Modeling and Analysis of Disproportionate Collapse of RC Structures

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ABSTRACT

Collapse analyses of a 10-story reinforced concrete frame building are carried out to investigate the robustness of structural systems against column removal scenarios. Computationally efficient reduced models are developed and used in the analyses. The building was designed according to the requirements of moderate seismic zones (Seismic Design Category C). Reserve capacity is adopted as a measure of the performance of the building under column removal scenarios. It is calculated as a ratio of applied load to service load (Dead load plus 25 % Live load or 1.0DL + 0.25LL) using static pushdown analysis. Gravity load is proportionally increased until collapse of the building is initiated. Structural system redundancy is examined by checking whether collapse occurs due to the sudden removal of columns under service loading. Comparison between results from two-dimensional (2D) and three-dimensional (3D) analyses indicates the importance of considering the contribution of floor system in disproportionate collapse analysis.

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1. INTRODUCTION

Although documents issued by the U.S. General Services Administration (2003) and the Department of Defense (2009) provide guidelines for design and analysis of buildings to resist disproportionate collapse (or progressive collapse), there is still a general lack of information on detailed procedures, particularly numerical modeling guidelines to carry out efficient yet reliable disproportionate collapse analysis of reinforced concrete (RC) structures. Furthermore, a quantitative measure of system robustness is still a challenging problem which requires further study to reach a consensus within the structural engineering profession.

Numerical simulation of disproportionate collapse of RC structures has been studied by researchers employing various analysis approaches, including detailed finite element analysis using high-fidelity models (Hansen et al. 2006) and reduced finite element analysis using component-based models (Bao et al. 2008). In general, high-fidelity models are considered capable of reproducing the structural behavior in greater detail and accuracy. However, they require intensive computing time which becomes an obstacle to limit its application in system-level analyses. It is shown that component-based models are able to reproduce the structural behavior accurately and efficiently (Lew et al. 2011). In disproportionate collapse analysis, the analysis approach is dependent upon whether the triggering event is explicitly defined or not. If the event is defined, a direct analysis is followed, as presented in the paper by Hansen (2006). On the other hand, if the event is not defined, an indirect analysis is followed, as presented in the paper by Bao (2008). For this paper, the modeling and analysis presented are based on indirect analysis using reduced models.

2. COMPUTATIONAL MODEL

Reduced models are developed to represent beams, columns, slabs and beam-column joints. Beams and columns are represented by one-dimensional elements with cross-section integration. Material properties are specified to each integration point representing a fiber section of the discretized cross section. In this way, reinforcing bars in concrete and different behavior of cover and core concrete due to confinement effects can be modeled appropriately. A reduced beam-column joint model for planar frames was developed previously by Bao (2008). This model was improved and validated by tests of two full-scale beam-column subassemblies (Lew et al. 2011). In this paper, a 3D connection model is developed based on the 2D model developed for the planar frame as showing in Fig. 1. The joint shear behavior is assumed to be uncoupled. The joint region is comprised of three rectangular frames. Rigid beams of each frame are connected at the end nodes with in-plane deformation represented by rotational springs. Frames are connected at the middle nodes of the rigid beams with rotational degrees of freedom (DOFs) released. The beam-joint interface is modeled similarly to the 2D model. Beams and columns are connected to joints by defining a multipoint constraint in which the DOFs of the interface beam nodes are interpolated from the translational DOFs of the four adjacent joint nodes located on the beam-joint interface plane.

The floor system is modeled using layered shell elements with multiple integration points through the slab thickness. Shell elements are connected with beam elements by nodal rigid body (NRB) constraints as depicted in Fig. 2. Element nodes defined in the NRB constraints must be located on the same beam cross-section plane.

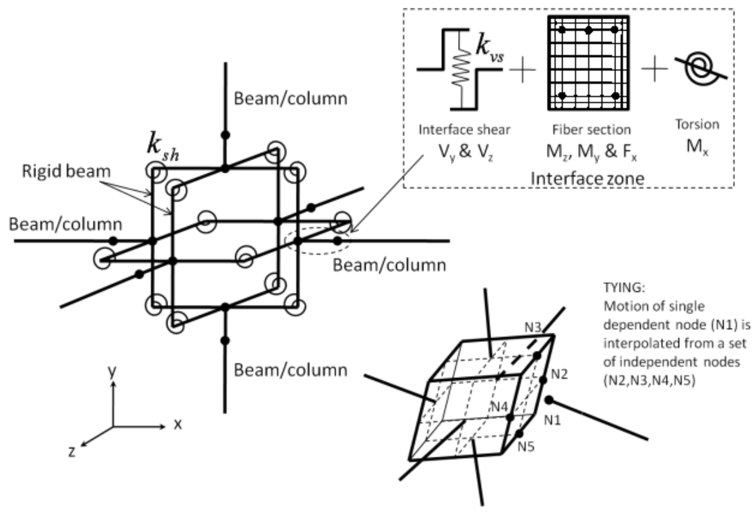

Fig. 1. 3D Beam-column connection model

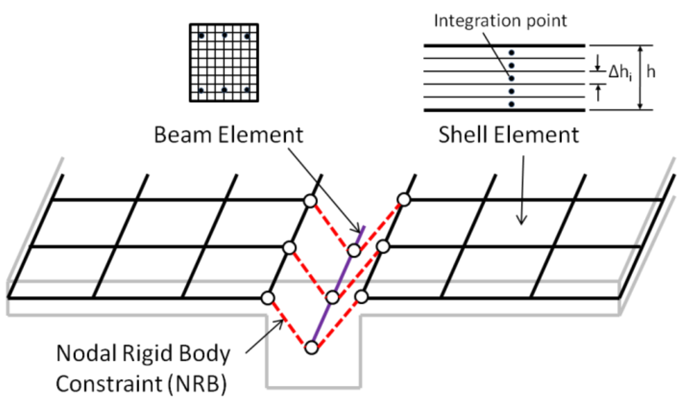

Fig. 2. Floor model

3. MATERIAL MODELING

Both concrete and steel properties are represented using uniaxial stress-strain relationships. The stress-strain relationship of the core concrete is generated based on confinement conditions. To reduce mesh dependency due to the material softening behavior, the benchmark stress-strain relationship should be modified according to fracture energy and element length. The pseudo-softening behavior of steel material should also be taken into consideration to reduce the mesh dependency. This is because the cross-section area of a beam element is assumed to be unchanged which does not reflect accurately the necking effect before fracture of reinforcing bars. A typical tensile test is simulated by using beam elements with different mesh sizes as shown in Fig. 3. Similar to the softening behavior of concrete, inconsistent results are observed if the same stress-strain relationship is used regardless of element size. A simple way to overcome such an inconsistency is to adjust the fracture strain according to the length of beam elements through an iterative calibration process (Lew et al. 2011).

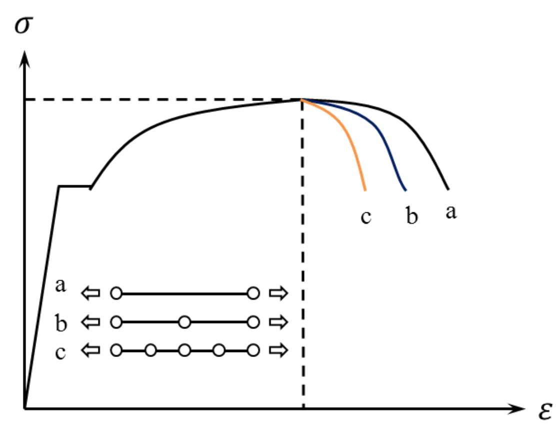

Fig. 3 Inconsistency due to softening behavior of reinforcing bar

4. 3D ANALYSIS OF 10-STORY FRAME BUILDING

The developed computational model as described above is used in collapse analyses of a 10-story reinforced concrete frame building. Slab effects will be addressed by comparing structural performance from 3D analyses presented herein and 2D analyses of the same building presented in an earlier published paper by the authors (Bao et al. 2008). Fig. 4 shows the plan and elevation views of the prototype building.

In this study, exterior columns of the first story are selected for column removal. A set of column removal cases is identified, with an increasing number of columns removed in each successive case. For each column removal case, the analysis procedure is summarized as follows:

1. Apply service loading (1.0DL+0.25LL) to all floors of the building.
2. Suddenly remove the selected column(s) and perform a dynamic analysis to determine whether the structure collapses under service loading.

3. Start a new analysis in which the selected column(s) are removed prior to loading, and gradually increase the gravity loads (beyond service loading, if necessary) until the building collapses.

In the above described analyses, collapse is defined by the occurrence of any one of the following: 1) the second floor falls on the ground when the first-story column is removed; 2) the ratio of kinetic energy to internal strain energy exceeds 0.1; or 3) the total reaction force of the remaining first story columns starts to drop. The following column removal cases are considered: (a) column F5 and F6, (b) column F5, F6 and E6, (c) column F4, F5, F6 and E6, and (d) column F3, F4, F5, F6 and E6. Fig. 5 shows the computational model of the prototype building using the aforementioned reduced models.

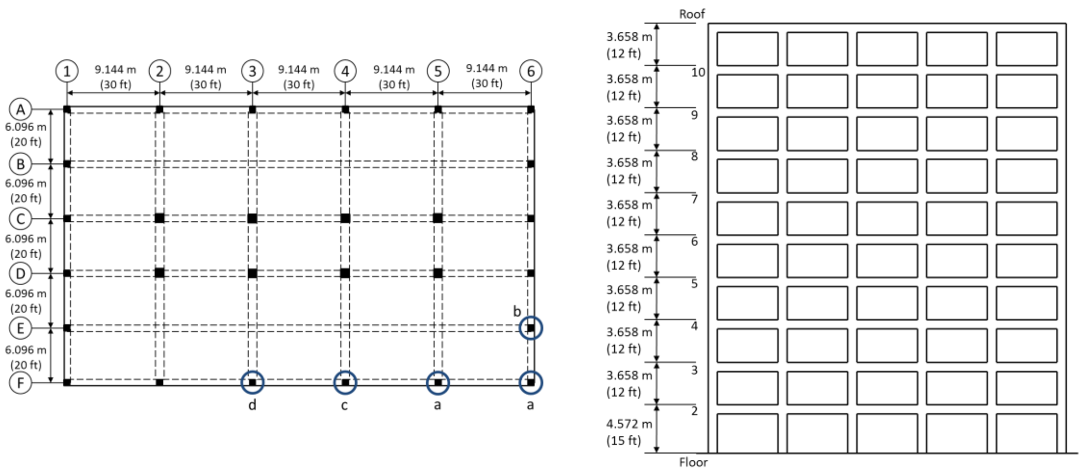

Fig. 4. Plan view and elevation of prototype building

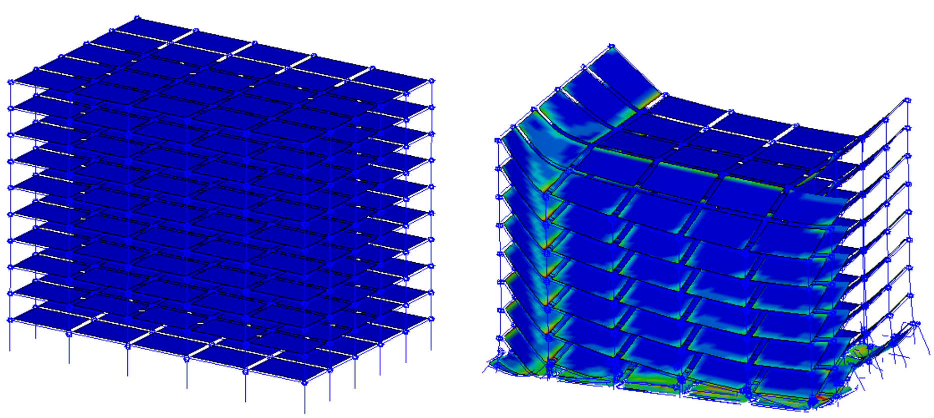

Fig. 5. Computational model of prototype building: (a) intact building under service load (b) collapsed building by push down analysis

Pushdown analyses are carried out for all four column removal cases as well as the intact building. For column removal cases (a), (b) and (c), the building did not collapse under sudden column removal. However, the building collapsed in case (d). The results of the analyses are listed in Table 1. In the table, the applied load (gravity load) is normalized by the service load for the pushdown analyses. A larger value of load ratio reflects a larger reserve capacity or a greater safety margin of a building.

Table 1 Results of analyses

		Collapse under sudden column removal	$\frac{Applied\ load}{Service\ load}$
Number of columns removed	0 (intact)	N/A	2.84
	2 (Case a)	No	2.12
	3 (Case b)	No	1.84
	4 (Case c)	No	1.61
	5 (Case d)	Yes	1.25

A planar frame taken from the same prototype building was analyzed under different column removal scenarios in a paper by Bao et al. (2008). Collapse was observed when two outermost columns (E6 and F6) were removed. In the present study, no collapse is triggered by removing the same two columns. This highlights the important contribution of the three-dimensional floor system, including the floor slab, in the collapse analysis.

SUMMARY AND DISCUSSION

This paper proposed a new approach for modeling and analysis of disproportionate collapse of reinforced concrete structures. The new approach is illustrated by analyzing a 10-story reinforced concrete frame building. Reserve capacity is calculated as a ratio of applied load to service load. Three-dimensional analysis of a prototype building also highlights the necessity of considering the contribution of the floor system in resisting disproportionate collapse.

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REFERENCES

Bao, Y., Kunnath, S.K., El-Tawil, S., and Lew, H.S. (2008). "Macromodel-based simulation of progressive collapse: RC frame structures", *J. Struct. Engrg.*, Vol. **134**(7), 1079-1091.

Department of Defense (2009). *Design of buildings to resist progressive collapse*, Unified Facilities Criteria 4-023-03, Washington, D.C.

General Service Administration (2003). *Progressive collapse analysis and design guidelines for new federal office buildings and major modernization projects*, Washington, D.C.

Hansen, E., Levine, H., Lawver, D., and Tennant, D. (2006). Computational failure analysis of reinforced concrete structures subjected to blast loading. *Proc.: the 17th Analysis and Computation Specialty Conference*, St. Louis, Missouri.

Lew, H.S., Bao, Y., Sadek, F., Main, J.A., Pujol, S., and Sozen, M.A. (2011). *An Experimental and Computational Study of Reinforced Concrete Assemblies under a Column Removal Scenario*, NIST TN 1704, National Institute of Standards and Technology, Gaithersburg, MD