# PROGRESSIVE COLLAPSE:
# THE CASE OF COMPOSITE STEEL-CONCRETE FRAMES

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## ABSTRACT

Residual strength and alternate load paths are two fundamental design strategies to ensure adequate resistance against progressive collapse of structures. This paper presents an experimental study carried out on two full-scale steel and concrete composite frames to investigate their structural behaviour in case of a column collapse. The study focusses on the redundancy of the structure as provided by the beam-slab floor system as well as by the ductile beam-to-column joints. The specimens were ground floor sub-frames 'extracted' from two reference buildings designed in accordance to the Eurocodes. The frames have the same overall dimensions, but a different, symmetric and asymmetric, configuration of the column layout. In both tests, the collapse of an internal column was simulated. The paper presents the main features of the frames and the principal outcomes of the test on the symmetric frame.

## INTRODUCTION

In the last decades, important and numerous studies have been conducted about the collapse of structures caused by accidental loss of columns. The interest in studying the effects of extreme loading conditions has being triggered by a few catastrophic events occurred in recent years since the Ronan Point Building case (UK, 1968). These tragic events lead many countries to include, in their design codes [1-6], integrity and structural robustness requirements in order to design a *robust* structure. As to design principles, the Eurocode 0 [7] prescribes that "a structure shall be designed and executed in such a way that it will not be damaged by events such as explosion, impact and the consequences of human errors, to an extent disproportionate to the original cause". As to design practice, the Eurocode 1-7 [4] provides several strategies to design structures against accidental events. In particular, strategies for identified accidental actions and strategies for limiting the extent of localised failure.

Column loss in a building is one of the most common and effective damage scenario recommended for progressive collapse investigations. The collapse of vertical members causes dynamic effects, large deformations of the floor system and high rotation in the beam-to-column connections. The collapse of the entire structure can be avoided if the damaged part is able to redistribute loads to the undamaged parts so that a new stable equilibrium configuration is achieved. In this context of the alternate load paths, the ductility offered by the joints and the 3D performance capabilities of the floor system represent essential factors for a robust structural response. In order to improve the knowledge about progressive collapse and to study the effects that a column loss causes to a structure, 3D full-scale experimental tests are the most complete approach. On the other hand, these experiments are very complex and expensive, and, to date, very few experimental data are available.

Recently, the ‘RobustImpact’ research project [8] studied the robustness of composite steel-concrete frames affected by accidental actions. This European research project aimed at developing a new robust design approach against impact loading based on the residual strength and alternate load path method. Within this project, the University of Trento activity focused on the contribution provided by the concrete slab and by the beam-to-column joints. Analytical, numerical and experimental activities were planned and executed. For a better insight into the mechanisms of forces redistribution in the structures, two experimental tests were conducted on 3D full-scale steel and concrete composite structures ‘affected’ by the loss of an internal column. The specimens had the same geometric and structural properties, but two different column layouts. This paper presents the main features of the experimental study, with particular reference to the main outcomes of the first ‘symmetric’ test.

## THE REFERENCE STRUCTURES

Two ‘typical’ five-storey steel and concrete office buildings were selected as reference structures. In particular, two different columns layouts were investigated: the first configuration is symmetric with respect to both the plan X and Y axes (Figure 1-2), while the second one is symmetric only with respect to the Y axis. In this sense, the structures were named as “*Symmetric*” and “*Asymmetric*” respectively.

The design was based on the Eurocodes rules [9-13] and no seismic consideration was made in order to decouple the issues of seismic and robust design. Structural design aimed at getting for both structures the same section of the structural elements. In particular, columns were HEB220, steel beams IPE240 and concrete slab thickness 150 mm. Beams were made composite with full shear connection. Beam-to-column joints (Figure 3), the same in both structures, were bolted flush-endplate designed according to the component method as in the Eurocode [12]. Structural steel grade S355, rebars grade B450C, bolts class 10.9 and concrete C30/37 were the materials of the structural elements.

## THE SUB-STRUCTURES

The tests were performed on full-scale 2x2 bays sub-frames ‘extracted’ from the first floor of the corresponding reference building, as illustrated by the dotted area in Figure 1. The circle underlines the column that was removed during the test. Plan view and cross section of the symmetric specimen are reported in Figure 4.

Finite element analysis of the full-frame and of the sub-frame provided the background to the design of the experimental test and, in particular, the lateral restraining system that connects the specimen to the counter-walls of the laboratory. The goal of the analyses was to mimic in the test the presence of the bracing system and of the remaining part of the reference structure. Furthermore, a system of crowning beams, pinned to the top of the columns, was set up to take into account the influence of the upper stories of the reference structure. As to the sub-frame restraining system, three different options, as illustrated in Figure 5, were considered in the analysis. Comparing the results in terms of deformations and internal forces with the ones obtained from the analysis of the corresponding full-frame, option 3 was selected, where all the lateral restraints are made up by truss elements connected to the steel frame. More details about the design of the lateral restraining system can be found in [14].

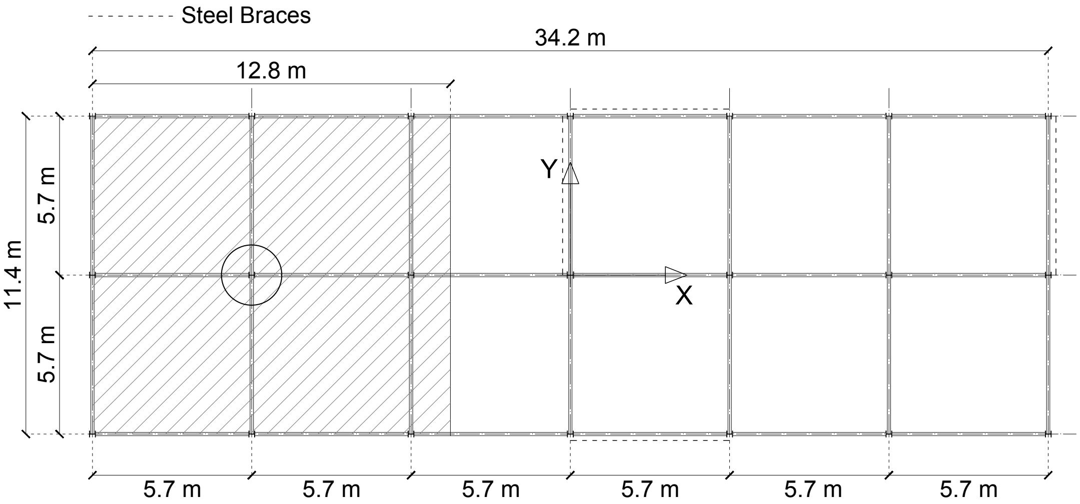


Fig. 1 – The plan view of the symmetric reference building

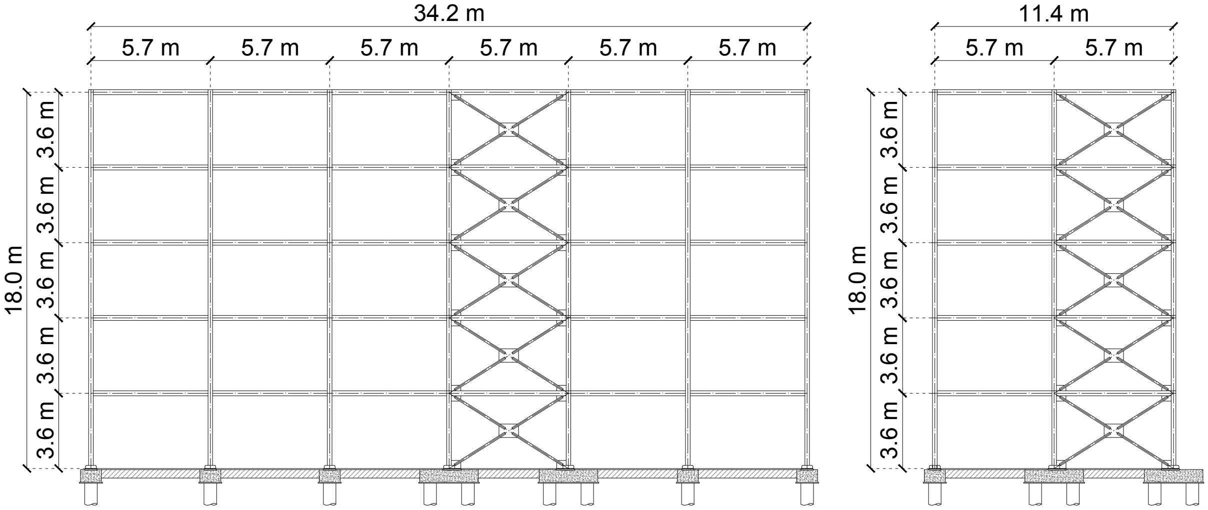


Fig. 2 – Elevation view

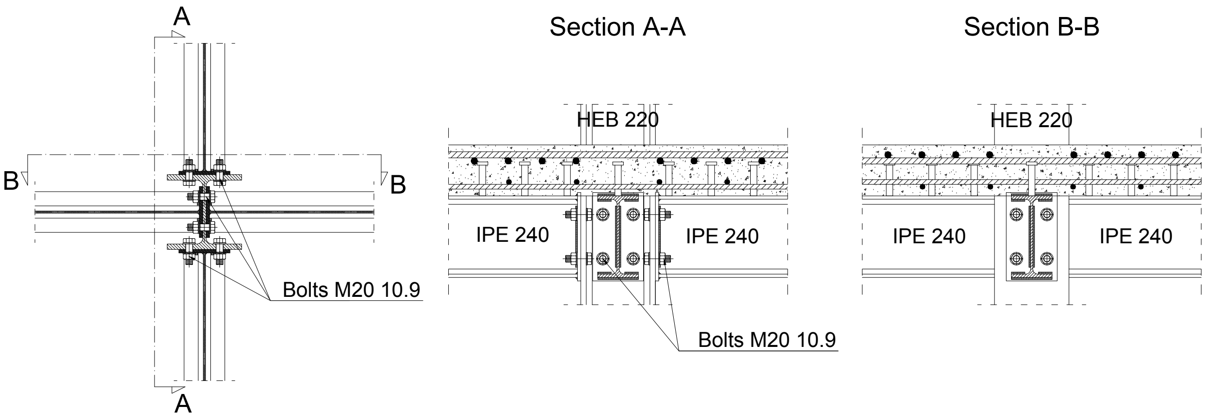


Fig. 3 – Beam-to-column internal joint

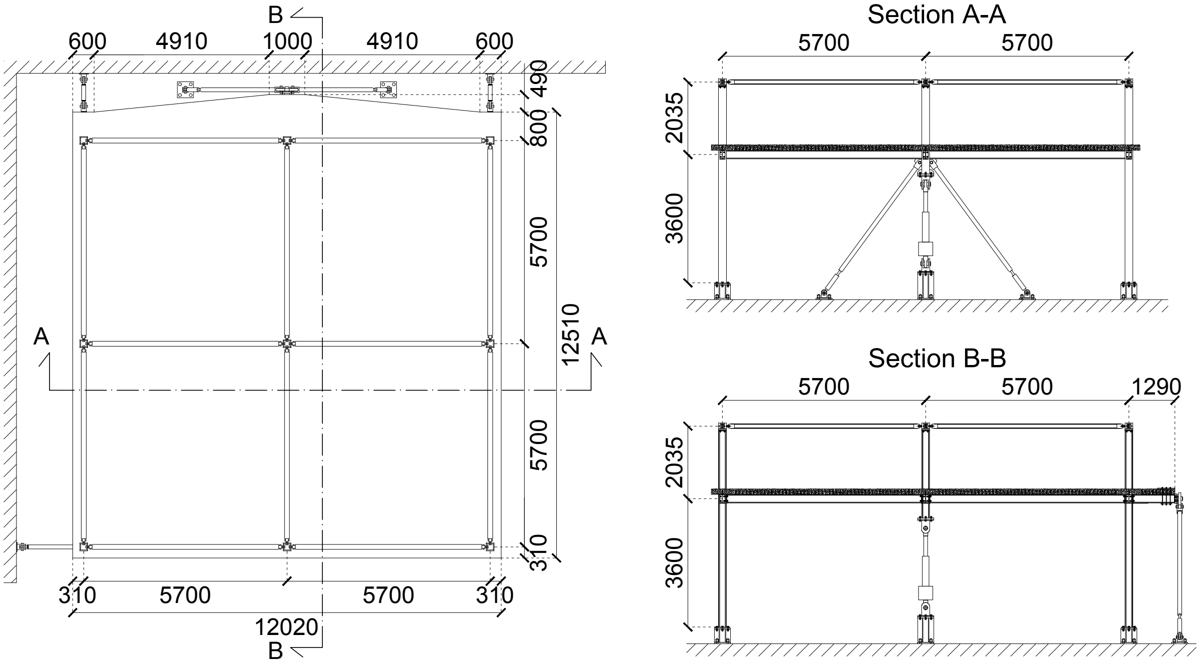


Fig. 4 – Plan view and sections of the symmetric sub-frame (measures in mm)

The specimens were built inside the Laboratory of Materials and Structures Testing of the University of Trento. The construction of the frame started with the erection of the steel skeleton and the formwork installation (Figure 6a-b).The reinforcement bars were then positioned and the concrete poured (Figure 6c). Figure 7a-b shows the symmetric specimen completed, while Figure 7c shows the ‘central column’ that was replaced by a hydraulic jack in order to simulate the collapse. During the constructional phases, the central beams were held in position by using a provisional propping system, which was removed when the hydraulic jack was activated.

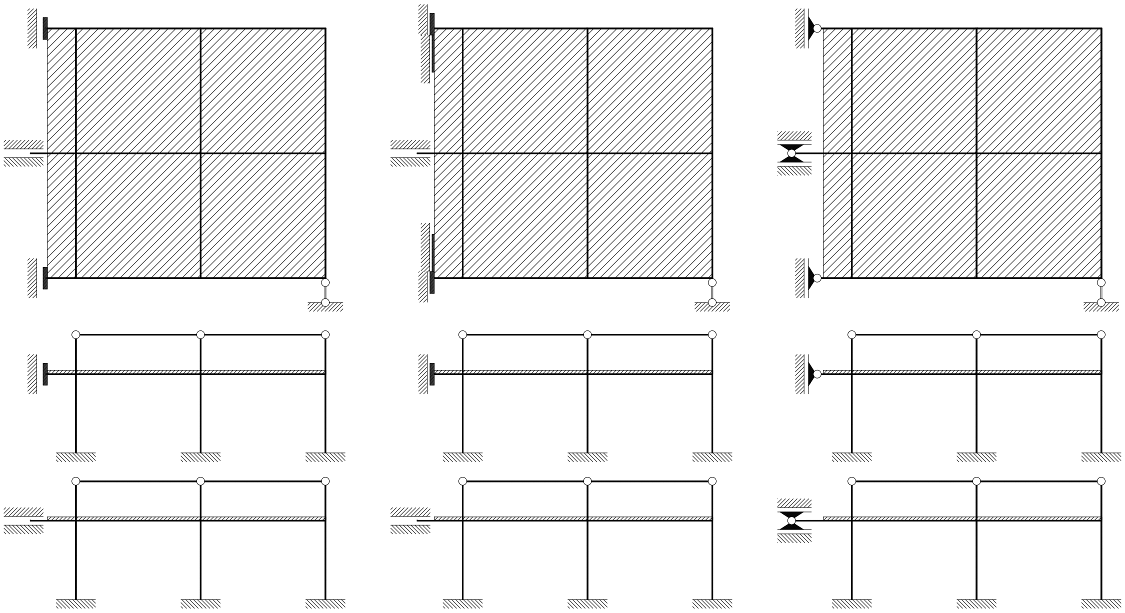

a) Option 1 b) Option 2 c) Option 3

Fig. 5 – Lateral restraints options


a) b) c)

Fig. 6 – The constructional phases

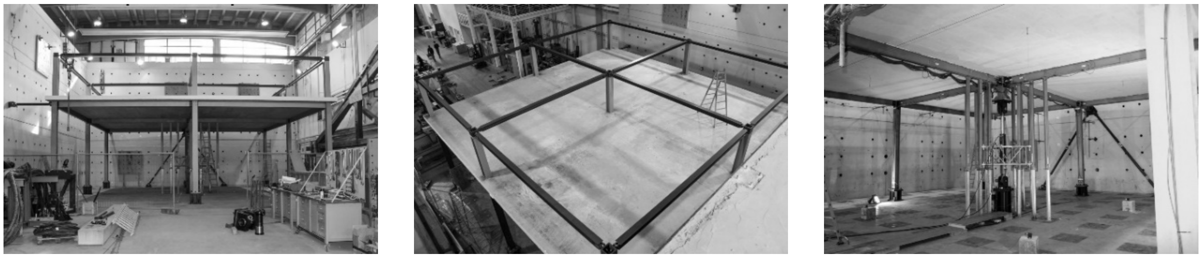

a) b) c)

Fig. 7 – The specimen

## THE MATERIALS

Compression and splitting tests on concrete samples were performed according to the criteria of [15] and [16] respectively. During the casting phase, 18 cubes (150 mm side) and 15 cylinders (150 mm diameter and 300 mm height) were prepared. In order to appraise the evolution of the concrete compression resistance, tests on cubes were performed at age, from casting, of 7, 28 and 102 days (e.g. the time of the full-scale test), while splitting tests on cylinders were conducted at ages of 28 and 102 days. Table 1 reports the measured concrete properties.

As to steel, Table 2 and 3 report the yield stress and ultimate tensile strength of the rebars and structural steel respectively.

Table 1: Concrete properties

| | Concrete's age (days) | n. of tests | Average cube compressive strength (MPa) | Average tensile splitting strength (MPa) |
|---|---|---|---|---|
| Cubes | 7 | 3 | 43.83 | - |
| | 28 | 9 | 56.47 | - |
| | 102 | 6 | 65.74 | - |
| Cylinders | 28 | 6 | - | 3.81 |
| | 102 | 9 | - | 4.25 |

Table 2: Rebars steel properties

| Rebar's diameter (mm) | Yield stress (MPa) | Ultimate tensile strength (MPa) | $A_{gt}$ (%) |
|---|---|---|---|
| 10 | 496 | 586 | 10.5 |
| 16 | 523 | 631 | 9.4 |

Table 3: Structural steel properties

| Component | Yield stress (MPa) | Average yield stress (MPa) | Ultimate tensile stress (MPa) | Average ultimate tensile stress (MPa) | A (%) |
|---|---|---|---|---|---|
| Column HEB220 | 300 | 303.3 | 441 | 440.3 | 34.9 |
| | 306 | | 442 | | 34.5 |
| | 304 | | 439 | | 36.1 |
| Beam IPE240 | 383 | 409.3 | 537 | 540.7 | 28.2 |
| | 391 | | 541 | | 27.0 |
| | 454 | | 544 | | 33.3 |

## THE MEASUREMENT SET-UP

The specimen was extensively instrumented to maximise the information gained from the experiment. Due to the complexity of the frame response, the most important parameters to be measured during the test were carefully identified. The attention was focused on the response of the columns, beams and joints. In particular, strain gauges were installed to measure the strain state at the columns base, at the mid-span of the central and lateral beams and near the central column in the central beams. From the readings of the strain gauges, it was possible to obtain some parameters such as the average axial strain or the curvature of the section, and consequently, assuming the material in the elastic range, the axial force and the bending moment. Strain gauges to measure the axial strain were also installed in the lateral truss restraining elements, in the crowning beams and in some reinforcement bars in the vicinity of the central column. Displacement transducers and inclinometers were installed in correspondence of the beam-to-column connections to measure the joints' rotation. Further transducers enabled to monitor the torsional rotation of the lateral beams and the rotation of the external columns in correspondence of the beams joints. At the central node of the frame, a wire transducer measured the vertical displacement and a load cell the force 'supported' by the central column. Furthermore, the vertical displacements at the centre of the slab panels were monitored. Instruments' signals were logged at a frequency of 2 Hz. Figure 8 provides the layout of the instrumentation set-up, and Table 4 lists the instruments together with the related parameters.

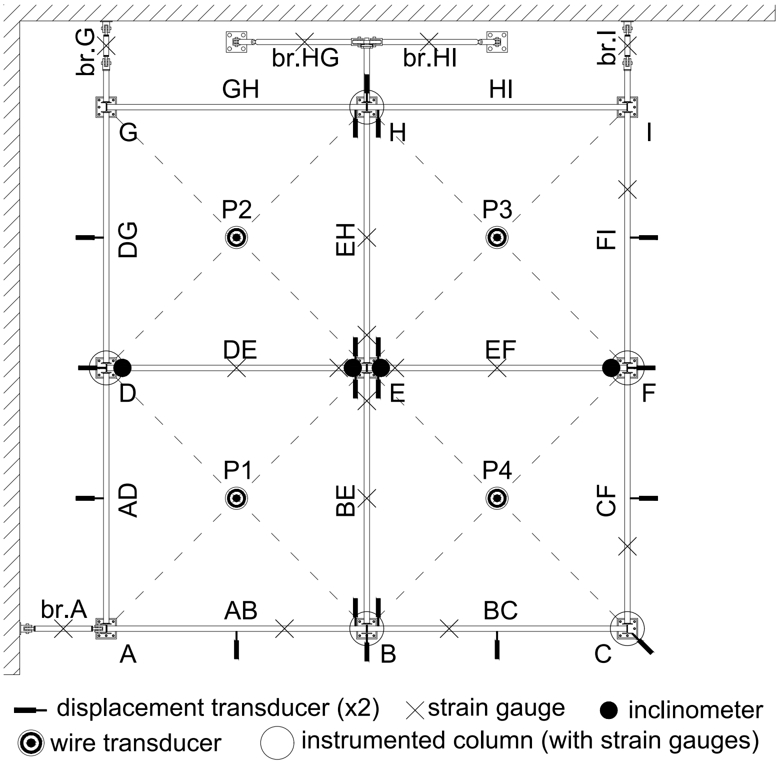


Fig. 8 – The measurement set up

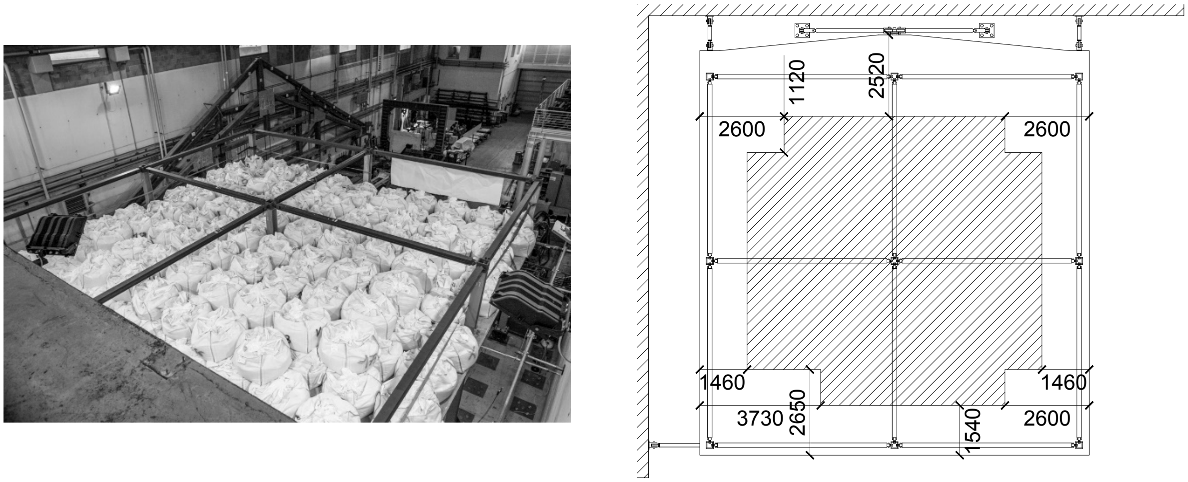
Table 4: Instruments and parameters measured

| Structural element | Instrument | Parameter measured | Parameter deduced |
|---|---|---|---|
| Columns | Strain gauges at the base | Average axial strain | Axial force |
| | | Curvature (strong-weak axis) | Bending moments |
| | Displacement transducers at the beam level | Rotation | |
| Central beams | Strain gauges at mid-span and near the central column | Average axial strain | Axial force |
| | | Curvature (strong axis) | Bending moment |
| Lateral beams | Strain gauges at mid-span | Axial strain | Axial force |
| | Displacement transducers at mid-span | Torsional rotation | |
| Crowning beams | Strain gauges at mid-span | Axial strain | Axial force |
| Lateral restraints | Strain gauges at mid-span | Axial strain | Axial force |
| Reinforcement bars | Strain gauges near the central column | Axial strain | Axial force |
| Joints | Displacement transducers | Rotation | - |
| | Inclinometers | Rotation | - |
| Slab panels | Wire transducer | Deflection | - |
| Hydraulic jack (central column) | Load cell | Axial load | - |
| | Wire transducer | Vertical displacement | - |

## THE TESTING PROCEDURE

The test plan comprises the following phases:

- activation of the hydraulic jack and removal of the propping system;
- application of the vertical loads. At this aim, bags filled with sand were placed on the slab reproducing a uniform distributed load of 8.80 kN/m$^2$ to approximate the factored design load, including finishes, partitions and live loads (Figure 9a). The bags were placed on two layers: the first one is distributed uniformly on the slab, the second one is placed on a reduced area as shown in Figure 9b;
- simulation of the column removal by reducing the pressure of the hydraulic jack down to zero;
- stabilization of the specimen;
- application, by means of the actuator, of a tensile force increasing up to the ‘collapse’.



a) b)

Fig. 9 – Vertical loads on the slab (measures in mm)

## THE MAIN RESULTS

The deflection of the central node is plotted in Figure 10 with respect to the load measured by the load cell (in the graph positive values of the load mean compression). The central column was completely loss at a central node displacement of about 165 mm. The load carried by the central column (E) has redistributed in the other columns as shown in Table 5. As a result, columns B, D and F carried about twice the axial force acting before the column removal. The axial force increase in column H was the greatest due to the nearby restraining truss system. At the contrary, the corner column C unloaded due to the effect of the concrete slab action. The test was ended when, under the applied tension force, the connection between the central column E and the beam EH failed. This occurred for a vertical displacement of approximately 300 mm and a corresponding applied force of 300.85 kN. The failure was associated with the fracture of the two bolts of the bottom row of the joint c (see Figure 12a). At this stage, the column H was the most stressed, while columns B, D and F are stressed almost at the same level (see Table 5). The slab effect ‘maintains’ the corner column C axial force basically constant.

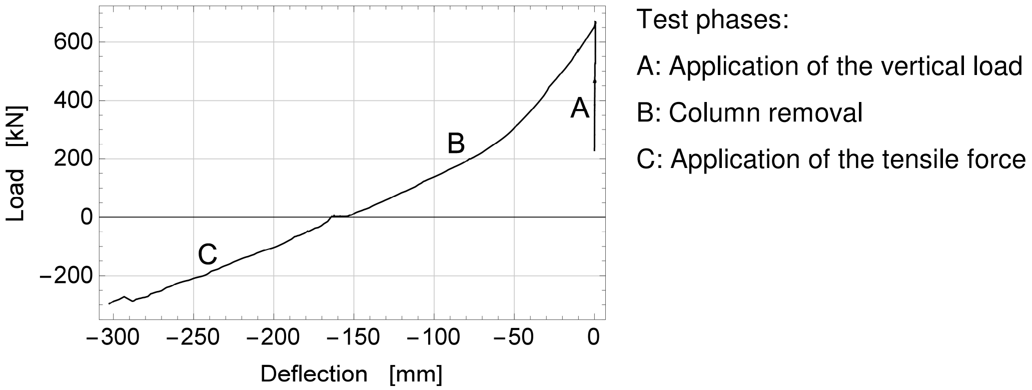


Fig. 10 – Load-deflection relation of the central node

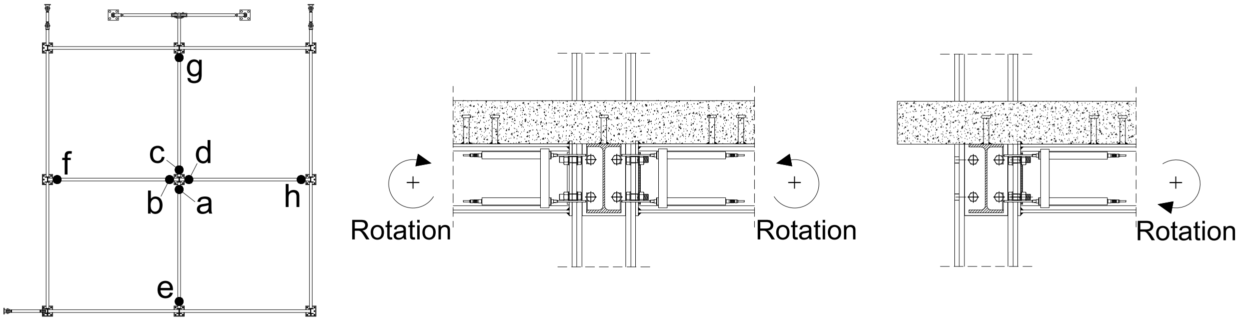
Fig. 11 – The specimen at the end of the test

Table 5: Axial force in the columns (kN)

| Column | End of the loading phase | End of the column removal | End of the test |
|---|---|---|---|
| E | 669.89 | 2.64 | -300.85 |
| B | 143.82 | 319.08 | 373.08 |
| C | 58.01 | 49.49 | 63.01 |
| D | 148.99 | 285.07 | 330.83 |
| F | 151.63 | 308.04 | 365.02 |
| H | 212.07 | 546.84 | 635.54 |

Both central and external beam-to-column joints sustained important deformations at the end of the test. In particular, the following phenomena occurred: at the central node significant plastic deformations of the endplate of the beams BE and EH (Figure 13b-c); instability of the bottom flange of the beam EH in the vicinity of the external column H (Figure 14a); shear deformation of the web panel of column B in correspondence of the connection with the beam BE (Figure 14b); horizontal cracks in the slab at external columns D and F (Figure 14c). Figure 15 reports the connections rotation with respect to the load applied by the hydraulic jack (Joint f rotation is not reported due to an instrument malfunction). The substantial rotational demand is apparent.

Focusing on the central beams, Figure 16 reports the axial force (normalised on the yield force of the steel section) near the central node and at the beam mid-span. As a first appraisal of the response, near the central node (Figure 16a) the axial force evolved from negative to positive due to the change of the bending moment sign during the column removal. In correspondence with the beam mid-span (Figure 16b), the steel section remains in tension during all the duration of the test. The process of passing from a negative to a positive bending moment at the central node was pointed out as well by the evaluation of the axial strains in the instrumented reinforcement bars near the central column E. During the application of the tensile force by the jack, the rebars registered a significant axial force increase, and, at the end of the test, some bars reached the yielding force.



a) Joints position b) Central joints c) External joint

Fig. 12 – Joints position and positive rotation assumption

a) Central node b) Connection a c) Connection c

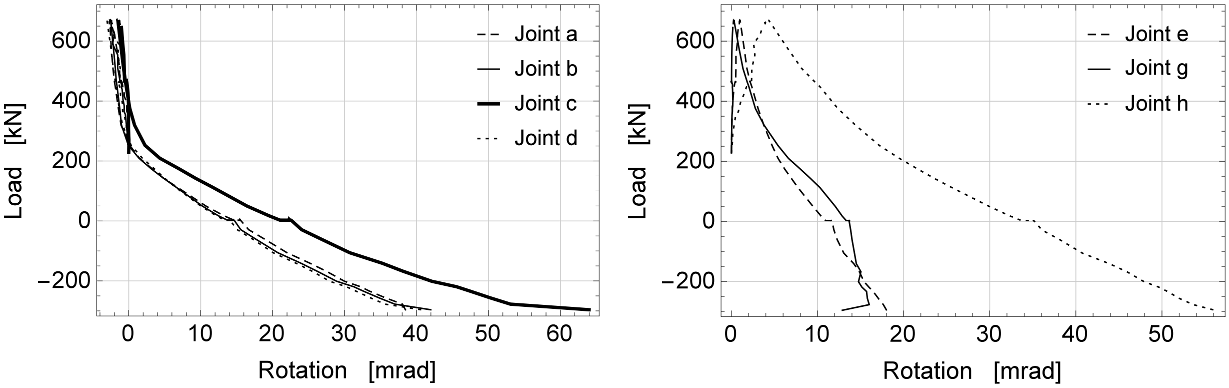
Fig. 13 – Central connections at collapse (see Figure 12a)

a) Connection g b) Connection e c) Joint f

Fig. 14 – External connections at collapse (see Figure 12a)

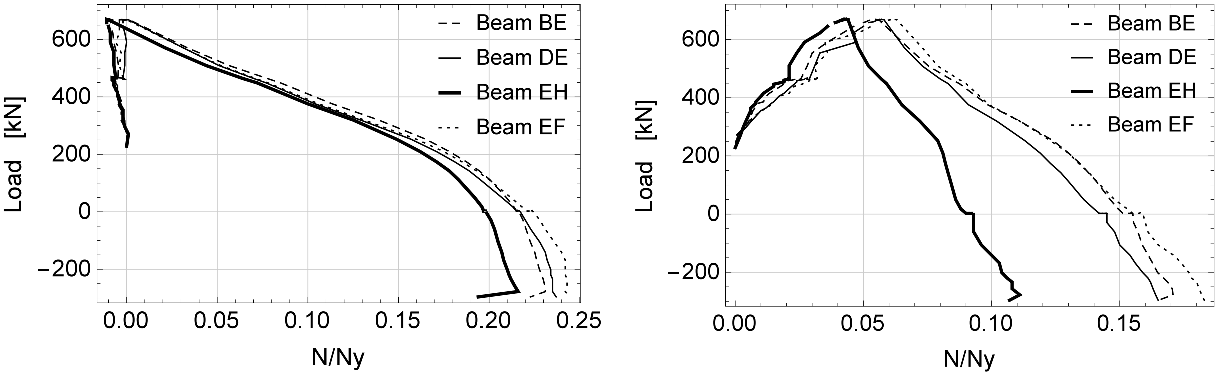
## CONCLUDING REMARKS

This paper presented the main results of an experimental test performed at the University of Trento on a full-scale steel and concrete composite structure subjected to a column loss. It enables investigating the importance of the joints' ductility and the role of the concrete slab for allowing the forces redistribution in the structure associated to the alternate loading path activated after the column loss.



a) Internal connections b) External connections

Fig. 15 – Connection rotation



a) Near the central node b) At the beam mid-span

Fig. 16 – Axial force in the central beams

The full-scale specimen was ‘extracted’ from the first floor of a reference building designed in accordance to the Eurocodes. The central column collapse was simulated by replacing the column with a hydraulic jack that was kept inactive before the beginning of the loading. The test was carried on with the following sequence: the hydraulic jack was first activated and the propping system removed, the vertical loads were then applied on the slab and the column removal was simulated reducing the pressure of the jack down to zero. Finally, with the aim of appraising the structural residual strength, an incremental tension force was applied at the central node up to the ‘frame collapse’ associated with the failure of a central joint.

The results reported in this paper pointed out that the joints, designed as ductile, enable achievement of very high rotations. Joint ductility is provided by plastic deformations, mainly of the end-plate and the column web in shear. Local beam buckling and horizontal cracks of the outstanding slab at external joints should be considered in order to ensure adequate ductility.

Despite the collapse was associated with joints’ failure, the key role of the slab for ensuring loads and forces redistribution from the damaged to the undamaged parts of the structure is apparent.

The cracking pattern on the top side of the concrete slab revealed the formation of ‘compressive rings’ typical in slabs where the membrane forces are activated.

## ACKNOWLEDGMENTS

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