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Strengthening of the panel zone in steel moment-resisting frames

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Abstract. Rehabilitation and retrofitting of structures designed in accordance to standard design codes is an essential practice in structural engineering and design. For steel structures, one of the challenges is to strengthen the panel zone as well as its analysis in moment-resisting frames. In this research, investigations were undertaken to analyze the influence of the panel zone in the response of structural frames through a computational approach using ETABS software. Moment-resisting frames of six stories were studied in supposition of real panel zone, different values of rigid zone factor, different thickness of double plates, and both double plates and rigid zone factor together. The frames were analyzed, designed and validated in accordance to Iranian steel building code. The results of drift values for six stories building models were plotted. After verifying and comparing the results, the findings showed that the rigidity lead to reduction in drifts of frames and also as a result, lower rigidity will be used for high rise building and higher rigidity will be used for low rise building. In frames with story drifts more than the permitted rate, where the frames are considered as the weaker panel zone area, the story drifts can be limited by strengthening the panel zone with double plates. It should be noted that higher thickness of double plates and higher rigidity of panel zone will result in enhancement of the non-linear deformation rates in beam elements. The resulting deformations of the panel zone due to this modification can have significant influence on the elastic and inelastic behavior of the frames.

Keywords: double plates; lateral drift; moment-resisting frames; panel zone; rigidity; rigid zone factor; steel structure

1. Introduction

In recent times, significant amount of research have been undertaken by researchers and various organizations in different parts of the world, in an attempt to better understand the effect of dynamic loads and actions on structures, and their contribution towards the behavior and response

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of structures (Abedini *et al.* 2019, Mehrmashhadi *et al.* 2019, Kim and Lee 2017, Mutalib *et al.* 2013, Abedini *et al.* 2017). Steel structures are widely used in different structural and infrastructural engineering applications as; for roof trusses, halls and warehouses, towers for power and telecommunication transmissions, pipes, bridges, foot bridges and high-rise buildings (Castro *et al.* 2005, Heidarpour and Bradford 2009). Maintenance, repair and strengthening of existing steel structures are important activities for civil and construction engineers (Chan and Lin 2007, Kazantzi *et al.* 2014), since the functionality of structures deteriorate due to loading, aging and environmental factors. Structural engineering experts, designers and constructors are concerned with analysis of existing steel structures, as well as the design and execution of repair and strengthening measures. Heavy damage and total collapse of structural steel construction due to major seismic activity in recent decades has initiated studies on strengthening techniques (Jin and El-Tawil 2005). One of causes for severe damage after an earthquake is the insufficiency in terms of lateral stiffness (Abedini *et al*. 2018). Considering this, it is essential to strengthen the structure to enhance the lateral stiffness and subsequently the behavior of structure under seismic loading (Kim and Engelhardt 2002).

The behavior of a moment-resisting frame essentially depends the properties, arrangement and behavior of the structural elements used in its formation, i.e. columns, beams, supports and connections (Tena-Colunga and Hernández-Ramírez 2017). In this research, welded flanges and webs connections were assessed, where their behavior is mainly controlled by the panel zone in a moment-resisting frame. The panel zone is characterized as the region within the column web contained within the extension of the beam flange lines into the column, as shown in Fig. 1 (Davila-Arbona 2007). It is one of the essential components of joints, where its stiffness and rigidity can contribute significantly towards the response and ductility of the frame (Lee *et al.* 2005, Mulas 2004). Specifically, the response of panel zone can have considerable influence on the behavior of ordinary moment frames. Moment frames subjected to lateral loads experience high shear forces within the panel zone.

Several experimental and analytical studies on the significance of the panel zone in the response of frames have been performed to determine the behavior of panel zone when subjected to different loading and construction conditions (Kosarieh *et al.* 2015). Steneker and Wiebe (2016) studied the influence of panel zones in the global behavior of moment-resisting frames under seismic load. Meanwhile, Loulelis *et al.* (2017) performed explicit analysis for different of strength reduction factors, including strength deterioration and their influence on panel zones' response, for the first significant modes of steel moment-resisting frames. In a study by Mosallam *et al.* (2017) which assessed the performance of two 1/6-scale, single-bay, three- and eight-story steel moment-resisting frame structures representing rigid and flexible framed structures, respectively, using fragility function method, it was deduced that the eight-story structure was more vulnerable when subjected to seismic loading conditions (Mosallam *et al.* 2017). Generally, the panel zone is subjected to shear stresses and its mode of failure is characterized by yielding under shear (Mirghaderi and Moradi 2006). Past experimental investigations established that shear failure mode is stable and ductile under cyclic loading, and these element have been considered in structural design guidelines towards the end of 1980's where panel zone can be considered as a dissipative element. However, severe damage was observed in the connections of steel moment-resisting framed structures after the 1994 Northridge earthquake. Several studies were conducted and it was established that weld failures were developed caused by excessive distortions in the panel zone region (Davila-Arbona 2007). Various methods and practices have been recommended in subsequently published guidelines and standards, but a reliable and widely accepted method has

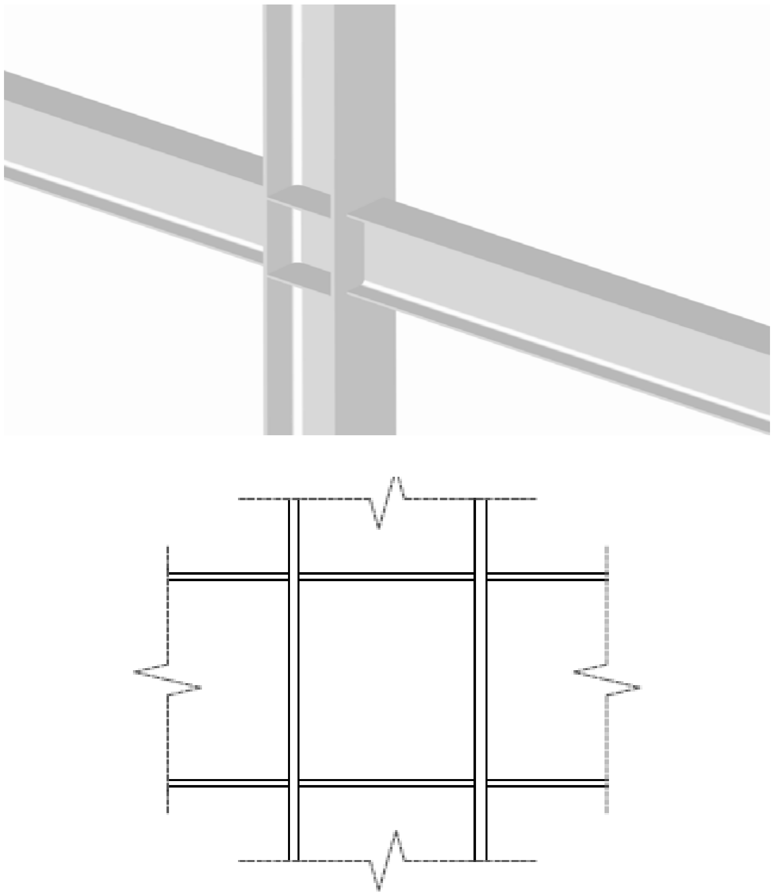

Fig. 1 Illustration of the panel zone, as illustrated by Davila-Arbona (2007)

not been fully recognized until now.

This study was undertaken to investigate the influence of five parameters (1. Different rigid zone factor; 2. Thickness of double plates; 3. Effects of different rigid zone factor and thickness of double plates together; 4. Effects of real panel zone; and; 5. Evaluation on ordinary moment-resisting frames) on moment-resisting frames by adopting a computational approach.

2. Modeling procedure

Six stories frame under 23 cases were analyzed and evaluated in 6 cases, which involved one case with panel zone to structures and the other five cases with different values of rigid zone factor from 0.1 to 1.0. The panel zone rigidity was achieved through double plates' thickness and assigned rigid zone factor. The computational analysis necessary for this investigation was performed using the ETABS software. This included linear static analysis for six stories steel moment-resisting frames. The modeling of six stories frames in ETABS software was undertaken in the first part of the analysis. The next step involved the analysis of frames, and finally, the

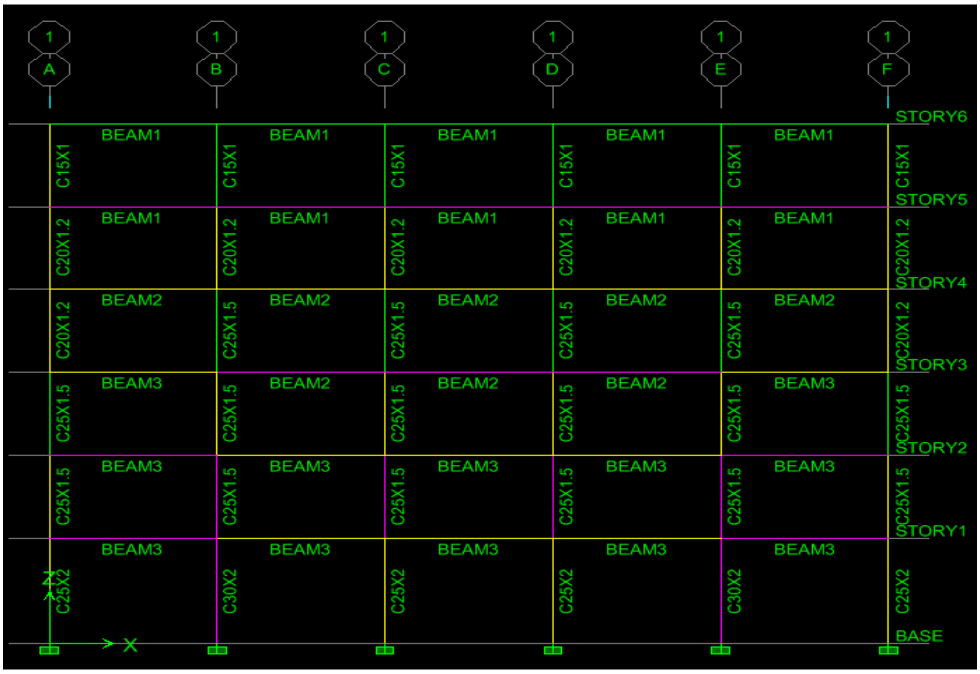

Fig. 2 Typical beams and columns in 6 stories frames

design of each frame separately. Steel frame's behavior were analyzed and compared without modifying the beams and columns profiles, by changing the panel zone. The properties of the structure are firstly described and explained in each part separately. Fig. 2 is shows the details of six stories frame.

The height of the first story in the moment-resisting frames was 3.8 m and typical stories height were 3.0 m. The spans of the beams were 5.0 m. For the cross-section of the structural elements, the sections for all the columns were Box, while for beams, they were Plate Girders. Linear analysis was conducted using ETABS Program Version 9.2. Load combinations that were applied in this study included dead load, live load and earthquake load in *x*-direction. In accordance to FEMA-273 (1997), two load combinations were considered in the analysis, which are

$$Q_G = 0.9Q_D + Q_E \tag{1}$$

$$Q_G = 1.1(Q_D + Q_L) + (Q_E) \tag{2}$$

Where
Q_D = Dead load
Q_L = Live load
Q_E = Earthquake load in x direction

The aim of this investigation was to consider five parameters and their effect on the behavior of moment-resisting frames. The five parameters were

1. Different rigid zone factor (R.Z.F.)

2. Thickness of double plates (D.P.)
3. Effects of different rigid zone factor and thickness of double plates together (R.Z.F. and D.P.)
4. Effects of real panel zone (P.Z.)
5. Evaluation on ordinary moment-resisting frames (O.MRF.)

Rigid zone factor values available within the ETABS program are 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0. In this study, three values were assigned, namely 0.1, 0.5 and 1.0. The thickness of double plates that were adopted were 0.8, 1.2 and 2.0 cm.

3. Verification of numerical model

In the initial stage, the steel moment-resisting frame was modeled. The results have been compared with the provisions of Standard 2800, the Iranian Code of Practice for Seismic Resistant Design of Buildings – 2007 (BHRC 2007). The actual relative displacement, at each story level is the displacement that can be determined if the actual non-linear response of the structure is considered in the analysis. This behavior is noticeable only for the design earthquake level. Based on the recommendation in code No. 2-5-3, the relative displacement can be computed using Equation (3), if a linear analysis is performed (BHRC 2007)

$$\Delta_M = 0.7R.\Delta w \tag{3}$$

Where
Δ_M = The actual design story drift
R = Building behavior factor
Δw = The design story drift

R is obtained from code No. 2-3-8-9, Table 6 of Iranian Code of Practice for Seismic Resistant Design of Buildings – 2007 (BHRC 2007), which R is 7 for ordinary moment resistance frames. According to code No.2-5-4 of Iranian Code of Practice for Seismic Resistant Design of Buildings – 2007 (BHRC 2007), Δ_M equation will eventually lead to the following equation

$$\Delta_M \leq 0.02\ H \tag{4}$$

Where
H = Total height of the story
H = 18.8
R = 7
Δw = 0.00362
Δ_M = 0.7 * 7 * 0.00362 = 0.0177
$\Delta_M \leq$ 0.02 * 18.8 = 0.376 OK

Consequently, it has been determined that the models used in this analysis were accurate.

4. Results and discussion

Moment-resisting frames constructed of steel structures are considered ductile. Hence, they are flexible structures and are able to fulfil essential requirements for satisfactory seismic design. Since the ductility of beams and panel zone control the non-linear deformation in such frames, the

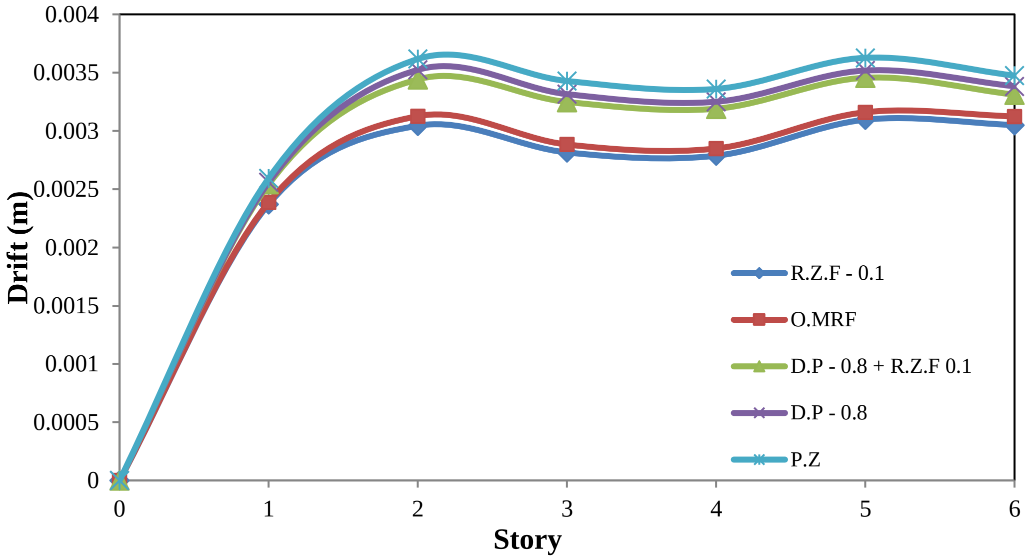

Fig. 3 Drift results of 6 story frame (R.Z.F. = 0.1, D.P. = 0.8)

seismic design should rely on these elements (AISC 2005). In this research, investigation was carried out to analyze the influence of the panel zone in the response of structural frames. This is achieved through the analysis of buildings in different state, which is representative of the behavior of a moment-resisting frame (Castro *et al.* 2005). The results of drift for six stories moment-resisting frames are plotted in Figs. 3 to 17 for different parameters. The parameters which were evaluated include different rigid zone factors, different thickness of double plates, effects of different rigid zone factors and different thickness of double plates' together, ordinary moment-resisting frame and real panel zone. As mentioned, the values for different rigid zone factors analyzed in this study were 0.1, 0.3, 0.5, 0.7 and 1.0 for rigid zone factors, and the findings were compared to each other. On the other hand, different thicknesses of double plates analyzed in this study were 0.8, 1.2 and 2.0 cm, and the findings for each thickness are shown in Figs. 3 to 17.

The relative deflection of stories is formed by total deformations due to beam bending, panel zone shear deformation and column moment deformation. The findings from this study have shown that the consideration of the panel zone can enhance the seismic performance of moment-resisting frames. Generally, the drift of structures will increase with the increase in number of stories. In this study, rigidity has decreased the drift in the six story frames. Based on the findings presented in Figs. 3 to 17, it can be observed that rigidity lead to reduction of the frames' drifts; and also, as a result, lower rigidity (0.1, 0.3) will be used for high rise buildings, while higher rigidity (0.7, 1.0) will be used for low rise buildings (under 5 stories).

Meanwhile, the possibility of fracture in connections on the moment-resisting frames can be increased when deformation of its panel zone becomes high that causes to reduce the ductility capacity of connection (El-Tawil *et al.* 1998). According to FEMA-335D (2000), the design of the panel zone should consider the balance between the flexural yield strength of the beam and the shear strength of the panel zone. This criterion includes the thickness of the double plate. During seismic loading actions, shear forces, torsional forces and bending moments that are applied from

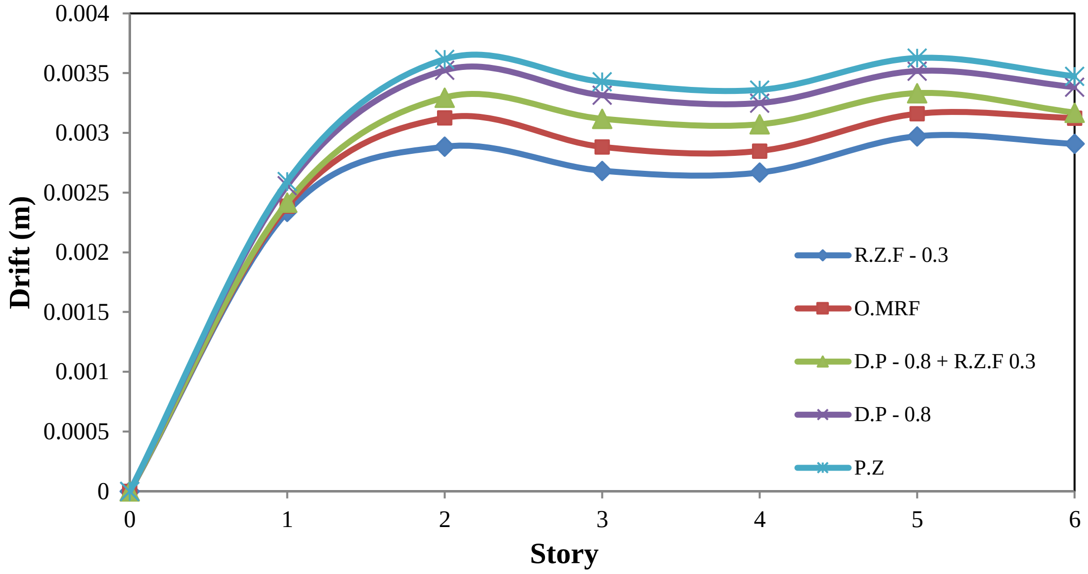

Fig. 4 Drift results of 6 story frame (R.Z.F. = 0.3, D.P. = 0.8)

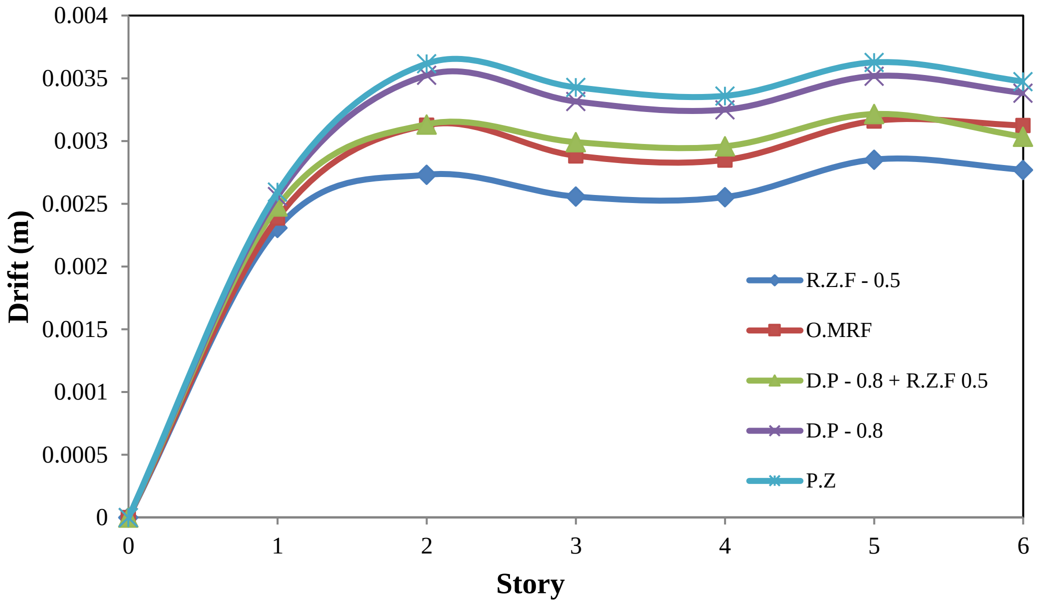

Fig. 5 Drift results of 6 story frame (R.Z.F. = 0.5, D.P. = 0.8)

beams to columns are very important. Therefore, double plates should be used for proper transfer of tension and compression forces. This transfer of forces results in a more stable structure and reduces the problems for column web within the panel zone.

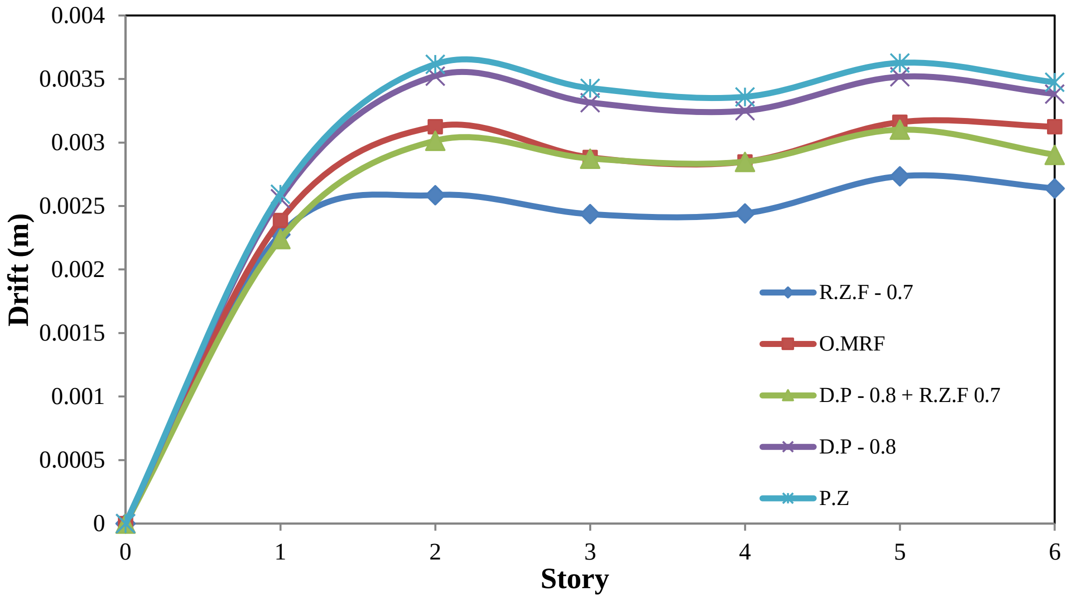

Fig. 6 Drift results of 6 story frame (R.Z.F. = 0.7, D.P. = 0.8)

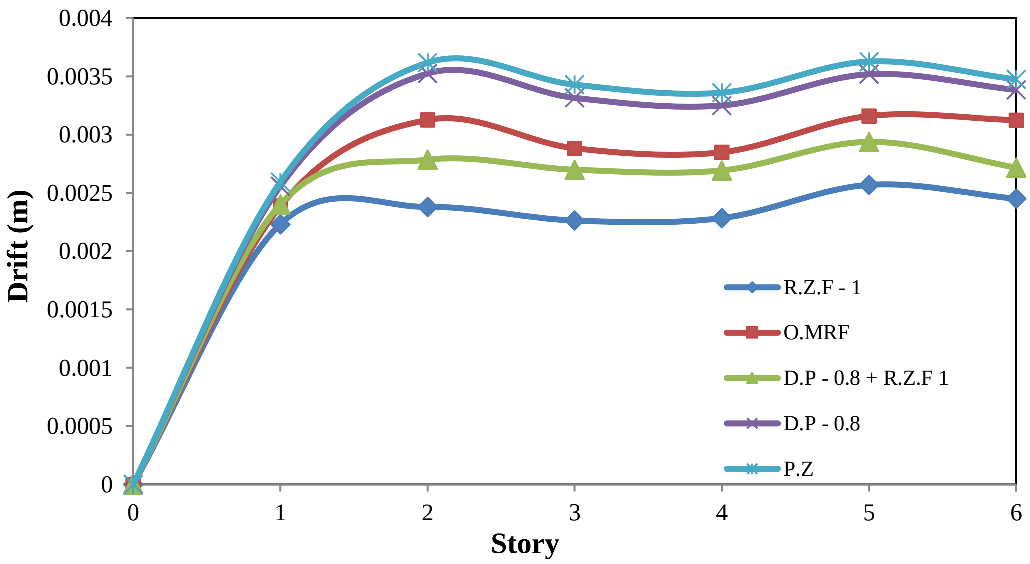

Fig. 7 Drift results of 6 story frame (R.Z.F. = 1.0, D.P. = 0.8)

In the present study, double plates with varying thickness were applied in the panel zone, and the response and performance level of the frames were studied. It is recognized that increased beam deformation can be generated with reducing the panel zone's deformations and beams located in extra ultimate performance level than the panel zone's and column's performance level.

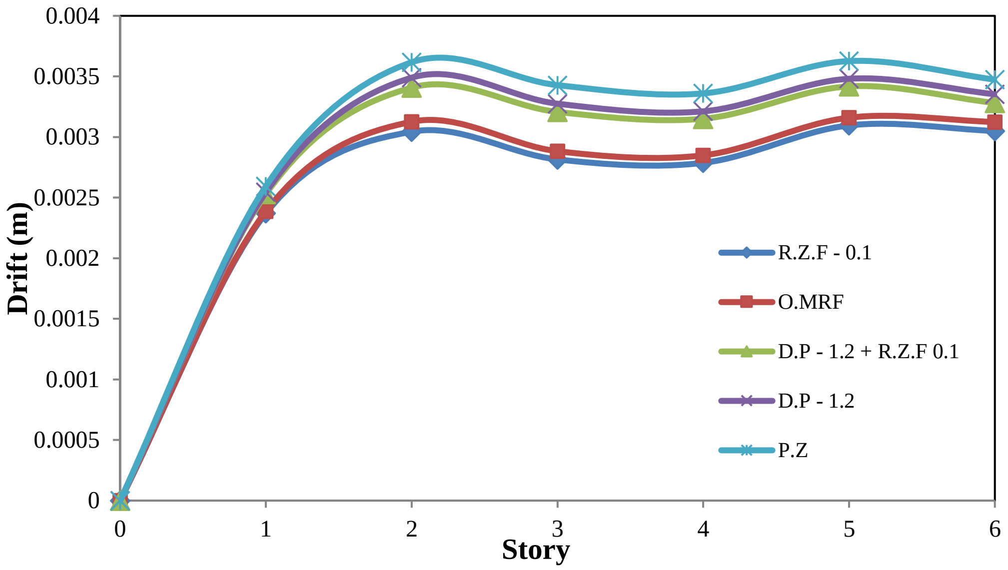

Fig. 8 Drift results of 6 story frame (R.Z.F. = 0.1, D.P. = 1.2)

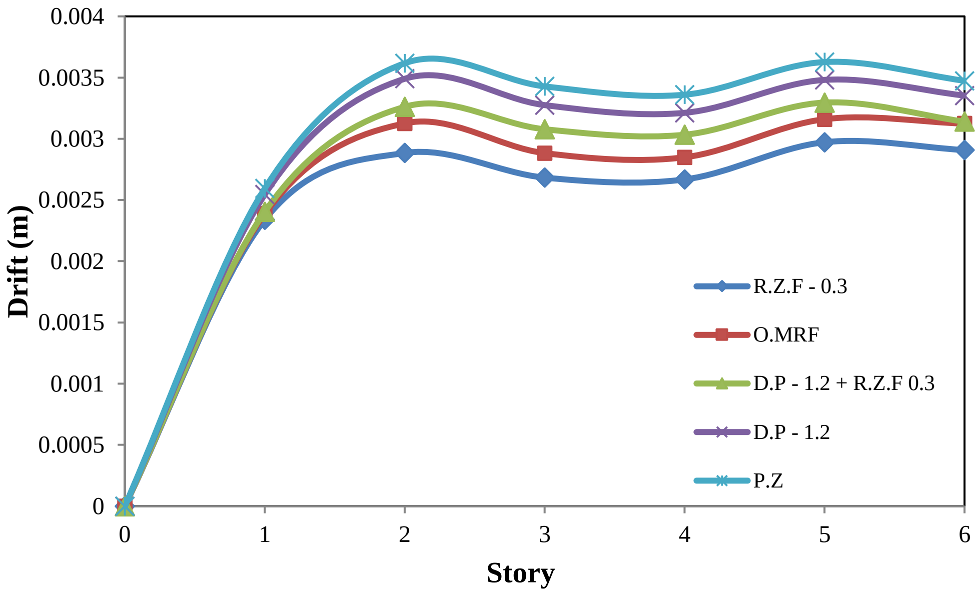

Fig. 9 Drift results of 6 story frame (R.Z.F. = 0.3, D.P. = 1.2)

However, the use of double plates in panel zone causes an increase to the drift story to be higher than the drifts of ordinary moment-resisting frame. In this study, to modify this limitation, rigidity was increased with double plates, which improved the condition and drifts were reduced. Results represent that double plates play an important role in connection behavior, and so in this details, plastic hinges form in beams as, it is expected, and panel zone performs its balanced behavior and, replacing of column web panel zone plates with thicker plates has been recommended as the key to supply the required stiffness and strength of panel zone (Mirghaderi and Moradi, 2006).

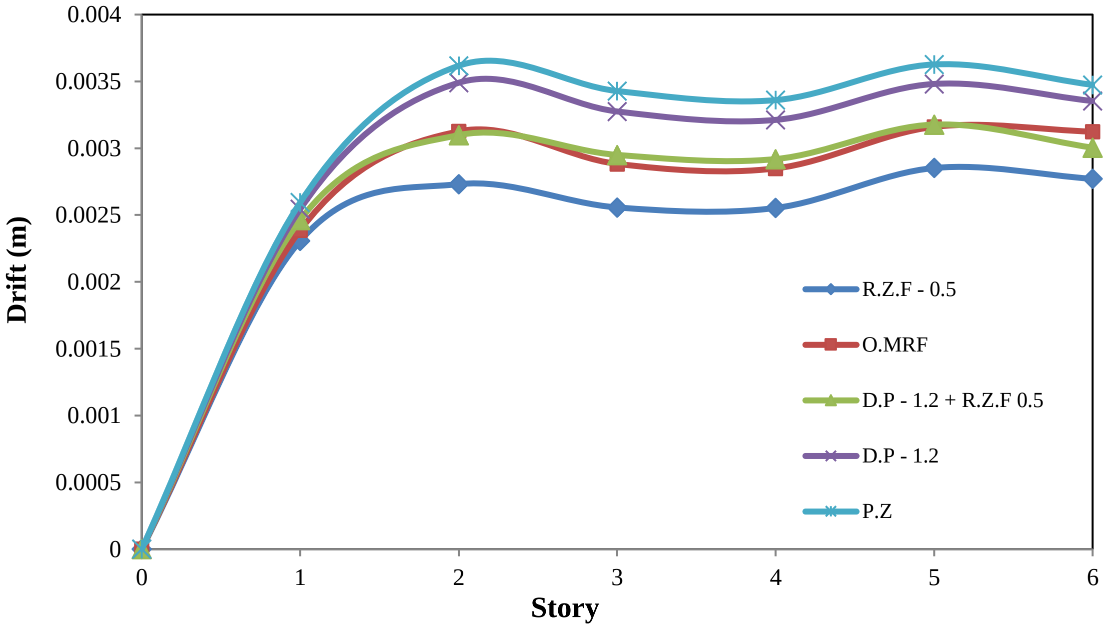

Fig. 10 Drift results of 6 story frame (R.Z.F. = 0.5, D.P. = 1.2)

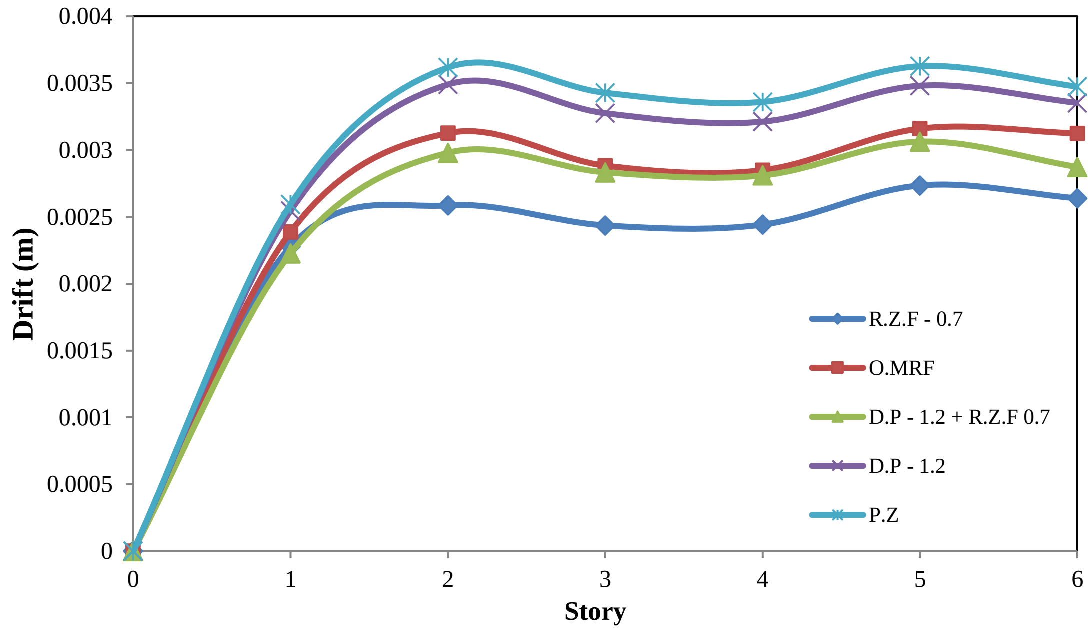

Fig. 11 Drift results of 6 story frame (R.Z.F. = 0.7, D.P. = 1.2)

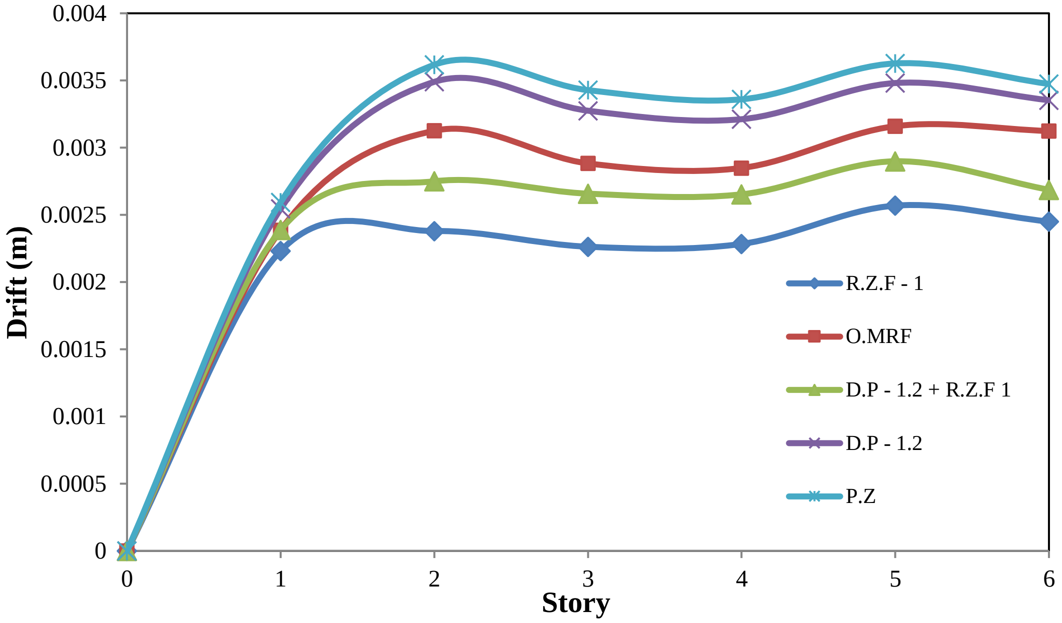

Fig. 12 Drift results of 6 story frame (R.Z.F. = 1.0, D.P. = 1.2)

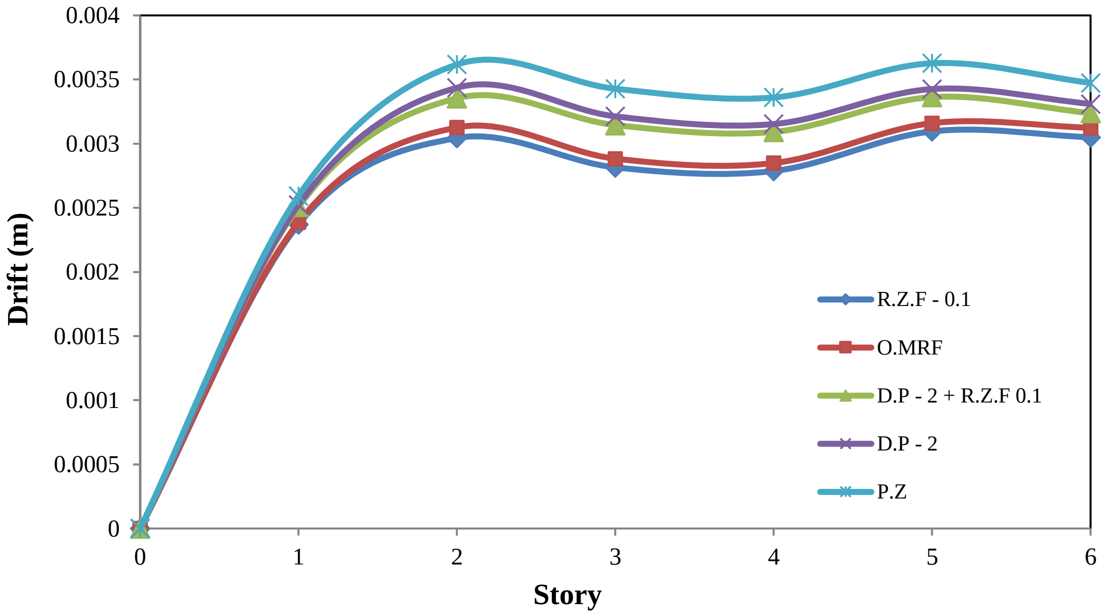

Fig. 13 Drift results of 6 story frame (R.Z.F. = 0.1, D.P. = 2.0)

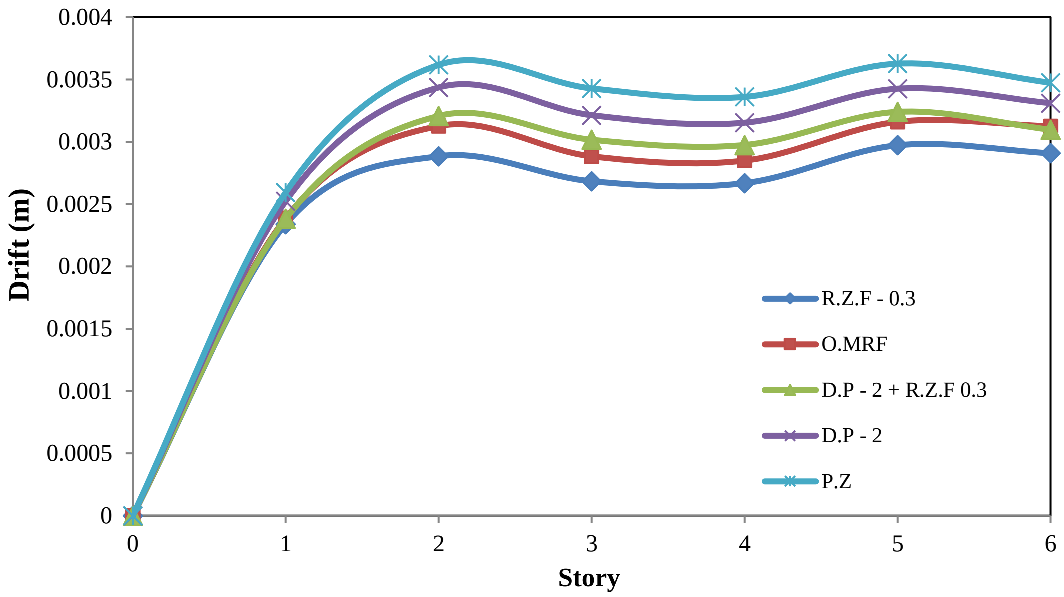

Fig. 14 Drift results of 6 story frame (R.Z.F. = 0.3, D.P. = 2.0)

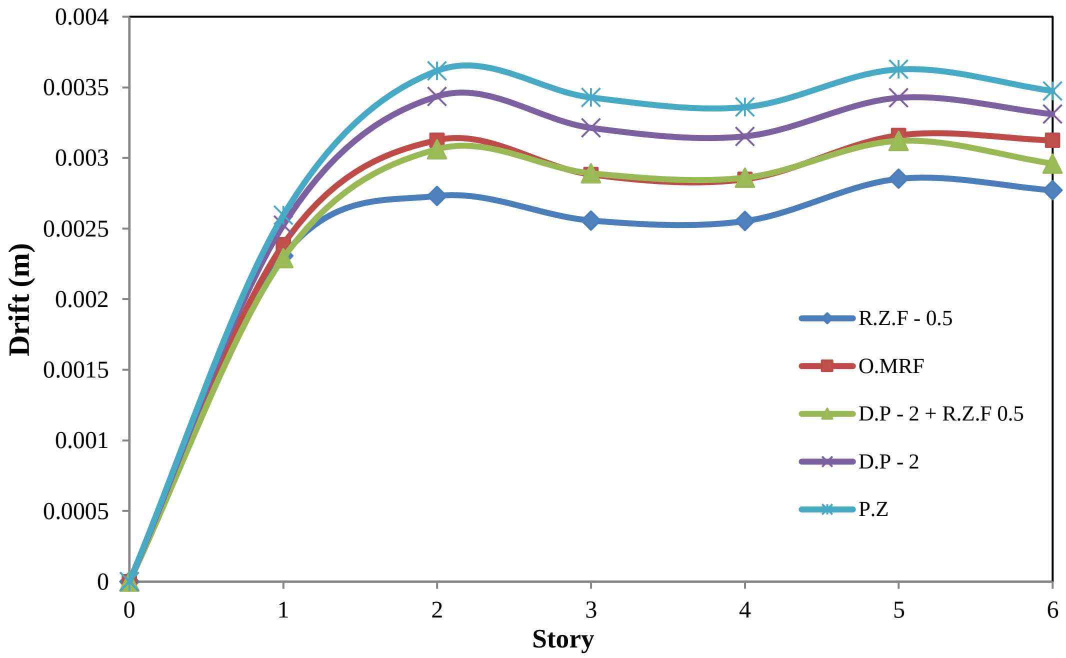

Fig. 15 Drift results of 6 story frame (R.Z.F. = 0.5, D.P. = 2.0)

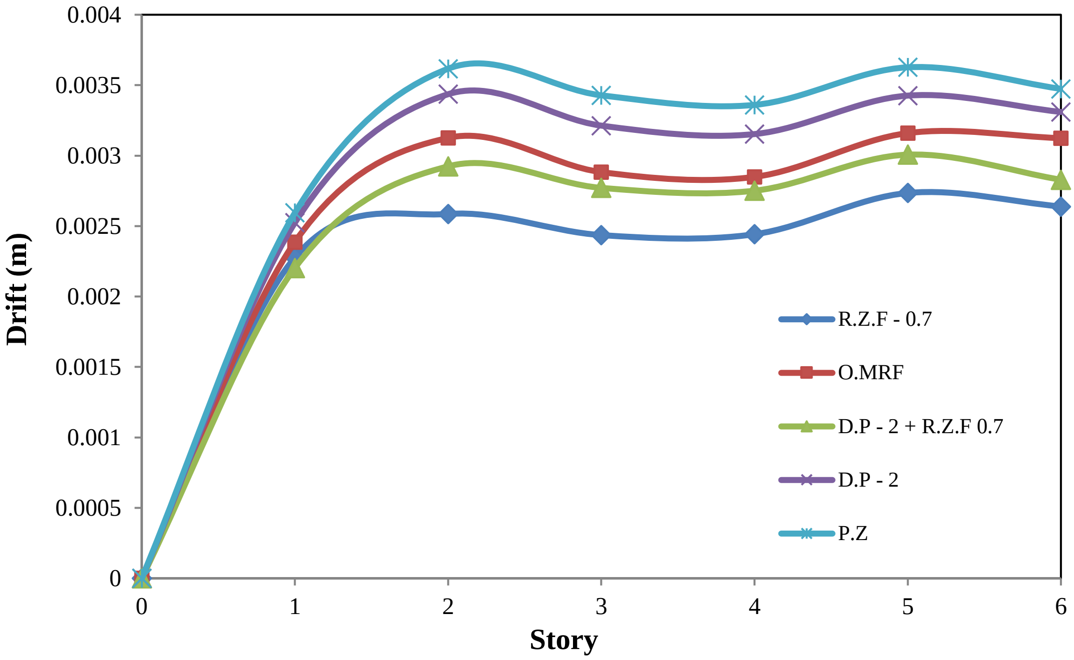

Fig. 16 Drift results of 6 story frame (R.Z.F. = 0.7, D.P. = 2.0)

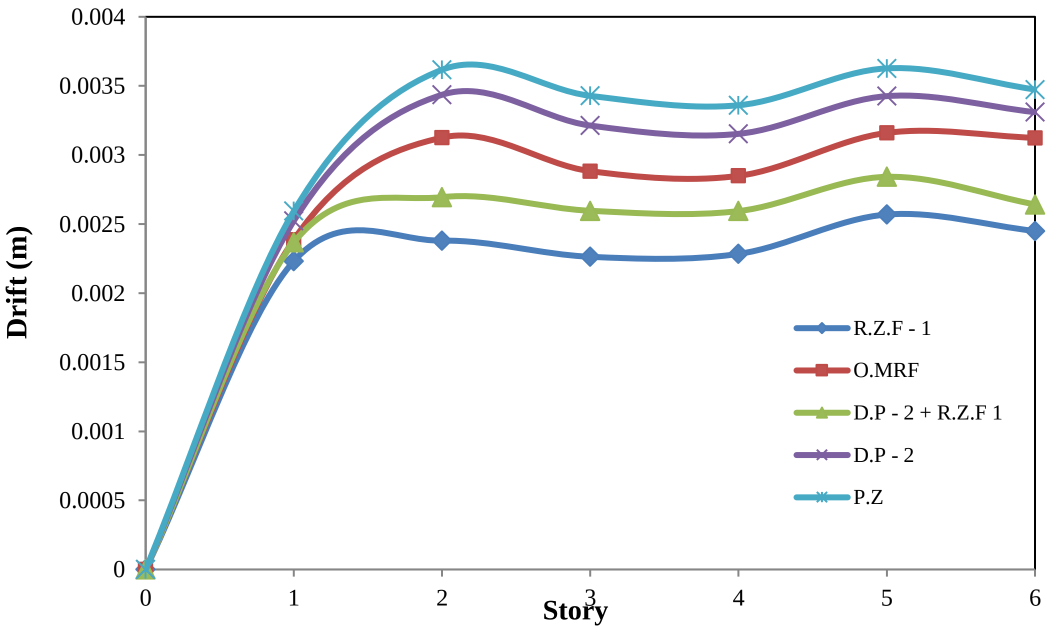

Fig. 17 Drift results of 6 story frame (R.Z.F. = 1.0, D.P. = 2.0)

Another parameter which was considered sensitive within the ETABS program is the allocation of the panel zone. The rigidity of the panel zone has significant influence on the beam element. Also, the panel zone has supplementary critical performance level than another element. When panel zones were assigned within ETABS, the drift was decreased because the results were more accurate. Different thickness of double plates assigned on connections of moments resisting frame does not contribute significant effects on drifts of frames. The results demonstrated that the combined use of different rigid zone factor and different thickness of double plates causes the reduction in the drift on the moments resisting frames.

The results demonstrated that by using double plates in the panel zone, deformations panel zone reduces with increasing panel zone rigidity and develops its performance level. Nevertheless it must be considered that non-linear deformation rates of beam can be increased by increasing the rigidity of panel zone and double plates' thickness. Consequently when the plastic hinge is created in beam, the panel zone can prevent beam damage by assigning double plate. Also the frame function improved by enhancing the height of frames.

5. Conclusions

This paper deals with the panel zone region modeling in steel moment-resisting frames. The influence of panel zone deformation to the story drift of frames is usually important and attention should be given by adopting suitable models. In this study, various modeling procedures applied to combine the influence of panel zone deformation in the analytical model. This is achieved through the analysis of buildings in different state, which demonstrates the behavior of a moment-resisting frame. The numerical models have been simulated and verified using the ETABS Version 9.2. The effect of connection stiffness on structural performance such as drift of buildings was studied. The results of drift values for six stories building models were plotted. The findings indicated that the rigidity caused to reduce the drift in moment-resisting frames and the stiffness of the frames were enhanced. Also, it is demonstrated that double plates have strong impact on the design of panel zone. This strong impact is due to the creation of a plastic hinge in steel beams and losing significant energy induced by seismic loads. Here, the panel zone non-linearly deforms and absorbs a high portion of the earthquake energy which averts the beam to destruct.

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