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A neural network based modelling and sensitivity analysis of damage ratio coefficient

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ABSTRACT

The level of structural damage after an earthquake can often be expressed using the damage ratio (DR) coefficient. This coefficient can be calculated using different formulas. A previously valorised new original formula for damage ratio derived for regular structures is implemented. This formula uses the structure response parameters of a single degree of freedom (SDOF) model. The structure response parameters of the SDOF model are obtained by analyzing a large number of non-linear numeric structure responses using earthquakes of different intensities as load input. In this paper, a multilayer perceptron (MLP) neural network is used to model the relationship between the structure parameters (natural period, elastic base shear capacity, post-elastic stiffness and damping) of an SDOF model and the damage ratio (DR) coefficient. The influence of the individual structure parameters on the damage level of a structure is then determined by performing a sensitivity analysis procedure on the trained MLP neural network.

1. Introduction

Structural damage evaluation is an important aspect in the assessment of the inelastic response of reinforced concrete structures subjected to large alternate actions. The nature and amount of structural damage depends on the quality of the materials that compose the structural and non-structural elements, on the configuration and type of structural systems, and on the nature of the loads acting on the structures. Until recently, the damage was basically defined in qualitative terms, normally through the definition of the probable localization of such damage in a structure. The problem of damage quantification is complex, and there are not yet defined criteria for the definition of the analytical models and for the description of the damage itself. This fact is due essentially to the great variety of structural types and their properties, as well as to the characteristics of the actions. A significant development in the establishment of damage models has recently been made. These models assess the structural damage in quantitative terms (Comité Euro-International du Béton, 1996).

The methods for determining the degree of damage to a building after an earthquake can be divided into empirical, subjective, and theoretical. Empirical methods are based on statistical observation of damage to buildings hit by earthquakes, while the subjective method is based on personal experience of the person who evaluates the degree of damage. Theoretical methods are based on a detailed analysis of dynamic models of structures exposed to action of one or more earthquakes. The basis for this method is to use one or more response parameters to define the level of construction defects. The outcome is a damage function, an analytical expression that defines the dependence of the degree of damage and the selected structure response parameter. Several approaches for the structural damage evaluation have been proposed in the literature as well as reports which critically review the different assessments (Coelho, 1992; Kappos 1992; Morić, 1985; Powell & Allahabadi, 1988).

Seismic resistance analysis is basically the analysis of the damage ratio (DR) coefficient, a parameter which defines the level of structural damage. In economic terms, this coefficient actually represents the ratio of funds needed for the rehabilitation of structures damaged by earthquake and the resources necessary for the construction of an identical structure.

Based on some known damage models, a valorised new original deterministic declaration of the damage ratio, DR, is given in Morić, Hadzima, and Ivanušić (2003). They propose that the seismic response analysis of regular structures (structure with symmetric plans and constant vertical stiffness) is acceptable if it is done as a simplified non-linear dynamic analysis with the time history function of ground motion as input load, and a single degree of freedom (SDOF) model with known weight, elastic stiffness, damping, elastic base shear capacity and post-elastic stiffness representing the structure.

The structure response parameters of an SDOF model, obtained by analyzing a large number of non-linear numeric structure responses using earthquakes of different intensities and dominant

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frequencies as load input, are input into this previously valorised new original deterministic declaration of damage ratio (DR), thereby interpreting the level of structure damage at the end of the earthquake.

Neural networks are used to model the relationship between the structure parameters (natural period, elastic base shear capacity, post-elastic stiffness and damping) and the damage level. This data is obtained from a databank of damage ratios, grouped by ground motion. A sensitivity analysis procedure is then applied to identify, qualitatively, the structure parameters that have a greater influence on the damage level. This would provide useful information as to the influence of the individual structure parameters on the damage level of a structure based upon an earthquake load.

The rest of this paper is organized as follows: a brief description of the new original deterministic declaration of damage ratio, DR, provided by Morić et al. (2003) is given in Section 2. A classification of the structures used in the experiment is provided in Section 3. In Section 4, a brief introduction to neural networks is given as well as the structure of the neural network used. An explanation of how sensitivity analysis can be performed using neural networks is also given. Section 5 includes the results obtained after modeling the relationship and performing sensitivity analysis. A brief conclusion is provided in Section 6.

2. Damage ratio coefficient

Usually, in literature, the problem of structural damage is solved by calculating the damage ratio (DR) coefficient. There exist many different definitions of damage ratio (DR) coefficient. Detailed definitions and discussions can be found in several state-of-the-art reports such as Chung, Meyer, and Shinozuka (1987), Williams and Sexsmith (1995), Kappos (1997) and Coelho (1992).

Seismic resistance analysis can be performed either on the structural elements (partial or local) or on the whole structure (global). As a result, damage ratio coefficients can generally be considered as either local or global coefficients depending on how the analysis is performed (Comité Euro-International du Béton, 1996). Depending on how they are defined, damage ratio coefficients can be categorized as deterministic or probabilistic coefficients (Banon & Veneziano, 1982; Ciampoli, Giannini, Nuti, & Pinto, 1989; DiPasquale & Cakmak, 1989), structural or economic coefficients (Dolce, Kappos, Zuccaro, & Coburn, 1994; Gunturi & Shah, 1992; Kappos, Stylianidis, & Michailidis, 1996; Park & Ang, 1985), structural or non-structural coefficients (e.g., Gunturi & Shah, 1992). Other categorizations include coefficients based on deformation, stiffness, or energy, or even a combination of two or more of them, noncumulative (i.e., peak response values) or cumulative coefficients, low-cycle versus high-cycle fatigue coefficients, global coefficients as a weighted average of local indicators or modal coefficients, etc. (Comité Euro-International du Béton, 1998).

For example, Chung et al. (1987) determine "damage" as a level of physical degradation with precisely defined consequences to residual capacity of resistance and deformations. Failure is the specific level of damage without any capacity of resistance and deformations. The Park and Ang (1985) model defines damage ratio as a linear combination of plastic deformation (ductility) and energy dissipation.

In Morić et al. (2003), the seismic damage ratio model of regular structures is analyzed and a valorised new original formula for damage ratio is given and is briefly explained herein. The seismic damage ratio model is based on following assumptions:

- Seismic response of regular structures (symmetric plans and constant vertical stiffness) can be well interpreted by using SDOF system as a mathematical model of the structures.
- The structure response parameters: ductility, stiffness change, energy balance and number of plastic excursions can describe the real level of structural damage.

The level of structural damage (damage ratio, DR) can be described as a function of the following calculated structure response parameters:

- Displacement ductility (D) defines the measure of post-elastic region in which a structure was during an earthquake.
- Maximum base shear force, $(\mathrm{BS})_{\max}$, and maximum top displacement ($u_{\max}$) defines the residual stiffness (K') of the structure at the end of the earthquake.
- Number of yield excursions (N_Y) and hysteresis energy (E_H) define the post-elastic cyclic nature of damage ratio developing.

The first two parameters define damage mechanism under monotonic load while the third parameter takes into account the cyclic failure. The damage ratio coefficient (DR) is defined as the linear combination of plastic deformations, stiffness degradation and energy dissipation of a structure during an earthquake:

$$DR = \frac{1}{30}\left[D + \Delta K + \sqrt[3]{(N_\mathrm{Y}E_\mathrm{H}/W)}\right], \tag{1}$$

where

$D = \frac{u^{\max}}{u^{y}}$	the displacement ductility demand
$\Delta K = \frac{K_e}{K'}$	the relative degradation of stiffness at the end of the earthquake
$K_e = \frac{(BS)_y}{u^y}$	the initial structure stiffness
$K' = \frac{(BS)_{\max}}{u^{\max}}$	the residual secant stiffness of a structure after an earthquake
N_Y	the number of yield excursions reached during the earthquake
$\frac{E_\mathrm{H}}{W}$	the hysteresis energy per unit of structure mass, dissipated during an earthquake

The importance of the damage ratio coefficient (DR) in the damage model is to describe the condition of a structure after an earthquake. In such an approach, the damage ratio value can be used to declare a decreased residual seismic resistance and increased residual damping coefficient of a structure.

The damage indices can be categorized in various ways. The simplest way is to correlate the damage indices and observed damage. For example, Park and Ang (1985) and Park, Reinhorn, & Kunnath (1987) classified the structural damage as: None, Minor, Moderate, Severe and Collapse. Similarly Bracci, Reinhorn, Mander, and Kunnath (1989) defined the following categorization: undamaged or minor damage, repairable, irrepairable, collapsed.

Morić et al. (2003) implemented the damage ratio values (DR) in pre and post earthquake damage analysis by relating the dam-

Table 1
Physical interpretation of damage ratio coefficient.

Damage ratio (DR)	Structural damage description	Possibilities of technical and economic reparation	Code damage level (S) (1°–6°)
$0 \leqslant DR \leqslant 0.3$	Insignificant	Repairable	1°–2°
$0.3 < DR \leqslant 0.5$	Moderate	Repairable	3°
$0.5 < DR \leqslant 0.8$	Severe	Repairable	4°
$0.8 < DR \leqslant 1.0$	Heavy	Repairable	5°
$1.0 < DR$	Extremely high level or collapse	Non-repairable	6°