EVALUATION OF NONLINEAR STATIC PROGRESSIVE COLLAPSE IN IRREGULAR CONCRETE STRUCTURES

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ABSTRACT

Progressive collapse is a structural catastrophic phenomenon, which can cause by natural disasters or human negligence where local failure of a member causes significant deformations that leads to destruction of structure. In this study, evaluation of the progressive collapse in concrete structures with intermediate moment frame in irregular state in plan according to GSA(2003) & DOD(2009) and using APM on “Open Sees” software with nonlinear static analysis in 3D structures 3, 6 and 10 stories has been carried out. The obtained results indicate that in creating this phenomenon the location of the removed column and the height of the structure has the most effect.

INTRODUCTION

Structural engineering science has always tried to predict events which in the lifetime of the structures has significant influence on the efficiency and strength of the structure. Progressive collapse is a kind of those events that if they will not be predicted they can bring about much financial and human losses. In general, buildings have not been designed with loading conditions such as gas explosions, bomb explosions, vehicles collision, plane collision, terrorist attacks and, etc... when these structures have been encountered with such loads they may suffer great damages. This phenomenon can also create problems for structures during severe earthquake, which leads to destruction of the structure. Initially after the destruction of the Ronan Point in London in 1968 engineers' attention were paid to this phenomenon. The collapse of the World Trade Centre on 11 September 2001 attracted vast attention and several standardization committes such as the United States Department of Defence (DOD) or UFC and United States General Services Administration (GSA)[1] start designing of structures against such progressive collapses. Two general methods have been created to decrease the progressive collapse in regulations:

1) indirect method, which prevents the progressive collapse by determining minimum essentials in strength, continuity and adequate development for alternative loading path among structural elements.
2) direct method, which prevents progressive collapse by being able to compensate the damages as part of the design and it consists of two sub categories A) Alternative load Path Method(APM) and B) Specific Local Resistance Method (SLRM).

Elingwood&Leyendeker are one of the first people who performed researches on progressive collapse in 1978 and discussed about the design methods against this phenomenon.[7] Kapil Khandelwal & Sherif El-Tawil in 2009 evaluated the progressive collapse in EBF and CBF and their results showed that because of more ductility EBF than CBF, this frame is more resistant against progressive collapse.[8] Taewan Kim & Jinkoo Kim in 2009 studied the progressive collapse of the steel frames with three types of seismic connection and conclusion indicated that the designed structures with high seismicity are more resistant against progressive collapse.[9] Hartanto Wibowo & Silvena Reshotkina evaluated the progressive collapse in the concrete bridges during earthquake in 2009 and it was seen that this phenomenon is not limited to gravity load and may also occur during the earthquake.[10] In this study, evaluation of the progressive collapse in concrete structures with intermediate moment frame in irregular state in plan, according to GSA(2003) & DOD(2009) and using APM on “Open Sees” software with nonlinear static analysis in 3D structures 3, 6 and 10 stories has been conducted.

VERIFICATION

In this section before the main model, for verification of “Open Sees” software we created a model of concrete frame under artificial acceleration. This model is shown in Example1 in Chapter 4 from seismic structure verification report for version 6[11]. By comparing the models it was indicated that in Figure1 there is a high accuracy of “Open Sees” software in nonlinear analysis.

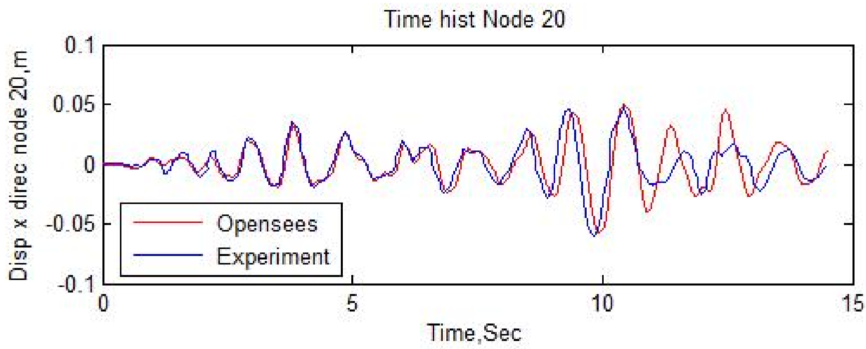


Figure 1. result of verification

ANALYSIS PROCEDURE

ACCEPTANCE CRITERION FOR PROGRESSIVE COLLAPSE

Plastic hinge rotation is the most important part of guidelines for evaluation of the progressive collapse. The guidelines determine (CP) performance level for beams which their under column has been destroyed as the limit of the plastic hinge rotation. If the hinges rotation of these beams exceed this limit, the structure has high potentiality for progressive collapse.

APPLIED LATERAL & GERAVITY LOAD FOR STATIC ANALYSIS

In nonlinear static analysis, the structure by DL+0.25LL according to GSA (2003) is loaded, then the structure is pushed by the length of Target Displacement when in the selected column plastic hinge was created, the column is removed and in the spans which the column is removed the gravity load is doubled that dynamic effects are considered for the removed column.

According to FEMA 356[2] at least two lateral load patterns should be used for nonlinear static analysis, in this study the uniform and triangular load pattern is applied.

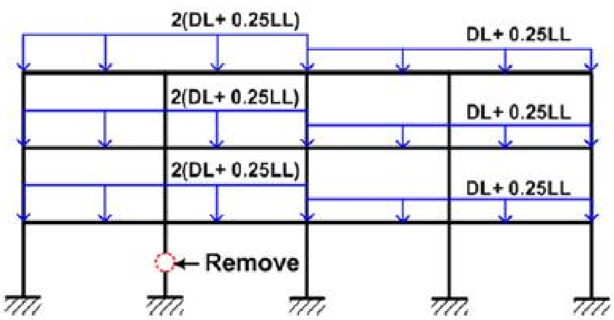


Figure 2. Applied load for analysis of progressive collapse [3]

STRUCTURAL PROPERTIES

All structures in this study have been designed according to Iranian building code [4] and have intermediate moment frame in both directions. The height of the first story is 2.9 meters and other stories are 3.2 meters. Dead load of the ceiling and interior partitions has been considered as follows: for the first story 540 Kg/m^2 and for other stories 665 Kg/m^2 and for roof 680 Kg/m^2. Live load has been considered for stories 200 Kg/m^2 and for roof 150 Kg/m^2 .

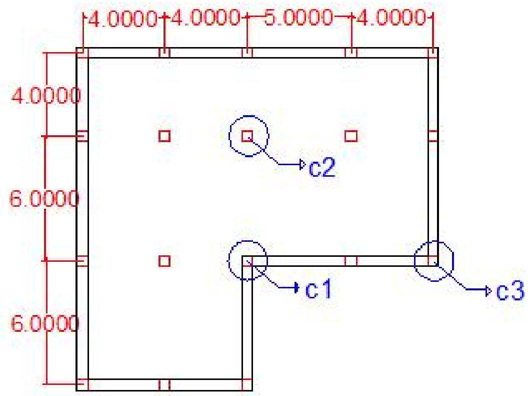


Figure 3. Structural plan and location of select column

MODELING ON "OPENSEES" SOFTWARE

In finite element softwares for nonlinear analysis nonlinear element, nonlinear material and nonlinear section must be simultaneously used .In this study we applied nonlinear Beam-Column element for design of beams and columns which has a wide distribution of plasticity in over element and fiber section was used for the design of cross-section of elements and for concrete and steel bars in model respectively Concrete01 and Steel02.To consider the effects of confinement of concrete, we employed the Kent and Park's model in the fiber concrete section which two kinds of concrete material are used: one of them is concrete with common characteristic for cover of concrete and the second is concrete with more ductility for core of concrete which has been shown in Table2. In 3D models for considering the torsional stiffness of elements we should calculate a torsional stiffness equal to G*J for per unit of section then add on main section in which G is the concrete mouduls of torsion and J is the torsional moment of inertia. In all structures, yielding strength of reinforcement F_y=4000 Pa and 5% rayleigh damping has been practiced.

Table2. parameters of concrete material in opensees

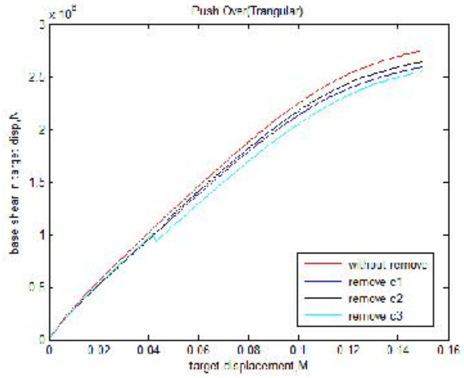
	Peak stress	Peak strain	Ultimate stress	Ultimate strain
Core	$-28*10^6$	-0.0035	$-21*10^6$	-0.015
Cover	$-24*10^6$	-0.003	$-18*10^6$	-0.005

ANALYSIS RESULTS

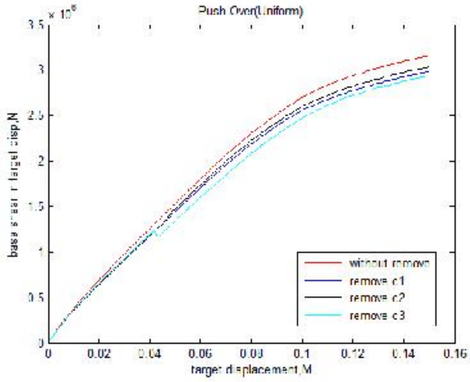
CAPASITY CURVES

In this part capacity curves in 3D structures in irregular were investigated. The structures were pushed by the length of target displacement which in FEMA356 was been explained how to attain it. The method of removal column in part of analysis procedure was explained. In Figure 4 the capacity curves have been shown in the states of triangular and uniform load pattern.

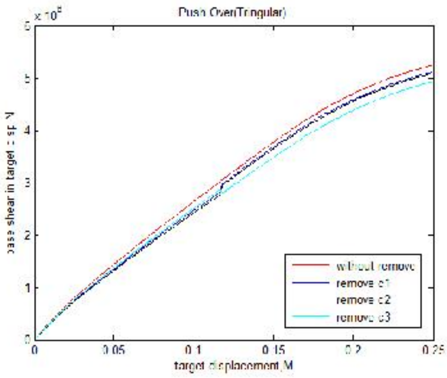
Investigations showed that triangular load pattern has less capacity than uniform load pattern. Also with the rise of stories base shear of structure increases. In all states with removal of column3 shear capacity of structure in comparison with two other columns reduces more.



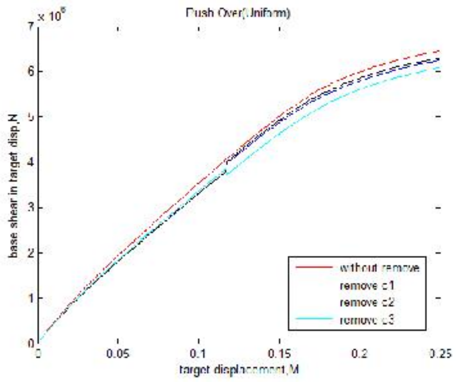
3story



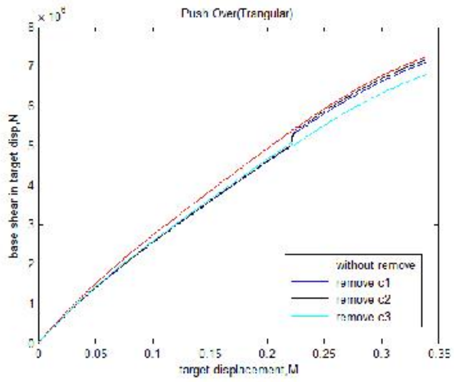
3story



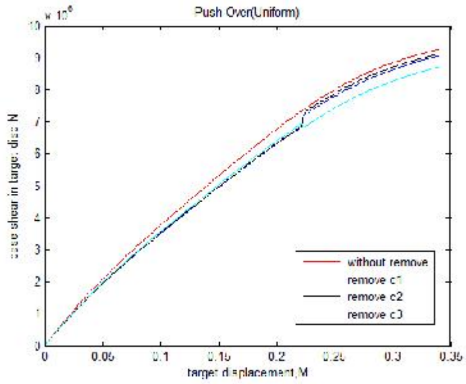
6story



6story



10story
a) Triangular



10story
b) uniform

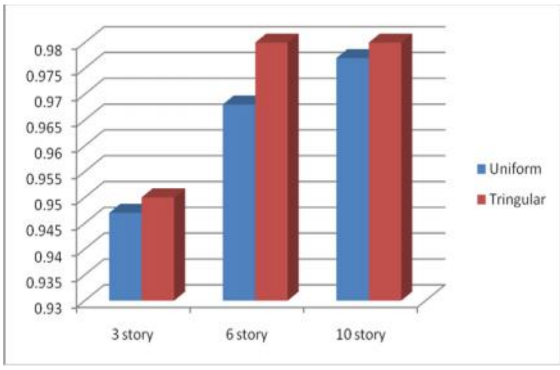
Figure 4. Capacity curves

ROBUSTNESS INDEX IN STATIC ANALYSYS

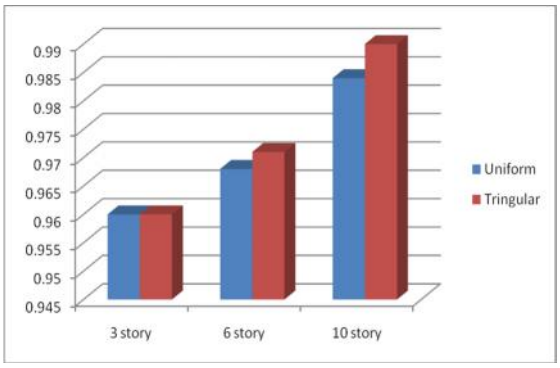
Structural robustness was defined as a lack of sensitivity to a local failure. In order to categorize the results in a better way robustness index is applied which can be defined as follows [5]:

$$R = \frac{V_{(damaged)}}{V_{(\text{int}\,act)}} \qquad (1)$$

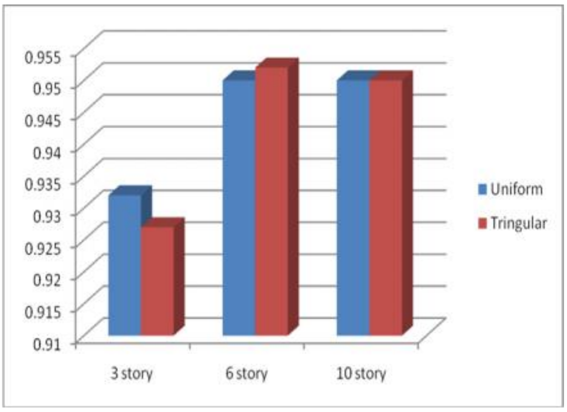
V_d is the shear capacity of damaged structural and V_i is the shear capacity of intact structural, which their amounts have been taken from capacity curves.



Remove c1



Remove c2



Remove c3

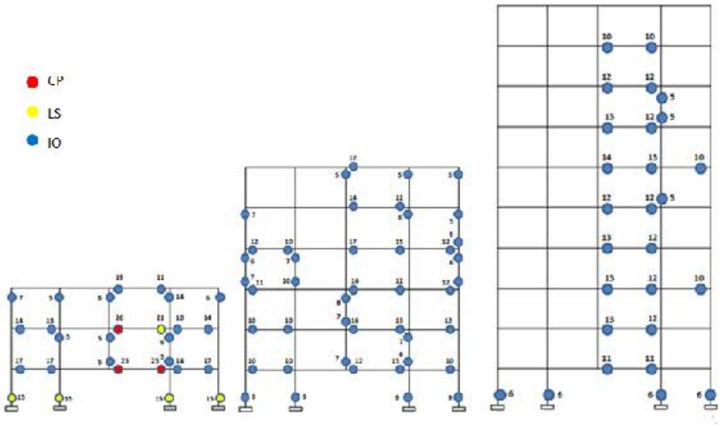
Figure 5. Robustness index

In state of removal of column3, the robustness of structure is less than two other columns indeed energy redistribution with removal of this column among elements of structure is less in comparison with the others. Also with the rise of stories, robustness index of structure increases which indicates the high importance of more elements in structure.

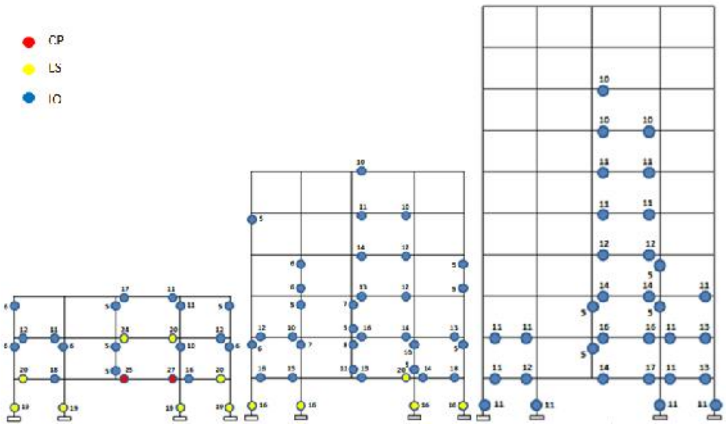
PLASTIC HING ROTATION IN STATIC ANALYSIS

As mentioned before, the most important part of guidelines in evaluation of progressive collapse is plastic hinges rotation. The created hinges in static analysis in target displacement and process of hinges creation have been investigated according to FEMA 356.

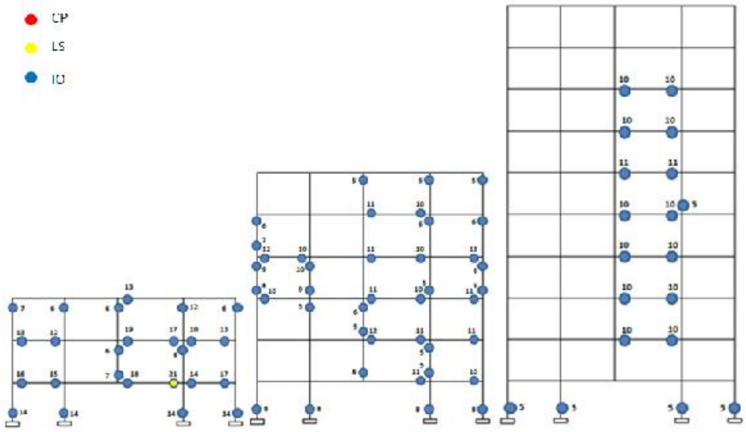
The following figures are the structures with removal column1&2 in triangular and uniform load pattern.



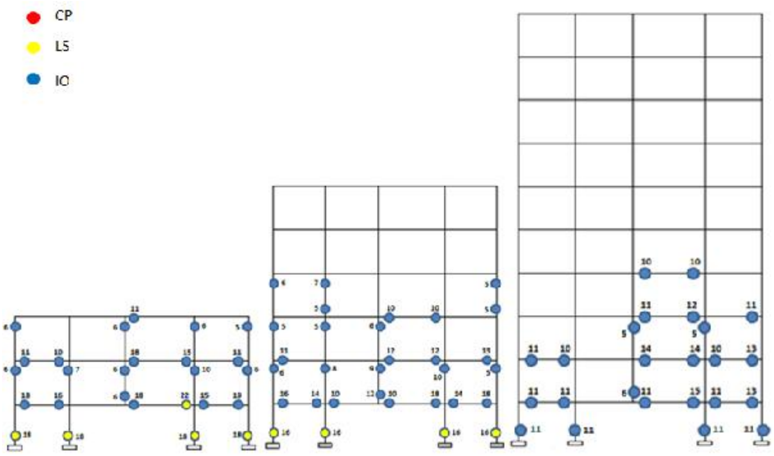
a) triangular load pattern with removal column 1



b) Uniform load pattern with removal column 1



c) Triangular load pattern with removal column2



d) Uniform load pattern with remove column 2

Figure 6. Plastic hinge rotation (rotation in thousandth of radian)

Paying attention to the Figures 6, it will be understood that in the irregular 3story by removing column1 hinges rotation increases from the limit of guidelines and has high potentiality for progressive collapse but in other states, structure with other removal columns is resistant against this phenomenon.

CONCLUSIONS

1) Whenever column1 in irregular 3story structure loses its freight task according to guidelines the structure has high potentiality for progressive collapse.
2) Surrounding columns are more vulnerable to damage and indeed they have less ability to redistribute energy of the removal column then it is better to apply smaller spans for surrounding ones in structure.
3) All studies declare that with the rise of stories the structure shows better ability against this phenomenon which indicates the importance of partnership of more elements in structure for the creation of alternative load paths.

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