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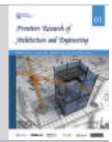

ARTICLE

Nonlinear Analysis of Progressive Collapse of Reinforced Concrete (RC) Building by Different Kinds of Column Removal

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ABSTRACT

Building collapse mostly can be caused by the loss of loading capacity in a primary structural component, resulting in the failure of surrounding elements, which in turn cause a failure propagation. Progressive collapses may be accidental, due to design deficiencies or errors, material failure or natural phenomenon (e.g. earthquakes) but it can be prevented by upgrade the concrete components' material[1,2]. Well-engineered RC buildings generally have a good performance under normal loading conditions. However, faulty design, construction errors, material deterioration, and overloading are always occurred. When part of structure fails, the total load in the whole system will not disappear, which means the load will be redistributed unevenly to the adjacent part of structure. This phenomenon revealed that sustained high stresses in RC elements can lead to catastrophic collapse. Due to very few of papers did the research on the RC elements under high stress level sustained load, relevant experiments should be performed in this area. This paper gives the suggestions about how to apply the load in an experiment if researchers want to know the behavior of elements near to collapse especially focus on RC columns.

1. Introduction

A four-story building (Figure 1a) is designed following the U.S. codes ASCE 7-10 (2010) [3] and ACI 318-14 (2014) [4]. The building, assumed with office occupancy, is located in a non-seismic region. It has five bays in each direction with 28 ft span length (Fig. 1b). The story height is 14 ft at the first floor and 12 ft at all other floors. The structural system of this building is non-prestressed two-way slabs with beams spanning between supports on all sides. Assume the moment can be transferred between slabs and beams totally. The second step is designing the beam, column and slab cross section of this building based on structural analysis software SAP2000 [5]. This structure was designed to carry only vertical load. Use the control load combination 1.2D+1.6L (IBC 2015). The gravity load includes 112.5 psf self-weight of slab for all floors with additional superimposed dead load 17 psf for roof and 20 psf for floor accounting for partition walls, floor finishes, tiles, water proofing, cable wires, plumbing pipes, etc.

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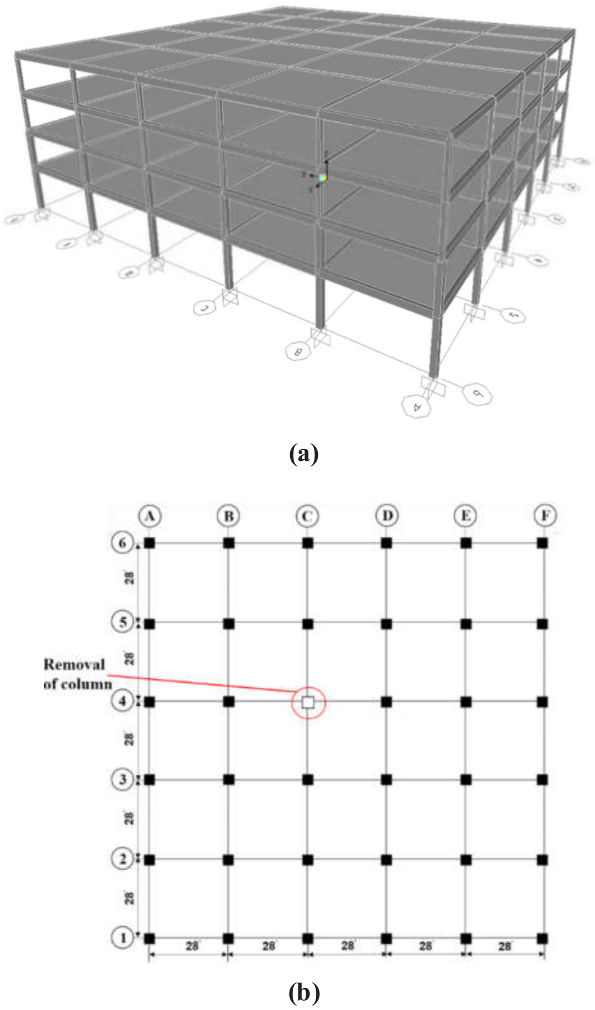

Figure 1. Prototype RC frame building: (a) 3D view and (b) Floor plan

2. Elastic Analysis of Whole Building

For live load, use 20 psf for the roof and 50 psf for the floor separately (ASCE 7-10). All the members in this prototype structure were constructed using Grade 60 reinforcement and concrete with 5500 psi as specified compressive strength. Due to the change of moment, shear and axial force of members after one of the first-floor column been removed need to be considered, member's maximum moment, shear and axial force next to the column will be removed before it has been removed are required as well. In order to obtain the maximum moment, shear and axial force of the members surrounding the column will be removed, the most unfavorable condition should be considered. In this structure, assume dead load and superimposed dead load will maintain unchanged, applies on all spans and all floors of the whole structure. However, for live load, based on the symmetry of live load patterns, four different live load patterns have been determined finally as shown in Figure 2.

After live load patterns have been determined, the boundary condition is also an important part of this model. Due to the load path of whole system is slab to beam to column, assume moments and shear force can be transferred from slab to beam smoothly. It is very important to make sure slab-beam connection is fixed. This can be achieved by mesh the beam and the edge of slab with the same number of elements, which all elements are sharing the same nodes and the same degree of freedom. Assign "automatic area mesh" in SAP 2000, divide the beam and area edge with both 35 elements, then choose do not create edge constraints. In this way, all the force can be transferred and this is the same as real world.

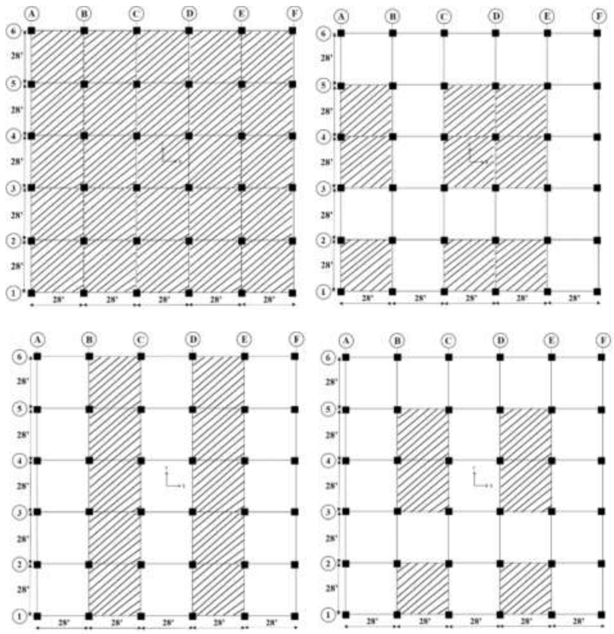

Figure 2. Live load patterns

All beam-column connections in this model are fixed connections and all supports are fixed as well. Based on the four live load patterns shown in Figure 2, assign an envelope of both four load combinations (dead load plus live load) to obtain moment envelope, shear force envelope and axial force envelope of whole structure as shown in Figure 3.1 to Figure 3.3.

From the analysis result shown above, for floor levels, the maximum negative moment -2179.5 kip·in appears at joint 5C on the third floor in x-z direction. The maximum positive moment appears at the third floor between node 4B and 4C, which value is 1115.4 kip·in. Maximum negative moment and maximum positive moment for the roof level are -1730.2 kip·in and 806.5 kip·in respectively.

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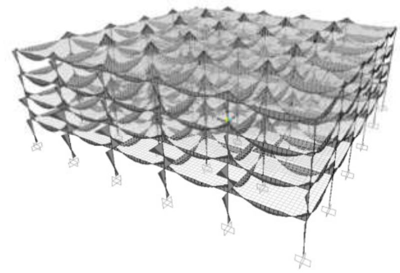


Figure 3.1 Moment envelope

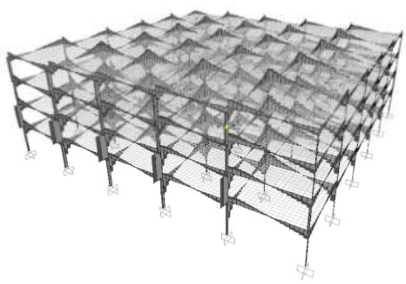


Figure 3.2 Shear envelope

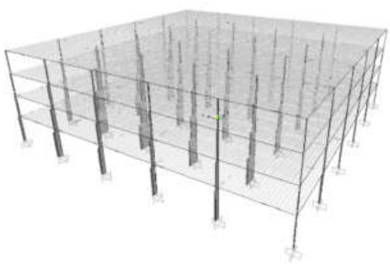
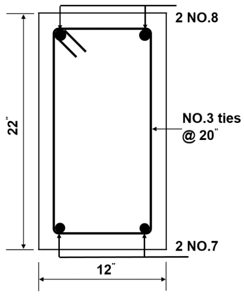
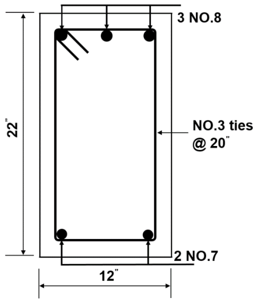


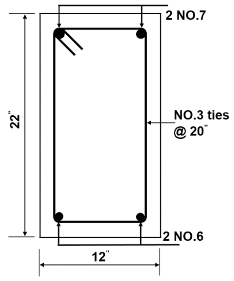
Figure 3.3 Axial load envelope



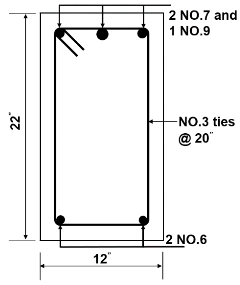
Floor beam section Positive moment



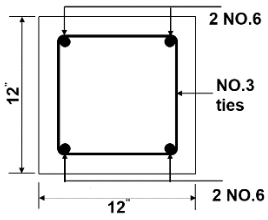
Floor beam section Negative moment



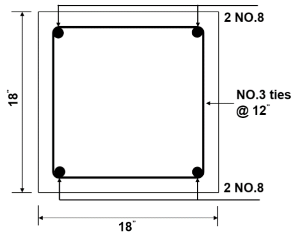
Roof beam section Positive moment



Roof beam section Negative moment



Top two layers column

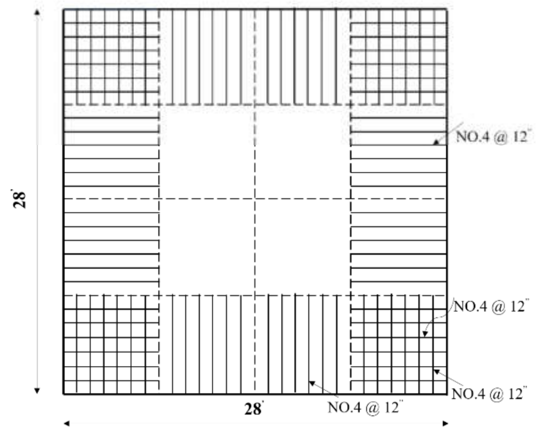


Bottom two layers column

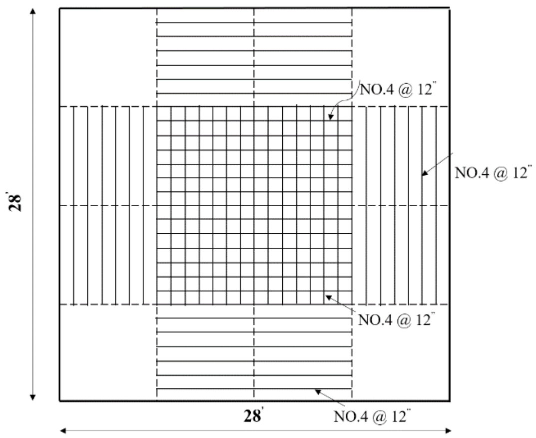
Figure 4. Design section of beam and column

Then, the beam and column sections based on the maximum value of the envelope of moment are designed, shear and axial load as it is shown in Figure 4. Divide the slab into column strip which width is 7 ft and middle strip 14 ft. For column strip negative moment, use NO.4 @ 12", for middle strip negative moment, use NO.4 @ 18", for column strip positive moment, use NO.4 @ 15", for middle strip positive moment: use NO.4 @ 15" as well. However, ACI code provides minimum reinforcement for the slab is 0.194 in^2/ft for two-way slab with grade 60 steel. Modify the design result to use NO.4 @ 12" for the whole slab. The reinforcement distribution for one 28'x

28’ slab is shown in Figure 5.



(a)



(b)

Figure 5. Reinforcement distribution of slab: (a) Negative and (b) Positive

3. Plastic Analysis of Prototype Structure After Column Removal

After one column of the first level has been removed, some corresponding elements will enter to the plastic stage. Due to the limitation of structural design software, the result of plastic analysis of structure is not very well. However, finite element software ABAQUS can solve this problem, this software is commonly used in many related areas [6-8]. Concrete and steel properties are shown in Figure 6 and 7.

Table 1. Concrete Damage Plasticity parameters

Dilation Angle	Eccentricity	f_{b0}/f_{c0}	K	Viscosity Parameter
30	0.1	1.16	0.667	0

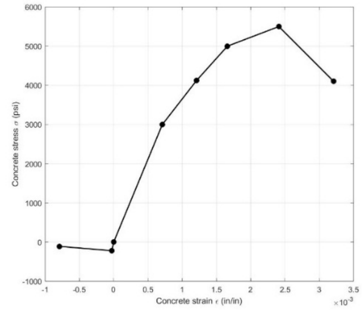


Figure 6. Stress-strain relationship of concrete (f'_c = 5500 psi)

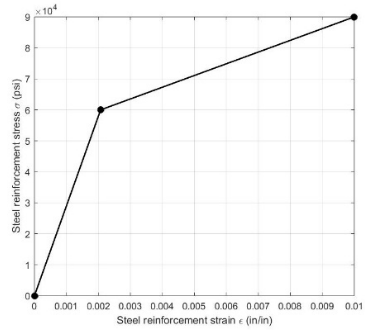


Figure 7. Stress-strain relationship of steel reinforcement (f_y = 60000 psi)

The concrete property of plastic part is defined in Table 1. In order to better simulate the effects of suddenly removing a column, use an equivalent analysis approach. First, do the static analysis of the whole building to determine the forces existing in the supporting column which will be removed in the future. For this step, only consider axial load only. For simplicity, use element type beam for both beam and column, use element type shell for slab cross section, set the rebar layer the same as the reinforcement layout shown in Figure 5. The axial load diagram of the building is shown in Figure 8. From the analysis result, the axial load of the column will be removed later is 595 kips.

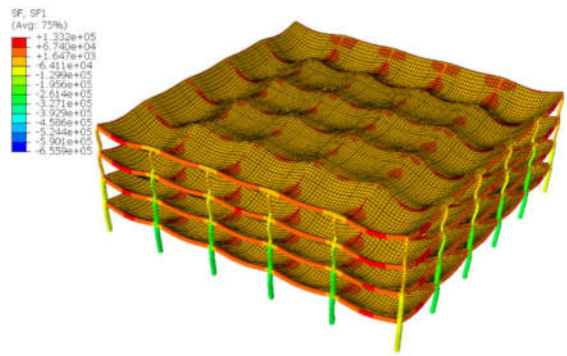


Figure 8. Axial load of structure without any column removal

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After the axial load of the column has been determined, applying an opposite direction of force which is the same as the support force of column as shown in Figure 9.[9] The moment and axial load analysis results are shown in Figure 10 and 11. Due to the first column removed, the controlled maximum moment appears at the top floor, so get the maximum moment and maximum axial load about the corresponding column to determine the experiment column's eccentricity. From the analysis result, the controlled column moment is 957.9 kips·in and the controlled axial load is 186.1 kips. The eccentricity of the moment to axial load is 5.14", because the column at the top floor is 12" x 12", so the eccentricity/column width ratio is about 0.428

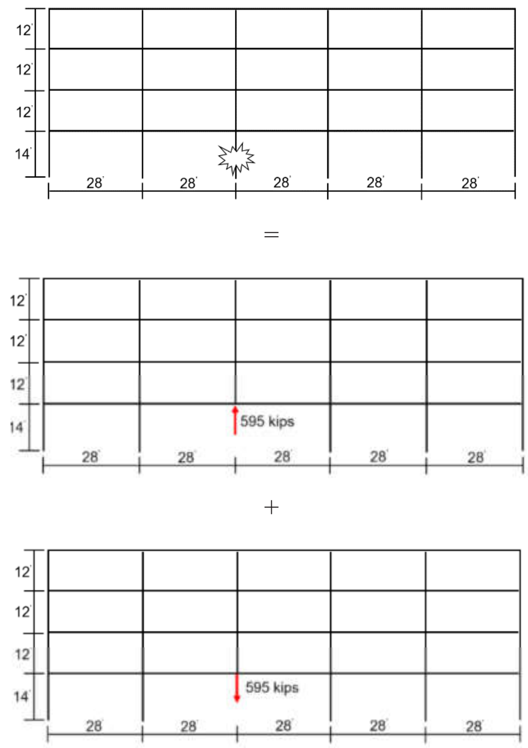
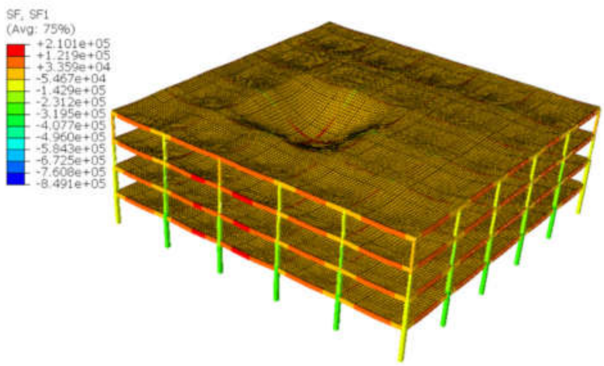
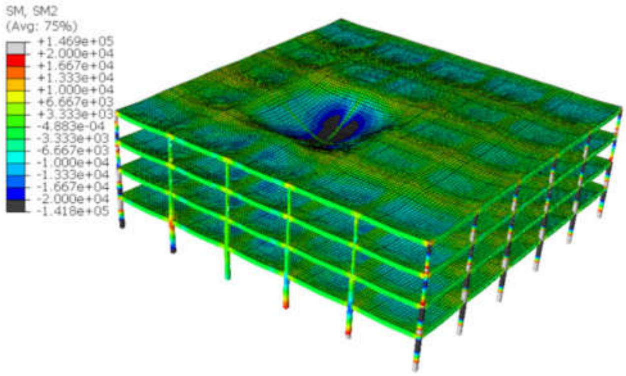


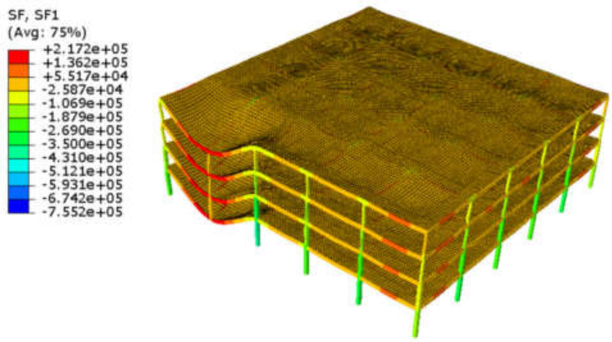
Figure 9. Analysis procedure



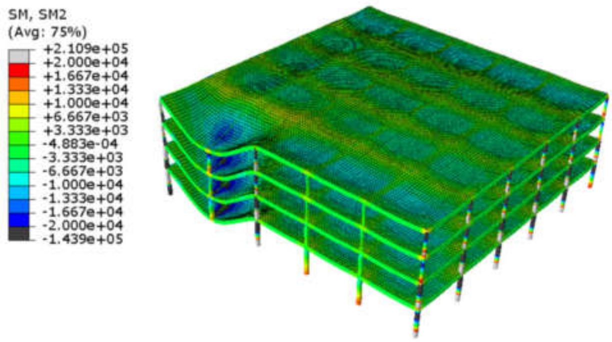
10.1 Axial diagram with interior column removal



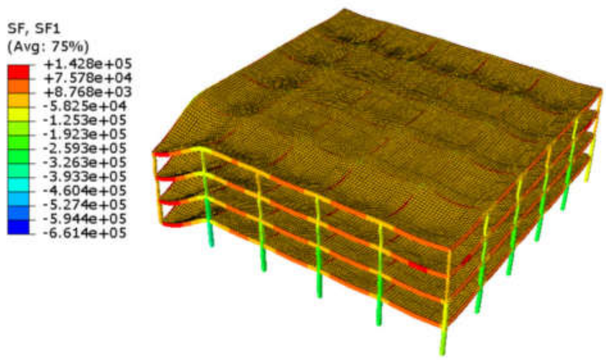
10.2 Moment diagram of with interior column removal



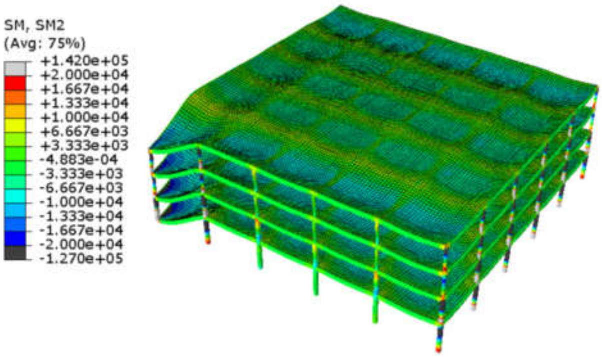
10.3 Axial diagram with edge column removal



10.4 Moment diagram of with edge column removal



10.5 Axial diagram with corner column removal



10.6 Moment diagram of with corner column removal

Figure 10. Axial and moment diagram of whole building with different column removal

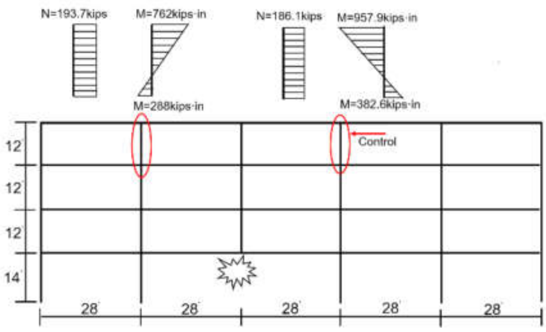


Figure 11. Top floor column's moment and axial load next to column removed

With the same method, the controlled column moment for edge column removal is 948.2kips·in and the controlled axial load is 91.7 kips. This time, the eccentricity of moment to axial load is 10.34", and the eccentricity ratio is about 0.86. On the other hand, the controlled column moment for corner column removal is 572 kips·in and the controlled axial load is 82 kips. This time, the eccentricity of moment to axial load is 6.97", and the eccentricity ratio is about 0.58.

4. Conclusion

Based on the analysis result, the column of the first floor destroyed will affects the top floor column's internal force most.

Remove the interior column of the first floor will cause the maximum axial load appears at the top floor's column. The first floor's edge column removal will cause the maximum moment to axial load ratio appears at the top floor's column.

The author recommends the eccentricity ratio of a column under sustained loading is between 0.4 to 0.9 for the future relevant concrete column experiments as the large eccentricity ratio. The value is based on the prototype structure design of the whole structural system. For the small eccentricity column test, researchers can choose 0.1 to 0.25 as the eccentricity ratio according to the former structural concrete column's test. [10]

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