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Approaches to the rapid seismic damage prediction of r/c buildings using artificial neural networks

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ABSTRACT

The present paper deals with the investigation of the ability of Artificial Neural Networks (ANN) to reliably predict the r/c buildings' seismic damage state. In this investigation, the problem was formulated as a problem of approximation of an unknown function as well as a pattern recognition problem. In both cases, Multilayer Feedforward Perceptron networks were used. For the creation of the ANNs' training data set, 30 r/c buildings with different structural characteristics, which were subjected to 65 actual ground motions, were selected. These buildings were subjected to Nonlinear Time History Analyses. These analyses led to the calculation of the buildings' damage indices expressed in terms of the Maximum Interstorey Drift Ratio. The influence of several configuration parameters of ANNs to the level of the predictions' reliability was also investigated. In order to investigate the generalization ability of the trained networks, three scenarios were considered. In the framework of these scenarios, the ANNs' seismic damage state predictions were evaluated for buildings subjected to earthquakes, neither of which are included to the training data set. The most significant conclusion of the investigation is that the ANNs can reliably approach the seismic damage state of r/c buildings in real time after an earthquake.

1. Introduction

The seismic vulnerability assessment of existing reinforced concrete (r/c) buildings is one of the most significant problems of earthquake engineering. For this reason, it is the subject of continuous research globally. Results of this extended research are the development and the evolution of methods which are utilized for the assessment of the seismic vulnerability of existing buildings, as well as for the estimation of their seismic damage state due to future earthquakes. The available methods used for the solution of the two aforementioned problems can be classified into two general categories: (a) methods that can estimate the seismic performance of individual buildings and (b) methods that can rapidly assess the seismic vulnerability of groups of buildings with common structural characteristics.

The methods of the first category concern linear and nonlinear analytical procedures suitable for individual buildings for which preliminary investigations confirm that a detailed evaluation of their seismic vulnerability assessment or/and their pre-seismic strengthening or post-seismic retrofitting is required. Due to their inherent complexity, these methods are time consuming but absolutely necessary for buildings considered to be seismically vulnerable (e.g. buildings which have suffered seismic damages or old buildings designed without the provisions of seismic codes) or for buildings considered to be important (e.g. schools, hospitals, fire stations, etc.). The methods of the first category (which are mainly based on the Finite Element Method (FEM)) have been adopted and described in the modern seismic codes (e.g. [1,2]). However, the fact that a big percentage of the existing r/c buildings located in high seismicity regions are old constructed and/or have been designed on the basis of old and inadequate seismic codes (or without the provisions of any seismic code) led to the development of methods of the second category. These methods are based on procedures that can accomplish rapid and approximate assessment of the seismic vulnerability of big groups of buildings with common structural characteristics (e.g. the seismic vulnerability curves, the damage probability matrices and procedures of rapid visual screening of structures: e.g. [3–6]). Thus, they can be used as decision-making tools, either in pre-seismic periods in order to help the engineers to make decisions about the necessity (or not) of a more detailed vulnerability assessment of individual r/c buildings (by the use of methods of the first category), or immediately after a strong earthquake in order to help the authorities to detect the most damaged zones in the stricken area.

The ability of the methods of the second category to extract

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approximate results about the seismic vulnerability of numerous buildings in a very short time led to research efforts in order to improve their reliability. In the context of these efforts, in the past 25 years many research studies have been conducted aiming to utilize the capacities of artificial intelligence, such as the Artificial Neural Networks (ANNs). The inherent ability of ANNs to embed and deploy results of problems which have known input data in order to extract predictions for the solution of the same type of problems with unknown input data instantly (e.g. [7,8]), led to the thought of utilizing them for the approximation of the seismic damage state of existing buildings in real time after an earthquake. An additional reason which led to this thought is the existence of available data for seismic damages of existing buildings caused by several earthquakes globally, as well as the fact that it is feasible to create the respective data using well-documented analytical methods such as, for example, the Nonlinear Time History Analysis (NTHA). Moreover, if it is taken into consideration that the problem of prediction of damage state of buildings is a multi-parameter problem, the use of ANNs for its solution can be considered as very promising because their structure is capable of effectively handling such problems. Thus, when using ANNs there is neither a need to consider only one parameter for the quantification of earthquakes' magnitude (seismic parameter), nor a need to consider a limited number of parameters which describe the seismic response of buildings (structural parameters). The ANNs give the ability to consider any number and combination of seismic and structural parameters for the study of the optimum correlation between them and the damage state of buildings which is defined with the aid of various expressions of damage indices (e.g. [9,10]). The first attempt for the utilization of ANNs as computational tools for the solution of civil engineering problems was made by Adeli and Yen [11], who examined their performance in the design procedure of steel beams. Since then, the ANNs have been the subject of numerous research studies in the field of civil engineering problems such as the structural health monitoring, the damage identification, the model updating, the optimization of structural design, the estimation of the characteristics of soil materials and the response of soil structures. The use of the ANNs for the solution of the aforementioned problems led to very interesting and promising results. A very detailed survey of the research studies about the use of ANNs in civil engineering problems can be found in [12,13]. The utilization of ANNs for the estimation of the seismic damage state of buildings was first studied by Stephens and VanLuchene [14], and Molas and Yamazaki [15]. After them, several research studies were focused on the utilization of ANNs in the prediction of seismic damage on the basis of analytical or statistical data (e.g. [16–24]).

In the present paper, the results of the study the ability of ANNs as regards the rapid and reliable prediction of r/c buildings' seismic damage state are presented. This study was performed by taking into consideration two different formulations of the problem. Firstly, the problem was formulated and solved as a problem of approximation of the values of an unknown function (Function Approximation (FA) problem). More specifically, an attempt was made to approach the relation between the values of the damage index of r/c buildings with parameters which describe the seismic response of structures (structural parameters), as well as with parameters which evaluate the impact of seismic motions on structures (seismic parameters). Consequently, the problem was formulated and solved as a Pattern Recognition (PR) problem. More specifically, the ability of ANNs to correctly classify the r/c buildings in seismic damage categories which are defined by specific values of the damage index was investigated. In both cases, Multilayer Feedforward Perceptron (MFP) networks were utilized. For the training of networks, a data set which consists of 1950 input and target vectors was created. This data set was configured by means of NTHA. More specifically, 30 3-D r/c buildings were selected and analyzed performing NTHA for 65 pairs of horizontal bidirectional actual ground motions. The selected structural parameters were the total height of buildings, their structural eccentricity and the ratio of base shear received by r/c walls (if they exist) along the two orthogonal construction axes. As seismic parameters, 14 parameters widely used in literature (e.g. [25]) were chosen. The 65 seismic excitations were selected in order to cover a wide range of values of these seismic parameters. The Maximum Interstorey Drift Ratio (MIDR) was utilized as the overall damage index of the selected r/c buildings (e.g. [26,27]). Three training algorithms were used for the training of networks, namely the Levenberg-Marquardt (LM) algorithm, the Scaled Conjugate Gradient (SCG) algorithm and the Resilient Backpropagation (RP) algorithm. In both cases of the formulation of the problem (FA problem or PR problem), the influence of the parameters which are used for the configuration of networks on the reliability of their predictions was investigated. These parameters are the number of the hidden layers, the number of neurons in the hidden layers, as well as the neurons' activation functions. This investigation led to the optimum configured networks on the basis of the optimization of the utilized performance evaluation parameters (the correlation factor R and the Mean Square Error (MSE) in the case of the FA problem, and the percentage of correct classifications of buildings in the seismic damage state categories in the case of the PR problem). The generalization ability of the optimum configured networks (i.e. the ability of the optimum configured ANNs to extract reliable predictions for r/c buildings subjected to earthquakes which are both unknown to them) was examined by means of three seismic scenarios. In these scenarios, r/c buildings or/and earthquakes which were not utilized in the creation of the training data set were used.

2. The Artificial Neural Networks (ANN)

It is well-known that the ANNs are complex computational structures which are able to solve problems using the general rules of the human brain functions (e.g. memory, training, etc.). Thus, the use of ANNs makes it feasible to approximate the solution of problems such as pattern recognition, classification and function approximation, with the aid of computers utilizing algorithms based on a different philosophy than the conventional ones.

Various types of ANNs have been proposed (e.g. Radial Basis Function Networks [8], Counterpropagation Networks [28], Gradient-Based Networks [29]). However, in the present paper, Multilayer Feedforward Perceptron (MFP) networks were utilized. Fig. 1(a) presents the model of the function of a typical artificial neuron which receives the input signals ($x_1, x_2, \dots, x_m$) through its synapses (connecting links) and transforms them to an output signal (y_k) through the use of an adder (which adds the products of the input signals by the respective synaptic weights ($w_{k1}, w_{k2}, \dots, w_{km}$) of the neuron's synapses and the bias) and the use of an activation function (in which the argument is the u_k that results from the adder and transforms it to the output signal y_k). More details are available in specialized references (e.g. [7,8]). The function of ANNs is based on the combined action of interconnected artificial neurons (Fig. 1(b)). Due to the fact that the function of ANNs is based on the general rules of the human brain functions such as the memory and the training, the necessary procedure for the successful solution of problems by them is the training. The training of an ANN consists of the detection of values of the synaptic weights of neurons (vector **w**) which produce the minimum output error. This detection is achieved through the use of training algorithms (e.g. [8]). These algorithms require a set of *n* input vectors **x** and the corresponding *n* output vectors **d** that are called target vectors. The *n* pairs of vectors **x** and vectors **d** constitute the training data set. A trained ANN includes the optimum vector of synaptic weights which incorporate the "knowledge" acquired from the used training data set. Thus, a trained ANN is capable of extracting predictions about the solution of problems with input data that are not included in the training data set (generalization ability). The generalization ability can be constantly improved through the re-training of ANNs (i.e. the re-calculation of values of the synaptic weights) using wider training data sets.