Effect of Progressive Collapse in Reinforced Concrete Structures with irregularity in height

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SUMMARY

Progressive Collapse is a rare event during which all or part of the structure is destroyed due to damage or failure of a small section of the structure. Reliable evaluation of progressive collapse resistance of structures requires substantiated methods and techniques for analyzing the response of critical elements subjected to large deformations. In this paper, progressive collapse resistance is studied for 3 reinforced concrete buildings with 6 stories also with irregularity in height .The reinforced concrete structures have been designed according to Iranian concrete code (ABA) and have been checked by ACI, also was modeled in OpenSees to verify the place of plastic hinge. Analysis first has been done with considering seismic design load, and then has been done without it according to UFC2009, and then the critical column has been removed from the models. Our results showed that In the case of without considering seismic effects, structures need to retrofit against progressive collapse and also structures with more stiffness are more resistant against progressive collapse and their irregularity should be restricted.

Keyword: progressive collapse, Removed Column, RC frame, Pushover.

1. INTRODUCTION

The first collapse in 1968 in residential building of Ronan Point happened because of gas break out in the outer side and it attracted the notice of all. Later on similar collapses happened in Skyline Tower Building, L'Ambiance and Bankeer Trust Building. The regulations related to progressive collapse entered English Building Regulations in 5th Amendment in 1979. These requirments were for the tall buildings (more than 5 stories) and high rise structures and considered element strength in the case of eliminating. Before that and in the year 1972 the American National Standard Institute, some regulations like details about connection and serial activities in structure were presented for the deduction of probability of progressive collapse. This code used linear static analysis for medium height buildings and nonlinear static analysis for those buildings more than 10 floors. Finally the GSA in 2003 and UFC in the years 2005 and 2009 in he filed of progressive collapse were published. These codes are acceptable and complete references in the field of progressive collapse for many kinds of building such as, high rise, public and military buildings of modern type and also are used. Analysis and design in both codes due to the complex calculations and the damages that are asserted to the structure are independent from the load. These two references use the alternative path method (APM) for designing building against progressive collapse. The method of TFM is a non-direct design method in which the list resistance plasticity and indeterminacy in the structure in the production of resistance against collapse is provided. And the method of Alternate Path Method is a direct design method in which the general stability of the structure against collapse is considered. The GSA code uses APM, TFM method for designing the structure against progressive collapse. In this present article, the

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response of a 6-story-concrete building designed by special bending frame method of Iranian code (also checked by ACI) and with high deformation in two case that are regular and irregular in high is compared with 6-story-building without considering seismic load and with low deformation in the case of removing same column according to UFC2009 method.

2. MODELING

In the present research the OpenSees software was used. OpenSees is an object-oriented framework for finite element analysis.
OpenSees' intended users are in the research community. A key feature of OpenSees is the interchangeability of components and the ability to integrate existing libraries and new components into the framework (not just new element classes) without the need to change the existing code. Core components, that is the abstract base classes, define the minimal interface (minimal to make adding new component classes easier but large enough to ensure all that is required can be accommodated).This software possesses a complex useful ability such as modeling elements with finite element method.

In this software for modeling of reinforced concrete framed element, fiber elements were used. The cross-section of the element was divided to many cells and with considering the position of these cells the specification of material defines. For determining optimum number of fibers in the cross section of the columns, analysis of moment of the curve was performed also at least 3-layer for the cross section of the column it is needed so that the core of longitudinal reinforces and covering concrete can be modeled. Each node of frame element has 6 degree of freedom. Also since the cross-section of fiber only considers the axial and curving forces after defining the cross-section based on elements, the twisting and shearing specification of cracked cross section would be defined with the usage of section aggregator in the software.

2.1. Assessment of modeling

For the assessment of correctness of modeling of removing of column in the building with OpenSees, the result from experimental investigation that Wei-Jian Yi, et al have done on the frame of reinforced concrete are used. Our analysis was done on a concrete frame 6-story, 4-bay with irregularity in height then compared with the model of Wei-Jian Yi, et al that has done on 8 story with 4 bay. Its design is based on China codes. For the study of its collapse the column was removing with static unloading. (Fig. 1)

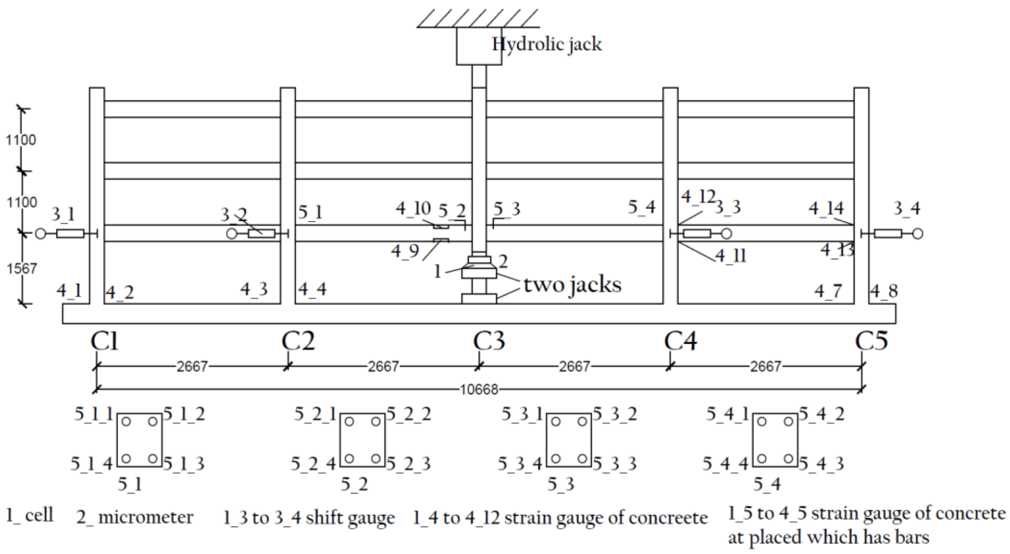

Figure 1. Details the experimental test that was done by Wei-Jian Y. et al.

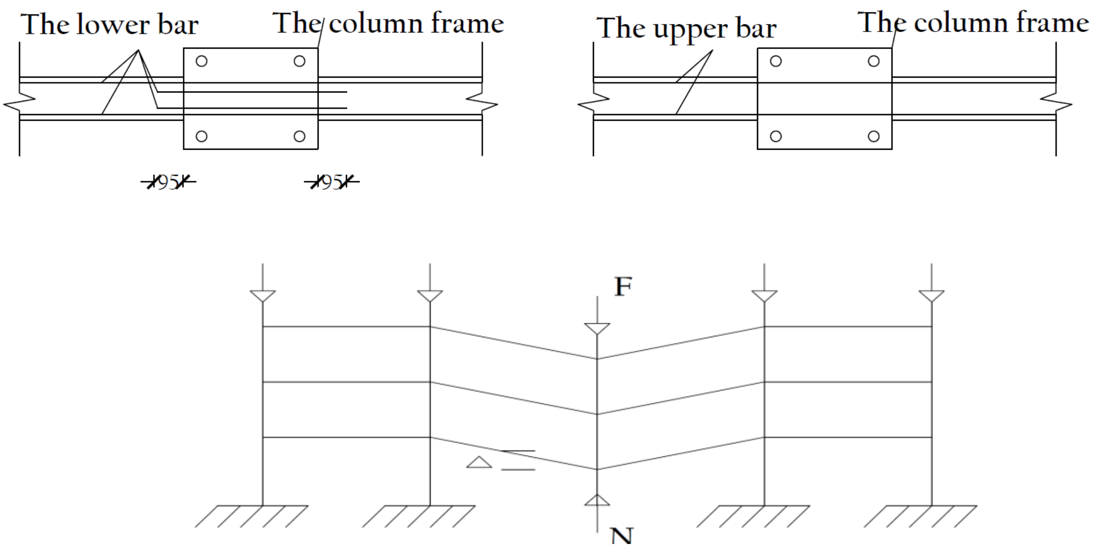

Figure 1. Details the experimental test that was done by Wei-Jian Y. et al. (continued)

First a load "F" in the middle column on higher story is applied. Then step by step the unloading is done by a mechanical jack located at the lower story. For simulating of Gradual failure of Lower column, the downward displacement in gradual form is applied. The displacement is applied to the level that the force against the jack is equal to F and in this situation the column is fully omitted. The changes of axial force in the jack are measured and its results are compared with our model in the OpenSees software which is illustrated in Fig. 2.

The results show the correctness of our modeling.

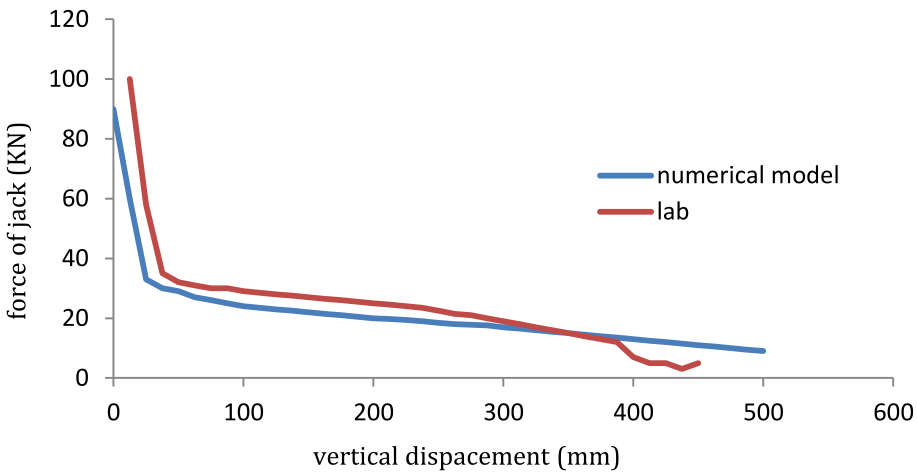

Figure 2. Comparing with our result and Wei-Jian Yi, et al

3. THE RESPONSE OF THE CONCRETE BUILDINGS AGAINST REMOVING OF THE COLUMN

For assessment of progressive collapse in concrete buildings, the 6 stories Building frame with high ductility was designed with National Construction code of Iran (ABA) and also with regarding of Seismic considerations of another code in Iran named standard 2800, and then checked with ACI. This building was simulated in ETABS in 2way,first a regular building second previous building but with irregularity in height, finally the regular building was designed again in ETABS but without considering Seismic considerations of Iranian code (2800) and the effect of removing column in that was investigated and compared according to UFC2009 was designed. For the aim of considering and study of progressive collapse in the mentioned building, it was simulated in OpenSees and by the affect of rapid omission of side column of the building the static non-linear response of them were specified.

3.1. Making the model

In this research the 6-story building with and without considering Seismic considerations was modeled in ETABST. The building has 256 sq. m plan with four equal bays in each side and the height of each story considered 3 m. The loading of the building was according to the 6th chapter of national code of construction of Iran and designing the structure was according to Iranian Concrete code (ABA).

The profile section of building in the case of considering Seismic considerations and without it was showed in table 3.1.1. and 3.1.2. and also the shape of buildings in ETABS are illustrated

Table 3.1.1. Profile sections of concrete in buildings with high plasticity (regular and irregular)

stories	Story 1	Story2	Story3	Story 4	Story 5	Story 6	Story 7
Column cross-section	B(cm)	35	35	35	35	30	30
	H(cm)	35	35	35	35	30	30
	Bars(a)	4 × T 14	4 × T 14	4 × T 14	4 × T 14	4 × T 12	4 × T 12
	Bars(b)	8 × T 14	8 × T 14	4 × T 14	4 × T 14	4 × T 12	4 × T 12
Beam cross-section	B(cm)	30	30	30	30	30	30
	H(cm)	30	30	30	30	30	30
	TOP	3 × T 20	3 × T 20	3 × T 20	3 × T 16	3 × T 14	3 × T 14
	BOTTOM	2 × T 20	2 × T 20	2 × T 20	2 × T 16	2 × T 14	2 × T 14

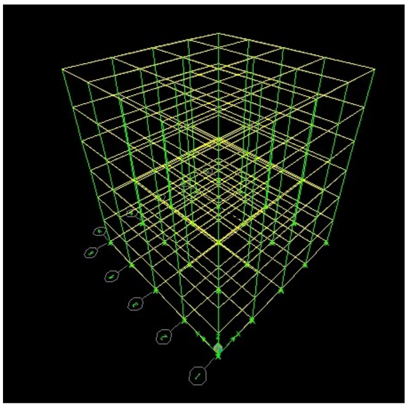

Figure 3.1.1. Regular building was simulated in ETABS (with and without considering seismic effect)

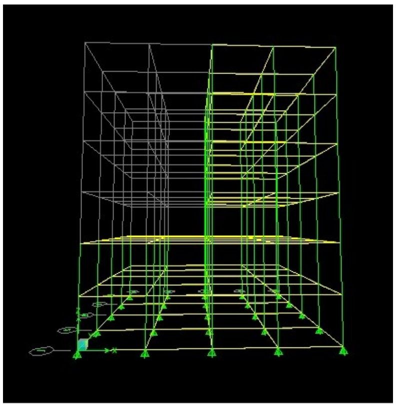

Figure 3.1.2. Irregular building was simulated in ETABS (with considering seismic effect)

Table 3.1.2. Profile sections of concrete in the building regardless of the seismic load

stories	Story 1	Story2	Story3	Story 4	Story 5	Story 6	Story 7
Column cross-section	B(cm)	40	40	35	35	30	30
	H(cm)	40	40	35	35	30	30
	Bars(a)	4 × T 16	4 × T 16	4 × T 14	4 × T 14	4 × T 14	4 × T 14
	Bars(b)	4 × T 16	4 × T 16	4 × T 14	4 × T 14	4 × T 14	4 × T 14
Beam cross-section	B(cm)	30	30	30	30	30	30
	H(cm)	30	30	30	30	30	30
	TOP	3 × T 20	3 × T 20	3 × T 20	3 × T 20	3 × T 20	2 × T 20
	BOTTOM	2 × T 20	2 × T 20	2 × T 20	2 × T 20	2 × T 20	2 × T 20

3.2. Static nonlinear analysis of UFC2009

According to the UFC code for High and medium level of protection, the tie forces must be according to Fig. 3.2 These ties which are in inner forms, outer form and circumferential forms join structural elements to each other and help the building against serial failure like progressive collapse in the time of elimination of elements.

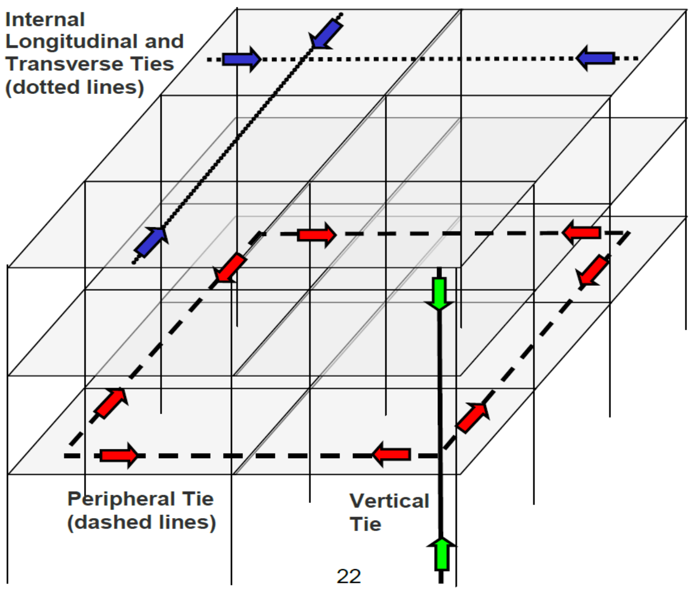

Figure 3.2. Schematic view of the Tie Forces

The tie force in connective elements has significant role in keeping the structure. According to UFC, first the tie-force should be controlled in the structure. The tie force according to UFC code is given in table 3.2.1. This force is produced from the cross sections. If the numbers of necessary bars for tie force is less than existing bars, then the Tie force in building has provided. If not, the building has got a high potential against progressive collapse and it needs a re-design against progressive collapse. In the table 3.2.1 the amount of existing bars (cross section) is more than needed bars .Thus the tie force in the structure is provided, also in the regular building with low plasticity and without considering seismological loads the tie force is provided with existing bars from which the table is disregarded.

Table 3.2.1. Tie force required and existing in the 6 story building

Tie type	Required Tie Force (kips)	Available bar ($inch^2$)	Required Tie Force<available Tie Force
Peripheral ties	F_t=Lesser of 4.5+9.5 n_0 or 13.5kips	1.460	ok
Internal ties	Greater of : $\frac{(D+l)}{156.6} \times \frac{l_r}{16.4} \times \frac{1.0}{3.3} \times F_t$ or $\frac{1.0}{3.3} \times F_t$	1.460	ok
Horizontal ties to column	Greater of : $0.03\ A_{trib}(4)(D+L)$ $or\ Lesser\ of\ 2.0\ F_t\ or\ \left(\frac{l_s}{8.2}\right) F_t$	1.460	ok
Vertical ties to column	$A_{trib}(D+L)+\ girder\ tributary\ load$	2.49	ok

n_0= 6 L_r = 4m (1016 inch) L_s = 3 S=4m (1016 inch) A_{trib}=4×4 =16m^2 (24800inch^2) D=.0297(kip-in) L=0.0112(kip-in)

3.3. Necessary tie force

$$F = \Omega \times Øs \times fy \times As_{req} \quad (1)$$

in the above relation (1), F is the necessary tie force ,n_0 stands for the number of stories, D,L stands for dead load and live load of each story, L_s is the center to center distance of column, L_s is the hight of the columns, S is interior ties, A_{trib} is the area underneath effect of omitted column $Ø_s$, is the coefficient of deduction of steel resistance (0.75) , Ω is coefficient of strength of bar (1.25), f_y is yield strength of bar, As_{req} is required bar area for inhibiting tie-force. All units are in lbf. Inch.

After control (TFM) method in the building, according to UFC2009 the building should be capable to alternate path method (APM). Then the building should be able to retain its stability against omission of the element and the building response against omission of the column does not exceed from the criteria criterion.

For the control of alternate path method, the corner column of the building has been omitted and the response of the building under static nonlinear analysis UFC 2009 is done, then the displacement are compares with allowable amount. The statistical analytical nonlinear processes are as follows. Since the omission of column is a dynamic phenomenon in static analysis for considering of this subject the dynamic effect coefficient is used. The level of this coefficient with regard to the relation 2 for concrete reinforced frame building is equal to:

$$\Omega_N = 1.04 + 0.45/(\frac{\theta_{pra}}{\theta_Y} + 0.48) \quad (2)$$

In equation (2), Ω_N the coefficient of dynamic load, θ_{pra} level of plastic curvature (its level with regard to tensile steel and the existing force in the existing code is available), Θ_Y level of yield curvature of cross section.

Finally for doing analysis, the loading element is omitted from structure and imposed loads from zero to entire of load in the form of cumulative are imposed to the structure (in 10 steps it reaches to the highest level). For the upper bay of removed column the load is equal to:

$$G_N = \Omega_N(1.2DL + 0.5\,LL) \qquad (3)$$

In this equation (3), DL is dead load, LL is live load and G_N is increased static load, for other bays amount of load is:

$$G = 1.2DL + 0.5\,LL \qquad (4)$$

For considering of p-Δ effect lateral load at a measure of $0.002\sum p$ is exerted to the building where P is the total live and dead load of each story after applying the load. The level of rotation of the plastic hinge is measured with allowable amount that is given by UFC2009. If the rotation doesn't increase from allowable the structure is resistant against progressive collapse. Otherwise the new structure should be redesigned and the existing structure must be retrofitted. The diagram of vertical displacement of the omitted column against loading for the building with high plasticity and regular (Fig. 3.3.1), building without seismological considerations (Fig. 3.3.2) and the building with high plasticity and irregular in height (Fig. 3.3.3) are illustrated. The loads are applied in 10 steps imposed from the omission of the column.

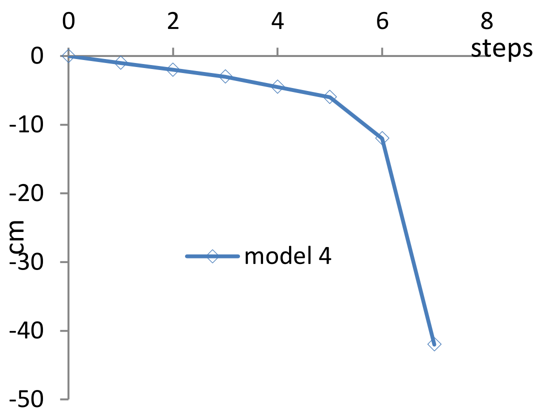

Figure (3.3.1): vertical displacement of the omitted column against loading for the building with high plasticity and regular with seismological considerations

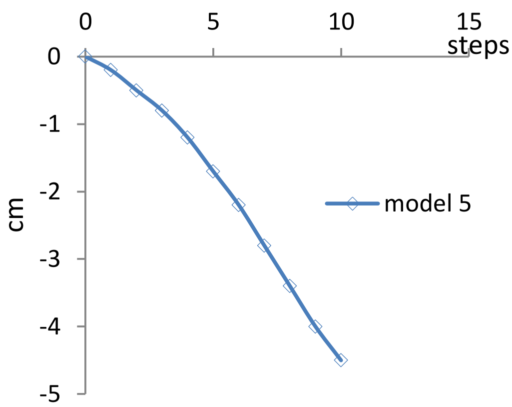

Figure (3.3.2): vertical displacement of the omitted column against loading for building without seismological considerations

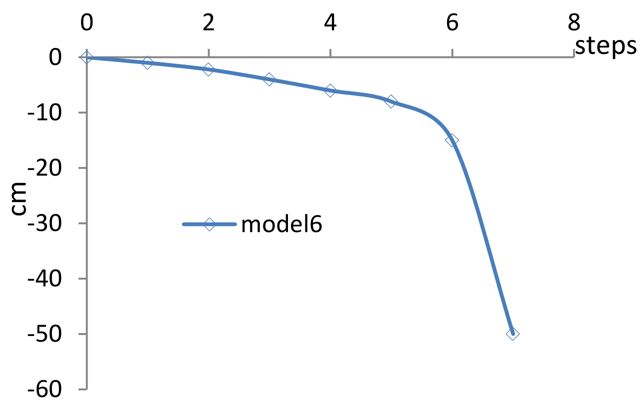

Fig (Fig. 3.3.3): vertical displacement of the omitted column against loading for building with high plasticity and irregular in height with seismological considerations

Also nodal rotation of buildings is compared with allowable amount in UFC2009 in the tables 3.2.2, 3.2.3, and 3.2.4.

Table 3.2.2. Rotation for the building with high plasticity and regular with seismological considerations

Amount of rotation	Rotation of plastic hinge (Radian)	Acceptable (Radian) = 0.063
First floor	0.011	OK
roof	0.0087	OK

Table 3.2.3. Rotation for the building without seismological considerations

Amount of rotation	Rotation of plastic hinge (Radian)	Acceptable (Radian) = 0.063
First floor	0.139	NOT OK
roof	0.136	NOT OK

Table 3.2.4. Rotation for the building with high plasticity and irregular in height with seismological considerations

Amount of rotation	Rotation of plastic hinge (Radian)	Acceptable (Radian) = 0.063
First floor	0.015	OK
roof	0.0091	OK

4. DISCUSSION

Table 3.2.2-3.2.4 shows that building with high plasticity and irregular in height with building with high plasticity and regular with seismological considerations are resistant against progressive collapse while the building without seismological considerations is not strong enough and need to retrofitting.
According to Fig 3.3.1 to 3.3.3 in irregular building because of eliminating many element such as beams and columns total stiffness is less than it in regular building so amount of displacement is increased

5. CONCLUSION

The level of devastation in the structure with energy absorption has got vice versa relation, the more undetermined and plasticity of the structure has more ability in energy absorption the devastation arisen from progressive collapse is less. And in the other words the structure is more resistant. And as it is shown in the example the structure with more stiffness is more resistant under remove of column.

About the example of this article and also the buildings with similar from, it is very important that the effect of clash of debris resulted from devastation of highest story on the vicinity roof should be considered and the structure should have the ability of encountering the clash and energy resulted from the trashes resulted from devastation of highest story or ceiling.

On the matter of asymmetric of structure in the height, the level of deduction or increment of ability in absorption of energy by the structure, according to this asymmetry should be noticed. The existence of asymmetric in height, in this model is against certainty because of it decreases the degree of indeterminacy and level of energy absorption.

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