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Modeling of masonry failure surface under biaxial compressive stress using Neural Networks

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HIGHLIGHTS

- Neural Networks are used in order to approximate the experimental results for masonry failure.
- A two-step procedure is proposed, with the training of two types of Neural Networks.
- The NNs showed great performance in fitting the experimental input data.
- The curves generated by the NNs are continuous and smooth, but not necessarily convex.

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ABSTRACT

Masonry is a brittle anisotropic material that exhibits distinct directional properties because the mortar joints act as planes of weakness. To define failure under biaxial stress, a 3D surface in terms of the two principal stresses and their orientation to the bed joints, is required. In the present study, a novel method is proposed on applying Neural Networks (NNs) to approximate the failure surface for such brittle anisotropic materials. The method comprises a series of NNs that are trained with available experimental data. The results demonstrate the great potential of using NNs for the approximation of masonry failure surface under biaxial compressive stress.

1. Literature review

Masonry exhibits distinct directional properties due to the influence of the mortar joints. Depending upon the orientation of the joints to the stress directions, failure can occur in the joints alone or simultaneously in the joints and the blocks. The failure of masonry under uniaxial and biaxial stress state has been studied experimentally in the past by many researchers but to the authors' knowledge there have not been many attempts to apply a Neural Network (NN) for the prediction of masonry behavior in general.

NNs have been used in many ways for various other problems in the literature. Duan et al. [1] studied the applicability of NNs in modeling the elastic modulus of recycled aggregate concrete. In this study, an NN-I was first constructed by using 324 data sets collected from 21 international published works, which were randomly divided into three groups as the training, testing and validation sets, respectively. Then a NN-II was also trained with 16 more data sets of the authors' own experimental results to examine whether the performance of the Artificial Neural Network (ANN) could be further improved.

In another work, Yurdakul and Akdas [2] tried to model the uniaxial compressive strength of building stones using non-destructive test results as Neural Networks input parameters. The uniaxial compressive strength value was used as a critical input parameter in determining the engineering properties of natural building stones. The purpose of the study was to develop a model to determine the strength of natural building stones via relatively simple and low-cost mechanical tests with the application of NNs.

Alexandridis et al. [3] proposed a Neural Network approach for compressive strength prediction in cement-based materials through the study of pressure-stimulated electrical signals. They presented a non-destructive method for predicting the compressive strength of cement-based materials by studying the appearance of weak electrical signals at specimens that are under

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mechanical stress. A series of lab experiments were conducted in order to record the pressure-stimulated electrical signals in cement mortar specimens.

In [4], Tanarslan et al. proposed the use of a NN model to predict the shear capacity of reinforced concrete beams, retrofitted in shear by means of externally bonded wrapped and U-jacketed fiber-reinforced polymer. Unlike the existing design codes the model considered the effect of strengthening configurations dissimilarity. In addition it also considered the effect of shear span-to-depth ratio at the ultimate state. Mechanical properties of strengthening material and mechanical and dimensional properties of beams were selected as inputs for the NN.

Mashrei et al. [5] proposed a Back-Propagation Neural Network (BPNN) model for predicting the bond strength of FRP-to-concrete joints. Published single-lap shear test specimens were used to predict the bond strength of externally bonded FRP systems adhered to concrete prisms. A database of one hundred and fifty experimental data points from several sources was used for training and testing the BPNN. The data used in the BPNN were arranged in a format of six input parameters including: width of concrete prism; concrete cylinder compressive strength; FRP thickness; bond length; bond width (i.e. FRP width); and FRP modulus of elasticity. The output parameter was the bond strength.

Zhang et al. [6] applied artificial intelligent techniques for directly predicting the cracking patterns of masonry wallets, subjected to vertical loading. The von Neumann neighborhood model and the Moore neighborhood model of cellular automata (CA) were used to establish the CA numerical model for masonry wallets. Techniques for the analysis of wallets whose bed courses have different angles with the horizontal bottom edges were also introduced. Two criteria were used to match zone similarity between a “base wallet” and any new “unseen” wallets. This zone similarity information was used to predict the cracks in unseen wallets. A back-propagation NN was also used for predicting the cracking pattern of a wallet based on the CA model of the wallet and some data of recorded cracking at zones.

El-Shafie et al. [7] proposed a model based on radial basis function neural networks (RBFNN) for predicting creep in concrete and masonry structures which was compared to a multi-layer perceptron neural network (MLPNN). Accurate prediction of creep was achieved due to the simple architecture and fast training procedure of RBFNN model especially when compared to MLPNN model. The RBFNN model showed good agreement with experimental creep data from brickwork assemblages.

Zhou et al. [8] proposed an artificial intelligence technique for predicting the failure/cracking loads of laterally loaded masonry wall panels based on their corresponding failure/cracking patterns derived from the laboratory experiments. The numerical modes of failure/cracking patterns of experimental wall panels and the corresponding normalized failure/cracking loads were used as the input and output for the NN training. Three types of NN models for predicting the failure/cracking load of the unseen wall panel were achieved by repeatedly training and adjusting to optimize its parameters.

Mathew et al. [9] proposed the use of NN for solving complex nonlinear problems for the analysis of masonry panels under biaxial bending. A Neural Network, trained with the use of a set of data, which was representative of the problem domain, was shown to be successful in solving new problems with reasonable accuracy. The experimental results obtained from the testing of panels were analyzed, and the method that gave good correlation between the theoretical prediction and the experimental result was recommended for other panels of similar properties and boundary conditions. An artificial intelligence based technology, the case-based reasoning (CBR), had been used to solve new problems by adapting solutions to similar problems solved in the past, which were stored in the case library. A hybrid system was described that utilized the capabilities of both ANNs and CBR.

As a conclusion on the literature review, it is apparent that although Neural Networks have been successfully used in numerous engineering applications in the past, only very few studies have incorporated the use of Neural Networks for the approximation of masonry behavior.

2. Introduction and methodology

Despite the fact that masonry is one of the oldest structural materials and, actually, the main element in monumental structures such as churches, castles, and mosques, our knowledge regarding its mechanical behavior is not as thorough as it should be and many aspects of its behavior remain to be investigated. One reason for this lack of knowledge is the highly anisotropic brittle nature of masonry, which makes complicated, difficult and expensive, the realization of reliable experimental tests under conditions of biaxial stress, and, even more, under conditions of biaxial tension or heterogeneous stress. Taking into account the numerous uncertainties of the problem, a computational model, describing the masonry failure surface in a simple manner should be an efficient tool for the investigation of the behavior of masonry structures. Many analytical criteria for masonry structures have been already proposed [10–15]. Experimental investigations can also be considered as an important support to the aforementioned efforts [16–19].

Researchers have long been aware of the significance of the bed joint angle to the applied load and many experimental tests have been carried out on brick masonry discs to produce indirect tensile stresses on joints inclined at various angles to the vertical compressive load. The highest strength of masonry is observed for cases when the compressive load is perpendicular to the bed joints or in other words when the principal tensile stress at the center of the disc is parallel to the bed joints. In this case failure occurs through bricks and perpendicular joints. The lowest strength is observed when the compressive load is parallel to the bed joints or when the principal tensile stress at the center of the disc is perpendicular to the bed joints. In this case failure occurs along the interface of brick and mortar joint.

Our current work utilized the experimental data reported by Page [16], referring to a total of 102 panels, which have been already used by many other researchers [1,11,20]. Ratios of vertical compressive stress σ_I to horizontal compressive stress σ_{II} of 1, 2, 4, 10 and ∞ (uniaxial σ_I) have been used in conjunction with a bed joint angle θ with respect to σ_I, in directions of 0°, 22.5°, 45°, 67.5° and 90°. A minimum of four tests were performed for each combination of σ_I/σ_{II} and θ.

This data set has been used in the framework a novel methodology, proposed in the present study, which applies Neural Networks in order to approximate the experimental failure curves of a brittle anisotropic material such as masonry. The aim of the study was to introduce an anisotropic (orthotropic) Neural Network – generated 3D failure surface under biaxial stress for masonry for any angle of the joints to the vertical compressive load, as described in detail in the next paragraphs. First, for each angle θ (0°, 22.5°, 45°) of the joints to the vertical compressive load, a Neural Network was trained with the experimental data of Page as inputs (3 NNs in total). Then each one of the three NNs was asked to produce the whole 2D failure curve for each angle as its output, filling also the gaps between the experimental points, thus “enriching” the experimental data with appropriate approximations. Then another bigger, “global” NN was trained using the results of the three NNs as inputs with the angle θ as an input, also. The new NN was then asked to fill also the gaps between the angles