ROBUST DESIGN OF STEEL AND CONCRETE COMPOSITE STRUCTURES

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ABSTRACT

Accidental events, such as impact loading, are rare events with a very low probability of occurrence but their effects often leads to very high human losses and economical consequences. An adequate design should not only reduce the risk for the life of the occupancy, but should also minimize the disastrous results and enable a quick rebuilding and reuse. A robust design prevents the complete collapse of the structure when only a limited part is damaged or destroyed. Design against disproportionate collapse is usually based on the residual strength or the alternate load path methods. Identification of an alternate path may lead to an effective and cost efficient design for progressive collapse mitigation by redistributing the loads within the structure. The continuity of the frame and of the floor represent essential factors contributing to a robust structural response. They in fact enable development of 3D membrane action. A European project focusing on robustness of steel and steel and concrete composite structures subjected to accidental loads is still ongoing. In the framework of the project the authors concentrated their studies on the redundancy of the structure through slab-beam floor systems as well as through ductile joint design. At this aim, two 3D full scale substructures were extracted from a reference building and experimentally investigated with the purpose to get an insight into the mechanisms allowing the activation of the alternate load paths resources, when a column collapse. The paper illustrates the main features of both the specimens tested and the experimental campaign. The preliminary results of the tests are presented and discussed.

KEYWORDS

Robustness, alternate path strategy, collapse of a column, steel and concrete composite structures, membrane action, full-scale tests.

INTRODUCTION

Accidental events, such as impact loads, extreme fires or blasts, are rare events with a very low probability of occurrence but their effects often leads to very high human losses and economical consequences. An effective design strategy should pursue the twofold objective of reducing the risk for the life of the occupancy and of minimizing the disastrous results enabling a quick rebuilding and reuse. Difficulties in identifying all the possible damage scenarios and sources of damage activation, associated with the need to adopt design strategies economically sustainable, lead to the set up of design strategies able to limit the spreading of the damage rather than avoid it. This concept is associated to the term ‘structural robustness’.

A definition of robustness has been attempted aiming at provide the background to its implementation in design practice. The Eurocode 0 (CEN 2002) defines robustness as *“the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause”*. Design a structure so that this requirement is met means to adopt structural measures economically justifiable to limit failure to an acceptable extent. A more recent definition (Sørensen 2011) describes robustness as *“the attitude of a system to survive to damage”*. In accordance with this definition, robustness is a combination of vulnerability, i.e. the attitude of an element to be damaged, and damage tolerance, i.e., the attitude of a system to survive to damage. Damage tolerance, vulnerability and robustness are properties of the structure and do not depend on the actions/events.

As to design practice, the Eurocode 1-7 (CEN 2006), which covers accidental actions, recognizes several design strategies to be adopted in design diversified on the basis of the impact that the collapse would produce on the society. Such an impact is evaluated by considering the consequences on people, on the economy and on the environment. Depending on the building type and occupancy, structures are categorized in 3 classes of consequences. For each of these classes, various strategies of prevention are identified. For low consequence of failure the adoption of minimum structural requirements are prescribed, while a risk analysis and the use of refined methods based on dynamic analyses, non-linear models and incorporation of the interaction between the load and the structure are suggested for the highest consequence class. The choice of the strategy of prevention is also influenced by the peculiar features of the accidental actions. By considering the unforeseen probability of the events and the practical impossibility to define “a priori” all the possible scenarios, the Eurocode (CEN 2006) distinguishes between ‘identified’ and ‘unidentified’ accidental actions. Different design strategies are hence associated with each of the two categories of action (Figure 1).

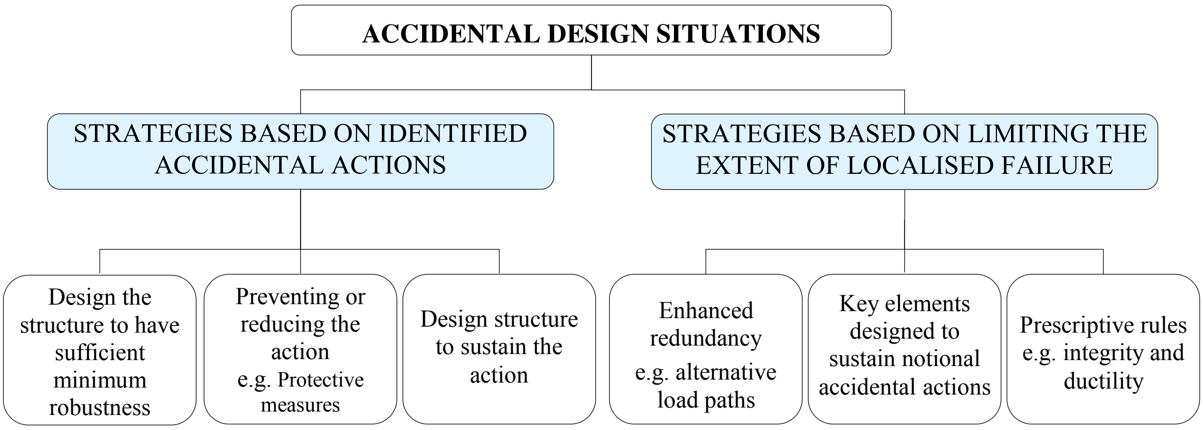


Figure 1 Strategies for accidental design situations as in EN 1991-1-7

The most recent structural Codes recognize robustness as a key structural requirement to be considered in design together with resistance, durability and serviceability. Studies and researches performed in recent years greatly contributed to the enhancement of the knowledge of the structural response under accidental actions and to the development of general design strategies to achieve robustness. The peculiar characteristics of the accidental actions oriented the studies first on the response of reinforced concrete structures subjected to extreme loads such as impact or blast, while only little research has been carried out on structures built up in different materials. Steel and steel concrete composite structures for their peculiar nature possess excellent reserve of resistance to extreme loading due to their high bearing capacity and high ductility, which lead to high energy dissipation capacity. The limited specific knowledge of their behaviour under exceptional load has a substantial impact in design practice. Aiming to fill such a gap, a number of research studies of composite steel-concrete systems were worldwide activated with the aim to develop Standards recommendations and practical tools enabling a reliable and effective robust design approach.

Residual strength and alternate load path methods are two effective and cost efficient design strategies for progressive collapse mitigation in case of framed structures. The general principle pursued is to allow the structure to reach new and stable equilibrium configurations by redistributing the loads to the undamaged parts through the continuity of the frame and of the floors enabling the development of a membrane action. In this context, the redundancy offered by the joints, including the column bases and the 3-D performance capabilities of the floor system are essential factors to achieve a robust structural response.

A European project, whose acronym is RobustImpact, focusing on robustness of steel and steel and concrete composite structures affected by accidental loads is ongoing (Hoffmann *et al*. 2015). The main aim of the research is the development of a robust design approach in case of impact loading based on the residual strength and alternate load path methods. Design guidelines for advanced impact design of steel and steel and concrete composite structures will also be an outcome. At this aim, the residual strength of impacted vertical members with different support conditions subjected to high dynamic lateral loads is numerically and experimentally investigated. Particular attention is paid to the interaction between the member and the surrounding structure and to the ductility demand to the joints for partially damaged elements. The residual strength of multi degree of freedom systems (MDOF) is a further issue for which numerical investigations are planned. Studies of the activation of alternate load paths on 2D and 3D systems are also parts of the project. To this purpose, quasi-static tests on 3D sub-structures and tests under high speed loading and impact loading on composite joints, beam-to-column joints, column bases and T-stubs are included.

In the framework of this project, the authors concentrated their studies on the redundancy of the structure through slab-beam systems as well as through ductile joints. At this aim, analytical, numerical and experimental activities were planned and executed. For a better insight into the mechanisms allowing the activation of the alternate load paths resources, two 3D full-substructures were extracted from reference buildings and experimentally investigated simulating the collapse of a column. This paper focuses on the experimental part of the study. The main features of both the specimens tested and the experimental campaign are highlighted. The preliminary results of the tests are presented and discussed.

REFERENCE STRUCTURES

All the activities of the RobustImpact project are made consistent by the reference to two cases representative of typical European office buildings. The two buildings are 5 storeys and 6 bays x 2 bays steel and concrete composite framed structures characterised by the same plan overall dimensions of 34,2m x 11,4m. One configuration is symmetric with respect to both the plan directions while the other one is symmetric only with respect to one plan direction. The two case study structures, which will be referred to hereinafter as Symmetric and Asymmetric configurations, are shown in Figure 2 and 3 respectively. The location of steel braces designed to resist the horizontal actions in Y direction is asymmetric in both the frames. This solution, despite less effective with respect to the seismic performance, was adopted in order to have no steel brace in the sub-structures to be experimentally investigated. This makes the sub-structures more representative of a general case.

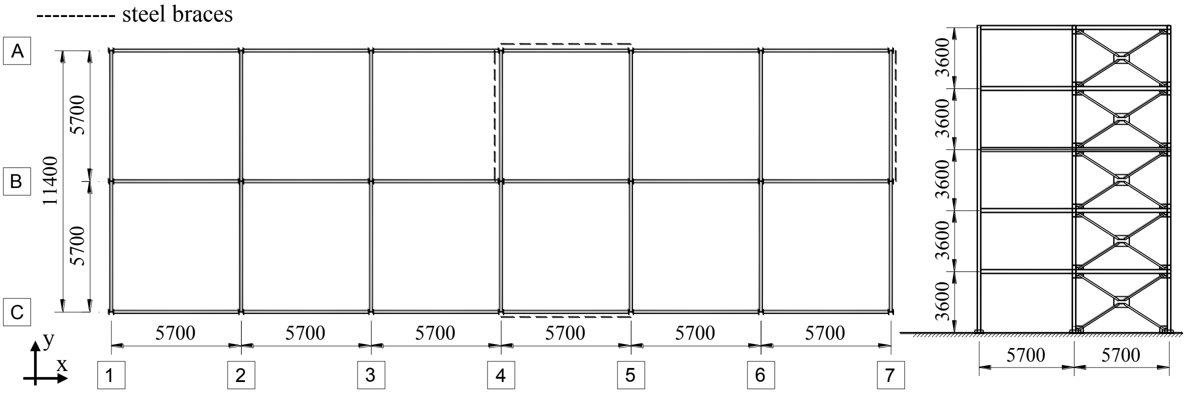


Figure 2 The reference building (Symmetric configuration - measures in mm)

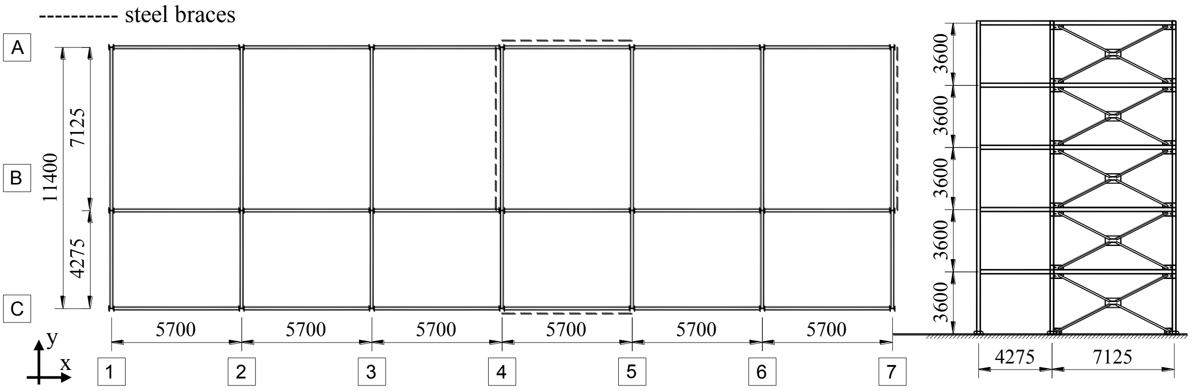


Figure 3 The reference building (Asymmetric configuration - measures in mm)

The design of both structures was based on the relevant Eurocodes (CEN 2004a, CEN 2010, CEN 2005, CEN 2004b), and in order to decouple issues of seismic and of robust design, no seismic considerations were made. As to the materials properties the following assumptions were made: concrete C30/37, structural steel grade S355, rebars grade B450C, bolts class 10.9 and shear studs Nelson SD 3/4"x4.". In order to reduce the number of variables to be accounted for when comparing the responses of the two structures, the same steel sections for the beams (IPE 240), the columns (HEB 220) and the diagonal braces, and the same thickness of the concrete slab (150mm) and the same steel connections were adopted. The rebars size and layout in the solid slab were obviously different. Beam-column steel connections are bolted flush end-plate connections (Figure 4), and full shear connection between steel beams and concrete slab were assumed in design.

3D SPECIMENS

The removal of a structural element is a typical design scenario, simulated in various studies and also prescribed by Codes in order to identify the structural resources to survive to accidental actions. The collapse of a column is normally considered for framed structures. Within such a scenario, the floor system is expected to undergo large deformations in order to provide an alternative load path, so allowing the redistribution of the loads to the "undamaged" part of the structure to occur. This is an evolutionary phenomenon which is associated with the development of large displacements. In the case of framed steel and steel and concrete composite structures, the collapse of a column requires the joints do possess a large rotation capacity, sufficient to make catenary forces in the members and membrane forces in the floor slabs to activate. Aiming at investigating such phenomena the experimental study performed in Trento concentrated on the response of a portion of the first floor of the reference structures presented in the previous section. In order to identify the structural resources against accidental actions the collapse of a column was simulated.

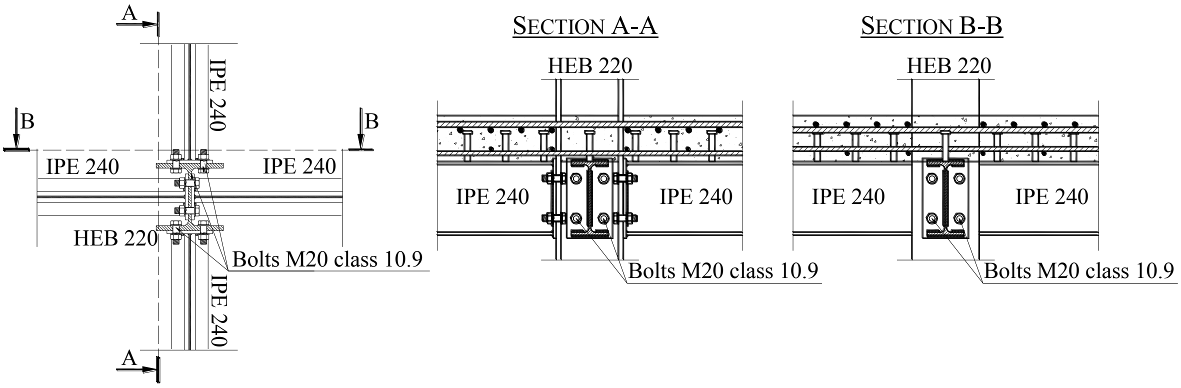


Figure 4 Beam-column interior joint with flush end-plate connection

The floor framing plan of the two specimens for the Symmetric and Asymmetric configurations are represented by the dotted area in Figure 5. In both the tests the collapse of the central column, the one indicated with a circle, was simulated.

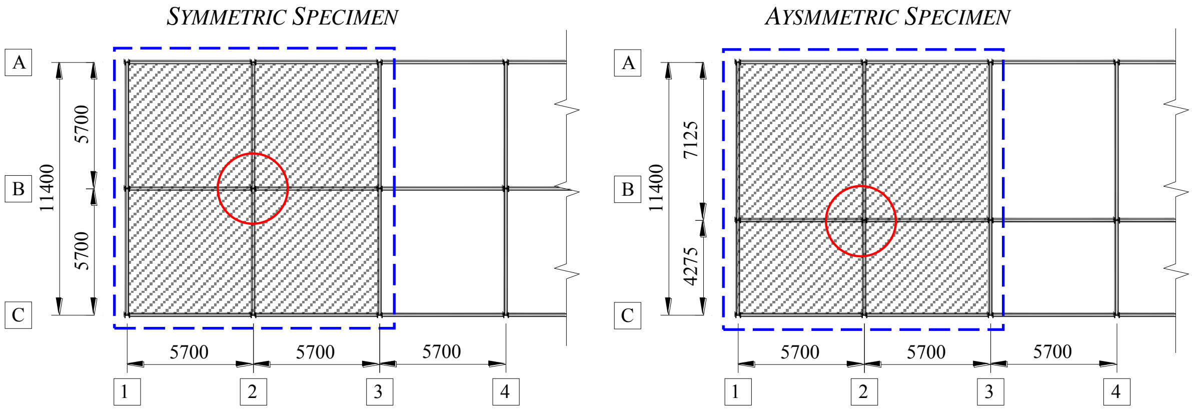


Figure 5 The full-scale specimens (plan view - measures in mm)

A critical point of the test design was the design of the restraints of the specimens. The sub-frames should be representative of the full-frames and hence the restraints have to approximate effectively the remaining part of the structure. Numerical studies were hence performed focusing on this subject. FE models of the full-frames (i.e., the reference buildings) and sub-frames (i.e., the specimens) were developed by using the Abaqus program (Abaqus 2010). In the models beams and columns were modeled as "Frame" elements while the slab was modeled by means of "Shell" elements. The rebars were embedded within the slab, the slab was rigidly connected to the beams and, in this preliminary study, a rigid connection was considered between the beams and the columns. The structural steel and the rebars were modeled by an elastic-perfectly plastic material model, and the Popovics law was assumed for the stress-strain relationship of the concrete.

Three facets of the problem were investigated: the restraints at the columns base, the possible need of connecting the columns at a certain height above the floor and the restraints at the floor level. Various solutions were considered and their adequacy was checked by comparing the results, in terms of deformations and internal forces, for the sub-frames and the corresponding full-frame. The analyses led to the restraining system showed in Figure 6 where:

- the columns are rigidly connected to the lab floor and interconnected by truss members at mid-height of the 'second storey';
- at B the X d.o.f. is left free (central beam in Figure 6), while the vertical and lateral displacements (along Y and Z) are prevented;
- at A and C the relevant d.o.f. along X is fully restrained;
- at L, to ensure stability to the specimen, the Y d.o.f. is prevented. FE analyses proved that the influence of this restraint on the specimen response is modest.

All the restraints are made up by truss elements connected to the steel frame.A more detailed coverage of this point can be found in (Zandonini *et al*. 2014).

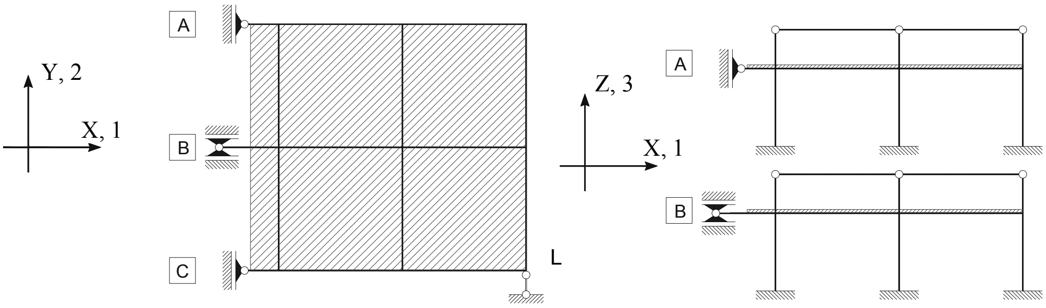


Figure 6 The restraining system (symmetric specimen)

TESTS

The specimens were built inside the Laboratory of Materials and Structures Testing of the University of Trento. Figure 7 shows the main phases of the construction of the symmetric specimen. The steel skeleton was first erected (Figure 7a) and connected to the strong floor and to the counter-walls by means of the restraining system described in the previous section. The slab was then cast (Figure 7b-c).


a) b) c)

Figure 7 The constructional phases

The column whose collapse is simulated in the tests was 'replaced' by a hydraulic jack (Figure 8a). During the constructional phases the hydraulic jack was held in place in a non operating state. The central beams were hence held in position by means of props which were removed just before the beginning of the test (Figure 8b). After formwork's removal the specimen measuring instruments were installed.


a) b)

Figure 8 The central column

The considerable amount of parameters affecting the response required an accurate selection of the quantities to be measured during the test. The attention was mainly focused on the response of columns, beams and beam-to-column joints.

Displacement transducers and clinometers allowed measuring the rotations of the columns at the beam level and of the beam-to-column joints. The central joints (position E in Figure 9) and of the joints between the internal beams EH, BE, EF, DE and columns H, B, F and D were instrumented. The instruments were positioned so as to decouple the joint and steel connection response. Additional transducers were employed to measure the torsional rotations of the external beams, the rotation of the corner column C, and the horizontal displacement of the column H at the beam level. Furthermore, the vertical displacements at the central joint and at the centre of the four slab panels were monitored.

Acquisition of all the instruments' signals, including the load cell connected to the hydraulic jack, was done at a frequency of 2Hz.

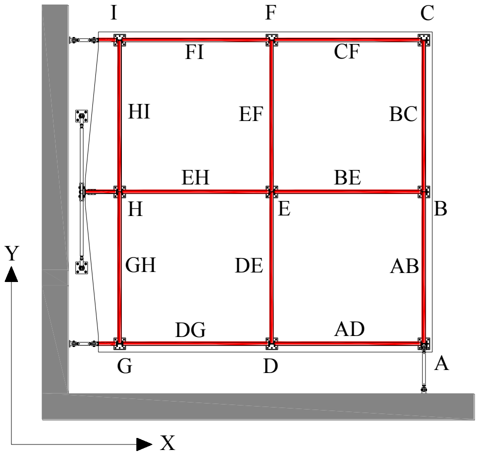
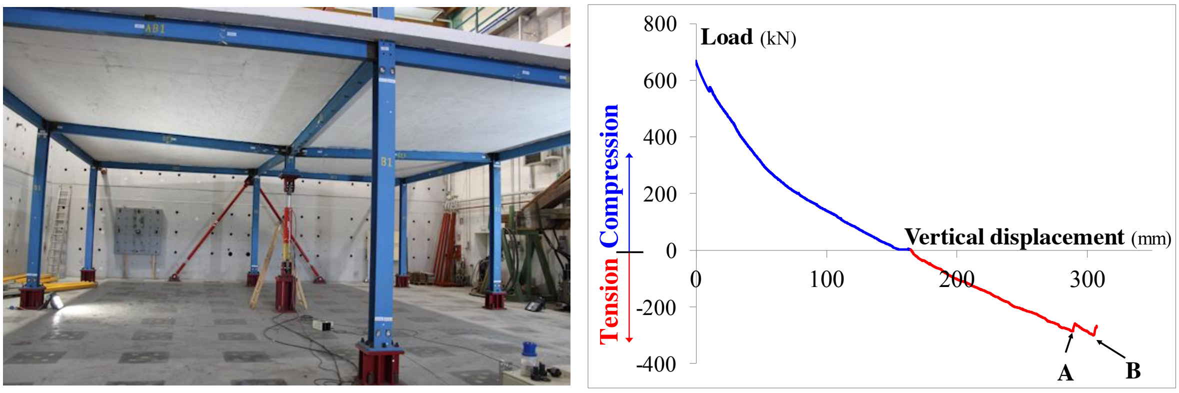


Figure 9 Layout of the steel frames (Symmetric configuration)

The tests comprise the following phases:

- activation" of the hydraulic jack, and removal of the props. The load measured by the loading cell allowed evaluating the self-weight portion of the specimen sustained by the central column;
- application of the vertical load to the slab. At this aim, bags filled with sand were placed on the slab surface reproducing a uniform distributed load of 8,8kN/m2 so as to approximate the factored design load including finishes, partitions and variable loads;
- gradual removal of the column simulated by reducing the pressure of the hydraulic jack down to zero;
- stabilization of the specimen;
- application by means of the hydraulic jack of a tensile force increasing up to the end of the test, with the aim of appraising the extent of the safety margin.

Figures 10 and 11 illustrate the deformation of the two specimens at the end of the test (Figures 10a-11a) and the load-central joint vertical displacement relation (Figures 10b-11b).



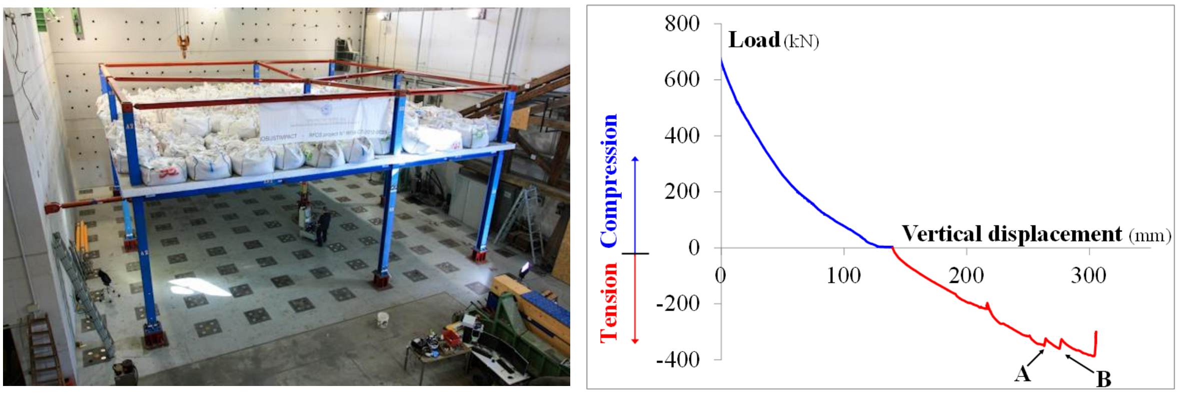
a)

b)

Figure 10 Symmetric configuration: a) Specimen at the end of the test; b) Load-displacement curve of the central column

TESTS RESULTS

In both the tests, the beam to column connection at the central joint revealed themselves as the critical components. In both the tests, the collapse of a bolt of the bottom row of the connection between the central column and the beam EH took place first (point A in Figures 10b and 11b). The tests were continued up to the second bolt in the same row fractured (point B in Figures 10b and 11b). The tests were then stopped for safety reason due to the remarkable plastic deformation of the connections (Figure 12a) and the state of 'distress' of the concrete at the central joint (Figure 12b). For the asymmetric configuration, a tensile force was again applied, with the goal to further check the residual strength capacity. The collapse of a third bolt (bottom row of the connections with beams EF and DE) took place almost immediately (Figure 12c).



a) b)

Figure 11 Asymmetric configuration: a) Specimen at the end of the test; b) Load-displacement curve of the central column

The visual inspection of the specimens allowed also identification of significant deformations of the external columns H, F, B and D, mainly in the vicinity of the beam-to-column joints. Deformations were very similar in both tests: Figure 13 relates to the asymmetric specimen. A concentrated 'rotation' of the column reveals the significant plastic shear deformation of column B web panel (see Figure 13a). Furthermore, the mechanism of force transmission between column and beam induces compression at the beam lower flange with associated instability phenomena (Figure 13b). Horizontal cracks developed in the slab thickness on the outer side of the slab at columns F and D associated with the transmission of shear forces between concrete slab and column (Figure 13c).

a) b) c)

Figure 12 Deformation at column's collapse: the central joint (Asymmetric configuration)

a) b) c)

Figure 13 Deformation at the end of the test: joint (Asymmetric configuration)

The slab crack pattern at the end of the test, showed in Figure 14 for the asymmetric specimen, indicates the activation of a mechanism of force transmission between the central column, i.e., the collapsed column, and the external ones.

The measured data allow describing the evolution of key parameters such as the rotation of the beam-to-column joints and the axial and bending deformations of columns and beams. This outcome provides the base for a first appraisal of the demand of beam-to-column joints' ductility and of the redistribution of the internal forces between the main structural elements. As an example of the tests results, Figure 15 shows the load-rotation curves associated to the joints at the central column for the symmetric configuration.

Bottom side   Top side

Figure 14 Experimental crack pattern (Asymmetric configuration)

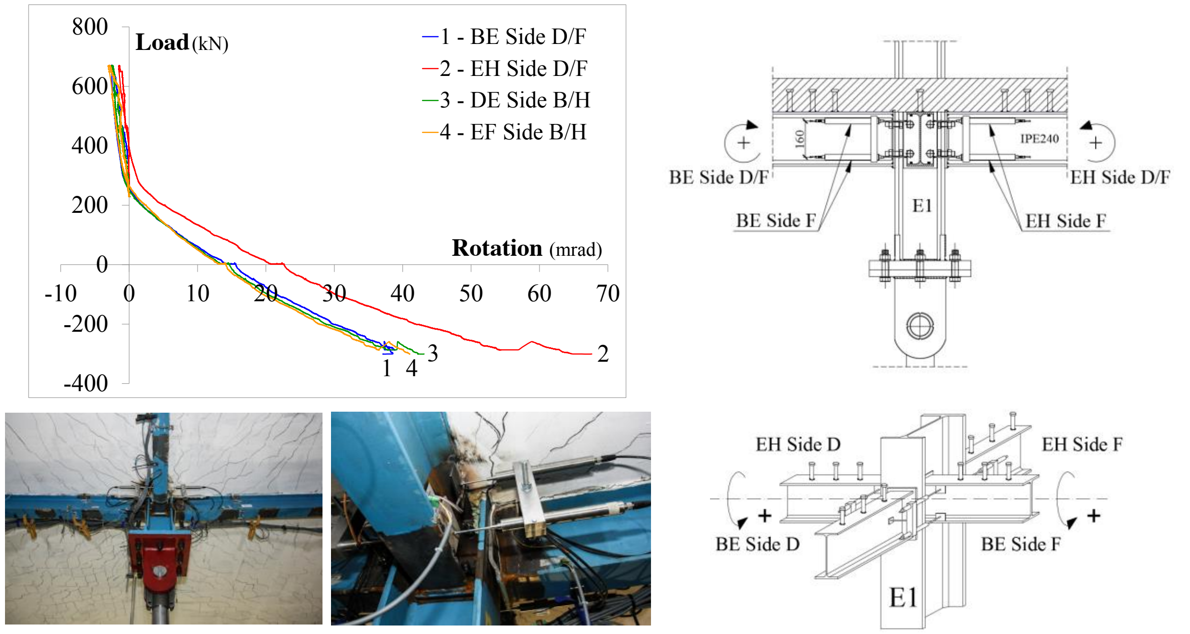


Figure 15 Deformation of the beam-to-column central joint (Symmetric configuration)

The collected data are currently accurately evaluated. As a general comment, based on the present results, it can be said that the importance of the 3D action associated with the continuity offered by the joints and by the flooring system is clearly pointed out. The need of a ‘adequate’ design of these components is also stressed.

CONCLUDING REMARKS AND CURRENT DEVELOPMENTS

A number of dramatic events leading to building collapses pointed clearly out the potential ‘fragility’ of structural systems, when solely designed to meet the traditional requirements of stiffness in service, strength at ultimate and durability. A new term entered recently in the design and Code dictionary: robustness. A robust design prevents the complete collapse of the structure when only parts are damaged or destroyed. Design against accidental actions is usually based on the residual strength or the alternate load path methods, and a combination of these strategies may lead to an especially effective and cost efficient design for progressive collapse mitigation by redistributing the loads within the structure. To this aim, the continuity of the frame and of the floor enables development of membrane action. They hence represent essential factors contributing to a robust structural response.

A European project focusing on robustness of steel and steel and concrete composite structures affected by accidental loads is still ongoing. In the framework of the project the authors concentrated their studies on the redundancy of the structure through slab-beam-systems as well as by ductile joint design. At this aim two 3D full-substructures were extracted from a reference building and experimentally investigated with the purpose to get an insight into the mechanisms allowing the activation of the alternate load paths resources. In both tests the collapse of an internal column was simulated.

The paper illustrates the main features of the specimens and how the tests were carried out. Some of the important behavioural parameters, such as: the vertical displacement of the central node, the rotation of the joints at that node, the collapse mode, the deformed shape at ultimate and the crack pattern, are briefly presented. The extensive set of measured data is still under detailed evaluation. Preliminary results confirm the joints and the concrete slab as the critical actors against progressive collapse.

Aiming at a deeper understanding of the mechanisms of force transfer, numerical FE models were developed with the software ABAQUS (ABAQUS 2010). Their calibration against experimental results is in progress. The key role played by the beam-to-column joints suggested devoting particular attention to their modeling. At this aim different levels of complexity were adopted: the 'ideal' cases of hinged and fixed connections were considered first, the semi rigidity of the beam-to-column joints was then taken into account by the component method. As an example of the output of the analysis Figures 16 and 17 compare the experimental slab crack pattern at collapse and the principal tensile stresses, for the top and bottom side of the slab, respectively. The results are related to the symmetric configuration for the case of fixed beam-to-column joints modeling. The agreement is more than satisfactory.

The evaluation of the experimental data and the validation of the numerical models will provide a deeper understanding of the different facets of the frame response. The Authors count to highlight them at the Conference.

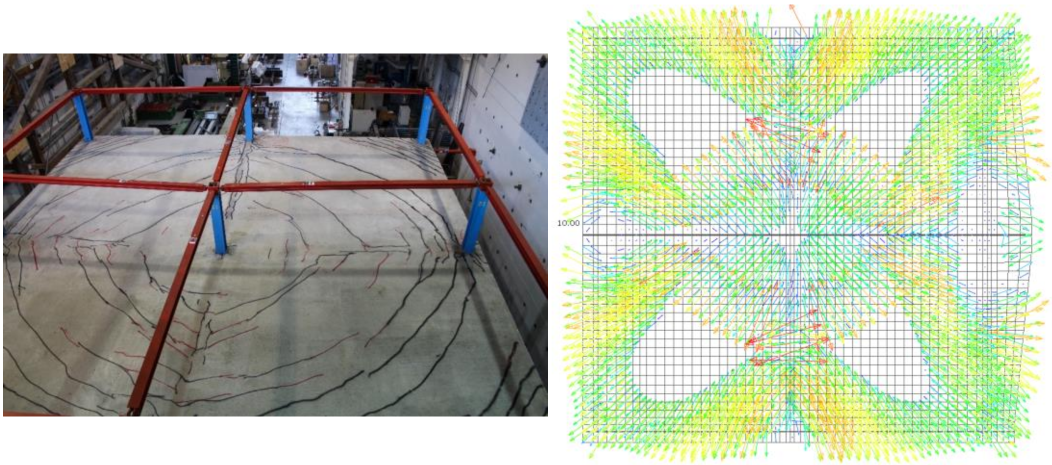


Figure 16 Experimental crack pattern and principal tensile stresses at slab top

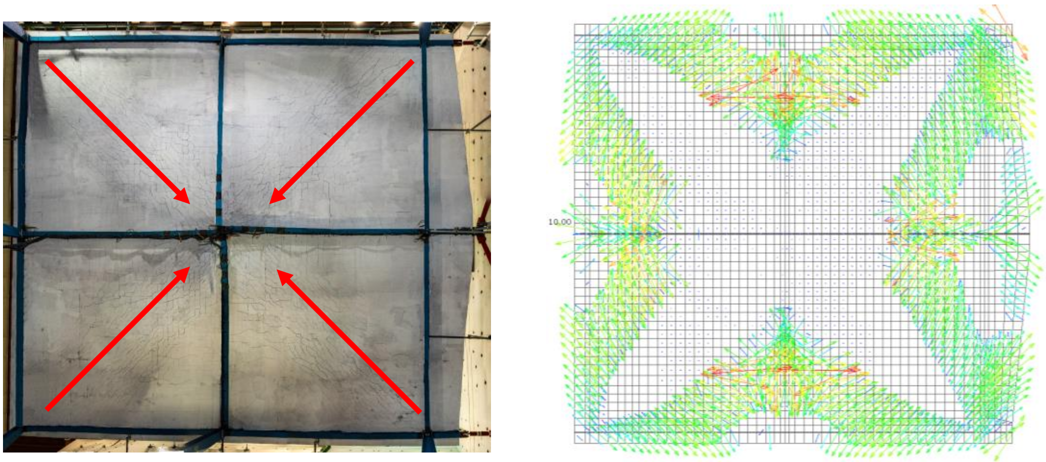


Figure 17 Experimental crack pattern and principal tensile stresses at slab bottom

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