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REVIEW

Damage Assessment of Reinforced Concrete Structures through Damage Indices: A State-of-the-Art Review

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ABSTRACT

Due to the developments of computer science and technology in recent years, computer models and numerical simulations for large and complicated structures can be done. Among the vast information and results obtained from the analysis and simulations, the damage performance is of great importance since this damage might cause enormous losses for society and humanity, notably in cases of severe damage occurring. 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. Numbers of damage indices proposed and developed rely on the fact that the damage causes noticeable changes in the structural and dynamic properties of the structural components or the whole structure. Therefore, this study presents a comprehensive review of the damage assessment of Reinforced Concrete (RC) structures. It presents step by step the development of the damage indices that are most widely used to estimate the performance of structural components in the structure and subsequently assess the damage degree of such these structures either based on the structural properties or dynamic properties of the structure. Also, several damage states have been introduced to estimate the performance level of the structure. Finally, case studies, methodologies, and applications on the damage assessment of RC structures are reviewed and presented.

KEYWORDS

Structure properties-based damage indices; dynamic properties-based damage indices; damage states

1 Introduction

Microcracks are initiated in the reinforced concrete elements due to shrinkage, hydration, etc., even if they have not been subjected to an external load. Subsequently, these microcracks propagated and led to macrocracks formulation during the structure life cycle due to various types of external loads and various types of structural shortcomings such as cracking, buckling, yielding of steel reinforcement, crushing of concrete. Structural damage and collapse might occur due to various types of external loads and, according to different structural faults, which might cause enormous losses for society and humanity, see Fig. 1. Therefore, structures must be accurately evaluated for structural safety [1]. Damage assessment of the structures is significantly needed in performance-based structural analysis.

The structural damage can be defined as the degradation degree, which represents the structure capacity resisting and withstand further loadings since the failure of the structures might cause considerable losses. Therefore, performing the damage assessment and determining the structural damage degree became the main challenge for structural analysts. As a subsequent step for the damage assessment, the structural analysts can estimate the maximum loading capacity and the structure's remaining capacity before reaching the failure limit. Accordingly, the structure safety can be assessed. Many researchers have studied the damage and safety performance of different RC structures from various perspectives [2–5].

(a) (b)

Figure 1: Structural damage and collapse during Wenchuan Earthquake, Sichuan Province, China, 2008 [6] (a) Collapsed four-story Xuankou Middle School in Yinxiu (b) The total collapse of buildings at Xiaoyudong due to Surface rupture

The damage progression index has been widely used to investigate the performance of structural elements and assess the degree of damage for the structure. In seismic regions, damage indices have a fundamental role in decision-making about retrofit and maintenance [7]. Elenas et al. [8] mentioned that parameters that can reflect and represent the structural damage had attracted many researchers' attention among several parameters of the structural response. Consequently, their studies have mainly focused on these parameters. It is also worthy to note that damage indices have many other applications, such as they can contribute to selecting earthquake records for structural design [9] and mapping the spatial distribution of the damage potential of recorded ground motions [10].

Damage index at the structural level has been defined according to the main characteristic associated with the structure. The classification of the damage index has been done in four groups based on resistance demands (in the linear and nonlinear stages), ductility requirements, energy dissipation, and finally, the reduction of stiffness. It has been suggested by Krawinkler et al. [11] to estimate the structural behavior against a seismic hazard by evaluating the damage indices of the nonlinear models. The need for such damage indices as an effective estimation tool has been appeared and developed since the 1970s, mainly in earthquake engineering, in whose several formulae for estimating the damage degree of beam-column structures have been proposed and developed [12,13].

The damage index based on mathematical functions, which depend accordingly on many structural parameters that determine the structural damage, has ranged from 0 to 1. Zero indicates that there is no damage in the structure and the structural behavior remains in the elastic stage. In contrast, the unit value of the damage index represents the failure state or collapse of the structure [14]. The force-based approach and the deformation-based approach [15] have been adopted in the current seismic design codes to indicate the damage performance. However, this method does not take into consideration the accumulative damage.

Significant and considerable efforts have been presented to describe the damage level of specific structures through damage indices which can assess and quantify the damage degree. For instance, Powell et al. [16] mentioned that damage assessment and evaluation of a structure could be investigated with several damage indices (DIs), accurately reflecting the amount and the degree of the damage. Also, the structural damage index could be calculated and determined through several ways, such as demand and capacity of the structure, balancing, or degradation of some structural property. Reinhorn et al. [17] mentioned that demand of ground motion and structure capacity are the main factors in evaluating the structural damage index. This evaluation contains two sources of damage, including cyclic loading and permanent deformation under the earthquake effect.

Two different methodologies have been proposed and introduced to provide a reliable prediction for the damaged structure state. The first approach is based on the structural response and the change in the structural properties when the structure is subjected to a particular loading condition. In the case of reinforced concrete, several structural response parameters can numerically represent the degree of structural damage, including structure's drift, displacement, strain, plastic dissipated energy, or a combination of these [18]. The second category of damage indices has been developed according to the concept, the structural element's degradation changes the dynamic response of the structure, including fundamental frequencies, damping ratios, and mode of shape. Hence, Modal analysis also reveals information about the damage of the structures according to the variation in dynamic characteristics.

Kappos [19] has presented a detailed classification for the damage indices according to response criteria and parameters affected, formulation, and the use or capability of these damage indices. According to this classification, the damage indices have been divided into local damage indices and global damage indices used to assess the damage that occurred in individual elements or the whole structure. The local damage indices can also be divided into two categories: cumulative and non-cumulative [20].

The following sections introduce the alternative methods for implementing these approaches and the formulae of different damage indices. Section 2 presents the damage assessment based on structural properties, where Section 3 presents the damage assessment based on modal analysis, Appendix 1.

2 Structure Properties-Based Damage Indices

The classification of damage indices based on structure properties has been introduced by several researchers [21–23]. In general, damage indices have been divided into two kinds of damage indices, including local damage indices and global damage indices.

2.1 Local Damage Indices

The local damage indices have been divided and classified as follows:

- Cumulative damage index in case of cyclic loading.
- Non-cumulative damage index if no-cyclic loading exists.

2.1.1 Cumulative Damage Index Accounting for Cyclic Load

These sets of damage indices depend on the number of loading and unloading cycles. It has been generally concluded that the degree of the damage for a structural element is not only dependent on the maximum displacement recorded under the earthquake effect but also on the number of load cycles and hysteretic energy absorbed [18,24–26].

(1) Displacement-based cumulative indices

Banon et al. [18] developed the normalized cumulative rotation (NCR) damage index based on the ductility-based methodology to consider the cyclic loading effect if it exists. This damage index has been developed based on the low-cycle fatigue law, reflecting the damage accumulated due to cyclic loading, such as the damage that occurred due to seismic hazard. The low-cycle fatigue index (DI_{NCR}) or the NCR damage index has been presented as follows:

$$DI_{NCR} = \frac{\sum_{i=1}^{n} \left|(\theta_{max})_i - \theta_y\right|}{\theta_y} \tag{1}$$

Here $(\theta_{max})_i$ refers to the maximum rotation in cycle i, θ_y represents the yield value and n indicates the number of cycles. One of these index limitations is that this index is limitedly dependent on the value of the parameter n, which also depends on the structure type, which might be challenging to obtain in some cases. For example, quantifying the damage for containment structures subject to cyclic loading, it is difficult to find the parameter n. Subsequently, the damage index cannot be accurately estimated.

Miner [27] has proposed the low-cycle fatigue index D_F, and it has been expressed as follows:

$$D_F = \sum_{i=1}^{n} \left(\frac{\mu_i - 1}{\mu_{i,alw} - 1}\right)^b = \sum_{i=1}^{n} \left(\frac{\Delta x_i}{\Delta x_{i,alw}}\right)^b \tag{2}$$

Here n refers to the total number of plastic cycles, μ_i represents the kinematic or cyclic ductility corresponding to the generic plastic displacement, $\mu_{i,alw}$ refers to the maximum allowable value of the hysteresis ductility, $\Delta x_i = x_{max} - x_y$ where x_{max} refers to the maximum plastic deformation and x_y refers to the deformation at the elastic limit, $\Delta x_{i,alw} = x_{i,alw} - x_y$ where $x_{i,alw}$ refers to the ultimate displacement, and b refers to an empirical damage coefficient whose value is mainly associated with the structure type and material. Reliable values of b can be determined and obtained through experimental data. Mainly for RC structures, and steel structure values range from 1.6 to 1.8 can be considered for this parameter b; in damage analysis, sometimes for conservative purposes, a value of 1.5 is used. The limitation of this damage index also lies in obtaining parameter b experimentally for some structures such as dam structures.

(2) Hysteretic energy-based cumulative indices

Plastic dissipated energy is considered one of several structural response parameters, which can numerically reflect the damage degree of the structure. Therefore, it has been used to define energy-based damage indices. The energy dissipated by the structure is supposed to be less than or equal to a threshold value before the structure reaches the collapse limit. Gosain et al. [28] have proposed a formula for an energy-based damage index based on the maximum loading capacity of the structure (the failure load), the yielding force, the maximum and yield displacement of the structure, and this damage index has been expressed as:

$$I_D = I_w = \sum_{i=1}^{n} \frac{F_i d_i}{F_y d_y} \tag{3}$$

where F_i, F_y represent the failure force and the yield force, d_i refers to failure displacement, d_y represents the yield displacement, respectively, and n indicates the number of hysteretic cycles. It worthy mentioned that this formula could only use for $F_i \geq 0.75\ F_y$.

Hwang et al. [29] also proposed another formula based on the dissipated energy to assess the structural damage degree through the damage index $I_{D,}$ and this damage index has been presented as follows:

$$I_D = \sum_{i=1}^{n} \frac{k_i d_i^2}{k_e d_y^2} \tag{4}$$

Here k_i, k_e refer to bending stiffness and elastic bending stiffness, respectively, d_i represents maximum displacement, d_y represents the yield displacement, and n refers to the number of cycles.

(3) Combined cumulative indices

The stated damage indices in the previous sections have been developed and expressed based on the deformation or the energy dissipated individually depending on the structure response. However, the displacement index or displacement ductility index cannot give a reliable description for damage performance and the dynamic response of structures [30,31]. In this section, the damage indices have been developed based on the change in the displacement and the energy dissipated together, and they have been expressed as the summation of the two quantities, called combined cumulative damage indices. In this regard, Park et al. [32,33] proposed the well-known and most widely used Park–Ang damage index $DI_{p,A}$. This index has been initially developed in 1985 to estimate the damage and became one of the broadest damage indices used over the last several years. It combines a linear combination of normalized deformation and hysteric energy absorption, and its value equals the summation of these quantities. The Park–Ang damage index for an individual component has been expressed as:

$$DI_{p,A} = \frac{\delta_m}{\delta_u} + \frac{\beta}{F_y \delta_u} \int dE \tag{5}$$

Here δ_m refers to the maximum displacement under the seismic effect, $\int dE$ represents the cumulative hysteretic energy also under seismic event which absorbed by the component, δ_u and F_y indicate the ultimate displacement and yield force of the component, respectively. β is a positive factor that considers the cyclic loading effect, and it needs to determined experimentally, and it has been expressed as follows:

$$\beta = (-0.447 + 0.073\lambda + 0.24n_0 + 0.314\rho_t) \times \rho_w \tag{6}$$

where:

λ Represents the shear span ratio (a value of 1.7 is used if λ less than or equals to 1.7),

n_0 Refers to the axial compression ratio (a value of 0.2 is recommended if n_0 less than or equals to 0.2),

ρ_t Represents the percentage of longitudinal reinforcement (replaced by 0.75% when ρ_t less than or equals to 0.75%),

ρ_w Indicates the transverse reinforcement ratio.

Cosenza et al. [34] stated that the value of β ranges from −0.3 to +1.2 with a median nearly equal 0.15 as resulted from a regression curve through comprehensive experimental study. Also, according to several experimental tests, several values of β, ranges from 0.05 to 0.24 for reinforced concrete and from 0.025 to 0.23 for steel structures [35–37], have been estimated and used to assess the damage. Several experimental damage statistics has calibrated this index, and it has been found that $DI_{p,A} > 1.0$ represents the complete damage, and a value of nearly 0.4 to 0.5 can be considered the repair limit of the structure [38]. One of the limitations of this index is that the experimental evaluation of the parameter β is complex, and the methodology has not been well stated. Another limitation of this index is that it is limited to adopting a simple linear set of deformation and energy terms, given the cleared nonlinearity of the dynamic behavior and the possible interdependence of the two quantities. This index has been widely used to assess the damage of different reinforced concrete RC structures, where many studies have used the original formula or its modification to calculate the damage [39–42]. In this index, the response components δ_m and $\int dE$ which is needed to estimate the damage of a certain structure under an earthquake, can be obtained through a random vibration method for nonlinear hysteric systems. For such nonlinear material response analyses, idealization and discretization of structural systems are necessary [43], see Fig. 2.

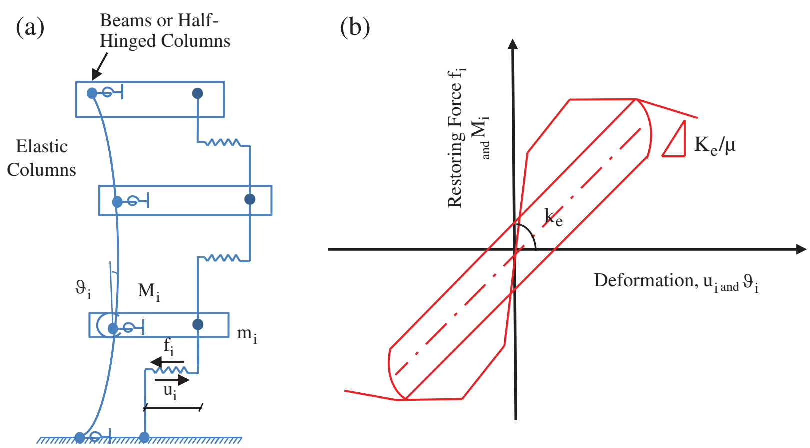

Figure 2: Modeling of building [35] (a) Structural modeling (b) Force-displacement relation

Kunnath et al. [44,45] developed the Park–Ang damage index by replacing the deformation with curvature in the first term using the moment-curvature concept instead of load-displacement. The developed damage index has been represented as follows:

$$D = \frac{\varphi_{Max} - \varphi_y}{\varphi_u - \varphi_y} + \beta_e \frac{\int dE}{M_y \varphi_u} \tag{7}$$

Here φ_{Max} refers to the maximum curvature, φ_u represents the ultimate curvature under monotonic loading, M_y represents the yield moment, dE refers to the increment in the absorbed hysteretic energy, and β_e refers to a positive parameter as defined in the Park–Ang damage index.

According to the basic concept and original definition of the damage index, the damage index values range from 0 to 1.0. Therefore, the value of the damage index is supposed to be equal to 1.0 at the maximum deformation limit δ_m under the influence of the monotonic load, which can indicate the failure stage of the structure. However, according to the Park–Ang damage index's original formula, the damage index value at the maximum deformation δ_m seems to be more than 1.0, which is considered another disadvantage of this index. To modify this shortcoming, Chai et al. [37] have developed the Park–Ang damage index by considering the plastic strain energy dissipated by the structure under the effect of monotonic loading, and it has been subtracted from the second term in the original Park–Ang damage index. The modified formula has been presented and expressed as follows:

$$D = \frac{\delta_m}{\delta_u} + \beta^* \frac{\int dE - E_{hm}}{F_y \delta_u} \tag{8}$$

Here E_{hm} represents the plastic strain energy dissipated by the structure under the effect of the monotonic loading, and β^* is defined as the strength deterioration parameter.

Another modification has been presented for the Park–Ang damage index regarding the elastic response. However, the value of the damage index is supposed to be zero in the elastic response indicating no damage occurred; the value of the original formula of the Park–Ang damage index or its modifications seems to be more than zero. To overcome this drawback, Bozorgnia et al. [46,47] have presented two modified formulae for the damage index, in which the sum of the weight factors of deformation and energy dissipation is equal to 1.0; the two modified damage indices have been presented as follows:

$$D1 = \left[\frac{(1-\alpha_1)(\mu - 1)}{\mu_{mon} - 1} \right] + \alpha_1 \left(\frac{E}{E_{mon}} \right) \tag{9}$$

$$D2 = \left[\frac{(1-\alpha_2)(\mu - 1)}{\mu_{mon} - 1} \right] + \alpha_2 \left(\frac{E}{E_{mon}} \right)^{0.5} \tag{10}$$

Here μ refers to the displacement ductility ratio δ_{Max}/δ_y, δ_{Max} represents the maximum deformation δ_y represents the yield deformation, $\mu = 1$ if the behavior remains in the elastic range ($\mu \leq 1$). M_{mon} refers to displacement ductility capacity under monotonic response, E represents the incremental dissipated energy demanded by seismic wave, E_{mon} refers to the hysteretic energy capacity under monotonic loading, and $0 \leq \alpha_1 \leq 1.0$ and $0 \leq \alpha_2 \leq 1.0$ are constant parameters.

Kunnath and the National Institute of Standards and Technology (US) have investigated the Park–Ang damage index and its association with the different values of displacement and the energy dissipated. This investigation resulted in some discoveries; one of these findings has been stated that at different deformation values, the same energy dissipated leads to different values of damage index and damage level. Based on these findings, Wang et al. [48] have provided another contribution to modify for the Park–Ang damage index, and it has been expressed as follows:

$$D = (1-\beta)\frac{\delta_m - \delta_y}{\delta_u - \delta_y} + \beta \frac{\sum \beta_i E_i}{F_y(\delta_u - \delta_y)} \tag{11}$$

Here β_i represents the energy weight factor relevant to the loading histories and has been used to account for Kunnath's phenomenon [49]. The other parameters have been taken as the exact meanings of the original Park–Ang formula. The Park–Ang damage index has also been modified to overcome non-convergence problems at their limits [50].

However, the structural members most likely would be subjected to three-dimensional loading during the seismic events, i.e., the damage probably could be in the three dimensions. The original formula of the Park–Ang damage index has been proposed and used considering axial load and uniaxial bending only. Based on this fact, the structural elements most likely would be subjected to three-dimensional loading. Consequently, it would be subjected to three-dimensional damage. Guo et al. [51] have developed the Park–Ang damage index and proposed a modified formula for the Park–Ang damage index called a three-dimensional damage index to account for the biaxial effect due to earthquake events. Therefore, his study has been based on the Park–Ang damage index and its improvements to modify the Park–Ang damage index with a biaxial effect to get a relation between moment and rotation for a more effective and more precise determination of the damage index of the reinforced concrete pier. Lastly, a three-dimensional damage index has been proposed and presented as follows:

$$D = (1 - \beta)\, \mu_{\bar{\theta},max} + \beta \int \alpha_{max} \frac{dE_p}{E_{mon}} \tag{12}$$

Here β refers to the weight factor of energy dissipation, $\mu_{\bar{\theta},max}$ refers to the maximum normalized rotation ductility factor, dE_p represents the plastic energy dissipation increment, E_{mon} represents the value of plastic energy dissipation due to the effect of monotonic loading at the failure limit of the structure member, and α_{max} refers to the correction of the energy dissipation term where the normalized rotation ductility can be expressed as follows:

$$\mu_{\bar{\theta}(\theta_i)} = \frac{\theta_i - \theta_{y,i}}{\theta_{u,i} - \theta_{y,i}} \tag{13}$$

Here θ_i refers to the rotation vector modulus ($\theta_{2,i}$, $\theta_{3,i}$) in the principal axes and its value is always positive, $\theta_{2,i}$, $\theta_{3,i}$ refer to rotations about the principal axes 2 and 3, respectively, and 1–3 represent the local coordinate system of the element. $\theta_{u,i}$ and $\theta_{y,i}$ represent the ultimate rotation and the yield rotation in the direction of the response vector ($\theta_{2,i}$, $\theta_{3,i}$) corresponding to the plastic hinge area's axial load level. Both $\theta_{u,i}$ and $\theta_{y,i}$ refer to positive values.

2.1.2 Non-Cumulative Damage Index if No Cyclic Loading Exists

(1) Drift damage index

Damage indices, mainly dependent on degradation in structure stiffness, have been widely explored [52,53]. The drift damage index or the maximum deformation damage index is considered one of the most detailed damage indices in which the lateral displacement or the floor drift can indicate the structural damage if no cyclic loading exists. This index can be simply calculated by evaluating the inter-story drift based on the maximum lateral displacement between floors [52]. According to the lateral deformation between floors, the inter-story drift damage index (DI_{Drift}) has been presented as follows:

$$DI_{Drift} = \frac{\Delta_{Max}}{H} \tag{14}$$

Here Δ_{Max} refers to the maximum lateral deformation of the floor, and H refers to the floor height.

The damage in the structures is mainly occurred due to the plastic deformation, not the total deformation. Consequently, the inter-story drift damage index has been modified and presented in another formulation by subtracting the part related to elastic displacement from the maximum displacement and the plastic drift damage index $DIp,_{Drift}$ has been expressed as follows:

$$DIp,_{Drift} = \frac{\Delta_{Max} - \Delta_y}{H} \tag{15}$$

Here Δ_y refers to the yielding lateral deformation of the floor.

(2) Displacement ductility-based damage index

In the set of the non-cumulative damage indices, another formula for the damage index called displacement ductility-based damage index based on the ductility of the member had been developed and introduced. Since the ductility tends to the structure ability towards plastic deformation without complete failure and degradation of structural strength, therefore it has been used as an indication of the structural damage, and ductility damage index has been widely used in seismic analysis to evaluate the seismic damage and the capacity of structures [54]. The ductility-based index (DI_μ) has been presented as a simple tool to express the damage. It generally equals the proportion of the concurrent ductility response to the ductility capacity and has been expressed as follows:

$$DI_\mu = \frac{\Delta_{Max}}{\Delta_y} \tag{16}$$

Here Δ_{Max} indicates the maximum lateral deformation of the floor and Δ_y denotes the yielding lateral displacement of the same floor.

(3) Flexural damage ratio (FDR)

It has been generally concluded that the structural element's damage level depends on the maximum deformation and mainly depends on the number of load cycles and the energy dissipated [24,25]. Hence, a new formula for damage index developed as a measure of the local stiffness degradation and called the flexural damage ratio (FDR), and it has been expressed as follows:

$$D_L = FDR = \frac{K_0}{K_m} \tag{17}$$

Here K_0 indicates the initial tangent stiffness of the structural element, and K_m represents the maximum stiffness of the same member during a complete cycle. Stiffness is derived from the ratio of force to the displacement and can be estimated from the studied element's hysteresis curves. FDR has been considered a better damage indicator than displacement ductility-based damage index since it considers stiffness and strength degradation of the element.

In the nonlinear analysis of structures subjected to static horizontal load, it is necessary to consider damage index, which incorporates stiffness degradation. Relying on this fact, Skærbæk et al. [55] proposed a new formula of the damage index for the individual column or beam and the damage index for beam or column DI_e has been introduced as follows:

$$DI_e = 1 - \sqrt{\frac{k_i}{k_i - 1}} \tag{18}$$

Here k_i refers to the current tangent stiffness and $k_i - 1$ denotes the initial tangent stiffness.

According to the stiffness degradation, a new formula for the damage index has been proposed and presented [56]. The formulation of this damage index was associated with the relationship between ultimate and yielding deformation at the ultimate and yielding stiffness. This index has included a design ductility value and has been presented as follows:

$$DI = \frac{\frac{X_{max}}{Z_{00}} - 1}{\mu - 1} \tag{19}$$

Here X_{max} refers to the maximum deformation during the event, and μ represents the maximum ductility, and Z_{00} refers to the displacement at which the single-degree-of-freedom oscillator reaches the elastic limit.

2.2 Global Damage Indices

This section introduces the global damage indices used to assess the damage for the whole damaged structure. The global damage indices are most likely quantified by weighting the local indices of the different elements of a specific structure. The global damage indices have been classified as follows:

- Strength-based global damage indices.
- Weighted average global damage indices.

2.2.1 Strength-Based Global Damage Indices

Powell et al. [16] have mentioned that the deformation-based damage index $\left(DI_{\mu}\right)$ which assess the seismic capacity of structures that may not be affected and not sensitive to the accumulative damage criteria could be done using the common relation of ductility, which can only reflect the state of the structure at the last stage. DI_{μ} has been presented as follows:

$$DI_{\mu} = \frac{\Delta_{Max} - \Delta_y}{\Delta_{mon} - \Delta_y} \tag{20}$$

where Δ_{Max} refers to the maximum deformation, Δ_y denotes the yield deformation and Δ_{mon} represents the maximum deformation under monotonic loading.

By adopting the same previous concept, Roufaiel et al. [57] have introduced a formula for the damage index, and the formula presented as follows:

$$DI_{\cdot s} = \frac{\delta_{Max} - \delta_y}{\delta_u - \delta_y} \tag{21}$$

where δ_y refers to the yielding displacement, δ_u denotes the ultimate displacement at failure and δ_{Max} refers to the maximum displacement under seismic effect. If the maximum displacement remains below the yielding displacement, the value of the damage index is negative, and thus the seismic behavior of the structure remains within the elastic limits, and the structure did not suffer any seismic damage.

2.2.2 Weighted Average Global Damage Indices

The most prevalent global damage indices that use the energy absorbed at different locations are the weighting function developed and presented by weighting and summing the local damage indices of the individual elements [33,44]. The overall damage index D of the structure has been expressed as:

$$D = \sum_{i}^{N} \lambda_i D_i \tag{22}$$

Here N represents the number of structural components, D_i refers to the damage index of the individual i component and λ_i represents the weighting coefficient of the i component. λ_i has been calculated by the following formula:

$$\lambda_i = \frac{E_i}{\sum E_i} \tag{23}$$

where E_i represents the hysteretic energy of the i component.

However, severely damaged members might limit its overall stability; this has not been reflected in the averaging effect of the previous equation. Therefore, Bracci et al. [58] proposed a global damage index that accounts for the severity of damage in the structure, and it has been presented as follows:

$$D_G = \frac{\sum_{i=1}^{N} w_i D_{l,i}^{(b+1)}}{\sum_{i=1}^{N} w_i D_{l,i}^{(b)}} \tag{24}$$

Higher values of parameter b are used when more emphasis on the most severely damaged member is required. w_i denotes the ratio of the gravity load carried by the i component to the total gravity load on the structure.

Moreover, Amziane et al. [59] presented a methodology to evaluate the global damage indices taking into account pseudo plastic hinges. Hanganu et al. [60] presented a procedure to assess RC structural local and global damage based on a concrete damage model.

3 Dynamic Properties-Based Damage Indices

Natural frequencies, damping ratios, modal participation factor, and mode shapes represent the most common modal properties obtained from the analytical solution of time histories, which can indicate the damage performance of the structures and have been used to calculate story damage index [61,62]. Pandey et al. [63] have presented a procedure to assess the damage by flexibility matrices based on the changes that occurred in the mentioned dynamic parameters.

3.1 Damage Indices Based on Natural Frequencies (Fundamental Periods)

Based on the fact that modal damage assessment can be performed based on changes in these dynamic properties, Dipasquale et al. [62] have proposed the ultimate stiffness degradation using the fundamental period of the undamaged structure as a reference, and the damage index has been introduced as follows:

$$D_G = \frac{T_j - T_0}{T_0} \tag{25}$$

where T_0, T_j indicate the fundamental period of the undamaged structure and the fundamental period at cycle j, respectively. It is clear from the formula that the value of this index increases with structure degradation.

Since the structures suffering softening when damage increases and after a specific step, structures suffering severe softening and become irreparable. Therefore, several damage indices have been proposed to account for this softening and accounting for the fundamental period variation [62,64–66]; thus, the following damage indices have been developed and presented:

(1) The maximum softening damage index

$$D_{G,M} = 1 - \frac{T_0}{T_m} \tag{26}$$

(2) The plastic softening damage index

$$D_{G,M} = 1 - \left(\frac{T_0}{T_{max}}\right)^2 \tag{27}$$

(3) The final softening damage index

$$D_{G,M} = 1 - \left(\frac{T_0}{T_{dam}}\right)^2 \tag{28}$$

Here T_0 refers to the initial natural period (the fundamental period of undamaged structure), T_{max} denotes the natural period at the maximum softening during the response time history and T_{dam} represents the natural period at the final softening (the fundamental period of the damaged structure), as shown in Fig. 3.

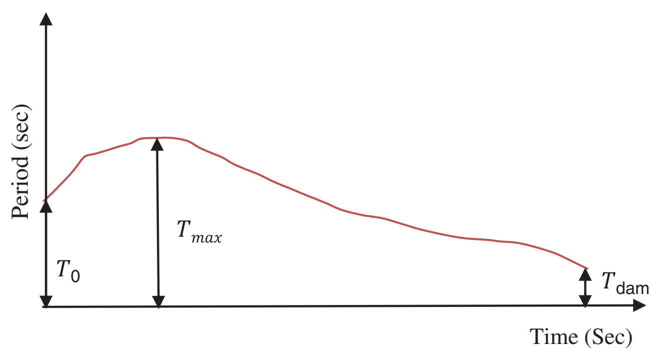

Figure 3: Fundamental period time history [66]

The period degradation might be considered as an indication of the stiffness degradation. According to this concept, Hori et al. [67] have developed a formula to quantify period degradation based on design ductility, and it has been presented as follows:

$$T_\mu = 2\pi \sqrt{\frac{\mu}{\alpha_y}} T_0 \tag{29}$$

Here T_μ refers to the period at failure, μ represents the design ductility, α_y denotes to the stiffness degradation dependent parameter and T_0 refers to the elastic period of the structure.

3.2 *Damage Indices Based on Damping Ratio*

3.2.1 Normalized Damping Ratio

As common knowledge, structure deterioration creates an increase in damping, especially in nonlinear material such as concrete, where damping enhancement is related to concrete cracking and yielding steel reinforcement. Therefore, the normalized damping ratio changes and then serves as a damage indicator [68]. Hence, damage evaluated and presented as follows:

$$D_G = \frac{\xi_j - \xi_0}{\xi_0} \tag{30}$$

where ξ_0 refers to the initial damping ratio and ξ_j represents the damping ratio at cycle j.

Moreover, Wang et al. [61] used different modal parameters such as damping ratio, natural frequency, participation factor, and mode shape to estimate the story damage index.

4 Damage States

The damage states are usually used to estimate the structural damage level, and this has been done according to the values of the damage indices determined for the structure, as mentioned in published literature. Also, these damage states are used to correlate the damage indices with the damage that occurred in the actual structures. Therefore, the damage states have been classified according to the damage indices values. The damage index is a normalized quantity where the value of this quantity ranges from zero and 1.0. Zero value of the damage index represents the undamaged structure and mean that the structural behavior still in the elastic stage and did not suffer any damage, while the unit value of the damage index refers to the failure of the structure, and this means a part of the whole of the structure is collapsed. The damage states also can be classified according to the cost required for repairing the structure due to the occurred damage. Priestley [69] mentioned that the damage state of the structures is significantly associated with their member's deformation and their maximum strain.

Generally, the available damage states have been defined based on damage factors, engineering judgment, or experimental calibration. One of the limitations of the available damage states that most of these damage states have not been defined or classified according to the structural response parameters and have not considered the differences in the structure lateral load resisting system and nonstructural elements damage. Here are some of the damage states mentioned in the literature. One of the damage state definitions was related to Park–Ang damage indices [35], where the degree of the damage of the structure has been determined according to the Park–Ang damage index calculated for the structure as provided in Tab. 1.

Table 1: Damage states defined based on Park–Ang damage indices [35]

D_{PA}	Damage state	Comment
0	No damage	–
0∼0.2	Minor damage (MID)	Repairable
0.2∼0.4	Moderate damage (MOD)	–
0.4∼1.0	Strong damage (SD)	Almost unrepairable (repair cost is very high)
>1.0	Collapse damage (CD)	Total loss of the structure

Also, Kunnath [23] introduced ranges for five degrees of the damage states according to the values of the normalized damage index, and it has been presented in Tab. 2.

Table 2: Normalized damage index ranges for a five-level scale [44]

Damage levels	Damage index
No damage	0∼0.10
Light damage (MID)	0.10∼0.24
Moderate damage (MOD)	0.25∼0.4
Strong damage (SD)	0.40∼1.0
Collapse damage (CD)	>1.0

The degree of the damage can also be evaluated through the damage index by comparing the specific structural response parameters induced by the seismic event with the structural deformation capacity. However, the ductility demand and amount of dissipated hysteretic energy are effective parameters of the nonlinear response; they do not provide information on the degree of damage by themselves. Therefore, the structural available deformation capacity must be known to get a reliable estimation of the damage level of the structure. Ladjinovic et al. [70] defined the relationship between the damage index and the damage degree according to the data recorded on damage in RC buildings that subjected to moderate or severe damage during several seismic hazards in the USA and Japan, and the classification of the damage states has been presented as in Tab. 3.

Table 3: Interpretation of damage index [70]

Damage state	Damage index	State of the structure
Minor damage (MID)	0∼0.2	Serviceable
Moderate damage (MO)	0.2∼0.5	Repairable
Severe damage (SD)	0.5∼1.0	Irreparable
Collapse damage (CD)	>1.0	Total loss of the structure

Since the story drift is considered one of the most influential and earliest tools to evaluate and assess structural damage, in many building codes [71–73], floor drift has been used as a damage indicator of the structure. The FEMA 356 guidelines [73] described the performance levels of the structure based on the floor drift as presented in Tab. 4.

Table 4: Performance levels, type of damage, and drift corresponding to the damage

Performance level	Damage state	Damage index (Drift) (%)
Immediate occupancy	No damage	<0.2
Damage Control (DC)	Minor Damage (MID)	<0.5
Life Safety (LS)	Moderate Damage (MOD)	<1.5
Collapse Prevention (CP)	Severe Damage (SD)	<2.5
Collapse	Collapse	>2.5

5 Case Studies and Applications on Damage Assessment of RC Structures

Cho et al. [74] presented an approach for evaluating seismic damage of concrete containment structures using nonlinear finite element analysis. In this study, two types of damage indices have been introduced and quantified at the finite element and structural levels. Nonlinear time-history analysis for the studied containment has been performed using a layered shell approach, and the damage indices at the finite element and structural levels have been estimated, which was also then used to evaluate the damage of the containment structure. Thirty as-recorded seismic waves have been considered in this study. For each wave, values range from 0.1 to 1.6 g for the peak ground acceleration (PGA) have been considered. The damage index at the finite element level and the structural level has been investigated. The damage index proposed by Roufaiel et al. [57] has been adopted to determine the damage index at the structural level as expressed in Eq. (21). This index uses δ_y as the yielding displacement, δ_u as the ultimate displacement at failure, which can be obtained from pushover analysis and δ_{Max} as the maximum displacement due to the seismic wave. This study showed that the structural damage index calculated using Roufaiel and Meyer damage index increased with the PGA. The damage index at the finite element level also has the same sequence; the corresponding standard deviations increase as nonlinearity dominance of the seismic behavior also grows with the PGA. Also, the results showed that the behavior of the containment structure remains in the elastic stage, and no damage occurred at PGA of 0.1 and 0.2 g, and this was clear from the negative values of the calculated damage index showing a good agreement with the nonlinear finite element analysis, see Fig. 4.

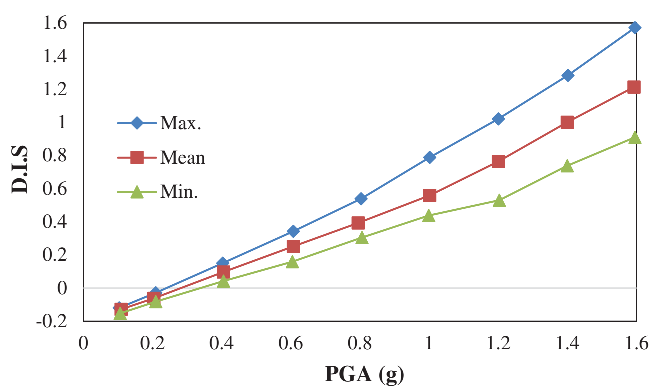

Figure 4: Damage index at the structural level [74]

Zhang et al. [75] have presented a study to investigate the effects of aftershocks on the damage of concrete gravity dams by considering 30 as-recorded main shock–aftershock seismic wave, taking Konya dam as a case study. In this study, a two-dimensional gravity dam was analyzed by applying the chosen seismic sequences to investigate the nonlinear behavior and the seismic damage for the Koyna dam under mainshock–aftershock seismic sequences. The local and global damage indices have been used in this study to investigate the effect of strong aftershocks seismic waves on the cumulative damage of concrete gravity dams. The results showed that the as-recorded sequences of ground motions significantly affected the accumulated damage and consequently the structural design of concrete gravity dams, see Fig. 5. In this study, the global damage has been calculated by weighting the local damage index at the ends of each element, with the dissipated energy where the local damage index DI_{li} has been calculated through the following formula:

$$DI_{li} = \left(\frac{L_{Di}}{L_i}\right) \tag{31}$$

Here L_i indicates the expected total length to which crack path i extends and L_{Di} denotes the damage path length in the crack path i. Crack paths along the damaged elements could be obtained; consequently, the global damage index (DI_G) has been calculated as follows:

$$DI_G = \frac{\sum_{i=1}^{n} DI_{li} E_i}{\sum_{i=1}^{n} E_I} \tag{32}$$

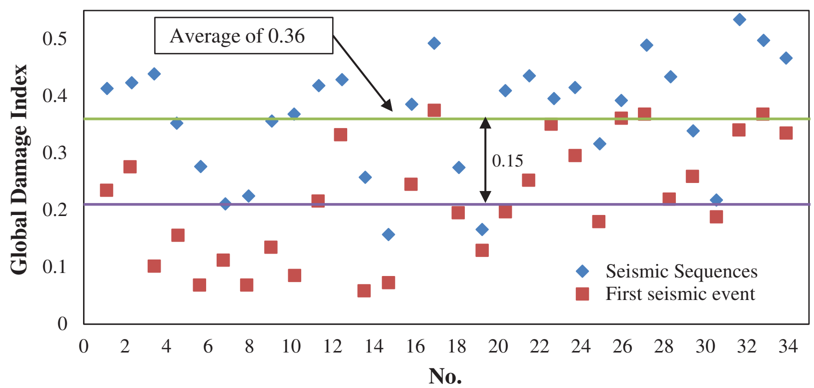

Figure 5: Seismic wave effect on the global damage index calculated for the dam [75]

Zhai et al. [20] presented a comprehensive study to explore the influence and effect of aftershocks on the accumulative damage of containment structures by estimating the after-main shock damage levels. In this study, material stiffness degradation in the concrete damage plasticity (CDP) model has been used as an indication of the damage process and used to describe the damage that occurred in the concrete. The accumulative tensile and compressive damage have been reflected through the damage parameters *dt* and *dc*, respectively. The normalized damage ratio (*DR*) quantifying for tensile and compressive damage has been adopted to evaluate the accumulative damage due to different seismic waves with several durations. *DR* has been defined as the proportion of the damaged area where damage parameter values exceed a certain threshold to the entire area of the containment structure, and it has been expressed by the following equation:

$$DR = \frac{\int dt(ds)}{\int ds} \tag{33}$$

where *dt* refers to the tensile damage parameter, s denotes the total dimension of the containment. For example, $DR_{t0.1}$ expresses the damage proportion where the value of the concrete tensile is equal to or more than 0.1. Similarly, $DR_{t0.9}$ refers to the damage ratio in which the tensile damage of concrete is more than 0.9 representing the tensile damaged area of the containment, where *dt* equal 0.9 represents the maximum tensile damage. Furthermore, the damage ratio for the compressive damage of concrete can be quantified using *dc* in the damage ratio *DR* formula instead of *t*. The results demonstrated that aftershocks seismic waves with larger durations have a significant effect on the containment structure leading to more severe accumulative damage and greatly affected the damage performance.

Massumi et al. [76] have modified the Park–Ang damage index to consider the structural fundamental period in damage index estimation and introduced a new formula for the damage index for RC structures according to the variations of the nonlinear fundamental period, which could be estimated experimentally through field tests. In this study, a correlation between the Park–Ang damage index and the fundamental period elongation has been presented. This new damage assessment has great importance since it accounts for the fundamental period elongation, which reflects the structure softening and encompasses one of the most effective, significant, and widely used damage indices (Park–Ang damage index). Also, this criterion is considered more reliable since it has associated with the fundamental period, which can reflect the actual seismic behavior of the structures that are induced due to their configuration, their construction quality, dissipated energy, and deformation of different elements. For this purpose, six flexural RC frames have been analyzed. Pushover analyses have been used to identify and reflect seismic behavior and performance of the RC frames step by step. In each step, the fundamental period and damage of analyzed frames have been investigated. Finally, a new damage index based on this significant correlation has been proposed and introduced. During the analysis process, the assessment indicates an increase in the fundamental period with the increase of the base shear parameter in each step according to the Park–Ang damage index, and this approach continued till the fundamental period suddenly shift, as shown in Figs. 6 and 7 for a 10-story frame (δ is the fundamental period elongation).

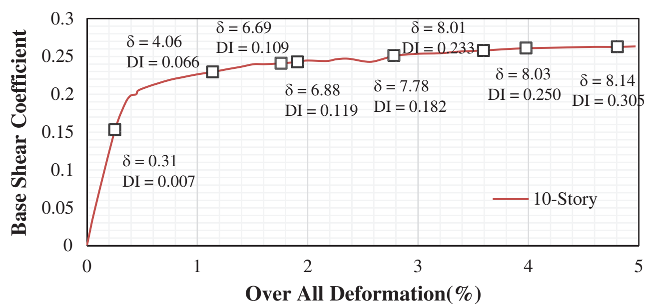

Figure 6: Fundamental period elongation corresponding to the damage rate [76]

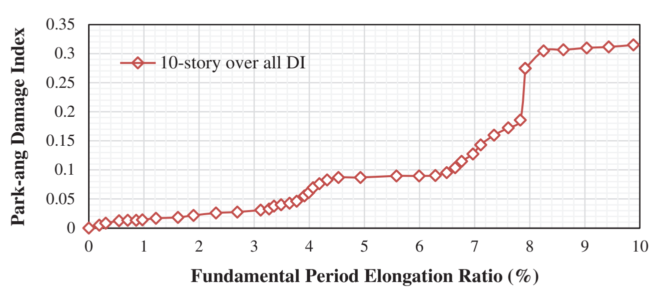

Figure 7: Period elongation pursuit corresponding to the damage rate [76]

Based on this study, the developed damage index has been presented as follows:

$$DI = \frac{1}{\alpha - \beta\delta^{0.5}} \tag{34}$$

where α and β refer to the damage parameters that are related to the initial elastic period of frames, where the initial elastic period can be calculated as follows:

$$T_{elastic} = 0.07\, H^{0.75} \tag{35}$$

Moreover, the deformation has been expressed as follows:

$$\delta = \frac{(T_{plastic} - T_{elastic})}{T_{elastic}} \tag{36}$$

Here H refers to the height of the reinforced concrete frames presented in meters, $T_{plastic}$ refers to the period of existing damaged RC buildings, which can be obtained experimentally and $T_{elastic}$ represents the initial period when the structure has not suffered any damage under the effect of an earthquake. The correlation curves of the damage parameters α and β with the fundamental elastic period are shown in Fig. 8.

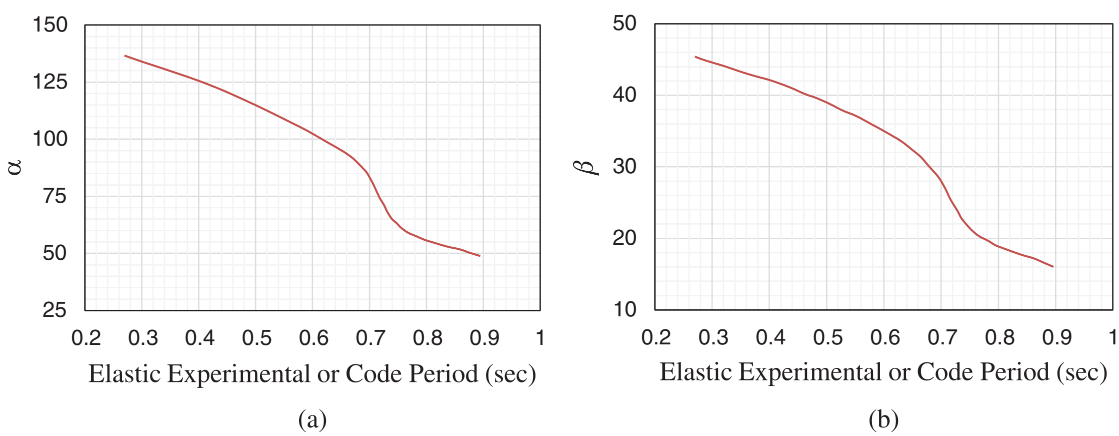

Figure 8: Damage coefficient value of α and β [76] (a) Damage coefficient value of α (b) Damage coefficient value of β

The proposed damage pattern in this study also represented in a new format as follows:

$$DI = \frac{1}{\beta(\delta_{critical}^{0.5} - \delta^{0.5})} \tag{37}$$

The value of $\delta_{critical}$ indicates the initial elastic period; based on some references; the experimental elastic period can be replaced by the analytical elastic period in this newly developed damage formula since it slightly affected the results. Therefore, this new approach has great importance for structures whose initial elastic periods not available or cannot be determined experimentally.

Carrillo et al. [77] investigated and assessed the damage of squat, thin, and lightly-RC walls by modifying the Park–Ang damage index. In this study, the damage performance of the squat, thin, and lightly-RC walls has been experimentally investigated and tested under monotonic and cyclic loading until the failure occurred. During these tests, the damage evolution and the cracking pattern on the tested RC walls have been observed at different damage states. The experimental program contained 25 RC walls, including walls with and without openings with different height-to-length ratios equal to 0.5, 1.0, and 2.0. Three different concrete types, including (normal-weight, light-weight, and self-consolidating) concrete, have been used in the tested specimens using compressive strength of 15 MPa. In this study, the Park–Ang damage index has been adopted to evaluate the damage on these specimens. For most of the tested specimens, parameter β was quantified using Eq. (6), which was presented by Park et al. [32,33] in the original formula of Park–Ang damage index calculations resulting in negative values. Consequently, the damage index could not be calculated. Therefore, it has been concluded from this study that for squat, thin, and lightly-RC walls where shear deformation is dominated instead of flexural deformations, the formula initially proposed by Park et al. [33,35] to calculate parameter β in slender elements was not applicable for such these walls. In this study, parameter β has been experimentally determined from the hysteretic response of 25 wall specimens to overcome Park–Ang damage index shortcoming, and a new formula for the parameter β has been provided. The new formula for β has been developed by considering that all wall specimens reached the failure limit and at the failure limit, the damage index is supposed to equal 1.0, accordingly the experimental-based formula for parameter β has been presented as follows:

$$\beta_{exp} = \left(1 - \frac{\delta_{uc}}{\delta_{um}}\right)\frac{F_y \delta_{um}}{E_H} \tag{38}$$

The values of β calculated using the previous formula of β_{exp} show a wide range from 0.08 to 0.60. A significant correlation has been done between the parameter β and the main variables of the tested walls, such as the cumulative ductility μ_{cum} and web reinforcement ratio ρ_w. This strong correlation assured the results mentioned before for squat reinforced concrete members. The regression analysis has been used to represent the correlation proposed in this study by comparing the computed damage index and crack pattern noticed in the tested walls at different loading stages; which proved the model's capability to evaluate the damage of the wall specimens for different performance levels when the Park–Ang damage index is applied. The proposed equation leads to a novel formulation that can be used to numerically assess the damage for squat, thin, and lightly-reinforced concrete structural elements, and it has been presented as follows:

$$\beta_3 = 1.39 \times \left(\frac{\mu_{cum}}{0.001\rho_w}\right)^{-.042} \tag{39}$$

where μ_{cum} refers to the cumulative ductility, which represents a response parameter related to the cumulative damage effect due to cyclic loading. The cumulative ductility can be quantified as the sum of the ductility demands beyond the elastic limit [78] as presented in the following equation:

$$\mu_{cum} = \frac{\sum_{k=1}^{n} \delta_k}{\delta_y} \tag{40}$$

where δ_y refers to the displacement at the top of the wall corresponding to the flexural yield condition, and δ_k represents the maximum plastic displacement at the top of the wall for cycle k and can be determined using the following equation:

$$\delta_k = \begin{cases} 0 & when\ \delta_k < \delta_y \\ \delta_k & when\ \delta_k > \delta_y \end{cases} \tag{41}$$

Moreover, much work has been performed to investigate and identify the seismic response of several RC structures subjected to near-fault ground motions [44,79]. For the same intensity and duration of ground motions, near-fault ground motions lead to severe damage and higher seismic response on the structures compared with far-fault ground motions [80]. Rodriguez et al. [81] have done a further study to estimate the DI for RC columns. In this study, DI depends on hysteretic energy has been investigated by a structural member and the drift ratio of 76 RC columns.

Guo et al. [39] developed a new formula to account for the mainshock-aftershock seismic wave based on the modified Park–Ang formula, which has been introduced previously by Kunnath et al. [44,45]. According to this study, the accumulative damage of the structures due to a mainshock-aftershock D_{seq} has presented as follows:

$$D_{seq} = \Delta D_{\mathrm{a}} + D_m \tag{42}$$

The first term in the previous equations refers to the damage that occurred due to mainshock D_m and it can be calculated by the modified Park–Ang formula expressed in Eq. (7). The second term refers to the damage that occurred due to the aftershocks ΔD_{a} and it has been presented as follows:

$$\Delta D_a = \begin{cases} \beta \dfrac{\Delta Eh, a}{M_y \varphi_u} & \varphi_{max,a} \le \varphi_{max,m} \\[2ex] \dfrac{\Delta_{\varphi_p}}{\varphi_u - \varphi_r} + \beta \dfrac{\Delta E_{h,a}}{M_y \varphi_u} & \varphi_{max,a} > \varphi_{max,m} \end{cases} \tag{43}$$

Here $\Delta Eh, a$ is the incremental hysteretic energy dissipated due to aftershock, φ_r refers to the recovered value of the maximum curvature, φ_u represents the ultimate curvature under monotonic loading, M_y represents the yield moment, and β refers to a positive parameter as defined in the Park–Ang damage index. $\Delta_{\varphi_{\mathrm{p}}=\varphi_{\mathrm{p,m}}} - \varphi_{\mathrm{p,a}}$ where $\varphi_{\mathrm{p,m}}$, $\varphi_{\mathrm{p,a}}$ refer to the changes in the unrecovered parts of the maximum curvatures before and after excitation due to aftershocks, and can be estimated as follows:

$$\varphi_{p,m} = \varphi_{max,m} - \frac{M_{max,m}}{\alpha_1 EI} \tag{44}$$

$$\varphi_{\mathrm{p,a}} = \varphi_{\mathrm{max,a}} - \frac{M_{\mathrm{max,a}}}{\alpha_2 EI} \tag{45}$$

where $M_{\mathrm{max,m}}$ and $\varphi_{\mathrm{max,m}}$ represent the maximum moment and curvature, respectively, during a mainshock, $M_{\mathrm{max,a}}$ and $\varphi_{\mathrm{max,a}}$ represent the maximum moment and curvature during an after-shock, EI refers to the elastic flexural stiffness of the element, and α_1 and α_2 are the stiffness reduction factors of the unloading process.

6 Conclusion

In this study, an overview of available damage assessment methods through damage indices is presented. Their formulation, features, limitations, and progressive development of these indices have also been introduced. According to this review, it can be concluded that:

- These damage indices are considered an effective tool to quantify the degree of structural components' damage or the overall structural damage.
- Damage indices can practically be used in the evaluation of damage induced due to seismic events.
- In this context, it should be mentioned that researchers widely use the well-known Park–Ang damage index to assess the damage because of its high accuracy and simplicity in application.
- Park–Ang damage index is initially proposed for slender sections (slender beam and columns) where the flexural deformations dominated. However, it is rarely calibrated for shell structures or for the element in which shear deformation dominated instead of flexural deformations such as RC walls.

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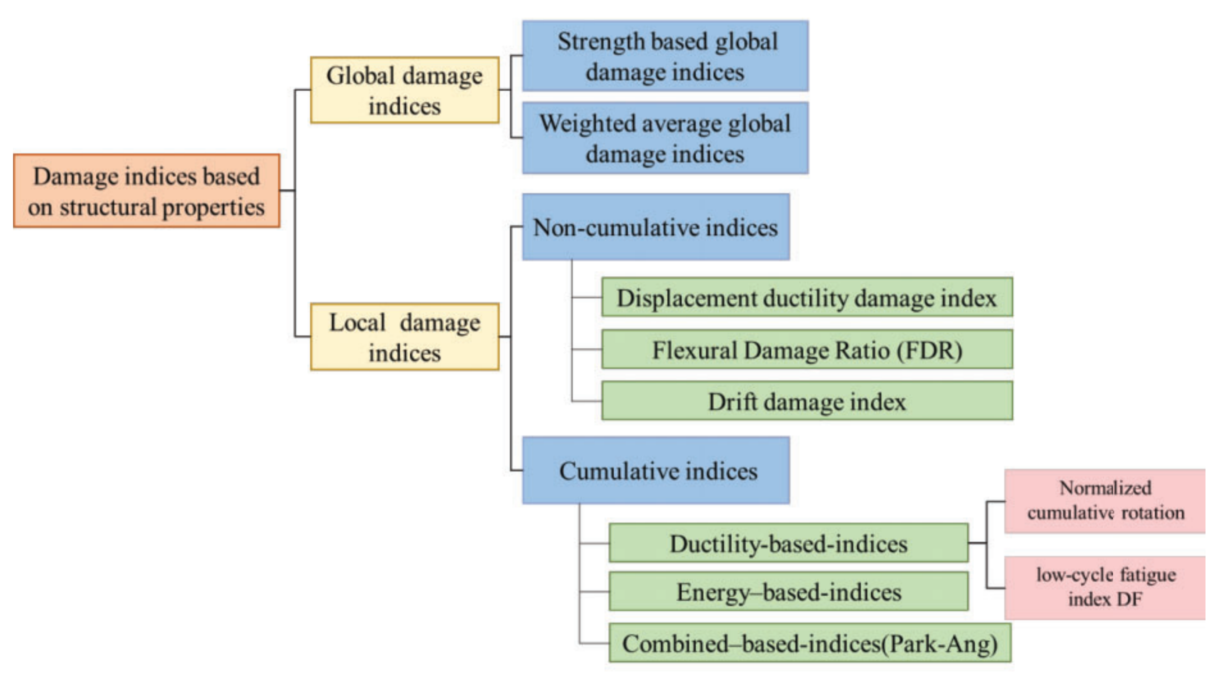
Appendix 1

Damage indices based on structural properties



Damage indices based on dynamic properties