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# Collapse simulation of reinforced concrete moment frames considering impact actions among blocks

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ABSTRACT

A simulation system based on the **Discrete Element Method** (DEM) was developed to model the collapse behavior of reinforced concrete (RC) moment frame structures subjected to seismic loads or explosions. This system mainly consists of two parts: a numerical analysis part that simulates the collapse process of RC moment frame structures quantitatively, and a visualization system that vividly shows the dynamic responses obtained from the numerical analysis. Using this system, the whole damage process of a structure can be numerically analyzed and visually simulated. Consequently, the collapse mode, mechanism and duration and the distribution of the debris after the collapse can be obtained. The numerical analysis is based on the DEM, in which the element shape is assumed to be cuboid, and the elements are connected by dummy concrete springs and steel springs. The impact actions among elements, particularly after breaking of the connecting springs, are taken into account with the application of impulse-based impact models, which are derived from the results of the experiments and the numerical tests. Finally, two examples, including a frame building demolished by a controlled explosion and a scaled model structure of an RC moment frame subject to an earthquake, are presented to verify the impact models and simulation system and to reveal the collapse mechanism of RC moment frame structures subjected to abnormal loadings.



## 1. Introduction

The damage investigations of buildings that have undergone various disasters caused by blasts or earthquakes have found that the collapse hazards of the buildings are becoming increasingly serious [1–4]. When a building is subjected to a strong-motion earthquake, the collapse itself is the main cause of casualties and the overall destruction. Building collapse can create traffic obstructions, disrupt energy supplies and affect the overall infrastructure of the area, resulting in severe impacts on society. As a consequence, great interest has focused on the collapse of buildings caused by strong-motion earthquakes. In this study, a collapse simulation system based on the Discrete Element Method (DEM) is proposed for the prediction of collapse behavior and elucidation of the collapse mechanism.

The DEM proposed by Cundall was developed to analyze the failure process of soil or rock [5]. Hakuno modified Cundall's DEM and applied it to concrete structures [6]. A concrete structure is modeled as an assembly of small elements that make up the structure. It is assumed that the adjacent elements are connected by a set of dummy springs. The elements as a whole are considered rigid bodies, and their internal deformations are represented by spring deformation around each element. Several element modes, based on the material component, the planar micro-unit or the cross section of the structural members, have been proposed for different analyses of concrete structures or members [7–9].

The DEM has, however, an obvious drawback: it requires an enormous amount of calculation time, as explicit numerical integration is unstable unless the time step used is very short. Therefore, in the simulation of the overall collapse of a structure, the number of elements must be reduced to as few as possible for computational efficiency. Thus, for the analysis of an overall structure, an element mode based on the cross section of structural members is favored.

During the collapse process of a structure, the impact actions among structural components are of obvious importance [10,11]; therefore, it is necessary to take into account the impact actions among the elements for an objective analysis [12]. During the collapse analysis of reinforced concrete (RC) structures, pseudo-static methods, which are based on force-response rigidity [13], are common for the treatment of the impacts between concrete elements or blocks [5,9]. To obtain accurate results, the methods must involve the detailed processes of the impact and the time history

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of the contact force; however, this is inappropriate, even impossible, for the analysis of an overall concrete structure.

Some scholars have proposed dynamic analysis methods [14,15]. In these methods, a coefficient of restitution or a factor of kinetic energy loss is assumed; and, the impact between concrete blocks is then solved using dynamic theory. These methods are also based on impulse-response rigidity [13], so the detailed process of the impact is not involved in the analysis. However, the drawback of these methods is that the factor of kinetic energy loss or the coefficient of restitution is assumed to be constant for any initial impact situations. In this paper, impulse impact models based on experiments and numerical tests between concrete blocks [16], and the successive impact hypothesis [17] are applied to simulate the collapse behavior of reinforced concrete (RC) moment frame structures.

## 2. Numerical models

### 2.1. Element formulation

Two structural division systems or methods for RC frame structures were proposed by Huang et al. [18]. The element modes in the two systems are based on the cross sections of structural members. The first method is the beam–column–joint system, as shown in Fig. 1. The deformation of the beams can be considered in the system, but the effect of floor slabs on collapse is not taken into account. The second method is the slab–column system, as shown in Fig. 2. It is assumed that the beams, slabs and joints are rigidly connected in the same floor of the structure, so that the larger slab elements are modeled as assemblies, as shown in Fig. 2c. The disadvantage of the slab–column system is that the deformation of the beams cannot be considered, and their effects on collapse are ignored. The slab–column system is, however, appropriate for the collapse analysis of strong beam/weak column RC frame structures. In Figs. 1 and 2, *XOYZ* represents the global coordinate system, and *xoyz* represents the local coordinate system.

Adjacent elements are connected with concrete and reinforcement springs in a structural division system, as shown in Fig. 3. It is assumed that the two ends of the springs are fixed at the corresponding interfaces of the adjacent elements during the analysis. The concrete and reinforcement springs can bear the compression and tension in a random spatial direction. The sites of the reinforcement springs are the actual sites of the longitudinal reinforcement in the corresponding structural members; and, the representative area of the reinforcement springs is the true area of the section of the corresponding reinforcements. According to the effect of the restraint of the stirrups, the concrete cross section of an element is divided into two parts: the covering layer or the shell, and the core section.

Every part is composed of eight lattices, as shown in Fig. 4. The sites of the concrete springs are the centroids of the corresponding lattices, and the representative area is the true area of the corresponding lattices.

### 2.2. Constitutive models and failure criteria of the springs

The true length of the concrete and the reinforcement springs is zero, and the representative length is:

$$l_r = (l_1 + l_2)/2 \tag{1}$$

where $l_1$ and $l_2$ are the lengths of two adjacent elements.

The restoring force and the deformation of the concrete springs are:

$$\left.\begin{array}{l} p_c = A_c\sigma_c \\ d_c = l_r\varepsilon_c \end{array}\right\} \tag{2}$$

where $p_c$ is the restoring force of a concrete spring; $A_c$ is the representative area of a concrete spring; $\sigma_c$ is the mean stress of a concrete lattice; $d_c$ is the deformation of a concrete spring; and $\varepsilon_c$ is the mean strain of a concrete lattice.

The force–deformation relationship of the concrete springs was proposed by Li [19] and is shown in Fig. 5. The spring constants, as shown in Fig. 5a, are defined as:

$$d_{ct} = \varepsilon_{to}l_r, \quad p_{ct} = f_tA_c \tag{3}$$

$$d_{cy} = \varepsilon_{co}l_r, \quad d_{cu} = \varepsilon_{cu}l_r, \quad p_{cy} = f_cA_c \tag{4}$$

$$K_{ced} = K_{co}\left(\frac{d_{cy}}{d_{cmax}}\right)^{0.2} \tag{5}$$

where $\varepsilon_{to}$ and $\varepsilon_{co}$ are the strains corresponding to the tensile strength and the compressive strength of concrete, respectively; $\varepsilon_{cu}$ is the ultimate compressive strain of concrete; $d_{ct}$, $d_{cy}$ and $d_{cu}$ are the deformations of the concrete springs corresponding to concrete strains $\varepsilon_{to}$, $\varepsilon_{co}$ and $\varepsilon_{cu}$, respectively; $d_{cmax}$ is the maximum compression deformation that the concrete springs reach during the whole deformation process; $f_t$ and $f_c$ are the tensile and prism compressive strengths of the concrete, respectively; $p_{ct}$ and $p_{cy}$ are the restoring forces of the concrete springs corresponding to the tensile and compressive strengths of concrete, respectively; and $K_{co}$ and $K_{ced}$ are the initial and unloading stiffnesses of the concrete springs.

For the core section concrete, considering the constraint condition of the stirrups, the envelope curve of the force–deformation relationship [20] is adjusted as shown in Fig. 5b. The spring constants, as shown in Fig. 5b, are defined as:

$$d_{cy}^{Core} = (1 + 10\rho_{sv})d_{cy}^{Shell}, \quad d_{cu}^{Core} = (2 + 600\rho_{sv})d_{cu}^{Shell} \tag{6}$$

$$p_{cy}^{Core} = (1 + 10\rho_{sv})p_{cy}^{Shell}, \quad p_{ct}^{Shell} = K_{co}^{Shell} \cdot d_{ct}, \quad p_{ct}^{Core} = K_{co}^{Core} \cdot d_{ct} \tag{7}$$

$$\rho_{sv} = n_{sl}(b_{cor} + h_{cor})A_{sv1}/(b_{cor}h_{cor}s) \tag{8}$$

where $\rho_{sv}$ is the volume ratio of reinforcement of the stirrups; $b_{cor}$ and $h_{cor}$ are the width and height of the core section, respectively; $A_{sv1}$ is the sectional area of a single stirrup; $n_{sl}$ is the number of the stirrup legs; and $s$ is the stirrup spacing.

The restoring force and the deformation of the reinforcement springs are:

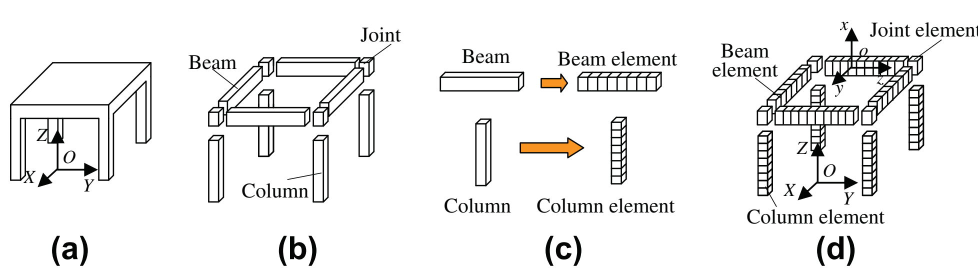


**Fig. 1.** Beam–column–joint discrete system: (a) floor of structure, (b) beam, column and joint, (c) beam and column elements, and (d) discrete system.