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Experimental investigation of progressive collapse resistance of one-way reinforced concrete beam–slab substructures under a middle-column-removal scenario

Peiqi Ren [a,b], Yi Li [a], Xinzheng Lu [b,*], Hong Guan [c], Yulong Zhou [b]

[a] Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing Collaborative Innovation Center for Metropolitan Transportation, Beijing University of Technology, Beijing 100124, China
[b] Key Laboratory of Civil Engineering Safety and Durability of Ministry of Education, Tsinghua University, Beijing 100084, China
[c] Griffith School of Engineering, Griffith University, Gold Coast Campus, Queensland 4222, Australia

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ABSTRACT

Floor systems composed of beams and slabs are critical structural elements of frame structures to resist progressive collapse. Previous experimental studies have focused mainly on beam–column or continuous-beam substructures and have ignored the influence of the slab. To study the progressive collapse-resisting mechanisms of reinforced concrete (RC) floor systems, seven 1/3-scaled one-way substructure specimens, including five beam–slab specimens and two continuous-beam specimens without slabs, were tested under a middle-column-removal scenario. The effects of various structural parameters, including sectional dimensions (beam height, slab width, and slab thickness) and seismic reinforcement, on the progressive collapse resistance were studied by analyzing material strains and load–displacement curves. Under small deformations, the progressive collapse resistance was largely affected by the beam height, slab width and seismic reinforcement in the beams. However, the effect of the slab width, upon exceeding the effective flange width, became insignificant. Note that increasing the slab thickness simultaneously increased the amount of slab reinforcement according to the minimum requirement of reinforcement ratio for slabs, such an increase will in turn enhanced the progressive collapse resistance. In addition, the existence of the slab led to an over-reinforced damage in the compressive zones of the beam ends, which accelerated the bending failure and the presence of the catenary action of the specimens. Under large deformations, the progressive collapse resistance was mainly influenced by the reinforcement area of the entire beam–slab section. The total reinforcement area of a beam–slab substructure designed to meet a higher seismic requirement was not significantly increased, and consequently, the progressive collapse resistance of the substructure under the catenary mechanism was not notably improved. This finding stands in stark contrast to those of previous tests of beam–column specimens without slabs.

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1. Introduction

The progressive collapse of a building structure is defined as a disproportionate or overall structural collapse caused by an initial local failure which propagates in the structural system [1]. Progressive collapse not only results in casualties and property damage but also has significant social, psychological and economic consequences. As such, how to minimize the risk of progressive collapse has increasingly attracted worldwide attention. Several design methods for improving the progressive collapse resistance of building structures have also been proposed by various design codes [1–3] and special guidelines [4,5].

The progressive collapse-resisting performance of reinforced concrete (RC) frames has been theoretically investigated in three major aspects. Izzuddin et al. [6], Xu and Ellingwood [7] and Li et al. [8] have proposed various design methods. Li et al. [9,10] and Tsai and Lin [11] have examined the dynamic effect associated with the progressive collapse. Brunesi et al. [12] and Fascetti et al. [13] proposed the theoretical methods to assess the progressive collapse resistance of RC framed structures. Numerical simulations have been also conducted to investigate the progressive collapse resistance of RC beams [14] and frames [15]. In addition, many researchers have studied collapse mechanisms using experimental

* Corresponding author.
E-mail address: luxz@tsinghua.edu.cn (X. Lu).

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means. A recent experimental study by Qian et al. [16] has revealed that RC frames exhibit different progressive collapse-resisting mechanisms under different deformation states: for small deformations, the collapse resistance is provided by the flexural capacity at the beam ends and the compressive arch action (CAA) within the beams themselves; whereas for large deformations, the resistance is provided by the so-called catenary action through the tensile force in the beams.

It should be noted that previous experimental investigations [17–21] have mainly focused on beam–column subassemblies and have mostly neglected the effect of slabs on the progressive collapse-resisting performance of frames. In real structures, however, RC slabs play an important role in redistributing unbalanced loads and bridging initial local failures. This is because slabs are cast monolithically with beams and act as horizontal members in transferring the unbalanced gravity loads induced by the initial local failure of the column.

Qian and Li [22] conducted a series of static collapse tests on beam–slab substructures under a corner-column-removal scenario. In their work, the contribution of the slab to progressive collapse resistance was analyzed by comparing the beam–slab substructures with beam specimens. Their test results indicated that the risk of collapse can be significantly reduced by the slab contribution. Qian and Li [23] also performed dynamic collapse tests on beam–slab substructures in the corner areas of RC frames, in which the effect of slabs during the dynamic collapse process was studied through comparison with the results of their static tests [22]. In an experimental study conducted by Pham and Tan [24], the beam–slab substructures were subjected to a penultimate internal column loss under a uniform load. The collapse mechanism of the substructures and the impact of the aspect ratio and the amount of slab reinforcement on the failure mode were studied. Gouverneur et al. [25] tested a restrained RC slab strip exposed to a simulated accidental failure of a central support and found that the collapse resistance was significantly increased by the tensile membrane action of the slab.

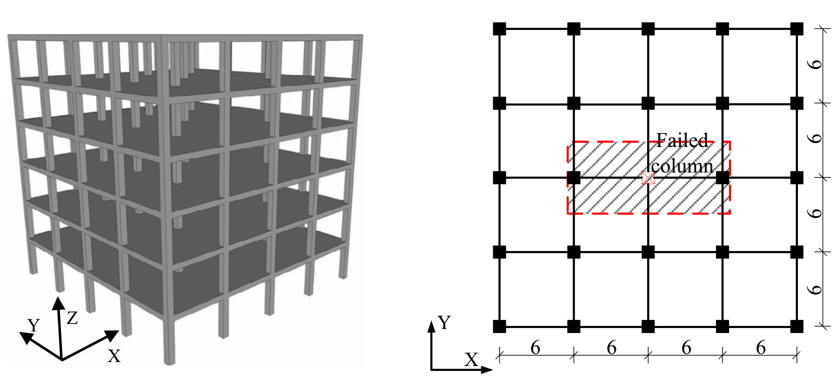
The outcomes of the experimental studies mentioned above indicate that slab contribution to the collapse resistance is significant. This is because, in addition to the CAA and the one-dimensional catenary action of beams, slabs are able to develop two-dimensional (2-D) compressive membrane action (CMA) under small deformations and 2-D tensile membrane action (TMA) under large deformations. These 2-D actions are thought to provide additional progressive collapse resistance. Although many researchers have studied CMA [26] and TMA [27,28] in slabs, and some [29] have considered the influence of TMA on collapse resistance, an in-depth and systemic study in this area is still needed. In particular, emphasis should be given to the beam–slab interaction in resisting collapse under different deformation scenarios and the influence of various structural parameters on the collapse resistance.

In this work, a series of experimental tests were performed to investigate the collapse mechanism and resistance of RC beam–slab substructures. Given the complicated spatial mechanical behavior of slabs, a one-way beam–slab substructure was considered and its one-dimensional mechanical behavior was examined. A total of seven 1/3-scaled specimens were tested in response to the failure of a middle column. These specimens include five one-way beam–slab substructures and two continuous-beam substructures. Various structural parameters to be considered were the sectional dimensions (i.e., beam height, slab thickness and slab width) and the seismic reinforcement. The failure modes of the substructures and the effects of the various structural parameters on the progressive collapse resistance of beam–slab substructures were examined systematically.

2. Experimental program

2.1. Design of the specimens

The prototype structure is a six-story RC frame (Fig. 1) designed in accordance with the Chinese building codes [30,31]. The first story is 4.2 m in height, and the remaining stories are 3.6 m in height. The span length in both directions is 6 m. The design dead and live loads are 5.0 kN/m^2 and 2.0 kN/m^2, respectively. The beams and columns in the structure are designed to be ductile-bending-controlled while the shear and torsional failure can be prevented [30,31]. According to the code requirement [30,31], the beams and columns are expected to be damaged in bending in which the tension reinforcement yields while concrete in compression crushes, resulting in a large ductile rotational deformation. The beam–slab substructure being tested is highlighted with the shaded area enveloped by the red rectangle, as shown in Fig. 1b. Due to the restraint of the laboratory space, the substructure was scaled down to 1/3. Published research confirmed that the critical scaling factor for RC specimens not damaging in shear is 1/4 which can well represent the resistance mechanisms and load–displacement relations of large scaled specimens [32]. Hence, 1/4 [16,24], 1/3 [17,21–23] and 1/2 [19,20] scales were adopted in many progressive collapse tests on RC substructures, in which the size effect on the collapse mechanism and resistance can be neglected [20,32]. The sectional dimensions of the prototype structure and the control specimen are given in Table 1. The thicknesses of the concrete cover of the beams and slabs of the test specimens were 6 mm and 5 mm, respectively.



(a) Perspective view (b) Plan view

Fig. 1. The prototype structure (units: m).