CHARACTERISTIC FORMULAS OF DAMAGE INDICES FOR REINFORCED CONCRETE STRUCTURES: A GENERAL GUIDELINE

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ABSTRACT

The damages to structures are quantified by employing a damage index (DI). This paper deals with the existing damage indices proposed for the reinforced concrete (RC) structures. The existing formulas and models were proposed at different forms for the damages mainly caused by the earthquake. Generally, damage indices are based on the plastic deformation, inelastic deformation, and energy distribution. In this paper, the main characteristic formulations proposed for damage indices to quantify the damges to reinforced concrete structures presented.

Keywords; reinforced concrete, plastic deformation, inelastic deformation, energy distribution, monotonic loading, cyclic loading

INTRODUCTION

Reinforced concrete structures are exposed to loads coming from different sources during their lifetime. The structure should be able to stand with damage without any collapse under the effect of an earthquake. Earthquakes and hurricanes can cause stresses and deformations on structures that might damage to the structural members or to the entire structure.

Quantifying damage has been one of the most important research areas in the world. Different methods were proposed to predict damage state of the structures. Damage assessment takes into account potential and a real case of degradation in the structures. In addition, damage assessment techniques are applied when structural retrofit, repair, and post-earthquake evaluation needed.

Damage indices are used to quantify damages under the effect of earthquake loading and determine their vulnerability. DI is the mathematical model for the numerical definition of the damage of structures. Structural damage level is estimated by DI by comparing specific structural response parameters exerted by the earthquake with appropriate structural deformation capacity. When the economic aspect is taken into consideration, it can be defined as the proportion of money needed for restoration of structures that damaged by the earthquake and the resources needed for the construction of a structure.

Table 1. DI commentary (Ladjinovic, 2004)

Degree of damage	DI	State of structure
Minor	0,0-0,2	Serviceable
Moderate	0,2-0,5	Repairable
Severe	0,5-1,0	Irreparable
Collapse	>1,0	Loss of buildings

Furthermore, the measure of structural damage is based on the seismic analysis of buildings. Several damage indices were proposed to evaluate the state of structures. DI is a normalized

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quantity that has a value between 0 and 1. The damage degree of the reinforced structures from DI can be determined by proposed DI formulas.

Reinforced concrete buildings can be separated into categories according to their damage indices. The relationship between the degree of damage and DI has shown in above table 1.

DI proposed by Park and Ang

Park-Ang (1985) damage formula evaluates DI as a linear combination of plastic deformation and energy distribution. It was improved for reinforced concrete structures to undertake the calculation of damage caused by cyclic deformations into the past-yield level. It describes DI as a result of a linear combination of the damage caused by excessive deformation and repeated cycling loading, taken in the form of dissipated energy.

$$DI = \frac{\Delta_i}{\Delta_u} + \frac{\beta}{P_Y.\Delta_u}\int dE \qquad (1)$$

Δ_i: peak deformation,

Δ_u: ultimate deformation capacity under monotonic loading,

P_Y: calculated yield strength,

dE: hysteresis dissipated energy,

β: constant value that depends on the structural characteristics and checks the strength deterioration in the relationship with the dissipated energy.

DI proposed by Mizuhata and Nishigaki

The Mizuhata and Nishigaki (1983) model identifies DI like as a linear combination of plastic deformation and energy distribution as a result of maximum deformation, failure deformation under the effect of monotonic load and a number of real cycles which causes the failure.

$$DI = \frac{|\Delta_{max}|}{\Delta_u} + \sum_{i=1}^{k}\left(\frac{n_i}{N_{fi}}\right)^{0{,}91}\left(1 - \frac{\Delta_i}{\Delta_u}\right) \qquad (2)$$

$|\Delta_{max}|$: maximum displacement,

Δ_u: collapse displacement ,

n_i: number of cycles (with displacement range Δ_i) of actually loading,

N_{fi}: number of cycles (with displacement range Δ_i) to failure.

DI proposed by Hwang and Scribner

Hwang and Scribner (1984) proposed a model which is based on Gosain's energy index. The formula standardized by energy distribution, stiffness and maximum displacement in the i^{th} cycle included with initial stiffness, yield displacement and a number of cycles in which $P_i > 0.75P_Y$.

$$DI \quad = \sum_{i=1}^{n} E_i \frac{K_i}{K_e}\left(\frac{\Delta_i}{\Delta_Y}\right) \qquad (3)$$

E_i: energy dissipated in the i-th cycle,

K_i: secant stiffness of the i-th cycle,

K_e: initial stiffness,

Δ_i: maximum deformation in the i-th cycle,

Δ_y: yield deformation,

n: number of cycles for which is $P_i \geq 0{,}75P_Y$.

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DI proposed by Powell and Allahabadi

Powell and Allahabadi (1988) proposed DI which is based on plastic deformation. DI depends on displacement ductility. It offers a right value of damage cause by static unidirectional load. However, it does not show information on the repeating cycles of inelastic deformation and energy distribution.

$$DI \quad = \frac{u-u_y}{u_u-u_y} = \frac{\mu-1}{\mu_u-1} \tag{4}$$

u: maximum inelastic displacement in the course of a ground motion,

u_y: yield displacement,

u_u: an ultimate displacement capacity of the system under the effect of monotonically increasing lateral deformation,

μ: maximum ductility request in the course of an earthquake ($\mu = u/u_y$),
while μ_u ($\mu_u = u_u/u_y$) is the monotonic ductility capacity.

DI proposed by Mahin and Bertero

A number of the repeated cycles of inelastic deformations have potential to happen in the time of ground movement which occurs during an earthquake. Hysteretic energy contains cumulative effects of inelastic reactions that is corporate with structural damage. Mahin and Bertero (1981) proposed a formula for describing normalized hysteretic energy ductility μ_h.

$$\mu_h = 1 + \frac{E_h}{F_y u_y} \tag{5}$$

E_h: hysteretic energy,

F_y: yield strength of the structure,

u_y: yield displacement.

$$\varepsilon = \frac{E_h}{F_y u_y} \tag{6}$$

Eq. (6) is called hysteretic energy. Hysteretic ductility μ_n is the displacement ductility of an elastic-perfectly-plastic system under the effect of a constant enhancement lateral deformation which distributes the hysteretic energy like a real system. DI for the elastic perfectly plastic system related with the hysteretic energy can be described by Eq. (8).

$$DI \quad = \frac{E_h}{F_y(u_u-u_y)} = \frac{\mu_n-1}{\mu_u-1} \tag{7}$$

This DI can be simplified for the general force displacement as,

$$DI \quad = \frac{E_h}{E_{hu}} \tag{8}$$

E_{hu}: The hysteretic energy capability of the system under the effect of monotonically enhancement of lateral deformation

DI proposed by Ladjinovic

Ladjinovic (2011) proposed the progress DI by modifying the existing Park-Ang model directly by eliminating insufficiencies related with physical meaning of DI. This DI is presented as a function of its displacement history, hysteretic energy E_h, and plastic deformation as;

$$DI \quad = \frac{u-u_y}{(u_u-u_y)} + \alpha\beta \frac{E_h}{F_{y(u_u-u_y)}} \tag{9}$$

α: The coefficient used to yearly the impact of the hysteretic energy under the effect of monotonically growing deformations. The coefficient is expressed by;

$$\alpha = 1 - \frac{\mu_c}{\mu_{ac}} \tag{10}$$

μ_c: cyclic ductility,

μ_{ac}: accumulative ductility.

Cyclic ductility μ_c ($\mu_c = u_{c,max}/u_y$) depends on the maximum cyclic displacement request $u_{c\,max}$ pending a ground movement (Mahin and Bertero (1981)). Accumulative ductility depends on the total inelastic displacements $u_{p,i}$ which is related with the past repeated cycles of inelastic deformations in the time of earthquake. Therefore, DI depends on ultimate deformation capacity under the effect of monotonically growing deformations and maximum inelastic deformations. The monotonically growing deformations and maximum inelastic deformations occur because of earthquake and accumulative impacts of the replicated cycles of inelastic deformation. Structural damage mainly depends on magnitude of inelastic deformation. As a result, Modified damage index DI is arranged for the cases of şarhe number and small number of the repeated cycles of inelastic deformations.

$$DI = \frac{\mu_p}{\mu_u - 1}\left(1 + \alpha\beta\frac{\varepsilon}{\mu_p}\right) \tag{11}$$

$$\mu_p\text{: plastic ductility } \left(\mu_p = \mu - 1\right) \tag{12}$$

DI proposed by Rodrigueza and Padilla

Rodrigueza and Padilla (2009) have proposed a DI from the seismic damage parameter that was presented by Rodriguez (1994). This seismic damage parameter takes into account a level of admissible seismic performance. This parameter was regulated by using previous earthquake records which did not result in collapse. It describes DI using drift ratio.

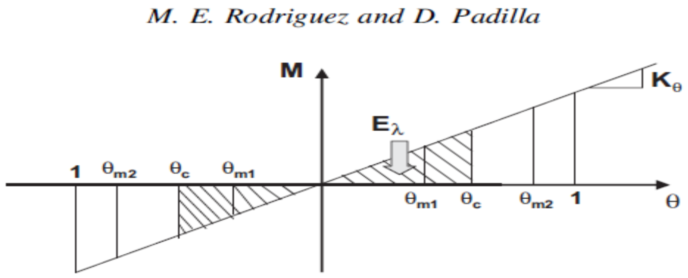

Figure 1. Parameters of the proposed DI (Rodrigueza and Padilla, 2009)

$$\theta = \frac{u}{h} \tag{13}$$

θ: drift ratio,

u: displacement,

h: column Height.

The proposed DI for a single degree of freedom (SDOF) was described as:

$$DI = \frac{E_H}{E_\lambda} \tag{14}$$

$$E_\lambda = k_\theta . \theta_c^2 \tag{15}$$

θ_c: Maximum drift ratio,

E_λ: Energy absorbed in elastic system,

E_H: Hysteretic energy,

k_θ: Elastic energy absorbed by a single degree of freedom system while it achieves;

$\theta = \mp 1$ (Figure 1)

At collapse situation ($E_H = E_\lambda$), $I_d = 1$. As a result, Eq. (16) has been obtained.

$$\theta_c^2 = \frac{E_\lambda}{k_\theta} \tag{16}$$

Parameter γ is used for estimation of ground motions. It depends on structural and ground movement criterias.

$$\gamma^2\theta_m^2 = \frac{E_H}{k_\theta} \tag{17}$$

$\gamma^2\theta_m^2$: Dimensionless plastic work demand in the single degree of freedom system.

It is fact that, $E_H = E_\lambda$ indicates collapse of the structures. Therefore, for the cases of $E_H < E_\lambda$, by using Eqs. (16) and (17) results in $\gamma\theta_m < \theta_c$, which leads to obtain Eq. (18) which shows that $I \quad < 1$.

$$I \quad = \left(\frac{\gamma\theta_m}{\theta_c}\right)^2 \tag{18}$$

Therefore, the plastic work capacity of a reinforced concrete member and the anticipated shape of the hysteresis loops are learned. Moreover, reinforced concrete member fail can be predicted for a target displacement history and deformation θ_m.

Damage indices proposed by Sadeghi

Sadeghi has proposed different forms of damage indices' formulas to simulate and quantifying the local and global behaviors of structures by proposing different models of numerical and experimental simulations for RC structures ((Sadeghi, 1994, 1995, 1998, 2001, 2002, 2011, 2014, 2015, 2017a, 2017b,), (Sadeghi and Nouban, 2010a, 2010b, 2013, 2016, 2017a, 2017b, 2017c, 2018), (Hashemi et al., 2018)). Summary of Sadeghi's damage indices formulas are reported below:

DI proposed by Sadeghi (implicit global version)

The proposed DI statement is the maximum value of DI^+ and DI^-, by considering DI^+ for the positive displacements and DI^- for the negative displacements as follows:

$$DI = Max[DI^+,\ DI^-] \tag{19}$$

With:

$$DI^+ = \frac{\sum_{i=1}^{i=i} E_{pi}^+}{E_u^+} \times C^+ \qquad \text{(for displacements in positive direction)} \tag{20}$$

$$DI^- = \frac{\sum_{i=1}^{i=i} E_{pi}^-}{E_u^-} \times C^- \qquad \text{(for displacements in negative direction)} \tag{21}$$

Where:

The adaptation factors "C^+ and C^-" are expressed as showing below:

$$C^+ = \frac{(F_{max}^+ \times \delta_{max}^+)_{Monotonic}}{(F_{max}^+ \times \delta_{max}^+)_{Cyclic}} \tag{22}$$

$$C^- = \frac{(F_{max}^- \times \delta_{max}^-)_{Monotonic}}{(F_{max}^- \times \delta_{max}^-)_{Cyclic}} \tag{23}$$

and:

i: cycle number

E_{pi}^+: absorbed energy during $(PHC)_i^+$ in positive direction,

E_{pi}^-: absorbed energy during $(PHC)_i^-$ in negative direction,

F_{max}^+ : maximum force applied in positive direction,

F_{max}^- : maximum force applied in negative direction,

δ_{max}^+ : maximum displacement in positive direction,

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δ^-_{max}: maximum displacement in negative direction,

E^+_u: absorbed energy at failure in the case of positive monotonic loading,

E^-_u: absorbed energy at failure in the case of negative monotonic loading.

The developed form of Eqs. (20) and (21) united with the Eqs. (22) and (23) are written as follows:

$$DI^+ = \frac{\sum_{i=1}^{i=i} \int_{\delta^+_{p(i-1)}}^{\delta^+_{pi}} F^+_{pi}.d\delta^+_{pi}}{E^+_u} \times \frac{(F^+_{max} \times \delta^+_{max})_{monotonic}}{(F^+_{max} \times \delta^+_{max})_{cyclic}} \quad \text{(for displacements in positive direction)} \tag{24}$$

$$DI^- = \frac{\sum_{i=1}^{i=i} \int_{\delta^-_{p(i-1)}}^{\delta^-_{pi}} F^-_{pi}.d\delta^-_{pi}}{E^-_u} \times \frac{(F^-_{max} \times \delta^-_{max})_{monotonic}}{(F^-_{max} \times \delta^-_{max})_{cyclic}} \quad \text{(for displacements in negative direction)} \tag{25}$$

Where:

F^+_{pi} : applied force during $(PHC)_i^+$ in positive direction,

F^-_{pi} : applied force during $(PHC)_i^-$ in negative direction,

δ^+_{pi}: displacement during $(PHC)_i^+$ in positive direction,

δ^-_{pi} : displacement during $(PHC)_i^-$ in negative direction.

Therefore, to apply the global implicit energy-based DI, Eqs. (19), (24) and (25) are used.

DI proposed by Sadeghi (explicit global version) for fatigue case

The explicit version which consists of Eqs. (19), (20) and (21), yields Eqs. (31), (32) and (33) for predicting the number of cycles at failure due to fatigue as follows:

$$DI^+ = \frac{\sum_{i=1}^{i=i} E^+_{pi} + \sum_{j=1}^{j} \sum_{k=1}^{k} \lambda^+_j E^{j+}_{fk}}{E^+_u} \quad \text{(for displacements in positive direction)} \tag{26}$$

$$DI^+ = \frac{\sum_{i=1}^{i=i} E^-_{pi} + \sum_{j=1}^{j} \sum_{k=1}^{k} \lambda^-_j E^{j-}_{fk}}{E^-_u} \quad \text{(for displacements in negative direction)} \tag{27}$$

Where:

i: cycle number (considering all cycles, equals $j \times k$ for regular repeating cases),

j: group number of constant amplitude cycles,

k: number of cycles in group j,

E^{j+}_{fk}: absorbed energy during $(FHC)_k^+$ at each different amplitude number j,

λ^+_j: fatigue factor for group j (for positive displacements),

E^{j-}_{fk}: absorbed energy during $(FHC)_k^-$ at each different amplitude number j,

λ^-_j: fatigue factor for group j (for negative displacements).

The developed form of Eqs. (20) and (21) are written as follows:

$$DI^+ = \frac{\sum_{i=1}^{i=i} \int_{\delta^+_{p(i-1)}}^{\delta^+_{pi}} F^+_{pi}.d\delta^+_{pi} + \sum_{j=1}^{j} \sum_{k=1}^{k} \int_{\delta^{j+}_{f(k-1)}}^{\delta^{j+}_{fk}} \lambda^+_j F^{j+}_{fk}.d\delta^{j+}_{fk}}{E^+_u} \quad \text{(for positive displacements)} \tag{28}$$

$$DI^- = \frac{\sum_{i=1}^{i=i} \int_{\delta^-_{p(i-1)}}^{\delta^-_{pi}} F^-_{pi}.d\delta^-_{pi} + \sum_{j=1}^{j} \sum_{k=1}^{k} \int_{\delta^{j-}_{f(k-1)}}^{\delta^{j-}_{fk}} \lambda^-_j F^{j-}_{fk}.d\delta^{j-}_{fk}}{E^-_u} \quad \text{(for negative displacements)} \tag{29}$$

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Where: δ_{fk}^{j+}: displacement during $(FHC)_k^+$ at each different amplitude number j,

δ_{fk}^{j-}: displacement during $(FHC)_k^-$ at each different amplitude number j.

To apply the global explicit energy-based DI, Eqs. (19), (28) and (29) are used.

Estimation of the number of cycles at failure cause of fatigue

An extra advantage of this form of explicit DI is that, it possible to predict the number of cycles at failure (n_j) cause of fatigue. n_j is obtained as follows for these identical cycles set type j:

$$DI = Max[DI^+,\ DI^-] = 1 \tag{30}$$

$$n_j = Min\,[n_j^+, n_j^-] \tag{31}$$

With:

$$n_j^+ = \frac{E_u^+ - E_{p1}^+}{\lambda_j^+ E_{f1}^{j+}} \qquad \text{(If at failure: DI = DI}^+\text{, or for DI}^+ > \text{DI}^-) \tag{32}$$

$$n_j^- = \frac{E_u^- - E_{p1}^-}{\lambda_j^- E_{f1}^{j-}} \qquad \text{(If at failure: DI = DI}^-\text{, or for DI}^+ < \text{DI}^-) \tag{33}$$

Where:

E_{p1}^+: absorbed energy for a $(PHC)_j^+$,

E_{f1}^{j+}: absorbed energy for an $(FHC)_j^+$,

E_{p1}^-: absorbed energy for a $(PHC)_j^-$,

E_{f1}^{j-}: absorbed energy for an $(FHC)_j^-$.

The improved form of Eqs. (31) and (32) are written as follows:

$$n_j^+ = \frac{E_u^+ - \int_0^{\delta_{p1}^+} F_p^+ . d\delta_p^+}{\lambda_j^+ \int_0^{\delta_{f1}^{j+}} F_f^{j+} . d\delta_f^{j+}} \qquad \text{(If at failure: DI = DI}^+\text{, or for DI}^+ > \text{DI}^-) \tag{34}$$

$$n_j^- = \frac{E_u^- - \int_0^{\delta_{p1}^-} F_p^- . d\delta_p^-}{\lambda_j^- \int_0^{\delta_{f1}^{j-}} F_f^{j-} . d\delta_f^{j-}} \qquad \text{(If at failure: DI = DI}^-\text{, or for DI}^+ < \text{DI}^-) \tag{35}$$

Where:

δ_{p1}^+: maximum displacement for a $(PHC)_j^+$,

δ_{f1}^{j+}: maximum displacement for an $(FHC)_j^+$,

δ_{p1}^-: maximum displacement for a $(PHC)_j^-$,

δ_{f1}^{j-}: maximum displacement for an $(FHC)_j^-$.

To find out the number of cycles at failure due to fatigue, Eq. (31), (34) and (35) are used.

DI proposed by Sadeghi (simplified global version)

This version is simple, direct and more accurate at failure for the cases of cyclic loading, but it is not valid for fatigue loading.

In this case, a monotonic loading test is not needed for the cyclic loading case (Sadeghi 2011). This simplified version consists of the Eqs. (19), (38) and (39) as follows:

$$DI^+ = \frac{\sum_{i=1}^{i=i} E_{pi}^+}{\sum_{i=1}^{i=n} E_{pi}^+} \qquad \text{(for displacements in positive direction)} \tag{36}$$

$$DI^- = \frac{\sum_{i=1}^{i=i} E_{pi}^-}{\sum_{i=1}^{i=n} E_{pi}^-} \quad \text{(for displacements in negative direction)} \quad (37)$$

The developed form of Eqs. (36) and (37) are written as follows:

$$DI^+ = \frac{\sum_{i=1}^{i=i} \int_{\delta_{p(i-1)}}^{\delta_{pi}} F_{pi}^+ . d\delta_{pi}^+}{\sum_{i=1}^{i=n} \int_{\delta_{p(i-1)}}^{\delta_{pi}} F_{pi}^+ . d\delta_{pi}^+} \quad \text{(for displacements in positive direction)} \quad (38)$$

$$DI^- = \frac{\sum_{i=1}^{i=i} \int_{\delta_{p(i-1)}}^{\delta_{pi}} F_{pi}^- . d\delta_{pi}^-}{\sum_{i=1}^{i=n} \int_{\delta_{p(i-1)}}^{\delta_{pi}} F_{pi}^- . d\delta_{pi}^-} \quad \text{(for displacements in negative direction)} \quad (39)$$

To apply the global simplified DI, Eqs. (19), (38) and (39) are used.

Local DI Proposed by Sadeghi

The calculation of the different terms of the different versions of the proposed local DI is performed using the same procedure as explained in global DI by replacing force-displacement curve by the moment-curvature curve. The different versions of the proposed local DI are given below.

Generally, since there is a strong interaction between local and global behaviors of the columns under lateral loading due to the role of the critical section, the local and global damage indices give approximately similar results, while each of them has its own advantages.

DI* proposed by Sadeghi *(implicit local version)

Eqs. (19), (40) and (41) are proposed to calculate the implicit local DI:

$$DI^+ = \frac{\sum_{i=1}^{i=i} \int_{\varphi_{p(i-1)}^+}^{\varphi_{pi}^+} M_{pi}^+ . d\varphi_{pi}^+}{E_{mu}^+} \times \frac{(M_{max}^+ \times \varphi_{max}^+)_{monotonic}}{(M_{max}^+ \times \varphi_{max}^+)_{cyclic}} \quad \text{(for positive loading directions)} \quad (40)$$

$$DI^- = \frac{\sum_{i=1}^{i=i} \int_{\varphi_{p(i-1)}^-}^{\varphi_{pi}^-} M_{pi}^- . d\varphi_{pi}^-}{E_{mu}^-} \times \frac{(M_{max}^- \times \varphi_{max}^-)_{monotonic}}{(M_{max}^- \times \varphi_{max}^-)_{cyclic}} \quad \text{(for negative loading directions)} \quad (41)$$

Where:

M_{pi}^+: applied bending moments during $(PHC)_i^+$ in positive direction,

M_{pi}^-: applied bending moments during $(PHC)_i^-$ in negative direction,

φ_{pi}^+: curvature during $(PHC)_i^+$ for positive PHC curvature,

φ_{pi}^-: curvature during $(PHC)_i^-$ for negative PHC curvature,

M_{max}^+ : maximum moment applied in positive direction,

M_{max}^- : maximum moment applied in negative direction,

φ_{max}^+ : maximum curvature in positive direction,

φ_{max}^-: maximum curvature in negative direction,

E_{mu}^+: area under the curve of moment-curvature at failure in the case of positive monotonic loading,

E_{mu}^-: area under the curve of moment-curvature at failure in the case of negative monotonic loading.

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DI proposed by Sadeghi *(explicit local version)*

Eqs. (19), (42) and (43) are proposed to calculate the explicit local DI:

$$DI^{+} = \frac{\sum_{i=1}^{i=i}\int_{\varphi_{p(i-1)}}^{\varphi_{pi}} M_{pi}^{+}.d\varphi_{pi}^{+} + \sum_{j=1}^{j}\sum_{k=1}^{k}\int_{\varphi_{f(k-1)}}^{\varphi_{fk}} \lambda_j^{+} M_{fk}^{j+}.d\varphi_{fk}^{j+}}{E_u^{+}} \quad \text{(for positive loading directions) (42)}$$

$$DI^{-} = \frac{\sum_{i=1}^{i=i}\int_{\varphi_{p(i-1)}}^{\varphi_{pi}} M_{pi}^{-}.d\varphi_{pi}^{-} + \sum_{j=1}^{j}\sum_{k=1}^{k}\int_{\varphi_{f(k-1)}}^{\varphi_{fk}} \lambda_j^{-} M_{fk}^{j-}.d\varphi_{fk}^{j-}}{E_u^{-}} \quad \text{(for negative loading directions) (43)}$$

Where:

φ_{fk}^{j+}: curvature during $(FHC)_k^{+}$ at each different amplitude number j,

φ_{fk}^{j-}: curvature during $(FHC)_k^{-}$ at each different amplitude number j.

Estimation of the number of cycles at failure due to fatigue in local level based on Sadeghi's formula

Eqs. (31), (44) and (45) are used to estimate the number of cycles at failure due to fatigue in local level:

$$n_j^{+} = \frac{E_{mu}^{+} - \int_0^{\varphi_{p1}} M_p^{+}.d\varphi_p^{+}}{\lambda_j^{+}\int_0^{\varphi_{f1}} M_f^{j+}.d\varphi_f^{j+}} \quad \text{(If at failure: DI = DI}^{+}\text{, or for DI}^{+} > \text{DI}^{-}) \quad (44)$$

$$n_j^{-} = \frac{E_{mu}^{-} - \int_0^{\varphi_{p1}} M_p^{-}.d\varphi_p^{-}}{\lambda_j^{-}\int_0^{\varphi_{f1}} M_f^{j-}.d\varphi_f^{j-}} \quad \text{(If at failure: DI = DI}^{-}\text{, or for DI}^{+} < \text{DI}^{-}) \quad (45)$$

DI proposed by Sadeghi *(simplified local version)*

The Eqs. (19), (46) and (47) are used for calculation of the proposed simplified local DI:

$$DI^{+} = \frac{\sum_{i=1}^{i=i}\int_{\varphi_{p(i-1)}}^{\varphi_{pi}} M_{pi}^{+}.d\varphi_{pi}^{+}}{\sum_{i=1}^{i=n}\int_{\varphi_{p(i-1)}}^{\varphi_{pi}} M_{pi}^{+}.d\varphi_{pi}^{+}} \quad \text{(for positive loading directions)} \quad (46)$$

$$DI^{-} = \frac{\sum_{i=1}^{i=i}\int_{\varphi_{p(i-1)}}^{\varphi_{pi}} M_{pi}^{-}.d\varphi_{pi}^{-}}{\sum_{i=1}^{i=n}\int_{\varphi_{p(i-1)}}^{\varphi_{pi}} M_{pi}^{-}.d\varphi_{pi}^{-}} \quad \text{(for negative loading directions)} \quad (47)$$

CONCLUSION

Damage index formulas quantify the degree of structural damage relative to damage values. Many researchers proposal formulas according to the investigations on the damage on the existing buildings. As a general rule, when the DI is smaller than 0.2, buildings have no damage but if the DI value is greater than 1, the buildings will collapse.

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