking it to a much higher stiffness. The design approach itself, as proposed by the codes, shall be improved in its principles and the new adequate specific solutions shall be proposed by the manufacturers.

a) b)

Figure 2. Collapsed wall panels in a) L'Aquila and b) Grenada

Figure 3. Details of the failure of the fastening system (made with anchor channels)

Figure 4. Failure of other types of fastenings

From the above considerations it is clear that the original design criterion, that leaves the walls to break since after their failure the remaining structure will resist anyway by itself, does not work when the failure implies the fall of panels up to 10 tons of weight. The mortal danger of these collapses requires a different approach. And this considerations hold true for all, precast and cast-in-situ concrete structures: the fall of a masonry large cladding wall represents an as much serious danger. New technological solutions for connectors with proper design approaches are therefore urgently required.

The SAFECLADDING project analyses the ways to improve the performance of existing buildings as well as new solutions proposed to tackle the above described issues.

The activity is going on under the coordination of the European Federation for Precast Concrete Industry, BIBM. All principal actors in the precast construction sector, including producers of precast elements and producers of fastening systems, are represented in the consortium. Each of the partners offers special assets to the consortium as a whole, making it possible to tackle the research needs chosen as the object of the project at the best foreseeable level. The number of Partners, 12 in total, is deemed ideal to provide a complete range of competences and resources at the same time allowing a relatively easy management and effective mutual communication and interaction. The extensive research effort planned in this proposal is distributed among 5 different RDT performers (Joint Research Centre - Elsa Laboratory, Politecnico di Milano, National Technical University of Athens, Istanbul Technical University, University of Ljubljana), according to their peculiar facilities and capabilities.

The presence of 2 SMEs (B.S. Italia innovative concrete connections and Yapi Merkezi Prefabrication) and of VBBF (Verein zur Förderung und Entwicklung der Befestigungs-, Bewehrungs- und Fassassentechnik e.V.) is meant to guarantee constant feedback on the results and their applicability and also a door open to issues and possible topics of interests for further research that might come along based on the findings of tests or analyses.

Provision of specific technological needs as inputs and dissemination of the results is vital in reaching project’s objectives. For these reasons, the 3 National associations (ASSOBETON – Italian National Italian Association of Precast Concrete Producers, TPCA - Turkish Precast Concrete Association and ANDECE - Asociación Nacional de la Industria del Prefabricado de Hormigón) and the European association of precast concrete producers will take care of the dissemination and exploitation activities.

The project analyses the ways to improve the performance of existing buildings as well as new solutions proposed to tackle the above described issues. The new proposals can be gathered according to three different approaches that constitute the Project Work Packages:

- <u>Isostatic arrangement</u>, the connection between frame structure and panels allow mutual displacements that satisfy the deformation demands of the frame, uncoupling it from the kinematic behaviour of the panels.
- <u>Integrated arrangement</u>, in this case the frame and panels are restrained and the displacement is coupled between the parts. The connections must be adequately overproportioned to bear the higher stress level requested.
- <u>Dissipative arrangement</u>, the joints between structure and panels – or among the panels – are designed to dissipate energy during the shock, in this way the overall building response can be balanced to reduce displacements keeping low loads in the connections.

The planned experimental activity consists of two kinds of tests:

- <u>Monotonic and cyclic tests on fastening devices and small subassemblies</u>. These tests are carried out in order to fully characterize the behaviour of mechanical connectors. The fundamental parameters affecting the response throughout the different ranges, from elastic to plastic and up to failure, are directly measured or derived by appropriate post-tests data treatment. The basic parameters, such as strength, energy dissipation capacity, deformability, ductility, are thus experimentally quantified.
- <u>Pseudodynamic tests on full-scale prototypes of complete structures</u>. This part of the activity is meant to provide experimental validation on the effectiveness of the numerical models for structural analysis implemented on the basis of the information on the behaviour of single connections, as derived from the previous experimental phase. Also, 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 are foreseen to be carried out on one-storey precast buildings with cladding wall panels.

The investigation focuses on:

- the effectiveness of fastening systems in terms of strength and ductility;
- the effectiveness of the diaphragm action;
- the redistribution of seismic forces between walls and frame system.

During the pseudodynamic tests both global and local behaviour of the structures will be also monitored. The investigation of real failure mechanisms developing in full-scale mock-ups, monitored throughout the different ranges of the response, from the elastic to the fully nonlinear one, will allow a thorough review of capacity design concepts for complex precast structures to be carried out and a quantification of the effects of the interaction among the different structural parts to be provided.

The behaviour of existing connections

The seismic behaviour of the existing cladding panel connections, which are typical for European industrial buildings, is far from being clarified, particularly in the plane of the cladding panels. Some of these connections that are typically used in the practice were experimentally investigated. Three typical cladding-to-structure connections were analysed (Fig. 5): (a) sliding connection with hammer-head strap, (b) angle connection, and (c) cantilever connection. In this way the connections of vertical as well as horizontal panels were addressed. Before the experiments there was no data available at all about their seismic response. Thus, the most of performed tests were cyclic. To be able to compare the cyclic and monotonic response, a limited number of monotonic tests was also performed. One of the main outcomes of these investigations was the identification of the main phases of the response, which are summarized in Fig. 6. It was observed that the strength of the sliding connections, subjected to the cyclic load was considerably smaller than that registered and expected under the monotonic load. Response of these connections in the vertical direction was predominantly sliding. Angle and cantilever connections responded in a different manner than the sliding connections, and their strength under the cyclic load was considerably larger, particularly that of the cantilever connections. A summary of this experimental campaign is reported in Isakovic et al. (2014).

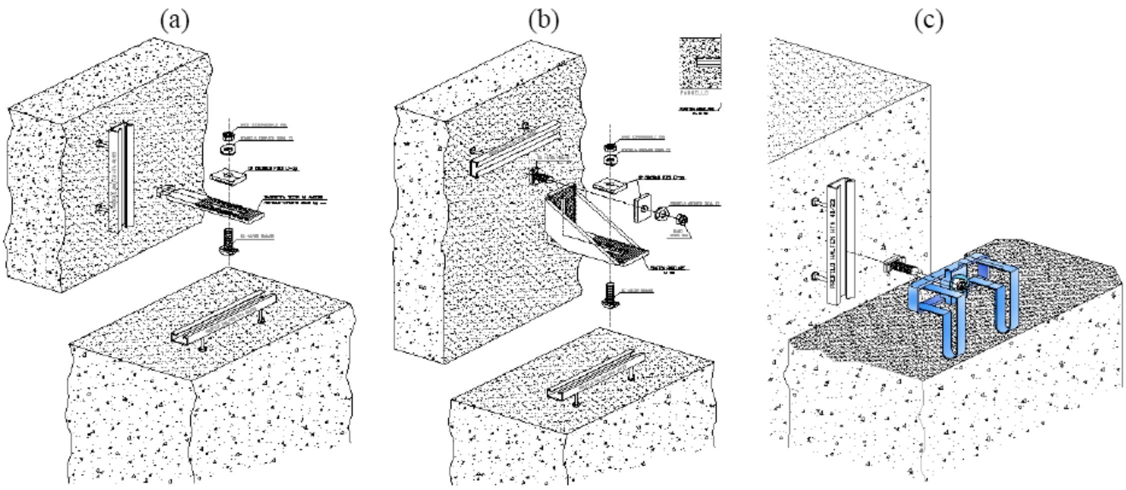


Figure 5. Typical panels' connections: a) sliding connection, b) angle connection, c) cantilever connection

Isostatic configuration

The "isostatic" configuration is based on wall panels connected to the structure with supports that allow the free development of the large displacements expected for the frame structure under seismic action. This solution maintains the traditional design approach of the analysis applied to a bare frame model.

Different panel-to-structure connection systems can ensure an isostatic arrangement of the panel. The systems analysed within the SAFECLADDING project are reported in Fig. 6 for vertical and horizontal panels.

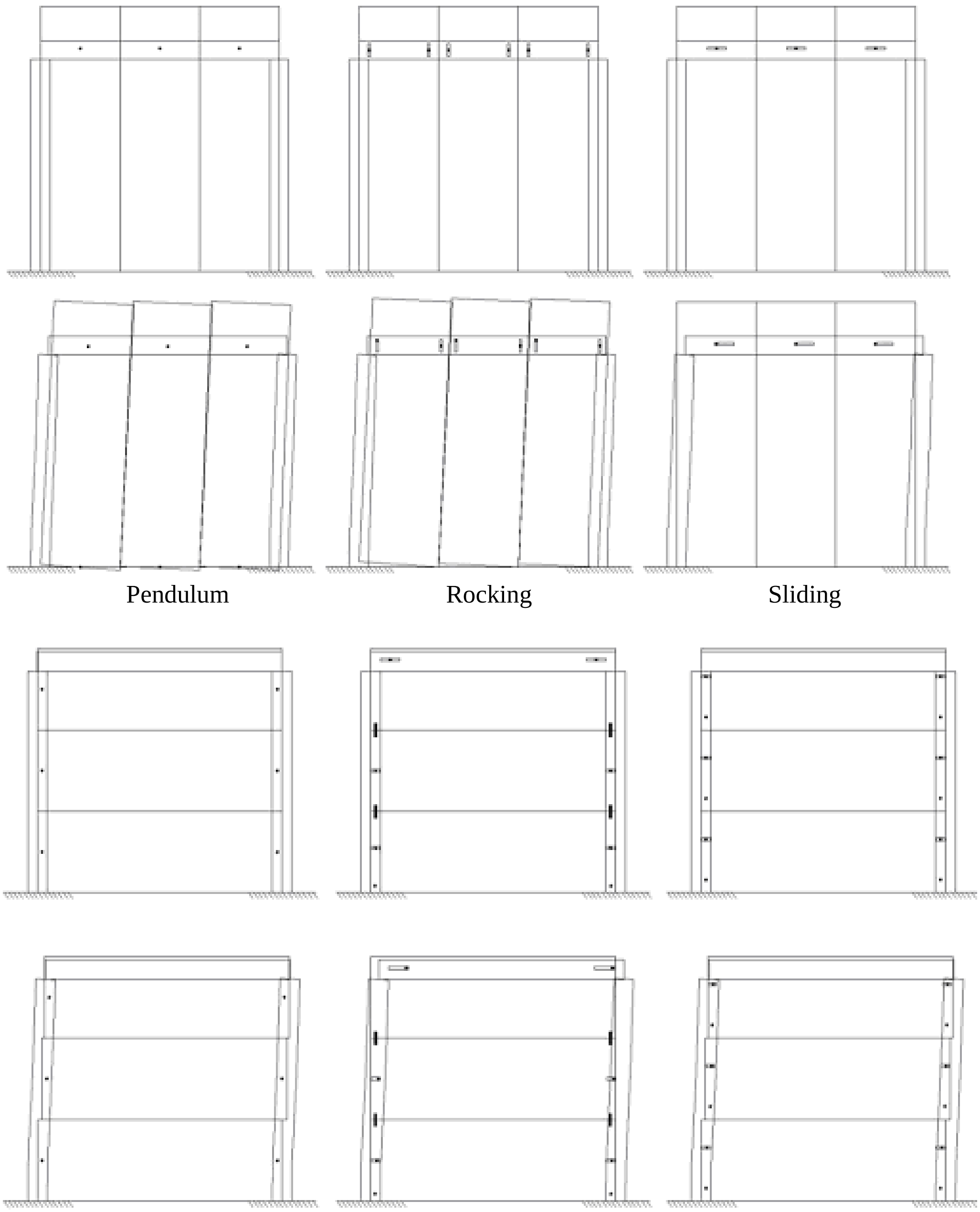


Figure 6. Possible isostatic configurations for vertical and horizontal panels

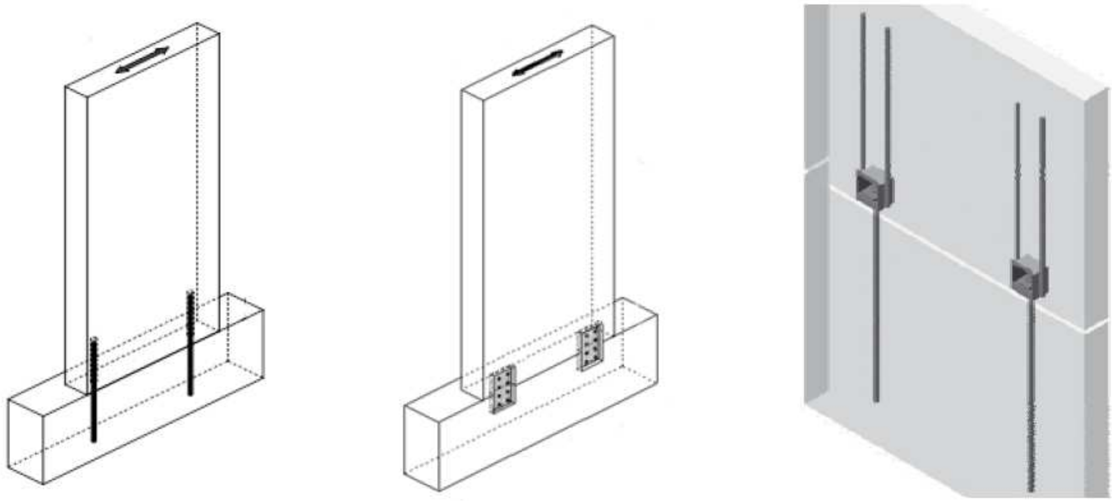
Integrated arrangement

Part of the investigation carried out within the SAFECLADDING project concerns fixed panel connections, also referred as “integrated” connections, which are designed to restrict large relative displacements and capable to sustain the large forces developed. In the integrated systems, the panel connections are based on a hyperstatic arrangement of the fixed supports of each panel and, thus, the panels are part of the earthquake load bearing system. Simplified structural calculations show that the seismic forces induced to the connections of the panels can be quite large for typical structures. An experimental and numerical investigation on the monotonic and cyclic behaviour of ‘fixed’ connections has been planned within the project.

The experimental campaign concerns a series of tests on panels connected to beams with fixed connections. Three types of connections are examined, namely:

- ‘Rebar’ connections (Fig. 7a) made of reinforcement bars which protrude from the beam into the panel or vice versa;
- ‘Steel plate’ connections (Fig. 7b) in which the connection of the panel to the beam is achieved using a steel plate;
- Industrially manufactured connecting mechanisms, as the wall shoes shown in Fig. 7c.

The experimental campaign is still ongoing. Results concerning one of the studied solutions (the ‘rebar’ type of connections, i.e. connections materialised with vertical reinforcement bars) are reported in Psycharis et al. (2014).



a) b) c)

Figure 7. Connection types considered in the experiments: (a) ‘rebar’ connections; (b) ‘steel plate’ connections; (c) industrial wall shoes.

Dissipative arrangement

Among the different envisaged solutions to frame the design of precast buildings including the contribution of the cladding panels, additional dissipative devices can implement a statically determined panel connection arrangement, allowing to smartly exploit the resistance and stiffness of the traditional massive peripheral wall panels. Several dissipative devices aimed to improve the behaviour of precast buildings under lateral load excitation through the control of forces and displacements have been analysed within the project (Fig. 8). Those connections consist in simple low cost devices, based on friction or plasticity, engineered in order to be inserted between vertical or horizontal panels. A summary of this experimental campaign is reported in Biondini et al. (2014).

a) b) c) d)

Figure 8. Tested systems: Friction based connection (a) and multiple slit devices (b, c and d)

The full scale tests

The SAFECLADDING project intends to test the proposed solutions on single connections or in sub-assemblies as well as on a full-scale building prototype. For the case of full-scale tests, the experiment, the mock-up and the test sequence were planned to assess the most common claddings using the same frame structure in different tests. Façade configurations with horizontal and vertical panels were selected as the most common in the European industrial buildings.

The mock-up is a single-storey building, 8.1 m high with three bays of 8.0 m and a nave 8.0 m width. The frame is made by square columns, 400 mm side, which bear roof beams and slabs with masses similar to a common construction for this typology. The mock-up is shown in Fig. 9 in two different steps of the construction.

The experimental programme, at present on going, foresees a huge number of tests in both vertical and horizontal panels configurations. In details: 9 test setups, after changes in the connections, are tested, whereas for horizontal panels 7 tests setups are experimentally analysed. The panels in vertical configuration are tested with different kinds of connection: isostatic, dissipative and over resisting (integrate arrangement) using both pendulum and rocking restraints. The horizontal arrangement, besides the aforementioned connections types, assesses the most common types of assembly for this façade, including strip windows.

The Project includes both Quasi Static (QS) and Pseudodynamic (PsD) Tests and investigates also the effects caused by the sealant (silicone) between panels and the new types of mechanical joints developed by project partners. The work being conducted during the experimental campaign on the full-scale prototype held by ELSA is reported in Negro et al. (2014) together with a preliminary evaluation of these results.

Figure 9. Two different steps of the construction of the mock-up

Expected results of the project

The main contribution of this Research Project is to propose design solutions able to improve the safety of the people living or working in precast building structures in case of hazardous natural event such as earthquakes.

The outcomes of the research are also meant to be directly reflected into normative documents: the aim of assessing and improving the design approach currently codified in EC8 for cladding panels in precast structures, as for the specific issues of joint design, will be pursued; the codification of specific design rules for precast joint design and the possible experimental and numerical validation of innovative dissipative joints (currently allowed but not specified in EC8) are a direct interest of the precast industry, testified by the vivid expressions of interest of many Associations and SMEs of the sector in joining the consortium.

All results obtained will be presented in the form of two design guidelines. In the first document, titled *Desıgn Guıdelınes for Wall Panel Connectıons*, design equations for all studied configurations will be provided. The second document, *Desıgn Guıdelınes for Precast Structures wıth Claddıng Panels*, will refer to the methods of structural analysis to be applied for the seismic design of precast structures of either single-storey and multi-storey buildings, with special attention devoted to the proper representation of cladding panels within the model of the resisting system. Specific indications will be given about the level of refinement required for the models used in the analysis of the different solutions.

Both documents will have public access.

CONCLUSIONS

For many types of buildings it is common design practice to base the structural analysis on the bare frame made of columns, beams, floors, and roof, considering the peripheral cladding panels as masses without any rigidity. Following such an analysis, the frame elements are designed in terms of strength, ductility and deformations, while the cladding panels are connected to the structure with fixed fastenings dimensioned only for local actions.

Experiences in recent earthquakes have shown that this practice needs to be improved. In fact, in general it led to good seismic behaviour of the structures themselves, but the failure of connections and the collapse of heavy cladding panels with severe danger to human life. If the structural analysis is based on the bare frame, the connections of the cladding system must be designed to effectively allow the large displacements calculated from the analysis. If the cladding panels are fixed to the structure, they must be included with their stiffness as an integral part of the structural system in the analysis; the design including the design of the connections must then be based on the results of such analysis.

Design rules for both panel connection systems and for structures as a whole are badly missing. Aim of the SAFECLADDING Project is to provide design guidelines for both problems.

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