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THREE DIMENSIONAL PROGRESSIVE COLLAPSE ANALYSIS OF STEEL MOMENT RESISTING FRAMES WITH DIFFERENT DUCTILITY

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ABSTRACT

In the last decade, many studies have been done on progressive collapse analysis of structures to avoid this catastrophic phenomenon. Most of recent researches has focused on two dimensional analysis of progressive collapse. These analysis can't consider out of plane member, forces and catenary action completely, So three dimensional progressive collapse analysis of special moment frames (SMF) and intermediate moment frames (IMF) using the program code OpenSees (Mazzoni et al. 2006) were investigated in this study. Structures modeled in this study were designed by using latest seismic guidelines to study their progressive collapse potential. A series of three and two dimensional nonlinear dynamic analyses were performed to determine the resistance of a structure to different column loss scenarios, detecting the associated failure mode and comparing these structures, methods and scenarios together. Both force-controlled and deformation controlled actions based on UFC and ASCE 41 were implemented to define the acceptance criteria for twelve loss scenarios (six column loss scenarios in three dimensional and six column loss scenarios in two dimensional) defined in this study. In these scenarios middle column of first, third and sixth floor were removed to compare 3D and 2D models in different situation. The results show that both SMF and IMF buildings in 3D and 2D analysis can resist against progressive collapse. But DCR values in three dimensional analysis were smaller than those from the two dimensional analysis. Moreover column and beam forces and force swings after removing column in three dimensional analysis were smaller in comparison to two dimensional analysis. This demonstrated that the out of plane members and forces should be considered in progressive collapse analyses and the effect of 3D redistribution gravity loads should not be ignored.

Keywords: progressive collapse; three dimensional model; steel moment resisting frame; nonlinear dynamic analysis, demand to capacity ratio (DCR)

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1. INTRODUCTION

Collapse is defined as failure from one member to another that finally leads to total or partial collapse of structures. Probable dangers and abnormal loads that can cause progressive collapse contains these items: aircraft impact, design and construction error, fire, bomb or gas explosions, accidental overload, etc. As these accidents have low probability of occurrence, they are not considered in structural calculations and design. GSA [1] and UFC [2] are the main guidelines that provide detailed information to resist buildings from progressive collapse and include Alternate Path Method (APM). In this approach, if one of the members of structures fails the alternate paths redistribute the loads and prevent progressive collapse. According to these guidelines a building must have adequate strength to survive predefined scenarios in each one of the building's that columns is eliminated.
Progressive collapse researches first started at 7th decade, when ronan point apartment fails through gas explosion. After that several investigations have been carried out on progressive collapse behavior of steel frames, especially since the terrorist attack on the World Trade Center (WTC) towers. First study including progressive collapse analysis of steel frames done by groos[4] et al. in this study they evaluate behavior of 2D steel moment frames against removing one column or increasing load on beams that represents debris with numerical method. Pawell[5] compared linear, nonlinear static analysis and nonlinear dynamic analysis together and concluded that dynamic coefficient 2 that was used in linear static analyses can shows the same overestimated results. He emphasized that nonlinear analysis must be used. Ruth et al[6] [3] concluded that coefficient 1.5 shows dynamic impact better especially for steel frames. Kim et al [4] did pushdown analysis for evaluating the resistance of steel moment frames against progressive collapse. They considered two bays structures with different bay's length and different number of stories. Structures were evaluated for static and nonlinear dynamic analysis, after that process of forming plastic joints under pushdown analysis in structures were discussed. They showed that increase in number of bays will cause more capacity to resist gravity loads, and structures with more bays can have better performance against progressive collapse. Song et al. [5] performed an experimental study on a steel building and concluded that using the amplification. Hashemi Rezvani et al. [6] studied the effect of span length on progressive collapse behavior of steel moment resisting frames. Hashemi Rezvani and Asgarian [7] showed that seismic detailing can be used as an indirect tool to enhance the robustness of concentrically braced frames against progressive collapse.
Although progressive collapse analysis are commonly studied in many researches but most of researches evaluate this phenomenon in 2D models, to evaluate real potential of structures against progressive collapse , 3D modeling with considering nonlinear dynamic analysis is needed. As steel moment frames are the lateral load bearing system in many buildings, we decided to study this lateral load bearing system potential against progressive collapse. This research aims to investigate the real structural response of a generic steel moment resisting frame to sudden column removals in 3D models and compare responses with 2D models. In addition, to consider different situation and different ductility both special moment frame and immediate moment frames lateral load bearing system are modeled. Also different scenarios of removing column is considered to shows the different in modeling in different conditions.

2. THREE AND TWO DIMENSIONAL ANALYSES METHOD AND ACCEPTANCE CRITERIA

In order to investigate the progressive collapse analysis of special moment frames and immediate moment frames, Three dimensional and two dimensional 10-story frame is studied. Three loss levels are selected for both three and two dimensional structures, namely, first level, third level and sixth level. For each level two loss locations are defined, one exterior column and the other one is interior column. All named scenarios are done for both SMF and IMF structures. Ordinary moment frame lateral system

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[4] Groos et al.

[5] pawell

[6] Ruth et al.

wasn't modeled, because structures are in high seismic zone and this lateral system can't be used in these areas. To analyze the structure under these removal scenarios, nonlinear dynamic analyses is performed. For nonlinear analyses of steel structures, UFC states that the modeling parameters and nonlinear acceptance criteria of ASCE 41 [8] can be used with the exception of the connections and elements discussed in it. These acceptance criteria include force-controlled and deformation-controlled actions, which depends on the yield rotations of structural members. In order to calculate the yield rotation in structural members we used ASCE 41. At the first step of this investigation we determine the yield rotation of all structural elements for each removal scenario. Sudden loss of a structural element is a dynamic process, so performing nonlinear dynamic analyses will provide a better insight to the response. Therefore, nonlinear dynamic analyses are performed to determine whether a sudden column loss cause failure progression or not. The response of the structure is investigated by performing a nonlinear dynamic analysis, these analysis are performed for each removal scenario (APM case). To determine whether the structure collapses progressively or not the analysis results are checked against performance-based criteria. The acceptance criteria are based on both force-controlled and deformation-controlled actions. The yield rotations obtained from the first step are used for the latter. The building is susceptible to progressive collapse and the analysis ends in that scenario if a structural element fails. If not, it means that the structure is capable of reaching a static balance after the specific element removal. In next step, removal scenarios in three dimensional model compare with the same removal scenario in two dimensional model and then different scenarios compare together in order to detect the critical scenarios. In the last step SMF and IMF structures will compare together in same removal scenarios to choose more resistant lateral system in each removing scenario. In order to check whether a sudden column loss leads to progressive collapse or not acceptance criteria are defined based on UFC and ASCE-41. UFC states that nonlinear acceptance criteria for structural steel components shall meet the Life Safety condition for primary and secondary elements provided in ASCE 41, except for beams subjected to flexure or flexure plus axial tension for which the Collapse Prevention (CP) condition have to be used. In this study, the structural performance of all structural elements are controlled at every stage of the analysis based on this acceptance criteria. These criteria include both deformation-controlled and force-controlled actions as explained in [2, 8]. For the rotation control, the acceptance criteria are defined using Force-Deformation (or Rotation) table 9.6 of ASCE-41.

For columns, controlling the actions depends on the axial load level applied to them. Deformation-controlled action or a force-controlled action should be considered in order to check the potential of failure occurrence. UFC states that columns under high axial compressive forces ($P/P_{CL} > 0.5$) shall be considered force-controlled, with the considered forces (P and M) equal to the maximum loads from the analysis. The P-M interaction equation shall not exceed unity. For $P/P_{CL} \leq 0.5$, the interaction equation shall be used with the moment considered as deformation-controlled and the axial force as force-controlled. The P-M interaction is determined using Equations 1 to 3.

$$For \quad \frac{P_{UF}}{P_{CL}} < 0.2: \quad DCR = \frac{P_{UF}}{2P_{CL}} + \frac{M_x}{m_x M_{CEx}} + \frac{M_y}{m_y M_{CEy}} \leq 1.0 \tag{1}$$

$$For \ 0.2 \leq \frac{P_{UF}}{P_{CL}} \leq 0.5: \quad DCR = \frac{P_{UF}}{P_{CL}} + \frac{8}{9}[\frac{M_x}{m_x M_{CEx}} + \frac{M_y}{m_y M_{CEy}}] \leq 1.0 \tag{2}$$

$$For \quad \frac{P_{UF}}{P_{CL}} > 0.5: \quad DCR = \frac{P_{UF}}{P_{CL}} + \frac{M_{UFx}}{M_{CLx}} + \frac{M_{UFy}}{M_{CLy}} \leq 1.0 \tag{3}$$

Where P is axial force, Pye is Expected axial yield force, DCR is Demand over capacity ratio, P_{CL} is Axial compression capacity, P_{UF} is Axial force in the member, M_x and M_y are Bending moments in the member for the x-y axis, M_{CEx} and M_{CEy} are Expected bending strengths of the column for the x-y axis, m_x and m_y are Values of m for the column bending about the x-y axis, M_{UFx} and M_{UFy} are Bending moments in the member about the x-y axis, $M_{CLx}$and M_{CLy} are Lower-bound flexural strengths of the member about the x-y axis.

For the beams, only the deformation-controlled actions are required. This action checks rotations of the beams in every step of the analysis against the acceptance criteria.

3. INVESTIGATED STRUCTURE

To study the progressive collapse analysis of steel moment frames with different ductility (SMF) and (IMF), three dimensional and two dimensional 10-storey buildings were investigated. The plan and elevation view of the building are shown in Figs. 1 and 2. The dead and live loads of 6 and 2 kN/m^2, respectively, were used as gravity loads for all stories. For member design subjected to earthquake, equivalent lateral static forces were applied to all story levels. Tables 1 to 4 shows the steel sections selected for the studied structure.

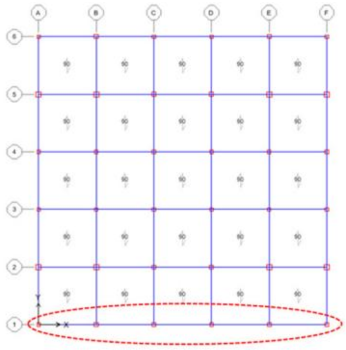

Figure 1. Plan view of the structure and exterior frame that modeled in 2D modeling.

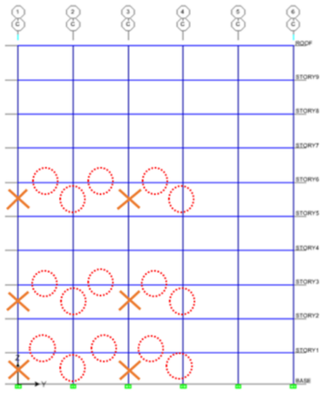

Figure 2. Elevation view and critical members that are most affected from the removed column.

Table 1. Beam sections selected for the SMF structure.

	Frame 1 , 6			Frame 2 , 5			Frame 3 , 4		
Level	**Beam Bay A-B**	**Beam Bay B-C**	**Beam Bay C-D**	**Beam Bay A-B**	**Beam Bay B-C**	**Beam Bay C-D**	**Beam Bay A-B**	**Beam Bay B-C**	**Beam Bay C-D**
Level 10	IPE220	IPE220	IPE220	IPE220	IPE220	IPE220	IPE220	IPE220	IPE220
Level 9	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300
Level 8	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300
Level 7	IPE300	IPE330	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300
Level 6	IPE300	IPE330	IPE300	IPE330	IPE330	IPE330	IPE330	IPE300	IPE330
Level 5	IPE300	IPE330	IPE300	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 4	IPE300	IPE360	IPE300	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 3	IPE300	IPE360	IPE300	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 2	IPE300	IPE450	IPE360	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 1	IPE300	IPE450	IPE360	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
	Frame A , F			**Frame B , E**			**Frame C , D**		
Level	**Beam Bay 1-2**	**Beam Bay 2-3**	**Beam Bay 3-4**	**Beam Bay 1-2**	**Beam Bay 2-3**	**Beam Bay 3-4**	**Beam Bay 1-2**	**Beam Bay 2-3**	**Beam Bay 3-4**
Level 10	IPE220	IPE220	IPE220	IPE220	IPE220	IPE220	IPE220	IPE220	IPE220
Level 9	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300
Level 8	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300
Level 7	IPE330	IPE300	IPE330	IPE300	IPE300	IPE300	IPE330	IPE330	IPE300
Level 6	IPE330	IPE300	IPE330	IPE330	IPE330	IPE300	IPE330	IPE330	IPE300
Level 5	IPE330	IPE300	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 4	IPE330	IPE300	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 3	IPE330	IPE300	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 2	IPE330	IPE300	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 1	IPE330	IPE300	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330

Table 2. Column sections selected for the SMF structure.

	Frame 1 , 6			Frame 2 , 5			Frame 3 , 4		
Level	**Col A, F**	**Col B, E**	**Col C, D**	**Col A, F**	**Col B, E**	**Col C, D**	**Col A, F**	**Col B, E**	**Col C, D**
Level 10	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2
Level 9	BOX20X1.2	BOX25X2	BOX25X2	BOX25X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2
Level 8	BOX20X1.2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2
Level 7	BOX20X1.2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2
Level 6	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2
Level 5	BOX25X2	BOX30X2.5	BOX30X2.5	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 4	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 3	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX45X2.5	BOX45X2.5	BOX35X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 1	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX45X2.5	BOX45X2.5	BOX35X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
	Frame A , F			**Frame B , E**			**Frame C , D**		
Level	**Col A, F**	**Col B, E**	**Col C, D**	**Col A, F**	**Col B, E**	**Col C, D**	**Col A, F**	**Col B, E**	**Col C, D**
Level 10	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX20X1.2
Level 9	BOX20X1.2	BOX20X1.2	BOX20X1.2	BOX25X2	BOX20X1.2	BOX20X1.2	BOX25X2	BOX20X1.2	BOX20X1.2
Level 8	BOX20X1.2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2
Level 7	BOX20X1.2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2
Level 6	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX30X2.5	BOX25X2
Level 5	BOX25X2	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 4	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 3	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 2	BOX30X2.5	BOX45X2.5	BOX30X2.5	BOX30X2.5	BOX45X2.5	BOX30X2.5	BOX30X2.5	BOX35X2.5	BOX30X2.5
Level 1	BOX30X2.5	BOX45X2.5	BOX30X2.5	BOX30X2.5	BOX45X2.5	BOX30X2.5	BOX30X2.5	BOX35X2.5	BOX30X2.5

Table 3. Beam sections selected for the IMF structure.

	Frame 1 , 6			Frame 2 , 5			Frame 3 , 4		
Level	**Beam Bay A-B**	**Beam Bay B-C**	**Beam Bay C-D**	**Beam Bay A-B**	**Beam Bay B-C**	**Beam Bay C-D**	**Beam Bay A-B**	**Beam Bay B-C**	**Beam Bay C-D**
Level 10	IPE270	IPE270	IPE270	IPE270	IPE270	IPE220	IPE220	IPE270	IPE270
Level 9	IPE270	IPE270	IPE200	IPE270	IPE270	IPE270	IPE270	IPE270	IPE270
Level 8	IPE270	IPE330	IPE270	IPE270	IPE300	IPE270	IPE270	IPE270	IPE270
Level 7	IPE270	IPE330	IPE270	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300
Level 6	IPE270	IPE360	IPE270	IPE330	IPE330	IPE300	IPE300	IPE300	IPE330
Level 5	IPE270	IPE360	IPE270	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 4	IPE330	IPE400	IPE270	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 3	IPE330	IPE400	IPE270	IPE360	IPE330	IPE330	IPE330	IPE330	IPE330
Level 2	IPE330	IPE450	IPE360	IPE360	IPE330	IPE330	IPE330	IPE330	IPE330
Level 1	IPE330	IPE450	IPE360	IPE360	IPE330	IPE330	IPE330	IPE330	IPE330
	Frame A , F			**Frame B , E**			**Frame C , D**		
Level	**Beam Bay 1-2**	**Beam Bay 2-3**	**Beam Bay 3-4**	**Beam Bay 1-2**	**Beam Bay 2-3**	**Beam Bay 3-4**	**Beam Bay 1-2**	**Beam Bay 2-3**	**Beam Bay 3-4**
Level 10	IPE220	IPE270	IPE220	IPE270	IPE270	IPE220	IPE220	IPE270	IPE220
Level 9	IPE270	IPE270	IPE270	IPE270	IPE270	IPE270	IPE270	IPE270	IPE270
Level 8	IPE300	IPE270	IPE300	IPE270	IPE300	IPE270	IPE270	IPE300	IPE270
Level 7	IPE300	IPE270	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300	IPE300
Level 6	IPE330	IPE270	IPE330	IPE330	IPE330	IPE300	IPE300	IPE330	IPE330
Level 5	IPE330	IPE270	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 4	IPE360	IPE270	IPE360	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 3	IPE400	IPE360	IPE360	IPE330	IPE330	IPE330	IPE330	IPE330	IPE330
Level 2	IPE400	IPE360	IPE360	IPE330	IPE330	IPE330	IPE360	IPE330	IPE330
Level 1	IPE400	IPE360	IPE360	IPE330	IPE330	IPE330	IPE360	IPE330	IPE330

Table 4. Column sections selected for the IMF structure.

	Frame 1 , 6			Frame 2 , 5			Frame 3 , 4		
Level	**Col A, F**	**Col B, E**	**Col C, D**	**Col A, F**	**Col B, E**	**Col C, D**	**Col A, F**	**Col B, E**	**Col C, D**
Level 10	BOX20X1	BOX20X1.2	BOX25X1.2	BOX20X1	BOX20X1	BOX20X1	BOX20X1.2	BOX20X1	BOX20X1
Level 9	BOX20X1	BOX25X2	BOX25X1.2	BOX25X1.2	BOX25X1.2	BOX25X2	BOX25X2	BOX25X1.2	BOX25X1.2
Level 8	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX30X2.5	BOX25X2	BOX25X2	BOX25X2	BOX25X2
Level 7	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX40X2.5	BOX30X2.5	BOX30X2.5	BOX25X2	BOX30X2.5
Level 6	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX40X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 5	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX40X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 4	BOX30X2.5	BOX35X2.5	BOX30X2.5	BOX30X2.5	BOX40X2.5	BOX35X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 3	BOX30X2.5	BOX35X2.5	BOX30X2.5	BOX45X2.5	BOX45X2.5	BOX35X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 2	BOX40X2.5	BOX40X2.5	BOX40X2.5	BOX45X2.5	BOX45X2.5	BOX40X2.5	BOX35X2.5	BOX35X2.5	BOX35X2.5
Level 1	BOX40X2.5	BOX40X2.5	BOX40X2.5	BOX45X2.5	BOX45X2.5	BOX40X2.5	BOX35X2.5	BOX35X2.5	BOX35X2.5
	Frame A , F			**Frame B , E**			**Frame C , D**		
Level	**Col A, F**	**Col B, E**	**Col C, D**	**Col A, F**	**Col B, E**	**Col C, D**	**Col A, F**	**Col B, E**	**Col C, D**
Level 10	BOX20X1	BOX20X1	BOX20X1.2	BOX20X1.2	BOX20X1	BOX20X1	BOX25X1.2	BOX20X1	BOX20X1
Level 9	BOX20X1	BOX25X1.2	BOX25X2	BOX25X2	BOX25X1.2	BOX25X1.2	BOX25X1.2	BOX25X2	BOX25X1.2
Level 8	BOX25X2	BOX25X2	BOX25X2	BOX25X2	BOX30X2.5	BOX25X2	BOX25X2	BOX25X2	BOX25X2
Level 7	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX40X2.5	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 6	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX40X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 5	BOX25X2	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX40X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX30X2.5
Level 4	BOX30X2.5	BOX30X2.5	BOX30X2.5	BOX35X2.5	BOX40X2.5	BOX30X2.5	BOX30X2.5	BOX35X2.5	BOX30X2.5
Level 3	BOX30X2.5	BOX45X2.5	BOX30X2.5	BOX35X2.5	BOX45X2.5	BOX30X2.5	BOX30X2.5	BOX35X2.5	BOX30X2.5
Level 2	BOX40X2.5	BOX45X2.5	BOX35X2.5	BOX40X2.5	BOX45X2.5	BOX35X2.5	BOX40X2.5	BOX40X2.5	BOX35X2.5
Level 1	BOX40X2.5	BOX45X2.5	BOX35X2.5	BOX40X2.5	BOX45X2.5	BOX35X2.5	BOX40X2.5	BOX40X2.5	BOX35X2.5

4. MODELING OF THE STRUCTURES

OpenSees [9] was used for analyzing the 3D and 2D structure model losing its columns. In 2D model dynamic analyses were performed for the exterior frame of the building as shown in Fig 1. (with dotted lines) and Fig. 3. In 3D model the total structure was considered. In order to model the steel behavior, Steel02 from the material library of OpenSees with the strain hardening modulus of 2% E was used. For beams and columns nonlinear displacement-based beam-column elements (nonlinearBeamColumn) were used which employ distributed plasticity approach. An initial mid span imperfection of L/500 was applied to all columns. It was assumed that the beams are connected to the columns by using rigid connections and moment-rotation behavior of the connection follows the beam behavior. No nonlinear spring was used in order to model the nonlinear behavior of the connection. To verify OpenSees models with designed structures, the main period time in both 2D and 3D models are checked, for example the main period time in ETABS and OpenSees was 2.1s in both 2D and 3D SMF structures and 1.98s for both 2D and 3D IMF structures. Also displacements and member forces and analytical calculations at all scenarios in 2D and 3D models are the same before removing the columns.

Based on the main objective of this study and considering computational efficiency and structural representation, the analyses were performed on the 2D frame and 3D structure illustrated in Fig. 3. Obviously, out of plane elements on redistribution of loads is not considered in 2D frame and both 2D and 3D models can't consider the effect of floor slab. However, since the main objective is to study the differences between 3D and 2D analyze and comparing these two analyses together. A 10story structure was modeled with both two and three dimensional and these two model are verified together and have same period , members, loads, analyze method, scenarios and etc. the only different is in the frames, that in 2D model one of exterior frames that showed in Fig. 1 is modeled and in 3D model the total structure is modeled. In order to evaluate progressive collapse potential and capacity of structures, different scenarios were performed that exterior and interior columns of first, third and sixth story were removed. Figure 2 shows the critical members (specified by red dotted lines) of each scenario that are most affected from the removed column. These members have most role in redistributing the loads of removed column in APM method. Totally, for the investigated steel SMF and IMF, twelve removal scenarios were analyzed for both 2D and 3D models.

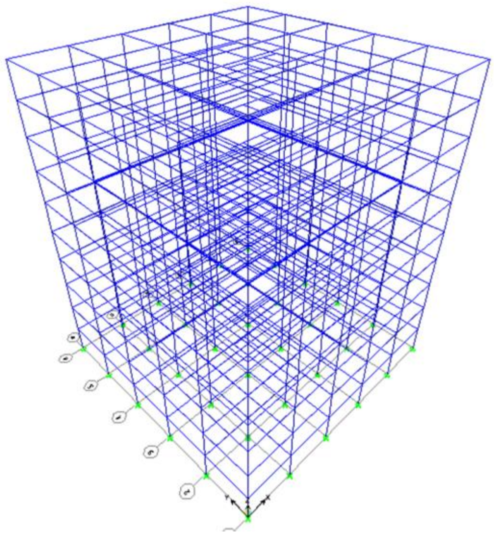

Figure 3. 3D view of the case study structure.

5. ANALYSIS METHOD, RESULTS AND DISCUSSION

5.1. Dynamic analysis

In dynamic analysis, the gravity loads of structure were linearly increased for 5 seconds until they reach their final values, and after that, they were kept unchanged for 2 seconds until the structure reached stable situation. At t=7 sec gravity loads were fully applied and a column that predefined in scenario was remove suddenly, and afterwards the subsequent response of the structure was investigated. During the dynamic analysis sudden removal of columns could be performed through which a new stiffness matrix is formed and the analysis continues. The simulations were analyzed with 5% mass and stiffness proportional damping. For the analysis, the time step Δt=0.01 sec was considered that can be accurate enough to show the abrupt increases in the loads and displacements. The response of the structure is evaluated in order to compare 3D model with 2D, different scenarios and determine whether structure fails progressively or not. We study elements that are near to the removed column and have critical situation after removing the column. After that to evaluate progressive collapse potential of structures maximum forces that results from removed column in different scenarios were extracted. We control Maximum forces of elements with ASCE41 acceptance criteria that was noted past. Figs. 4 and 5 shows the structural responses of some cases in both 3D and 2D models including axial loads of the columns for SMF structure, respectively.

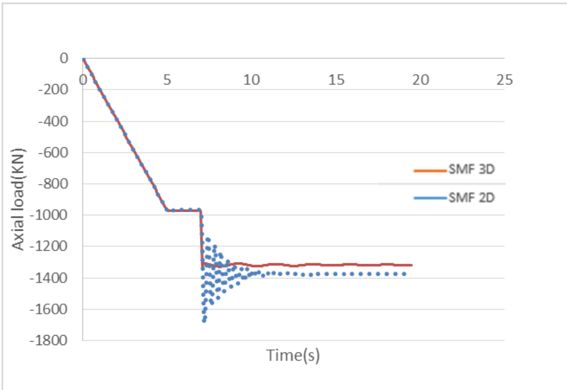

Figure 4. Comparing 2D and 3D time history response of axial force of col B, scenario 1.

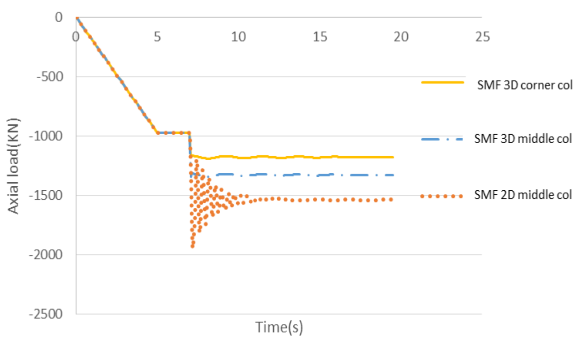

Figure 5. Comparing axial force of col B in exterior and middle removal scenarios, floor1.

Fig. 5 shows time history response of critical columns (next to the removing column) for both corner and middle column removing scenarios. As shown in Fig. 6 shows displacement in upper point of the removing column to see different of responses in 3D and 2D models. After evaluate these pictures we found that structure's displacements and also structure's oscillations in 3D models are less than those in 2D models, the reason is distributing the dynamic loads through more number of members in two direction inside and outside plane. This phenomenon cause restraint the point in upper of the removing column in two directions and prevent structure from more oscillations and displacements. As is seen in Fig. 5 the amounts of maximum initial forces in beams and columns in different scenarios of removing corner column are less than those in middle column removing scenarios.

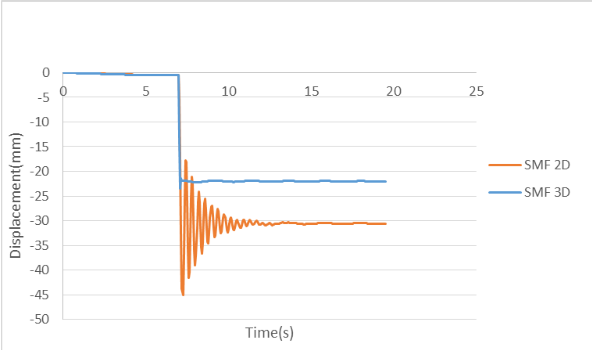

Figure 6. Comparing 2D and 3D time history displacement in upper point of the removing column.

All DCR values coming from P-M interaction equations in all scenarios didn't exceed unity so the probability of progressive collapse in designed structures is very low. Performance of structure elements are compared to ASCE-41 allowed plastic rotation deformation acceptance criteria. Amount of deformation of beams obtained from dividing displacement in upper point of removing column to the beam's length. After that these amounts has been compared to allowed plastic rotation. Allowed plastic rotation is calculated as a ratio of θy and according to table 9.6 from ASCE-41 guideline, performance condition of structure come out.
Table 5 and 6 shows performance levels of beams next to the removing column that are critical beams in each scenario for both 2D and 3D models. m-factor in these tables shows ratio of rotation of beam to allowed plastic rotation of beam. Considering m-factors in these tables shows that in SMF structure, beams in both 3D and 2D have most critical condition in second scenario and after that sequentially third and first scenarios are critical. Beams in 2D models are more critical than those in 3D models, performance levels in 2D models reaches LS but in 3D models is IO in all scenarios, except scenario 3 in IMF structure. In IMF structure, beams in both 3D and 2D have most critical condition in third scenario and after that sequentially second and first scenarios are critical. Also in this structure Beams in 2D models are more critical than those in 3D models and performance level in 3D model only in third scenario reaches LS and in second and first scenario don't exceed IO level, but in 2D model performance level of beams are LS in all scenarios. As table 5 and 6 shows SMF structure's beams have better performance against progressive collapse in compare to IMF structure. Briefly all beams elements exist in frames are resistant against progressive collapse and deformations in beams can't cause collapse in these structures.

Table 5. Performance levels of critical beams in SMF structure.

SMF Scenario 1 3D				SMF Scenario 2 3D				SMF Scenario 3 3D			
	θ_y	m	performance		θ_y	m	performance		θ_y	m	performance
IPE450	0.0052847	-0.887	IO	`	0.0052847	-0.972065	IO	IPE360	0.0071562	-0.906891	IO
IPE 360	0.0065613	-0.714416	IO	IPE 270	0.0078734	-0.652452	IO	IPE 270	0.0078734	-0.824277	IO
SMF Scenario 1 2D				**SMF Scenario 2 2D**				**SMF Scenario 3 2D**			
	θ_y	m	performance		θ_y	m	performance		θ_y	m	performance
IPE450	0.0052847	-1.705575	LS	IPE400	0.0052847	-2.40672	LS	IPE360	0.0071562	-2.208849	LS
IPE 360	0.0065613	-1.373721	LS	IPE 270	0.0078734	-1.615395	LS	IPE 270	0.0078734	-2.007633	LS

Table 6. Performance levels of critical beams in IMF structure.

IMF Scenario 1 3D				IMF Scenario 2 3D				IMF Scenario 3 3D			
	θ_y	m	performance		θ_y	m	performance		θ_y	m	performance
IPE450	0.0052847	-0.86044	IO	`	0.0059197	-0.877797	IO	IPE360	0.0065613	-1.100477	LS
IPE 360	0.0065613	-0.693024	IO	IPE 270	0.0087573	-0.593372	IO	IPE 270	0.0087573	-0.824519	IO
IMF Scenario 1 2D				**IMF Scenario 2 2D**				**IMF Scenario 3 2D**			
	θ_y	m	performance		θ_y	m	performance		θ_y	m	performance
IPE450	0.0052847	-1.677058	LS	IPE400	0.0059197	-2.245038	LS	IPE360	0.0065613	-2.997753	LS
IPE 360	0.0065613	-1.350753	LS	IPE 270	0.0087573	-1.517598	LS	IPE 270	0.0087573	-2.24603	LS

Comparing maximum axial and moment in columns next to the removed column with acceptance criteria in ASCE41 shows that removing column in all scenarios can't cause progressive collapse in this study's structures. To compare vulnerability of structures in different scenarios and detect most critical scenario in each structure, demand to capacity Figs. that obtained from the P-M interaction equations are used. Demand to capacity ratio is shown with DCR values in the Figs. 7 to 15. As DCR values increase elements tolerate more critical condition and maximum DCR value shows the most critical scenario.

5.1.1. Comparing 2D and 3D modeling results in SMF structure

From Figs. 7 to 9 can conclude that DCR values of members in 3D models are less than those in 2D models in all scenarios. After evaluating demand to capacity Figures in SMF structure we obtained that first scenario is the most critical scenario. Demand to capacity ratio for this scenario in 3D model is 0.302 that is related to the column that is parallel to removed column in adjacent frame (frame 2). Also In 2D model we have 0.302 DCR value but in adjacent column in the same frame (frame 1). To evaluate how level of removing column effect on demand to capacity ratio, DCR values compare together for both 3D and 2D models in different scenarios.

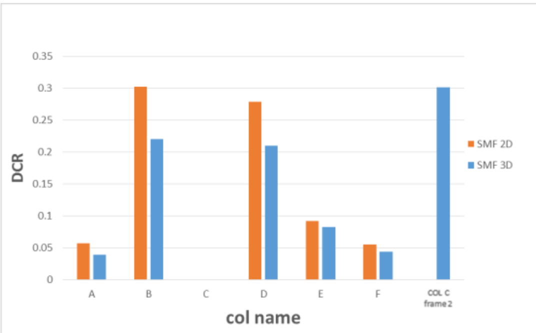

Figure 7. Comparing DCR values of columns next to removing column in 2D and 3D models, scenario 1.

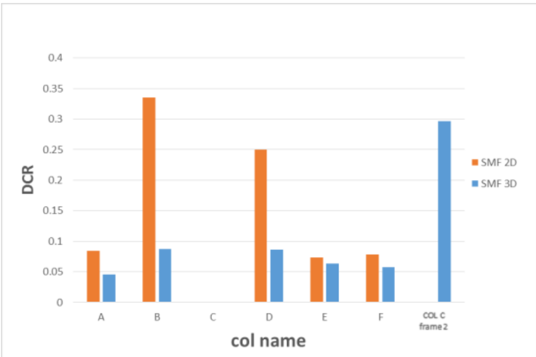

Figure 8. Comparing DCR values of columns next to removing column in 2D and 3D models, scenario 2.

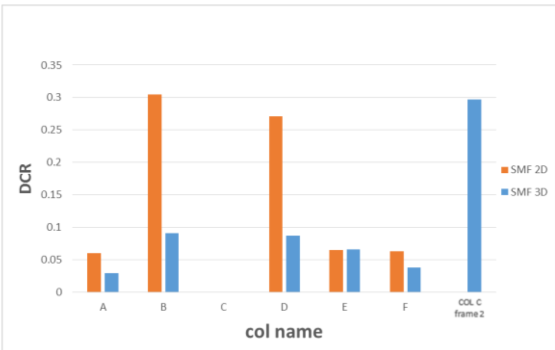

Figure 9. Comparing DCR values of columns next to removing column in 2D and 3D models, scenario 3.

Fig. 10 illustrate DCR values for different scenarios, comparing these values shows that in middle column (column C) removing in 3D models respectively scenarios 1,3 and 2 are critical. Maximum DCR amount of these coefficients in 3D models are respectively 0.302, 0.297 and 0.2966. But in 2D models respectively scenarios 2, 3 and 1 are critical and amount of DCR are respectively 0.335, 0.305 and 0.302. This means that SMF structure in 3D model has most critical condition in removing first floor column and removing third floor column is more critical than removing sixth floor column. But in 2D models the most critical condition is in removing third floor column and removing second floor column with a little different is more critical than removing first floor column. To detect the most critical column to remove in each floor, element's internal forces will compare together in corner and middle removing column scenarios. From Fig. 5 scenarios that corner column (col A) are removed amounts of column's forces is less than those in middle removed column (col C). In reviews was shown that columns are more critical than beams and columns in middle removed scenarios are more critical than columns in corner removed scenarios. So corner column removing scenarios are not critical and we neglect calculating DCR values in this scenarios.

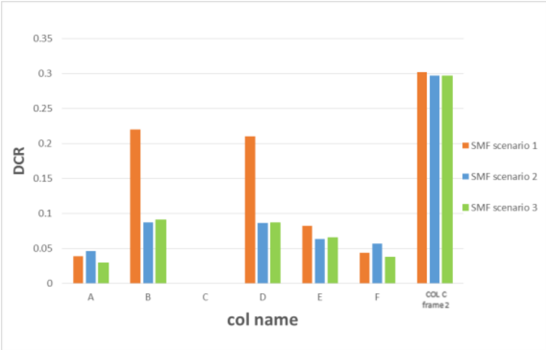

Figure 10. Comparing DCR values of columns in 3D models in different scenarios of SMF.

5.1.2. Comparing 2D and 3D modeling results in IMF structure

We also evaluated demand to capacity Figures in IMF structure and concluded that DCR values of members in 3D models are less than those in 2D models in all scenarios like SMF structure. Also we obtained in 3D models that first scenario is the most critical scenario as same as SMf structure. But in 2D models second scenario is the most critical scenario with a little different to first scenario. In 3D models DCR values are respectively 0.316 for first scenario, 0.237 and 0.1218 for second and third scenarios. But in 2D models first scenario is more critical than the third one and the DCR values are 0.315 and 0.195 respectively. Finally in 3D models first, second and third scenarios are critical respectively. In 2D models second, first and third scenarios are critical respectively. Figure 11 illustrates DCR values of columns in 3D modeling IMF structure at different removal scenarios.

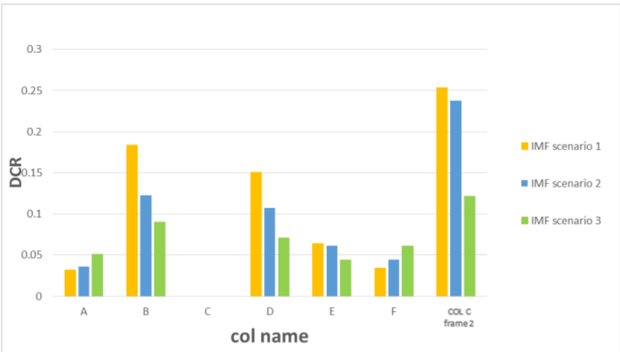

Figure 11. Comparing DCR values of columns in 3D models in different scenarios of IMF.

5.1.3. Comparing SMF and IMF structure together

In this part we detect resistance level of structures with different ductility with comparing their DCR values together in both 2D and 3D models with different removing scenarios. Fig. 12 shows that in 3D model first scenario of removing middle column in SMF structure has the most critical condition and after that third scenario of SMF, second scenario of SMF, first scenario of IMF, second scenario of IMF and third scenario of IMF are critical respectively. In 2D model according to Fig. 13 second scenario of SMF structure is the most critical scenario and after that second scenario of IMF, first scenario of IMF, third scenario of SMF, first scenario of SMF and third scenario of IMF are critical respectively.

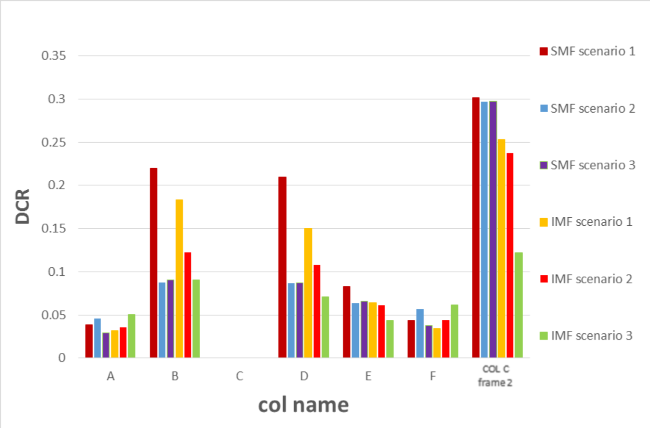

Figure 12. Comparing DCR values of SMF and IMF structure together in different scenarios in 3D models.

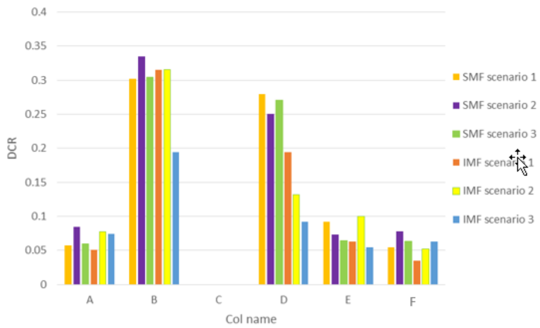

Figure 13. Comparing DCR values of SMF and IMF structure together in different scenarios in 2D models.

After evaluating above results we detect that in 3D model removing first floor column cause the most critical condition in both SMF and IMF structures. Also we shown that in all 3 scenarios SMF structure is more critical than IMF. Critical member in all 3 scenarios is the column next to the removing column in adjacent frame (frame 2) that this column can't be modeled in 2D models. In 2D model removing third floor middle column in SMF structure cause the most critical condition, also first floor removing column in IMF is more critical than SMF and removing sixth floor column in SMF is more critical than IMF. Briefly in 3D model in first scenario IMF is more resistant than SMF against progressive collapse, although in second and third scenarios SMF shows better resistance than IMF.
In 2D model SMF shows better performance in compare with IMF at first scenario, but in second and third scenarios IMF is more resistant.

6. CONCLUSIONS

In this study, three and two dimensional progressive collapse analysis of steel moment resisting frames with different ductility was investigated. To evaluate progressive collapse analysis in steel moment frames, special moment frame and immediate moment frame are modeled, analyzed and compared

together in both 2D and 3D models. Results of paper are descripted below:
- All structures that are modeled in this study are resistant against progressive collapse in all scenarios.
- Different between modeling 2D and 3D steel moment frames structures are impressive and 3D modeling is needed to show real behavior of structures against progressive collapse.
- Demand to capacity ratios of same members in 3D modeling is less than 2D models in all scenarios.
- Critical member that has most DCR value in all scenarios is adjacent column to removing column that is in adjacent frame (frame 2) and because of being in out of plane frame can't be modeled in 2D modeling.
- Amounts of force and force's oscillations of members after removing column in 3D modeling in all scenarios are less than those in 2D model.
- Amounts of displacement and displacement's oscillations of the upper point of removing column after removing column in 3D modeling in all scenarios are less than those in 2D model.
- Maximum DCR values in steel moment frame structures in 3D models are 0.302, 0.297 and 0.2966 respectively for SMF structures. So SMF structures are more vulnerable than IMF structure against progressive collapse in this study.
- In IMF structures with increasing height of removing column, DCR values decrease. In SMF structure with increasing height , DCR values in scenario 2 decrease in compare with scenario 1 and in the following scenario 3 increase in compare with scenario 2 but the amounts is still less than scenario 1.
-According to results we can say that in 3D models, removing middle column in first floor and for 2D models, removing middle column in third floor are the most critical scenarios.
- In structures that modeled in this study removing middle column scenarios was more critical than removing corner column scenarios.
-Comparing these results shows that Although in 3D models DCR values of member decrease, but in this modeling we consider some members that are critical and didn't modeled in 2D models. These members can cause more critical condition than members in the exterior frame. So predict structure's behavior against progressive collapse in 2D models is so difficult and 2D models must be very complete to show real behavior of structures against removing column. Finally we conclude that 3D models have different results in compare to 2D models and the results are more reliable than 2D models.

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