ROBUSTNESS OF FLOORING SYSTEMS IN 3-D FRAMES
An experimental assessment

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INTRODUCTION

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 consequence and economical losses. An adequate design should not only reduce the risk for the life of the occupancy, but should also minimize the disastrous result and enable a quick rebuilding and reuse. A robust design prevents the complete collapse of the structure when only components are damaged or destroyed.

Since 1940 there has been a growing interest to understand the response of reinforced concrete structures subjected to extreme loads such as impact or blast, while only little research has been carried out on steel and steel-concrete composite structures. Thus, rules for robust design are mainly based on test results performed on reinforced concrete structures and application of these concepts to steel or steel-concrete composite structures can lead to uneconomic solutions. In fact, these structures provide an excellent resistance to extreme loading, such as impact, due to their high bearing capacity and high ductility, which lead to high energy dissipation capacity. The limited specific knowledge has a substantial impact in design practice, where an efficient design for steel or composite structures against impacts is hampered by the lack of available standards enabling a detailed approach.

Impact is usually considered in the codes by equivalent static loads. This approach is easily applicable since it is based on a simple static analysis, but neglects the structural dynamics effects. In the cases of steel or composite structures, where light structural elements are employed, neglecting the dynamic effects and hence disregarding the dissipation capacity of the structure can lead to rather uneconomic solutions. In particular, steel and composite vertical elements are not utilized at their full potential due to the lack of appropriate knowledge. Up to now, impact investigations of steel members focused on the member behavior, neglecting the influence of the supports and of the surrounding structure. However, design against accidental actions is usually based on the residual strength or the alternate load path methods, and a combination of these strategies can lead to an effective and cost efficient design for progressive collapse mitigation by redistributing the loads within the structure. The continuity of the members and the floor 3-D action represent essential factors ensuring a robust structural response. Therefore, the investigation of robust design should concentrate on the redundancy offered by the joints, including the column bases, and by the 3-D performance capabilities of the floor system.

This paper illustrates the preliminary work carried on within a European Research Project, aimed at developing new design concepts for steel-concrete composite frames against accidental actions. The main goal of the study carried out in Trento is to get an insight into the behavior of steel-concrete composite 3-D framed structures subjected to a sudden loss of a column. Two full-scale experimental tests will be performed on frame sub-structures, and the present paper presents the preliminary studies for the design of the tests. By simulating the total loss of the impacted column, the experiments enable investigation of the redundancy of the 3-D floor system in terms of activation of different resistance mechanisms including slab membrane effects. Another important structural resource is the redundancy of the global structure through ductile joint design; this is a further major issue investigated by the project.

1 DESIGN OF CASE STUDY STRUCTURES

Two five-story steel-concrete composite structures have been selected as case studies. The overall dimensions of the building in plan are 34.2 m (6 bays) in the X direction by 11.4 m (2 bays) in Y direction and the total height is of 18 m with an inter-story height of 3.60 m. Two geometric configurations of the frames have been considered in this study. One configuration is symmetric with respect to both directions while the other one is symmetric only with respect to the Y direction. The two structures will be referred to hereinafter as *Symmetric* and *Asymmetric* configurations respectively and are shown in *Figs. 1* and *2*. As to the materials, concrete C30/37, rebars grade B450C, structural steel grade S355, and bolts class 10.9 were selected. Structural design aimed at getting for both structures the same steel sections for the beams (IPE 240), the columns (HEB 220) and the diagonal braces, and to keep as well the thickness of the slab (150 mm) and the steel connections. This choice was made in order to reduce the number of variables to be accounted for when comparing the responses of the two structures. The rebars size and layout in the slab were obviously different. The design is based on the relevant Eurocodes [1, 2, 3, 4], and no seismic considerations were made in order to decouple the issues of seismic design and of robust design. The location of steel braces has been chosen in order to have no steel brace in the sub-structure to be experimentally investigated. This makes the sub-structure more representative of a general case. Additional details of the case studies are reported in Baldassino et al. 2013 [5].

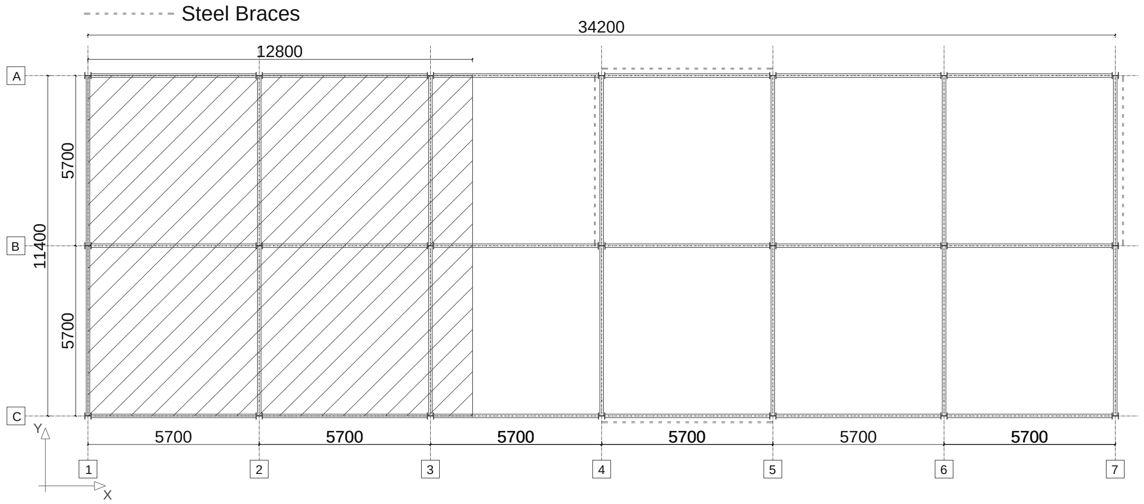

Fig. 1. Floor Framing Plan - Symmetric Configuration (dimensions in mm)

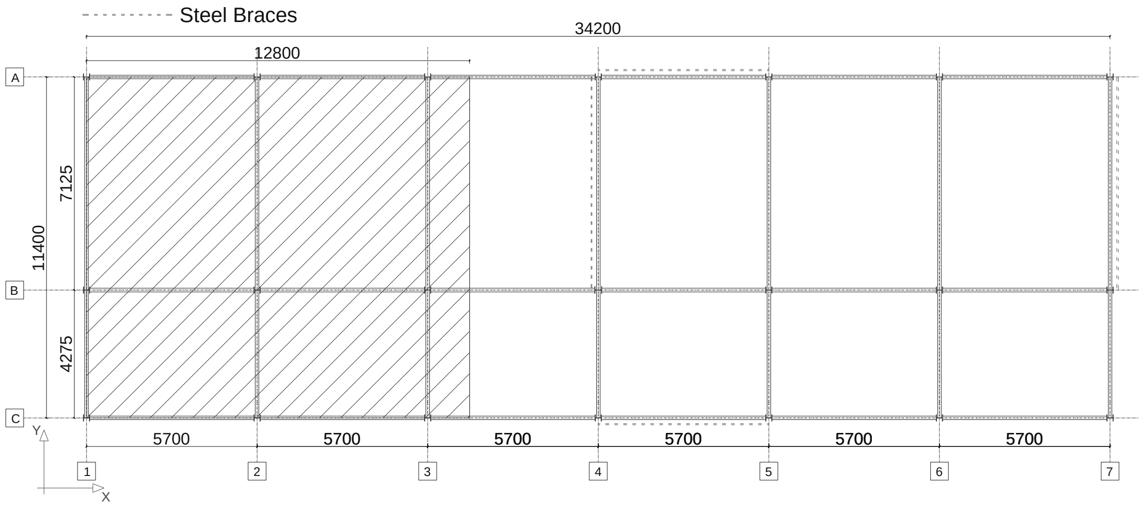

Fig. 2. Floor Framing Plan - Asymmetric Configuration (dimensions in mm)

The Finite Element Models of the 3-D frames used for the design have been developed by using the SAP 2000 program [6]. The frames are assumed fixed at the base in both directions. elastic 2-D elements "*Frame*" are employed to model beams, columns and the steel braces; the elastic "*Shell*" element is used to model the slab. The contribution of the composite action is considered in the analyses by rigidly connecting the slab to the steel beams in order to simulate the complete interaction provided by the shear connection. The global initial sway imperfection is accounted for directly in the model, while the effect of members' bow imperfections is considered when checking the individual structural elements. The creep of concrete has been allowed for by using the appropriate modulus of elasticity of the concrete depending on the design situation. All the beam-column connections are bolted flush end-plate connections as shown in *Fig. 3*. The rotational response of beam-column joints is calculated by means of the component method as specified in the Eurocodes [3, 4].

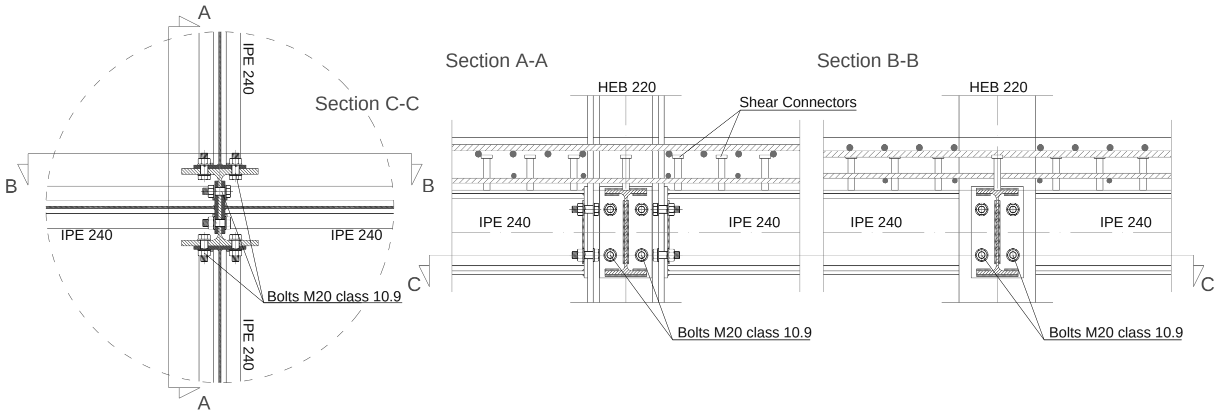

Fig. 3. Beam-Column Interior Joint with Flush-End Plate Connection

2 DESIGN OF THE EXPERIMENTAL TESTS

The experimental tests will be performed on a portion of the first floor of the corresponding full-frame, which will be referred to hereinafter as sub-frame. The floor framing plan of the sub-frames for the Symmetric and Asymmetric configurations are represented by the dotted area in *Figs. 1* and *2* respectively.

In order to design the experimental tests, refined Finite Element Models of the full-frames and sub-frames were developed by using the Abaqus program [7]. The tests will be performed in a three steps sequence. In the first step, the gravity load is applied on the slab defining the condition before the column's collapse; in the second step the central column is 'removed', while in the third step, additional load is applied onto the slab up to the collapse in order to get an appraisal of the available safety margin. While the first step is performed by using a static analysis, the second and third steps are modeled by a quasi-static analysis calibrating the velocity of the column displacement by checking that the ratio between the kinetic energy and the internal energy remains very low, so assuring that the dynamic effects are negligible. In *Fig. 4* is reported the sequence of the column collapse respectively in the full-frame and in the sub-frame.for the symmetric case.

The sub-frame should be restrained in a way that permits simulation of the presence of the remaining part of the structure and this issue was of primary interest in the preliminary study for the test design. The sub-frame is 'extracted' from the ground floor of the full-frame and hence the columns are fixed at the strong floor. The columns are longer than the story height, and continue up to the middle height of the second story, where they are connected among them by steel truss elements as represented in *Fig. 5a*. This specimen's configuration allows for approximating well the distribution of the moments in the columns and the rotational stiffness of the beam-column joints. While the definition of the columns' upper restraints was almost immediate, calibration of the connection between beams and slabs with the reaction system required greater attention. The results of this investigation are reported in Baldassino et al. 2013 [5]. In particular, only the steel beams are restrained while the slab is not connected to the reaction wall. The presence of the bracings in the full-frame prevents from any significant longitudinal displacement and hence, the relevant d.o.f. U1 is fully restrained in the sub-frame. This d.o.f. is left free at the central beam (B in *Fig. 6*) where the vertical and lateral displacements (U2 and U3) are restrained. The adequacy of these choices was confirmed by comparing the results of the numerical analysis of the full-frame and of the sub-frame. *Fig. 5a* reports the 3-D representation of the sub-frame including the elements employed to reproduce appropriate boundary conditions. *Fig. 5b* represents the position of the sub-frame in the laboratory and the relative position with respect to the reaction walls.

a) **b)** **c)** **d)** **e)** **f)**

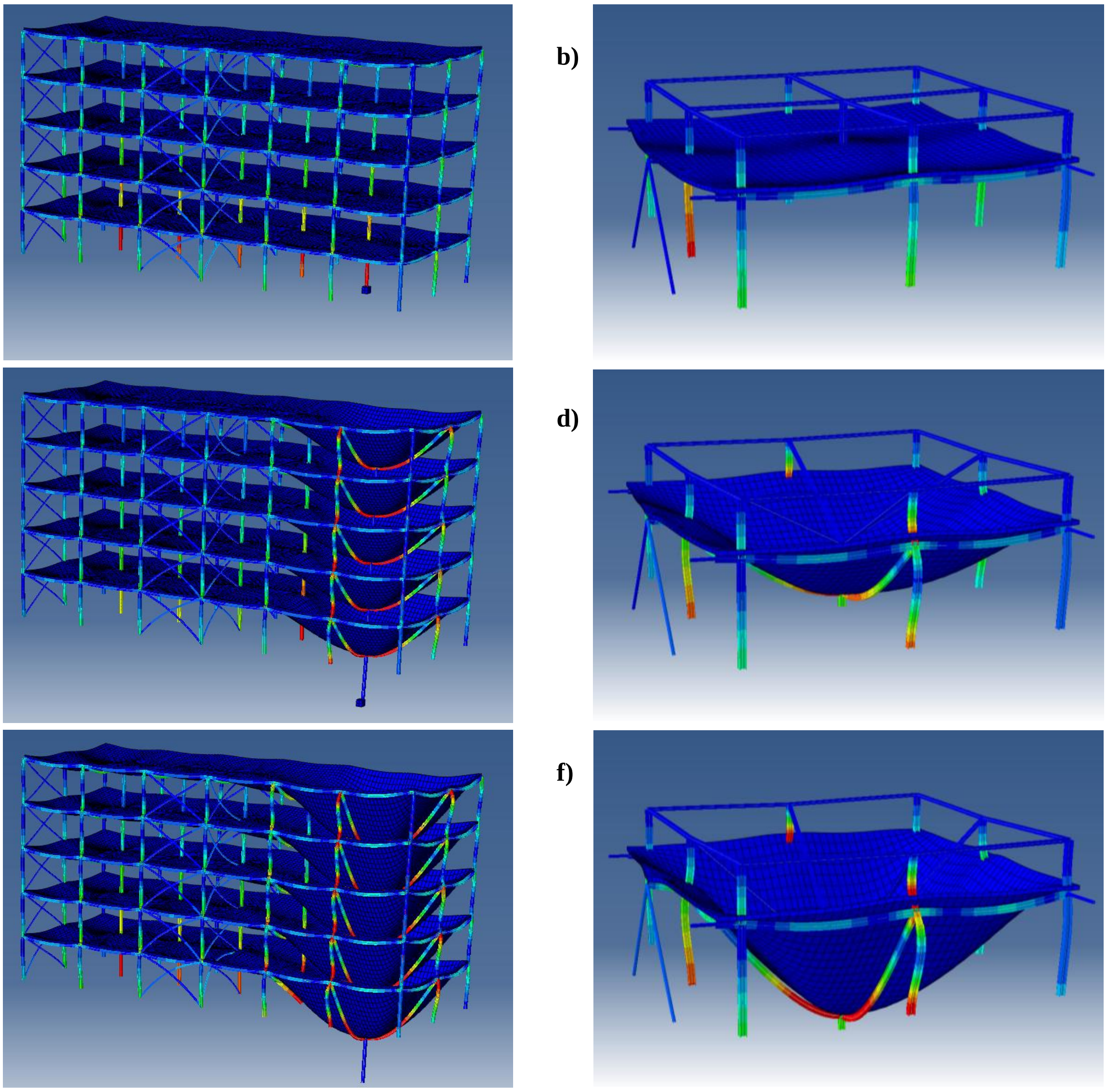

Fig. 4. Sequence of collapse for the full-frame and sub-frame with the following loading steps: a) and b) Application of gravity load; c) and d) Removal of column; e) and f) Increase of load.

a) **b)**

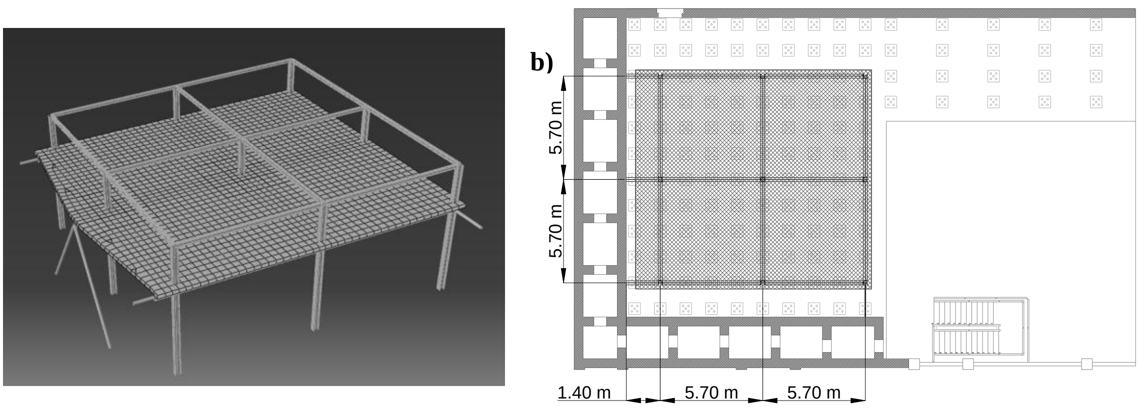

Fig. 5. Sub-frame for the Symmetric configuration: a) 3-D representation; b) Position in the laboratory

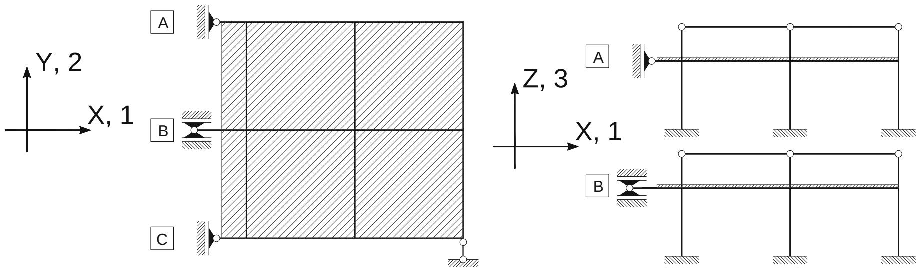

Fig. 6. Restraining condition for the sub-frame - Symmetric configuration

2.1 Increase of load after the column removal

Additional load should be applied onto the slab up to the collapse in order to get an appraisal of the available safety margin. However, application of a distributed load in the frame during the experimental test is not feasible and other solutions have been explored. During the first and second steps the presence of the column is simulated by using a hydraulic ram in which the compression force is gradually reduced down to zero. The hydraulic ram might then used to apply a tension force so simulating the increase of the vertical load in an ‘easy’ and feasible way. The influence on the frame response of this loading approach was explored by comparing the results of the numerical analysis of the full-frame and of the sub-frame by using the two different loading solutions. The responses were compared in terms of deformations and internal forces at several significant sections of the structure identified in *Fig. 7*. Due to the space limitation, only the results related to section 1 of the Symmetric configuration are here reported, similar results have been obtained for the Asymmetric configuration.

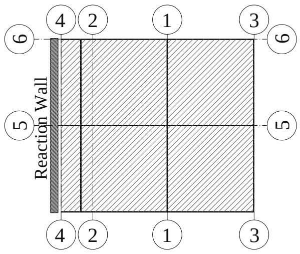

Fig. 7. Significant sections used for the comparison - Symmetric configuration

In order to permit the comparison between the results of the sub-frame and of the full-frame by neglecting the effects of the higher axial load on the columns of the full-frame, concentrated loads are applied on the columns of the sub-frame model and are varied during the analysis in order to simulate the axial force variation of the full-frame. *Fig. 8* shows the comparisons of the vertical displacements and bending moments on the slab positioned on the section 1 of the sub-frame with the concentrated load applied in the central column and the full-frame where the increase of load is made by increasing the distributed load on the slab. The dotted lines indicate the responses of the sub-frames while the continuous line is related to the full-frame. The responses are reported for three steps of the numerical tests. In the step 1 the gravity load is applied on the slab, in step 2 the central column is completely removed, while in the step 3 the load on the slab is increased with a load factor equal to 1.3. In this case the concentrated force is the equivalent force based on the influence area of the central column. By looking at *Fig. 8* is possible to observe that there is almost no difference between the results obtained in the step 1 and 2. This result confirms the adequacy of the boundary conditions adopted to simulate the presence of the remaining part of the full-frame. Moreover, the results for the step 3 indicate that the proposed solution is able to approximate more than satisfactorily the behavior of the full-frame in term of displacements (with an error of 1.5 %) and bending moments. Similar results were obtained also for the other sections identified in *Fig. 7* and by comparing other quantities (i.e. shear, axial force, etc.). The analyses demonstrate that is possible to apply a concentrated force in the central column to increase the vertical load during the test in order to investigate the available safety margin.

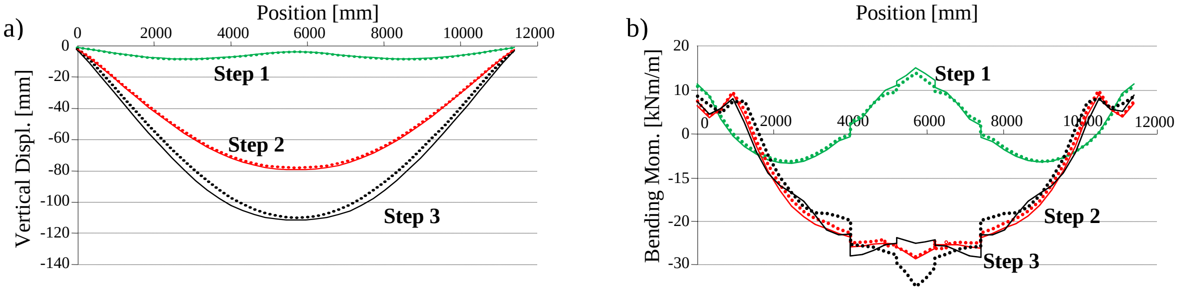

Fig. 8. Comparison of the vertical displacements and bending moments of the Section 1 - Symmetric configuration

3 CONCLUSIONS AND FUTURE DEVELOPMENT

The paper illustrates the preliminary study of an experimental investigation about the robustness of the steel-concrete composite frames. The test structures consist of two 3-D frames with 2 bays by 2 bays and one story and they are extracted from full-frame structures accurately chosen as case studies. Each specimen will first be subjected to the design vertical load and then the 'central column' of the frame will be 'removed' simulating its collapse as consequence of an accidental action. Finally, the load will be increased further to appraise the residual margin of safety of the system. The central column is simulated by a hydraulic ram in which the compression force is gradually reduced down to zero. A further increase of the distributed load on the slab not being possible, the hydraulic ram will then apply a concentrated tension force up to the collapse situation. The feasibility of this loading solution has been explored by comparing the results of numerical analyses of full-frame and of sub-frame under the two different loading solutions. The numerical analysis showed that while the load on the slab is increased with a load factor equal to 1.3, the proposed solution approximates more than satisfactorily the behavior of the full-frame in term of displacements and bending moments.
The specimen related to the symmetric configuration was just built up and the results of the test will be available in the next few months.

4 ACKNOWLEDGMENTS

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