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Predicting residual strength of non-linear ultrasonically evaluated damaged concrete using artificial neural network

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ABSTRACT

This paper deals with the combination of non-linear ultrasonic and artificial neural networks (ANNs) for the non-destructive evaluation of the damages in concrete under stressed state. Two networks, one using raw variables and another using dimensionless variables were trained and tested to predict concrete damages. Input data to the neural network is the time-domain signals of the received ultrasonic waves, obtained from the experimental studies carried out as reported in the earlier literature involving experimental data base of 75 ultrasonic measurements performed on concrete cubes with water–cement (w/c) ratios of 0.40, 0.50 and 0.60 respectively. Both networks were two-layer-perceptrons trained according to back-propagation algorithm. The results of this research highlight the potential of artificial neural networks for solving the problem of concrete damage evaluation using non-linear ultrasonic measurements. It was found that the proposed ANN models predict the strength of concrete laboratory cubes with low absolute errors. The performance of ANN model for predicting the residual strength of concrete using the raw data is better than the prediction using grouped dimensionless variables.

1. Introduction

During the life cycle of concrete structures, degradations occur under mechanical, thermal or chemical actions which often lead to the development of micro and macro cracks in the material. The state of deterioration is often invisible and is only evident at a stage when there is a significant reduction in the load carrying capacity. Ensuring better performance in structures requires early detection of distress and identification of the resulting damage. Techniques that can detect and characterize the damage using non-destructive evaluation (NDE) techniques are of great interest to practicing structural engineers [1]. The NDE techniques such as Ultrasonic Pulse Velocity or Echo [2], Impact Echo [3,4], Surfaces Waves [5,6] and Ultrasonic Tomography [7] are commonly used. However, the use of these linear non-destructive testing methods, in damage evaluation has low efficiency [8]. They can provide very little indication of the damage in concrete until it progresses to the point of causing failure [8,9].

In the case of in situ controls, access is often limited to one side and the depth or thickness of the structural element is sometimes unknown. In these conditions, determining the ultrasonic pulse velocity is clearly difficult. Ultrasonic techniques, investigating non-linear response of materials, offer a potential for measuring certain concrete properties more effectively than methods assuming linear behavior [8–10]. Thus non-linear ultrasonic method can be used as an effective tool in detecting early age cracks or defects in concrete. This method has shown higher sensitivity to applications involving damage assessment including micro-cracks over the linear ultrasonic methods [11]. The experimental procedure involving non-linear ultrasonic method is based on low to high-voltage ultrasonic measurements and monitoring the occurrence of non-linearity in concrete at different loading stages. Preliminary studies as observed from the literature have shown good correlation between the non-linear parameters and damage assessment in concrete [12]. Some other investigators also reported that the decrease in the pulse amplitude (ultrasonic pulse attenuation) and shifts in the peak frequency (harmonic generation) are more sensitive and more reliable measures to characterize distributed damage and diffuse cracking in the concrete than pulse velocity [12,13]. Selleck et al. [13] used ultrasonic longitudinal pulses to evaluate damage on concrete due to freeze–thaw cycles and salt scaling. They have studied changes in the pulse velocity, peak-to-peak attenuation, and peak frequency. It was observed that peak-to-peak amplitude and peak frequency were more sensitive to concrete damage induced by freeze–thaw cycles and salt scaling than pulse velocity. Both peak-to-peak amplitude and peak frequency, however, showed a large scatter during the experiments. Shah et al. [14] and Woodward et al. [15] used the non-linear ultrasonic signals in order to detect concrete damages.

The technical developments in the field of non-linear ultrasonic applications to concrete are still under way [16,17] as it lags in

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correlation functions for establishing a link between these measurements and characteristics of concrete [18,19]. Though many investigators have applied artificial neural networks (ANNs) for the prediction of compressive strength of concrete [20–23] there is limited number of works reported on ANN applications in the field of the NDE of reinforced concrete structures. For instance, based on an inductive sensor method, Zaid et al. [24] developed two feed-forward back-propagation neural networks: one to estimate bar diameter and the other for bar depth evaluation. Hola and Schabowicz [25] have presented a neural model for the evaluation of concrete strength based on the coupling of different non-destructive techniques. The authors found this model effective for accurate on-site prediction of concrete strength. As far as non-linear ultrasonic applications are concerned, Shoukry et al. [26] used ANN for radar signal interpretation in order to detect concrete defects. Sbartaï et al. [27] used a combination of radar technology and ANN for the non-destructive evaluation of the water and chloride contents of concrete slabs. ANN has the potential to efficiently classify ultrasonic signals in the nondestructive testing of concrete structures. ANN can also be applied for non-linear ultrasonic data interpretation in the characterization of concrete in order to evaluate the residual strength of concrete.

Predicting the residual strength of damaged concrete is difficult partly due to the complexity involved and partly because of the limitations of the analytical tool commonly used, which is statistical regression, by most of the investigators. Neural networks have advantages over statistical models like their data-driven nature, model-free form of predictions, and tolerance to data errors. The objective of this study was to analyze the non-linear ultrasonically evaluated concrete damage by employing the technique of neural networks with a view towards seeing if better predictions are possible. The experimental database involving 75 data points was used to train and test two neural networks for the prediction of residual strength of concrete. ANN structures and correlations between actual and predicted data are then presented. Efforts were also made to establish a methodology that would not only predict the residual compressive strength of concrete but provide an economic and rapid means for future experimental researchers as well. Two different models – one involving raw parameters and the other involving dimensionless parameters were investigated. The ANN models have five input parameters for the raw parameter model and four for the other model.

2. Data employed

The data used in this study, as given in Table 1, has been obtained from an earlier study [28] wherein ultrasonic measurements at different loading and power levels were made on progressively damaged concrete cubes of 150 mm size under the action of monotonic axial compression loading. The damages to each test specimen were induced in compression in increments of 20% of the ultimate strength of the specimen. After each loading increment, the load was held constant while specimen was ultrasonically evaluated in the through transmission mode. The effects of the applied load and damage were, therefore, both taken into account in the ultrasonic measurements, which is the case in most field applications of NDE techniques. Each specimen was carried through cycles of loading, and nondestructive testing analysis for loads of 0%, 20%, 40%, 60%, and 80% of the estimated failure load. The ultrasonic testing paths through the concrete were normal to the loading direction. Thus the data covers different levels of stress and hence different damage levels to which concrete may be subjected in real structure.

The data consists of five input parameters viz. input voltage V_i, arrival time t_a, peak to peak voltage of output signal V_{pp}, water to cement ratio w/c and compressive strength of concrete f'_c. The output parameter is the residual strength of concrete f_r. The arrival time and peak-to-peak voltage were obtained from the recorded signals, as indicated in Fig. 1. These signal parameters represent the non-linear interaction through which the input signals have undergone while passing through concrete of different damage levels. Conventional ultrasonic non-destructive testing equipment is normally a mono-frequency instrument which makes use of the amplitude and phase variations of the input signal due to its scattering by defects. One can bear with such inadequate amount of information as long as the wave-defect interaction is considered to be linear. The nonlinear ultrasonics is associated with classical idea of elastic wave distortion due to material nonlinearity: waveform deformation caused by a local velocity variation accumulation with propagation distance and provides progressive transition of a harmonic wave to a different form. As a result, the spectrum acquires higher harmonics of the fundamental frequency which deliver information on the matter. The mass density of concrete is taken as 2200 kg/m^3. The first, second and third quartile values of different basic as well as the non-dimensional variables are given in Table 2. The values of variables corresponding to the 0% and 100% percentile given in the table are the lower and upper bounds of variables.

3. ANN models

ANNs have been widely described by several authors [29–32]. The ANN concept consists of learning the relation between input and output data using mathematical training processes [32]. The manner in which the data are presented for training is the most important aspect of the neural network method. Often this can be done in more than one way, the best configuration being determined by trial-and-error. It can also be beneficial to examine the input/output patterns or data sets that the network finds difficult to learn. This enables a comparison of the performance of the neural network model for these different combinations of data. In order to map the causal relationship related to the residual strength of damaged concrete, two separate input/output schemes (called Model-A1 and Model-A2) were employed, where the first took the input of raw causal parameters while the second utilized their non-dimensional groupings. This was done in order to see if the use of the grouped variables produced better results. The Model-A1 thus takes the input in the form of causative factors namely, voltage of the input pulse, V_i, arrival time, t_a, peak-to-peak amplitude, V_{pp}, water-to-cement ratio, w/c, and concrete compressive strength, f'_c and yields the output, the residual concrete strength, f_r. The peak-to-peak amplitude and arrival time are measured as shown in Fig. 1. For Model-A1, thus, the equation is given as under:

$$\text{Model-A1}: \quad f_r = g_1(V_i, t_a, V_{pp}, w/c, f'_C) \tag{1}$$

The Model-A2 employing dimensionless variables viz. V_{pp}/V_i, t_a/T_{pi}, w/c, $f'_c/(\rho_c v^2)$ and the corresponding dimensionless output f_r/f'_c is given by:

$$\text{Model-A2}: \quad \frac{f_r}{f'_c} = g_2\left(\frac{V_{pp}}{V_i}, \frac{t_a}{T_{pi}}, \frac{w}{c}, \frac{f'_c}{\rho_c v^2}\right) \tag{2}$$

where T_{pi} is the time period of input pulse (=0.01 ms), ρ_c is the mass density of concrete and v is the average pulse velocity in the specimen ($v = t_a/B$, where B is the size of cube). The current study employed the data described above (75 data points) for the prediction of residual strength in damaged concrete. The training of the above two models was done using 67% of the data (50 data points) selected randomly. Validation and testing of the proposed models was made with the help of the remaining 33% of the data (25 data points), which were not involved in the derivation of the model. The network input training set for both models was preprocessed by applying a principal component analysis.