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Investigating the Effect of Amount of Damage in Columns on Possible Occurrence of Collapsing in Flexural Frames under Earthquake

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Abstract: Considering the expansion of the field of study among the structural researchers regarding the structure behavior under different conditions, it would be a new research topic to assess structure behavior before earthquake, supposedly with preliminary deficiency or preliminary damage in elements. Man-made threats including gas cylinder explosion, intentional sabotage, or vehicle collision with the main elements of the building like columns, can set bases for huge destructions or total demolitions of the structures under natural earthquakes. In this study, after designing a 3D steel structure based on valid regulations, the mid-frame is cropped and modelled by ABAQUS software. With and without column deficiency, the frame is subjected to three records with maximum various acceleration to find the drift response of each story. The results show that the presence of preliminary deficiency in the columns can alter the response significantly. As well, the results indicate that the performance rate of the structure at the desired records vary from elastic and immediate occupancy to life safety performance level.

Keywords: Steel Structure, ABAQUS Software, Preliminary Deficiency, Immediate Occupancy, Life Safety

Introduction

During their useful lives, buildings are exposed to various threats. They could because of natural or unnatural origins. During the last decades, the engineering knowledge of analyzing and dealing with natural events such as wind and earthquake, the structural and nonstructural reaction of the buildings has expanded. As well, research about man-made and unnatural threats including terrorist activities, explosion, fire, vehicle or airplane collision and such, are the recent challenging topics for structure engineers. With such threats, breakdown of one structural element may lead to the destruction of a structural component and partly or wholly collapse of the building. This event is known as progressive collapse. In such case, after a local damage, the structure fails to reach a static balance, so, the damage may expand to other elements, considering different conditions and structural system type. The destruction of the famous twin towers of the World Trade Center in 2001 is an example of such progressive collapse. In this event, the collision of the planes with the towers destroyed some columns and exterior load capacity systems of the towers and the following explosives and gasoline explosions destroyed the central bearing system, removing the load capacity of the level. Afterward, the collapse of the upper levels on the lowers smashed the remaining structure and along with the heavy weight of the rubble, the damage expanded and destroyed the entire tower. Progressive collapse mainly happens by gravity load, but the lateral force of earthquakes can cause preliminary damages and reveal structural weak points. In the case of preliminary damages, it is possible to witness progressive destruction and total collapse of the structure. After Ronan Point (1968) and the later similar events like the collapse of New York Twin Towers (2001), various codes such as General Service Administration (GSA), Department of Defense (DOD), ASCE (2005) and ACI (2005) introduced suggestions to control these events ((USGSA, 2003), (DOD, 2010), (ASCE 7-05 (2005), (ACI 318R-05 (2005)).

Asgarian and HashemiRezvani (2010) investigated the progressive collapse of braced steel frames. In this research, critical columns and related bracings were omitted simultaneously and the structure ability to correct these deficiencies were studied. In order to investigate the generated forces in the frame components and relocation of the nods, they applied a nonlinear Time History Analysis (THA). The results indicate that elimination of the corner columns of a braced building makes more critical situation than the central columns. Also, a more critical situation in the elimination of the columns at the lower stories. Shahrozi and SaqaKhorramshahri (2011) investigated the bracing design with progressive collapse strategy as a result of column elimination. Considering defense strategy in this research, a new method of nonlinear static analysis and the effect of various bracing arrangement on expansion of progressive collapse has been investigated. HashemiRezvani and Asgarian (2010) reviewed the different results of static analysis and the linear and nonlinear dynamics of progressive collapse in steel structures.

Husseini *et al*. (2013) reviewed the modification to the alternative load path in progressive deterioration of the steel structures by using amplification factor to consider inertia effect, static loading is modified and the factor is discussed. The results show that amplification factor, operating to simulate the dynamic nature of this phenomenon, leads into more conservative results of the static analysis than dynamic analysis. In this study, a new approach is suggested to employ these factors while analyzing alternative load path. Deilami and Islami (2013) investigated the impact of the design basis earthquake amplification on the behavior of earthquake-resistant steel buildings in case of progressive collapse. The effect of structure design, based on the earthquake magnitude, on the possibility of progressive collapse is great significance. Thus, this article performed nonlinear static analysis of the 10-stories moment frames of special and normal types, designing for strong and moderate earthquakes. The results indicate that the structures with intermediate moment resisting frame and those designed for heavy loads show greater resistance to progressive deterioration. Laledani *et al*. (2013) investigated the behavior modification of simple steel frames with bracing during progressive collapse due to column elimination. In this research, a new method is introduced to deal with progressive collapse in braced simple steel frames and the corner column elimination is considered as design scenario. Porbozorg and SojodiTosarvandani (2013) studied the progressive collapse in steel buildings with Concentrically Braced Frame (CBF). The purpose of the research was to assess structure safety in civil projects. In this research, three buildings of 5, 10 and 15 steel stories were controlled under Iranian 2800 seismic standards (Iranian seismic code-2800), then their resistance against progressive collapse was investigated under Unified Facilities Criteria (UFC) applying Alternative Path Method (APM). The nonlinear dynamic analysis method was used in order to carry out this assessment. The results show that corner column elimination creates a more critical condition. Farshahi (2011) studied the bracing design as a result of progressive collapse due to the elimination of a single-column. Single-column elimination is a capacity design method of building frames to handle the deterioration and expansion under sudden explosion or hostile attacks. Rahmani *et al*. (2014) studied the effect of chain performance on the vulnerability reduction rate of steel moment frame structures facing progressive demolition. In this research, the structure performance was investigated after elimination of a column, using nonlinear static analysis, vertical envelope and nonlinear dynamic analysis on steel moment frames, designed by the National Building Regulations. The results indicate that as the corner column is removed, the structures shows highest potential for progressive deterioration, yet the least chain performance. Fallahi *et al*. (2018) did numerical test on reinforced concrete frame with infilled wall and investigate the effect of seismic loading on columns and walls. Roudsari *et al*. (2017) had studies on RC columns under axial loading with ABAQUS software. He evaluated different aspect of damage for RC columns during the different step of loading condition while column was with and without retrofitting. Nateghi and Parsaeifard (2013) conducted a study on the effect of preliminary damages on the collapse of a single-story building. According to that, in the case of earthquake the presence of preliminary damage may extend the damage to other elements or the whole structure. Regardless of the number of the stories, earthquake-made progressive deterioration may extend to the entire building. In this study, a building behavior is assessed under earthquake-made progressive collapse, applying the definition of preliminary damage of single-story building columns.

Model and Software Introduction

In this research, a 3D four-story three-span structure was designed in ETABS15.0 software in accordance with AISC-LRFD standards. Table 1 shows obtained profile of the beams and columns of the structure. The resistant system of this frame was considered as steel intermediate moment resisting frame. The soil type was 2 and located at a highly vulnerable area. Each story was 3.5 m high and each span 5 m wide. The total weight of the dead load and the partition load is taken as 600 kg/m^2 and the live load 200 kg/m^2.

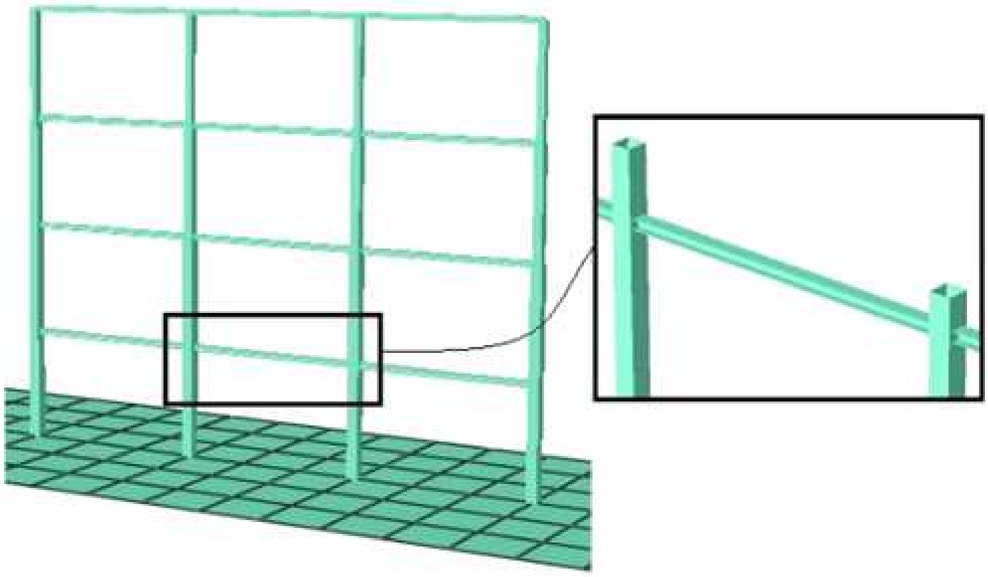

Fig. 1: Cropped mid-frame from 4-story structure

Table 1: Sections of beams and columns design

Story	Beam	Column
1	IPE400	BOX320×320×15
2	IPE360	BOX280×280×15
3	IPE330	BOX260×260×15
4	IPE300	BOX240240×15

The dead load weight of the last story is taken 550 kg/m^2 and the live load 150 kg/m^2. The researcher applied 2800.v4 standard (Iranian seismic code-2800) to calculate earthquake magnitude. In order to perform time history analysis, the mid-frame of the structure is extracted by ABAQUS software. In this case, the Dynamic Explicit analysis has used to consider the extreme loading condition as earthquake in which amplitude can be used to apply the load (Sayyed Soleimani and Sayyar Roudsari, 2015). Figure 1 shows the mentioned mid-frame of the structure. The beam- column elements are defined as solid with C3D8R family mesh and they are considered as a merge method since the beam-column interaction was not issue in this research. Also, meshing criteria has been used by Roudsari *et al*. (2018). The load is applied as lateral displacement-control method, too.

Studied Earthquakes

In order to perform nonlinear dynamic analysis of the models, 7 accelerograms of Kobe 1995 in Nishi Akashi station, Chichi 1999 in TCU045, Kocheli 1999 in Arcelik were applied. These accelerograms relate to type 2 soil. The mentioned earthquakes were scaled with highest accelerations of 0.2, 0.4, 0.6 and 0.8 g. In another word, 12 records with different maximum accelerations were developed.

Research Methodology

Considering the symmetry structure in this research, 8 scenarios (8 columns) exist. It is supposed in every scenario that one of the frame columns has lost 70% of its plastic anchor before the earthquake, due to multiple damages. The structure is exposed to twelve earthquakes and maximum drift condition of the story is compared to the intact condition. Generally, time history analysis is performed 8 times in each scenario and 96 times for all.

Analysis Results Presentation

The eight desired scenarios are assessed individually to present analysis results and collapse possibility is investigated.

First Scenario: Lateral Column of the First Story

Based on Fig. 4, the imposed earthquakes acceleration is shown as 0.2 and 0.8 g. 0.3C indicates 30% of column plastic anchor which is a column by 80% of plastic moment that assigned for designed section and 1C the intact column. Respectively, IO, LS and CP are performance rate of immediate occupancy, life safety and collapse prevention. According to journal 361, the equivalent drift of these levels in steel moment frames are 0.7, 2.5 and 5%, respectively. Figure 2 to 25 show the maximum drift results under the earthquake.

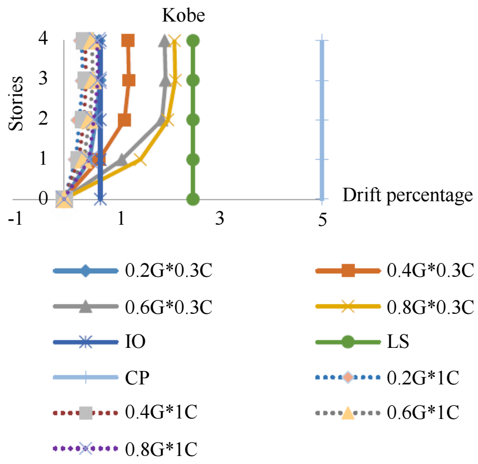

Fig. 2: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kobe earthquake in the 1st scenario

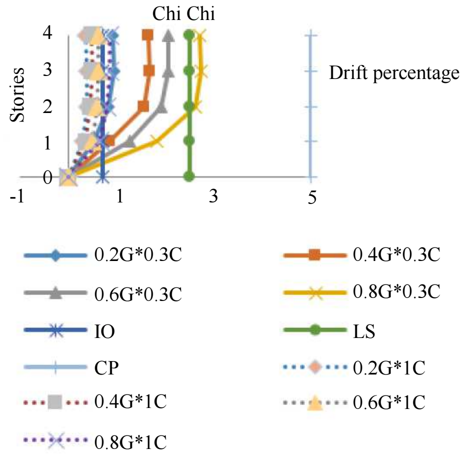

Fig. 3: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Chi-Chi earthquake in the 1st scenario

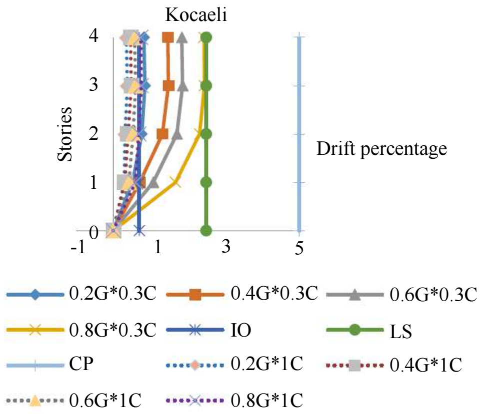

Fig. 4: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kocaeli earthquake in the 1st scenario

2nd Scenario: First Floor, Middle Column

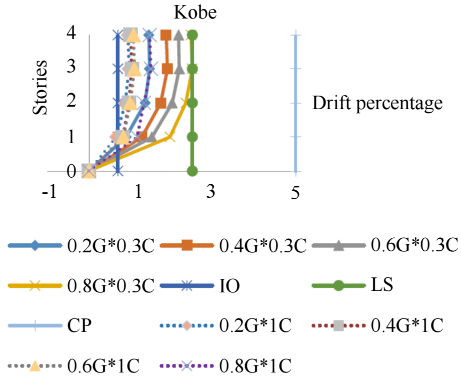

Fig. 5: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kobe earthquake in the 2nd scenario

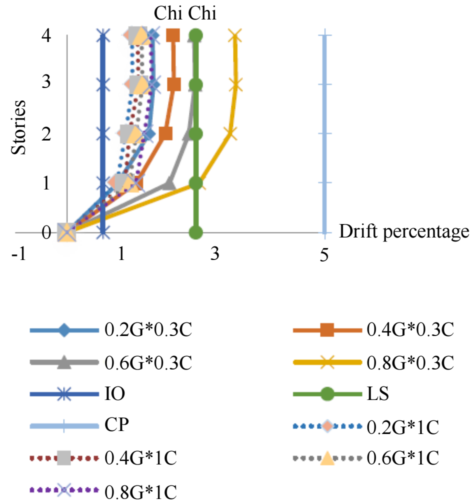

Fig. 6: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Chi Chi earthquake in the 2nd scenario

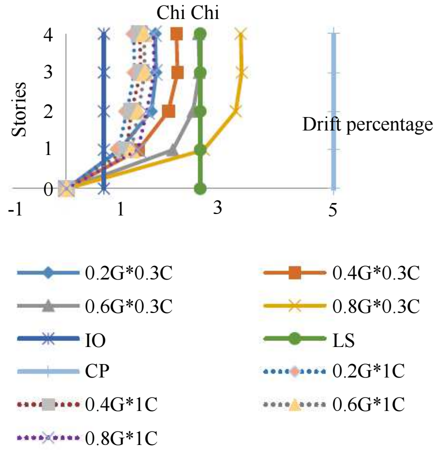

Fig. 7: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Chi Chi earthquake in the 2nd scenario

3rd Scenario: Second Story, Lateral Column

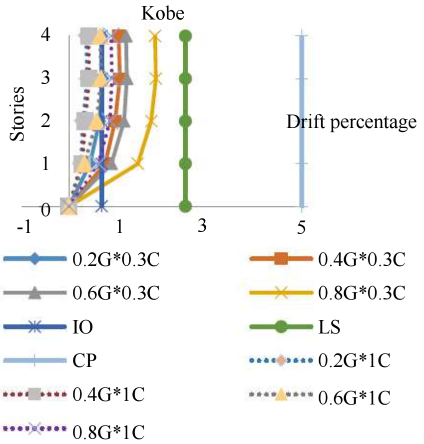

Fig. 8: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kobe earthquake in the 3rd scenario

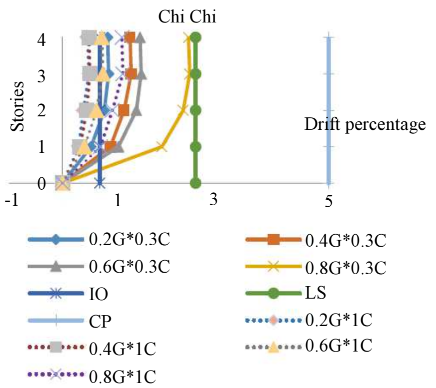

Fig. 9: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Chi Chi earthquake in the 3rd scenario

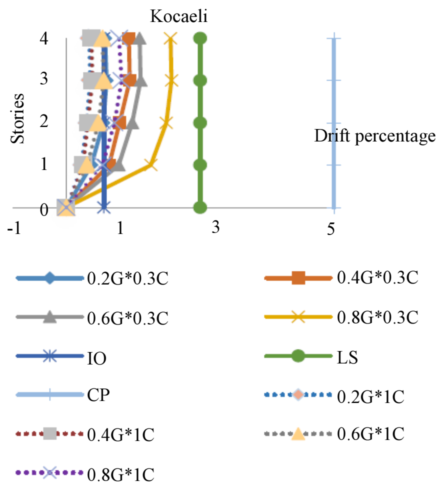

Fig. 10: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kocaeli earthquake in the 3rd scenario

4th Scenario: 2nd Story, Middle Column

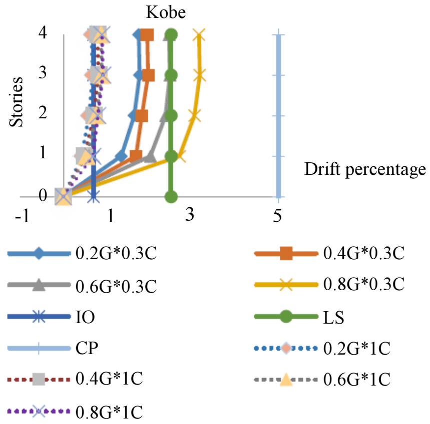

Fig. 11: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kobe earthquake in the 4th scenario

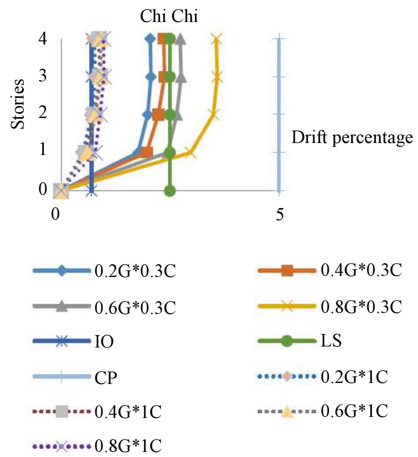

Fig. 12: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Chi Chi earthquake in the 4th scenario

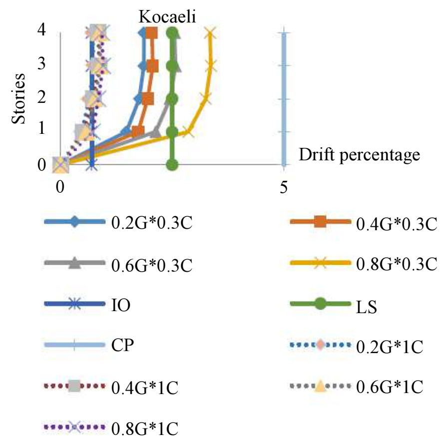

Fig. 13: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kocaeli earthquake in the 4th scenario

5th Scenario: Third Story, Corner Column

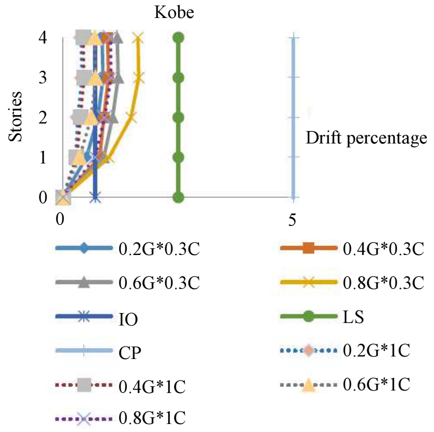

Fig. 14: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kobe earthquake in the 5th scenario

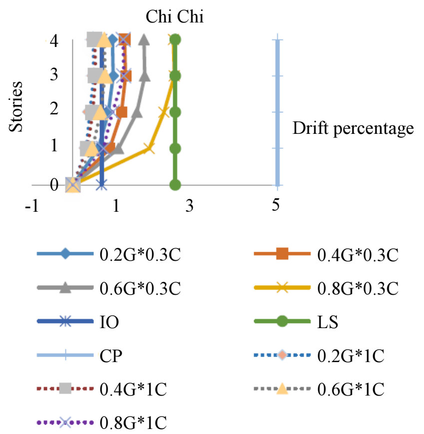

Fig. 15: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Chi Chi earthquake in the 5th scenario

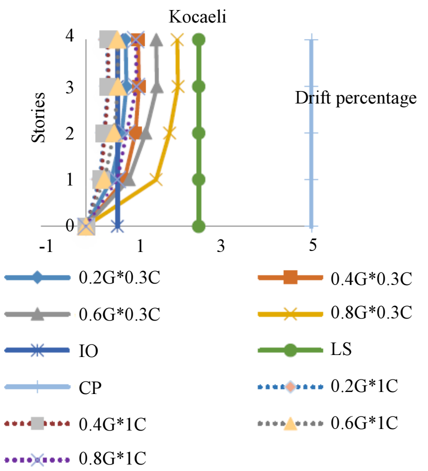

Fig. 16: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kocaeli earthquake in the 5th scenario

6th Scenario: 3rd Story, Middle Column

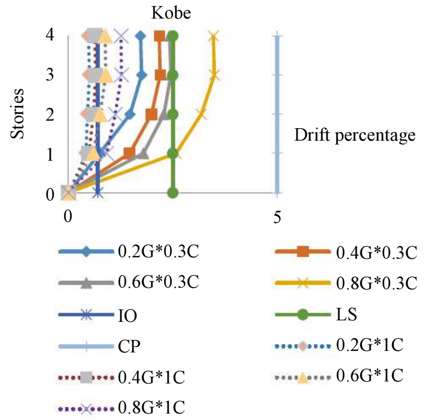

Fig. 17: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kobe earthquake in the 6th scenario

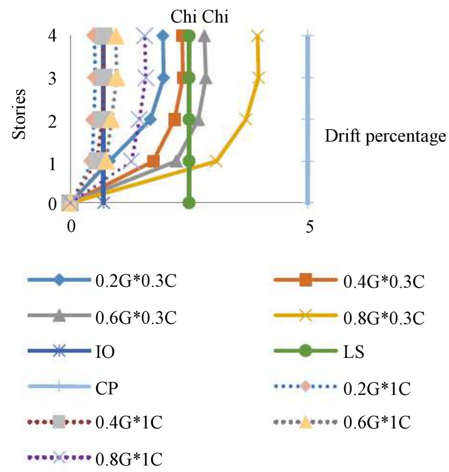

Fig. 18: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Chi Chi earthquake in the 6th scenario

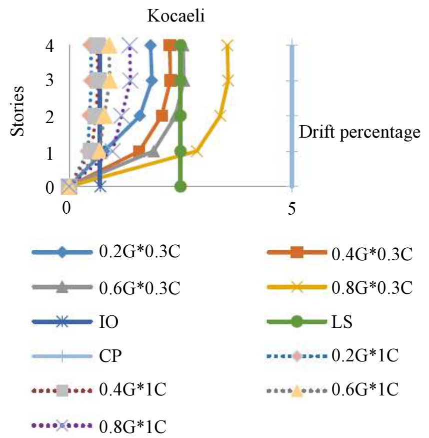

Fig. 19: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kocaeli earthquake in the 6th scenario

7th Scenario: 4th Story, Corner Column

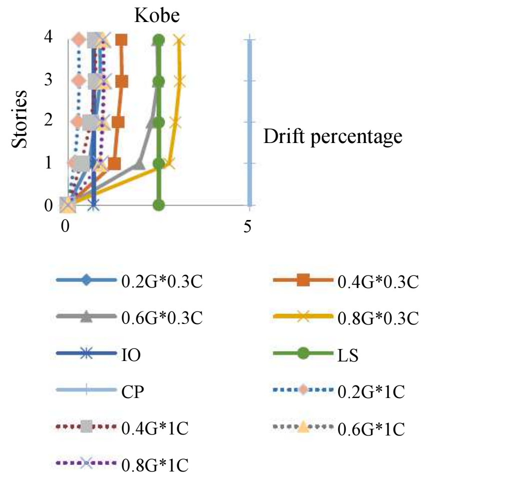

Fig. 20: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kobe earthquake in the 7th scenario

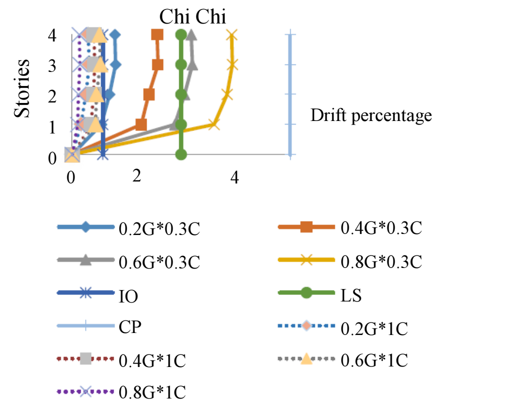

Fig. 21: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Chi Chi earthquake in the 7th scenario

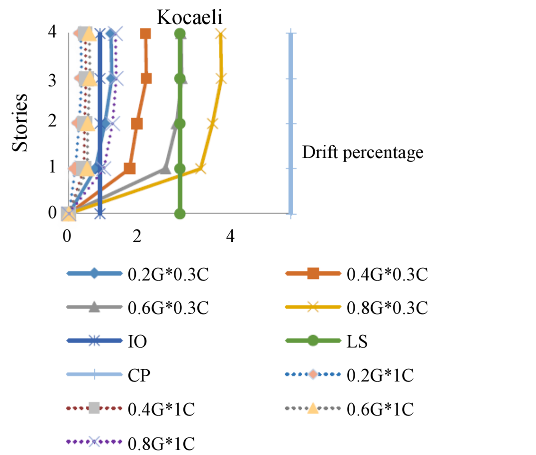

Fig. 22: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kocaeli earthquake in the 7th scenario

8th Scenario: 4th Story, Middle Column

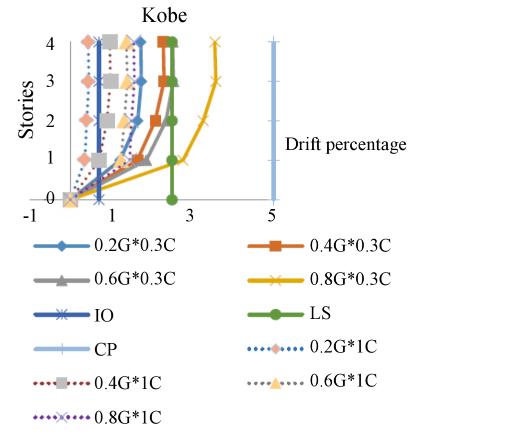

Fig. 23: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kobe earthquake in the 8th scenario

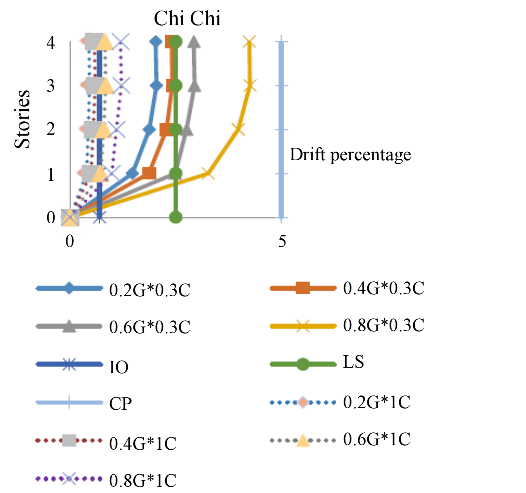

Fig. 24: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Chi Chi earthquake in the 8th scenario

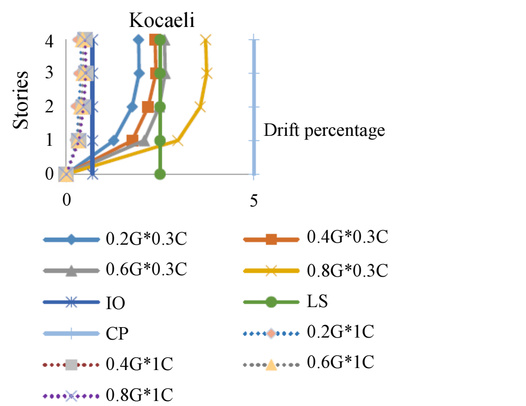

Fig. 25: Maximum drift percentage for story frames in two modes of with and without preliminary deficiency under Kocaeli earthquake in the 8th scenario

Reviewing the results, it is indicated that performance of the structure with intact columns is slightly higher than IO in the first scenario while it stands higher than LS in preliminary damage condition. In the second scenario, there is a greater maximum drift in Chi-Chi earthquake. In this case, despite the preliminary damage, performance level is beyond LS. In the third scenario, the second story stands higher than IO in intact mode, while it is slightly lower than LS in column damage. Scenarios 4 to 8 display almost the same condition. They illustrate higher performance level than LS under stronger earthquakes (0.8 maximum acceleration). In none of the cases CP performance level is seen. The performance level of intact structure is slightly more than IO, while it stands lower than it under weaker records.

Conclusion

In this study, after designing a three-dimensional structure with four stories according to the valid principles in ETABS 15.0 software, its intermediate frame is cropped and modelled by the finite element ABAQUS 6.14 software. The considered frame is placed in status of with and without the preliminary column damage under three records with the maximum accelerations of 0.2g, 0.4g, 0.6g and 0.8 g. The preliminary deficiency rate of plastic anchor decrease equivalent cross columns is 70%. Most relative replacement responses of the stories were for Chichi earthquake. The results showed that preliminary column damage can considerably change the structure responses. The results also show that preliminary damage of the intermediate columns, comparing with the side columns, can increase more the maximum drift response of the frame. The results also revealed that the structure performance rate under the considered records changes from elastic state and immediate occupancy to the performance level of life safety and despite presence of preliminary column damage, performance level does not lead to collapse in any of the structure analyses.

Author's Contributions

Reza Salehi: Performed modeling with FEM software and data analysis. Also, participated in writing the manuscript.

Abbas Akbarpour Nikghalb Rashti: Provided the research topic and guided the research development, experimental plan and data analysis. Also, participated in writing the manuscript.

Ethics

This article is an original research paper. There are no ethical issues that may arise after the publication of this manuscript.

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