博士論文

Development of Simplified Numerical Model for Seismic Collapse of RC Frame Structures

(RCフレーム構造物の地震破壊解析のための

簡便型数値解析手法の開発）

by

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Abstract

Collapse of buildings due to an earthquake is completely unacceptable. The combination of wide usage of Reinforced Concrete (RC) framed structures for residential buildings in earthquake prone areas and shoddy design and construction practices, exposes the high vulnerability of this type of buildings to a seismic hazard. Collapse of weak buildings has been the main cause of deaths during the past large earthquake disasters in the world, therefore, assessing the collapse capacity of such buildings in advance is very important for disaster reduction.

There are various methods to assess the collapse capacity of buildings but there always seems to be a stand-off between the applicability/ reliability of these methods and the computation effort involved. For practical engineering purposes, the following characteristics are desirable in a collapse simulation, (i) capturing the complete behavior of a structure i.e. from its normal state to a complete collapsed state during an earthquake, (ii) should be accurate and reliable, (iii) computationally efficient (to be performed in conventional personal computers), (iv) easiness in modelling, comprehending and workability, and (v) good visualization of the analysis results.

Considering the above criteria, the Extended Discrete Element Method (EDEM) provides a good platform to meet the requirements. However, the EDEM has some limitations, namely, (i) requirement of a small time step for stability and accuracy, due to the use of an explicit time integration scheme, (ii) no proper theory for spring stiffness derivation, and (iii) inaccuracies due to neglect of Poisson’s ratio. These limitations can be overcome by the assembly of a global stiffness matrix, for the discretized system, which contains theoretically derived spring stiffness that implicitly considers the Poisson's ratio effect. The Lattice Models or Spring Networks consists of an assembly of interconnected springs. When an appropriate spring network is chosen, a model similar to the assembly of joint-springs in the EDEM can be obtained, the difference being the effect of the contact-springs i.e. inter-element interaction at the surface.

By combining this property of both the models, an effective two-phase numerical collapse simulation of structures can be performed, which can predict the initial behavior of structures (elastic/nonlinear/crack initiation/ stiffness degradation/ maximum load capacity) through a spring network (implicit numerical integration) and predict the final behavior of structures (geometric non-linearity, instability, separation, and collision) through the EDEM (explicit numerical integration).

The first part of the research involves the development of a linear elastic spring network. A finite element mapping scheme is used to derive the spring stiffness for two kinds of spring network discretization, namely, the CST (Constant Strain Tringle) spring network and the Quad spring network. The validity of the mapping scheme, which was earlier used for an infinite domain, is checked for the finite domain of an RC structure. The global finite element matrix and a corresponding spring network global stiffness are assembled. The spring stiffness are derived and were observed to be equal to the theoretical spring stiffness from past literature. To adopt in the EDEM, the domain was discretized by linear quadrilateral elements/constant strain triangle elements and the corresponding spring stiffness were obtained. There were three kinds of springs for the Quad spring network, namely, (i) inner edge (ii) inner diagonal (iii) boundary springs. There were two kinds of spring for the CST spring network, namely (i) inner spring (ii) boundary spring. The inner edge and diagonal springs were mutually orthogonal, whereas the boundary springs were orthogonal along the Eigen direction. In order to obtain this there is a Poisson ratio's limit of ($0.03 < \nu < 0.47$). Once the spring network, with these derived spring stiffness, are assembled, the same finite element global matrix is obtained. A simple cantilever analysis is performed to check for accuracy. In a special case in the CST network when Poisson's ratio =1/3, the spring network reduced to a network of 1D springs.

Since the global stiffness matrix of the assembled spring network is the same as the finite element stiffness matrix it showed (i) good accuracy (ii) convergence in energy (iii) ability to model the Poisson's ratio. The assumption of lumping of mass at nodes was verified through modal analysis, and good results were obtained. This implies the spring network can accurately perform linear dynamic analysis also.

The second part of the research involves the simulation of concrete non-linearity. The spring were divided based on their physical location as (i) Reinforced concrete spring (ii) Plain concrete spring (iii) Steel spring. Spatially averaged material models were used for concrete and steel. Spring networks are known to suffer from mesh dependency.

A secant stiffness based formulation is used for the nonlinear analysis of RC. To cater for this effect, the softening curve of the tension model is varied based on the element size, in order to maintain constant fracture energy. A size effect analysis is performed of a concrete cube under tension. It was observed that the mesh density dependency effect had reduced.

Using the simple CST spring network, and only concrete compression/tension model, numerical validation of the spring network was performed for a series experiments on RC beams. Good correlation between the experimental data and numerical simulation was obtained. Numerical validation of an RC frame using the CST spring network with varying element sizes was performed. Good agreement was observed between experimental and analytical data even when the element size is increased. Crack pattern matched the experimentally observed cracks in an averaged sense.

In order to incorporate a shear model into the spring network, a quad spring network with shear models are used. Numerical simulation of a series of concrete panel experiments were performed. It was observed that the spring network could model the cases where reinforcement were isotopically arranged. The shear transfer post-cracking due to aggregate interlock must be appropriately considered.

Once the structure has been subjected to significant damage, the analysis shifts to the EDEM phase. The cracked springs represent the ruptured joint springs. Simplified linear material models are adopted, whose stiffness has been reduced based on the softening of material models from Phase I. The RC frame validated earlier is used for analysis. The joint spring stability is checked under gravity load for the undamaged frame and damaged frame as well. The damaged and undamaged frame reached a stable state under gravity loading. Once stable the frame is subjected to displacement based loading. The model could follow the collapse of the frame. A 12 storey RC frame is subject to damage, and is subjected to input displacement loading. The EDEM phase could follow the collapse of the 12 storey RC frame effectively.

Through this two-phase analysis method, a new, relatively simple method is proposed which can, (i) model elastic behavior of structures accurately, (ii) follow the initial non-linear behavior of RC buildings, (iii) given the initial cracking and propagation of cracks, (iv) perform large deformation analysis, (v) model separation, collision and collapse, (vi) due to its simplicity, computation time for collapse of buildings has been drastically reduced, and (vii) can be used for research that requires analysis of a large building stock or probabilistic analysis which involves a large number of analysis.