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Dynamic and residual behavior of reinforced concrete floors following instantaneous removal of a column

Kai Qian [a], Bing Li [b,*]

[a] College of Civil Engineering and Architecture, Guangxi Key Laboratory of Disaster Prevention and Engineering Safety, Guangxi University, 100 Daxue Road, 530004, China
[b] School of Civil and Environmental Engineering at Nanyang Technological University, 639798, Singapore

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ABSTRACT

With the increasingly real threat of terrorism around the world, many iconic and important buildings may become targets of terrorist attack. This can lead to severe casualties and economic losses as such extreme loading events are not considered in conventional building design. However, experience from past events has shown that most well designed structures will not completely collapse immediately upon the loss of one or more columns as in cases of sabotage. As such, the residual load resisting capacity is crucial in post damage situations where engineers have to make a decision of whether to rehabilitate or rebuild the damaged building. To better understand the behavior of such damaged structures, a series of tests are conducted in this present study. The dynamic response of the specimens is assessed through dynamic tests. Following dynamic tests, the specimens, which have suffered different degrees of damage, are re-tested by push-down loading regimes to capture their residual behavior. The experimental and analytical results indicated that the damage caused by the dynamic response will significantly degrade the initial stiffness and detriment the efficiency of compressive arch action and compressive membrane action even if the specimens actually only experience elastically dynamic response. However, when the specimens undergo a considerable plastically dynamic response, no compressive arch action and compressive membrane action are able to develop. The load resisting capacity would derive mainly from tensile membrane action and catenary action in large deformation stage.

1. Introduction

Past events such as bomb attacks on the Murrah Federal Building, 1995, Khobar Towers, Saudi Arabia, 1996, London Docklands, 1996, World Trade Center, 2001, and Lahore City, Pakistan, 2008 have shown that intentional targeted bomb attacks by terrorists may result in severe loss of live and properties. Researchers (Sasani and Kropelnicki [1]; Sasani et al. [2]) have shown that the main cause of severe casualties is the occurrence of progressive collapse rather than direct blast pressure, such as the collapse of Murrah Federal Buildings in 1995. Thus, it is necessary to evaluate the capability of the buildings to mitigate progressive collapse. Among various methods, the Alternate Load Path (ALP) method is frequently utilized to investigate the ability of the buildings to redistribute the loads safely from the notionally removed column to remaining surrounding elements. A number of researchers have conducted experimental investigations on the behavior of reinforced concrete (RC) buildings to resist progressive collapse via ALP method.

A 3/8 scaled RC beam-column sub-assemblage (Sasani and Kropelnicki [1]) was tested via push-down loading method (a typical expression of ALP method) to investigate the behavior of RC frames subjected to the loss of an interior or exterior column scenario. It concluded that catenary action developed in top reinforcement is the main source of the load resisting capacity in large displacement stage. The catenary action is lost when the beam end rotation reaches 11 degrees.

Su et al. [3] conducted three series of reduced-scale tests to investigate the influences of design parameters on compressive arch action developing in RC beam-column sub-assemblages. It was found that compressive arch action could contribute 50 to 169% extra load resisting capacity beyond the flexural strength of the beams. Moreover, on applying fast loading, compressive arch action still could be developed.

Qian and Li [4] tested two series of specimens to quantify the slab effects on the behavior of RC buildings to mitigate progressive collapse. It was concluded that the RC slab could increase the load resisting capacity of the bare frame by 40% to 63% and reduce the progressive collapse risks effectively.

* Corresponding author.
E-mail address: cbli@ntu.edu.sg (B. Li).

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Qian and Li [5] studied the behavior of RC flat slab or flat plate subjected to the loss of a corner column scenario where punching shear failure was identified as the most critical failure mode. However, the experimental results indicated that drop panels could improve the behavior of flat plate structures effectively and ensure tensile membrane action to develop in the slab.

As mentioned above, a number of experimental and analytical studies [1–10] had been carried out to understand the reliable load resisting mechanisms for RC buildings to mitigate progressive collapse. However, quasi-static push-down tests were applied in these experimental studies. The realistic behavior of RC buildings subjected to the sudden column missing scenarios could not be well captured by push-down tests. As such, some dynamic tests, which are closer to reality, are also carried out in the past several years.

Sasani et al. [2] carried out an in-situ dynamic test on an actual 10-story RC building following the explosion of an exterior column. As the column was not removed clearly and the live loads on the floor were removed before tests, the recorded maximum vertical displacement was only 6.4 mm and the building only achieved elastic response.

Sheffield et al. [11] conducted two dynamic tests on a special fabricated full-scale four-story RC building. Comparing to the test carried by Sasani et al. [2], the additional dead load and design live load was applied before the removal of the columns. In addition, the columns were removed clearly by pre-installed explosives. It was found that the maximum vertical displacement was 200 mm when only one exterior column was removed. When the adjacent interior column was also removed, the maximum vertical displacement could reach 968 mm with significant concrete crushing as cracks formed in the beams and floors.

As conducting full-scale multi-story tests is discouragingly expensive and it is very difficult to install critical instrumentations, simplified dynamic tests could be carried out in a controlled simulated environment instead. Qian and Li [12] conducted a series of 1/3-scale dynamic tests with special designed Instantaneous Column Removal Devices (ICRD). The load cell installed beneath the ICRD indicated that the ICRD could remove the temporary support as fast as 0.005 s, which was fast enough to simulate the column removal due to extreme loading, such as bomb or vehicular impact. Thus, the ICRD will also be utilized in this study to simulate sudden column loss scenarios.

When a building is subjected to the sudden column removal scenario, it may experience two phases: (a) dynamic phase, (b) post-dynamic phase or called residual phase. If a push-down test based on intact specimen is taken as a study on the residual behavior, it will over-estimate its residual behavior and will result in unsafe design as the initial damage caused by the dynamic vibration was ignored. Existing push-down tests mainly focus on evaluation of dynamic behavior and most researchers treat it as an alternative to complex dynamic tests. The dynamic increase factor and analytical models [energy based model from Izzuddin et al. [13] and Single-Degree-Freedom-Model from Qian and Li [14]] could convert the quasi-static response to dynamic response easily, although their reliability still needs further confirmation. Although some buildings may totally collapse when several columns are removed suddenly, many others with sufficient continuity, ductility, and/or redundancy could survive (Sasani et al. [2]; Sheffield et al. [11]). However, the Dead Load (DL) and Live Load (LL) applied on the floor will not decrease after removal of the columns. Thus, the residual performance of the buildings becomes critical when considering safety of rescue operations. From a longer term perspective, it would provide evidence to guide decisions as to repair or rebuild damaged buildings. However, little studies have been carried out on the residual behavior of buildings following sudden column removal. Thus, in this study, a series of three slab-beam-column specimens were designed and tested. A specimen, which was directly tested under push-down loading regime, was taken as a control specimen. The remaining two specimens, which have similar dimensions and reinforcement details, were tested dynamically to simulate the specimens subjected to sudden column removal scenarios. Following the dynamic tests, these two specimens with different degrees of dynamic damage were re-tested by push-down loading regimes to assess their residual behavior.

2. Description of test program

2.1. Experimental specimens

Three one-quarter scaled slab-beam-column RC specimens were tested in this study. These three specimens had identical designed dimensions and reinforcement details. The prototype building of these three specimens is a four-story RC frame, which was designed by Defence Science & Technology Agency (DSTA), Singapore based on Singapore Code CP65 [15] and checked to satisfy the requirements of ACI 318-08 [16]. The design live load (LL) of the prototype specimen is 5.2 kPa. The dead load (DL) due to the RC slab with thickness of 254 mm is 6.4 kPa. The dimensions and reinforcement details of the typical specimen are shown in Fig. 1 and Tables 1 and 2. The specimen was supported by five columns with size of 170 mm × 170 mm. The slab was extended by 563 mm (refer to hatched zone in Fig. 1) to simulate the additional constraints from the interior span adjacent to the test specimen. The slab thickness is 64 mm with a concrete cover of 7 mm. As the cover is only 7 mm, chipping with maximum size of aggregate of 10 mm was used. As mentioned above, the Control Specimen Con-1 was tested subjected to a push-down loading regime. The remaining two specimens were tested subjected to simulated sudden column removal scenarios. One of the specimens was tested dynamically with externally applied pressure of 8.9 kPa. Thus, including the dead load of the slab with 64 mm thickness (1.6 kPa), the total pressure applied on the specimen is 10.5 kPa, which is about 0.91(DL + LL) of the prototype frame. Thus, this specimen is designated as D-0.91. Similarly, another dynamically tested specimen is called D-1.16, as the externally applied pressure is 11.9 kPa. As after suddenly removal of the column, both D-0.91 and D-1.16 are able to stabilize in some position and without complete collapse, their residual strength was measured by subsequent push-down tests. In subsequent tests, these two specimens with initial dynamic damage were called R-0.91 and R-1.16, respectively.

The target compressive strength of the concrete is 25 MPa while the measured compressive strength of Con-1, D-0.91, and D-1.16 are 23.0 MPa, 24.4 MPa, and 25.1 MPa, respectively. Five types of reinforcing steel were utilized for reinforcing cage: R3, R6, R8, T10, and T13. The properties of reinforcing steel are tabulated in Table 3. For example, R3 and T10 represent plain round bar and deformed bar with diameter of 3 mm and 10 mm, respectively.

2.2. Design of test setup

Fig. 2 shows the experimental setup of dynamic test D-0.91. Five intact columns are fixed on the steel supports (Item 7 in Fig. 2) by bolts while the notionally removed column is supported by the special designed ICRD (Item 5 in Fig. 2) before applying the weights. A series of displacement transducers are installed at predesigned locations. Then, the weights are slowly applied on the slab symmetrically. The external weights in D-0.91 and D-1.16 are 9 ton and 12 ton, respectively. Moreover, several steel plates are also placed at the slab extensions (hatched area in Fig. 1) to simulate rotational constraints from the slab in surrounding panels partially. The details of ICRD are illustrated in Fig. 3. As shown in