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A THEORETICAL REVIEW OF THE DAMAGE INDICES USED TO MODEL THE DYNAMIC NONLINEAR BEHAVIOR OF REINFORCED CONCRETE STRUCTURES

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Abstract. Concrete is one of the most widely used building materials. Even before being subjected to any type of external load the reinforced concrete elements are damaged – cracks and fissures are present in concrete. These are the microcracks formed due to shrinkage, hydration and carbonation. Under various types of external loading microcracks lead to form macrocracks, which, under certain circumstances, propagate and can lead to structural failure. Given the nature of the seismic load, when analysing reinforced concrete structures subjected to earthquakes, it is desirable to account for the structural damage. This can be done by using damage indices. This paper reviews the measures of damage phenomena which governs structural degradation and/or collapse. It includes a general overview of damage indices either local or global. In the final part, the correlation between the analytically obtained damage indices and actual damage state is presented.

Key words: local damage indices; global damage indices; damage state.

1. Introduction

Structural vulnerability can be defined as the degree of damage to a component or a structure under the action of given characteristic earthquake (Suna *et al*., 2010). Structural vulnerability results in obtaining performance

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characteristics. These results can be obtained from engineering analysis using appropriate methods. The most suitable method is the nonlinear dynamic analysis. Based on the obtained results, conclusions can be drawn regarding the ductility requirements for structural elements or entire structural systems (Okada & Takai, 2010).

Given that the seismic action is a cyclical one, a parameter defining the behavior of elements in such scenarios is the ductility. In this case, the structural safety is based on a comparison between the maximum number of plastic incursions and a given value and taking into account only the plastic deformation cycles and neglecting other ones.

Another method consists in considering the hysteretic energy decay as a damage parameter (Decanini *et al*., 2004) and assuming a correlation between failure and the amount of energy dissipated by the structure. The basic assumption for this method is that each cycle, regardless of its amplitude, equally contributes to energy absorption. A observed drawback of this assumption is that in certain cases, the cycles with limited plastic deformation do not correlate with the damage state.

2. Damage indices classification

The problem of classifying seismically induced damage indices was approached by Kappos *et al*., (1992), Williams & Sexsmith, (1995), Golafshani *et al*., (2005), Mieses Hernandez, (2007) and others. Damage indices can generally be classified as follows:

a) *Local damage indices* – can have a cumulative nature if loads are cyclical and depend on the motion and the number of loading–unloading cycles, but can also be of non-cumulative nature if no cyclic loading exist.

b) *Global damage indices* – take into account the whole structure by combining local damage indices. Global damage indices are calculated by weighting the local indices or by comparing the modal properties of the structure before and after the seismic action;

c) *Individual damage indices* – refer to a subset of the structure or structural element.

2.1. Local Damage Indices

a) *Non-cumulative indices*

The development of damage models starting from the ductility concept led to the development of the first damage models.

Newmark and Rosenblueth, proposed in 1971 the ductility factor as a mean to assess damage. The factor can be expressed either as a function of curvature – ϕ , rotation – θ or displacement – *d*, using the following relations:

$$\mu_r(\Phi) = \frac{\varphi_m}{\varphi_y}, \tag{1}$$

$$\mu_r(\theta) = \frac{\theta_m}{\theta_y}, \tag{2}$$

$$\mu_r(d) = \frac{d_m}{d_y}, \tag{3}$$

where m denotes the maximum value and y – the yielding value.

The choice of kinematic or cyclic ductility as a damage measure is equivalent to assuming that the collapse of the structural model is expected for maximum plastic displacement, independent of the number of plastic cycles and the amount of dissipated energy.

Using a similar approach as Newmark and Rosenblueth, in 1977 Lybas and Sozen came up with a similar damage index:

$$I_D = \frac{k_0}{k_m}, \tag{4}$$

where: k_0 is the initial elastic stiffness, k_m – maximum elastic stiffness and I_D – damage index.

In 1981, using the stiffness based damage index (above presented), Banon *et al.*, presented a flexural damage index, computed according to the following relation

$$\text{FDR} = \frac{M_u\varphi_m}{M_m\varphi_u}, \tag{5}$$

where: M_u is the ultimate bending moment as resulting from a pushover analysis, M_m – maximum bending moment and ϕ_m and ϕ_u – corresponding curvatures.

Using a relation based on the final residual curvature ϕ_u, in 1989, Bracci *et al*. suggested the following damage index:

$$I_D = \frac{\varphi_m - M_u/k_m}{\varphi_u - M_u/k_u}, \tag{6}$$

where: M_u is the ultimate bending moment, k_u – ultimate stiffness, k_m – maximum stiffness, ϕ_m – maximum curvature, ϕ_u – ultimate curvature.

b) *Cumulative indices*

Cumulative indices consider damage as a function of accumulated plastic deformation and can incorporate a term referring to the seismically absorbed hysteretic energy.

b_1) *Displacement based cumulative indices*

In the following, N_{CR} will denote the normalized cumulative rotation damage index. Banon and Veneziano have introduced this index in 1982, the calculus relation being

$$N_{CR} = \frac{\sum_{i=1}^{n} \left| \varphi_{im} - \varphi_y \right|}{\varphi_u}, \quad (7)$$

where: ϕ_{im} is the maximum rotation in cycle *i*.

In 1987 Stephens and Yao introduced an index based on the cumulative displacement ductility, providing the following relation

$$I_D = \sum_{i=1}^{n} \left(\frac{\Delta d^+}{\Delta d_f} \right)^{1-br}, \quad (8)$$

where: Δd^+ is the incremental increases of positive displacements, Δd^- – incremental decreases of negative displacements, Δd_{df} – the value of Δd^+ for a cyclic load that leads to failure, Δd_f – recommended 10% of the floor height, *b* – constant ($b = 0.77$ recommended by Stephens and Yao), $r = \Delta d^+/\Delta d^-$ – incremental increase ratio.

b_2) *Force based cumulative indices*

The analytic model described by Wang and Shah, 1987, presents a force based damage index that is computed with relation

$$I_D = 1 - \frac{F_y}{F_m}, \quad (9)$$

where: I_D is the strength decay damage index, F_y – failure force during a loading cycles, F_m – maximum force during previous cycle.

An alternative expression that can be used to express the damage index (I_D) was proposed in 1988 by Jeong and Iwan. The approach takes into account the effects of combining cycles with various amplitudes, the damage index being determined by the following relationship:

$$I_D = \sum_{i=1}^{n} \frac{n_i \mu_i^s}{c} . \quad (10)$$

The model uses: n_i for the number of cycles with inelastic deformations, μ_i^s – for the curvature based ductility factor and c for a constant value.

b$_3$) *Hysteretic energy based cumulative indices*

When defining energy based damage indices it is assumed that the energy dissipated by the structure until its collapse is less than or equal to a threshold value. The parameter used is the hysteretic energy.

Gosain *et al*., (1977), have developed a relationship for an energy based damage index namely

$$I_D = I_W = \sum_{i=1}^{n} \frac{F_i d_i}{F_y d_y} , \quad (11)$$

where: F_i is the failure force, d_i – failure displacement, n – number of hysteretic cycles, F_y – yield force, d_y – yield displacement.

Relation (11) can only be used if $F_i \geq 0.75\ F_y$.

An alternative formulation, proposed by Hwang and Scribner, (1984), that uses the dissipated energy to quantify for the damage (using the damage index I_D) is

$$I_D = \sum_{i=1}^{n} \frac{K_i d_i^2}{K_e d_y^2} , \quad (12)$$

where: E_i is the dissipated energy, K_i – bending stiffness, d_i – maximum displacement, n – number of cycles, K_e – elastic bending stiffness.

b$_4$) *Combined cumulative indices*

Banon and Veneziano, (1982), proposed a damage model based on the maximum displacement, failure displacements and hysteretic energy dissipation. They proposed relationship is

$$I_D = \sqrt{\left(\frac{d_m}{d_y - 1}\right)^2 + \left[\left(\frac{2E_h}{F_y d_y}\right)^{0.38}\right]^2} , \quad (13)$$

where: d_m is the maximum displacement, d_y – yield displacement, E_h – dissipated hysteretic energy, F_y – yielding force.

The most widely used damage index is the Park and Ang one proposed by the cited authors in 1985, which is defined as the linear combination of the maximum displacement and the dissipated energy namely

$$I_D = \frac{d_m}{d_u} + \beta_e \frac{\int \mathrm{d}E}{F_y d_u}, \quad (14)$$

where: d_u is the ultimate displacement at monotonic loading, d_m – maximum displacement corresponding to the point of maximum capacity, β_e – parameter representing the cyclic loading, dE – incremental dissipated hysteretic energy, F_y –longitudinal reinforcement yielding force.

The Park and Ang index can take into account both maximum plastic displacement and plastic dissipated energy and is supported by a wide correlation with observed damage. However, the experimental determination of the parameter β_e is difficult and the methodology is not well stated. Another limitation is the linear combination of ductility and energy in a highly non-linear problems. The index does not take into account the plastic cycles distribution, but considers only the global amount of dissipated energy (Cosenza & Manfredi, 2000).

In a chronologic order, in 1997, Kunnath developed the following relationship:

$$I_D = \frac{\varphi_m - \varphi_y}{\varphi_u - \varphi_y} + \beta_e \frac{\int \mathrm{d}E}{M_y \varphi_u}, \quad (15)$$

where: ϕ_u is the ultimate curvature, ϕ_y – curvature at failure, ϕ_m – curvature corresponding to the maximum bending moment, M_y – bending moment at failure.

2.2. Global Damage Indices

Global damage indices take into account the whole structure and its characteristics and provide information about the global damage state as a function of the distribution and severity of local damage.

a) *Strength based global damage indices*

Using the structures capacity curve, in 1987 Roufaiel and Meyer, developed a global damage index that is defined as

$$I_{D\mathrm{global}} = \mathrm{GDP}\frac{d_m - d_y}{d_u - d_y}, \quad (16)$$

where: d_y is the yielding displacement, d_u – ultimate displacement, d_m – maximum displacement, GDP – global parameter defining the damage state.

The authors suggested accounting for the structure's height (H) through the relationship $d_u = 0{,}06H$.

b) *Global damage indices using global parameters*

It is common that structures encounter softening (period elongation) when damage increases. Assessments in each step show that after a specific step, structures encounter severe softening and become irreparable, therefore they are unreliable (Park *et al*., 1987). Accounting for the fundamental period variation, DiPasquale and Cakmak, (1988), developed the following damage indices:

a) Maximum softening damage index

$$I_{D\mathrm{ms}} = 1 - \frac{T_a}{T_m}. \tag{17}$$

b) Plastic damage index

$$I_{DIs} = 1 - \left(\frac{T_a}{T_m}\right)^2. \tag{18}$$

Final softening damage index:

$$I_{DFs} = 1 - \left(\frac{T_a}{T_d}\right)^2, \tag{19}$$

where: T_a is the initial natural period, T_m – natural period corresponding to the maximum softening, T_d – natural period corresponding to the final softening.

2.3. Structures' Damage Degrees and their Correlation with Observed Damage

A first classification of damage types in Romania was performed by Ifrim in 1984 and is presented in Table 1.

Table 1

Structures' Damage Degrees According to Ifrim, (1984)

Damage type	Damages' physical description
Light	Insignificant from structural strength point of view
Moderate	Localized only in certain horizontal and vertical elements of the load caring structure.
Large (major)	Affects large areas of the load caring structure.
Strong (severe)	Has generalized destructive consequences
Collapse	Partial or total

Worldwide there have been several attempts to correlate the analytically obtained damage indices with observed damage states. The correlation has been made using a classification of reinforced concrete structures based on the damage patterns it experiences. This classification is presented in Table 2.

Table 2
Damage Degrees Classification (Park & Ang, 1989)

Damage degree	Damages' physical description
Light	Minor, localized, fissures/cracks.
Minor	Minor fissures/cracks localized throughout the entire structure. Local crushing of concrete.
Moderate	Cracks on large surfaces. Failure of flexible reinforced concrete elements.
Sever	Failure of reinforced concrete elements throughout the entire structure. Colum's reinforcement buckling.
Total	Partial or total colapse

Applied Technology Council (Ifrim, 1984), proposed a technical assessment of buildings safety in order to evaluate their safety degree, based on a wide range of structural criteria such as: size of crack opening, column's failure and tilting etc.

In 1989 Bracci *et al*. proposed another classification that takes into account the possibility of repairing a building: undamaged building, minor damaged building, repairable building, collapsed building.

The latest scale used at the European level, the European macroseismic scale (ATC-20, 1989), brings a new concept – the explicit use of the seismic vulnerability. It makes and continuously uses a logical connection between macroseismic criteria and seismic vulnerability of human activities.

It is the first scale that depicts explanatory illustrative information in the form of graphics and detailed drawings for a better visual understanding of various degrees of damage. An example of this is presented in Fig. 1.

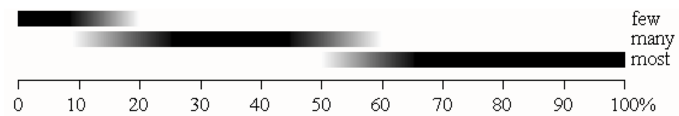

Fig.1. – Quantitative classification of damage according to EMS

For a better correlation between the analytical damage degree and observed damage, researchers have suggested that following aspects should be taken into account when performing a damage analysis (SEAOC Vision, 1995):

a) physical damage of structural and nonstructural elements;

b) the risks that buildings' occupants are subjected to;

c)functionality of the structure after the earthquake.

In 1997 Y.J. Park *et al*., have proposed a correlation between local signs of damage and five levels of damage, according to Table 3.

Table 3

Normalized Damage Index Ranges for a Five-Level Scale (Kunnath, 1997)

Damage level	No damage	Light damage	Moderate damage	Strong damage	Collapse
Ranges for I_D	0…0.1	0.1…0.24	0.25…0.4	0.4…1	≥ 1

3. Cloncluding remarks

This paper presented damage indices as a mean to numerically quantify the damage degree of structural components or the structure as a whole. They have a practical side as they can be used in the estimation of seismically induced structural damage.

Using these indices, the extent of degradation can be quantified in different ways. If an engineering model is used, it can be assumed that a structural degradation in analytical terms and damage indices can be defined. A particular problem which must be taken into account in practical applications is raised by the relationship between the damage indices or degradation state of the various structural components, on the one hand and the state of degradation of the structure as a whole, on the other hand.

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O ANALIZĂ TEORETICĂ A INDICILOR DE DEGRADARE UTILIZAŢI PENTRU A MODELA COMPORTAREA DINAMICĂ NELINIARĂ A STRUCTURILOR DIN BETON ARMAT

(Rezumat)

Betonul este unul din cele mai utilizate materiale de construcţie. Chiar înainte de a fi supuse la orice acţiune externă elementele din beton armat sunt deteriorate – crăpături şi fisuri sunt prezente în beton. Acestea sunt microfisuri formate ca urmare a contracţiei, hidratării şi carbonatării betonului. Sub diferite tipuri de încărcări exterioare microfisurile pot fuziona formând macrofisuri, care, în anumite circumstanţe, se pot propaga conducând la colaps structural. Având în vedere natura acţiunii seismice, în analiza structurilor de beton armat supuse la acţiunea cutremurelor este de dorit să ţină seama de stadiul de degradare al structurii. Acest lucru poate fi realizat prin intermdiul indicilor de degradare.

Se trec în revistă metricile utilizate în descrierea fenomenelor de deteriorare care guvernează degradarea structurală şi/sau colapsul. Articolul include o prezentare generală a indicilor de degradare locali sau globale. În partea finală este prezentată corelaţia dintre indicii de degradare obţinuţi analitic şi starea reală a structurii.