Structural Safety 63 (2016) 47–58

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Simplified energy-based analysis of collapse risk of reinforced concrete buildings

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ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form 21 July 2016
Accepted 23 July 2016

Keywords:
Progressive collapse
Energy equivalence
Reinforced concrete buildings
Risk analysis

ABSTRACT

This paper presents a simplified method for evaluating the risk of progressive collapse of reinforced concrete (RC) buildings. The method is formulated based on a recently developed two-scale numerical model for RC structures. In this model, all structural members are modeled by a set of coarse-scale cohesive elements representing the potential damage zones (PDZs). The cohesive constitutive behavior is determined by fine-scale finite element (FE) simulations of the corresponding PDZs. In the present study, a new energy-equivalent linear elastic cohesive model is developed for RC buildings. The damage status of the PDZ is determined by comparing the elastic energy stored in the cohesive element with the actual energy dissipation capacity of the PDZ. This model is applied to analyze the behavior of a two-dimensional frame subassemblage under a column removal scenario, and it is shown the model is capable of capturing the total energy dissipation of the entire failure process. This cohesive model is combined with a sequential analysis method to identify different possible failure paths leading to collapse initiation. The present model is applied to analyze the collapse initiation risk of a prototype RC building, where the randomness in both gravity loads and material properties is taken into account. The results are compared with the recent simulations using a nonlinear dynamic model. It is shown that the present analysis is much more efficient than the conventional nonlinear dynamic analysis, and it yields a reasonable upper bound of the collapse probability.

1. Introduction

Progressive collapse of buildings primarily involves gravity-driven propagation of local structural damage, which often leads to catastrophic large-scale structural failure. Over the past decade decades, there has been a continuing interest in understanding the vulnerability of buildings against progressive collapse through both computational modeling [9,6,28,27] and large-scale experimental investigations [49,35,54]. In contrast to the wide spread of probabilistic analysis and design methods for civil structures against hazards like earthquakes, hurricanes, and fires, the current computational modeling of progressive collapse is still largely limited to deterministic frameworks [19]. However, the importance of probabilistic analysis is evident for design of civil engineering structures due to the inherent uncertainties in applied loading and material properties [14,20,36,23,15,30]. In view of the severe consequences of progressive collapse, there is a clear need to develop a probabilistic model that could be used to evaluate the occurrence risk of such a failure event.

The concept of probabilistic analysis of progressive collapse was first proposed by Ellingwood and Leyendecker [22]. Bennet [12] proposed a simple analytical method for evaluating the collapse risk of buildings, which is limited to structures with a small number of failure sequences. Recently, there has been a considerable interest in applying probabilistic methods to numerical analysis of progressive collapse [21,23,46,56]. The general mathematical formulation for the risk analysis of progressive collapse can be expressed as [21,23]

$$P_f = \sum_H P[C|LD]P[LD|H]\lambda_H \tag{1}$$

where λ_H = annual occurrence rate of hazard H, such as gas explosion, fire, blast, etc.; $P[LD|H]$ = probability of local structural damage due to the abnormal loading caused by H, which is typically set to be unity for the alternate load path analysis [44]; and $P[C|LD]$ = probability of building collapse due to the local structural damage LD. It is clear that the essence of the risk analysis of progressive collapse is the calculation of $P[C|LD]$. From the viewpoint of the system reliability analysis, $P[C|LD]$ is equivalent to the union probability of the occurrence of all possible failure sequences that could lead to a collapse event [18,38], i.e.:

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http://dx.doi.org/10.1016/j.strusafe.2016.07.003
0167-4730/

$$P[C|LD] = \Pr(\cup_i S_i) \tag{2}$$

where $S_i = i$th failure sequence. For large structural systems, it is common to approximate Eq. (2) by considering only the significant failure sequences, which are believed to contribute to most part of the overall failure probability. Over the past two decades, extensive efforts have been devoted towards the development of efficient methods for calculating this union probability for large structural systems, such as the branch and bound method [43], the importance and adaptive sampling methods [40,31,42], the hybrid simulation-based method [38], bounds estimation using linear programming [51,52], etc. In most applications of these methods, the calculation of the structural resistance usually considers either ductile or brittle failure under a single mode of loading. However, for the analysis of the collapse behavior of reinforced concrete (RC) buildings, in which structural components are often subjected to a mixture of different loading modes, it is essential to consider realistic constitutive models for damage and fracture of materials under a general loading state [6,35,57].

For deterministic analysis of progressive collapse, various computational models have been developed, which include finite element (FE) and discrete element models [3,39], macroelement model [6], applied element model [27] and cohesive element model [33]. These models have been shown to be able to capture some essential damage and fracture behaviors with large deformations. However, there is a limited amount of studies focusing on combining these sophisticated structural models with stochastic methods to simulate the probabilistic behavior of buildings subjected to local structural damage.

In a recent study [33,57], a stochastic cohesive element model was developed to calculate the collapse probability of RC buildings through nonlinear dynamic analysis. The model adopted the concept of cohesive fracture to simulate the nonlinear behavior of RC structural members. The probability distributions of constitutive parameters of each cohesive element were determined through the stochastic FE simulations of the corresponding part of the structural member. The cohesive model was applied to perform stochastic simulations of collapse behavior of buildings subjected to certain local structural damage, and the occurrence probabilities of different collapse extents were calculated. The model was shown to be able to handle normal-size RC buildings with a reasonable computational cost. However, it is still a computational challenge to directly apply the model to high-rise RC buildings. Furthermore, the computational efficiency of the model has not reached a level suitable for reliability-based design optimization of general RC buildings against progressive collapse, in which the design optimization and stochastic simulations need to be combined [24]. Therefore, there is still a need to develop more efficient numerical models to facilitate the reliability-based analysis and design of RC buildings against progressive collapse.

In this study, we develop a simplified computational model for assessing the collapse risk of RC buildings subjected to local structural damage. The model combines an energy-equivalent cohesive element model and a sequential linear analysis method. Here a collapse event refers to the formation of a collapse front, which causes the structure to lose its integrity. This is because studies have shown that, once a collapse front is formed and moves under gravity, the lower intact part of the building is likely unable to resist the upper falling part [53,33,57]. Such a definition of collapse also aligns with the Unified Facilities Criteria (UFC) recommendations, in which the tolerable damage is only allowed in a limited area around the location where the local structural damage occurs [44]. This paper is planned as follows: Section 2 summarizes the recently developed cohesive element model for RC buildings; Section 3 formulates an elastic cohesive model with an energetic failure criterion; Section 4 presents a sequential analysis method using the proposed elastic cohesive model; and Section 5 applies the present model to evaluate the collapse probability of a prototype RC building.

2. Nonlinear cohesive modeling of RC structural members

We first briefly review the recently proposed nonlinear cohesive model of RC buildings [33,57], which serves as a foundation for the development of the present model. In this model, a set of coarse-scale cohesive elements is used to simulate the nonlinear behavior of various structural members, such as beams, columns, walls, and slabs (Fig. 1). Each cohesive element represents a physical potential damage zone (PDZ) that could possibly form during the loading process. In other words, damage can occur only in the PDZs and the materials outside these zones are considered to be elastic. From the perspective of system reliability analysis (Eq. (2)), this approach essentially reduces the search scope for the significant failure sequences. The locations of the PDZs must be first determined based on the understanding of the structural behavior. For example, the PDZs in the beams and columns are located to account for the flexural behavior [7]. For slabs, the PDZs are placed along the yield lines as well as at locations where potential shear failure could occur [29]. For wall panels, the PDZs can be located along the diagonals and perimeters of the sub-wall panels, which resembles a recently developed truss model for RC walls [45]. Fig. 1 shows the cohesive element modeling of different structural subsystems.

The constitutive behavior of the cohesive element is formulated by separating the PDZ into two parts, namely the effective concrete section and the longitudinal reinforcement (Fig. 2a). The effective concrete section consists of the concrete and transverse reinforcement (if applicable). Each cohesive element consists of four integration points. The traction-separation relationship of each integration point is written as

$$\sigma_n(w_n, w_m, w_l) = \sigma_n^c(w_n, w_m, w_l) + \rho_s \sigma_n^s(w_n, w_m, w_l) \tag{3a}$$

$$\tau_m(w_n, w_m, w_l) = \tau_m^c(w_n, w_m, w_l) + \rho_s \tau_m^s(w_n, w_m, w_l) \tag{3b}$$

$$\tau_l(w_n, w_m, w_l) = \tau_l^c(w_n, w_m, w_l) + \rho_s \tau_l^s(w_n, w_m, w_l) \tag{3c}$$

where $\sigma_n, \tau_i (i = m, l)$ denote the total tractions in the normal and two orthogonal shear directions, σ_n^c, τ_i^c are the normal and shear tractions of the effective concrete section, σ_n^s, τ_i^s are the normal and shear tractions of the longitudinal reinforcement, w_n, w_i are the normal and shear separations, and ρ_s is the longitudinal reinforcement ratio. In order to use a single cohesive element to capture the flexural behavior of the PDZ, the height of the cohesive element is set to be $0.85D_e$ for beams and slabs and $0.75D_e$ for columns and walls [37], where D_e is the distance between the centroid of tensile reinforcement and the extreme compressive material fiber.

For the effective concrete section, the constitutive relationship is formulated in an effective traction-separation space, where the effective separation is defined as $\bar{w} = \sqrt{w_n^2 + \alpha_i^2 (w_m^2 + w_l^2)}$ and the mode mixity angle is defined as $\theta = \tan^{-1}\left(w_n / \alpha_i \sqrt{w_m^2 + w_l^2}\right)$ ($\alpha_i (i = t, c)$ are constants corresponding to the tension-shear and compression-shear loading modes, respectively) [13,16]. The work-conjugate effective traction $\bar{\sigma}$ can be determined based on the principle of virtual work, which yields $\sigma_n^c = \bar{\sigma} \sin\theta, \tau_m^c = \alpha_i \bar{\sigma} \cos\theta \sin\varphi$ and $\tau_l^c = \alpha_i \bar{\sigma} \cos\theta \cos\varphi$, where $\varphi = \tan^{-1}(w_m / w_l)$. Therefore, the constitutive behavior of the effective concrete section can be fully characterized by the relationship between the effective traction and separation. Since the entire collapse initiation process involves failures of a number of PDZs, the overall collapse behavior would be governed by the total energy dissipation of the cohesive elements. This implies that the exact