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# A simplified approach to assess progressive collapse resistance of reinforced concrete framed structures

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ABSTRACT

Progressive collapse resistance of reinforced concrete (RC) building structures can be assessed by sudden column loss scenarios. Penultimate column loss is among the most critical scenarios since it leaves the affected beam-slab systems with lack of external lateral restraints. Under such accidental situation, flexural action in the double-span beams and slabs bridging over the removed column is experimentally identified as the main mechanism to redistribute the gravity loads, which is amplified by double span effect and dynamic effect. This paper presents a simplified approach for progressive collapse assessment of RC building structures subjected to a penultimate column loss. The collapse resistance is calculated based on an idealized elastic–plastic static response of a double-span beam-slab structure, which is constructed with (*i*) ultimate flexural capacity of the beam-slab structure that is determined by yield-line method of analysis and (*ii*) displacement ductility at the removed column position that is established based on curvature ductility of a critical connection touching on the affected area. The idealized static response is validated by experimental results of 12 beam-slab sub-assemblage tests. A simple step-by-step procedure together with worked examples are provided. Practical application of this approach and design recommendations for mitigating progressive collapse are discussed.



## 1. Introduction

Analytical approaches for progressive collapse assessment of multi-storey buildings using sudden column loss scenarios have been addressed in recent publications. Kaewkulchai and Wiliamson [1] developed a computer programme for analyzing the dynamic behavior of a planar frame subjected to a sudden column loss. Brunesi and Nascimbene [2] proposed a fibre-based model to quantify progressive collapse resistance of reinforced concrete (RC) building structures subjected to an instantaneous removal of a bearing element. Based on this model, a finite element program was created in which the demand-to-capacity ratio of a critical beam was used as a failure criterion. The program was applicable for both 2D and 3D moment resisting frames. Elkoly and El-Ariss [3] presented a numerical procedure that can be used to evaluate the potential for progressive collapse of RC continuous beams due to removal of interior columns. Izzudin et al. [4] proposed a simplified framework consisting of three main stages: (*i*) determination of the nonlinear static response of affected structures under gravity loading condition, (*ii*) simplified dynamic assessment to establish the maximum response due to sudden column loss, and (*iii*) ductility assessment of the critical connections within the affected areas.

The most detailed design document, published recently for progressive collapse mitigation, is UFC 4-023-03 [5]. Three analysis procedures are introduced in this document: linear static, nonlinear static and nonlinear dynamic. To assess the potential for progressive collapse of a building, a three-dimensional finite element model is required whereas two-dimensional models are not allowed. To establish structural acceptance criteria, all structural elements (beams, slabs) should be designated as either primary or secondary members and all actions (moment, shear and axial forces) should be classified as either deformation-controlled or force-controlled. In static analysis procedures, dynamic effect on the floor areas directly above the removed column, defined as *Dynamic Increase Factor*, is evaluated based on rotational ductility ratios ($\theta_{pra}/\theta_y$) of structural elements connected to the affected floor areas. The smallest ratio of $\theta_{pra}/\theta_y$ is chosen for any primary element to obtain the largest value of the dynamic increase factor for overall static analysis.

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Although UFC 4-023-03 is a well organized and systematic design document, it seems only suitable for the design of DoD facilities where progressive collapse mitigation under column loss scenarios is the top priority. For civilian structures such as residential or office buildings, where progressive collapse is a rare event, its applicability is in question. First, in order to analyse and evaluate a building with either static or dynamic procedure, the designer should be capable of managing a relatively complicated multi-step procedure in which every step must be conducted with an advanced finite element software. Second, in creating a model of the entire building structure, load-deformation behavior of all structural elements such as beams, slabs and beam-column connections, should be explicitly modelled incorporating the strength degradation and residual strength. These make the structural analysis highly time-consuming and less productive for engineers. Besides, no worked example with three analysis procedures for RC structures is provided in this guideline. It is also not clear whether the nonlinear analysis procedures have been validated with actual test results for progressive collapse. Thus, even if engineers carefully follow the stipulated procedures, there is no guarantee that the numerical predictions will be accurate and reliable.

In view of the limitations of the existing software, a simplified approach is proposed in this paper to assess the progressive collapse resistance of ordinary RC buildings under sudden penultimate column loss scenarios. This approach, which is developed upon the experimental results of 12 beam-slab sub-assemblage tests, overcomes the above-mentioned difficulties to enable practicing engineers to quickly evaluate the resistance against progressive collapse.

In this paper, Section 2 describes the main assumptions, idealization, and derivations, while Section 3 provides experimental validation of the proposed approach. Section 4 provides a step-by-step procedure together with worked examples. Applicability and limitation of this approach is discussed in Section 5, concluding remarks are included in Section 6.

## 2. Simplified approach

### 2.1. Assumptions and idealization

Potential for progressive collapse of building structures can be evaluated by column loss scenarios [4–7]. The loss of either a penultimate-external (PE) column or a penultimate-internal (PI) column, as illustrated in Fig. 1(a) and (b) respectively, is among the most critical scenarios for two reasons. Firstly, due to the lack of external lateral support, compressive arch action and catenary action, which can significantly enhance structural resistance, could not be fully mobilized in beams and slabs bridging over the removed column. Instead, flexural action remains the main mechanism for redistributing gravity loads that are severely amplified by the double-span effect and dynamic effect. Secondly, at large deformations, tension forces in the double-span beams may pull the perimeter columns inwards, accelerating progressive collapse [8]. It is worth noting that proportion of penultimate columns is often very large in a typical building structure. For example, in a structural layout with three bays and five spans (Fig. 1a), both PE and PI columns account for 50% of the total number of columns.

For residential or office buildings, it is common that gravity loads, including dead and live loads on all floors, remain unchanged so that structural configuration as well as the sizes of horizontal components such as beams and slabs of every floor can be typically designed. In some situations, slight reduction in column size may be allowed for every four or five stories from the foundation level to the top of buildings to increase usable space, so long as it does not affect the vertical continuity of structures, as well as serviceability conditions. Therefore, every floor is considered approximately identical in terms of gravity loads, structural strength and stiffness. When a column at the ground level is suddenly removed by an explosion, axial compressive forces in columns above the removed column vanish quickly within a few milliseconds [8]. As a result, the associated floors with the same gravity loads, strength and stiffness fall into almost identical vertical vibration mode. Progressive collapse resistance of building structures can therefore be assessed by considering one typical floor, instead of entire building structure (Fig. 1c).

### 2.2. Evaluation of dynamic effect

An equivalent single degree of freedom system (SDOF) is employed to analyze the dynamic response of a typical beam-slab floor system subjected a sudden penultimate column loss, as shown in Fig. 2(a). The maximum vertical displacement of the actual system, which is measured at the removed column location, is selected as a SDOF so that the displacement ductility ratios of the actual system and the equivalent system are identical [9]. Equivalent mass $M_e$ is converted from the total (uniform) gravity load by mass transformation factor $K_m$, which is given as:

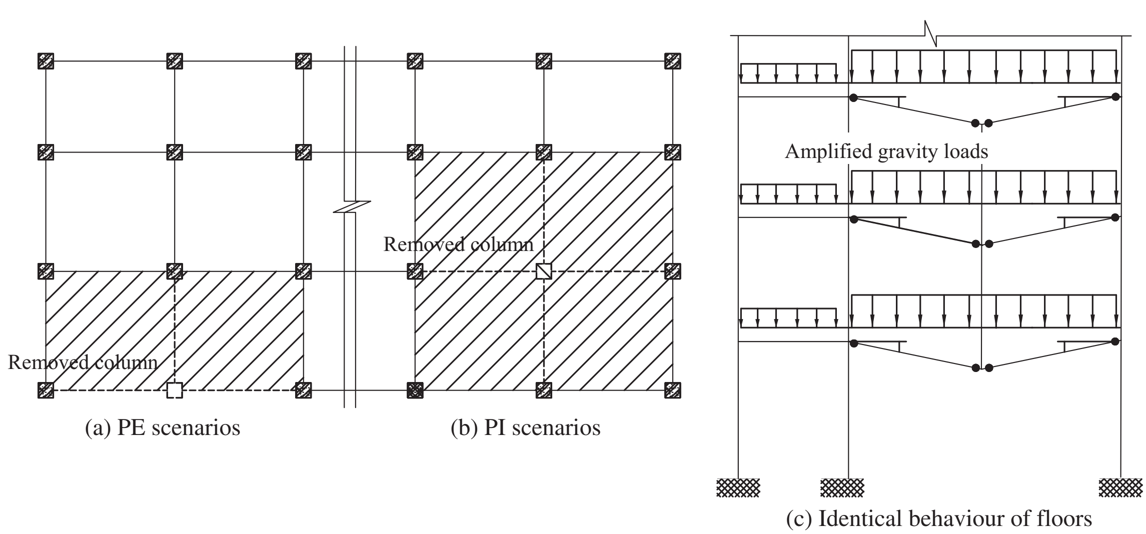


Fig. 1. Penultimate-external (PE) and penultimate-internal (PI) column loss.