ROBUSTEZZA DI SISTEMI INTELAIATI MISTI ACCIAIO-CALCESTRUZZO: IL MECCANISMO RESISTENTE DI PIANO IN CASO DI COLLASSO DI UNA COLONNA

ROBUSTNESS OF MOMENT RESISTING STEEL-CONCRETE COMPOSITE FRAME: THE FLOOR RESISTING MECHANISM IN THE CASE OF COLUMN COLLAPSE

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ABSTRACT

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. Accidental actions can be resisted by residual strength and alternate load path methods. Combination of these strategies can lead to an effective and cost efficient design strategy for progressive collapse mitigation by redistributing the loads within the structure. The first part of the study investigates the behavior of two geometrically different steel-concrete 3D composite frames subjected to the loss of an internal column. Two full-scale experimental tests will be performed on a part of the structure, 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 3D slab system in terms of activation of 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.

SOMMARIO

L'articolo illustra il lavoro preliminare svolto all'interno di un Progetto di Ricerca Europeo con l'obiettivo di definire nuovi principi di progetto per strutture miste acciaio-calcestruzzo nei confronti di azioni eccezionali. Le azioni eccezionali possono essere fronteggiate attraverso criteri sia di sovraresistenza sia di ridondanza strutturale. La combinazione di questi criteri può portare alla definizione di metodi di progetto efficaci ed economicamente efficienti atti a garantire la sicurezza nei confronti di un collasso progressivo attraverso la ridistribuzione dei carichi all'interno della struttura. La prima parte della ricerca si concentra sul comportamento di due telai 3D a struttura mista acciaio-calcestruzzo, differenti per geometria, nei confronti del collasso di una colonna interna. Due prove a scala reale saranno eseguite su una parte di queste strutture, e il presente articolo illustra lo studio preliminare necessario per il progetto delle prove. Simulando il collasso completo di una colonna sarà possibile studiare la ridondanza del sistema tridimensionale fornito dalla soletta attraverso l'attivazione delle forze membranali. Una importante risorsa addizionale è offerta dalla

ridondanza del telaio garantita dal progetto di nodi duttili. La valutazione di questo aspetto è anch'essa tra i principali obiettivi del progetto.

1 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 parts are damaged or destroyed.

Since 1940 there has been a growing interest to understand the response of reinforced concrete (RC) structures subjected to extreme loads such as impacts or blast but 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 RC 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. However, the design of steel and composite members for such loads is almost unknown in practice and an efficient design for steel or composite structures against impacts is hardly possible because nearly no standards are available considering this exceptional event in a more detailed way.

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 fact, steel and composite vertical elements are not utilized at their full potential due to the lack of appropriate knowledge. Up to now, impact investigations on steel members looked at the member behavior itself, neglecting the influence of the supports and of the surrounding structure. The continuity of the members and the floor 3D action represent essential factors ensuring a robust structural response. Therefore, the investigation of robust design should focus on the redundancy offered by the joints, including the column bases, and by the 3D performance capabilities of the floor system.

The main goal of the study carried out in Trento is get an insight on the behavior of steel-concrete composite 3D framed structures subjected to a sudden loss of column. Two full-scale experimental tests will be performed on frame sub-structures focusing on the response of the slab and of the joints. In this paper, the preliminary work needed to design the two experimental tests is presented.

2 DESIGN OF CASE STUDY STRUCTURES

Two five-story steel-concrete composite structures have been selected as case studies. The overall dimensions of the buildings plan are 34.2m (6 bays) in the X direction by 11.4m (2 bays) in Y direction and the total height is of 18 m. Two geometric configurations of the frames have been considered in this study. One configuration is symmetric with respect to both the directions while the other one is symmetric only with respect to the Y direction. The two case study structures will be referred to hereinafter as Symmetric and Asymmetric configurations respectively and are shown in Figs. 1 and 2. The geometric features of the structures have been chosen to be representative of composite steel-concrete frames in Europe. Both the structures have an inter-story height of 3.60m and a bays span in the X direction of 5.70m. In the Y direction the Symmetric frame has a bays' span of 5.70m while, in the Asymmetric frame the width of the two bays is of 7.125m and 4.275m respectively. 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 the same thickness of the slab (150mm) and the same 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 designed to resist the horizontal actions in Y direction is asymmetric in both the frames. This solution can lead to a low torsional stiffness of the structure and to less effective seismic performance. However, in this case, seismic forces are not considered and this choice is useful 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.

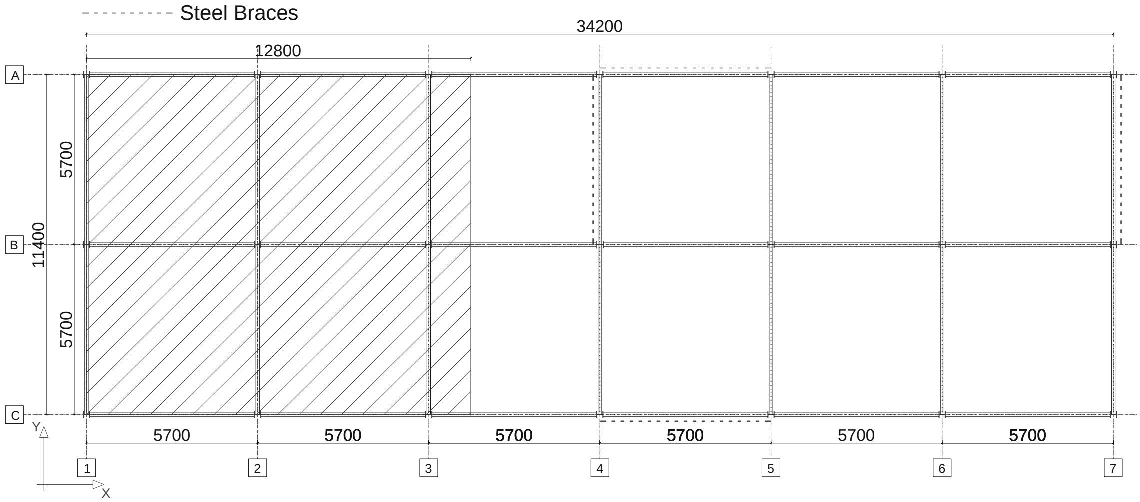

Fig. 1: Floor Framing Plan - Symmetric Configuration (dimensions in mm).

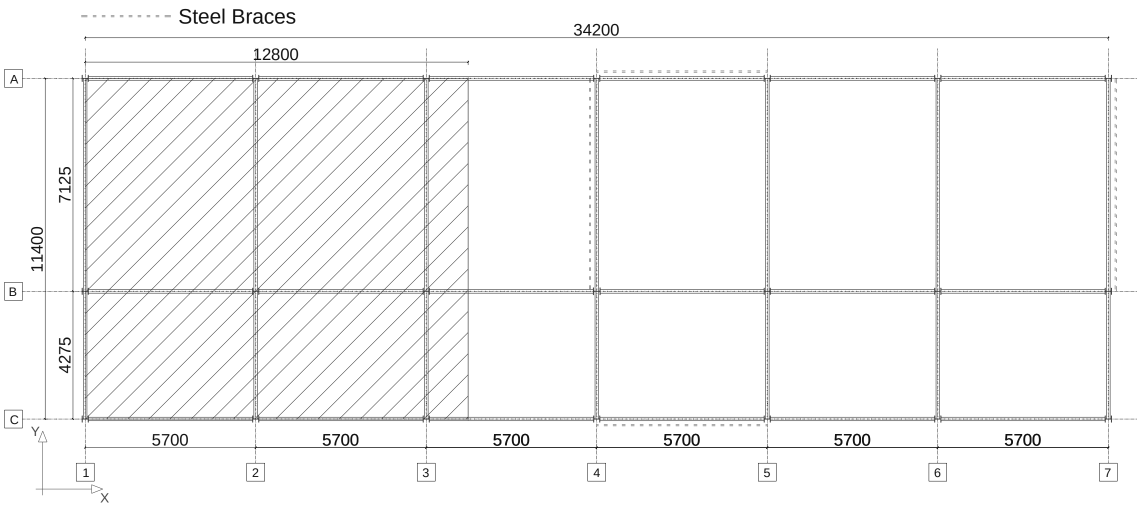

Fig. 2: Floor Framing Plan - Asymmetric Configuration (dimensions in mm).

The Finite Element Models of the 3D frames used for the design have been developed by using the SAP 2000 program [5]. The frames are fixed at the base in both the directions and employ elastic 2D elements "*Frame*" 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 has been accounted for directly in the model, while the effect of bow imperfections has been considered when checking the individual structural elements. The creep of concrete has been considered in the design by using the appropriate modulus of elasticity of the concrete depending on the design situation. The beam-column joints are generally characterized by a rotational stiffness calculated by using the component method as reported in the Eurocodes. The external joints between beams and columns are modeled as pinned joints in the Y direction, where the beams are connected to the web of the column. The beam-column connections are always bolted flush end-plate connections as shown in Fig. 3.

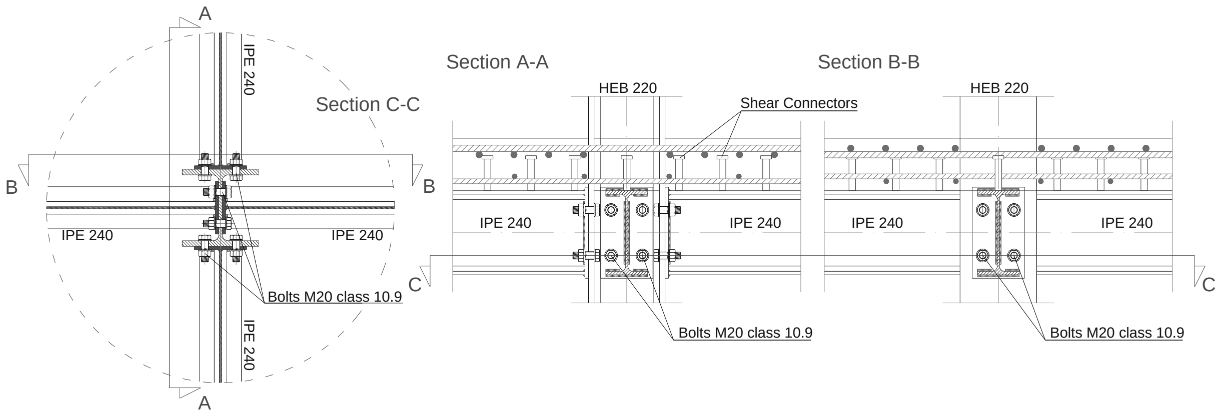

Fig. 3: Beam-Column Interior Joint with Flush End-Plate Connection.

3 DESIGN OF THE EXPERIMENTAL TESTS

The experimental test 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, accurate Finite Element Models of the Full-frames and Sub-frames were developed by using the Abaqus program [6]; beams and columns are modeled as "*Frame*" elements while the slab is modeled as a "*Shell*" element. The rebars are embedded within the slab, the slab is rigidly connected to the beams and, in this preliminary study, a rigid connection is considered between the beams and the columns. The structural steel and the rebars are modeled by an elasto-plastic material model, while the stress-strain relationship for the concrete follows the Popovics law.

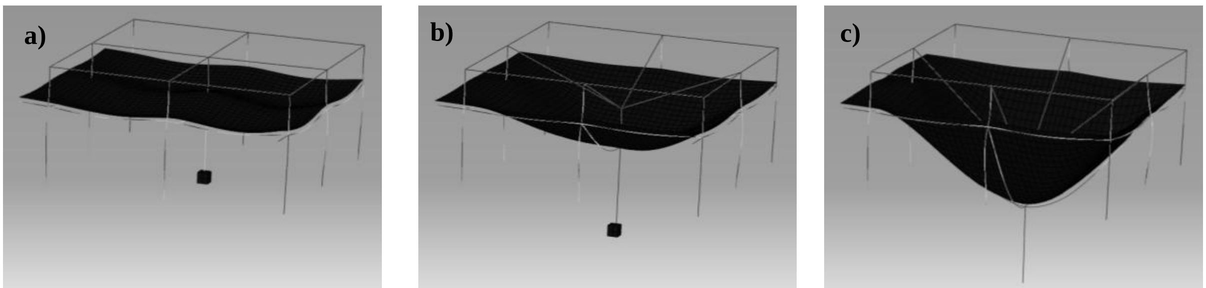

Fig. 4: Loading steps: a) Application of gravity load; b) Removal of column; c) Increase of load.

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 remain very low, so assuring that the dynamic effects are negligible. A view of the Sub-frame response in the three steps is illustrated in Fig. 4.

3.1 Sub-Frame Boundary Conditions

Due to the space limitation, only the results of the Symmetric configuration are reported and discussed in this section. Similar results have been obtained for the Asymmetric configuration. Fig. 5a reports the 3D representation of the Sub-frame, while Fig. 5b represents the position of the Sub-frame in the Laboratory and the relative position with respect to the reaction walls.

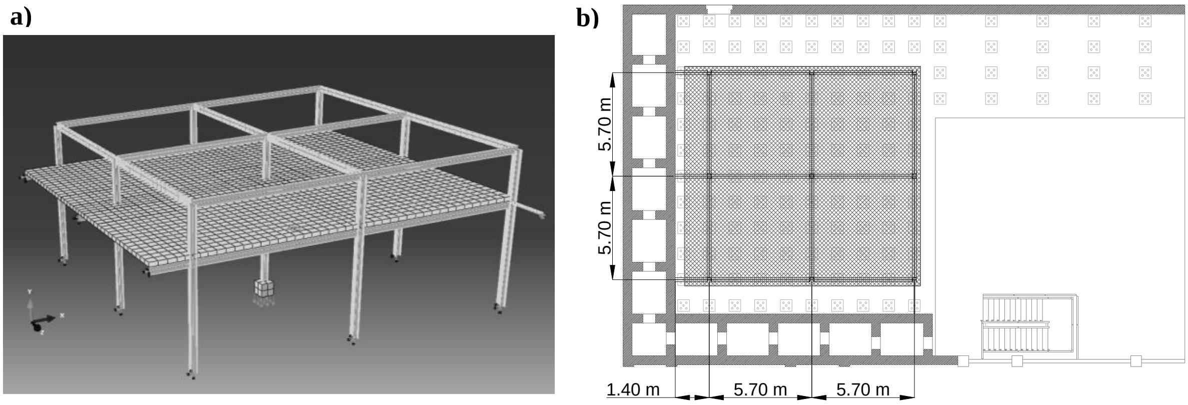

Fig. 5: Sub-frame for the Symmetric configurations a) 3D representation, b) Position in the Laboratory.

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 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. The adequacy of these choices was confirmed by comparing the results of the numerical analysis of the Full-frame and of the Sub-frame.

While the definition of the columns’ restraints was almost immediate, calibration of the connection between beams and slabs with the reaction wall required greater attention. Three different restraining options, as illustrated in Fig. 6, were considered in the analyses, and the main results in terms of deformations and internal forces were compared with the corresponding ones obtained by the analysis of the Full-frame. In particular, the adequacy of the boundary restraints is checked by comparing the response at several significant sections of the structure reported in Fig. 7. In this paper, only the results related to section 1 are reported.

In the Option 1 and 3, only the steel beams are restrained while the slab is not connected to the reaction wall. Both the Options consider that the presence of the bracings in Full-frame prevents from any significant longitudinal displacement: i.e., the relevant d.o.f. U1 is fully restrained. This d.o.f. is left free at the central beam (B in Fig. 6). Besides, in the Option 1, the end rotations of beams A and C about both principal axes (R2 and R3) are restrained , and the central beam’s end is restrained against vertical and lateral displacements (U2 and U3), and again against rotations R2 and R3. In the Option 2, in addition to the restraints of the Option 1, also the part of the slab adjacent to the lateral beams are connected, for a width of 0.5m, to the reaction wall, restraining all the translational degrees of freedom. The Option 3 is similar to the Option 1 but all the rotations are released.

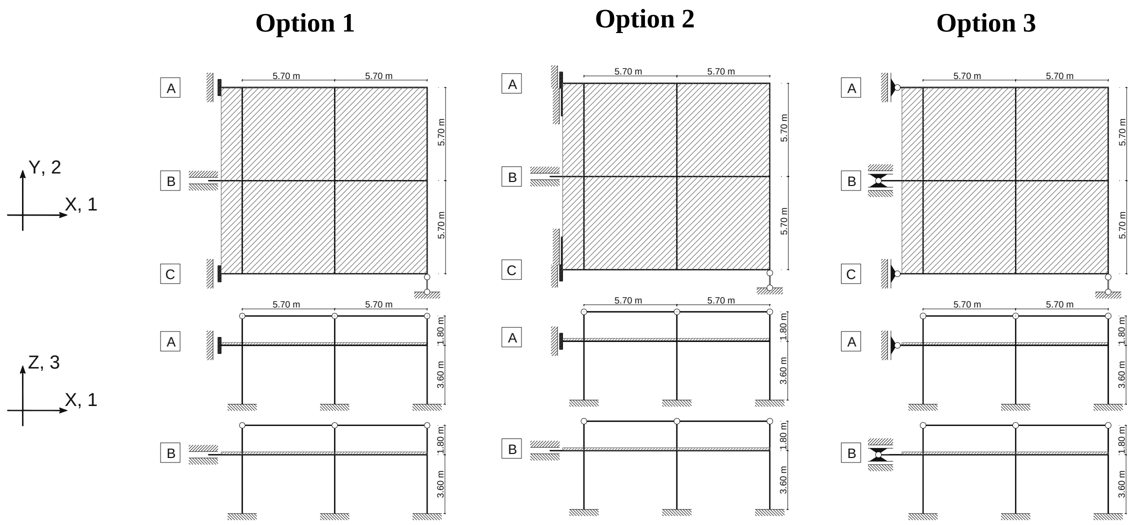

Fig. 6: Restraining Options for the Sub-Frame - Symmetric Configuration.

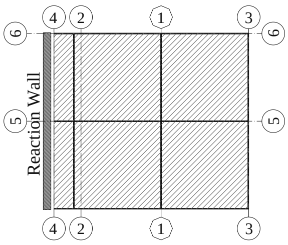

Fig. 7: Significant Sections used for the comparison - Symmetric Configuration.

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 sections 1 of the Sub-frame with one of the three restraining options and the Full-frame. 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 coefficient equal to 1.3. By looking at Fig. 8 is possible to observe that there is no significant difference between the results obtained by the three restraining options. Moreover, is possible to observe all of them are able to approximate more than satisfactorily the behavior of the Full-frame in term of displacements and bending moments. Similar results were obtained also for other sections identified in Figure 7 and by comparing other quantities (i.e. shear, axial force, etc.).

Fig. 9 compares the Von Mises stresses at the bottom and top side of the slab between the Full-frame and the Sub-frame modeled by using the restraints of Option 1. It is possible to observe that the distribution of the stresses obtained in the Full-frame is well approximated by the Sub-frame model. Analogous results have been obtained also by using the restraint Options 2 and 3.

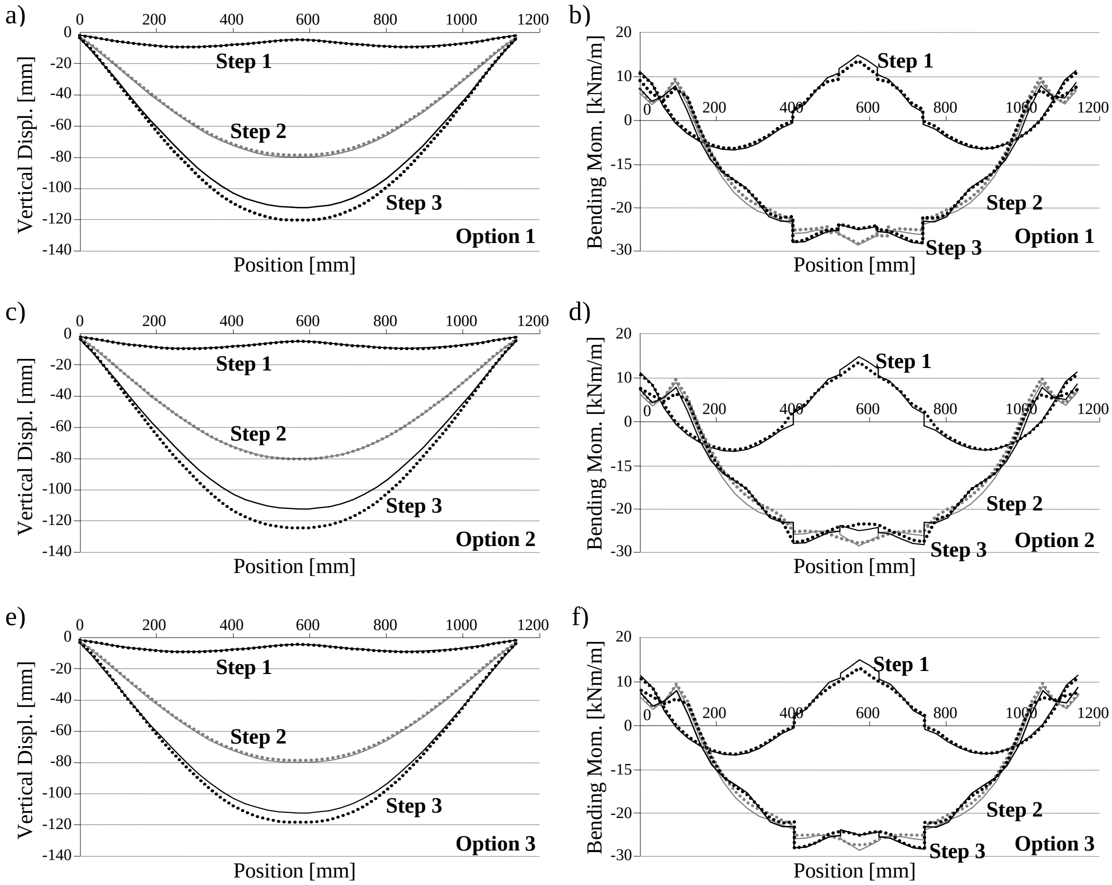

Fig. 8: Comparison of the Vertical displacements and Bending moments on the Section 1 - Symmetric Configuration.

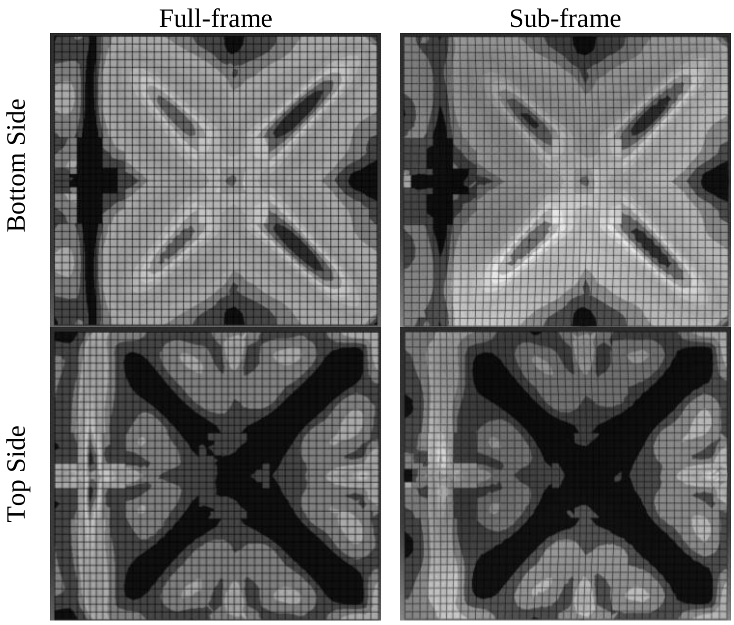

Fig. 9: Comparison of the Von Mises Stresses on the slab - Symmetric Configuration.

The comparison between the results of the three Options clearly indicates that the behavior of the floor subjected to the collapse of the central column is weakly sensitive to the boundary conditions used to its continuity in the Full-frame. This outcome allows the use of the simplest restraining solution during the test.

8 CONCLUSIONS AND FUTURE DEVELOPMENTS

The paper illustrates the preliminary study of an experimental investigation about the robustness of the steel-concrete composite structures. The test structures consist on two 3D frames with 2 bays by 2 bays and one story and they are extracted from Full-frame structures accurately chosen as case studies. The tests will first be loaded and then the central column of the frame will be removed simulating the collapse as consequence of an accidental action. Finally, the load is increased further to appraise the residual margin of safety of the floor system. The numerical analyses dealt also with the selection of the adequate boundary conditions for the Sub-frame needed to simulate satisfactorily the behavior of the whole structure. A limited sensitivity to the selected restraining condition was pointed out, which indicates the possibility to reduce the complexity of the connection system with the counterwalls.

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KEYWORDS

Steel-Concrete Composite frames; Robustness; Experimental analysis, 3D response, Semi-rigid joints.