Natural fuse-segmentation to arrest failure propagation in precast concrete buildings

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ABSTRACT

Our previous work on precast construction has shown that sufficient structural robustness can be achieved by adequately designing the connection detailing to withstand a sudden column removal under the accidental load scenario. However, the behaviour of such a system under larger initial failure has not been investigated to date. This article presents one of the recent tests carried out by the Building Resilient research group of the Universitat Politècnica de València, where a full-scale precast building of 2 storeys (6 m) and 3 x 2 spans (15 x 12 m^2) has been tested under removal of three columns. Preliminary computational simulations were performed using the applied element method (AEM) to design the load scenarios. The test results indicated that the precast system has a natural segmentation ability, which is beneficial to arrest the failure propagation, limiting the collapse extent to a minimum.

Keywords: progressive collapse, full-scale testing, precast building, applied element method.

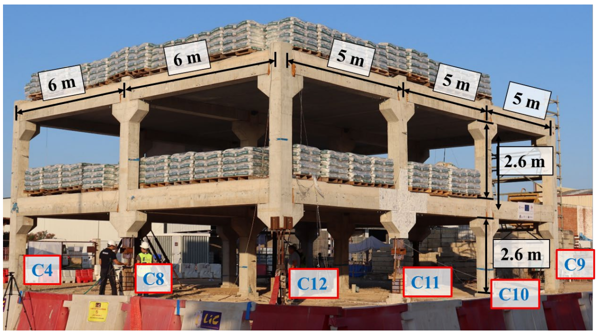
1. INTRODUCTION

Precast construction has several practical advantages compared to concrete cast-in-situ buildings, including faster construction time, minimum waste, and better quality control. In our past projects [1], we had proven that, with appropriate construction details, precast concrete structures are sufficiently robust to withstand several single-column removal scenarios without collapsing through an extensive tying system, which provides excellent connectivity between elements. However, the behaviour of such a structure under larger initial failure (multiple column losses) remains unknown. To better understand the phenomenon, the purpose-built precast specimen, which was used in [1] to perform several single-column removal scenarios, was retested but with larger initial failures involving the removal of three columns. Numerous preliminary computational simulations using the applied element method (AEM) were conducted to plan for this final test.

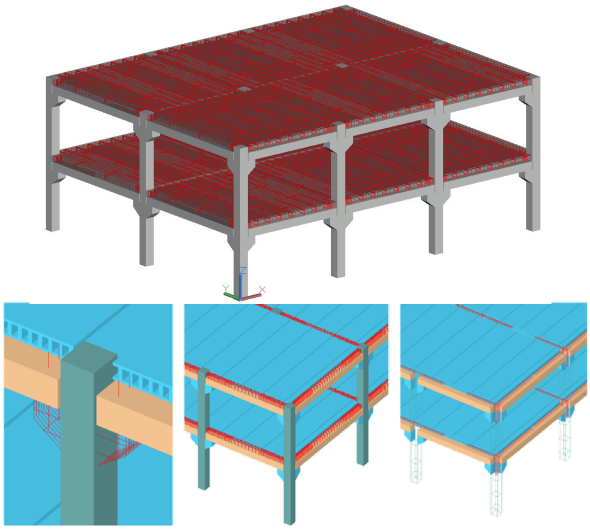
2. DESCRIPTION OF THE TEST CAMPAIGN

2.1. Test specimen

The purpose-built specimen had two 2.6 m high floors with a floor plan of 15 x 12 m^2. The longer span of the building consists of 3 bays of 5 m span whereas the shorter side is composed of 2 bays of 6 m span. All the columns were precast with a dimension of 40 x 40 cm^2 (including corbel systems) except in a few locations where the columns were made of triple-hinged steel columns, specially designed to perform the removal scenario [1]. The beams were partially precast with a depth of 60 cm (35 cm precast + 25 cm topping) and a width of 40 cm. These beams were supported on elastomeric pad bearings atop the column's corbel. Hollow core slabs with a total depth of 26.5 cm (20 cm precast + 6.5 cm topping) and a unit width of 1.2 m were used as the floor system, spanning 6 m between the primary beams (see **Figure 1a**).



(a)



(b)

Figure 1. *(a) General overview and dimensions of the purpose-built precast specimen; (b) The numerical model of the specimen analysed using the applied element method (AEM).*

2.2. Preliminary simulations conducted using the applied element method (AEM)

The applied element method (AEM) is a numerical technique to predict the behaviour of structures based on the concept of discrete cracking as it allows accurately simulate different phases of failures from elastic, crack initiation and propagation in tension-weak materials, yielding, separation, impact (debris), and collision between separated elements or between the separated elements and the system boundaries [2]. As the present experimental test involves phenomena like separation and collision, it was decided that AEM is more appropriate to be adopted for such a purpose (see **Figure 1b**). The numerical model was built and initially calibrated using the test results on a single removal scenario [1]. Then, the calibrated model was utilised to explore combinations of different removal scenarios with various magnitudes of the applied gravity load (see **Figure 2**). The objective was to determine the optimum removal scenario that fulfils the following criteria: 1) the initial failure shall be sufficient to induce a partial collapse of the system; 2) the collapse involves (or activates) both main axes of the building; 3) the scenario requires a reasonable gravity load to trigger the local failure. After some considerations, scenario D, involving three-column removals in the corner bay of the structure, was chosen (see **Figure 2d**). This scenario requires the lowest failure load to reproduce while also creating a failure border in both the long and weak axes of the building.

2.3. Column removal procedure

Regarding the column removal strategy, careful planning was undertaken to ensure the safety of all people involved during the test. The procedure consists of a two-phase removal: 1st phase is the quasi-static removal of the two edge columns (adjacent to the corner column), and the 2nd phase is the sudden (dynamic) removal of the corner column.

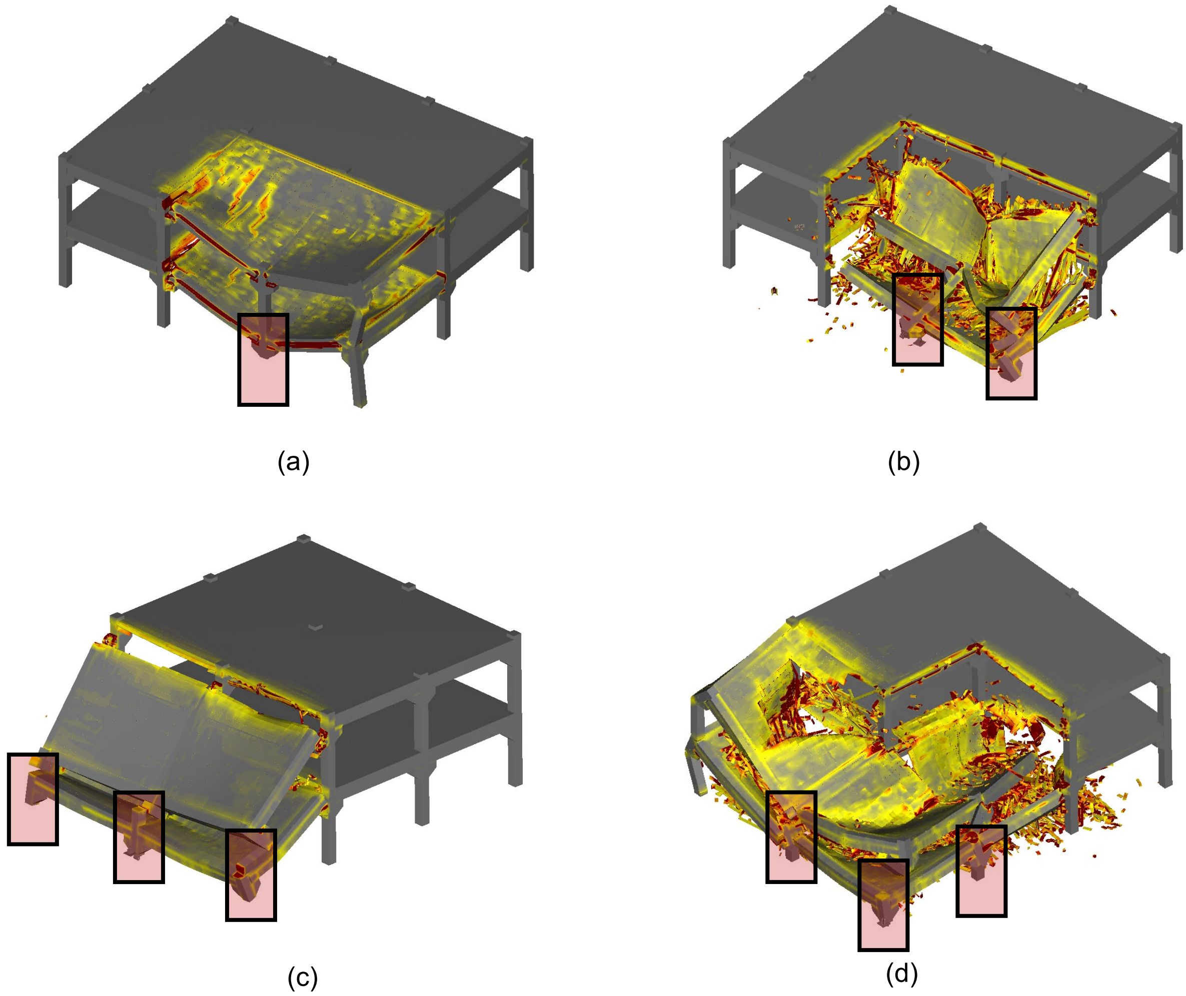


Figure 2. *Results of numerical simulations considering various initial damage scenarios: (a) single-column removal (collapse load of 19.25 kN/m^2); (b) two-column removals (12 kN/m^2); (c-d) three-column removals (load of 8.50 and 7.00 kN/m^2 respectively).*

3. RESULTS AND DISCUSSION

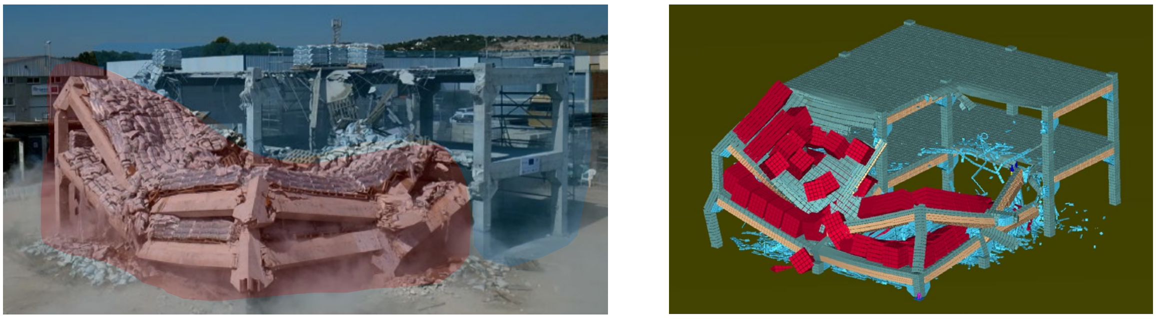
3.1. The structural response during the 1st testing phase (quasi-static removal of two edge columns)

After removing the two edge columns, the precast structure remained standing without any collapse. The measured beam rotations connected to the removed column location were about 0.01-0.015 radians, which were still far below the failure rotation under catenary action (0.2 radians) yet sufficiently high to induce cracking and permanent deformation. The 1st testing phase proves that the continuity provided to the system through peripheral and internal ties helps to prevent collapse under small initial failures.

3.2. The structural response during the 2nd testing phase (dynamic removal of the corner column)

After removing the corner column, the local failure was triggered, and then the failure propagated, leading to a partial collapse of the building. Interestingly, as the ties (which were supposed to provide continuity between structural members) were broken due to a significant increase in strain during the 2nd testing phase, the propagation was arrested and did not spread further to the rest of the building.

As a result, only partial collapse occurred, and a clear border could be seen between the collapsed and intact parts (refer to the boundary between the red and blue shaded regions in **Figure 3a**).



(a) (b)

Figure 3. *(a) Test specimen after the partial collapse; (b) Failure predictions obtained using the AEM.*

Comparing the collapsed state of the specimen from the test with the predictions obtained using the AEM (see **Figures 3a** and **b**), it can be clearly observed that both are in excellent agreement.

4. CONCLUSION

The behaviour of precast concrete structures under small and large initial failures was investigated by testing a full-scale purpose-built specimen involving the removal of three columns. Results obtained from the 1st and the 2nd testing phases revealed that both continuity and segmentation could improve the robustness of building structures against abnormal events. Continuity helps redistribute the excess forces and prevent failure from occurring under small initial failures. In contrast, segmentation provides the last line of defence mechanism to arrest failure when collapse propagation becomes inevitable. An excellent agreement was found between the measured and the predicted responses obtained using the applied element method (AEM).

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