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Seismic Vulnerability Assessment of Existing RC Moment Frames using a New Stiffness Based Damage Index

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ABSTRACT

Earthquakes cause a lot of damage to structures. A quantitative estimate of the amount of damage to the structure always seems quite necessary after an earthquake. For this purpose, seismic damage indices have been introduced as dimensionless quantities that can report the extent of damage using various criteria. This quantitative assessment can help make decisions about the process of improving, repairing, and strengthening structures. This paper presented a new stiffness-based damage index with simple formulation by performing pushover analysis on existing concrete models and applying the results. Using the capacity curve obtained from the pushover analysis output, this index can provide a quantitative estimate of the amount of damage to the entire structure. To validate the results, damage estimation was also performed using several reliable models such as the Park-Ang model and then compared with the proposed index results. Then, a series of theoretical suggestions were presented to address the existing weaknesses, which were implemented, and new results were obtained. Finally, the implemented reform proposals led to an improvement in the performance of the proposed index, resulting in excellent accuracy due to the simple computational process compared to the complex implementation of the Park & Ang index.

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1. INTRODUCTION

Different structures are made to last for long periods. However, they may suffer some damage during their service life as a result of changes in loading patterns and random excitations such as earthquakes. Predicting the extent of damage to the structure over its service life is a probabilistic issuem. Nevertheless, many researchers have proposed several equations to quantify damage by applying various engineering parameters, such as curvature, rotation, strength, stiffness, and dissipated energy [1]. The performance-based structural design method allows designers to purposefully control the amount of damage to the structure as a result of mild to severe earthquakes. One of the most effective tools to handle the results about the damage performance of the structure is the damage index (DI) together with the damage states, which are used to correlate the damage indices with the damage that occurred in the actual structures [2]. Damage indices use different initial parameters to estimate the amount of damage, and therefore, the degree of complexity in how they are used varies. Given the importance of detecting seismic damage, several studies have been performed on the seismic performance of reinforced concrete frames based on seismic indices. These studies aimed to investigate the condition of a reinforced concrete building following an earthquake and estimate the amount of damage according to seismic demands. Another goal was to study the relationship between structural damage level and the important characteristics of the input earthquake. Wen and Loh [3] attempted to determine the relationship between design level and performance level. The project investigated the relationship between the annual probability of exceeding the seismic hazard level and the performance of a building subjected to a certain intensity of earthquake loading. The Park-Ang index was used as a damage criterion to quantitatively introduce the

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performance level. Also, the relationship between the components of earthquakes in Iran region and the amount of damage to concrete frames was investigated in a research project [4]. De Domenico and Hajirasouliha [5] investigated the steel frames criteria and the damage index in the performance-based design method of reinforced concrete buildings. They also studied the relationship between damage to components and the values of the above criteria. In another study, researchers investigated the relationship between the proposed levels of FEMA and different damage indices. In this research project, several models of steel frames were analyzed, and the time history and damage index curves were plotted against different performance levels [6]. In addition, the correlation assessment between the damage criteria obtained from the results of a pushover analysis at different performance levels of a 2D bending moment frame was performed in another research work [7]. Some researchers conducted a laboratory study on the seismic response of concrete foundations of existing bridges. They attempted to build a model of a multi-column concrete foundation in the laboratory and measure the behavior of the structure at different performance levels under the effect of cyclic loading [8]. Tasnimi [9] investigated the Park index at the seismic performance levels of reinforced concrete frames using the results of nonlinear dynamic analysis. The vulnerability of concrete frames was examined in another study. They performed nonlinear dynamic analysis on multi-story concrete frames. They also examined the characteristics of the incoming earthquake and used the Park & Ang damage index to assess damage in numerical models [10]. Also, some researchers attempted to quantify the damage level of Shear Wall RC Frames based on nonlinear static and dynamic analysis results. They used the Park & Ang damage index as benchmark, examined other indices such as drift percent and finally introduced some practical relations [11]. Aghagholizadeh and Massumi [12] assessed the seismic vulnerability of concrete moment frames by nonlinear dynamic analysis. In their study, the relationship between changes in structural vibration period and damage index was investigated and finally a new relationship was proposed to estimate the damage [12]. Habibi and Asadi [13] developed drift-based index to estimate damage to reinforced concrete moment frames with vertical irregularity setback. They used inelastic dynamic time-history analysis on several frames with different types of setbacks and their damage is computed by the Park & Ang damage index [13]. Rastegarian and Sharifi [14] evaluated dependency of structural performance level on its corresponding inter-story drift in RC moment frames. They used pushover analysis and finally proposed equations to predict drift percent at performance levels. Hait et al. [15] studied the damage in RC buildings using an analytical method, presented a new damage index based on a combination of different structural response criteria which provided accurate results compared to the Park & Ang damage index. Ozturk et al. [16] evaluated precast industrial concrete buildings by using dynamic analysis and fragility curves that were designed and built according to the building codes of Turkey. Other researchers have performed static and dynamic analyses on a number of concrete frames [17]. Kassem et al. [18] presented by performing nonlinear static and dynamic analysis and by classifying damage levels, a simple and practical method to assess damage in reinforced concrete buildings based on the results of vulnerability damage index. In another paper, based on the suggested method of damage assessment using the vulnerability index, they examined the damage in a school building. With the help of the results of this research, it is possible to provide a proper assessment of the structural damages without the need for expert observations [19]. The evaluation of the effect of ductile details in reinforced concrete structures was investigated in another study. In this research, two ductile and non-ductile frames were modeled and using the results of pushover analysis, the effect of using ductile details on the safety, stability and economy of the models was investigated [20]. In another paper, Mibang and Choudhury [21] investigated seismic damage in reinforced concrete frames with shear walls. In this research, the Park & Ang damage index was used to calculate the amount of damage. The research results showed that in these structures, the most damage occurred on the ground story [21]. In another work, Nair et al. [22] evaluated the seismic vulnerability of high-rise concrete frames in the United Arab Emirates with the help of fragility curves. Zameeruddin and Sangle [7] proposed a damage index based on stiffness changes in order to estimate the structural global damage, and calculated its value at the proposed performance levels of FEMA-273. The history of using damage indexes in estimating post-earthquake damage was examined, indicating that most of the research was performed using the nonlinear dynamic analysis method. Limited research has been conducted on the relationship between pushover analysis and damage assessment, including. Also, some seismic instructions such as FEMA-273 [23] and ATC-40 [24] have stated the amount of damage to the structure based on the relative lateral displacement values resulting from pushover analysis.

The present paper presents a damage index based on pushover analysis output, which was performed on several concrete frames. The amount of damage can be measured based on the cumulative degradation of the stiffness. Then, to validate the results compared to the values of valid indices, the amount of damage was also calculated and classified based on the Park & Ang model and relative lateral displacement, followed by comparing the values of the presented index with its results. Several theoretical modifications were made to improve the performance of the introduced index and the results; the results were re-examined. As a result of the improvements made, the results improved compared to the original model and became more coherent with the Park index. The amount of damage to the whole structure can be properly estimated by performing a series of simple calculations away from the complexity of the Park index by using this index that only uses the information of the capacity curve of the structure.

2. DAMAGE INDEX

The main purpose of assessing the damage to the structure is to find a set of reliable quantities to determine the amount of damage to the structure. Over the years, a significant body of research has focused on developing such methods. An appropriate damage index has the following characteristics:

A) General usability: Damage indices should be able to be applied to different systems under different loads.

B) Easy evaluation: Damage indices should be usable in practice, and their introduced parameters can be understood, observed, and measured.

C) Physical interpretation capability: Damage indices should be able to express the physical meaning of the damage to the structure. Damage indices are generally defined either in terms of parameters related to economic conditions or in terms of resistance-safety considerations. Economic damage indices are usually defined in terms of the parameters representing the cost of replacing and repairing the necessary structural elements. Specific and complete information is required in this regard, and determining repair and replacement costs is relatively difficult. Resistance-safety damage indices are related to the amount of reduction in structural strength. The damage index is generally a normalized quantity with numerical values between 0 and 1, with 0 meaning no damage and 1 meaning collapse.

2. 1. Relative Lateral Displacement Based Damage Index

The criterion of " Story relative lateral displacement " can be used as a simple and popular tool to assess the total damage to the structure. Performance based design instructions such as FEMA-356 and ATC-40 detemine the structural performance level by setting four limit values for this index. This index can be calculated based on the results of pushover analysis using Equation (1) [25]:

$$DI_{drift} = \frac{\Delta_m}{H} \tag{1}$$

In this regard, Δ_m is the target displacement at the performance level and H is the height of the structure studied. In Table 1, the limit state values of this index are presented for each performance level.

2. 2. Park&Ang Damage Index

Extensive research has been conducted in recent years to develop an accurate model for assessing the extent of damage to structures. The Park and Ang model [26] is one of the most common damage indices used to analyze damage to members and, on a larger scale, structures. Three types of damage indices can be calculated using this model: member damage index (e.g., column, beam, and shear wall), floor damage index, and total structure damage index. The Park & Ang damage index was initially a combination of maximal non-cumulative deformation and hysteretic energy. Reinhorn et al. [27] modified the Park & Ang damage model based on Equation (2):

$$DI_{Park\,\&Ang} = \frac{\theta_m - \theta_y}{\theta_u - \theta_y} + \frac{\beta}{M_y \theta_u} \int dE \tag{2}$$

where θ_y , θ_m and θ_u are the yield rotation, maximum rotation, and maximum rotation capacity of the member section, respectively, under uniform incremental loading. This model is currently used in IDARC-2D software to analyze the damage to reinforced concrete structures. This damage index is proportional to the observed damage classified, as shown in Table 1 [28]. The value of this index is calibrated in the range [0, 1], reporting the absence of damage and complete damage and destruction of the member (or structure), respectively. Other performance levels, such as immediate occupancy, life safety, etc., will fall within these limits. Operational, immediate occupancy, life safety, and collapse prevention performance levels correspond to minor, low, moderate, and severe damage (Table 1 and references ATC-40 and FEMA-273).

TABLE 1. Classification of Structural Damage According to Park & Ang Index values and drift percent

Performance levels	Degree of damage	Park&Ang damage index value	Drift damage index(%)
Operational	Slight	$DI < 0.10$	$DI_{drift} < 0.70$
Immediate occupancy	Minor	$0.10 < DI < 0.25$	$0.70 < DI_{drift} < 1$
Life safety	Moderate	$0.25 < DI < 0.40$	$1 < DI_{drift} < 2$
Collapse prevention	Severe	$0.40 < DI < 1$	$2 < DI_{drift} < 4$
Collapse	Collapse	$DI > 1$	$DI_{drift} > 4$

2. 3. Stiffness-Based Damage Index The amount of damage can be calculated according to the slope of the structural capacity curve obtained from pushover analysis at different levels. Saleemuddin and Sangle [1], presented a stiffness-based damage index to the original form of Equation (3), derived from the following expression [29]:

$$DI_c = 1 - \frac{K_c}{K_o} \tag{3}$$

In Equation (3), DI_c is the damage index at the moment of collapse of the structure. Also, K_c and K_o are the structural stiffness at the collapse level and the service level, both derived from the capacity curve, respectively. From the above equation, it can be concluded that the amount of damage is estimated based on the occurrence of the first yield in the structure. To solve the challenge of not considering the cumulative effects of structural damage, a new equation was presented and used as follows [1]:

$$(1 - DI_c)K_o = K_c \tag{4}$$

$$(1 - DI_c)K_o d_p = V_p \tag{5}$$

According to Equations (4) and (5), stiffness can be replaced by base shear and displacement at the collapse level. According to the incremental steps of pushover analysis, Equations (6)-(9) can be written according to the capacity curve:

$$K_o d_1 = V_1 \tag{6}$$

$$K_1(d_2 - d_1) = V_2 \tag{7}$$

$$K_2(d_3 - d_2) = V_3 \tag{8}$$

$$K_n(d_p - d_n) = V_p \tag{9}$$

In the above equation, K_o is the structural stiffness at the full-service level, d_p is the displacement of the structure at the calculated level, and V_p is the shear force of the structure at the same level, obtained from the capacity curve. Also, d_n is the displacement at any desired point n and K_n is the structural stiffness at the desired point,

which must be read from the curve. For each step of pushover analysis, according to Equations (6)-(9) and Figure 1, the left-hand side of Equation (9) can be rewritten as a sum of several terms as Equation (10):

$$\sum_{i=0}^{n=l} K_o d_1 + K_1(d_2 - d_1) + K_2(d_3 - d_2) + K_n(d_p - d_n) = V_p \tag{10}$$

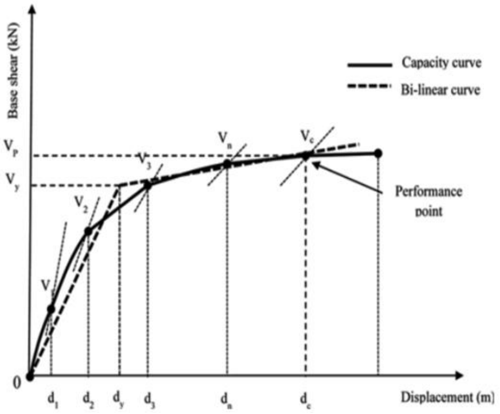


Figure 1. Display parameters on the pushover curve [1]

$$DI_c = 1 - \frac{V_p}{K_o d_p} = 1 - \frac{\sum_{i=0}^{n=l} K_o d_1 + K_1(d_2 - d_1) + K_2(d_3 - d_2) + \ldots + K_n(d_p - d_n)}{K_o d_p} \tag{11}$$

The above equation represents the value of the damage index at any desired level, which can also consider the reduced cumulative stiffness [1]. Therefore, the damage index values for the performance levels based on FEMA273, i.e., IO, LS, and CP were written as follows (Equations (12)-(14)):

$$DI_{IO} = 1 - \frac{\sum_{i=0}^{n=l} K_o d_1 + K_1(d_2 - d_1) + K_2(d_3 - d_2) + \ldots + K_{IO}(d_{IO} - d_n)}{K_o d_p} \tag{12}$$

$$DI_{LS} = 1 - \frac{\sum_{i=0}^{n=l} K_o d_1 + K_1(d_2 - d_1) + K_2(d_3 - d_2) + \ldots + K_{LS}(d_{LS} - d_n)}{K_o d_p} \tag{13}$$

$$DI_{CP} = 1 - \frac{\sum_{i=0}^{n=l} K_o d_1 + K_1(d_2 - d_1) + K_2(d_3 - d_2) + \ldots + K_{CP}(d_{CP} - d_n)}{K_o d_p} \tag{14}$$

The damage index calculates the total damage to the structure at different performance levels based on the above model.

3. THE RESEARCH PROCESS

3. 1. Description of Study Models Three concrete frame models were selected based on the specifications in the research conducted by Reinhorn et al. [27] and Ferracuti et al. [30]; modeled in the IDARC 2D Version 7.0 program [18]. In these frames, the number of floors is 3, 4, and 6, respectively, and the number of frame spans is 2, 3, and 2, respectively (Figure 2). The height of the floors in the first frame, taken from a frame with laboratory dimensions [18], is 1.5 meters, and the length of each span is 3 meters. In the second (three-span) and third (two-span) models, the height of the first floor was equal to 3.5 meters, and the height of the other floors was equal to 3 meters. Also, in the second model, the length of each span was equal to 5 m, and in the third model, it was equal to 5.5 and 5 m [30]. The concrete used in the first frame has a compressive strength of 40.2 MPa, and the steel used has a yield strength of 400 MPa. In the second and third models, the concrete used had a compressive strength of 30 MPa, and the steel used was considered to have yield strength of 414 MPa [27, 30].

3. 2. Numerical Modeling in the Program and Performing Nonlinear Analysis

The models introduced in the preceding section were generated in IDARC-2D V7.0. As a set with the ability to consider various aspects of concrete element behavior, the IDARC program was introduced in 1987, to study the nonlinear response of reinforced concrete structures [27]. This program is capable of doing nonlinear static and dynamic analyses and provides various information according to the user's request such as displacement status, stress ratio in elements, plastic hinge formation process, the amount of damage in the structure, and modal information of the structure in different steps during progress. In the mentioned program, columnar elements are considered as macro models with inelastic flexural deformations and elastic shear and axial deformations, and in the beam elements, inelastic flexural deformations are considered with elastic shear deformations [27]. Nonlinear static analysis is done on numerical models of the present paper.

To consider the nonlinear behavior of beams and columns, a concentrated plasticity model was used at both ends of the element (Figure 3). The IDARC-2D program uses a modified model in which the program considers two nonlinear rotational springs at both ends of the element while considering the element as elastic. As a result, the plasticity behavior of the element will be active only at both ends of the beams and columns. This model also includes rigid end zones [27]. Since the lengths of the beams and columns introduced to the program are center-to-center, the rigid end zones that must be defined by the user for both ends of the elements are the joint area where the elements connect to each other and to the ground, which is considered rigid in the element of the beam or column. In addition, to model, the behavior of beams and columns, a multi-linear hysteretic model was used. The selected cycle parameters for the elements were introduced as ductile sections with appropriate details. It must be mentioned that the IDARC program considers hysteretic behavior for both ends of the element. To introduce hysteretic behavior to the program, regarding the program guide, the user must specify the HC, HBD, HBE, and HS values. These values are determined based on the definitions provided in Table 2.

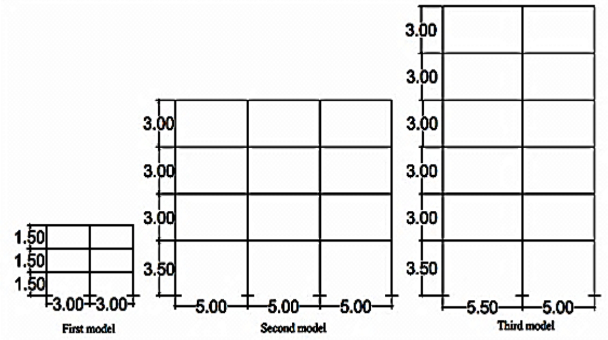


Figure 2. Geometric view of the numerical models

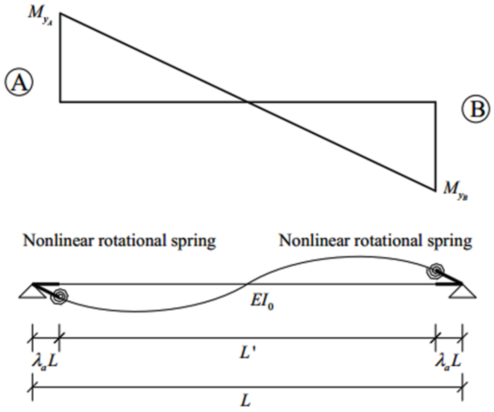


Figure 3. Concentrated plasticity model [28]

Generally, increasing the amount of HC delays the amount of stiffness degradation. In addition, increasing HBD and HBE will increase the resistance degradation rate, and increasing HS will reduce the slip value. Consequently, the HC value was considered equal to the default value of 200, which is the maximum value proposed for the introduction of behavior without stiffness degradation. To introduce the strength deterioration parameter, the values of HBD and HBE were equal to 0.01 to introduce the mode without strength deterioration and the value of HS was equal to one for bond slipping (Pinching) [27]. Regarding the program guide, the model intended for the rotational behavior of elements was introduced in Figure 4. Also, nonlinear geometric effects (P-Δ) were considered. The uniform vertical load applied to the floor beams was equal to 20 kN/m.

The IDARC program can perform pushover analysis in the form of displacement control and force control. In this study, pushover analysis was performed based on force control.

TABLE 2. Details of typical parameters and default values to introduce hysteretic behavior in members [27]

Parameter	Meaning	Value	Effect
HC	Stiffness degradation parameter	4	Severe degradation
		10	Moderate degradation
		15	Mild degradation
		200	No degradation (Default)
HBD	Strength degradation parameter (ductility-based)	0.60	Severe degradation
		0.30	Moderate degradation
		0.15	Mild degradation
		0.01	No degradation (Default)
HBE	Strength degradation parameter (energy-controlled)	0.60	Severe deterioration
		0.15	Moderate deterioration
		0.08	Mild deterioration
		0.01	No deterioration (Default)
HS	Slip or Crack-closing parameter	0.05	Severe pinched loops
		0.25	Moderate pinching
		0.40	Mild pinching
		1	No pinching (Default)

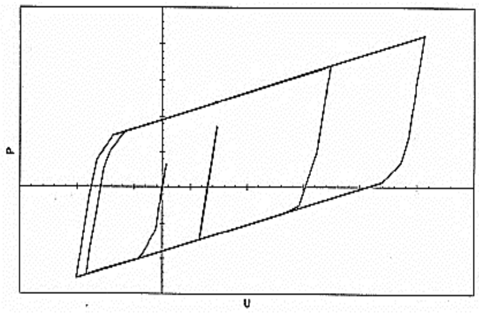


Figure 4. Multi-linear hysteretic model [28]

a) In the first model, the lateral load distribution was considered an inverse triangle. This distribution is often suggested by building codes, which assume that the building is subject to a linear acceleration distribution along its height (Figure 5(a)). Therefore, the incremental lateral force at each step is calculated for story i based on Equation (15):

$$\Delta F_i = \frac{W_i h_i}{\sum_{i=1}^{n} W_i h_i} \Delta V_b \tag{15}$$

b) In the second and third models, the lateral load distribution was assumed to be uniform. This distribution assumes a constant distribution of lateral load at the height of the building, regardless of floor weight .(Figure 5(b)). The increased lateral force in each step for story i is equal to:

$$\Delta F_i = \frac{\Delta V_b}{N} \tag{16}$$

where N is the number of floors of the building. After the analysis of pushover, a comparison was made between the initial results of the analysis to validate the modeling method and tools used, which included the vibration period of the first three modes and the structural capacity curve.

Briefly, information about the second model, the 4-story frame, is provided above. Based on the comparison of the first three modes of vibration, it was found that the model developed in the current paper has a mass and stiffness distribution almost similar to that was reported by Reinhorn et al. [27]. In addition, by pushover analysis, it was found that the observed trend in the obtained capacity curve is similar to the results presented in the reference article (Table 3 and Figure 6).

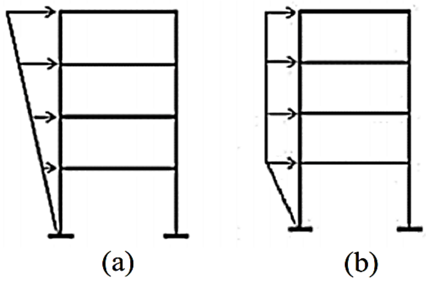


Figure 5. Lateral load distribution types (a: inverse triangle, b: uniform)

TABLE 3. Comparison between the results of the current study and Ferracuti et al. [30]

Results	Mode1	Mode 2	Mode 3
Ferracuti et al. [30]	0.50	0.17	0.11
Current Paper	0.51	0.175	0.104
Difference %	1.4	2.94	5.45

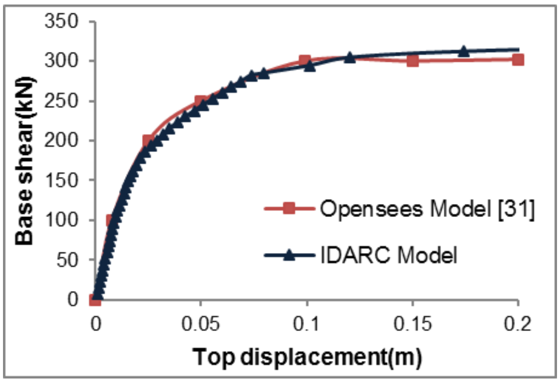


Figure 6. Comparison between the results of the current study and Ferracuti et al. [30]

4. DAMAGE ASSESSMENT BASED ON PARK-ANG MODEL AND STIFFNESS BASED MODEL

In the previous sections, the stifness based damage index was introduced which had previously been provided by the researchers for the performance levels of immediate occupancy (IO), life safety (LS), and collapse prevention (CP). Introducing this index at performance levels alone cannot validate the results. This index has not been calibrated based on valid numerical models, and its results have not been compared with those of other indices. Therefore, the present study calculated the stiffness damage index based on the results of the pushover analysis and compared it with the results of the Park-Ang model. The IDARC program can calculate Park-Ang index values at the same time as pushover analysis and present the results when requested by the user at different levels of analysis. Based on the description given above, numerical calculations were presented in a series of separate tables for each of the above three models. The first four columns of each table contain the results of the nonlinear static analysis performed on the model and the value of the global Park&Ang damage index, which are obtained from the program output.

The amount of stiffness was calculated using the data presented in these columns, followed by calculating the cumulative stiffness reduction ratio and, finally, the amount of damage index based on the stiffness model at different displacement levels. Tables 4 to 6 are related to the first, second, and third frames. Columns 3-6 from the left are related to stiffness-based damage index calculations. To cover the levels of "low to severe" damage according to the Park-Ang criterion, the domain of the index value varies from 0 (without damage) to 1 (structural collapse).

According to the results, the stiffness-based damage index was higher than that calculated based on the Park-Ang model. Accordingly, the following is a review of changes in stiffness-based damage index values with Park & Ang index values as well as drift levels for each model, separately (Figures 7 to 9). Based on analysis results mentioned above, the present study's findings indicated a limited range of changes in the stiffness-based damage index. In other words, at low damage levels where the value of the Park & Ang damage index is less than 0.10, the value of this index indicates a 50-60% damage.

In the literature of damage indices, this value does not mean the amount of damage is small and insignificant, which can be guessed based on the steep slope of the change curve. On the other hand, with a change in Park & Ang damage index value in the range of 20-60%, the value of the stiffness-based index has changed only about 15%. This is not a reliable criteria for determining the post-earthquake performance level of the structure in question. In summary, this index has shown the trend of rapid and slow changes at low and high damage levels, respectively.

TABLE 4. Damage index calculations for the first model

Drift%	$DI_{P\&A}$	Stiffness kN/m	$K_o d_p$	$\sum V_i$	DI
0	0	0	0	0	0.00
0.22	0.01	17305.79	168.13	168.13	0.00
1.66	0.13	3212.59	1291.19	376.61	0.71
1.72	0.13	3106.87	1337.91	385.00	0.71
1.78	0.14	3007.94	1384.79	393.15	0.72
2.02	0.16	2670.03	1573.02	423.50	0.73
2.26	0.18	2402.55	1762.57	450.86	0.74
2.32	0.18	2344.18	1810.15	457.30	0.75
2.53	0.20	2169.50	1970.26	477.93	0.76
3.70	0.30	1539.97	2881.41	559.01	0.81
6.04	0.50	1009.64	4703.71	665.33	0.86
7.22	0.60	871.73	5622.65	711.62	0.87

TABLE 5. Damage index calculations for the Second model

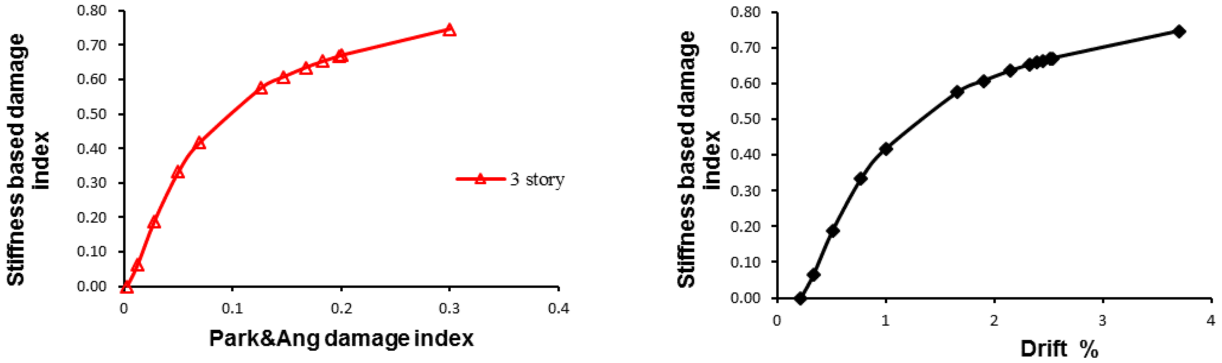
Drift%	$DI_{P\&A}$	Stiffness kN/m	$K_o d_p$	$\sum V_i$	DI
0	0	0	0	0	0
0.29	0.01	6167.58	215.52	215.52	0.00
0.42	0.02	4813.19	314.18	299.55	0.05
0.50	0.02	4346.57	369.02	339.16	0.08
0.54	0.03	4160.54	396.48	357.68	0.10
0.61	0.03	3835.62	453.84	394.05	0.13
0.66	0.04	3579.14	490.99	415.61	0.15
0.85	0.05	2903.58	625.61	478.99	0.23
1.00	0.06	2527.78	743.22	527.19	0.29
1.45	0.10	1793.16	1073.45	623.20	0.42
2.32	0.17	1149.27	1714.54	742.66	0.57
3.16	0.24	860.72	2342.30	830.27	0.65

TABLE 6. Damage index calculations for the third model

Drift%	$DI_{P\&A}$	Stiffness kN/m	$K_o d_p$	$\sum V_i$	DI
0	0	0	0	0	0.00
0.04	0.00	6126.33	50.10	50.10	0
0.12	0.01	5440.24	136.57	126.89	0.07
0.26	0.01	4109.30	289.01	229.14	0.21
0.45	0.03	2537.53	513.87	322.27	0.37
0.74	0.06	1600.39	835.29	406.24	0.51
1.10	0.10	1092.18	1241.61	478.68	0.61
2.19	0.22	569.16	2484.12	594.11	0.76

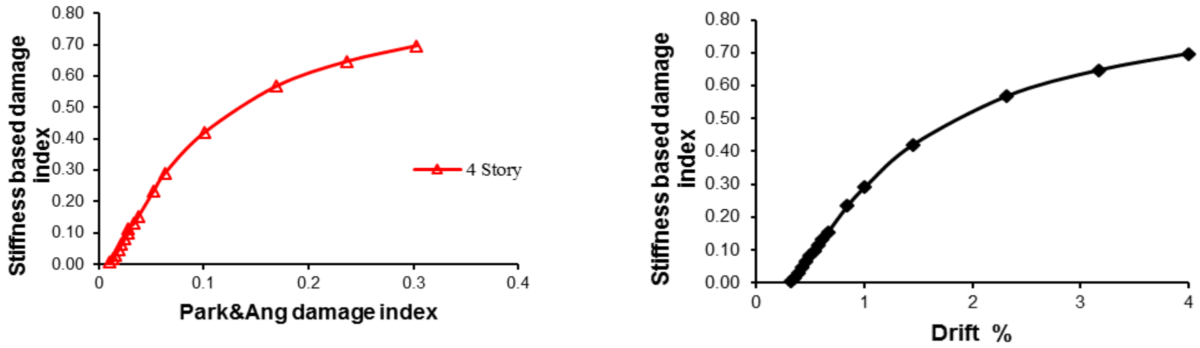
2.45	0.25	513.34	2782.09	619.08	0.78
3.60	0.36	364.20	4080.02	696.24	0.83
4.63	0.45	291.56	5248.42	751.84	0.86
4.76	0.46	284.72	5394.51	758.63	0.86
5.60	0.53	247.71	6344.61	797.05	0.87

To reduce these weaknesses, this paper proposes two models. Following the proposed changes, the results are represented in the form of a series of comparison charts between the models and then compared with the initial state of the proposed index.



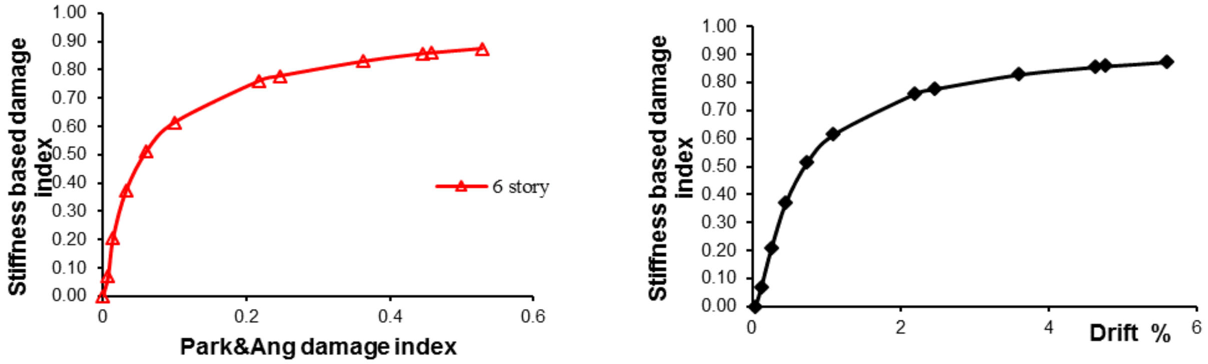
(a) (b)

Figure 7. Relationship between Stiffness based damage index and (a) Park-Ang damage index and (b) Drift index for the 3 story frame



(a) (b)

Figure 8. Relationship between Stiffness based damage index and (a) Park-Ang damage index and (b) Drift index for the 4 story frame



(a) (b)

Figure 9. Relationship between Stiffness based damage index and (a) Park-Ang damage index and (b) Drift index for the 6 story frame

5. PROPOSED MODELS TO IMPROVE STIFFNESS-BASED INDEX RESULTS

According to previous results from the study of the stiffness-based damage index, the following weaknesses can be mentioned:

A) Weakness in determining the amount of damage to the structure at low damage levels, which can be used to repair the structure if possible after the earthquake.

B) According to the basic definitions, the damage index is defined in the range between 0 and 1. However, the cumulative stiffness index has reported values above 0.5, even at low damage levels based on the Park index.

Accordingly, the present research work sought to provide new definitions according to which the mentioned weaknesses could be reduced.

5. 1. First Proposed Model (E1) According to the definition provided in section 2, the damage index introduced can be expressed on another basis. As a result, several corrections were defined as follows, based on which the results of previous calculations will be represented:

$$DI_c = 1 - \frac{\Sigma V_n}{K_o d_p} \tag{17}$$

$$V_o = K_o d_1 \tag{18}$$

$$V_1 = K_o (d_2 - d_1) \tag{19}$$

$$V_2 = K_1 (d_3 - d_2) \tag{20}$$

$$V_3 = K_2 (d_4 - d_3) \tag{21}$$

In the above equations, the values d_1 to d_p are the displacements read from the pushover analysis and the value of ΣV_n is the sum of the shear forces calculated according to Equations (18)-(21) to the desired performance level, respectively. The value of the damage index is between 0 and 1.

5. 2. Second Proposed Model (E2) Based on the changes that will occur in the fundamental period of vibration of a structure after damage, the softening index [31] was defined as Equation (22):

$$DI = 1 - \frac{T_o}{T_i} \tag{22}$$

where T_i and T_o are the fundamental period of vibration of the structure in position i after damage and o without damage, respectively. Given the relationship between period of vibration and stiffness, the period of vibration can be related to the stiffness of the condition i of the structure as follows, assuming that structural mass remains constant after damage:

$$T_i \propto \frac{1}{\sqrt{K_i}} \tag{23}$$

Therefore, the damage index changes according to the new form as follows:

$$DI = 1 - \sqrt{\frac{K_i}{K_o}} = 1 - \sqrt{\frac{K_i d_p}{K_o d_p}} = 1 - \sqrt{\frac{\Sigma V_i}{V_o}} \tag{24}$$

d_p represents the displacement of the node control of the structure in the performance level being calculated. To calculate ΣV_i , we must use the relations (25) to (29):

$$V_0 = K_o d_1 \tag{25}$$

$$V_1 = K_1 (d_2 - d_1) \tag{26}$$

$$V_2 = K_2 (d_3 - d_2) \tag{27}$$

$$V_n = K_n (d_c - d_n) \tag{28}$$

$$\Sigma_{i=0}^{i=n} V_i = V_0 + V_1 + V_2 + V_3 + \ldots + V_n \tag{29}$$

5. 3. Reviewing the Results of the Proposed Amendments According to the corrections presented in this study, the results should be evaluated in comparison with the first case. The following is a presentation of changes in the stiffness-based index versus changes in the Park index after applying (E1) and (E2) in a series of diagrams. Based on the results, it is clear that the results of the proposed index have improved compared to their initial state. (Figures 10 to 12) It is also clear that the second proposition has yielded better results than the first. At damage rates of up to 10% based on the Park & Ang model, the difference in results can be reduced to 25% by applying a second proposition. Also, there is little difference between the values of the two indices at high damage levels.

In light of the foregoing, a quantitative comparison can be made between the damage index results and the Park index values by averaging the results. Table 7 is based on the initial classification of damage status based on Park index values. Drift damage index values were also obtained from the results corresponding to the values of this index. The results of the stiffness-based damage index before and after the correction are presented below. Based on the obtained values:

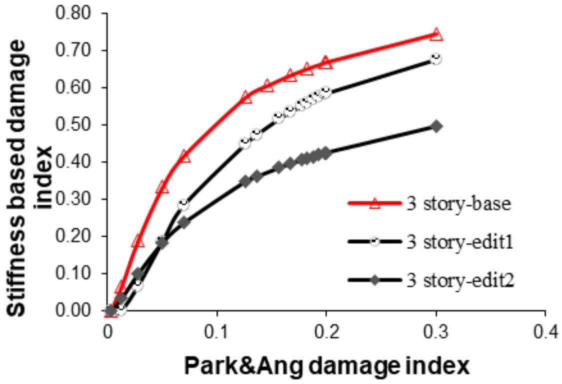


Figure 10. Comparison of changes in damage index results before and after corrections, 3story frame

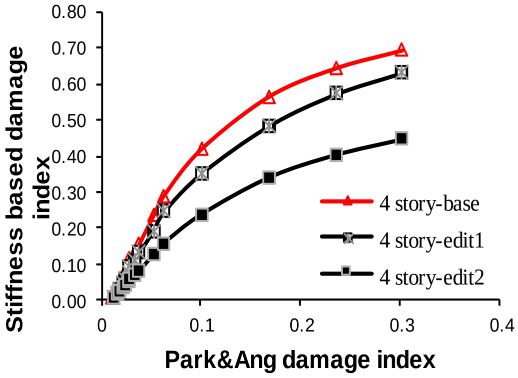


Figure 11. Comparison of changes in damage index results before and after corrections, 4story frame

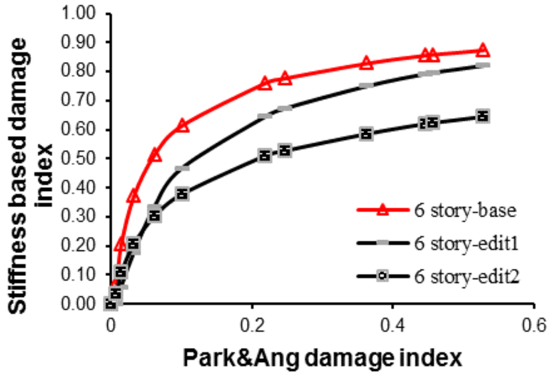


Figure 12. Comparison of changes in damage index results before and after corrections, 6story frame

A: Drift limit values corresponding to the performance levels of IO, LS, and CP were 1.24, 2.96, and 4.68%, respectively (Table 7). However, the recommended values for the FEMA guidelines are 1, 2, and 4%, respectively.

B: The stiffness-based yield index showed better results following improvements in its configuration. It is also clear from the results of Table 7 that the second proposed model introduced in this paper has succeeded in offering both a larger range of changes and more realistic values despite its relatively low computational complexity compared to the valid Park-Ang model.

TABLE 7. Comparison of the results of the indices in the studied models

$DI_{P\&A}$	**Drift index (%)**	**Initial Stiffness based damage index**	**Stiffness based damage index after first correction (e1)**	**Stiffness based damage index after Second correction (e2)**
$DI < 0.10$	Less than 1.24 %	Less than 0.56	Less than 0.42	Less than 0.31
$0.10 \le DI < 0.25$	Between 1.24-2.96 %	Between 0.56-0.74	Between 0.42-0.66	Between 0.31-0.49
$0.25 \le DI < 0.40$	Between 2.96-4.68 %	Between 0.74-0.81	Between 0.66-0.74	Between 0.49-0.57
$DI \ge 0.40$	More than 4.68%	More than 0.81	More than 0.74	More than 0.57

6. CONCLUSIONS

Given the importance of the issue of damage and vulnerability and the need for quantitative post-earthquake estimation of the damaged structure, this study introduced a new stiffness-based index. Thanks to its low computational complexity, this index can conveniently estimate the total damage of the structure based on the output of pushover analysis, i.e., the capacity curve. Three numerical models were developed to evaluate the performance of the index, and the results were compared with those of the valid Park-Ang damage index as well as the drift damage index. By comparison, the initial stiffness-based damage index model states that the results are somewhat higher than the actual values, based on the damage index technical literature. In other words, this index was not very sensitive at low damage levels. Two correction models were proposed to improve the results, and their performance on numerical models was re-examined. The results showed the ability of the modified models to quantify the damage a little better.

In other words, the scope of this index was also expanded to include low breakdown ranges after modifying the damage calculation algorithm. Also, changes in the results of stiffness-based damage index were presented in comparison with Park-Ang indices and relative lateral displacement index. Two main goals of this research were achieved:

1) Provide a new damage index with a low

computational complexity that can consider the cumulative effects of damage and reliably assess overall damage.

2) Calibration of the results of this damage index based on valid damage indices using correction suggestions.

Given the importance of evaluating structures after seismic damage, it is necessary to develop and provide a set of damage indices with acceptable accuracy due to their low computational complexity. This study analyzed concrete flexural frames. However, the performance of the stiffness-based damage index should also be examined in a series of separate studies on other systems due to the diversity of structural systems used in buildings. It is also suggested to conduct a study on the effects of various cyclical behavioral models for nonlinear modeling of structures and their effect on the progress of damage. The effect of lateral load distribution patterns on the damage process should also be considered.

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Persian Abstract

چکیده

در هنگام وقوع زلزله‌ها، سازه‌ها خسارات مختلفی را تجربه می‌کنند و همواره پس از وقوع زلزله تخمین کمی میزان خسارت وارد بر سازه امری بسیار ضروری به نظر می‌رسد. برای تخمین میزان خسارات در سازه‌ها، شاخص‌های خسارت لرزه‌ای به عنوان کمیت‌های بدون بعد معرفی شده‌اند که قادرند با استفاده از معیارهای مختلف، میزانی از خرابی را گزارش دهند. به کمک این ارزیابی کمی می‌توان در خصوص فرایند بهسازی و ترمیم و تقویت سازه‌ها تصمیم‌گیری کرد. در این مقاله با انجام تحلیل بارافزون بر روی مدل‌های بتنی موجود و استفاده از نتایج این تحلیل، شاخص خسارت جدیدی بر مبنای سختی و با فرمول‌بندی ساده ارائه شده است. این شاخص با استفاده از منحنی ظرفیت حاصل از خروجی تحلیل بارافزون، قادر است تا تخمینی کمی از میزان خسارت کل سازه را ارائه دهد. برای اعتبارسنجی نتایج، تخمین خسارت به کمک مدل‌های معتبری چون مدل پارک و انگ نیز انجام شده و سپس با نتایج شاخص پیشنهادی مقایسه شده است. سپس جهت رفع ضعف‌های موجود پیشنهاداتی تئوریک ارائه شده و این پیشنهادات به اجرا در آمده و نتایج جدید حاصل گردید. در پایان مشخص شد که با لحاظ‌کردن پیشنهادات اصلاحی، عملکرد شاخص پیشنهادی بهبود یافته بطوریکه با روند محاسباتی ساده که پیچیدگی پیاده‌سازی شاخص پارک را ندارد، به دقت بسیار مناسبی دست یافت.