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New analytical calculation models for compressive arch action in reinforced concrete structures

Xinzheng Lu[a,*], Kaiqi Lin[b], Chenfeng Li[c], Yi Li[d]

[a] Key Laboratory of Civil Engineering Safety and Durability of Ministry of Education, Tsinghua University, China
[b] Beijing Engineering Research Center of Steel and Concrete Composite Structures, Tsinghua University, China
[c] College of Engineering, Swansea University, Swansea SA1 8EN, UK
[d] Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, China

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ABSTRACT

Research challenges associated with progressive collapse of reinforced concrete (RC) structures have attracted growing attention from researchers and industries worldwide, since the 1995 explosion at the Murrah Federal Building in Oklahoma City. The compressive arch action (CAA), as a favorable mechanism to provide the structural resistance to progressive collapse under a column removal scenario, has been extensively studied using both experimental and theoretical approaches. However, the existing prediction models for the CAA resistance are either too complicated or in need of additional information like the peak deformation of the specimen. Another major weakness in the previous CAA calculation models is the negligence of the slab effect, which can contribute significantly to the structural resistance. In this study, based on the finite element analysis of 50 progressive collapse tests reported in the literature and 217 newly designed beam-slab substructures, explicit and easy-to-use CAA calculation models are developed for RC frame beams with and without slabs. The proposed models are validated against both experimental and numerical results with a mean absolute error being less than 10%. The findings from this study can serve to provide a quantitative reference for practical design of RC frame structures against progressive collapse.

1. Introduction

Progressive collapse study has become an important research frontier since the collapse of Alfred P. Murrah Federal Building in the 1995 Oklahoma City bombing attack [1]. Current research outcomes indicate that a structure can resist the progressive collapse through two major mechanisms, i.e., the beam mechanism at small deformations and the catenary mechanism at large deformations [2–10]. As such, fully utilizing these two resistance mechanisms has become the primary objective of the current progressive collapse design codes [11,12]. According to the existing experimental observations, compressive arch action (CAA) is commonly found in reinforced concrete (RC) beams at small deformations [5–10,13–19]. Quantitatively, CAA has been found to improve the structural resistance by 30–150% as indicated in the existing studies [10,14]. Therefore, an accurate and easy-to-use calculation model for CAA is of significant value for achieving a rational progressive collapse design.

An illustration of CAA is shown in Fig. 1, where the middle column fails and loses its load carrying capacity. The unbalanced gravity load from the structure above, which is originally carried by the failed column, is subsequently transformed into a concentrated load P on the beam-column joint. At the early stage of loading, the structural resistance to progressive collapse is provided by the flexural capacities (i.e., M_1 & M_2) of the frame beams (Fig. 1a). As the displacement increases, cracking of the concrete will cause a migration of the neutral axis, accompanied by an in-plane expansion of the specimen. When this expansion is restrained by the boundaries at the beam ends, CAA will be formed in the beams which will in turn enhance the strength of the specimens as shown in Fig. 1b [20].

Many theoretical investigations have been performed to evaluate the CAA resistance, among which Park & Gamble proposed one of the most widely accepted CAA calculation model [21]. The Park & Gamble's model was validated by Su et al. [14] and Qian et al. [10] with their experimental tests. Afterwards, Yu & Tan [22] and Kang & Tan [23] further updated the Park & Gamble's model, by calculating iteratively the force–displacement relationship of RC beams at the CAA stage. The existing literature shows that the computational models of Park & Gamble [21], Yu & Tan [22] and Kang & Tan [23] are sufficiently accurate when calculating the CAA resistance of RC frame beams. However, further studies are still required due to the following

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

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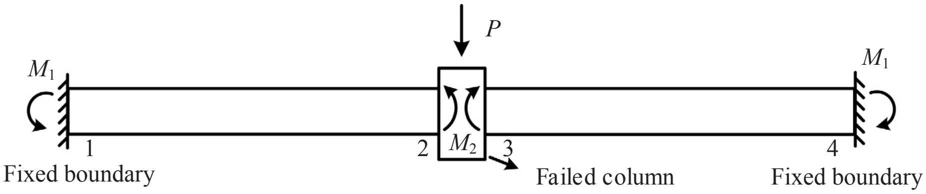
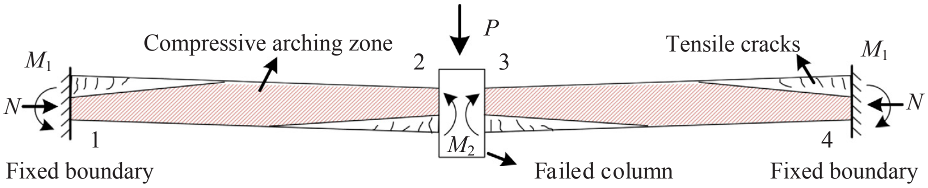


(a) Resistance mechanism of RC beams at initial loading stage



(b) Resistance mechanism of RC beams at CAA stage

Fig. 1. CAA in RC beams at small deformation stage under concentrated load (Note: 1, 2, 3, 4 denote various beam sections).

reasons:

(1) The abovementioned models are not suitable for practical use in progressive collapse design: (a) the Park & Gamble's model [21] requires the peak displacement of the CAA, which cannot be easily obtained for real structures; (b) the models proposed by Yu & Tan [22] and Kang & Tan [23] require iterative calculations of the relative depth of the equivalent compression zone, making the associated computation infeasible without dedicated computer programming.
(2) In real RC frame structures, the frame beams and slabs are always cast together to carry the dead and live loads. According to Ren et al. [7] and Lu et al. [8], the presence of slab can significantly improve the progressive collapse resistance at the CAA stage. However, existing models can only calculate the CAA of frame beams. In the presence of slabs, reinforcing steels on beam sections 1–4 (Fig. 1b) do not yield simultaneously, which violates the fundamental assumptions of the existing models. Hence, when these models are used for evaluating the CAA resistance of the frame beams with the slab effect, significant errors would be expected.

In this study, we simplified the boundary conditions as fixed ends in order to provide an explicit solution for calculating the CAA resistance of RC beams under interior column removal scenarios. Such simplification also helped to simplify the prediction equations, making the proposed model more practical and feasible for practical engineering applications. Note that in the alternate path (AP) design method as specified in most of the existing progressive collapse design codes [11–12], a column removal means removing the clear height of the selected column between the lateral restraints at both column ends. In real situations, the interior beams or beam-slab substructures are always surrounded by the peripheral structural components (i.e., beams, columns and slabs of the adjacent bays). These components will provide sufficient restraints to the deformation of the boundaries. It is therefore rational to assume such fixed boundaries when considering the interior column removal case in an RC structure.

To overcome the limitations of the existing calculation models for CAA, we established a series of finite element (FE) models fully validated against a large database of experimental outcomes. For both beam and beam-slab specimens, their sectional stress-strain distributions, key design parameters and the corresponding sensitivities were analyzed using the validated FE models. Following the experimental and numerical analysis, we proposed explicit and easy-to-use CAA calculation models for RC beams with and without slabs. Comparison with the published experimental results of other researchers confirms that the newly developed models can accurately produce the progressive collapse resistance of RC beams (with and without slabs) at the CAA stage. The computational procedure of the new models is simple and easy to implement. The findings from this study can serve to provide a quantitative reference for practical design of RC frame structures against progressive collapse.

2. Validation of the Park & Gamble's model

2.1. The Park & Gamble's model

The Park & Gamble's model [21] is based on the deformation compatibility and force equilibrium of RC beams under a concentrated load (Fig. 2a). Considering the isolated beam model shown in Fig. 2b, the progressive collapse resistance (P) at CAA stage can be expressed as:

$$P = \frac{2(M_1 + M_2 - N\delta)}{\beta l} \tag{1}$$

where δ is the peak displacement corresponding to the peak load; M_1 and M_2 are the moments at the beam ends; N is the axial force induced by CAA; l is the total length of the two-span beam; β is the ratio between the net span and the total span l. Note that M_1, M_2 and N can be derived by calculating the resultant forces at the corresponding cross sections.

In the Park & Gamble's model, the relative depths of the compression zones at Sections 1 and 2 are obtained by solving the equations of deformation compatibility and force equilibrium:

$$c' = \frac{h}{2} - \frac{\delta}{4} - \frac{\beta l^2}{4\delta}\left(\varepsilon + \frac{2t}{l}\right) + \frac{T' - T - C_s' + C_s}{1.7 f_c' \beta_1 b} \tag{2}$$

$$c = \frac{h}{2} - \frac{\delta}{4} - \frac{\beta l^2}{4\delta}\left(\varepsilon + \frac{2t}{l}\right) - \frac{T' - T - C_s' + C_s}{1.7 f_c' \beta_1 b} \tag{3}$$

where c' and c are the relative depth of the compression zone at Sections 1 and 2, respectively; h and b are the height and width of the