Lecture Notes in Civil Engineering

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Building for the Future: Durable, Sustainable, Resilient

Proceedings of the *fib* Symposium 2023 – Volume 2

fib CEB-FIP

Springer

Large-Scale Tests on RC Purpose-Built Buildings for Improving Robustness

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Abstract. Although recent years have been marked by a substantial research effort on the progressive collapse of steel as well as cast-in-place and precast concrete structures, the fact is that almost all studies are focused on reduced-scale tests, tests on isolated frame structures, tests on substructures or analytical and numerical analysis. Within this context, large-scale tests avoid size effects and allow all resisting mechanisms that a structure can develop after an initial-local failure to be studied. This paper presents the case of large-scale tests performed on two purpose-built buildings: one made of cast-in-place concrete and the other with precast concrete elements. In both cases, sudden column removal scenarios were considered for the robustness assessment of the structural system. The structures were provided with simple solutions to enhance the robustness and arrest progressive collapse initiated by the sudden failure of a column. The cast-in-place concrete building had two 3 m high floors, with 2 × 2 bays of 5 m span length. The total in-plan dimensions of the building were 10 × 10 m^2. This building was subjected to sudden corner column failure scenarios with and without the presence of infill masonry walls. The precast concrete structure also had two 3 m high floors, with 3 × 2 bays of 5 m and 6 m span, respectively. The total in-plan dimensions of the building were 15 × 12 m^2. This building was subjected to sudden column failure scenarios for three different tests, involving the removal of: a corner column, an edge column in a frame parallel to the direction of one-way hollow-core slabs, and an edge column in a frame perpendicular to the one-way slabs. This paper presents and discusses a summary of the results and outcomes of these studies.

1 Introduction

Extreme events (i.e. terrorist attacks, vehicle impacts, explosions, etc.) may cause local damage to building structures. 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 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 centres, theatres, etc.), to prevent injuries and deaths [2–6].

A. Ilki et al. (Eds.): *fib* Symposium 2023, LNCE 350, pp. 51–59, 2023.
https://doi.org/10.1007/978-3-031-32511-3_6

This paper summarises two large-scale tests on RC purpose-built buildings for improving structural robustness. One of the buildings is made with cast-in-place concrete, whereas the other is a precast concrete structure. Both structures were subjected to sudden column removals of corner and edge columns. However, this paper is focused only on corner columns since they are the most exposed and vulnerable in a building [7].

After this introduction, Sect. 2 describes the buildings. Sections 3 and 4 summrise the test results for the cast-in-place and precast concrete structures, respectively. Finally, Sect. 5 draws the main conclusions of the study.

2 Description of the Buildings

2.1 The Cast-in-Place Concrete Building

A real-scale RC building was designed only for research purposes. This building had two floors of 2.8 m in height, four bays with 5.0 m spans length, flat-slabs 20 cm thick and columns of 30×30 cm^2. Prescriptions of Eurocode 2 [8] were adopted, and a category of use corresponding to high occupancy buildings (C1, C2 o C3) was chosen. In addition to the self-weight of the structure, a dead load of 2 kN/m^2 and a uniformly distributed live load of 3 kN/m^2 were considered in the structure's design.

The building belongs to a consequence class 2a (Lower Risk Group) following Eurocode 1, Part 1–7 [2]. Still, it was categorised as a consequence class 2b (Upper-Risk Group) as it is a test aiming to reproduce the behaviour of high occupancy and taller buildings. At this point, the building was designed using the simplified methodology of tying forces and elements (horizontal and vertical ties). Discussion about the origins and the validity of the simplified tying method is discussed in [6]. As a result, the design of the building was only slightly modified concerning the design without accidental actions. This is a common trend when considering flat-slabs.

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) and 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 on the first floor and in those modules with more influence in the defined corner-column failure scenario. Figure 1 and Fig. 2 show the actual building prepared for the first and the second failure scenarios, respectively. A complete description of the building and test can be found in Adam et al. and Buitrago et al. [9–11].

Fig. 1. Building and definition of the first failure scenario.

Fig. 2. Building and definition of the second failure scenario.

2.2 The Precast Concrete Building

The building specimen constructed for the purpose of this study (Fig. 3) has a rectangular shape with six bays in plan and two floors. The longest 15 m side consists of three 5 m spans, while the shorter 12 m side consists of two 6 m spans.

Fig. 3. Completed building specimen prior to testing.

The design of the building was based mainly on conventional techniques typically used for precast concrete construction with hollow-core slabs. The structure consisted of precast columns and beams used to construct a skeletal frame on which the hollow- core slabs were rested before pouring a topping layer. However, some simple design measures were introduced to improve structural robustness [12]. This included casting the concrete columns with prepared sleeves to allow continuous horizontal ties to be placed above all perimetral and central beams in each floor. These ties were then joined via couplers to prepared anchors in the corner and relevant edge columns. Additional tying reinforcement was also placed between hollow-core planks based on recommendations in guidelines issued by the Institution of Structural Engineers [12]. A more detailed description of the building and test can be found in Buitrago et al. [13].

3 Tests and Summary of Results of the Cast-in-Place Concrete Building

3.1 First Failure Scenario

This section presents a summary of the results for the first failure scenario where there are no infill masonry walls in the structure. This is a common trend when considering structures under progressive collapse, where secondary elements such as infill masonry walls are not considered. This aspect could lead to inappropriate results since secondary elements are essential in arresting progressive collapse. Actually, infill masonry walls are considered an important alternative loading path in accidental scenarios [1].

Figure 4 shows the time-dependent maximum vertical displacement in the upper point of the removed column for the first failure scenario. As is shown, the RC structure achieves an important deflection after the accidental event. This response, as seen from the deformed shape (see Sect. 3.3), is governed by two main alternative load paths: a) bending; and b) Vierendeel action. Other alternative load paths, such as membrane or arch action, were not activated in this case. Arch action can be activated when an external or internal column is lost. In contrast, membrane action is usually activated after bending, with high rotations at joints and a stiff horizontal restrain.

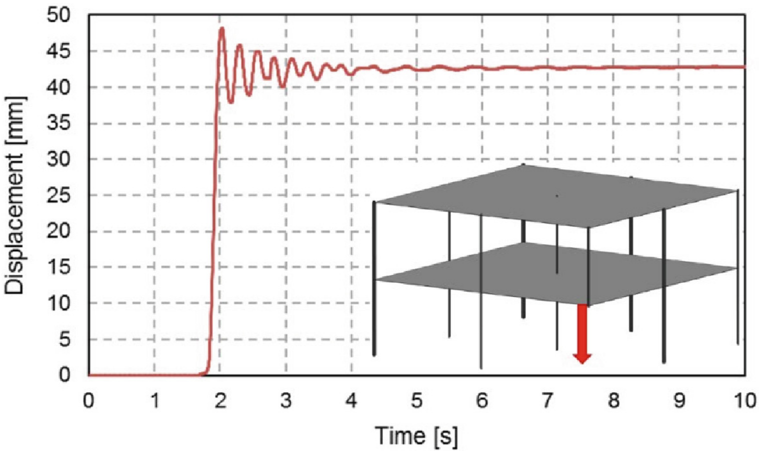

Fig. 4. Position and time-history vertical displacements in the upper point of the failed column registered in the test.

As an example of what occurred in the experimental test, Fig. 5 shows a photo of some cracks produced on the slabs near the slab-column joint attached to the failed column after the accidental event.

Fig. 5. Cracks on the slabs near the slab-column joint next to the failed column after its sudden failure.

3.2 Second Failure Scenario with Infill Masonry Walls

The inclusion of the infill masonry walls produced a significant influence on the structural response of the building. This can be seen from the vertical displacements in the upper point of the failed column (Fig. 6).

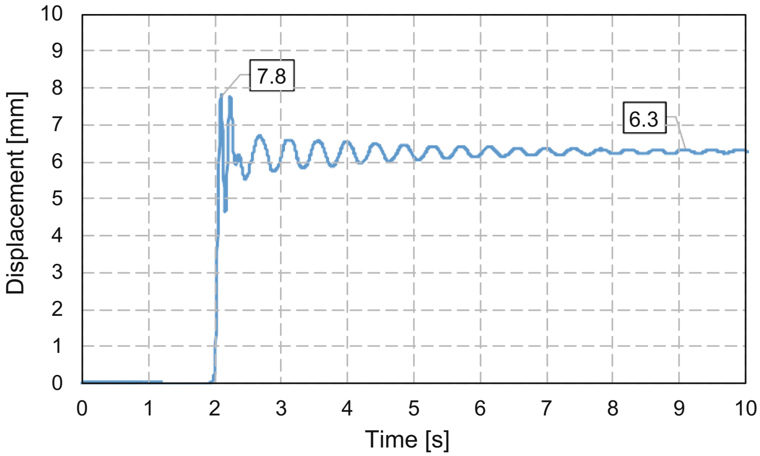

Fig. 6. Time-history vertical displacement in the failed column with infill masonry walls.

Results showed that the main alternative load path comprised the activation of the infill masonry walls, as represented in Fig. 7.

Fig. 7. Activation of an alternative load path based on the infill masonry walls.

3.3 Comparison

Figure 8 shows a comparison of the vertical displacements (deformed shape) for tests without (Test 1) and with (Test 2) infill masonry walls.

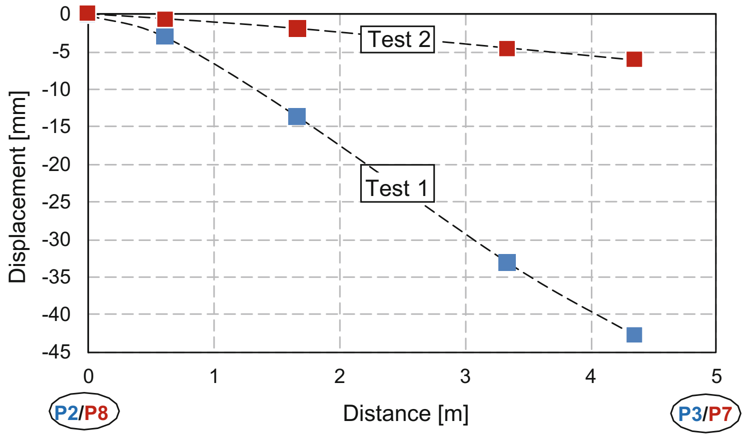

Fig. 8. Vertical residual displacement (2D deformed shape) of the first floor between adjacent and failed columns for Test 1 (without infill walls) and Test 2 (with infill masonry walls).

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).

4 Tests and Summary of Results of the Precast Concrete Building

Figure 9 shows the vertical displacement from the C7 column to the corner column on the first slab, in which the maximum drop registered reached a peak value of 12.1 mm.

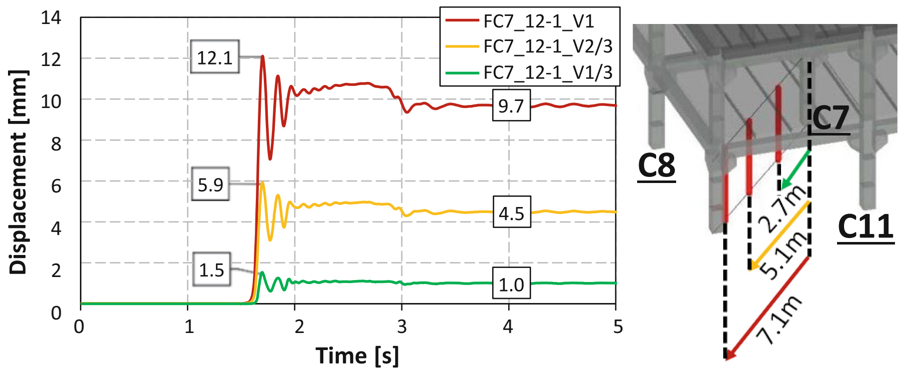

Fig. 9. Vertical displacement measurements on lines from columns C7, C8 and C11 to C12. First floor. Positive direction downwards.

After the test, the structure only showed minor residual damage (cracking) around the beam-column connections. The state of the structure after the test can be seen in Fig. 10, which shows the state of the building with the hinged metal column (yellow box) that allowed the free fall of the corner (12.1 mm maximum drop).

Fig. 10. Structure after the test.

5 Conclusions

Real-scale RC building structures were 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 and for cast-in-place and precast concrete structures. The sudden removal of a corner column was tested for the first time under accidental load combinations defined in codes and was the first experiment on a full-scale building made with precast concrete components. The experimental buildings were designed according to the latest international codes and standards in the field of progressive structural collapse and structural robustness. The structural details in the buildings were designed considering simple standard building practices and the need to conserve structural integrity after the sudden removal of a corner column.

Results extracted from the real-scale tests are expected to create an extensive database of experimental results useful for developing advanced numerical simulations and parametric analyses.

Acknowledgements. The work for the cast-in-place concrete building was carried out with the support of a 2017 Leonardo Grant for Researchers and Cultural Creators from the BBVA Foundation. The work for the precast concrete building was carried out with the funding received through grant BIA2017–88322-R-AR funded by MCIN/AEI/10.13039/501100011033 and "ERDF A way of making Europe". This research also serves as the basis of a project (Endure) that has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 101000396). The authors would also like to express their gratitude to the Levantina, Ingeniería y Construcción S.L. (LIC) company for funding the construction of the building, and to the Generalitat Valenciana/Fons Social Europeu [APOSTD/2019/101], grant IJC2020–042642-I funded by MCIN/AEI/10.13039/501100011033 and by "European Union NextGeneration EU/PRTR", and Universitat Politècnica de València [PAID-10–17] for funding received under different postdoctoral programs.

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