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EXPERIMENTAL RESEARCH ON PROGRESSIVE COLLAPSE ASSESSMENT OF RC BUILDING STRUCTURES UNDER CORNER-COLUMN FAILURE SCENARIOS

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Summary. Extreme events may cause local damage to building structures, and this can be most serious when one or more columns fail. Several studies were carried out for the failure of interior or end columns. The major advances in this direction come from numerical studies and testing of scaled substructures. However, some of the alternative load paths can not be evaluated by testing substructures. In this study, a complete and real-scale RC building structure was carried out by ICITECH of the Universitat Politècnica de València to assess its progressive collapse behaviour under corner-column failure scenarios without and with the consideration of infill masonry walls. Before testing, as a reference for the experimental tests, a finite element model was developed in ABAQUS considering a dynamic analysis and material and geometrical non-linearities. This paper analyses the results predicted by the numerical simulation (alternative load paths, displacements and damage of the RC structure) and shows some preliminary results of the tests..

1 INTRODUCTION

Extreme events (i.e. terrorist attacks, vehicle impacts, explosions, etc.) may cause local damage to building structures, and this can be most serious when one or more columns fail, leading to the progressive collapse of the entire structure or a large part of it [1]. Since the beginning of the 21st century there has been growing interest in the risks derived from extreme events, especially after the attacks on the Alfred P. Murrah Federal Building in Oklahoma in 1995 and on the World Trade Center in New York in 2001. The accent now is on achieving resilient buildings that can arrest progressive collapse after such an event, especially when they form part of critical infrastructures, have a large number of occupants, or are public buildings (e.g. hospitals, shopping centers, theaters, etc.), with the intention of preventing injuries and deaths [2–6].

To date, several studies have been carried out where the failure of interior or end columns have been studied [7–9]. However, the failure of corner columns has hardly been addressed, despite the vulnerability and major probability of an eventual progressive collapse triggered by

a corner-column failure:

- In a building structure, corner columns are the most exposed to extreme events, such as those due to terrorist attacks, vehicle impacts, or extreme environmental actions.
- The most advanced current standards consider corner columns as critical elements, whose sudden failure must be evaluated in the design phase of the structure.
- When a corner column fails, it is more difficult to find alternative loading paths.

The greatest advances in this direction come from numerical studies and testing of scaled substructures in the laboratory (e.g. [10,11]). However, some of the alternative load paths can not be evaluated by testing substructures, and results from numerical simulations are not reliable without the contrast with experimental and real results.

The research partially presented in this conference paper aims to fill the existing gap. In this study, dynamic and non-linear numerical models were performed to predict the behaviour of an experimental test. This test consisted of a real 3D building structure carried out by the ICITECH of the Universitat Politècnica de València (UPV). In this way, the novelty of the research and this conference paper remains in: i) the assessment under real conditions of any alternative load path against corner-column failure scenarios, ii) the use of an extensive monitoring system during test, and iii) the performance of the test under the accidental load combination prescribed by the codes as a real method for assess the dynamic performance and the effects under real conditions of load (it is worth to note that dynamic effects depends on the level of damage). This study also includes an analysis of the influence of infill walls to arrest the progressive collapse of RC structures in corner-column failure scenarios.

2 A BRIEF DESCRIPTION OF THE BUILDING AND TESTS

A real-scale RC building was designed with only research purposes. This building had two floors of 2.8m height, four bays with 5.0m span length, flat-slabs 20cm thick and columns of 30x30cm^2. Prescriptions of Eurocode 2 [12] were adopted and a category of use corresponding to high occupancy buildings (C1, C2 o C3) [13] was chosen. In addition to the self-weight of the structure, a dead load of 2kN/m^2 and a uniformly distributed live load of 3kN/m^2 were considered in the design of the structure.

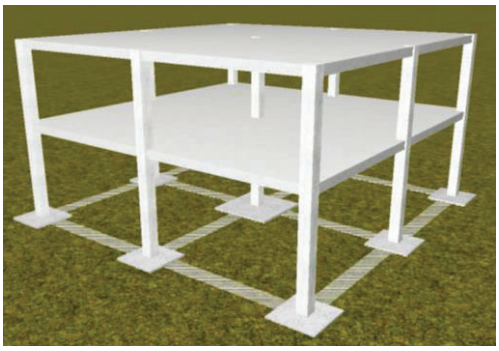

Figure 1: 3D view of the design.

The building, under accidental actions, was verified following EC-1, part 1-7 [2], for a consequence class 2b (Upper Risk Group). At this point, the building was designed using the

simplified methodology of the tying forces and elements (horizontal and vertical ties). A discussion about the origins and the validity of the tying simplified methodology is discussed in [6]. As a result, the design of the building was only slightly modified with respect to the design without accidental actions. This is a common trend when considering flat-slabs, as pointed out in [6]. Fig. 2 shows an example of horizontal ties working after an internal-column loss.

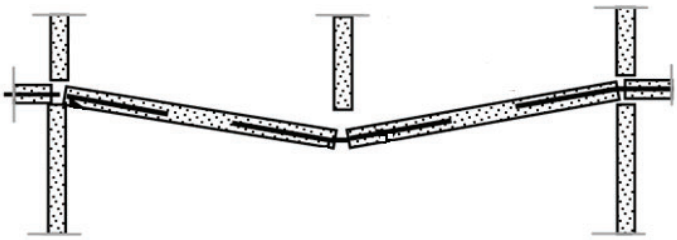

Figure 2: Example of horizontal ties working after and internal-column loss.

Two experimental tests for two different failure scenarios were considered in this study. In both cases, a corner-column loss was considered, selecting two opposite corners columns to avoid the influence of a damaged structure in the second test. These columns were steel-based (HE-300B profile) prepared with a mechanism to reproduce a sudden failure. Only the structure of the building was tested for the first failure scenario, whereas infill masonry walls were also introduced for the second failure scenario. These masonry walls were only reproduced in the first floor and in those modules with more influence in the defined corner-column failure scenario. Fig. 3 and Fig. 4 show the real building prepared for the first and the second failure scenarios, respectively.

Figure 3: Building and definition of the first failure scenario.

Figure 4: Building and definition of the second failure scenario.

Finally, and before testing the structures without and with infill masonry walls, the building was verified using the alternative load path method with the notional removal of the corner-columns selected (See Section 3). Experimental and predicted numerical results are presented in Section 4. The latter were used as a reference during the tests.

3 FINITE ELEMENT MODEL

A nonlinear dynamic finite element (FE) analysis was carried out in this work using ABAQUS Software [14] and considering material and geometrical non-linearities. The FE model included the RC structure, those steel columns prepared for the failure scenarios and the infill masonry walls (only in the second failure scenario).

RC and steel columns were modelled as BEAM elements (B33) with an elastic behaviour, considering that cracking in the concrete columns should be reduced. SHELL elements (S4R) were used for flat slabs and the infill masonry walls. For the floors, different areas with different amount of reinforcement were considered according to the structure design. A concrete damage plasticity model was adopted to reproduce the non-linear behaviour and damage of the concrete, adopting those expressions given by EC-2 [12]. As a first approach, results for the model with infill masonry walls were not predicted due to the variability of the results according to the unknown mechanical properties and connections with the RC structure. This model will be performed as a future work based on the experimental tested mechanical properties of the

materials and the results obtained from the test under the second failure scenario. Table 1 shows the parameters considered in this preliminary study.

Property	Value*	
	Steel	Concrete
Modulus of Elasticity [MPa]	210000	33000
Poisson's Ratio	0.3	0.2
Compressive strength [MPa]	---	38
Tensile strength [MPa]	---	2.9

**Values should be modified in future works according to the experimental results*

Table 1: Mechanical properties of steel and concrete elements.

The lower nodes of the concrete columns of the ground floor had restricted displacements and rotations, whereas those corresponding to the steel columns had restricted displacements and free rotations. Fig. 5 shows a 3D view of the FE model.

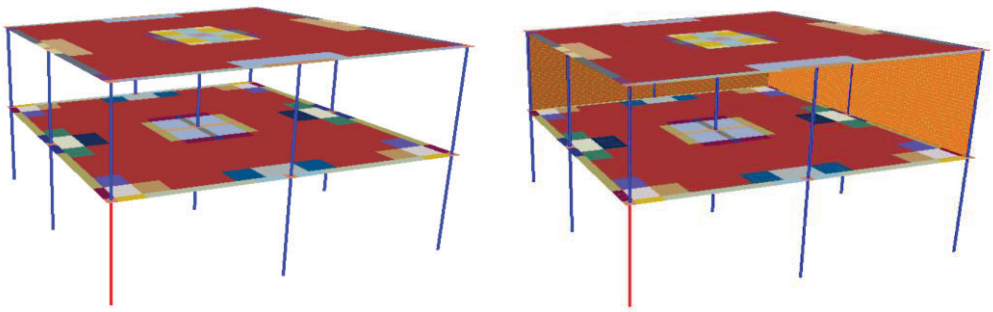

Figure 5: 3D view of the FE model without (left) and with infill masonry walls (right).

The self-weight was applied automatically with densities of 25kN/m^3 and 78.5kN/m^3 for concrete and steel, respectively. Dead load (DL) and live load (LL) were applied as a uniformly distributed mass on the slab. The accidental load combination was used in the analysis (i.e. 1.2DL + 0.5LL) in accordance with GSA [3]. This load was also reproduced experimentally.

The gravity acceleration was introduced gradually over time using a ramp function within t=0.0s and t=1.0s, similarly to Buitrago et al [15]. This was followed by an interval of stabilization and the introduction of the accidental events at t=1.0s. The response of the structure was computed until t=2.0s. As explained before, local failure scenarios followed the conventional notional member removal approach used traditionally for permanent structures to assess whether the structure can develop alternative load paths after accidental events [3,4,16–19]. Predicted results of the FE model are presented in Section 4 and were used as a reference for the experimental tests.

4 RESULTS

This Section presents the predicted results for the first failure scenario where there is no infill masonry walls in the structure. This is a common trend when considering structures under

progressive collapse, in which secondary elements as infill masonry walls are not considered. Future works will analyse that this could conduct to not appropriate results since the secondary elements play an important role in arresting progressive collapse. Actually, infill masonry walls are considered as an important alternative loading path in accidental scenarios [1].

Fig. 6 and Fig. 7 show the time-dependent vertical displacement obtained in the centre of the bay attached to failed column and in the upper point of this column for the first failure scenario, respectively. As it is shown, the RC structure achieve an important deflection after the accidental event within t = 1.0s and t = 2.0s. This response, as can be seen from the deformed shape, is governed by two main alternative load paths: a) bending; and b) Vierendeel action. Other alternative load paths, as membrane or arch action, were not mobilized in this case. Arch action can be mobilized when an external or internal column is lost, whereas membrane action is usually activated after the bending action, with high rotations at joints and a stiff horizontal restrain.

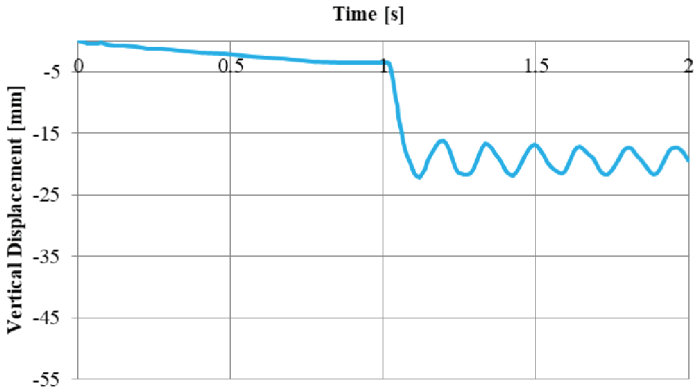

Figure 6: Position and time-history results (vertical displacement) in the center of the bay attached to the failed column.

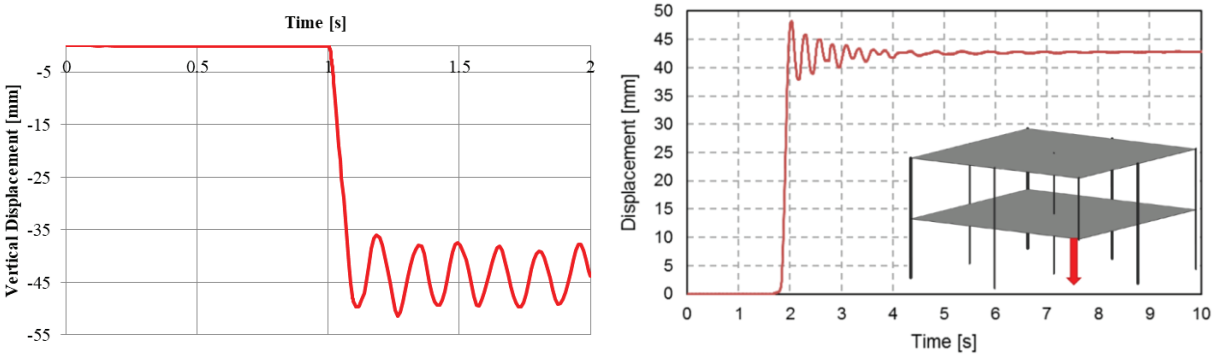

Figure 7: Position and time-history results (vertical displacement) in the upper point of the failed column: predicted by the FE model (left) and registed in the test (right).

Fig. 8 and Fig. 9 show the predicted damage (cracking) on the upper and lower part of the RC slabs, respectively. The most important cracked areas are represented as grey areas. As can be seen, this damage is localized in zones near the joints between slabs and columns, where

negative bending moments are important after the accidental event. Damage is also localized in the bottom part of the slabs near the failed column due to the flexural stresses introduced by the Vierendeel action. As an example of what occurred in the experimental test, Fig. 10 shows a photography of some cracks produced on the slabs near to the column-slab joint attached to the failed column after the accidental event.

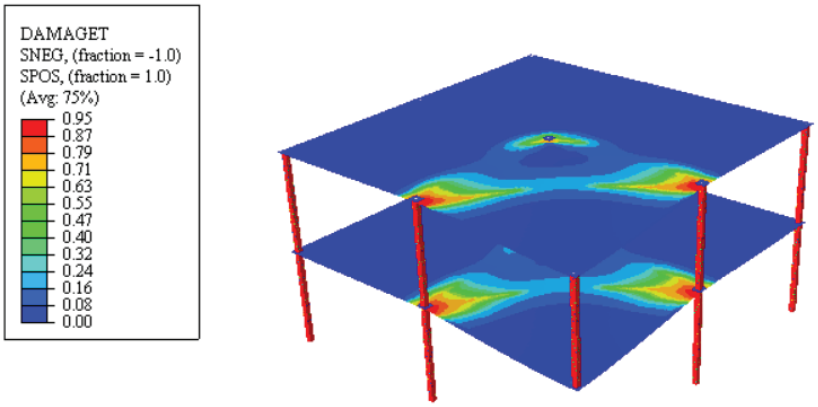

Figure 8: Predicted tensile damage of the upper part of RC slabs in the first failure scenario (deformed shape magnified 10 times) at 2.0s.

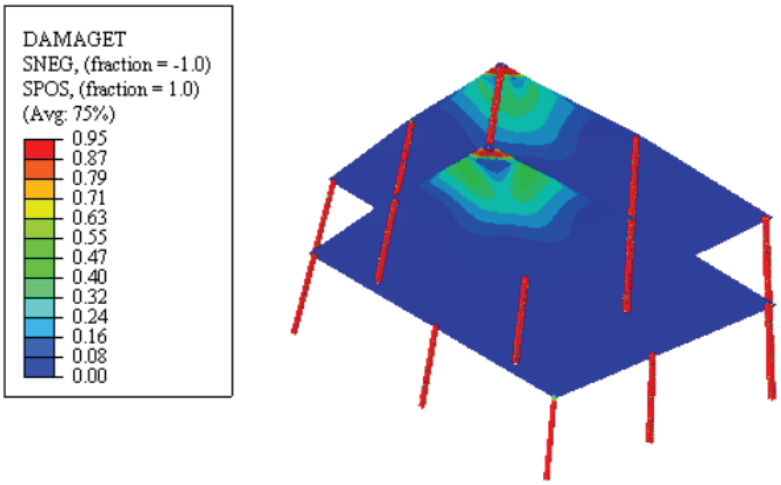

Figure 9: Predicted tensile damage of the lower part of RC slabs in the first failure scenario (deformed shape magnified 10 times) at 2.0s.

Figure 10: Cracks on the slabs near the joint column-slab attached to the failed column after its sudden failure.

With the inclusion of the infill masonry walls, we expect that the maximum vertical displacement and concrete damage are much lower than those predicted by the FE model without infill walls, as occurred in the experimental test (reduction about 80%-90% of the maximum vertical displacement).

5 CONCLUSIONS AND FUTURE WORKS

A real-scale RC building structure was carried out by ICITECH-UPV to assess its progressive collapse behaviour under corner-column failure scenarios without and with the consideration of the infill masonry walls. Before testing, as a reference for the experimental tests, a FE model was developed to predict the most important results and the general behaviour of the RC structure. This FE analysis consisted on a dynamic nonlinear numerical analysis performed in ABAQUS. From the experimental and predicted numerical results obtained, the following conclusions can be drawn:

- The design following the simplified methodology of the tying forces and elements [2] did not require any additional reinforcement detail for the horizontal ties. This is a normal trend when considering flat-slabs.
- After a sudden column removal, the RC structure was able to withstand the accidental action with the activation of some alternative load path.
- The accidental event produced some important deflections and damage on the RC structure. However, after the accidental event, the integrity of the structure was maintained and it was able to arrest effectively the possibility of propagating a progressive collapse.
- Bending and Vierendeel actions were the most important alternative load paths under corner-column failure scenarios. As it is confirmed by experimental testing, infill masonry walls were another important alternative load path, highly reducing displacements and damage of the RC structure (80%-90% of reduction). Other alternative load paths, as arch or membrane actions, were not activated. Arch action is not present in corner-column losses, whereas membrane action needs high rotations on column-slabs joints and stiff horizontal restrains, which is not the case

of this test.

As future works, experimental research and analyses with dynamic nonlinear numerical simulations fitted to the experimental results without and with infill masonry walls will be developed to precisely analyses the different alternative load paths and the influence of introducing the infill masonry walls on the structural behaviour against progressive collapse. This analysis will be extended to other cases through parametric analysis and other types of RC buildings.

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