Executive Summary:
Buildings in seismic areas shall provide a sufficient level of safety to people and, as much as possible, provide resilience to extreme events in order to guarantee a quick recovery of the functionalities of the pre-event situation. Frame structures made of precast concrete provide the required level of safety when correctly designed (e.g. following Eurocode 8 provisions). As proven in several recent violent shakes, like
L'Aquila in 2009 and Lorca in 2011, the main issue was linked to the frame-to-panel connections. 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. However, this design approach does not work. The panels, fixed in this way to the structure, come to be an 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. Therefore, the design of these connections cannot rely on the seismic reduction factor used for design of the bare structure. The project SAFECLADDING aimed at further investigating this phenomenon in order to improve the safety of people and the resilience of buildings. Tests, studies and numerical analysis have been carried out to explore new connection solutions (isostatic, integrated and dissipative) and to provide a feasible strategy for the reinforcement of those existing structures which might be unsafe today. Additionally, design rules both for the study of the seismic behavior of the frame+panel structure and for the design of the new connections have been provided.

With respect to the overall arrangement of connections and to the relative degree of interaction between cladding panel and the main structure, four solutions were identified and specifically treated. The first is a solution with the connections currently used in the design practice. It is considered that these connections in the existing buildings are frequently under proportioned. Some of such systems, in case of small seismic demand and/or structures with large over-strength and stiffness, can provide sufficiently safe design solutions. Therefore suitable design methodology, which is able to identify when the current systems can be safely used, is provided in the design guidelines drafted as a part of the project. It can be used for the design of the new structures and also, in the modified version, for the evaluation of the existing ones. Since the deformation threshold and the interacting mechanism are highly uncertain, the use of backup devices is always strongly recommended both for existing and new buildings.

The second is an isostatic arrangement of panel connections able to allow without reactions the large displacements expected for the frame structure under earthquake conditions. Very large displacement capacities are required for connectors with this choice, so P-delta effects should be taken into account in design. In addition to the ordinary output data used for the verification of member resistance at ultimate limit state, the sliding or rotation displacements shall be provided for the verification of the pertinent capacities of panel connection devices. The third is a hyperstatic arrangement of fixed connections that integrates the panels in the resistant structural assembly with a dual wall-frame system behaviour. Very high forces may arise in the connections with this choice. The forth is an arrangement of dissipative connections between the panels added to an isostatic system of fastenings to the structure, able to keep displacements and forces within lower predetermined limits.

The main result of the project was the drafting of design guidelines. Two documents were prepared: one refers to the design of the connection, the second to the design of the whole structure. The information reported into these documents are based on an extensive numerical campaign. A huge number of tests have been also carried out. The full experimental characterisation of the behaviour of existing and new connections has been performed.

Project Context and Objectives:
The latest version of the European design standard, Eurocode 8, recognizes that precast frame structures can be designed with the 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 violent shakes. 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, typically the capacity of the connections between cladding and structure is exhausted well before such large drifts can develop. Therefore 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 cladding fastenings to failure, leaving the frame of columns and beams practically undamaged.

It is clear that the original design criterion, that leaves the walls to brake 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 was focused on the investigation of the seismic behaviour of precast cladding wall systems in precast buildings. Scope of the project was to provide, to the participating associations of enterprises, the knowledge of the actual behaviour of connectors and the availability of appropriate analytical and design tools. Starting point of the project were the results obtained in three previous EC-funded projects:
- SAFECAST, contract FP7-SME-2007-2 Grant agreement n. 218417 (2009-2012)

to which many of the partners of the proposed consortium have taken part.

Different design solutions were identified at the beginning of the project. These solutions, called isostatic, integrated and secured, where then deeply investigated and modified till the definition of the four solutions (existing, isostatic, integrated, dissipative) for which specific design guidelines were derived at the end of the project.

Scope of SAFECLADDING was the clarification of the seismic behaviour of precast structures with cladding wall panels and the development of design aids and rules for a correct dimensioning of the fastening systems to guarantee good performance of the whole structural system throughout its service life. The final outcome of the project was expected to consist of methods and tools for the seismic design of precast systems with cladding wall panels and of their fastening systems, achieved by means of a balanced combination of experimental and analytical activity. In addition to this, significant resources were allocated to dissemination and training activities, since it is a vital need for precast producers to rapidly upgrade the know-how of their staff and to improve the level of quality and
performance of their solutions. The role of associations in reaching a great number of small and medium sized enterprises was a great added value.

Project Results:
Methods and tools for the seismic design of precast systems with cladding wall panels and of their fastening systems, were derived by means of a balanced combination of experimental and analytical activity.

The experimental activity consisted of three kind of tests:
1. Monotonic and cyclic tests on fastening devices and small subassemblies. These tests were 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, were directly measured or derived by appropriate post-tests data treatment. The basic parameters, such as strength, energy dissipation capacity, deformability, ductility, were thus experimentally quantified.
2. Shaking table tests performed to study the dynamic behaviour of panel connections. This were done using a one-bay frame on which horizontal or vertical panels were fastened with various types of connections and tested under extreme dynamic loading.
3. Pseudodynamic tests on full-scale prototypes of complete structures. This part of the activity was 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 was 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 were foreseen to be carried out on one-storey precast buildings with cladding wall panels. Tests were performed in different structural configurations for both horizontal and vertical panels.

During the pseudodynamic tests both global and local behaviour of the structures were 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, allowed a thorough review of capacity design concepts for complex precast structures and a quantification of the effects of the interaction among the different structural parts.

The numerical activity planned within the project was devoted to:
- the development of analytical models for seismic behaviour of the mechanical connectors in precast construction systems;
- the definition of procedures and tools for a proper design of the precast structures with cladding wall panels;

With respect to the overall arrangement of connections and to the relative degree of interaction between cladding panel and the main structure, four solutions were identified and specifically treated within the SAFECLADDING project.

Each solution has been deeply analysed. Technical solutions for the connection of panels to the structure were proposed together with their full characterisation and appropriate design rules for both the connections and the whole structures.

For the case of existing buildings a full mechanical characterisation and design equations was provided for the following existing systems:
- Hammer-head strap connection. These connections consist of two steel channels which are mounted in a beam (or column) and a panel and a hammer head strap which is fastened to the channel
mounted in the beam (or column) by means of a single bolt. Hammer head strap connections could be provided with channels of different strength. Principally, two different types of channels should be recognized: a) strong channel – when loaded in shear, the connection fails due to the failure of the strap; b) weak channel – when loaded in shear, the connection fails due to the failure of the channel.

- Cantilever box connection. These connections consist of a vertical channel, which is mounted in the columns and a special steel element which is mounted in the panel. The two components are then connected by means of a single bolt.

- Steel angle connections. These connections consist of two steel channels which are mounted in a beam (or column) and a panel and a steel angle which is fastened to the channels by means of bolts. A little invasive technique of intervention on existing buildings to prevent the fall of wall panels under earthquake conditions consists of short slack cables connecting the panel to the main structural element. This solution can be used only for a quick upgrading of existing buildings in order to ensure their operativeness for a (short) transitory period. Design equations for the evaluation of the force demand on the restrainers were proposed.

A new solution to be added to the original connectors in order to strengthen the connections of horizontal panels has also been proposed. It is based on the use of a steel angle properly shaped. The isostatic solution is based on the current design practice. There is no interaction between panels and structure. For this solution different structural configurations, to be used in seismic areas, has been identified. They are: 1) the cantilever solution; 2) the pendulum solution; 3) the rocking solution. For each of them the type of connections to be used has been identified. For each of them design equations have been derived.

In the integrated system the connections of each panel are arranged with a hyperstatic set of fixed supports. With this arrangement of connections the panels participate to the seismic response of the structure within a dual wall-frame system which has a much higher stiffness and a lower energy dissipation capacity compared to a pure frame and this leads to a structural seismic response with higher forces and lower displacements. The panel connections shall be proportioned by consequence, not with a local calculation based on the mass of the single panel, but from the analysis of the overall structural assembly with its global mass. The adoption of an integrated system has also some side effects such as those of a strong engagement of the floor diaphragm action necessary to take the inertia forces of the floors to the lateral resisting walls.

Three types of fixed connecting mechanisms are treated:

- Connections with protruding bars. This type of connections can be executed using steel bars (e.g: reinforcement rebars) protruding from the panels into the beams or vice versa. In both cases, waiting corrugated sleeves are provided in the opposite element for the insertion of the bars. These sleeves are filled with high strength, non-shrinking fluid mortar after erection.

- Connections with wall shoes. There are several companies in the market that produce this type of devices, usually called “wall shoes” and used to connect wall panels to beams or to other wall panels.

- Connections with bolted plates. This type of connections can be executed using steel plates that are connected to waiting nests fixed to the supporting beam and to the panel by an adequate number of bolts. The steel nests are embedded in the concrete and welded to reinforcing rebars so that the connection forces are gradually transferred to the concrete.

Between the two extreme solutions of isostatic systems, with their large displacement demand, and integrated systems, with their high force demand, the dissipative systems of cladding connections offer an intermediate solution able to keep displacements and forces within predetermined limits. The following
devices has been studied within the project:
- Friction devices. The friction devices considered in this project are made of two steel T shape parts that are fixed with a symmetrical set of bolted fasteners to the adjacent panels in special recesses and coupled with two lateral bolted steel plates. The length of the slotted holes made in the web of the T shape profiles gives the limit to the reciprocal slide between the parts. The tightening torque given to the bolts, controlled by dynamometric wrench, activates the friction between the plates determining the slip shear force. Two brass sheets are interposed between the steel plates and the profiles to ensure the stability of the repeated slide cycles. A centered limited longitudinal shear is transmitted through this device. The installation of the device described above requires the access from both the side of the panel. If the access is possible only from one side, the two T shape profiles are replaced by as many L shape profiles. In a set of several panels the chain of production and positioning tolerances can lead to relevant linear and angular deviations between the adjacent parts of the connection. This requires a three-dimensional system of slotted holes of adequate length to match the bolts with the corresponding threaded bushes inserted in the panels.
- Multi-slit devices. The multi-slit devices considered in this project have a composition similar to the friction devices. The two lateral solid steel plates used in the latter devices are replaced by as many lateral plates, with slits of various shapes and sizes, fixed to the adjacent T shape or L shape profiles. The slits isolate a number of slender strips and in this way move the shear behaviour of the solid plates to a flexural diffused behaviour of the single strips which is suitable for energy dissipation.
- Steel cushions. The steel cushions here considered are made of a flattened ring-shape plate that is fixed with central fasteners to the adjacent panels in special recesses. They can be utilized wherever multi-slit and friction devices are used. They can transmit longitudinal shear forces Vz when they are used between the panels.

In particular, the huge amount of numerical and experimental data derived allowed:
- the full mechanical characterisation of existing connection systems
- the development and the consequent full characterisation of restrainers
- the derivation of design guidelines for existing connections and for restrainers
- the derivation of design guidelines for buildings with existing systems
- the full mechanical characterisation of sliding connection systems
- the identification of structural configuration for isostatic solutions
- the derivation of design guidelines for buildings in isostatic configuration
- the full mechanical characterisation of integrated connection systems
- the derivation of design guidelines for buildings in integrated configuration
- the full mechanical characterisation of dissipative connection systems
- the derivation of design guidelines for buildings in dissipative configuration

The research activity was organised in 6 different WPs described in the following. WP1: Executive Summary

Task 1.1 Survey of existing systems
An overview of typical connections, which are usually used to attach cladding panels to the structural system of precast buildings in Italy, Slovenia, Greece and Turkey was made. The overview of the existing systems of panels’ connections is provided within Deliverable 1.1.

Task 1.2 Investigation of seismic risk of existing systems for the identification of seismic deficiencies
The aim of Task 1.2 was to perform experimental and analytical studies of typical connections joining cladding panels and structural elements in existing precast buildings in order to define the suitable macro
numerical models, which can be used in risk studies, and to define the appropriate design guidelines. This work was performed in three phases: 1) The typical connections were selected based on the survey, described in Task 1.1. They were experimentally investigated. Based on the experimental investigations the basic mechanisms of the seismic response of typical connections were explained for the first time; 2) Analytical studies with refined micro finite element models were performed using programme ABAQUS in order to generalize the results of experiments and to validate the observations regarding the basic mechanisms of the response of analysed connections; 3) Based on research performed in the first two steps, suitable macro models of connections were defined and the risk studies were conducted. Finally, detailed design guidelines for typical existing connections of cladding panels and the main structural system of precast buildings were provided, taking into account the results of overall research, performed within Task 1.2. Results of all studies, performed within Task 1.2 are presented in Deliverable 1.2. The design guidelines are provided within appropriate deliverable of WP 6.

Task 1.3 Conceptual design and analysis of second line back-up measures and retrofit techniques
The aim of task 1.3 was to improve the response of cladding panels using simple back-up devices, which can prevent the fall of the panels as well as the improved techniques of retrofitting. Appropriate experiments were performed and appropriate analytical models were proposed. Re-strainers were designed taking into account quite limited distance between cladding panels and structural elements. Traditional ropes manufactured using steel as well as innovative types of ropes manufactured from high-performance synthetic materials were studied. Different types of their terminations were analysed. Because the designed systems were completely new (including steel re-strainers), and have never been applied in precast structures, both experimental and analytical studies were performed. Based on the experiments the capacity properties (strength, stiffness) of re-strainers were determined and appropriate engineering numerical models were defined. The extensive parametric risk study of large sample of typical one-story precast buildings with re-strainers was performed. Based on these analyses the seismic demand on re-strainers was estimated. These studies were the basis for derivation of simple preliminary design procedures, which can be used in the design practice for estimation of the seismic demand on re-strainers. Results of these studies performed within Task 1.3 were presented in Deliverable 1.3.

Task 1.4 Previous Projects’ Findings
An overview of the previous projects’ findings was performed. It was provided in Deliverable 1.4 which is organized in two parts: The first part includes an overview of the previous projects, performed by the partners participating in the SAFECLADDING project, which were funded by the European Commission. The second part is an overview of the research activities related to the façade panels and their connections to the bearing structure in different countries all over the world. It includes: a) cladding systems that are typically used in buildings with frame structural systems b) conventional architectural panels, c) dissipative connections, and d) integrated systems of wall panels and bearing structure.

WP2: Executive Summary
The aim of WP2 is to design and check by testing on local samples panel-to-structure types of connections able to allow free large displacements as those shown by precast frame structures for industrial buildings under seismic action. Both analytical and experimental investigation was performed to this end. In the rigorous analytical investigation performed, typical one, two and three-bay one-storey industrial buildings with isostatic arrangement of vertical panels were analysed. The analyses were then extended to one-storey structures
with horizontal panels and to multi-storey structures with hinged and semi-rigid beam-column connections.

Three types of roof diaphragm were considered in all analysed buildings except multi-storey structures: null (columns arranged in different longitudinal axis can move independently in the longitudinal direction), deformable (in between the null and rigid diaphragm), and rigid (columns arranged in different longitudinal axis have the same displacements in longitudinal as well as transverse direction – their connection is infinitely rigid).

Two types of analyses have been performed: modal analysis and nonlinear response history analysis. First type of analysis has been performed to check the basic dynamic properties of the tested structures. The second type of analysis has been performed to estimate the response of the building under three seismic intensities: 0.18g, 0.36g, and 0.60g.

Since only the basic geometry of the panels was agreed, panels have been modelled with standard elastic beam-column elements without any limitations of strength. There has been no interaction between individual panels taken into account. The strength of the panel connections was also considered as unlimited.

Specific comments have been drafted with reference to each configuration.

A large experimental campaign was also scheduled and performed. The tests envisaged within WP2 regard the characterization of the mechanical properties of different connection devices through particular, local and sub-assembly tests. The scheduled tests have been completed both on single devices and on sub-assembly structural arrangements.

A series of tests was dedicated to a special sliding connection. It is a mechanical system conceived to provide a sliding support between wall panels and precast frame structures. The product has two different versions, one for vertical and one for horizontal panels. The experimental investigation was aimed to verify the free slide capacity of the connection under the combined longitudinal and orthogonal seismic actions, measuring the unintended longitudinal reaction forces produced by friction under the contemporary orthogonal inertia forces of the panel. Because of its complexity, not all the complete fixture of the connection was tested, but only the coupling of the threaded fastener with the channel bar.

In the version for vertical panels the sliding motion occurs under the contemporary presence of an orthogonal force due to the seismic out-of-plane force from the panel acting axially with respect to the threaded fastener, producing through friction a longitudinal reaction force. Therefore the fastener was subjected to the combined action of shear and axial tension. In the version for horizontal panels the sliding motion occurs under the contemporary out-of-plane force from the panel acting orthogonally with respect to the threaded fastener and so this latter was subjected to biaxial shear. The tests quantified, together with the verification of the slide capacity of the connection, the friction factor of the fastener-bar coupling that leads to the unintended forces reacting to the motion. Six series of tests were performed (three for each type of connection) with increasing out-of-plane forces.

Specific tests were performed to study the role of sealant. Silicone sealant is unavoidable in between precast cladding panels for a large number of reasons. It is engineered in order to resist large shear deformations without breaking, but its influence in terms of resistance and interference with the lateral load resisting structural system is has never been taken into account. Local testing of silicone sealant were widely performed, calibrated the test setup for the experimental programme. A relatively large number of tests were then performed to study the phenomenon, including specimens with strips of silicone of different length and thickness tested with different load velocities. A commonly used silicone sealant has been considered. Both monotonic and cyclic tests were performed.
The isostatic configuration can be obtained applying different structural configurations. They are realized using sliding connection devices with adequate capacities or pinned connectors for free rotations. At present the isostatic systems described below are of easy application with a sufficient reliability in seismic areas.

- Cantilever solution with base supports as protruding bars, bolted shoes or bolted plates and upper side with sliding connections.
- Pendulum solution with a traditional rotating device at the base and a shear key at the upper side.
- Rocking solution with the panel base simply seated on the supporting element and a shear key at the upper side.

WP3: Executive Summary

The aim of WP3 was to design and check by testing on local samples panel-to-structure new and existing types of connections able to transmit high forces, as those that develop in precast dual wall-frame industrial and residential buildings under seismic action. In the so called “integrated wall system”, the panel connections are based on a hyperstatic arrangement of the fixed supports of each panel.

Both analytical and experimental investigation was performed to this end. In the rigorous analytical investigation performed within tasks 3.1 and 3.3 two types of buildings were examined: (a) one-storey industrial buildings comprising of one bay / two bays / three bays with three roof configurations, namely: rigid roof diaphragm, deformable diaphragm and null diaphragm; (b) three-storey residential building. Nonlinear time history analyses were performed using the modified Tolmezzo (1976) record for three intensities: 0.16 g, 0.36 g and 0.60 g. In all cases, the cladding walls consisted of vertical panels connected to the beams with four connections (two at the top and two at the bottom) or three connections (two fixed at the bottom and two vertically sliding at the top –equivalent to one pinned connection) each.

The numerical model consisted of beam elements which represent the columns, the beams, the roof elements and the panels. Each panel was modelled with 5 elastic beam elements, in which the panel-to-beam connections were modelled with hinges, while inelastic zero-length rotational springs were considered to model the overall response of the connections. For the determination of the Moment-Rotation law that governs the behaviour of these springs, a finite element analysis was performed. In this analysis, the properties of the numerical model were calibrated against the results of experiments conducted at NTUA in the framework of task 3.2.

In addition to non-linear static (pushover) analyses performed in each case examined, 216 nonlinear time history analyses for the single-storey industrial building and 12 for the three-storey residential building were performed at NTUA and 12 nonlinear time history analyses for the single-storey industrial building with integrated panels were performed at UL. These analyses revealed the features of the dynamic response of buildings with integrated panels.

The experimental investigation (task 3.2) was performed at NTUA and concerned the behaviour of integrated connections under static (monotonic and cyclic) and seismic (shaking table) loading. In total, 11 static tests and 4 shaking table tests were performed. Three types of connections were investigated, namely: “Rebar connections”, industrial “wall shoe” connections and “Steel plate connections”.

In static, monotonic and cyclic, tests, the horizontal loading was applied at the top of the panel using a hydraulic jack fastened to the reaction wall. For cyclic loading, the protocol proposed in FEMA 461 was applied. In the shaking table tests, the application of the force at the top of the panel was achieved through a specially designed steel frame connected to the wall panel with a pinned connection.
The steel structure consisted of four steel columns and horizontal beams and aimed at supporting the 8 t additional mass (total top mass was equal to 10.3 t) and transferring the inertia forces to the panel. In order to guarantee that the horizontal load would be undertaken solely by the panel, both ends of the columns were hinged.

The results obtained from the experimental campaign can be summarized as follows:

- The envelope of the cyclic response follows satisfactorily the monotonic response.
- For large deformations, permanent opening of the panel – beam joint was observed, leading to pinching for all connections during the cyclic and the dynamic response.
- The shaking table tests showed that the overall dynamic behaviour follows the cyclic response for the corresponding maximum displacements.
- The attained ductility of rebar connections and wall shoe connections was satisfactory. Steel plate connections do not possess any ductility, since the bolts suffer brittle failure (shear failure).
- The maximum force that can be attained is proportional to the cross section of the rebars / bolts used in the connections.

Card files with details for each test and the presentation of the obtained experimental data were prepared for each experiment.

WP4: Executive Summary

The objective of WP4 is the design and check by testing on samples of panel-to-structure and panel-to-panel new types of connections able to dissipate energy and controlling in the meantime the level of forces and displacements in dual wall-frame precast structures under seismic action. To this purpose, numerical and experimental activities have been carried out by Politecnico di Milano and Istanbul Technical University.

In order to verify the actual influence of cladding panels on the seismic behaviour of precast buildings with different shapes, a wide parametric investigation has been performed by means of numerical analyses on several structural assemblies representing the most common typologies of precast buildings. Dynamic non-linear analyses have been performed with reference to both serviceability and no-collapse limit state, showing how selected cladding panel dissipative connection systems may dramatically reduce the overall structural displacement and damage under controlled forces, highlighting the role of the diaphragm action on the seismic response of the structure.

Experimental activity has been performed at both POLIMI concerning the mechanical characterisation of Friction Based Devices (FBD), Multiple Slit Devices (MSD) and Folded Plate Devices (FPD) and ITU concerning Steel Cushion Devices (SCD), also filled with several materials so to improve their behaviour.

The Friction Based Device is made by three elements assembled through bolts, namely steel support profiles, brass sheets and steel cover plates. The connection can be pre-assembled by mounting two support profiles, two brass sheets and two cover plates with bolts, nuts and washers without tightening, placed in position and then tightened, or assembled with each component at a time. The former solution eases the assemblage from one side only. A large experimental campaign with local cyclic tests on single devices, aimed at verifying the influence of several technological details on the behaviour of the connection, has been carried out.

Multiple Slit Devices are steel plates with slits of various shapes and sizes, where a set of elementary beams are formed by making linear laser cuts. The slits allow to move the stiff shear behaviour of the compact square or rectangular plate to a flexural type, which is more suitable for energy dissipation and allows to reach larger displacements, concentrating the dissipating zones in certain areas. Profiles with different elementary beam geometries have been designed and tested within local tests on single device,
from constant depth single or double row beams to optimised hourglass profiles. Local pushover and cyclic tests have been performed.

A single pilot cyclic test has been also carried out on a combined MSD-FBD specimen, suggesting that the combination of friction and plastic mechanisms may lead to a much larger displacement with respect to what attained by the MSD alone, increased by the friction slide.

Folded Plate Devices are steel plates bent at 90° in correspondence of three sections, so to have an asymmetric W shape. They are conceived to be installed in between precast horizontal panels and concrete columns. The folded plate offers a certain degree of resistance and stiffness both for the panel and column relative horizontal in-plane and out-of-plane displacements, much reduced with respect to more traditional connections such as stiff angle profiles. The maximum drift that the device can attain depends on the ductility of the device and is limited to the net distance between the column side and the orthogonal-to-panel plate portion. The behaviour of the connections is symmetric only for low displacements, while for large deformations a second order effect it tends to arise. 11 local cyclic tests have been carried out on this connection.

Large experimental campaigns were performed in the Structural and Earthquake Laboratory of Istanbul Technical University on the new low-cost energy dissipative cushions, which were made of mild steel, with different thickness. A complete set of quasi-static uniaxial and bi-directional local tests were conducted on the steel cushions with different thickness to investigate the uniaxial and biaxial behavior of steel cushions. Steel cushions made of mild steel can be used at different locations such as, between adjacent cladding panels, in beam to cladding panel connections and cladding panel to foundation connections. In this project at the ITU laboratory a total number of 70 tests have been carried out on the empty specimens with the thickness of 3, 5 and 8mm and on the infilled steel specimens with the thickness of only 8 mm using Cord, FRP, Neoprene and Steel infilling materials.

Cladding panel structural sub-assembly tests have been performed at both POLIMI with panel-to-panel FBD and MSD connections and ITU with panel-to-panel, panel-to-foundation and panel-to-beam SCD connections. Both institutions designed and built steel articulated frames transmitting horizontal load and displacement to two-panel assemblies. The results confirm the mechanical behaviour from the local tests, highlighting the importance of the cladding panel system deformation properties and the correct functioning of all connections.

WP5: Executive Summary

The primary purpose of the WP5 was the experimental assessment of the systems of panel and connections, studied within the Consortium. The task 5.2 – Pseudodynamic and cyclic tests, was entrusted to the European Laboratory for Structural Assessment (ELSA), with the contribution of the other participants. The aim of this activity was: the checking of hypotheses, the detecting of potential issues and the proposing of solutions to overcome them, if necessary.

The experimental campaign has comprehended two main arrangements of panels: vertical and horizontal, for a total of 37 tests, performed using both Cyclic Push-Over and Pseudo Dynamic loading histories. Finally, a “funeral” test was carried out on the bare frame only.

The experimental results are collected and presented with a brief description of the results gathered. Finally a dynamic non-linear analyses, performed at Politecnico di Milano, demonstrates a good agreement between the numeric model and the experimental results.

The results obtained from the experimental campaign can be summarised as follows:

- local problems in the devices, as clearance and friction, can lead the structure to malfunctioning or to failure;
• it is necessary to assume a large discrepancy between the functioning of the connections in the qualification tests and within the structure.

Looking the analysed solutions in detail some observation can be done.

Isostatic Systems

Current connections do not allow a clear separation between the frame and the panels for large displacements. This could potentially cause problems. The existing connections act as isostatics for low seismicity levels, but the identification of this threshold was not studied into this WP. A qualification test in realistic conditions is necessary to develop and check new kind of connections.

Dissipative Systems

Dissipative connections seem to be an effective option to reduce displacements keeping the loads low. The results obtained on vertical panels with this configuration went beyond the expectations. In any case the connections should be qualified in realistic conditions.

Integrated Systems

The horizontal load developed within the frame-to-panels connections, the highest tested during this campaign, could not supported by the connections already on the market, in the case of connections at the upper ends (hinges), as tested here.

Card files with details for each test and the presentation of the obtained experimental data are enclosed for each experiment.

WP6: Executive Summary

The first activity that has been activated at month 13, waiting for the availability of the results of the work of the other WPs, is the wide parametric investigation on several structural assemblies representing the most common typologies of precast buildings. The aim of this investigation is to analyse how the different connection systems (isostatic, integrated and dissipative) play their role in the structural response, so to spot the situations where this role is important and evaluate the conditions for practical applications.

With reference to frame systems of structures for one-storey industrial buildings, dynamic elastic analyses and dynamic non-linear analyses have been performed with reference to serviceability, no-collapse and collapse limit states. As input a recorded accelerogram has been used.

The analyses have been repeated for the 3 quoted connection systems, for 3 shape ratio of elongated, medium and compact buildings, for the 3 arrangements of null, deformable and rigid roof diaphragm, for the 3 action intensities of 0,18g, 0,36g and 0,60g and for action in the 2 main directions of the buildings, with a total 162 different analyses.

The results are synthetically represented by a reduced number of output parameters representative of the structural response. The numerical direct and adimensional values of these parameters are provided in 54 tables and proper related graphic diagrams are added.

The work has been performed by UL for the isostatic system of connections, by NTUA for the integrated system of connections, by POLIMI for the friction dissipative system of connections and by ITU for plastic dissipative system of connections. The detailed complete report of these analyses is attached to the Deliverable 6.1 (Annex O). Annex A of the same deliverable contains the design calculations for the proportioning of the analysed structures (made by POLIMI).

The analyses have been also extended to a type of precast 3-storey building, by NTUA for the integrated system of connections (Annex B), by UL for the isostatic system of connections (Annex C) and by ITU for the plastic dissipative system of connections (Annex D).

Following the availability of the results of the work of the other WPs, the design rules have been derived for panel-to-structure and panel-to-panel connections, organized in the six chapters of Deliverable 6.2 Design
guidelines for wall panel connections. All participants have contributed in providing the experimental and analytical data on the connections behaviour. In particular UL gave the main contribution to the chapter on Current systems, NTUA gave the main contribution to the chapter on integrated systems and ITU/POLIMI gave the main contributions to the chapter on dissipative systems. POLIMI ensured the coordination of the drafting work.

In parallel the drafting work on the Deliverable 6.1 Design guidelines for precast structures with cladding panels has been carried on, with the contributions of the same participants. The methods of structural analysis are presented, to be applied for the seismic design of precast structures with cladding panels. The cases of Existing buildings, Current systems, Isostatic systems, Integrated systems and Dissipative systems are treated.

With the issue within June 2015 of the final version of these two applicative documents, the work of WP6 has been positively finalized.

Potential Impact:
The main contribution of this Research Project was 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.

This research activity was directly relevant to the interests of the precast concrete industry, since the problem of reliably designing, dimensioning, installing and maintaining appropriate connection devices between the structural elements, able to guarantee predefined levels of performance under different loading situations (among which earthquake excitation plays a primary role) is the fundamental prerequisite for precast structures to be fully competitive from the point of view of safety and reliability of behaviour and performance.

The outcomes of the research were also meant to be directly reflected into normative documents: the aim of assessing and improving the design approach currently codified in Eurocode8 for cladding panels in precast structures, as for the specific issues of joint design, was 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 Eurocode8) was 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.

The envisaged project will contribute to improve the level of safety whilst providing competitive solutions for the precasting industry. This will improve the safety of the people living or working in precast building structures in the event of hazardous natural phenomena such as earthquakes. Earthquakes have been the cause of more than 1.5 million deaths worldwide and huge but incalculable economic losses during the 20th century. A number of the most deadly earthquakes have occurred in Europe. Large parts of Italy, Slovenia, Greece, Turkey and Spain (countries represented in the SAFECLADDING consortium) experience the highest seismicity in Europe, and most of the rest of the EU experiences some degree of seismic risk. In order to ensure Europe’s leading role as a knowledge-based economy, the results of the project can then be used to improve the safety of other seismic parts of the world which do not benefits of the same degree of expertise (the Caribbean area, the north-African area, the central and South-East Asia, Polynesia...)

In addition, it is important to remark that precast is fireproof, protects against the spread of fire between rooms or properties and it cannot catch fire, burn or drip molten particles. In tests, concrete performs consistently well in fire, often requiring only minor repairs.
The production and use of concrete in all its forms is central because concrete is second only to water as the most consumed substance on earth, with nearly three tons used annually for each person on the planet.

Precast concrete offers a competitive building solution based on long-term economic benefits, energy efficiency, lower maintenance and overall operating costs as well as opportunities for future reuse should the occupancy of a building change.

The proximity of precast plants, energy efficiency, recyclability and minimal waste are keys to meeting environmental standards that are gaining client interest.

The desire by clients — and therefore designers — to provide higher levels of sustainable considerations in their buildings is gaining popularity. Much of the attention is spurred by the growing attention to climate change and the consumption of energy and materials. To reach these goals, designers are turning more often to precast concrete components, which provide a number of “green” advantages, such as:

- Energy efficiency: precast concrete's key benefit comes from its thermal mass, which helps the material store heat and moderate daily temperature swings (thermal mass reduces loads and shift peak loads in most climates).
- Recyclability: concrete's inorganic and inert composition makes it an ideal material to be recycled, and it is frequently crushed and reused as aggregate for road bases or construction fill. The waste materials also are more likely to be recycled because concrete production takes place in one location under controlled conditions. For instance, gray water is often recycled into future mixes; for some products, between 5 and 20 percent of aggregate in a mix can consist of recycled concrete and sand used in finishing can be reused. Steel forms and other materials used in casting also are reused many times. In addition, precast concrete components often make use of materials with post-consumer recycled or post-industrial recycled content.
- Natural resources saving and waste reduction: less material is required to produce precast components (compared to traditional construction method) because precise mix designs and tighter tolerances can be achieved. Less concrete is wasted because quantities of constituent materials are tightly controlled in a precast plant. There is also less waste at the construction site, because only the needed precast components are delivered.
- Noise and pollution reduction: most precast plants are not far from the site chosen for their use, and the raw materials used to produce the precast concrete components — cement, aggregate, prestressing strand and rebar — usually are obtained from sources very close to the precast plant. Therefore fewer trucks and less time are needed. That is particularly beneficial in urban areas where minimizing traffic disruptions is critical. Less noise is produced at the site as well, reducing noise pollution.

Among the advantages of precast for health and quality of life, it is worth to note that:

- Precast is emission free: in its daily use, precast concrete is a totally inert substance, so it doesn’t emit or give off any gases, toxic compounds or VOCs (volatile organic compounds). This means allergy sufferers can breathe easy because precast does not contribute to the symptoms of "sick building syndrome".
- Precast helps create healthy indoor environments: The simple lines and smart edges of precast concrete are easy to clean and its hard, smooth finish therefore does not accumulate dust which may exacerbate asthma.
- The thermal mass properties of concrete help even out daily and seasonal temperature swings, making indoor spaces more comfortable without having to resort to air conditioning. This saves both energy and money, not to mention maintenance costs.
- Because precast can be moulded to any shape, size and texture it can be used to deflect or absorb
noise. This makes it a good acoustic host for music but also an effective sound barrier alongside busy roads.

The project was structured in order to obtain results with a clear commercial and economic value to be directly exploited by the SME-AG’s and SME’s participating to the project. Direct revenues were planned from the sales of experimental data for connections, precast design manual, connection design manual and organisation of training courses. Indirect revenues, coming from the increase of market share of precast buildings, thanks to their increased reliability coming from the use of new design approaches leading to optimize structural solutions and new connections developed within the project were also considered. The revenues and the operating costs related to the development of new connections were not estimated because this is an intangible result, i.e. this results will probably allow to increase to market size of precast structures but it can be hardly quantified in economic terms. The commitment towards exploitation activities within the Consortium was very high. Commercialisation and distribution at European and world level was the final intention of the group; this had to be achieved through the involvement, under appropriate conditions, of all the partners, considering that amount of technical background that must be necessarily used. This activity will be carried out after the end of the project. Furthermore, this project had allowed participants to become the owners of an innovative technology, not yet present on the market and this will probably increase their competitiveness on the European and extra-European market.

The main goal and objective of the SAFECLADDING project was to provide the participating SMEs and Associations as well as the engineering community in general with modified or/and new methodologies, tools and codes for economical design of earthquake resistant and safe precast building structures. The principal diffusion of the research results was, in any case, expected from the publication of the norms to which the research addressed (the series of Eurocodes in now under revision). The presence of members of the consortium in the competent European standardization groups (CEN/TC250/SC8 and CEN/TC229/WG1) will ensure the transmission of the information.

The SAFECLADDING dissemination strategy was based on progressively increasing dissemination efforts as project results were obtained, to ensure the widest possible awareness of the project and favourable conditions to facilitate exploitation after the end of project. The dissemination strategy was intended to optimise the dissemination of project knowledge and results to companies and organisations, which share an interest in the scientific results and the applications of the results obtained during project conduction. The dissemination programme for SAFECLADDING was planned to driven from both the European and individual partner country perspectives and will be applied both within each partner country, and across the European community and beyond. Dissemination activities had to be undertaken by the consortium as a whole, and by each partner on an individual basis.

The identified target audience was composed by research and wider scientific community, customers, general public. The dissemination channels chosen were: Events and exhibitions; Advertisements and notices in journals and newspapers; Participation at sector-relevant exhibitions and conferences; Scientific papers, journal articles, press releases. A web site for the project was also created. The project website was established and provides continuously updated information about the project as well as relevant news and events. The website is available at http://www.safecladding.eu. The project was and will be (after the end of the project) presented at seminars and conferences relevant to the specific domains of the project. The results of the scientific research work were (and will be) submitted for publication to international, peer-reviewed high-level scientific journals by all scientific partners. Partners of the consortium disseminated internally the project through their internal bulletins and by presentations at internal and external meetings.
The content of the project was presented 70 times considering oral presentations to a wider public, oral presentations to the scientific community, press releases, web applications. 5 papers appeared already in peer reviewed journals, 28 papers were presented in conferences, 3 papers appeared in edited books, 5 between thesis and dissertations were focused on the project. The participation to scientific conferences and the publications of papers in peer reviewed journals will continue after the end of the project.

The train the trainers approach was chosen within the project. For this reason a training session was organised just before the end of the project. Selected trainers from each partners were chosen. From the end of the project their role is to explain to the members of each associations of the consortium how to use the new connection solutions and how to apply the corresponding design equations. Specific courses will be organised by each partners (SME and SME-Ags) in order to present the results of the project to engineers.

List of Websites:
http://www.safecladding.eu/

Contact details of all partners are reported in the web site.

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