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INVESTIGATION ON SEISMIC EFFECTS OF NEAR-FIELD GROUND MOTIONS ON DAMAGE OF STEEL MOMENT FRAMES USING CUMULATIVE DAMAGE INDEX

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ABSTRACT

Assessing the effects of near-field ground motions shows that the directivity effects in velocity histories of these ground motions leads to one or more impact pulses with large amplitudes that yield in increased ductility demand of rigid structures placed in near source areas. In this study, the cumulative Park-Ang damage index has been used for comparing the damage potential brought about by the two acceleration components of ground motions that are normal to the fault direction or parallel to it. Two-dimensional steel moment frames with 4, 7, 10, 15 and 20 stories have been nonlinearly modeled and analyzed using the Opensees software. The investigations have been performed in different performance levels corresponding to target ductility values equal to 2, 3 and 4. The utilized ground motion records include 40 records divided equally to the normal and parallel sets regarding the fault direction. The scaling of the record sets have been performed so that the studied frames have met the considered target ductility values. The results show that the lower stories are more frequently affected by the normal records, therefore, more intense damages are attributed to these records. That is while, the parallel records have been found to affect mostly intermediate and especially upper stories. The results also show that increasing the target ductility values leads to an increased damage potential for the studied structures.

Keywords: Damage potential; steel moment frame; cumulative damage index; target ductility; near field.

1. INTRODUCTION

Studying the ground motions effects on the structures located within the near fault earthquakes is among the research topics which has been in the focus of consideration of many researchers. Near fault refers to a range less than 20 km from the active fault, albeit

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this distance also depends on the magnitude of the earthquake [1]. Damage and detraction in recent earthquakes have shown that even though buildings designed according to recent codes and regulations have performed well from the viewpoint of the safety of human lives, the level of damage to the buildings and the consequent economic losses are unexpectedly high. In order to assess the reliability of structures subjected to ground motions, it is necessary to evaluate failure modes, which lead to cyclic deterioration in strength, stiffness, and energy dissipation [2]. For this purpose, due to the importance of the near fault earthquakes, in this research by investigating the vulnerability of 5 steel moment resisting frames with 4, 7, 10, 15 and 20 stories and using the Park and Ang cumulative damage index, the effect of two fault-normal and fault-parallel horizontal components on the 2, 3 and 4 target ductilities, utilizing the OpenSees software, are compared to each other. The studies have shown that assessment of structures performance based only on the maximum parameters, does not give a complete and accurate picture of the way damage is distributed in the structures. In fact structure has a memory which always saves the experienced non-elastic deformations [3], therefore, in this research use has been made of the Park and Ang cumulative damage index which considers cumulative effects of the earthquake.

2- PARK AND ANG DAMAGE INDEX

This index is the most applicable damage index. Although it was first suggested for the concrete structures but due to its physical concept gradually found its way among the researchers and doing subsequent experiments upon steel structures it was also used for the steel structures. The damage index of Park and Ang [11] is expressed as a linear combination of the damage caused by excessive deformation and that contributed by repeated cyclic loading effects [12]. In the year 1992, Kunnath et al. modified the Park and Ang damage model according to the expression (1), which has been used in this research.

$$D = \frac{\theta_m - \theta_y}{\theta_u - \theta_y} + \beta_e \frac{\int dE}{M_y \theta_u} \quad (1)$$

In this expression θ_y , θ_m and θ_u indicate the rotation yield, the maximum rotation and the maximum rotation of the member cross section, respectively under the effect of uniform incremental loading. β_e, is the Park-Ang constant which indicates effect of the plastic hinge energy dissipation on the damage rate. The value of this factor is taken 0.025 for the steel elements [5,6,13]. For calculation of θ_y and θ_u use has been made of the relationships presented by Lingos et al. (2008) [7].

2-1-Global damage index

Many damage indices are defined at the member scale and, using some methods, should be transformed to the structure scale. One famous method which has also been used in this research, is the one presented by Park and Ang.

$$DI_j^s = \sum_{k=1}^{m_j} \lambda_{kj} . DI_{kj} \tag{2}$$

$$\lambda_{kj} = \frac{E_{kj}}{E_j} \tag{3}$$

In which DI_j^s , is the damage index of the jth story , DI_{kj} is the damage index of the kth element from the jth story, E_{kj} is the cyclic energy of the kth member of the jth story, $E_j = \sum_{i=1}^{m_j} E_{ij}$ is the cyclic energy of the jth story and m_j is the number of members of the jth story. Also the global damage index is defined as follows:

$$DI_G = \sum_{i=1}^{N} \lambda_i . DI_i^s \tag{4}$$

$$\lambda_i = \frac{E_i}{E_T} \tag{5}$$

In which DI_G is the global damage index, $E_T = \sum_{s=1}^{N} E_s$ is the total cyclic energy of the structure and N is number of the stories within structure [8].

3-RESEARCH HYPOTHESIS AND MODELING

3.1 Selection of the earthquake records

In this research, in order to assess vulnerability of the steel moment resisting structures within near field, use has been made of the 20 near fault pairs of accelerograms which are scaled based on attaining the 2, 3 and 4 target ductilities by the structure. All records are taken from the research work by Baker. The records characteristics, considering the research done by Baker [9], are given in Tables 1 and 2.

3.2 Structural models

In this section the frames designed for nonlinear analyses under the investigated earthquakes are presented. For design of the frames use has been made of ETABS-9.7.4 software. Models in this study include steel buildings with three bays in five types of 4, 7, 10, 15, and 20 storeys. The height of each storey was 4 m, and the length of each bay is 5 m. The buildings were designed based on the Iranian code of practice for seismic-resistant design of buildings (Standard 2800)[10] and ASD method of ASD-89. A lateral resistant system is a moment frame.

Table 1: Fault-normal components (SN)

Number	Earthquake name	Station	PGA (g)	Effective Duration (s)
1	Imperial Valley	EC County Center ff	0.18	15.46
2	Landerz	Yermo Fire Station	0.24	16.84
3	Northridge	Jensen Filter Plant	0.52	8.19
4	Imperial Valley	EC Meloland Overpass ff	0.38	6.21
5	Northridge	Newhall-Fire Sta	0.72	5.52
6	Chi-Chi,Taiwan	CHY101	0.38	30
7	Kobe,Japan	KJMA	0.85	9.56
8	Imperial Valley	El Centro Array#4	0.36	10.24
9	Northridge	Newhall-Canyon Rd	0.43	7.08
10	Imperial Valley	El Centro Array#5	0.37	9.42
11	Kobe,Japan	Takarazuka	0.64	5.1
12	Northridge	Rinaldi Receiving Sta	0.87	7.15
13	Imperial Valley	El Centro Array#6	0.44	8.6
14	Chi-Chi,Taiwan	TCU101	0.21	18.92
15	Northridge	Sylmar-Converter Sta	0.59	13.24
16	Imperial Valley	El Centro Array#7	0.46	4.8
17	Chi-Chi,Taiwan	WGK	0.3	28.49
18	Imperial Valley	El Centro Array#8	0.47	5.72
19	Northridge	Sylmar-Converter East	0.83	7.25
20	Imperial Valley	El Centro Differential Array	0.42	7

Table 2: Fault-parallel components (SP)

Number	Earthquake name	Station	PGA (g)	Effective Duration (s)
1	Imperial Valley	EC County Center ff	0.22	8.05
2	Landerz	Yermo Fire Station	0.18	19.6
3	Northridge	Jensen Filter Plant	1.07	5.55
4	Imperial Valley	EC Meloland Overpass ff	0.27	11.15
5	Northridge	Newhall-Fire Sta	0.65	6.2
6	Chi-Chi,Taiwan	CHY101	0.43	27.1
7	Kobe,Japan	KJMA	0.55	8.08
8	Imperial Valley	El Centro Array#4	0.47	6.71
9	Northridge	Newhall-Canyon Rd	0.28	9.03
10	Imperial Valley	El Centro Array#5	0.53	8.2
11	Kobe,Japan	Takarazuka	0.7	3.39
12	Northridge	Rinaldi Receiving Sta	0.42	10.1
13	Imperial Valley	El Centro Array#6	0.4	11.44
14	Chi-Chi,Taiwan	TCU101	0.24	19.47
15	Northridge	Sylmar-Converter Sta	0.79	11.92

16	Imperial Valley	El Centro Array#7	0.33	6.89
17	Chi-Chi,Taiwan	WGK	0.49	24.79
18	Imperial Valley	El Centro Array#8	0.59	6.83
19	Northridge	Sylmar-Converter East	0.53	7.05
20	Imperial Valley	El Centro Differential Array	0.44	6.48

4. ASSESSMENT OF NEAR FAULT EARTHQUAKES EFFECT ON THE PARK AND ANG DAMAGE INDEX

In this section the effects of two fault-normal and fault-parallel horizontal components of the earthquake on the vulnerability of considered frames , using the Park and Ang cumulative index, are obtained and compared to each other.

4.1 Investigating the beam element

In Figs. 1-5, the value of Park and Ang damage index for the 5m length beam elements for the 4, 7, 10, 15 and 20 story frames and target ductilities 2, 3 and 4 under the two fault-normal and fault-parallel components are shown.

It could be seen that by increase in the target ductility, the rate of vulnerability has increased. For example the index value in a beam at the third story of the 4 –story frame in which the greatest damage has occurred for the ductility 4 under the fault -parallel component of the earthquake is approximately 19% more than the ductility 3 and this value for the ductility 3 is approximately 41% more than that of ductility 2. Considering that in this research, both fault-normal and fault-parallel components of the earthquake have been applied on the frames and each had a different effect on the seismic parameters, comparison of the obtained results could be beneficial. As a whole, it could not be said which of them is dominant. The results show that in the beam element, the fault- normal component of the earthquake (SN) mostly affects the lower stories of the structures. That is while the fault-parallel component of the earthquake mostly affects the middle and upper stories. These results are more obvious for the intermediate and high ductilities that have resulted within the structures. For example with the 4 story frame, in the beam of the first story, the index value for the ductility 4 under fault-normal component of the earthquake is nearly 9% greater than its corresponding value under the fault-parallel component of the earthquake. That is while in the beam of the third story, in which the fault-parallel component of the earthquake is dominant, the Park and Ang index value for the ductility 4 is about 11% greater than that of the fault-normal component. Among studied frames, just the 20- story frame which represents a high-rise structure, for the target ductilities 3 and 4 and at all the stories, the fault –parallel component of the earthquake has been dominant.

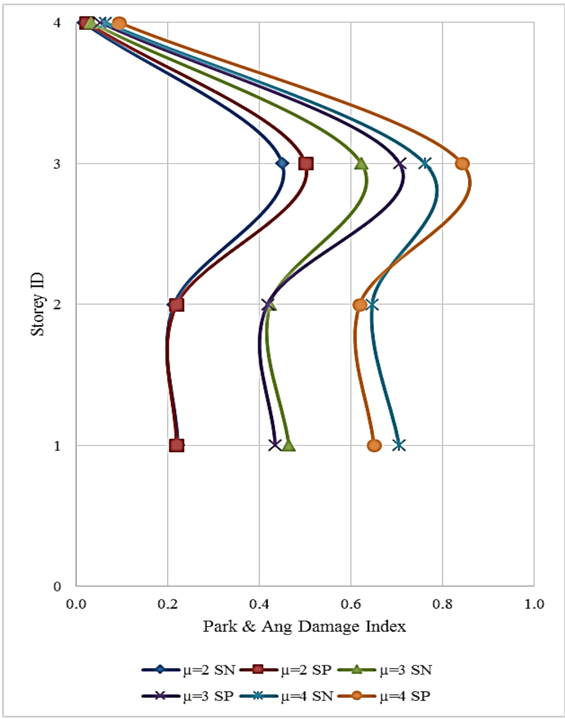

Figure 1. 4 storeys-beam

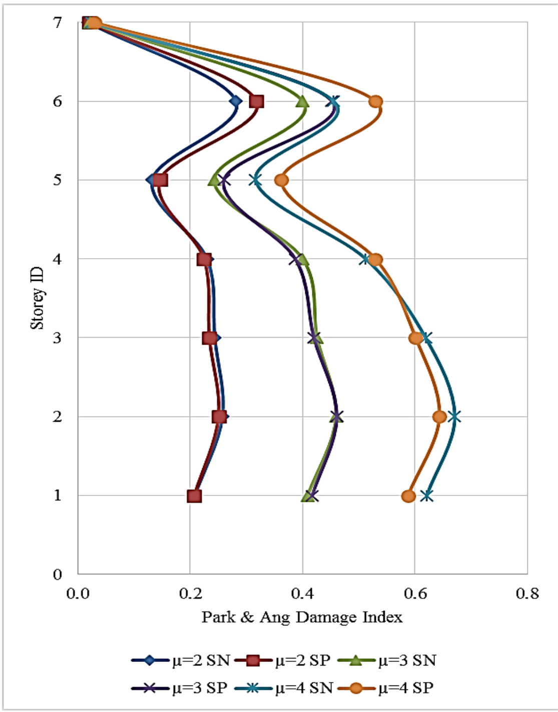

Figure 2. 7 storeys-beam

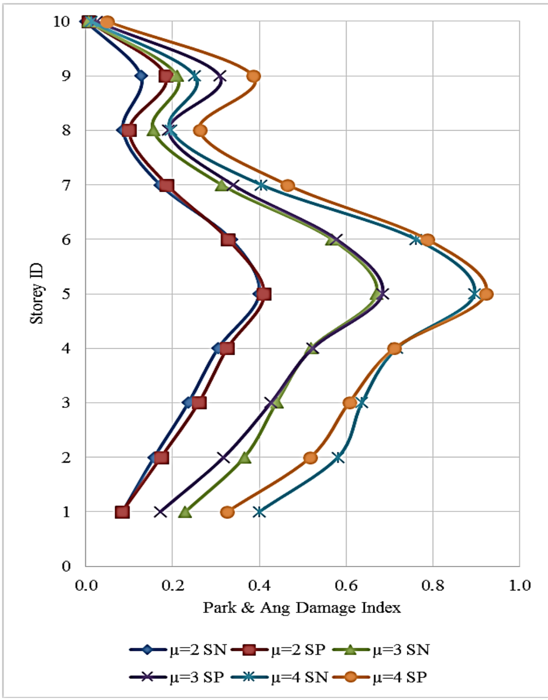

Figure 3.10 storeys-beam

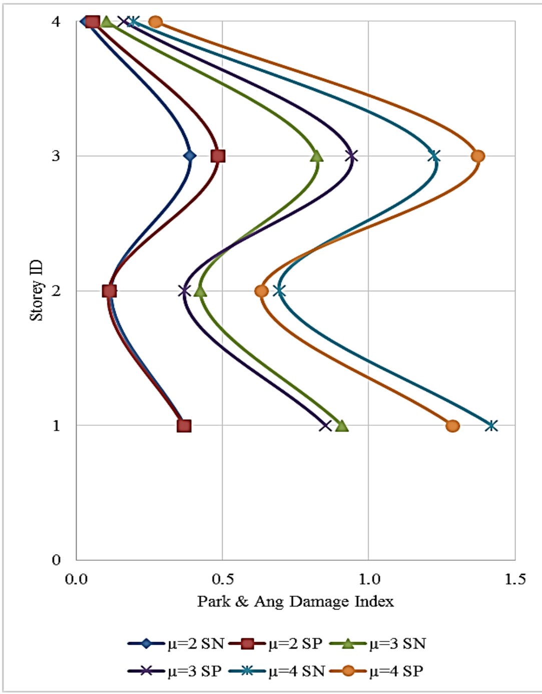

Figure 4.15 storeys-beam

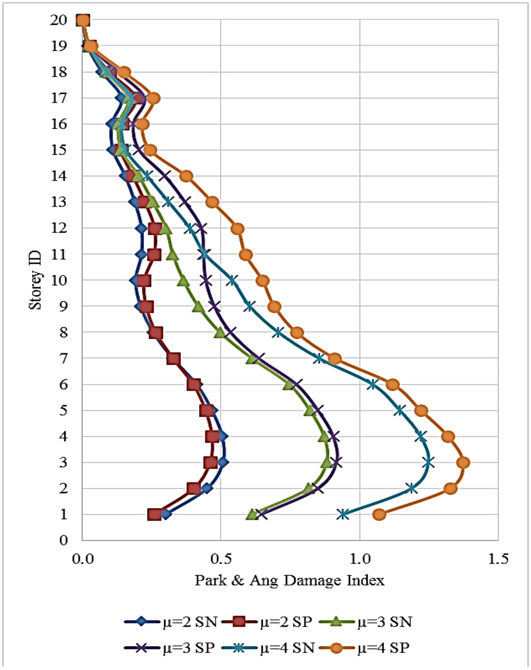

Figure 5. 20 storeys-beam

4.2 Investigating the column element

In Figs. 6-10 the Park and Ang index value in the 4m- height column elements of the 4, 7, 10, 15 and 20 story frames for the target ductilities 2, 3, and 4 and under two fault-normal and fault-parallel components of the earthquake are shown.

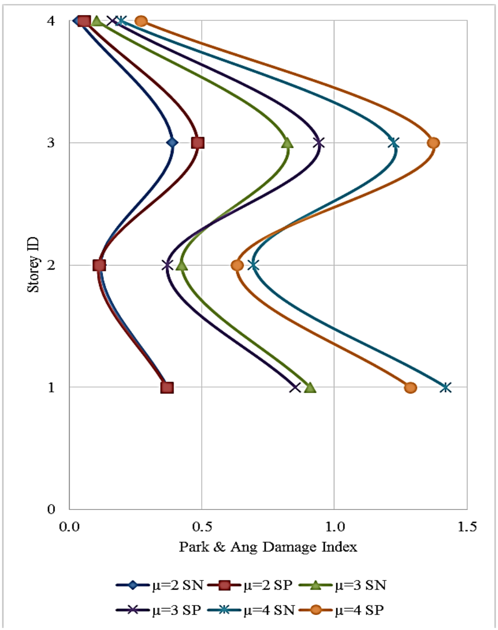

Figure 6. 4 storeys-column

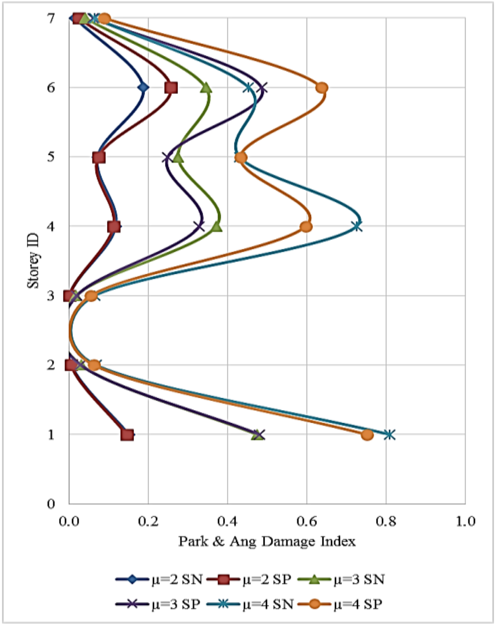

Figure 7. 7 storeys-column

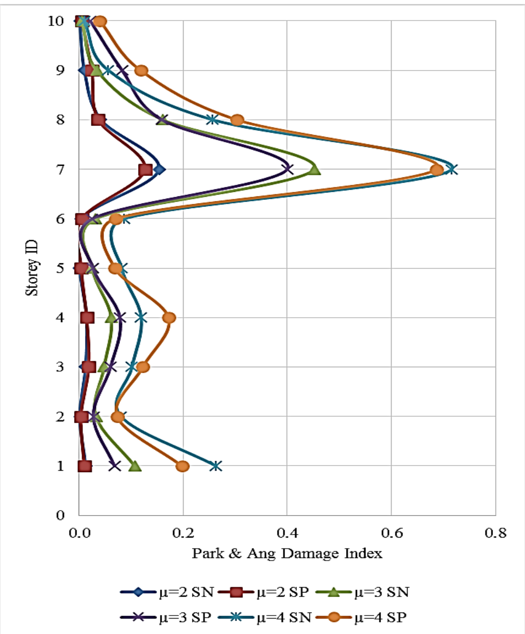

Figure 8. 10 storeys-column

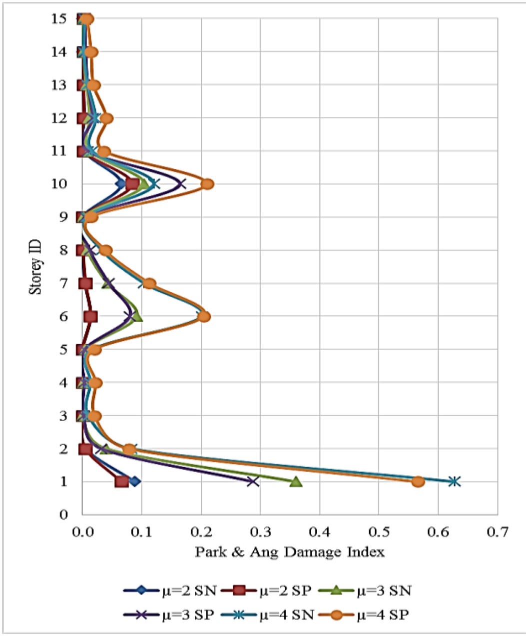

Figure 9. 15 storeys-column

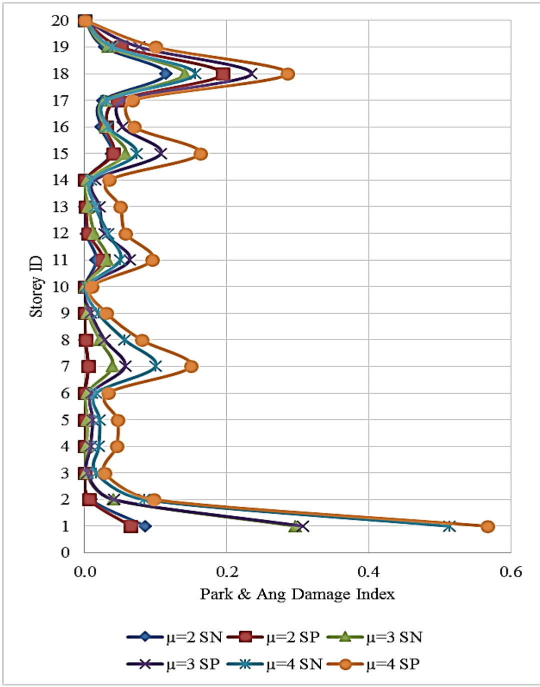

Figure 10. 20 storeys-column

As it is seen, in the column element, also by increase in the target ductility, the vulnerability also has increased. For example the column at the first story of the 4-story frame in which the greatest damage has taken place, the index value for the target ductility 4 under the fault-normal component of the earthquake is 56% more than its corresponding value for the ductility 3 and in the ductility 3 is about 145% more than that of the ductility 2. Concerning the comparison of the effects of two fault-normal and fault-parallel components of the earthquake, it could be said that for low-rise and mid-rise frames at the lower and middle stories the fault-normal component of the earthquake (SN) is dominant and at the upper stories, the fault-parallel component of the earthquake is dominant. For the 4-story frame which represents the low-rise structure, in the column element of the first story which bears the greatest damage, the Park and Ang index value under the fault-normal component of the earthquake, for the target ductility 4 is about 11% greater than its corresponding value for the fault-parallel component of the earthquake, That is while at the third story where the fault –parallel component of the earthquake is dominant, the index value is about 12% more than its corresponding value under the fault-normal component of the earthquake. Concerning the high-rise frames, for the 20story frame and at all of its stories the fault-parallel component of the earthquake has been dominant.

4.3 Damage at storey level

In this section in order to obtain damage at the story scale, use has been made of the weighted average method proposed by Park and Ang .In Figs. 11-15 the Park and Ang damage index value at the story level and for the considered frames are shown.

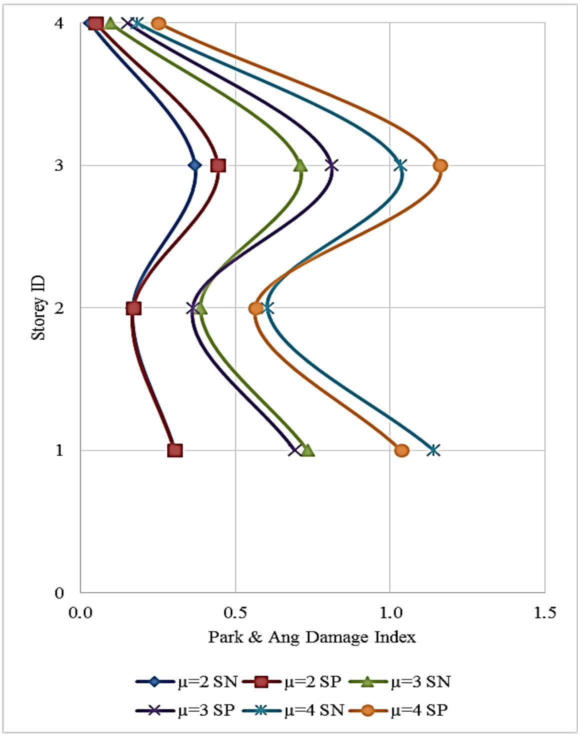

Figure 11. 4 storeys-storey level

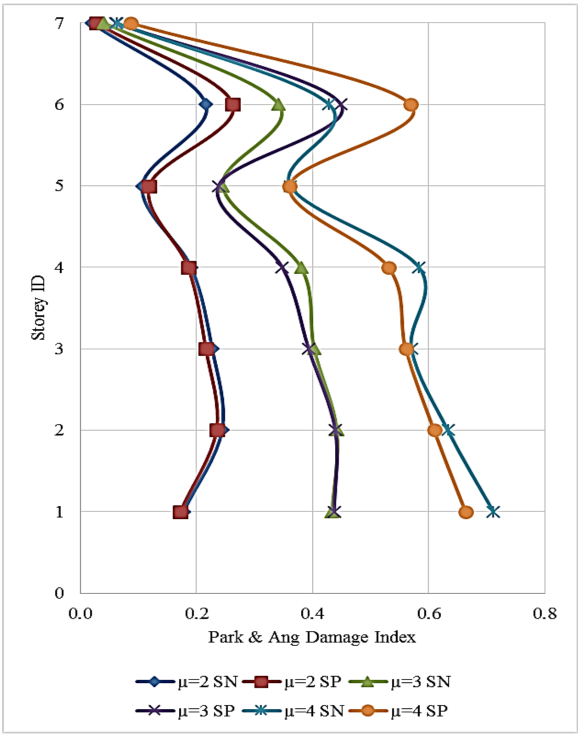

Figure 12. 7 storeys-storey level

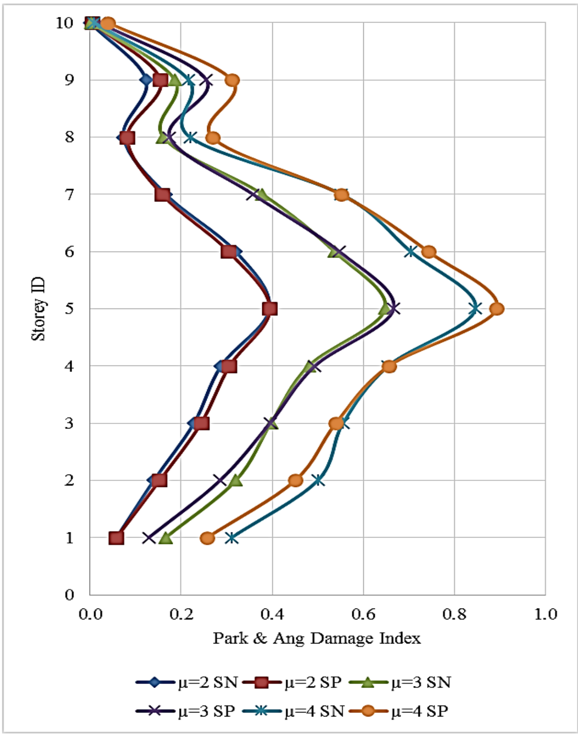

Figure 13. 10 storeys-storey level

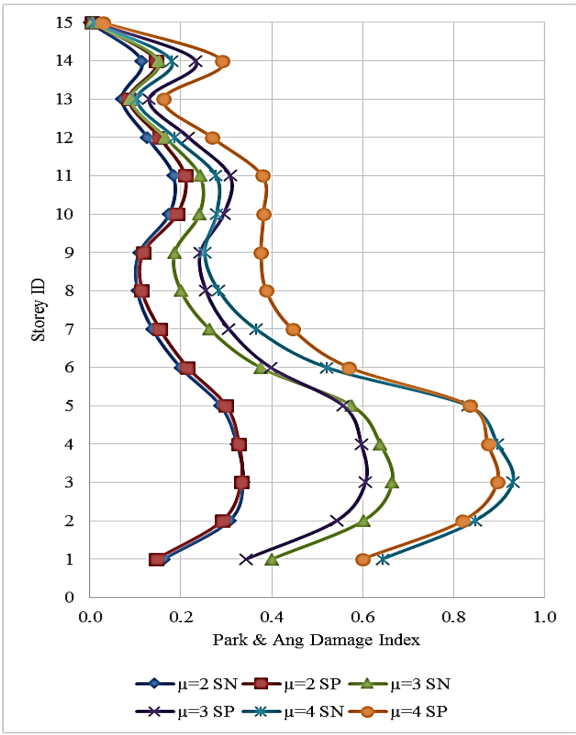

Figure 14. 15 storeys-storey level

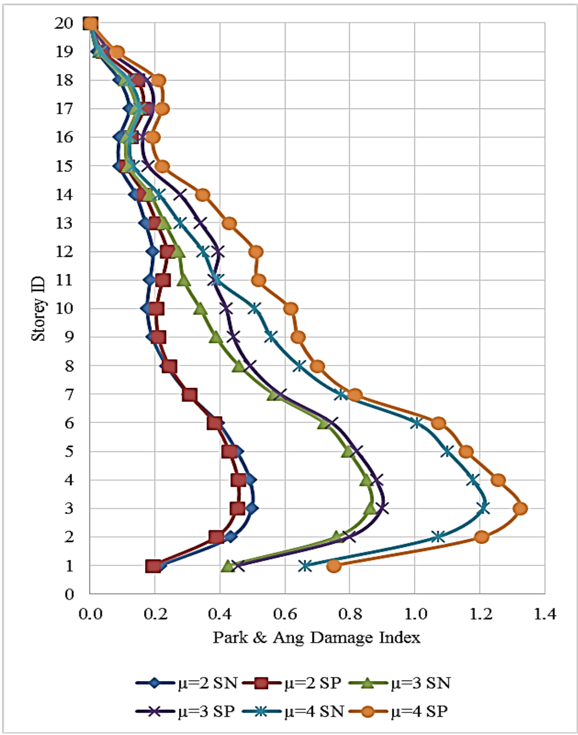

Figure 15. 20 storeys-storey level

As it is seen, the results at the story level are similar to those of the column and beam elements. So that with the low-rise frames, the effect of fault-normal component of the earthquake on the lower and middle stories is greater than that of the fault-parallel one, That is while at the upper stories the fault-parallel component of the earthquake is dominant and causes greater damages.

With the middle frames, at the lower stories the fault-normal component of the earthquake is dominant and mostly affects the structure, that is while at the middle and upper stories the fault-parallel component of the earthquake is dominant.

With the high-rise frames, for the ductilities 3 and 4 at all the stories, the fault-parallel component of the earthquake is dominant and causes greater damages in the structure. For the 2 ductility, just at the lower stories the Park and Ang index value under the fault-normal component of the earthquake is greater than its corresponding value under the fault-parallel component, and at other stories the fault-parallel component is dominant.

4.4 Investigating the global damage

For transforming the damage indices calculated at the member scale to that of the structure scale, use has been made of the method presented by Park and Ang. Fig. 16 shows the global Park and Ang index against the period. In the obtained graph it is seen that for the low ductility ($\mu=2$) with the low-rise and middle-rise frames, the fault-parallel component of the earthquake is dominant and the Park and Ang index is somehow greater than its corresponding value under the fault-normal component of the earthquake.

For example, with the 4-story frame, the Park and Ang index value under the fault-parallel component of the earthquake is approximately 8% more than that of the fault-normal component, which by increase in the structure height this difference decreases, so that this difference factor reaches up-to 2% for the 10-story frame. With the high-rise frames and for this ductility, the fault-normal component of the earthquake is dominant and causes more damage to the structure. So that with this frame the index value under the fault-normal component of the earthquake is approximately 7% more than its corresponding value under the fault-parallel component of the earthquake. For the intermediate ductility ($\mu=3$) ,this process is not as before, so that with the 4, 10 and 20 story frames, the fault-parallel component of the earthquake is dominant but with the 7 and 15 stories frames, the fault-normal component of the earthquake is dominant. For the high ductility ($\mu=4$) with low-rise frames, the fault-normal component of the earthquake is dominant, while with the high-rise frames the fault-parallel component of the earthquake is dominant. Concerning the middle-rise frames, with the 10-story frame the fault-parallel component is dominant but with the 15-story frame the fault-parallel component of the earthquake is dominant. Looking at the graph, also it should be noted that by increase in the target ductility, the vulnerability of the frames also has increased.

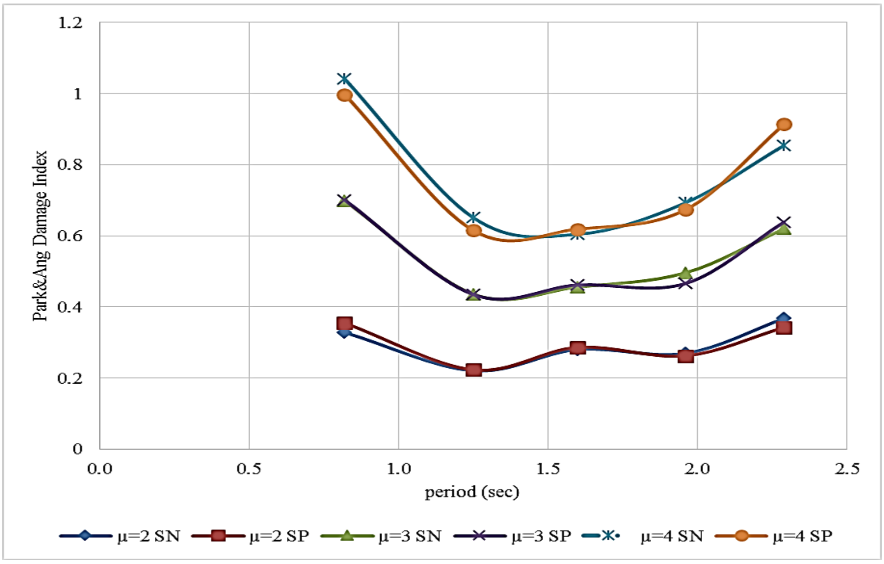

Figure 16. Global Park&Ang damage index

5. CONCLUSIONS

In this research the vulnerability of 4, 7, 10, 15 and 20 story steel moment resisting frames using the Park and Ang cumulative damage index under the 20 fault-normal and 20 fault - parallel accelerograms have been investigated and the following results have been obtained:

1. By increase in the target ductility, the vulnerability of the beam element, column element, at-the- story scale and global scale have increased and the difference between Park and Ang index value for the target ductility 3 with respect to that of the target ductility 2 is much greater than the difference between target ductility 4 with respect to that of the target ductility 3. So that with the 4-story frame the global Park and Ang index value for the target ductility 4, under the fault-parallel component of the earthquake is about 42% greater than its corresponding value for the target ductility 3 and the index value for the target ductility 3 is about 97% greater than that of the target ductility 2. The reason for this is that, the more structure undergoes nonlinear stage, for higher ductilities, the rate of increase in damage decreases and the difference between the damages at higher ductilities, decreases.
2. The comparison of the effects of two fault-normal and fault-parallel components of the earthquake shows that it could not be concluded with certainty that in all cases, which component is dominant, but the results show that with low-rise and mid-rise frames, mostly the fault-normal component affects lower stories of the frames and causes greater damages in them with respect to the other stories, that is while the fault-parallel component of the earthquake mostly affects the middle and especially upper stories of the structures.

3. With the high-rise frames, for the intermediate and high ductilities and at all the stories, the fault-parallel component of the earthquake is dominant, and this issue is related to the higher modes effects.

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