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Experimental study on dynamic responses of reinforced concrete frames under sudden column removal applying concentrated loading

Anh Tuan Pham, Kang Hai Tan *

School of Civil and Environmental Engineering, Nanyang Technological University, Nanyang Avenue, 639798 Singapore, Singapore

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This paper focuses on structural behaviour of storeys above the targeted column that is suddenly lost due to accidental/terrorist events. The pertinent question is whether these storeys will remain stable, or the ensuing dynamic motion will cause them to fail during the free-fall stage. It is assumed that the two-dimensional frame structure above the targeted column is in pristine state. Previous quasi-static studies on reinforced concrete beam-column structures under missing column scenario have highlighted the potential of catenary action on providing alternate load paths to prevent catastrophic collapse. However, corresponding dynamic tests, either did not share the same loading configuration with the static tests, or did not have sufficient headroom and the specimen hit the ground before catenary action could be fully mobilised. On this paper, a series of dynamic tests was carried out for two-dimensional reinforced concrete beam-column frames simulating the sudden removal of a supporting column via a quick-release device. The specimens were loaded and hung by a mechanism which could be released to effect free vibration. Development of catenary action, which has not yet been confirmed in any previous dynamic tests, was well captured. The study also showed the influence of inertial and strain rate effects on structural response. Most importantly, the dynamic tests applied the same method of concentrated loading at the middle joint as the previous quasi-static tests conducted on similar specimens. As a result, comparisons could be made on damage patterns and failure modes between the dynamic tests and the static tests. Compared to static environment, the dynamic tests only took a few seconds and their behaviours are closer to the actual behaviour of the storeys that undergo free-fall acceleration.

1. Introduction

Progressive collapse has been extensively studied during the last few decades due to its disastrous consequences in the loss of human lives. Recent guidelines and standards against this rare event [1–3] implement a threat-independent approach to assess structural resistance using the assumption of single column removal. Seeking for effective alternate load paths after a main supporting element has been ideally removed, several experimental studies on reinforced concrete (RC) double-span beams and beam-column frames have been conducted quasi-statically [4–12]. To simulate the loss of a supporting column, most of the quasi-static tests applied a point-load method with a displacement-controlled manner, in which the beam-column joint above the removed column was pushed downwards by either an actuator or a hydraulic jack. In these quasi-static push-down tests, structural behaviour started with flexural mechanism enhanced by compressive arch action (CAA) due to horizontally restrained boundaries. Thereafter, catenary action (CA) was mobilised when the deflection exceeded one beam depth, marked by a change of beam axial force from compression to tension. Subsequently, beam bottom rebars at middle-joint interfaces started fracturing, leading to a sudden drop in load-carrying capacity. Structural response after this state [4,8–10] showed an increase due to CA in the beam top rebars. The RC structure collapsed totally when those rebars fractured. To verify the structural behaviour within the dynamic regime, free-fall dynamic tests were also conducted simulating the column loss scenario by suddenly eliminating the supporting mechanism of the middle joint. Such pairs of static-versus-dynamic tests include: [6] and [13,14] and [15,16] (including both static and dynamic tests), [7,17]. In those studies, although the specimens from both testing environments shared the same design and boundary condition, they were applied with different loading methods. While the static tests had the single-point loading configuration above the removed column, the dynamic tests adopted a multi-point loading method by arranging several massive weights

* Corresponding author.
E-mail addresses: atpham@ntu.edu.sg (A.T. Pham), ckhtan@ntu.edu.sg (K.H. Tan).

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along the double-span structure. Such a difference in loading procedure could lead to different structural behaviours, load-carrying capacities, and possibly failure modes.

To overcome this shortcoming, Yu conducted two tests series under static and dynamic blast-induced conditions for RC subassemblages applying a similar method of concentrated loading [8,18]. The dynamic test series included three specimens named SD-1, SD-2, and SD-3. Specimen SD-2 was subjected to an applied load of 27 kN; the structure responded under flexure and compressive arch mechanisms but no tensile reaction was mobilised at the supports due to small applied load. On the other hand, SD-1 and SD-3 had a higher load level of 47 kN. The specimens deformed excessively within CA regime leading to the fracture of bottom rebars at the middle beam-column joint. However, due to insufficient head room for deflection, both specimens hit the ground before any final failure occurred. In other words, the development of CA after the fracture of bottom rebars, which had been confirmed in the corresponding static tests [8], was not yet demonstrated in the dynamic tests. Besides, only the horizontal reactions at the end joint were measured during the dynamic tests but not the vertical reactions. Therefore, the response of vertical load-carrying capacity obtained from the static tests could not be compared to the dynamic tests.

Another way to assess dynamic capacity of a structural system under progressive collapse is to convert its static response into a pseudo-static response using energy-based method [19,20]. This method assumes similar response and failure mode of the structure between the static and the dynamic free-fall regimes. It is important to establish an experimental programme to test if this assumption is indeed valid in the dynamic free-fall regime. This will be critical to establishing a reliable structural model, especially within CA stage.

To study the behaviour of RC beam-column frames against progressive collapse under different horizontal restraint conditions, a quasi-static test series including two RC frames designed according to Eurocode 2 [21], was conducted at Nanyang Technological University laboratory [10]. To extend the quasi-static study into the dynamic regime, a free-fall dynamic test series was conducted and is presented in this paper. The objectives of the dynamic free-fall tests were to investigate (a) dynamic effects caused by the sudden removal of a supporting column; (b) if the failure modes were different from those of static tests under the same loading configuration; (c) if catenary action could be mobilised after the fracture of bottom rebars at the middle joint; and (d) the usefulness of Izzuddin method [19] compared with actual dynamic responses. Test parameters included boundary conditions (full-restraint and partial-restraint) and applied loads at the middle joint. Unlike the displacement-controlled quasi-static tests in which the entire displacement-versus-load-capacity relationship could be obtained, in each dynamic test a specimen could only be subjected to a predefined fixed imposed load and therefore could only provide one corresponding maximum deflection. Hence, to clearly understand the dynamic behaviour of the frame structures, three different load levels were applied for each type of boundary condition. Extensive comparisons between static and corresponding dynamic tests could then be made in terms of displacement profiles, crack patterns and failure modes, as well as behaviours at cross-sectional and at structural levels.

2. Experimental programme

2.1. Specimen design and test setup

In the static tests [10], the two specimens, named as FR and PR, shared the same geometry and reinforcement design, except that the boundary conditions at two sides of the specimens were different. While FR represented an RC frame with both sides fully restrained (interior column loss), the frame in PR test was fully restrained at the right side but partially restrained at the left side (next-to-outermost column loss). Test results elucidated the differences in structural behaviour between the two specimens regarding CA, which was fully mobilised under the full-restraint condition (FR) after the fracture of bottom rebars at the middle joint. Considering the static test of PR, after the bottom rebars in the beam had fractured, the partially-restrained side column started moving inward excessively under the pull of CA in the double-span beam, thereby limiting the load-carrying capacity in CA phase. To protect laboratory equipment from being damaged by the abrupt collapse of the side column, PR specimen was stopped at a middle-joint displacement (MJD) of 396 mm before any top rebar fracture had occurred.

Similar to the static tests, the specimen design in the dynamic test series consisted of a double-span beam with a middle joint, two side columns and beam extensions as shown in Fig. 1. High strength deformed bars were used for beam longitudinal reinforcement while mild steel round bars were used as stirrups. Number of beam top reinforcing bars was reduced at curtailment points, located at 650 mm from the joint interfaces, while beam bottom rebars were continuous along the entire double span. The lengths of side columns and beam extensions were chosen to coincide with contra-flexural points of the 2D frames in the real structure. Therefore, only pin and horizontal supports were needed for such a test setup. Two types of boundary conditions, i.e. full-restraint and partial-restraint, were applied. For the fully restrained specimens, beam extensions were arranged at both sides of the double-span beam and were horizontally restrained by either an A-frame or a strong wall. Fig. 2 illustrates the test setup for a typical fully restrained specimen in which pinned supports and horizontal restraints were symmetrically arranged at both sides. On the other hand, for the partial-restraint specimens, the beam extension was only designed at the left side. As a result, the beam extension and the horizontal reaction RH2 at the right side of the specimen (as shown in Fig. 2) were omitted and the right-side column was only horizontally restrained at RH1 and RH3. To simulate the axial forces on the side columns generated by gravity loads from the above floors in the actual frame, before conducting the dynamic free-fall tests, pre-loaded forces were applied onto the side columns using four steel rods and a hydraulic jack was placed on top of each column (item 8 in Fig. 2).

Applied load at the middle joint was simulated using a set of steel plates which was hung underneath this joint with the total weight varying from test to test (Fig. 3(a)). The middle joint was suspended from a supporting H-frame by a quick-release device (Fig. 3(b)) which could suddenly release the joint by yanking a rope connected to it. Such a mechanism for progressive collapse dynamic tests had been successfully applied in a previous study on steel joints [22]. There was sufficient clearance height below the steel-plate system at the middle joint to ensure that the specimen could only hit the strong floor after final failure had occurred.

Four specimens, named as FD1 to FD4, were fabricated and tested under free-fall condition. Table 1 summarises the parameters of all the dynamic free-fall tests, as well as the information on the two static tests conducted previously [10]. In terms of concrete grade, the dynamic tests had higher cylinder strengths compared to the static tests, in particular FD3 and FD4. Concerning reinforcement material, the dynamic (Table 2) and the static test [10] specimens had fairly similar properties. Among the four specimens, FD1 and FD2 represented full-restraint frames and were tested under applied load levels of 20, 29, and 34 kN. On the other hand, FD3 and FD4 were designed for partial-restraint frames and