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Use of different numerical models to evaluate the robustness of reinforced concrete frame structures

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Abstract

According to Eurocodes, robustness is 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 [1].
Avoiding the progressive collapse of a building in presence of accidental loading conditions is one of the challenges for the designers.
The tie-force method is actually one of the most used design techniques for resisting progressive collapse, whereby a statically indeterminate structure is designed with reference to local simplified models determined in accordance to the failure mode considered.
In this work a computational study of a reinforced concrete frame is presented. The structure studied is a beam-column assembly which represents a portion of the structural framing system of a ten-story reinforced concrete frame building and is subjected to distributed loads and to monotonically increasing vertical displacement of the centre column to simulate a column removal scenario.

Keywords: Structural robustness, Tie-force method, Progressive collapse, Reinforced concrete.

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1. Introduction

The concept of structural robustness is applicable to a wide field, for this reason is not possible to give a univocal definition. In civil engineering, the expression structural robustness is used to indicate an inherent property of a structure that allows it to resist against an accidental event, preventing a progressive and/or disproportionate collapse.

Progressive collapse is one that affects more structural elements connected together, which collapse one after the other as happens, as an example, in a house of cards or with the dominoes; the concept of disproportionate collapse instead, is closely related to the event that caused it: the structure can be damaged as a result of an exceptional event, but damage must be proportional to the cause that produced it.

In order to prevent the progressive collapse can be adopted different strategies, one of the most used is the tie force method, which exploits the tie-behaviour of the beams in presence of large displacements.

Below will be numerically reproduced a load test on a beam-column assembly and will be analysed the structural behaviour in presence of different loads applied.

2. Test description

The full-scale specimen used is a beam-column assembly, part of an Intermediate Moment Frame (IMF), of a ten-story prototype reinforced concrete building for office occupancy, presented in [2].

All beams and columns were designed with concrete having a nominal compressive strength of 413.7 MPa. Tables 1 and 2 show the average compressive and tensile strengths of concrete and the mechanical properties of reinforcing bars used for the test.

As shown in Fig. 1, all beam longitudinal bars were anchored at the exterior beam-column joints by means of mechanical anchorage to simulate continuity of the longitudinal bars in the actual frame.

The footings for the end columns were designed to simulate two fully restrained joints. The top of the end columns were restrained from horizontal movement by a two-roller fixture, while the other degrees of freedom were allowed.

To apply the load to the centre column were used four 534 kN hydraulic jacks placed below the strong floor of the laboratory; the load was transferred to the specimen using four post-tensioning rods anchored to a steel plate that transferred the load at the top of the column. The test was performed under displacement control at a rate of approximately 25 mm/min. The use of four different hydraulic jacks to apply the load enabled control of any possible in-plane rotation of the centre column in the advanced stages of loading; while out-of-plane movement of the assembly was restrained by four steel channels fixed to the floor. Furthermore pulling down the beam with jacks, rather than pushing it from a support above, minimized the tendency for lateral movement of the beam.

Table 1. Concrete mechanical parameters.

Element	Compressive Strength f_c' (*MPa*)	Split-Cylinder Tensile Strength f_t' (*MPa*)
Footings	39	-
Beams and Columns	32	3.1

Table 2. Reinforcing bars mechanical and geometrical parameters.

Heat	Bar size	Bar Diameter (mm)	Yield Strength f_y (MPa)	Ultimate Strength f_u (MPa)	Rupture Strain (%)
A	#8	25.40	476	648	21
B	#9	28.65	462	641	18
C	#9	28.65	483	690	17
D	#4	12.70	524	710	14

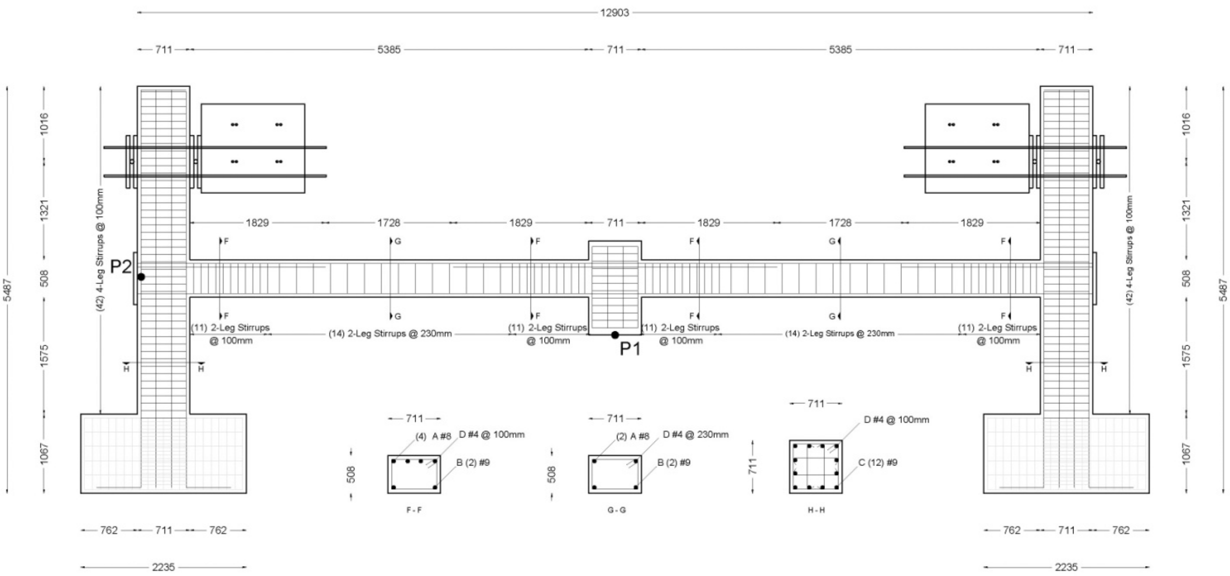

Fig. 1. Beam-column assembly experimental model.

3. Finite element models evaluation

In a previous work proposed in [3], the authors used two different finite element software, with distinct levels of modelling, in order to compare the numerical results with the experimental ones and to evaluate their reliability: SeismoStruct and ATENA 2D [4,5].

Below is a brief description of the models and the obtained results, a more detailed discussion can be found into the paper mentioned before.

In SeismoStruct models, beam elements type “infrmFB” were used, with a formulation based on the forces, able to model a frame taking into account both the geometric nonlinearity and the material inelasticity. The element behaviour was obtained by the integration of the uniaxial nonlinear response of the individual fibers which the section has been divided.

Two different concrete models were considered: the first one was defined in [6], the second one was the concrete complete model proposed in [7]. For each model different levels of confinement effect were defined, in order to show the difference in terms of structural response.

In ATENA 2D, the mathematical model was realized using plane stress finite elements with linear polynomial interpolation and 2 x 2 Gauss point’s integration scheme.

The material model used to take into account the nonlinear behaviour of concrete was the SBETA model, which allows to consider: the concrete mechanical nonlinear behaviour in compression, the concrete cracking under tensile stresses based on nonlinear fracture mechanic, the concrete compressive strength reduction due to cracking, the shear stiffness reduction due to cracking, and the tension stiffening effect. The failure criteria for a biaxial stress condition adopted by the SBETA model was the one proposed in [8].

About the compressive behaviour, the SBETA model shows a non-linear law since the reaching of effective peak strength $f_{c'ef}$ according to the relationships provided in [9], while the post-peak behaviour was modelled with a linear tension softening law characterized by a softening modulus E_d, calculated like a percentage of the tangent elastic modulus E_0. Three different values of E_d were adopted in order to evaluate the effect of this parameter on the structural behaviour.

The tensile behaviour was modelled with a linear elastic law since the achievement of the tensile strength $f_{t'ef}$, obtained in accordance with the biaxial failure domain. After cracking, a linear tension softening behaviour was defined. In this way, concrete presented a simple elastic-brittle constitutive law under tensile stresses. This choice was made after a software calibration procedure that has shown how this parameter has not a significant influence on the response of the structure.

Steel reinforcements were modelled using the element “Reinforcement”; mechanical behaviour under compressive and tensile stresses was modelled with an elastic-plastic law with hardening.

In Figs. 2a-2b and 3a-3b are summarized the results obtained with the different finite element models which are compared with the experimental ones.

The behaviour of the structure was evaluate considering the following parameters:

- The applied force on the structure;
- The vertical displacement of the centre column (Point P1 shown in Fig. 1);
- The horizontal displacement of the left end of the beam (Point P2 shown in Fig. 1).

SeismoStruct models differ one from each other for the concrete constitutive law and for the concrete confinement level considered, while ATENA 2D models differ for the compressive post-peak behaviour.

After this stage, according to the results found in [3], the software SeismoStruct was chosen to study the beam-column concrete assembly behaviour, taking into account the presence of a distributed load on the beams, in order to simulate the actual working conditions of the structure.

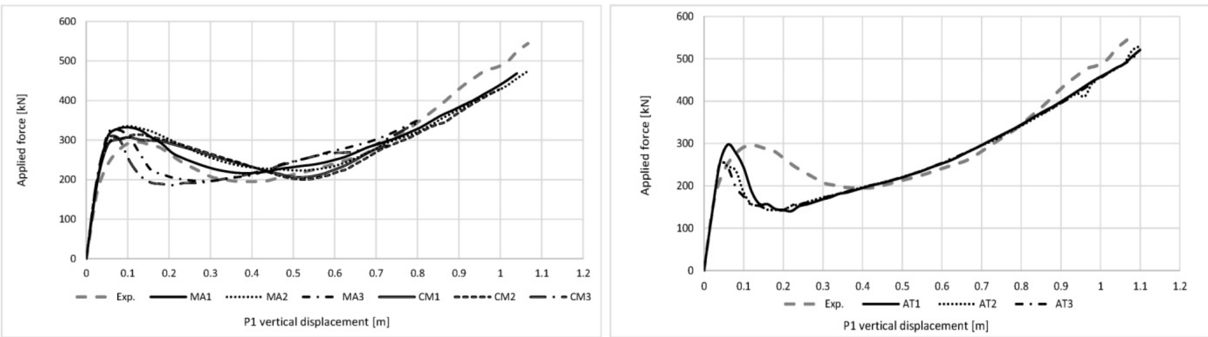

Fig. 2. (a) P1 vertical displ. – Applied force (SeismoStruct); (b) P1 vertical displ. – Applied force (ATENA 2D);

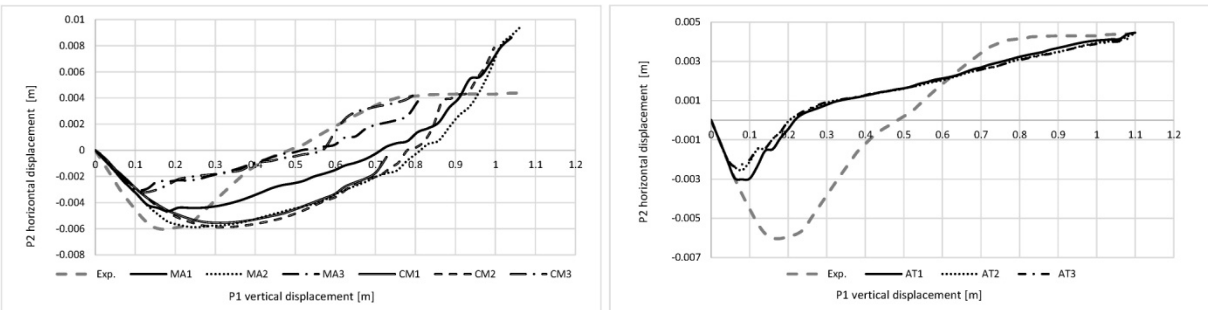

Fig. 3. (a) P1 vertical displ. - P2 horizontal displ. (SeismoStruct); (b) P1 vertical displ. - P2 horizontal displ. (ATENA 2D)

4. SeismoStruct numerical model results

In order to evaluate the role of the load applied at the column removal, the results of four different distributed load levels have been reported:

- Case A: no distributed load applied on the frame;
- Case B: distributed load applied on the frame equal to 36.5 kN/m;
- Case C: distributed load applied with a coefficient of 0.5 respect to case B;
- Case D: distributed load applied with a coefficient of 2.0 respect to case B.

In order to compare the obtained results, graphs reported in the following were corrected by removing the effects on the structure at the initial time due to the pertinent load combination.

From a general point of view, the structural behaviour can be divided into three different phases as shown in Figs. 4a-4b.

In the first phase, until reaching the flexural peak, the structural behaviour can be considered elastic, with a negative variation of the horizontal displacement of point P2. This means that the beam is subjected to a compressive axial force; compression is due to cracking that causes an increase of the beam length, which is partially prevented by the presence of the column. As can be noted in Figs. 4a-4b the value of the distributed load has not influence on the initial behaviour.

Subsequently it can be noted the arise of yield concentrated areas, close to the columns, due to the presence of negative bending moment for the lateral columns and positive bending moment for the central one, in this phase the behaviour is very similar for all the cases except for the Case D which presents a bigger stiffness reduction than the other tests.

The post-peak behaviour is initially characterized by a stiffness decrease, followed by an increase of the applied force due to the onset of the “tie-effect” in the beam. It can be noted that, for subsequent vertical displacements, initially the load decreases until the horizontal displacement of point P2 goes to 0 and the beam compression decreases progressively, then when the displacement becomes positive, the beam axial force becomes tension and the applied load returns to increase. This is confirmed by the horizontal displacement that is negative (and thus directed towards the outside) until reaching a vertical displacement of about 0.70-0.80 m, and then become positive (and therefore directed towards the inside) to the onset of the tie-effect. In this phase there is the switch from a flexural-behaviour to a tie-behaviour, up to the maximum experimental displacement of about 1.0 m. Also in this stage the main differences arise in Case D.

Numerical analyses highlight that the global behaviour of the frame is only marginally affected by the entity of load applied during the column removal. The parameter that is most strongly influenced is the horizontal displacement of the end columns, the entity of this displacement, in fact, increases with the increasing of the load applied. Furthermore, for high loading levels, the system showed a stiffness reduction in particular in the post-peak phase when yield concentrated areas and in the next phase when the flexural-behaviour switch into a tie-behaviour.

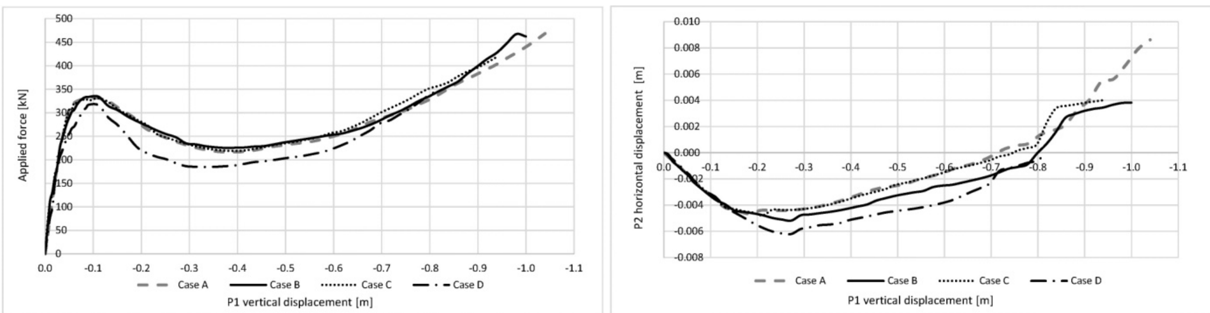

Fig. 4. (a) P1 vertical displ. – Applied force; (b) P1 vertical displ. - P2 horizontal displ.

5. Conclusions

The aim of this study was to numerically evaluate the behaviour of a reinforced-concrete beam-column system subjected to an increasing vertical displacement of the centre column to simulate a column removal scenario, in presence of different values of the distributed load applied.

Numerical analyses were carried out by using fiber frame elements, the calibration of these elements was performed in a precedent work. Four different load cases were considered in order to evaluate the role of the load applied at the column removal.

The study highlights that the global behaviour of the frame is only marginally affected by the entity of the load applied but, for high loading levels, the system shows a stiffness reduction especially after the arise of the yield concentrated areas near the columns and an increase of the end-columns displacement.

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