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"Research Note"

INELASTIC DAMAGE ANALYSIS OF RCMRFS USING PUSHOVER METHOD*

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Abstract– The main objective of this research is to develop a practical damage criterion based on pushover analysis. For this purpose, damage analysis is performed on several Reinforced Concrete Moment Resisting Frames (RCMRFs). In the static method, performance point of structures is firstly determined using capacity spectrum method and then values of several different damage indices are calculated at these points. By comparing the results of two methods and evaluating correlation between two sets, explicit damage relations are derived based on the static results.

Keywords– Damage index, nonlinear dynamic analysis, pushover, performance, capacity spectrum

1. INTRODUCTION

Quantification of the potential for damage of earthquake ground motion has a wide range of applications for analysis and design of new structures as well as for seismic evaluation of existing facilities [1]. A damage index (DI) is based on a set of structural response parameters such as force, deformation, and dissipation of energy. These indices include important features such as inelastic structural response, cumulative effects of repeated cycles of inelastic structural deformation, and the duration of strong motion. There are numerous DIs available [1-6].

Reviewing the literature of the subject reveals that most of the related researches need nonlinear time history analysis which, in turn, is quite a time-consuming and rigorous procedure. There are few researches in which the pushover method has been used for damage analysis of the structure. In this regard, studies of Ghobarah et al. 1999 [7] and Habibi et al. 2006 [8] can be mentioned. Also, some seismic guidelines such as FEMA273 and ATC40 [9, 10] quantify the degree of damage to a building framework by establishing the relationship between damage and inter-story drift resulting from pushover analysis.

The main objective of this research is to develop a simple and effective index to qualify the amount of damage to the structure on the basis of the numerical results of nonlinear static analysis. A practical method based on the static pushover analysis is proposed to estimate the expected damage to structures when subjected to earthquakes.

2. PROPOSED METHODOLOGY

In this research, the damage in reinforced concrete elements will be quantified with the Park-Ang damage index in order to evaluate the accuracy of the proposed damage criteria. The preference of this index is its conformity with experimental results and also its simplicity and ranking proportion with observed damage

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[2]. The index combines the maximum lateral displacement effects with the plastic dissipated energy at one end of the element according to the following relation [2]:

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

As mentioned before, the main objective of this research is to develop some damage criteria based on nonlinear static analysis. In this part with due attention to the characteristics of pushover analysis and considering the different aspects of structural behavior in this analysis, we attempt to propose some criteria for estimating the damage to the structure.

a) Plastic ductility damage index

This index was proposed by Powell and Alahabadi (1988) [11] and is known as a local damage index. Its simplicity makes it outstanding for researchers and engineers. In the present research, it is implemented to calculate the global damage of the structure using the capacity curve resulting from pushover analysis as follows:

$$(DI)_{\mu} = \frac{u_{\max} - u_{y1}}{u_{mon} - u_{y2}} \tag{2}$$

where $u_{\max}$ is the maximum displacement, u_{y1} is the yielding displacement relating to performance point, u_{y2} is the yielding displacement relating to ultimate capacity of the structure, and u_{mon} is the ultimate displacement under monotonically increasing lateral deformation.

To apply this damage index in pushover analysis, it must be noted that $u_{\max}$ corresponds to the displacement at the performance point and u_{mon} corresponds to the ultimate displacement on the capacity curve. u_{y1} and u_{y2} are computed from equivalent two linear capacity curve at performance point and ultimate point respectively.

b) Stiffness damage index

Habibi et al. [8] based on the Ghobarah’s damage index [7], introduced damage stiffness index for evaluation of seismic performance of RCMRFs. This damage index is obtained using pushover analysis from the following equation:

$$(DI)_j = 1 - \left(\frac{k_j}{k_{OP}}\right) \tag{3}$$

where k_j is the slope of the capacity curve (the base shear - roof displacement relationship) relating to different performance levels resulting from the pushover analysis of the frame and k_{OP} is the slope of the capacity curve relating to operational level.

c) Drift criterion

This criterion is one of the popular indices employed to determine the global damage of the structure. This criterion is also recommended by existing seismic guidelines such as FEMA273 and ATC40 for evaluation of the performance level of the structure. In this study, this index is obtained from pushover analysis using the following relation:

$$(DI)_{Drift} = \frac{\Delta_m}{H} \tag{4}$$

where Δ_m is the target displacement at the performance level under consideration and *H* is the height of the structure.

d) Park and Ang damage index

As mentioned before, this index, calculated from Eq. (1) is utilized to evaluate the proposed damage criteria. In addition, it is calculated based on the nonlinear responses resulting from pushover analysis and is compared with the damage index value calculated from the nonlinear dynamic analysis. To calculate this index in static method, monotonically increasing lateral loads along with constant gravity loads are applied to the frame until the control node (usually referred to the building roof) sways to a predefined 'target' lateral displacement. Consequently the relationship between the base shear versus roof displacement, known as the capacity curve and which is the fundamental product of the pushover analysis, is determined. Then intersecting the capacity spectrum and inelastic demand spectrum, the performance point is obtained (ATC40). So the nonlinear responses such as stiffness, displacement, force, etc are determined at the performance point. Now by having the values of rotation and dissipated energy of each element at the performance point, static damage index can be computed from Eq. (1). It is noted that calculation of this damage index by dynamic method needs more intensive computational effort than that by pushover method.

3. DAMAGE ANALYSIS OF THE SAMPLE FRAMES

To evaluate damage criteria proposed in section 2, which are named "static criteria" in the present research, inelastic damage analysis based on Park-Ang damage index, which is named "dynamic criterion" in the present research, is carried out on fourteen reinforced concrete frames with various numbers of stories and bays, as shown in Fig. 1, subjected to seven earthquakes listed in Table 1. For more details about the frames and the records refer to Habibi and Izadpanah (2012) [12].

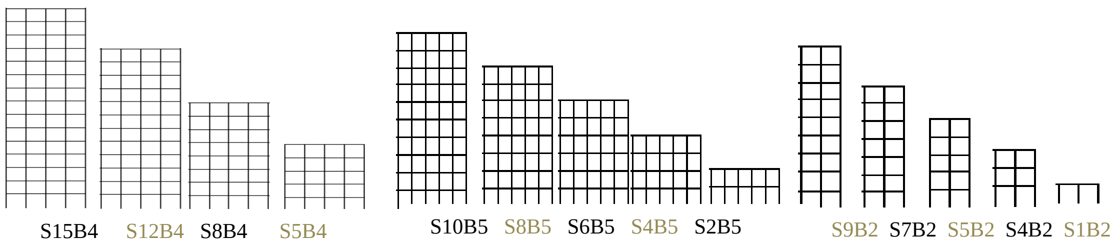

Fig 1. Geometry and names of the studied frames

Table 1. Ground motion records

Earthquake number	Record	Station	Component (deg)	PGA (g)
1	Imperial Valley	286	135	0.195
2	Landers	21081	90	0.146
3	Loma Prieta	58131	270	0.06
4	Loma Prieta	58151	90	0.09
5	Loma Prieta	58338	45	0.084
6	Northridge	23590	90	0.056
7	Northridge	90019	180	0.256

To perform nonlinear dynamic and static analysis of all the frames, IDARC 6.1 software was utilized. It must be noted that reinforcement is not directly modeled in the IDARC software. In this software, cross-sectional properties such as moment-curvature relationship are determined as functions of the section dimensions and reinforcement. The effect of bond-slip between reinforcement and concrete is ignored in modeling. Failure criterion is defined based on a special spread plasticity model. In this model, the moment distribution along a member subjected to lateral loads is considered to be linear. When the member experiences inelastic deformations, cracks tend to spread, forming the joint interface resulting in a curvature distribution. Sections along the element will also exhibit different flexibility characteristics, depending on the degree of inelasticity observed. The program IDARC includes a spread plasticity formulation to capture the variation of the section flexibility, and combines them to determine the element stiffness matrix.

To calculate the damage criteria in pushover analysis first, by using capacity spectrum method, performance levels of the structures were determined, and then the values of the indices were calculated in performance levels. The location of the performance point must satisfy two relationships: 1) the point must lie on the capacity spectrum curve in order to represent the structure at a given displacement , and 2) the point must lie on a spectral demand curve, reduced from the elastic 5 percent-damped design spectrum that represent the nonlinear demand at the same structural displacement. In the capacity spectrum method, spectral reduction factors are given in terms of effective damping. The effective damping is approximated based on the shape of the capacity curve, the estimated displacement demand, and the resulting hysteresis loop. In the general case, determination of the performance point requires a trial and error search for satisfaction of the two criterions specified above. For each sample frame, a 5% damping linear response spectrum has been modified to match the high damping of the frame in its nonlinear range from the following equation [10]:

$$\beta_{eq}=\frac{63.7(a_y d_{pi}-d_y a_{pi})}{a_{pi} d_{pi}}+0.05 \tag{5}$$

Where a_y, d_y are the acceleration and displacement of the yielding point respectively; and a_{pi} and d_{pi} are the acceleration and displacement of the performance point respectively.

To determine the relation among the mentioned criteria in a large range of the amounts of the damages, five performance levels were considered for each frame. These levels correspond to 1, 1.5, 2, 2.5 and 3 times the average response spectrum of the selected earthquakes. The values of the static damage criteria were calculated at these performance levels. In order to calculate the dynamic damage criterion for each one of the spectrums, the selected records were scaled and then nonlinear dynamic analysis was performed on the frames subjected to each record. In Figs. 2 to 5 triangle points are related to corresponding damages to the average spectrum (the design spectrum of standard 2800 [13]) and circle points are related to corresponding damages to one and a half times the average spectrum. The rest of the points are indicated by lozenge.

a) Evaluation of plastic ductility damage index

In this part, by comparison of the values of static plastic ductility damage index with values of dynamic Park-Ang damage index, their correlation is assessed. The relevant results have been shown in Fig. 2.

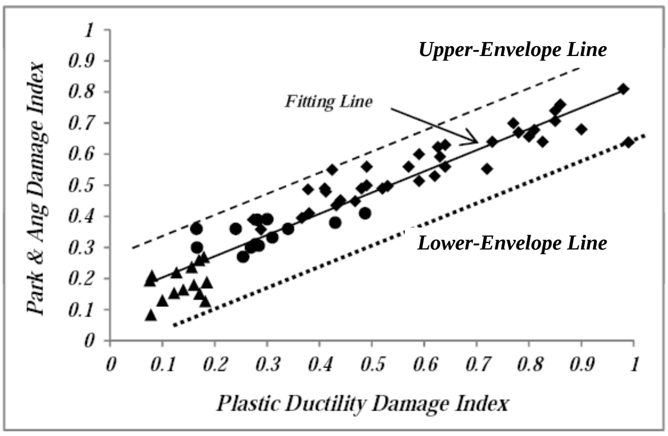

Fig 2. Relation between Plastic Ductility and Park-Ang damage indices

In this static index, the dispersion of points are quite satisfactory and, as a matter of fact, maybe the result of the considerable importance of the inelastic displacements when damage to the structures happens. For this reason, making use of the fitting curve in Fig. 2 according to the following equation will have little approximation.

$$DI_{PA\text{-}D} = 0.681\, DI_{P\text{-}S} + 0.135 \tag{6}$$

where $DI_{P\text{-}S}$ is the static plastic ductility damage index. The average value of this static index is 0.44. This value is quite close to the average value of Park-Ang damage index (0.43). Another tangible matter in this figure is the range of changes in corresponding with triangle and circle points which vary from 0.076 to 0.185 and from 0.165 to 0.487 respectively.

In this damage index, for the purpose of design the following conservative upper-envelop line can be utilized:

$$DI_{PA\text{-}D} = 0.681\, DI_{P\text{-}S} + 0.261 \tag{7}$$

b) Evaluation of Stiffness Damage Index

In this part, by comparing the values with the dynamic Park-Ang damage index, the static secant stiffness criterion is evaluated and then the correlation between them is investigated. Fig. 3 shows this relationship.

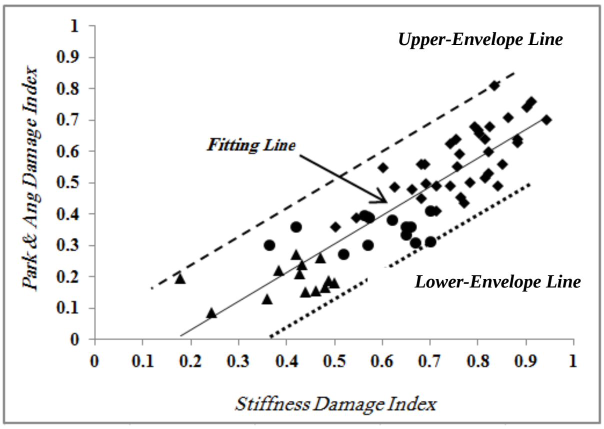

Fig 3. Relation between Stiffness and Park-Ang damage indices

As it is clear from the figure the stiffness damage criterion, in most cases, is more than corresponding Park-Ang damage index. The average value of it is 0.655. It is observed that the values of the static damage index vary from 0.178 to 0.5 and from 0.364 to 0.7 for triangular and circle points respectively. The highlighted matter in this criterion can be the improper scattering of points. This will cause the use of the proposed equation to be accompanied by high approximation. This scattering can in turn be the result of not considering the effect of hysteresis loops of structure.

c) Evaluation of drift criterion

In this section, comparing the static drift criterion which is introduced as a performance criterion in FEMA273 and ATC40 regulations with the amount of dynamic Park-Ang damage index, the correlation between these two damage indices is studied. This relationship has been shown in Fig. 4.

This figure shows that the range of changes of triangle and circular points is from 0.673 to 1.25 and from 0.915 to 2.1 respectively. From the achieved results, it can be seen that up to the drift of two percent (life safety definition in FEMA273), the amount of Park-Ang damage index is less than 0.4 (structure's reparability limit); though some points higher than 0.4 in the neighborhood around this drift value can be found. The correlation between the two criteria shows a high dispersion of points in this static index. This can be the result of the exclusion of the final capacity of structure in this criterion. Considering this matter, it can be concluded that employing this criterion for determination of seismic performance of structures can lead to incorrect results. Therefore it seems that the existing criteria in conventional seismic regulations need to be reviewed and revised.

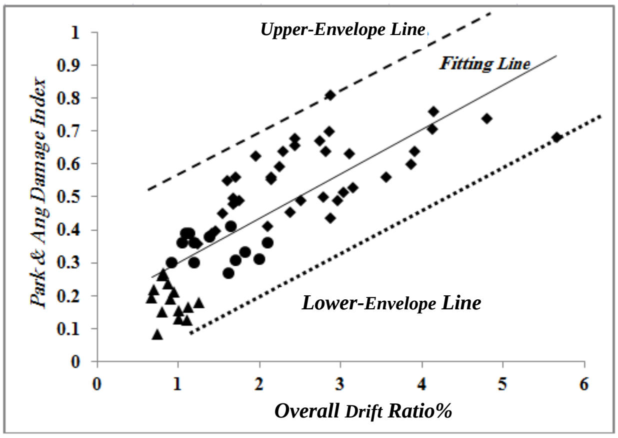

Fig 4. Relation between Drift and Park-Ang damage indices

d) Evaluation of static Park-Ang damage index

In this part, a comparison is made between static Park-Ang damage index resulting from pushover analysis and dynamic Park-Ang damage index resulting from nonlinear dynamic analysis. It must be noted that Eq. (1) is the basis for the damage index computation for both axes x and y in this Figure, although some considerations need to be taken into account as discussed below. Park-Ang damage index is calculated using Eq. (1) based on the results of two different methods including nonlinear dynamic analysis and pushover analysis. Vertical axis is considered to be dynamic DI and horizontal axis is considered to be static DI. That is, nonlinear dynamic analysis of each frame subjected to several earthquake records results in a value for dynamic DI (vertical axis), while pushover analysis of each frame subjected to corresponding demand spectrum results in a value for static DI (horizontal axis). To calculate the static damage index, the first performance point is determined using the capacity spectrum method and then the parameters used in Eq. (1) are computed at corresponding performance level. Accordingly, comparison of two damage indices is performed. The correlation between these two indices has been shown in Fig. 5.

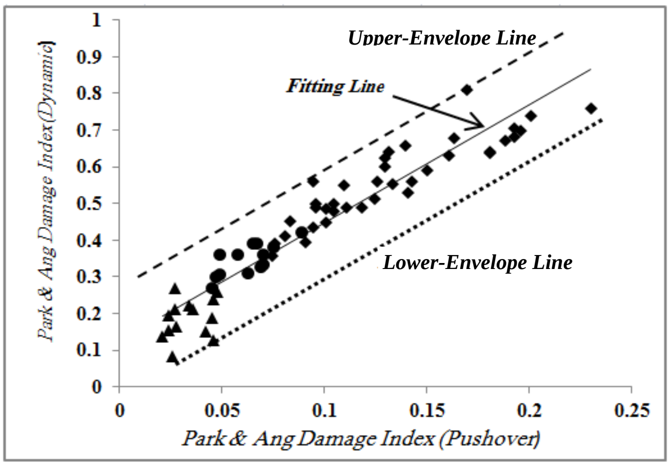

Fig 5. Relation between dynamic and static Park-Ang damage indices

As it is seen, the amounts of Park-Ang damage index in dynamic status are much more than the corresponding amounts of this index in static status. As an example, at the point with the highest static damage of 0.23, the corresponding dynamic damage is 0.76, and at the point with the lowest static damage of 0.026, the corresponding dynamic damage is equal to 0.0841. Also, the average static damage is 0.097 while the average dynamic damage is 0.43. The significant difference between the two criteria can be the result of different nature of dynamic and static analysis. In the pushover analysis, the structure is subjected to monotonically loading pattern. Moreover, unloading effects and higher vibration mode effects are ignored in the nonlinear static analysis. Despite the existing considerable difference between the two criteria, suitable dispersion among the points in Fig. 5 is seen. The consequent result would be that the proposed relation as shown below would have little approximation:

$$DI_{PA\text{-}D} = 3.221\, DI_{PA\text{-}S} + 0.125 \tag{8}$$

where $DI_{PA\text{-}S}$ is the static Park-Ang damage index resulting from pushover analysis. By referring to Fig. 5, it is observed that the values of static damage corresponding to triangular points and circular ones are variable from 0.021 to 0.048 and from 0.045 to 0.089 respectively. It is necessary to mention that although by having the static criterion the dynamic damage can easily be estimated, Park-Ang criterion is a local damage index and the global damage index is obtained from special combinations of local damage measures and this makes the calculations difficult and complicated. For this reason, use of global criteria such as static ductility criterion which is in proper consistence with the results of dynamic criterion can be more effective.

4. SUMMARY AND CONCLUSION

In the present research, to achieve a simple and effective criterion with the capability of satisfactorily estimating the damage to structure, several damage criteria based on the nonlinear responses resulting from pushover analysis were proposed and evaluated. The obtained results of inelastic damage analysis of different kinds of reinforced concrete frames subjected to various earthquakes indicated that static plastic ductility criterion has better performance than any other criteria evaluated in this research. In this regard, conservative upper-envelop relation was proposed for the purpose of design of RCMRFs with control damage based on this proper criterion.

The enormous disperse of drift criterion, which is recommended by existing seismic regulations such as FEMA273 and ATC40, showed that employing this criterion for determination of seismic performance of the concrete structures is not reliable and can lead to incorrect results.

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