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Computational study on the progressive collapse of precast reinforced concrete structures

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ABSTRACT: Although recent years have been marked by a substantial research effort on the progressive collapse of frame structures, precast reinforced concrete (RC) structures have been the subject of fewer studies when compared to cast-in-place RC or steel ones. Given that precast RC is being increasingly used and that it can be particularly vulnerable under accidental loading conditions, a better understanding of how secondary resisting mechanisms can be activated in such structural systems is a necessary requirement towards building more robust structures in the future. This paper presents computational simulations of a two-floor precast RC frame structure used to predict and extrapolate results from an ambitious experimental campaign involving the sudden removal of edge and corner columns from a purposely built real-scale building.

1 INTRODUCTION

Progressive collapse can be defined as the phenomenon through which an initial localised failure propagates to other parts of a structural system, often leading to the collapse of the entire structure or to a disproportionate part of it. Such events usually occur when structures are exposed to abnormal loading conditions and typically result in significant negative consequences for society. Some classic examples of progressive collapse of building structures include that of the Ronan Point tower (London, 1968) and of the A.P. Murrah Federal Building (Oklahoma, 1995), while more recent occurrences include the collapse of the Hard Rock hotel (New Orleans, 2019) and of the Champlain towers (Miami, 2021). The occurrence of such events over the years and the huge losses they entail have undoubtedly contributed to increased awareness on the need for robust structures that are insensitive to initial local damage. This is clearly evidenced by the growing number of publications on progressive collapse and structural robustness (Adam et al. 2018).

Precast reinforced concrete (RC) components are being increasingly used nowadays due to noteworthy advantages in terms of cost-effectiveness, quality assurance, and durability. However, this structural typology can be characterised by a greater vulnerability to progressive collapse due to the clear lines of weakness it exhibits at joints between precast components (Van Acker et al. 2012) which can contribute to limiting the available alternative load paths (ALPs) in the event of a partial collapse. Although deeply flawed design and construction can be considered as being the main culprits for the collapse of the Ronan Point tower, this case still exemplifies the aforementioned vulnerability as it involved a structure built with precast panels and connections that relied largely on friction (Pearson & Delatte 2005). It is also worth mentioning that this collapse, and the ensuing investigation that followed, greatly influenced the development of current robustness requirements in building codes (Russell et al. 2019).

Despite this fact, the vast majority of research on structural robustness that has been carried out up to now has focused on cast-in-place RC or steel/composite frame structures. In fact, to the best of the authors' knowledge, although there do exist examples of experimental tests involving the sudden removal of columns from full-scale building structures (Adam et al. 2020, Bermejo et al. 2017, Sasani et al. 2007, Song et al. 2014), no such test has ever been performed on precast RC structures.

To this end, the research presented in this paper aims to contribute to better understanding the ALPs that may be activated in precast RC structures after the sudden loss of key columns. This is to be achieved through an experimental campaign in which a full-scale precast RC building will be subjected to different sudden column removal scenarios. The two-storey 15×12 m^2 test structure will be heavily monitored during the tests and the acquired results will be employed to calibrate suitable numerical models. These will then be used to extrapolate the experimentally observed response to other extreme design situations that are relevant for robustness considerations. In this paper, results of simulations performed prior to testing the actual structure are presented. These have been used for supporting key decisions on the final design of the test structure and on the loading and monitoring strategy to be employed for testing. In addition, preliminary conclusions on the effectiveness of possible measures for improving robustness are also described.

2 EXPERIMENTAL CAMPAIGN

The test building that will be subjected to sudden column removal has two floors and a rectangular shape in plan (Fig. 1). The structure's skeleton consists of precast RC beams resting on corbels of precast RC columns. Each floor is made up of hollow-core slabs and a cast-in-place RC topping, with the precast slabs placed as indicated by the dotted lines in Figure 1. All components and basic reinforcement details were designed according to Eurocode 2 (CEN 2004).

Specific reinforcement details for improving continuity were designed based on requirements and recommendations for structural robustness found in relevant design codes and guidelines (CEN 2004, 2006, DoD 2009, Van Acker et al. 2012). In particular, tie reinforcements for accidental actions were introduced. The initial design of these elements were based on prescriptive tying force requirements which can differ from one building code to another (Russell et al. 2019). For the test building, requirements established in Eurocode 2 (CEN 2004) and UFC 4-023-03 (DoD 2009) were both considered. As described in greater detail in Section 4.1, the requirements established in UFC 4-023-03 were eventually employed for the final design.

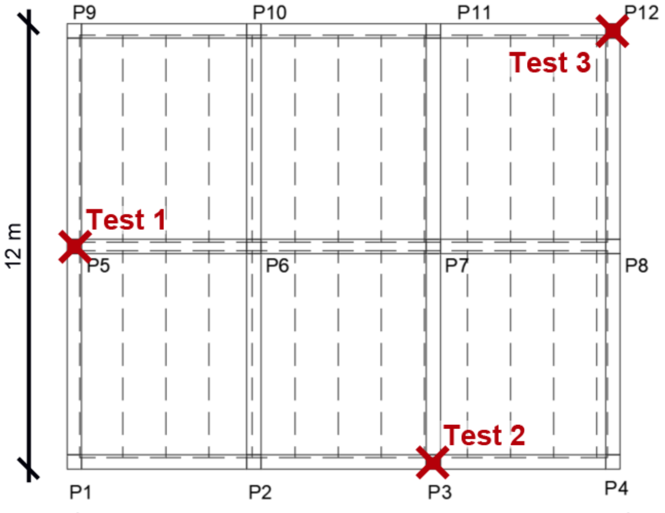

Figure 1. Schematic plan view of test building and location of columns to be removed for each test scenario.

The planned experimental program involves three individual tests, each intended to simulate the sudden loss of a specific edge or corner column of the first floor (Fig. 1). Column removal will be achieved using a hinged column with provisional blocks. A similar procedure was employed for sudden column removal in previous tests investigating the robustness of flat-slab RC building structures (Adam et al. 2020).

A suitable monitoring strategy was developed in order to adequately capture the structural response during each test. As a result, a total of 146 embedded strain gauges are being placed on reinforcement bars for monitoring strains at key locations (Fig. 2). In addition, 38 displacement transducers and 7 accelerometers will also be used together with digital image correlation to monitor the deformation, drift, and vibration of the building during testing.

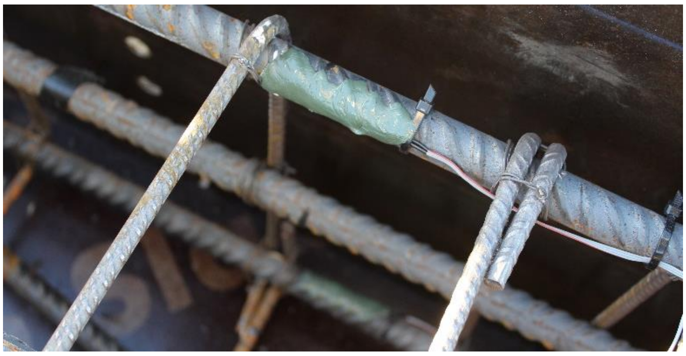

Figure 2. Strain gauge placed on main reinforcement of column prior to concreting.

3 COMPUTATIONAL SIMULATION

The Applied Element Method (AEM) has been used to perform nonlinear dynamic computational simulations of the sudden column removal scenarios due to its ability to accurately represent different stages of failure including cracking, separation, and collision (Meguro & Tagel-Din 2000, Tagel-Din & Meguro 2000a, 2000b).

Prior to performing any predictive simulations of the dynamic response of the test building, a validation exercise was carried out by reproducing experimental results reported in the literature involving column removal tests performed on cast-in-place and precast RC sub-assemblages. The cases used for validation have already been presented in another conference paper together with a comparison of experimental and simulation results (Makoond et al. 2021). For all validation cases, a very good agreement could be obtained between the observed experimental response and that predicted by the simulations, even when considering dynamic behaviour. As such, the chosen strategy for performing computational simulations was deemed as being adequate.

Following the validation exercise, a detailed model of the test structure was created using solid elements and springs to represent different precast components and the interface between them as well as specific reinforcements (Fig. 3). More details on the model geometry and on the material parameters employed can be found in the aforementioned conference paper (Makoond et al. 2021).

Figure 3. Geometry of computational model used for simulating sudden column removal scenarios.

For each of the planned test scenarios, two series of dynamic simulations were performed over an analysis duration of 2 s after sudden column removal. The first involved evaluating the structural response under the effect of a uniformly distributed load of 4 kN/m^2 imposed on bays adjacent to the column to be removed. This load will be reproduced during the planned experimental tests and corresponds to the minimum value of variable action that needs to be considered for accidental design situations according to Eurocode 1 (CEN 2006). These simulations are useful for predicting the ALPs expected to develop during testing (Fig. 4) and the magnitude of key physical parameters whose monitoring is of interest for characterising the test building's structural response.

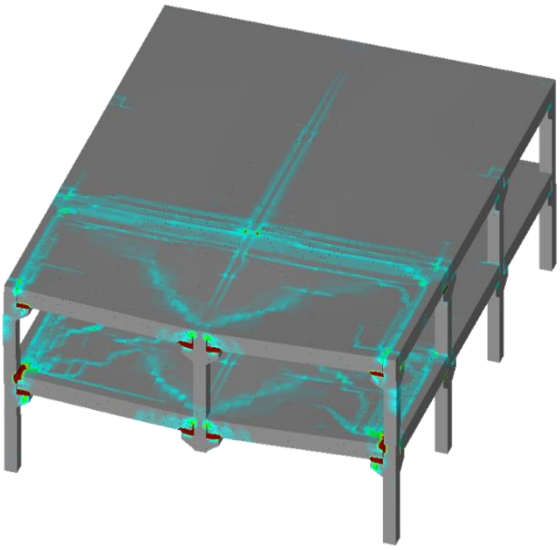

Figure 4. Prediction of alternative load paths that will be activated during Test 1.

The second series of dynamic simulations involved gradually increasing the distributed load until collapse occurred (Fig. 5) in order to estimate the residual capacity of the test structure after column loss.

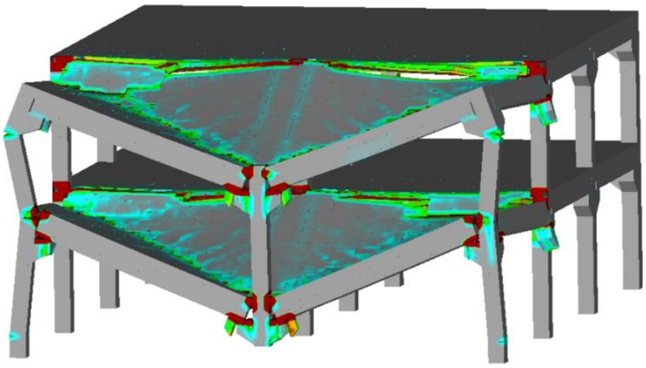

Figure 5. Collapse simulation for the sudden column removal scenario corresponding to Test 1.

4 RESULTS & DISCUSSION

4.1 *Prediction of experimental response*

As previously mentioned, both the tying force requirements established in Eurocode 2 and UFC 4-023-03 were considered for the design of tie reinforcements (see Section 2). The two series of dynamic simulations described in Section 3 were performed for both of these possible design options. Table 1 reports the expected peak displacement just above the removed column together with a safety factor computed as the estimated collapse load divided by the experimental load of 4 kN/m^2. The estimation of this collapse load for the case of Test 1 is presented in Figure 6 which shows the predicted response by nonlinear dynamic simulations of the test building under the effect of different uniformly distributed loads.

Table 1. Key simulation results for design options

	Peak displacement [mm]		Safety factor	
	EC 2	UFC	EC 2	UFC
Test 1	-31.4	-26.4	1.50	1.81
Test 2	-32.0	-23.9	1.13	1.38
Test 3	-24.6	-22.3	1.75	2.13

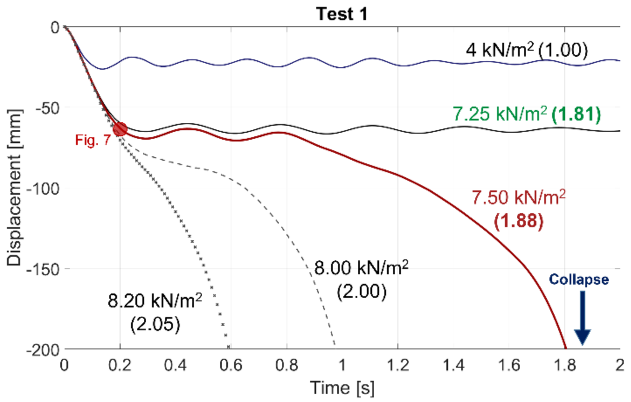

Figure 6. Predicted dynamic response after the column loss scenario of Test 1 under the effect of different loads.

Simulation results reveal that the test scenario for which the lowest displacement and greatest safety factor may be expected refers to Test 3. This can most probably be attributed to the fact that the tributary area actually supported by this column is smaller than that of the other two cases. On the other hand, the test scenario for which the greatest displacement and lowest safety factor may be expected refers to Test 2. This can most probably be attributed to the fact that the hollow-core slabs are mainly supported by frames perpendicular to their orientation and Test 2 involves removing a penultimate column from such a frame.

The results presented in Table 1 also show that if the Eurocode 2 tying force requirements are employed for the design, the estimated safety factor in the case of Test 2 can be considered as being rather low (1.13), particularly considering the many possible sources of uncertainty present in the analysis. For this reason, the tying force requirements established in UFC 4-023-03 were employed for the final design.

4.2 *Secondary resisting mechanisms*

Analysis of predicted resisting mechanisms at different stages after sudden column loss and under the effect of different loads showed that the main mechanism that can be expected to provide ALPs during the experimental tests refers to Vierendeel behaviour of the frame over the failed column (Fig. 7). Note that the analysis time corresponding to the contour plot shown in Figure 7 is indicated in Figure 6.

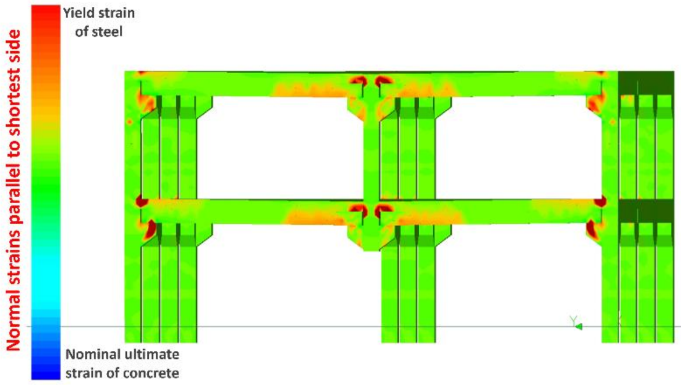

Figure 7. Vierendeel behaviour of frame over the failed column.

For all three column removal scenarios, the simulations performed at higher loads revealed that failure of the adjacent columns or corbels always occur before an equilibrium state relying on catenary action can be established. The failure of adjacent columns for the case of the column removal scenario corresponding to Test 1 is shown in Figure 8. This is an important observation since existing prescriptive robustness design rules for establishing tying force requirements typically rely on the assumption that tensile catenary action (TCA) can develop. This underlines the importance of full-scale testing for better understanding structural behaviour under extreme conditions.

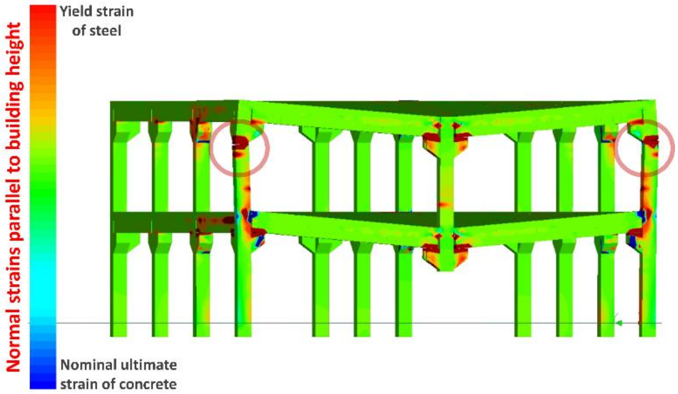

Figure 8. Failure of columns under the effect of a load of 7.50 kN/m^2 after the sudden column removal scenario corresponding to Test 1.

4.3 *Effect of other possible design options*

Given that simulation results indicate that premature failure of adjacent corner columns is the main culprit for preventing the activation of TCA in the case of Test 1, strengthening of these structural elements may at first sight seem like a possible solution for ensuring the activation of this secondary resisting mechanism. To properly evaluate the effectiveness of such a strategy, additional simulations were performed in which the diameter of the main reinforcement bars of corner columns was increased. Figure 9 shows the predicted dynamic response for this design option under the effect of the previously estimated collapse load.

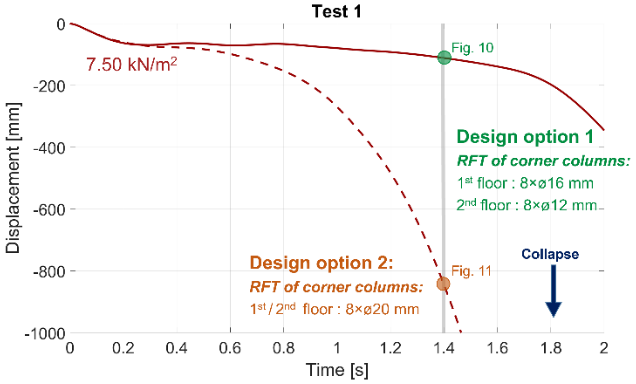

Figure 9. More brittle global mode of failure predicted after strengthening of corner columns.

As can be seen, the design option with stronger corner columns actually results in a more brittle global collapse. Closer analysis of the failure mechanisms reveal that this can be attributed to the fact that the presence of the stronger structural elements lead to unfavourable load redistribution to weaker adjacent structural members that fail even before the column would have in the previous design option with weaker columns. This effect is clearly evidenced by the contour plots of Figures 10-11 which show normal strains 1.4 s after the sudden column removal for both design options as indicated in Figure 9.

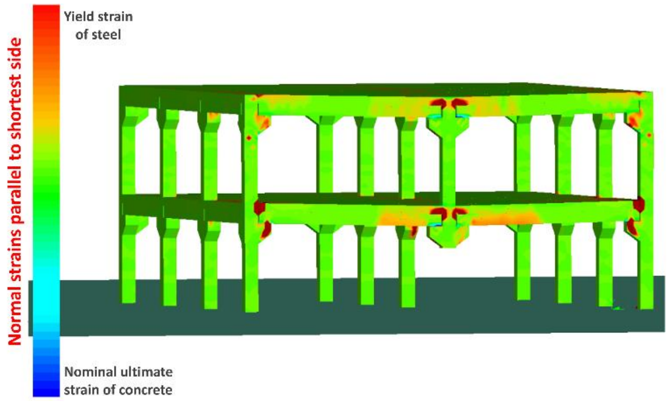

Figure 10. Normal strains predicted by simulation 1.4 s after column removal considering original design.

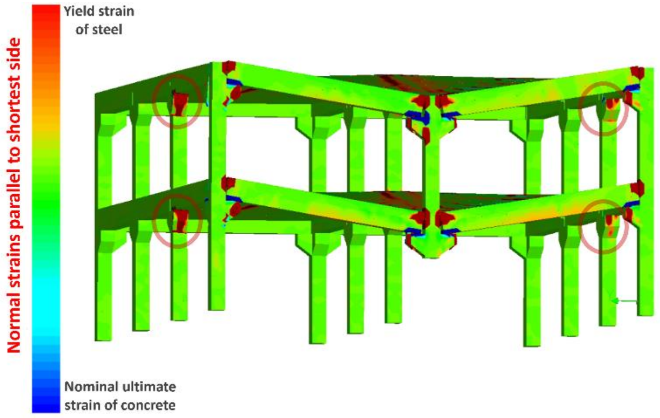

Figure 11. Normal strains predicted by simulation 1.4 s after column removal considering design with stronger corner columns.

5 CONCLUSIONS

This article presented preliminary results of simulations performed prior to an experimental campaign involving the sudden removal of edge and corner columns from a purposely built two-storey 15 × 12 m^2 precast reinforced concrete building. The usefulness of these preliminary simulations for supporting key decisions on both the structural design as well as the experimental setup to be employed are clearly demonstrated.

Additionally, the results also show that if prescriptive robustness design rules for establishing tying force requirements are used, it is also important to evaluate if adjacent parts of a structure can withstand the forces transferred to them during catenary action.

Finally, it was also shown that if adjacent structural members are found to have insufficient capacity for tensile catenary action to develop, simply strengthening these members may not be a viable solution to this issue. This is because such localised strengthening can lead to undesirable load redistribution to weaker parts of the structure and ultimately result in a more brittle global failure mode.

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