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Practical relations to quantify the amount of damage of SWRCFs using pushover analysis

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Abstract. Quantifying the amount of damage of structures under earthquakes is an interesting issue that researchers have attended on and have presented some damage indices. Whereas a lot of damage indices have been introduced based on nonlinear dynamic analysis, computational effort, the calculus complicacy and time-consuming of this analysis are the main drawbacks to widespread use of these indices. The objective of this study is to quantify the damage of Shear Wall Reinforced Concrete Frames (SWRCFs) based on pushover analysis as a procedure that can reflect the behavior of structures from elastic to collapse. For this purpose, firstly, several SWRCFs are designed and the capacity spectrum of each one is achieved via pushover analysis. After that, the static damage indices of the designed frames are obtained. Then, nonlinear dynamic analyses are performed on these frames and the Park and Ang damage index as the basis damage criterion is achieved. Afterward, some relations are presented to predict the dynamic damage of these frames via pushover analysis. Eventually, to confirm the validity of the proposed relations, the values of Park and Ang damage index of three new SWRCFs are acquired once utilizing nonlinear dynamic analysis and again applying the introduced relations. Outcomes prove the validity of some presented damage indices.

Keywords: damage index; nonlinear dynamic analysis; pushover; shear wall; performance point

1. Introduction

The exposed damage on structures were unacceptably large in sever earthquakes. Studies to cater better performance of structures led to the Performance-Based seismic Design (PBD) methodology. The PBD procedures encompass a set of methods to control the damage of a designed building structure such that its manner is ensured at predefined performance levels subjected to seismic ground motions; therefore, quantification damage of structures is one of crucial topics in PBD. There are a lot of damage indices (DIs) that have been presented by researchers to quantify the potential for damage of earthquake ground motion. These indices considered the significant structural features comprising inelastic behavior, cumulative effects of repeated cycles of inelastic structural deformation, dissipated energy, etc. Since calculating these damage indices (DIs) requires nonlinear dynamic analysis (NDA), none of them are widely enforceable because of their time-consuming and most rigorous procedure.

The proposed DIs fall into two categories: 1) local 2) global. Local DIs presented some relations to measure the damage of structural components, whereas global Dis considered the total behavior of structures. Researchers have considered different structural aspects to quantify the damage of structures. Powell and Allahabadi (1988) introduced a damage index based on ductility. Drift was considered as a damage criterion in many researches such as Saiidi and Sozen (1981), Erduran and Yakut (2004). Banon and Biggs (1981) proposed their damage index based on stiffness degradation. Wang and Shah (1987) presented a cumulative damage criterion based on the peak of deformations in each cycle. Kratzing and meyer (1989) put forward a damage index based on dissipated energy. Colombo and Negro (2005) suggested their damage criterion based on strength degradation. Some studies took a combination of effective parameters in suggesting their damage criteria such as Park and Ang (1985), Bracci *et al*. (1989), Zhang *et al*. (2007) and Banon and Veneziano (1982). Park and Ang (1985) introduced their damage index based on the combination of displacement and dissipated energy in their damage index. This index was improved by Kunnath *et al*. (1992b). Cakmak and Dipasquale (1990) proposed the softening of structure based on a variation of period. Otani and Suzen (1972) illustrated that drift ration is not an appropriate damage criteria and proposed the variation of stiffness as a reliable damage criterion. Estekanchi and Arjomandi (2008) applied endurance time method to assess the damage of structures. Faleiro *et al*. (2007) introduced a plastic damage criterion to predict the damage of RC structures. Estekanchi and Arjomandi (2007) and Habibi and Izadpanah (2012) proposed some practical relations between the DIs. Estekanchi and Arjomandi (2007) achieved some relationships between DIs and inter-

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story drift as the primary parameter in evaluating structural performance (ATC40 and FEMA273). Habibi and Izadpanah (2012) using the obtained relations between the DIs in pushover and NDA, introduced a new method to design of reinforced concrete moment resisting frames with damage control. Rodriguez and Padilla (2009) used the hysteretic energy dissipated by a structural member to present a damage index for the seismic analysis of RC members. They also applied a drift ratio related to failure in the structure. They calibrated this damage index based on observed damage in laboratory tests of 76 RC column units under various protocols and illustrated the effect of displacement history in the drift ratio capacity of structures. More recently, Zare Hosseinzadeh *et al*. (2016) developed a new procedure to quantify structural damage. They used continuous wavelet transform and wavelet residual force and presented a damage index to localize structural damage with a high level of accuracy. They evaluated this damage index in some case studies and results showed that their proposed method has acceptable performance in obtaining the damage of structures. Yue (2018) presented a generalized stiffness damage model based on the deformation equivalent principle. They acquired the stiffness damage value by the integration of the material stiffness damage. They proved that the proposed method is effective to evaluate the structure multilevel damage performance and to design a new structure. Do and Filippou (2018) put forward a hysteretic damage model to model the structural components response with strength and stiffness deterioration under cyclic loading. 1D continuum damage mechanics and relates any 2 work-conjugate response variables such as force-displacement, moment-rotation, or stress-strain are applied to introduce this model. They assessed the ability of the model to describe different types of hysteretic behavior, moreover, they compared the relation of the model's damage variable to the Park-Ang damage index. They concluded that the presented model is appropriate for the large-scale seismic response of structural systems with strength and stiffness deterioration. Hoseini Vaez and Tabaei Aghdaei (2019) evaluated the influence of the frequency content of earthquake excitation in determining the damage of steel frames. Zameeruddin *et al*. (2017) presented a stiffness damage index based on the nonlinear response of nonlinear static analyses. The validity of this proposed damage index was assessed using some RC case studies, and it was demonstrated that this proposed damage index agrees with drift damage values. Izadpanah and Habibi (2018) measured the values of Park and Ang damage index for an example to illustrate the influence of the considered plasticity model likewise gravity load effect on the damage of structures. There are some other researches evaluating the damage of structures such as: Mourlas *et al*. (2019), Sakka *et al*. (2018), Gharehbaghi (2018), Huang and Lu (2017), Kang and Lee (2016), Cao *et al*. (2014), Homaei *et al*. (2014) and so on.

As mentioned, the most of DIs have been proposed based on NDA; therefore, computational effort, calculus complexity and time consuming of NDA are some disadvantages of widespread use of them. Pushover is known as an analysis that is capable to reflect the behavior of structures from elastic to collapse has widely been adopted as the primary tool for nonlinear analysis due to its simplicity and facility contrasted to dynamic one. Studying the literature demonstrates that the damage analysis of SWRCFs based on pushover analysis is completely rare. The main objective of this study is to present some practical relations to achieve dynamic damage index (DIs that are computed using NDA) of SWRCFs using static damage index (DIs that are obtained using pushover analysis). To do so, firstly, some SWRCFs are designed, performance point of them is derived using the capacity spectrum method and static damages of them are achieved in performance points. After that, the values of the dynamic damage index of each frame are calculated in selected seven earthquake acceleration records (these records are scaled to match the Iranian 2800 standard response spectrum). Then, some appropriate relations are suggested to achieve the dynamic damage response of SWRCFs through performing pushover analysis and computing static damage index. Finally, the proposed methodology is applied for three new SWRCFs and the approximation of the presented relations are evaluated.

2. Proposed methodology

In this study, some relations are proposed to estimate the dynamic damage index based on static damage index. In fact, since quantifying damage of structures in pushover analysis needs lower computational effort rather than dynamic analysis, it is more practical to estimate the structural damage index through this analysis. It should be pointing out that in pushover analysis, some seismic properties of the structures such as higher mode effects and interaction of vibration modes cannot simulate appropriately; therefore, proposing some relations between static and dynamic DIs is so useful to remedy the aforementioned obstacles. Some static and dynamic DIs are chosen to quantify the damage of SWRCFs. The selected dynamic damage index is the proposed damage index by Park and Ang (1985) and static DIs are energy, stiffness and the plastic ductility damage index and overall drift ratio criterion. The aforementioned DIs are explained more in this section.

The well-known Park and Ang (1985) damage index is considered as dynamic damage index in the present study. Park and Ang (1985) damage index has been used in many studies, such as Diaz *et al*, 2017, Belejo *et al*. 2017, Hai *et al*. 2019, Moustafa and Mahmoud 2014, as well as it was calibrated for different levels of damage based on the experimental observations. This damage index is modified by Kunnath *et al*. (1992b) as follows

$$DI_{P\&A} = \frac{\theta_m - \theta_r}{\theta_u - \theta_r} + \frac{\beta E_h}{M_y \theta_u} \tag{1}$$

where θ_m and θ_r are the maximum and yield rotation, respectively, and θ_u is the ultimate rotation capacity of the section. M_y is the yield moment and β is a constant parameter, which depends on structural characteristics and history of inelastic response. E_h is the hysteretic energy. In this damage index, if the structure remains elastic, the damage index will be zero and if experiences failure, will be one.

Energy damage index (EDI) that was introduced by Habibi and Izadpanah (2012) is taken as one of static damage indices in this research. This damage index can be achieved based on pushover outcomes as below

$$EDI = \frac{E_{pp} - E_{ip}}{E_{fp} - E_{ip}} \quad (2)$$

where E_{pp} is the area under the capacity curve at the performance point, E_{ip} is the area under the capacity curve at the point in which the structure enters into nonlinear phase and E_{fp} is the area under the capacity curve related to the ultimate capacity of the structure. The first cracking of the structural elements (on capacity spectrum) is taken as the onset point that the structure experience damage. On the other hand, in this point, structure enters to inelastic phase. More detail about this damage index is available in Ref. Habibi and Izadpanah (2012).

The second damage index that is considered is the plastic ductility DI. This damage index was put forward by Powell and Alahabadi (1988) and is known as a simple and practical damage index. In this study, the global damage of the structures is achieved using plastic ductility damage index (PDDI) as follows

$$PDDI = \frac{U_{max} - U_{y1}}{U_{mon} - U_{y2}} \quad (3)$$

where $U_{\max}$ is the maximum displacement ralating to the displacement at the performance point on capacity spectrum curve, U_{y1} and U_{y2} are the yielding displacement achieved based on equivalent two linear capacity curve at performance point and at ultimate capacity of the structure, respectively. U_{mon} is the ultimate displacement under monotonically increasing lateral deformation..

Introduced by Habibi *et al*. (2006), the stiffness damage index (SDI) is implemented in this study to assess the damage of SWRCFs as follows

$$SDI = 1 - (\frac{k_j}{k_{op}}) \quad (4)$$

where k_j is the slope of performance point and k_{op} is the slope of the capacity curve relating to operational level.

The drift is one of the most practical criteria to evaluate the global performance of the structure in many researchers and seismic guidelines (FEMA273 and ATC40). In this study, this well-known damage index (Overall drift ratio) is acquired from pushover analysis as follows (hereafter referred to as ODR).

$$ODR = \frac{\Delta_m}{H} \quad (5)$$

Where Δ_m is the roof displacement of the performance point and H is the height of the structure. To obtain this criterion, after doing pushover analysis, the performance point is achieved (in this study using the capacity spectrum method) then having the value of the overall drift at the performance point, static damage index can be computed from Eq. (5).

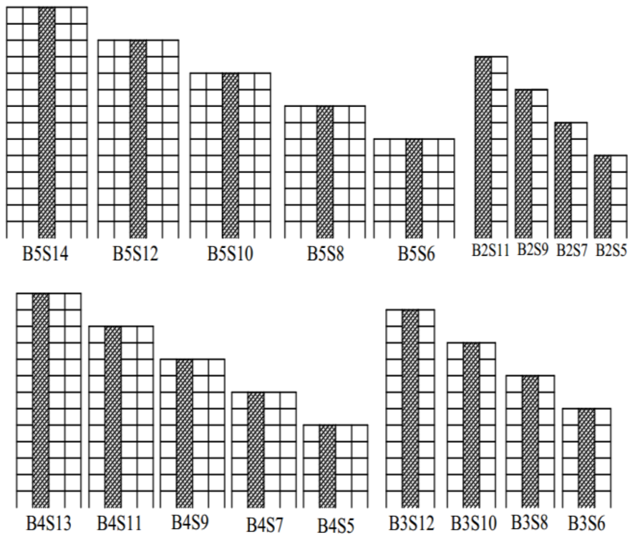

Fig. 1 The geometry and names of the studied frames

3. Nonlinear analysis

To cover the widespread range of the numbers of stories and bays, eighteen SWRCFs, as described in Fig. 1, are considered. It must be mentioned that since simulating 3D-models and performing nonlinear analyses, especially dynamic one and calculating Park and Ang damage index are time-consuming and calculus complicated, simulating building structures by 2 dimensional models as a proper alternative is considered in this study, as is common among most researchers. In the names of the frames in Fig. 1, "B" denotes the number of the bays and "S" denotes the number of the stories. In the five-bay frames, the numbers of stories are considered to be six, eight, ten, twelve, and fourteen. In the four-bay frames, the numbers of stories are assumed five, seven, nine, eleven and thirteen and in the two-bay frames, five, seven, nine and eleven stories are taken into consideration. In all frames, the height of each story and the length of each bay are assumed 3.2 meters and 4 meters, respectively. All frames lie on soil profile type II with shear wave velocity 375<V_s<750(m/s). These frames are loaded based on Iranian seismic code 2800 and designed according to ACI provisions for zone of high relative seismic hazard. The uniformly distributed dead and live loads of 21975 N/m and 1962 N/m (mean values) are applied to the beams of each story. The concrete is assumed to have the cylinder strength of 25 MPa (mean values), a modulus of elasticity of 25000 MPa, a strain of 0.002 at maximum strength and an ultimate strain of 0.003. The steel has the yield strength of 400 MPa (mean values) and the modulus of elasticity of 200000 MPa. Some design characters of these frames have been summarized in Table 1. It is worth emphasizing that since the achieved dynamic periods of these frames were more than 1.25 times of the empirical period of Iranian seismic code 2800, 1.25 times of the empirical period of Iranian seismic code 2800 was considered to acquire base shear coefficient for each frame. The base shear-roof displacement curves of these frames are depicted in Fig. 2. More details about cross-sectional characteristics of the structural elements are achievable in Ref. (Samadi 2016).

Table 1 Characteristics of the studied frames

Frame Number	Height(m)	Period	Base Shear
B2S5	16	0.5	184.2
B2S7	22.4	0.64	207.5
B2S9	28.8	0.78	228.5
B2S11	35.2	0.9	247
B3S6	19.2	0.57	283
B3S8	25.6	0.71	313.4
B3S10	32	0.84	348
B3S12	38.4	0.96	398.5
B4S5	16	0.5	335
B4S7	22.4	0.64	380
B4S9	28.8	0.78	422
B4S11	35.2	0.9	460
B4S13	41.6	1.02	495
B5S6	19.2	0.57	437.14
B5S8	25.6	0.71	488
B5S10	32	0.84	536
B5S12	38.4	0.96	582.4
B5S14	44.8	1.09	615

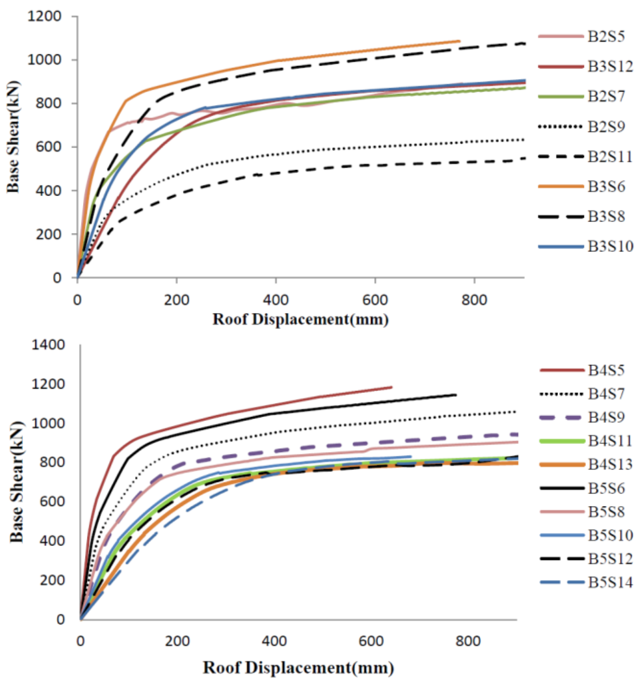

Fig. 2 The base shear versus roof displacement curves of all SWRCFs

In this study, seven earthquake records for soil profile type II in Iranian seismic code are chosen that are listed in Table 2. These records are scaled to match the Iranian 2800 standard response spectrum based on the explained scaling procedure in the Iranian seismic as depicted in Fig. 3.

In this research, the IDARC platform (Reinhorn *et al.* 2009) is applied to perform the nonlinear dynamic and static analyses. To simulate the nonlinear behavior of structural elements, the linear flexibility model (Kunnath and Reinhorn 1989) from the spread plasticity models is chosen. In spread plasticity models, unlike the lumped plasticity models concentrating the plasticity in the two ends of the element and the member between these two

Table 2 Ground motion records in the present study

Earthquake number	Record	Station	Component (deg)	PGA (g)
1	San Fernando	Castaic - Old Ridge Route	0	0.320
2	Irpinia, Italy-01	Arienzo	270	0.034
3	Loma Prieta	Coyote Lake Dam - Southwest Abutment	45	0.484
4	Landers	Silent Valley - Poppet Flat	0	0.049
5	Northridge-01	Wrightwood - Jackson Flat	90	0.056
6	Kobe, Japan	Chihaya	90	0.109
7	Taiwan SMART1(45)	SMART1 E02	90	0.142

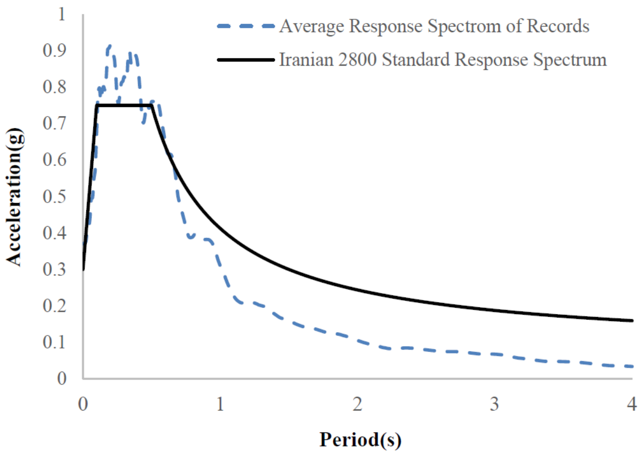

Fig. 3 Average response spectrum of the scaled accelerations

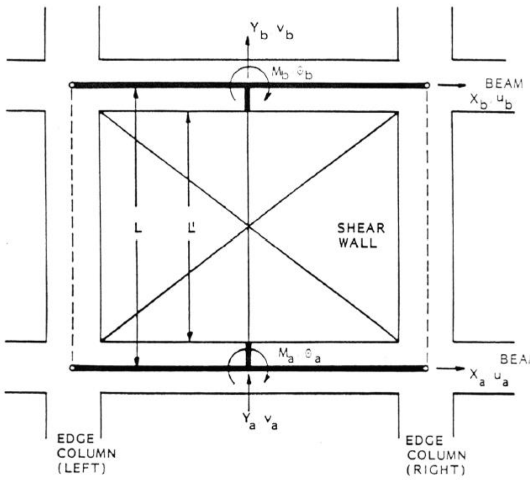

Fig. 4 Shear wall element and degree of freedoms (Reinhorn *et al.* 2009)

hinges is assumed fully elastic, flexibility is distributed along the member based on a prescribed distribution pattern that is more compatible with the nonlinear behavior of RC elements. Proposed by Park *et al.* (1984), the tri-linear moment-curvature relation is taken to model the nonlinear behavior of RC sections in which the uncracked, cracked and yielded section properties are presented. To derive the moment-curvature relation, the cross-sectional properties and stress-strain properties for concrete and steel are used. Shear walls are simulated as depicted in Fig. 4. The stiffness consists of flexural, shear and axial effects. The axial deformation component is simulated applying a linear-elastic spring. More detail about the assumed models is achievable in Reinhorn *et al*. (2009).

The vertex-oriented hysteric model is used to simulate the behavior of structural elements. Newmark's method is applied to carry out NDA, and the Newton–Raphson method is used for nonlinear analysis of structures; therefore, the assumptions and limitations of this procedure such as disability to following the full path of the capacity spectrum of structures are applied in the present study. The failure assumed is the situation in which the stiffness of the structure is very low, when displacement increases without increasing the load.

4. Deriving the damage relations

In this section, the catered relation between the selected static and dynamic DIs in section 2 for the considered frames in section 3 is achieved. To obtain the relation between the aforementioned indices in the wide range, four hazard levels are assumed for each frame including 1, 1.5, 2 and 2.5 times of the average response spectrum of the selected earthquakes. So for each frame, four performance points are calculated and the static DIs are obtained in these points. After that, for each response spectrum, the value of Park and Ang criterion is computed subjected to related earthquakes. Due to the importance of the average response spectrum (life safety hazard level) and 1.5 times of it (ME hazard level), the points relating these levels are distinguished using triangle (red color) and lozenge (green color) and the rest of the points are circle (blue color) shapes. It is worth pointing out that the presented relations of this study are just valid to quantify the damage of SWRCFs with soil profile type II. On the other word, types of soil and frame are considered as two important assumptions for this study, which may be studied in the future.

4.1 Energy damage index

In this part, the correlation between the values of Energy criterion with values of Park-Ang damage index is acquired. The relevant outcomes have been demonstrated in Fig. 5.

As shown in Fig. 5, the scattering of the acquired points is completely satisfactory and it can be concluded that using the fitting curve according to the following equation will have little approximation to estimate the dynamic damage index. It is evident that the values of Park and Ang damage index for all triangle and lozenge points are either in the damage state of no damage or serviceable (based on the presented interpretation of the overall Park and Ang damage index Reinhorn *et al*. 2009). It is worth emphasizing that referring to the calibrated values of the park and Ang damage index with the degree of observed damage in structures (Park and Ang 1985) demonstrates when the values of Park and Ang damage index are higher than 0.4, the degree of damage is severe or collapse. Accordingly, the value of the considered damage index is usually lower than 0.4 for all the conventional performances. Moreover, the studied frames are the shear wall reinforced concrete frames, which have high lateral stiffness and consequently experience low damage and lateral displacements in earthquakes. The static damage values are varied from 0.006 to 0.749 and from 0.006 to 0.152 for triangle and 0.018 to 0.282 for lozenge shape points, respectively. As shown in Fig. 5, two lines named fitting line (solid line) and upper-envelop line (dashed line) are presented. Although fitting line (equation is presented in Fig.5) can estimate optimum values for the damage index, for the purpose of design, the conservative upper-envelop line is proposed as follows.

$$DDIn=0.175SDIn+0.08 \tag{6}$$

Where DDIn (y in the equation of fitting line) is the dynamic index and SDIn (x in the equation of fitting line) is the static energy index.

Since the proposed Energy damage index is a simple global criterion achieved using pushover analysis and also has an appropriate correlation with Park and Ang damage

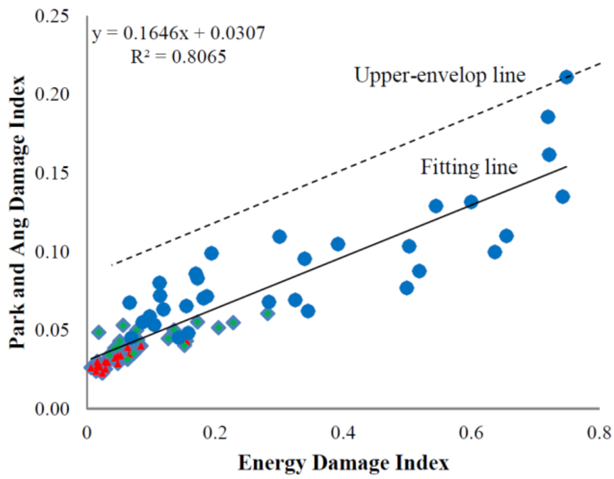

Fig. 5 Park and Ang damage index versus Energy damage index

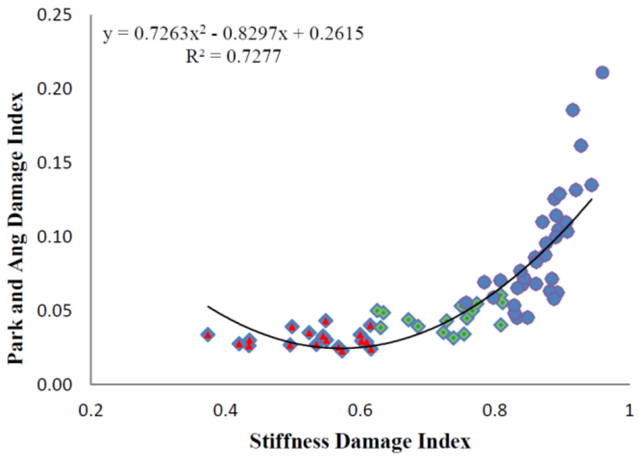

Fig. 6 Park and Ang damage index versus Stiffness damage index

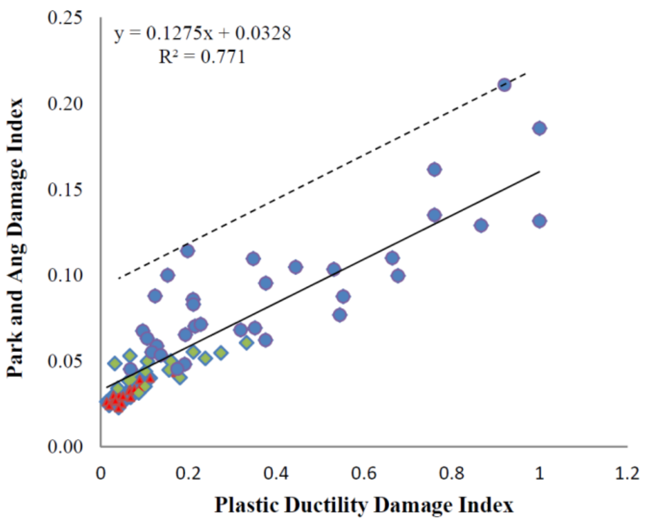

Fig. 7 Park and Ang damage index versus Plastic ductility damage index

index; therefore, the proposed methodology introduces a practical procedure to predict the nonlinear response of the structures.

4.2 Stiffness damage index

In this section, the values of Stiffness and Park-Ang damage index are achieved and depicted in Fig. 6.

As manifested in Fig. 6, due to the dispersal of the derived points, the linear interpolation cannot appropriately reflect the correlation of these indices; therefore, the square interpolation function is considered as the fitting curve. It is evident that the values of Park and Ang damage index is not sensitive to change of the values of the Stiffness criterion in range of 0.4 to 0.7 (for all triangles and the majority of lozenge points); therefore, the stiffness damage index is not an adequate damage index for estimating the damage of SWRCFs.

4.3 Plastic ductility damage index

The values Plastic ductility criterion and Park-Ang damage index are derived in this section and the correlation of them is presented in Fig. 7.

As it is demonstrated in Fig. 7, the calculated points are almost close to linear fitting curve, so the Park and Ang damage index can be appropriately approximated using the following equation. The static damage values vary from 0.014 to 0.17 for triangle and 0.032 to 0.332 for lozenge shape points, respectively. In this section, just like section 4.1, the conservative upper-envelop line is proposed to design aims (Eq. (7)).

$$DDIn=0.139SDIn+0.083 \tag{7}$$

The scattering of the points, as can be seen in Figs. 5 and 7, is different for various damage values. It is observed that for energy and ductility damage indices, the scattering of the points is great at large damages while that is good at the small ones.

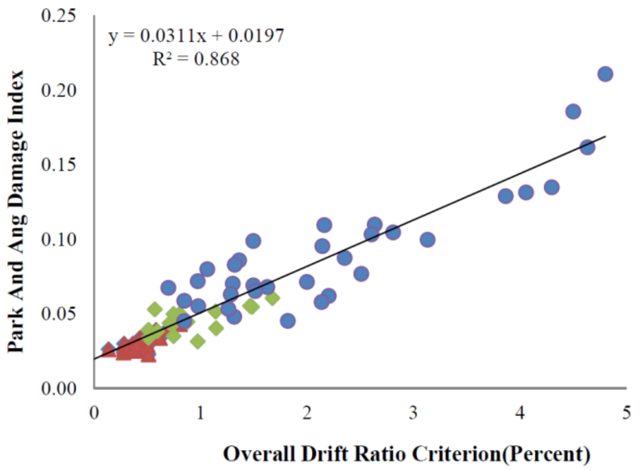

Fig. 8 Park and Ang damage index versus overall drift ratio criterion

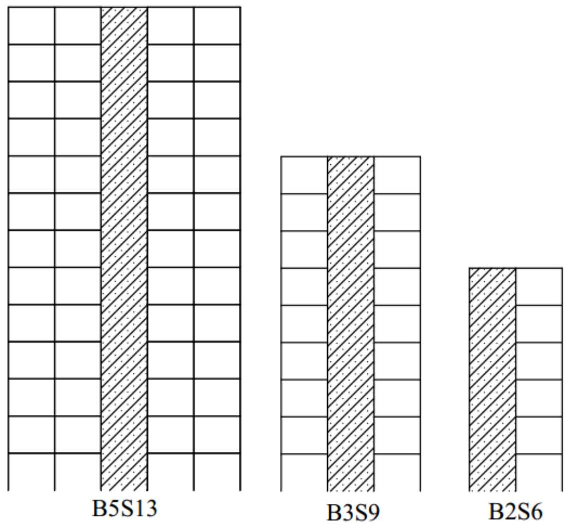

Fig. 9 The Geometry and names of the studied frames

4.4 Drift ratio criterion

In this part, the values of overall drift ratio criterion and Park-Ang damage index are derived and shown in Fig. 8.

As demonstrated in Fig. 8, of all evaluated criteria, the overall drift ratio has the best dispersion around the fitting curve or on the other hand, the overall drift ratio has an approximately linear relation with Park and Ang damage index. It is vivid that for all the triangle shape points, the percentages of overall drift ratio are lower than 1 and for lozenge shape points, are lower than 2 that these values show the proper performance of the designed SWRCFs. Likewise, it should be pointing out that even for overall drift ratio 5%, the values of the dynamic damage index is lower than 22 percent that prove the potential ability of SWRCFs in resisting lateral displacement with serviceable damage (Reinhorn *et al*. 2009).

5. Evaluating the proposed relations

In this section, to assess the accuracy of the derived

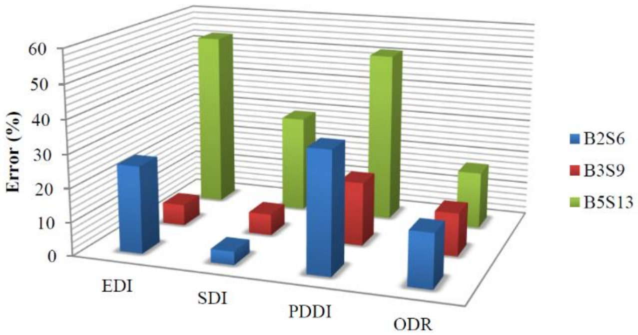

Fig. 10 The percent error of studied frames

relations in section 4, three new SWRCFs with various numbers of stories and bays as depicted in Fig. 9 are designed (the material and geometry properties are similar to section 3) and the static and dynamic damage analyses of them are carried out. First, considering the average response spectrum (section 3), the performance points of these frames are acquired and the static DIs are achieved. After that, once Park and Ang damage index is computed using the proposed relations of this study (refers to NDIPR) and again through NDA (NDI) and eventually, the percentage of errors are calculated. The outcomes are demonstrated in Fig. 10.

As demonstrated in Fig. 10, in spite of appropriate scattering of EDI and PDDI in section. 4, the errors of these indices are very high. For the SDI, the situation is completely inverse. On the other hand, despite the aforementioned shortcomings of this criterion, the percentage errors of this index for these frames are satisfactory. Of the assessed static DIs, the Overall drift ratio is the only criterion that has an appropriate dispersal (section 4) as well as proper outcomes in this section.

6.Conclusions

In this study, some practical relations are introduced to quantify the amount of damage of SWRCFs based on pushover analysis. To do so, the some static damage indices considering the various aspects of the seismic behavior of SWRCFs are taken into consideration and the values of damage of SWRCFs are obtained using pushover analysis. Afterwards, for the aforementioned SWRCFs, the values of Park and Ang damage index as a well-known damage index through nonlinear dynamic analysis are acquired and the correlation between each static damage index with Park and Ang damage index are presented. The results show that some static damage indices have more compliant with Park and Ang damage index due to more appropriate distribution of the achieved points. Eventually, to prove the validity of the proposed relations, the dynamic damages of three new frames are achieved once using pushover analysis and the proposed relations and again through nonlinear dynamic analysis. The outcomes show that of the static damage indices, the overall drift ratio criterion presents the best performance to estimate the Park and Ang damage index using pushover analysis.

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