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CLASSIFICATION OF SEISMIC DAMAGES IN BUILDINGS USING FUZZY LOGIC PROCEDURES

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Abstract. *It is well known that damage observations on buildings after severe earthquakes exhibit interdependence with the seismic intensity parameters, like peak ground acceleration, response-spectra, Arias intensity and strong motion duration. Numerical elaboration of structural systems quantified the interrelation degree by correlation coefficients. In addition, the seismic response of buildings is directly depended on the ground excitation. Consequently, the seismic response of buildings evaluated by a numerical analysis is directly depended on the used accelerogram and its intensity parameters. Among the several response quantities, the focus is on the overall damage indices (DIs) because they summarize the post-earthquake status of buildings on a single value, which can be easily handled. The Maximum Inter-Storey Drift Ratio (MISDR) and the damage index as defined by Park/Ang ($DI_{G,PA}$) characterize effectively the structural damages caused to buildings during earthquakes. Intervals for the values of the damage indices are defined to classify the damage degree in low, medium, large and total. This paper presents an Adaptive Neuro-Fuzzy Inference System (ANFIS) for the classification of seismic damages. The structural damage is presented by means of the two previously mentioned damage indices (MISDR and $DI_{G,PA}$). The seismic excitations are simulated by a set of artificial accelerograms and their intensity is described by a set of well-known seismic parameters. The proposed system was trained (using nonlinear dynamic analyses) and tested on an eighth-story reinforced concrete structure. The numerical results have shown that the fuzzy technique that is implemented in the proposed method contributes to the development of an efficient blind prediction of the seismic damage potential that an accelerogram possesses. The recognition scheme achieves correct classification rates over 90%.*

1 INTRODUCTION

Seismic accelerograms are records of ground acceleration versus time during earthquakes that cannot be described analytically. However, several seismic parameters have been presented in the literature during the last decades that can be used to express the intensity of a seismic excitation and to simplify its description. Post-seismic field observations and numerical investigations have indicated the interdependency between the seismic parameters and the damage status of buildings after earthquakes [1, 2]. The latter can be expressed by proper damage indices. The Maximum Inter-Storey Drift Ratio (MISDR) and the global damage index as defined by Park/Ang ($DI_{G,PA}$) characterize effectively the structural damage caused to buildings during earthquakes and thus, are used as metrics to classify the damage degree into 4 categories, low, medium, large and total. In this context, the damage degrees denote undamaged or minor damage-repairable damage-irreparable damage-partial or total collapse of the building, respectively.

This paper suggests a technique based on an Adaptive Neuro-Fuzzy Inference System (ANFIS) for seismic structural damage classification. A total set of 200 artificial accelerograms has been used and were correctively assigned to one of the above four categories with performances up to 90% and 87% of accuracy, for MISDR and $DI_{G,PA}$, respectively. High classification rates indicate that the proposed methodology is suitable for adaptive predictive control of the behavior of the concrete construction used, for any unknown seismic signal. The proposed method is applied to an eight-story reinforced concrete frame building, designed after the rules of the recent Eurocodes.

2 DAMAGE INDICES

MISDR is an overall structural damage index (OSDI) that can define the level of post-seismic corruption in a building [3, 4] and can be evaluated by the following equation:

$$\text{MISDR}=\frac{|u|_{max}}{h}100[\%] \tag{1}$$

Where $|u|_{max}$ is the maximum absolute inter-storey drift and h the inter-storey height.

Additionally, the OSDI after Park/Ang ($DI_{L,PA}$) is used to describe the structural damage [5]. First, the local damage index according to Park/Ang is calculated. The local damage index is a linear combination of the damage caused by excessive deformation and that contributed by the repeated cyclic loading effect that happens during an earthquake. The local DI is given by the relation:

$$DI_{L,PA}=\frac{\theta_m-\theta_r}{\theta_u-\theta_r}+\frac{\beta}{M_y\theta_u}E_T \tag{2}$$

Where θ_m is the maximum rotation during the load history, θ_u is the ultimate rotation capacity of the section, θ_r is the recoverable rotation at unloading, β is a strength degrading parameter (0.1-0.15), M_y is the yield moment of the section and E_T is the dissipated hysteric energy. The global damage index after Park/Ang is a linear combination of the maximum ductility and the hysteretic energy dissipation demand forced by the earthquake on the structure. Thus, the global damage index after Park/Ang ($DI_{G,PA}$) is given by:

$$DI_{G,PA} = \frac{\sum_{i=0}^{n} DI_L E_i}{\sum_{i=0}^{n} E_i} \tag{3}$$

where E_i is the energy dissipated at location i and n is the number of locations at which the local damage is calculated.

The two aforementioned global DIs are well known and used extensively in earthquake engineering, as they are experimentally proved to express the behavior of a structure [5-10]. In Table 1, intervals for the values of the DIs are defined to classify the damage degree in low, medium, large and total [11]. These categories refer to minor, reparable damage, irreparable damage and severe damage or breakdown of the building, respectively.

Structural Damage Indices	Structural Damage Degree			
	Low	Medium	Large	Total
MISDR	≤ 0.5	0.5 < MISDR ≤ 1.5	1.5 < MISDR ≤ 2.5	> 2.5
$DI_{G,PA}$	≤ 0.3	$0.3 < DI_{G,PA} \leq 0.6$	$0.6 < DI_{G,PA} \leq 0.8$	> 0.8

Table 1: Structural damage classification according to MISDR and $DI_{G,PA}$.

3 SEISMIC INTENSITY PARAMETERS

An accelerogram is the recording of the acceleration of the ground during an earthquake. Accelerograms exist in variant forms, and thus their similarity cannot be extracted directly. Therefore, a computer supported analysis has been done and a set of 20 features has been produced to describe the destructiveness of seismic excitations.

No	Seismic Intensity Parameter	References
1	Peak Ground Acceleration (PGA)	[13, 14]
2	Peak Ground Velocity (PGV)	[13, 14]
3	PGA to PGV ratio (PGA / PGV)	[13, 14]
4	Spectral Velocity (SV)	[13, 14]
5	Spectral Acceleration (SA)	[13, 14]
6	Spectral Displacement (SD)	[13, 14]
7	Central Period (CP)	[15]
8	Seismic Energy Input (E_{inp})	[16]
9	Arias Intensity (I_A)	[17]
10	Strong Motion Duration after Trifunac/Brady (SMD_{TB})	[18]
11	Power ($P_{0.90}$)	[19]
12	Root Mean Square Acceleration (RMS_a)	[13]
13	Seismic Intensity after Fajfar/Vidic/Fischinger (I_{FVF})	[20]
14	Spectrum Intensity after Housner (SI_H)	[21]
15	Spectrum Intensity after Kappos (SI_K)	[22]
16	Spectrum Intensity after Martinez-Rueda (SI_{MR})	[23]
17	Effective Peak Acceleration (EPA)	[24, 25]
18	Cumulative Absolute Velocity (CAV)	[26]
19	Maximum EPA (EPA_{max})	[24,25]
20	Destructiveness Potential after Araya/Saragoni (DP_{AS})	[27]

Table 2: Seismic intensity parameters.

In this study the parameters that have been selected are the following: peak ground acceleration PGA, peak ground velocity PGV, the term PGA/PGV, spectral acceleration (SA), spectral velocity (SV), spectral displacement (SD), central period (CP), absolute seismic input energy (E_{inp}), Arias intensity (I_A), strong motion duration after Trifunac/Brady (SMD_{TB}), seismic power ($P_{0.90}$), root mean square acceleration (RMS_a), intensity after Fajfar/Vidic/Fischinger (I_{FVF}), spectral intensities after Housner (SI_H), after Kappos (SI_K) and after Martinez-Rueda (SI_{MR}), Maximum EPA (EPA_{max}), cumulative absolute velocity (CAV), effective peak acceleration (EPA) and destructiveness potential after Araya/Saragoni (DP_{AS}). Table 2 presents the examined intensity parameters and their literature references, respectively.

4 STRUCTURAL MODEL

Figure 1 presents the examined reinforced concrete structure. The eigenfrequency of the frame is 0.85 Hz. The design of the 8-storey building is based on the recent Eurocode rules EC2 and EC8 [28, 29]. The cross-sections of the beams are T-beams with 40 cm width, 20 cm slab thickness, 60 cm total beam height and 1.45 m effective slab width. The distance between the frames of the structure is 6 m. The structure has been characterized as an "importance class II-ductility class medium" structure according to the EC8 Eurocode. The subsoil is of type C and the region seismicity of category 2 after the EC8 Eurocode (design around acceleration value equal to 0.24 g). External loads are taken under consideration and are incorporated into load combinations due to the rules of EC2 and EC8.

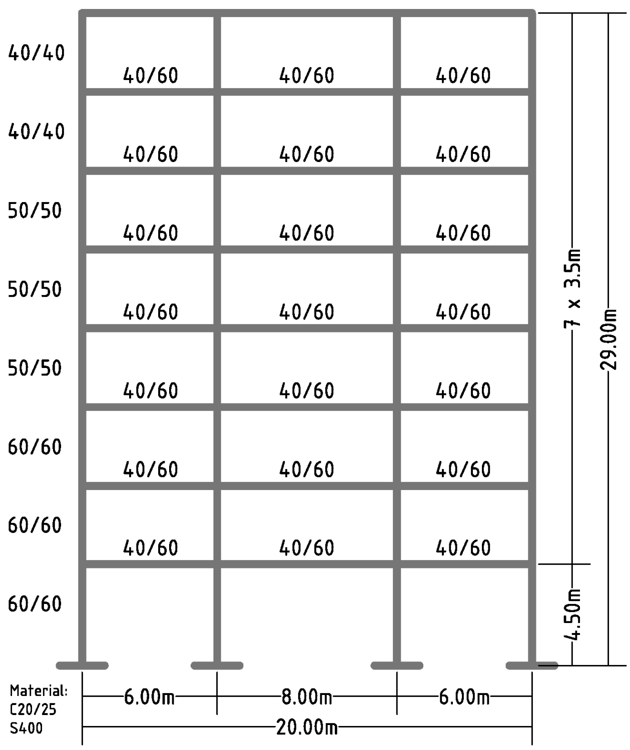

Figure 1: Reinforced concrete frame structure.

With the help of the IDARC software, the characteristics of the building are inserted into the program and a dynamic analysis is taking place, so as to estimate the structural behaviour of the building [7, 30].

5 ANFIS ALGORITHM

ANFIS was introduced in1993. ANFIS is able to extract a set of fuzzy “if-then” rules and define the membership functions in order to establish the association between inputs and outputs. Its structure is shown in Figure 2. Basically, ANFIS suggests a method that, through the training procedure, can estimate the membership function parameters that serve the fuzzy inference system (FIS) to consequently specify the desired output for a certain given input [31].

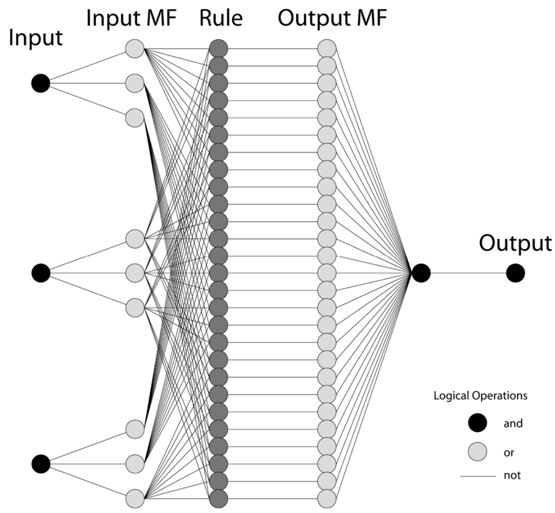

Figure 2: ANFIS structure.

ANFIS creates a fuzzy inference system in order to relate a certain input to the appropriate output. FIS interprets inputs into a set of fuzzy membership values and similarly the output membership functions to outputs. During the learning process, all parameters which define the membership functions will change. In order to optimize the model, these parameters are evaluated. Usually a gradient vector is used and an optimization routine could be applied in order to tune the parameters, so as to lead the model to a better generalization performance.

In this work, 20 seismic parameters are used as input data to describe the damage caused by one seismic event, and a total of 200 seismic events are used to train the system. All 20 seismic features have been normalized to belong in the interval [0, 1]. The 200 seismic events are distributed equally to all four damage categories in order to create a uniform data set.

First, inputs are related to membership functions (MFs), (Figure 3 shows the initial MF for one of the seismic parameters), to rules to outputs MFs, by using Fuzzy C-Means (FCM) technique [32, 33], which is analyzed later in this section. Next, the input/output data, which is a uniform set of 100 accelerograms, is used for training the model. The membership function parameters are tuned through the training process.

After the training, a model validation procedure is performed. During this procedure, an unknown input data set is presented to the trained fuzzy model for simulation. Thus, it can be evaluated the efficiency of the model. When a checking data set is presented to ANFIS, the fuzzy model selects the appropriate parameters associated with the minimum checking data model error. One crucial point with model validation, is selecting a suitable data set. This set must be representative of the data that the model is trying to simulate, and at the same time distinguishable from the training data. If a large amount of samples is collected, then all possible cases are contained and thus, the training set is more representative. In our case, a total number of 200 seismic excitations are considered as the data set.

FCM is a wildly used data clustering technique. Each data point is assigned to a cluster with a membership grade that is specified by a membership grade. It provides a method that shows how to group data points that populate some multidimensional space into a specific number of different clusters.

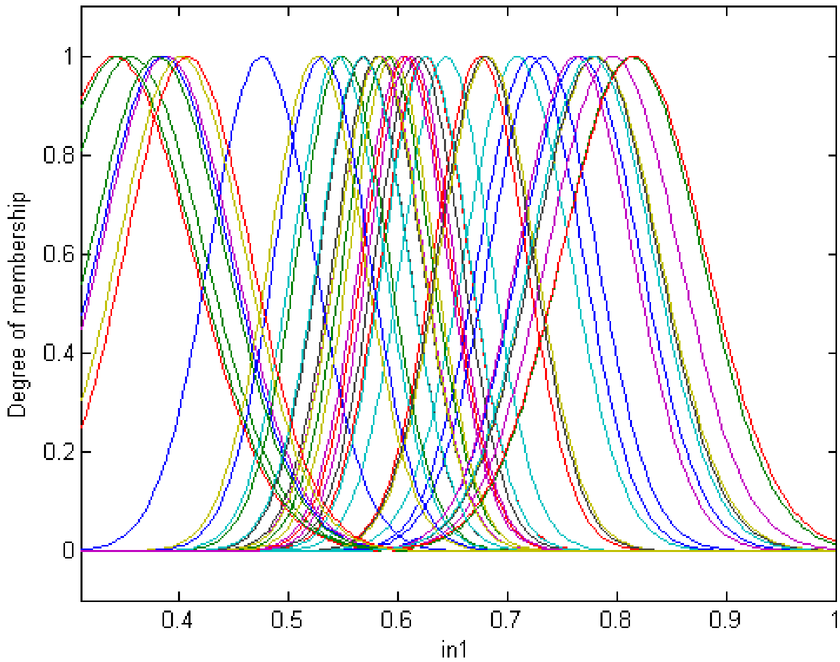

Figure 3: Initial membership function on input 1.

The purpose of data clustering is to discover similarities between input patterns from a large data set, in order to design an effective classification system.

At first, the FCM algorithm selects randomly the cluster centers. This initial choice for these centers is not always the appropriate. Furthermore, the variation of the cluster centers leads to different membership grades for each one of the clusters. Through the iteration process of the FCM algorithm, the cluster centers are gradually moved towards to their proper location. This is achieved by minimizing the weighted distance between any data point and the cluster centre. Finally, FCM function defines the cluster centers and the membership grades for every data point.

6 RESULTS

Simulation results are summarized in Table 3. The structural damage is presented by means of the two previously mentioned damage indices, MISDR and $DI_{G,PA}$, and the algorithm was tested for both damage indices. Experimental results indicate that using MISDR as metric for structural damage leads to higher performance, up to 90%, compared with the results when using $DI_{G,PA}$ which rates up to 87%.

Structural Damage Index	MISDR	$DI_{G,PA}$
Correct Classification Percentage (%)	90%	87%

Table 3: Comparative table for classification according to structural damage with MISDR and $DI_{G,PA}$.

In Figures 4 and 5, blue circles represent the seismic signals that have been misclassified with ANFIS algorithm using MISDR and $DI_{G,PA}$ respectively.

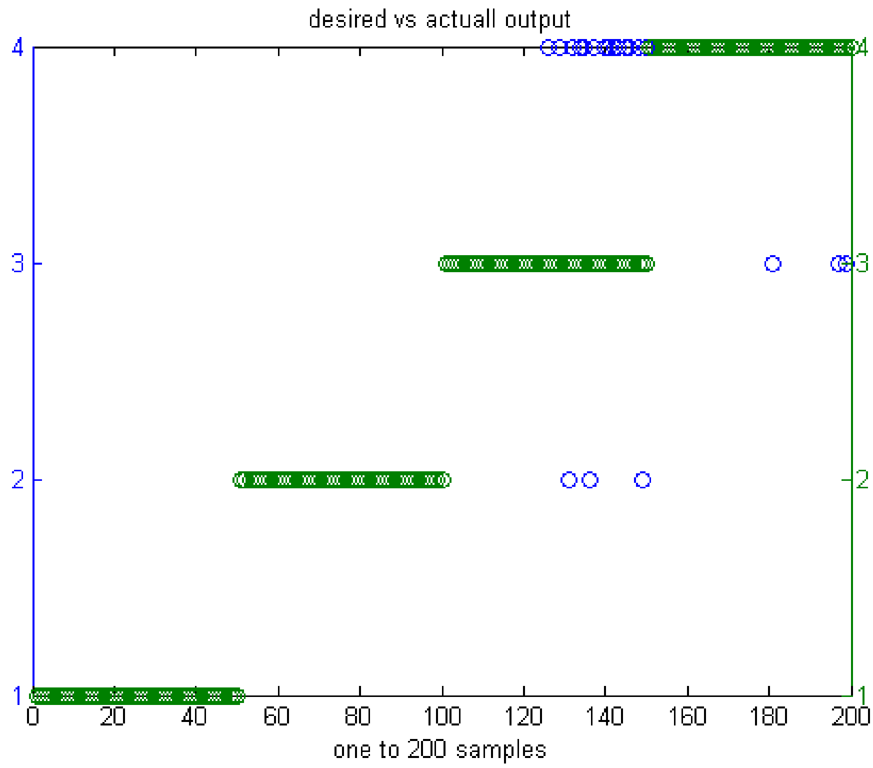

Figure 4: Classification of 200 seismic signals into 4 damage classes with MISDR as metric.
Correct classification percentage: 90%.

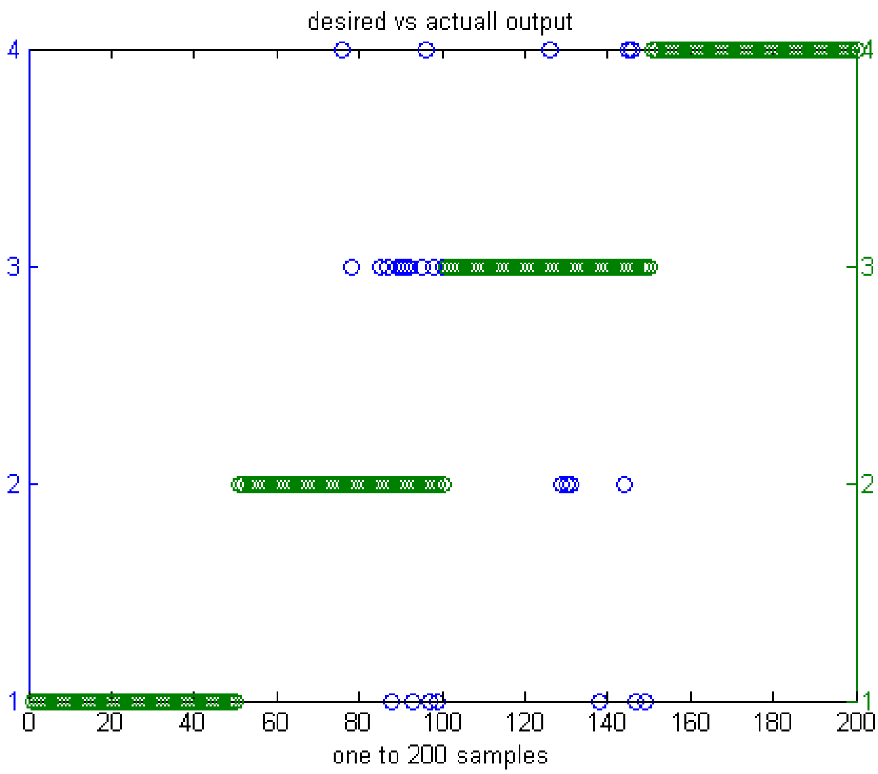

Figure 5: Classification of 200 seismic signals into 4 damage classes with $DI_{G,PA}$ as metric.
Correct classification percentage: 87%.

7 CONCLUSIONS

This paper presents an efficient algorithm based on ANFIS techniques for seismic signal classification. A number of 20 seismic parameters and a set of 200 artificial accelerograms with known damage effects were used. For each seismic excitation the induced structural damage of the examined building is estimated and quantified according to two widely used damage indices, MISDR and $DI_{G,PA}$. The structural damage is expressed in the form of 4 damage categories. The 4 damage categories (classes) are defined through threshold values of the used damage indices. An ANFIS model is trained and tested. The classification results reveal the effectiveness of the proposed system to estimate the earthquake's impact (damage category) on the examined structure. Classification rates up to 90% in the case of MISDR and 87% in the case of $DI_{G,PA}$ are achieved. The high percentage of correct classification in both cases, prove the efficiency of the method and show that the fuzzy technique that is implemented, contributes to the development of a competent blind prediction of the seismic damage potential that an accelerogram possesses.

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