TESTING OF FULL-SIZE CONCRETE BUILDING STRUCTURES UNDER SUDDEN COLUMN REMOVAL

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Abstract

Structural robustness and progressive collapse of building structures is a topic of great interest in structural engineering towards creating a resilient society. Experimental research in this field has been traditionally carried out on structural members or structural sub-assemblies which are tested under extreme conditions of loading and deflections. These tests show that large deformation resisting actions can develop in some cases subject to correct detailing of the members and the connections between them. However, the significance of these tests for whole structural systems is uncertain. Moreover, the assumptions often made in design for accidental actions are significant and in many cases they assume the activation of alternative load paths that might not be mobilised. Information from testing on full-scale buildings is much more limited. This paper provides a review of existing building tests including recent tests carried out by the authors at Universitat Politècnica de Valencia (Spain) in which a concrete flat slab building was subjected to a sudden corner-column removal. Test results are discussed as well as alternative load paths observed in these tests. Aspects such as the contribution of different structural and non-structural members are also analysed. The conclusions are put into context of different international design codes from Europe and America where the use of the alternative load path analysis is widely accepted.

Keywords: *Robustness, experimental study, extreme loading, column removal, flat slab structures.*

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 (Adam et al. 2018). 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 (BS 5975 2011; DoD 2009; EN 1991-1-7 2006; GSA 2013; Russell et al. 2019).

To date, several studies have been carried out where the failure of interior or end columns have been studied (Adam et al. 2018; Bermejo et al. 2017; Peng et al. 2018; Qian et al. 2018; Sasani and Sagiroglu 2010; Xue et al. 2018). 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.

The greatest advances in this direction come from numerical studies and testing of scaled substructures in the laboratory (e.g. (Ma et al. 2019; Qian and Li 2013a)). However, some of the alternative load paths cannot be evaluated by testing substructures, and results from numerical simulations are not reliable if performed independently from experimental and real results.

The research partially presented in this conference paper (Adam et al. 2020; Buitrago et al. 2020a) 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 designed at the ICITECH of the Universitat Politècnica de València (UPV). In this way, the novelty of the research remains in: i) the introduction of the influence of infill masonry walls in real-scale 3D RC structure subjected to corner-column failure scenarios; ii) the assessment under real conditions of any alternative load path against corner-column failure scenarios, iii) the use of an extensive monitoring system during test, and iv) the performance of the test under the accidental load combination prescribed by the codes as a real method for assessing the dynamic performance and the effects under real conditions of load (it is worth noting that dynamic effects depend 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. Experimental tests carried out

A real-scale RC building was designed with only research purposes (See Fig. 1). This building had two floors of 2.8m height, four bays with 5.0m span length, flat-slabs 0.2m thick and columns of 0.30x0.30m^2. Prescriptions of Eurocode 2 (EN 1992-1-1 2004) were adopted and a category of use corresponding to high occupancy buildings (C1, C2 o C3) (EN 1991-1-1 2003) 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.

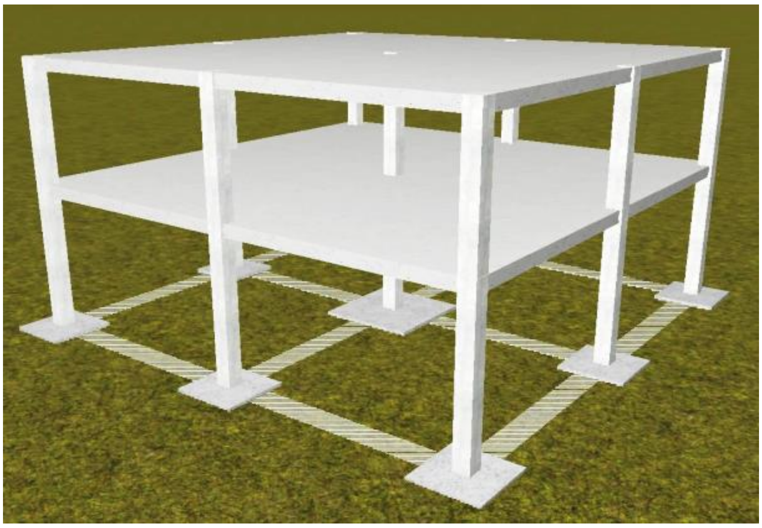

Figure 1. 3D view of the design.

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 corner-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 constructed in the first floor and in those modules with more influence in the defined corner-column failure scenario. Fig. 2 shows the real building prepared for the first and the second failure scenarios, respectively.

Figure 2. Building and definition of the first (left) and second (right) failure scenario.

Finally, 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 selected corner-columns (See Section 3). Experimental and predicted numerical results are presented in Section 4. The latter were used as a reference during tests.

3. Finite element model

A nonlinear dynamic finite element (FE) analysis was carried out in this work using ABAQUS Software (ABAQUS v16.4 2016) 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, as it was later demonstrated by the experimental results. 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 (EN 1992-1-1 2004). 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 interface 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.

Table 1. Mechanical properties of steel and concrete elements.

	Value*	
Property	Steel	Concrete
Young’s Modulus [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 experimental tests (Adam et al. 2020; Buitrago et al. 2020a).

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. 3 shows a 3D view of the FE model for both failure scenarios, without and with infill masonry walls.

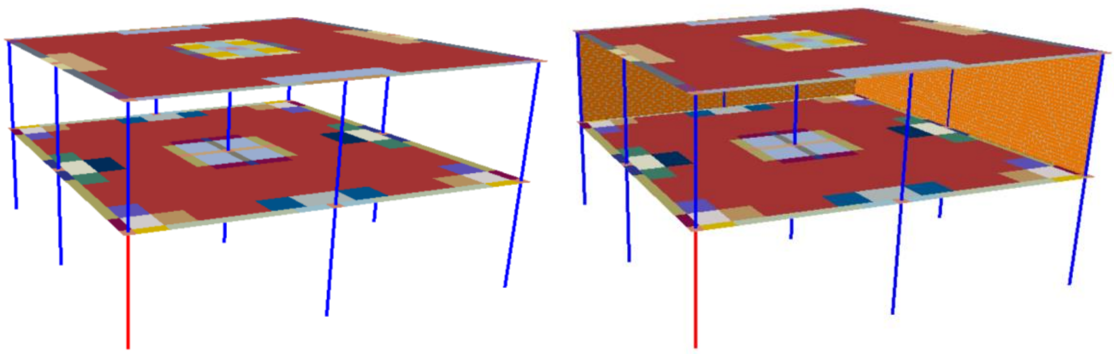

Figure 3. 3D view of the FE model without (left) and with infill masonry walls (right).

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 (GSA 2013). 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 (2018, 2020b). 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 notional member removal approach used traditionally for permanent structures to assess whether the structure can develop alternative load paths after accidental events (Dat and Tan 2015; DoD 2009; GSA 2013; Olmati et al. 2017; Qian and Li 2013b; Sagaseta et al. 2017). Predicted results of the FE model are presented in Section 4 and were used as a reference for the experimental tests.

4. Preliminary results

4.1. Without infill walls

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 walls are not considered. This aspect could lead to not appropriate results since secondary elements play an important role in arresting progressive collapse (See section 4.2 and 4.3 for more details). Actually, infill masonry walls are considered as an important alternative loading path in accidental scenarios (Adam et al. 2018).

Fig. 4 (left) shows the time-dependent vertical displacement predicted by the FEM in the upper point of the failed column for the first failure scenario. As it is shown, the RC structure achieves an important deflection after the accidental event within t = 1.0s and t = 2.0s. This response, as could be seen from the deformed shape (See Section 4.3), 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 activated in this case. Arch action can be activated 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. In addition, Fig. 4 (right) depicts the experimental results which were pretty similar to those predicted by the FEM during the design phase of the test.

Fig. 5 shows the predicted damage (cracking) on the upper and lower part of the RC slabs, respectively. As can be seen, this damage is localized in zones near the slab-column joints, where negative bending moments and dynamic punching demand are important during and 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. 6 shows a photography of some cracks produced on the slabs near to the slab-column joint attached to the failed column after the accidental event.

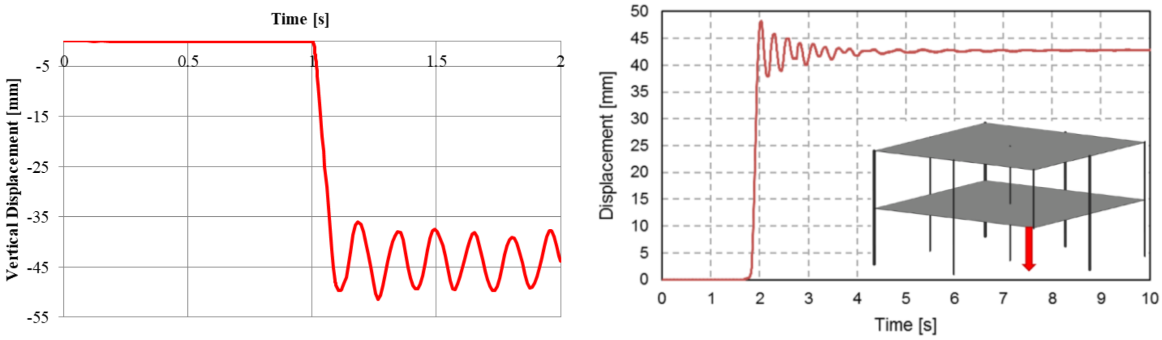

Figure 4. Position and time-history vertical displacements in the upper point of the failed column: predicted by the FE model (left) and registered in the test (right) without infill walls.

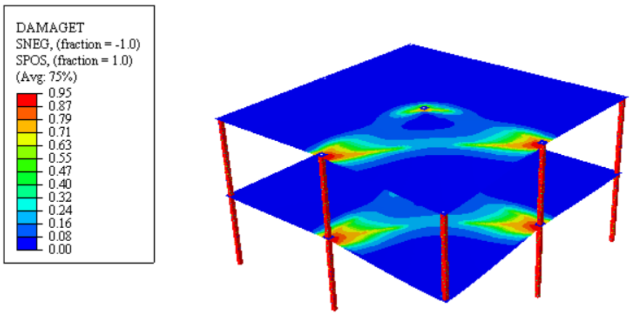

Figure 5. Predicted tensile damage of the upper (top) and lower (bottom) part of the RC slabs in the first failure scenario at 2.0s (deformed shape magnified 10 times).

Figure 6. Cracks on the slabs near the slab-column joint next to the failed column after its sudden failure.

4.2. With infill walls

The inclusion of the infill masonry walls produced a great influence in the structural response of the building. This can be seen from the vertical displacements in the upper point of the failed column (Fig. 7).

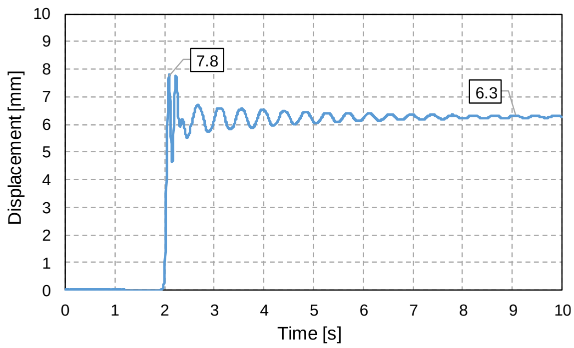

Figure 7. Time-history vertical displacement in the failed column with infill masonry walls.

Results showed that the main alternative load path comprised the activation of the infill masonry walls, as it is represented in Fig. 8.

Figure 8. Activation of an alternative load path based on the infill masonry walls.

4.3. Comparison

Fig. 9 shows a comparison of the vertical displacements (deformed shape) for tests without (Test 1) and with (Test 2) infill masonry walls.

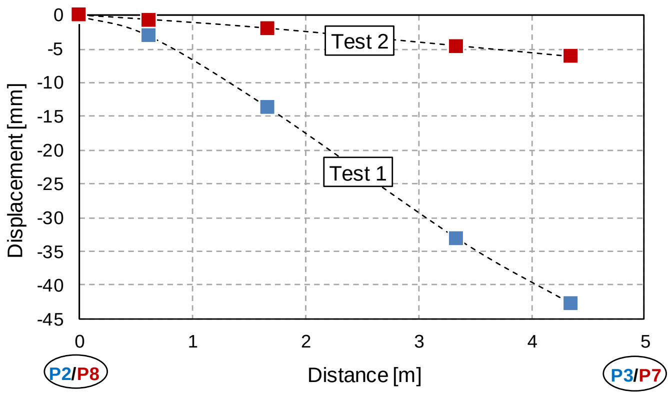

Figure 9. Vertical residual displacement (2D deformed shape) of the first floor between adjacent and failed columns for Test 1 (without infill walls) and Test 2 (with infill masonry walls).

A reduction of 83.8% was found in the maximum vertical displacement. Additionally, the structural response of the building changed, from the flexural and Vierendeel mechanisms (Test 1) to the main contribution of the infill masonry walls (Test 2).

5. Conclusions

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 cladding panels. 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:

- 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 (83% of reduction).

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