Neural network modeling of concrete bond strength to reinforcement

V P Yartsev¹, A N Nikolyukin¹, A O Korneeva²

¹Department of construction of buildings and structure, Tambov State Technical University, 106 Sovetskaya St., Tambov 392000, Russia
²Department of building material’s science and road technologies, Lipetsk State Technical University, 30 Moskovskaya St., Lipetsk 398055, Russia

E-mail: valax1@yandex.ru

Abstract. All the loss of bond strength of concrete to reinforcement is the main reason for loss of bearing capacity of a reinforced concrete structure. That’s why it is necessary to study the changes of bond strength of concrete to reinforcing bar by the influence of various factors. In addition, the mechanical characteristics of concrete change due to external and technological impacts. Making up an analytical model using artificial neural networks (NN), which allows determining the final bond strength through the mean values of shearing stress is considered in the article. The object of research is concrete of different strength classes, reinforced with steel and fibre-reinforced plastic rebar. The subject of study is the change in the value of bond strength of concrete to reinforcement after alternating freezing and thawing. It was found that the value of adhesion is associated with the strength characteristics of concrete and the type of reinforcement used. Also, a two-layer NN with reverse signal propagation was developed, which accurately describes the value of bond strength of concrete to reinforcement.

1. Introduction

The main characteristic of assessing the bond strength of concrete to reinforcement is the shearing stress $\tau_{bs}$ [1,2]. This value is formed in the zone of conditional cylindrical surface of interaction of concrete by reinforcement. It means that any case of using the different reinforcement (types or materials) there is a contact of materials on the surface, which has a roughness and different projections. In this case, there are stresses directed at some angle to the surface.

At the moment, theory of adhesion of reinforcement and concrete is not yet sufficiently complete developed. That’s why, the question of the theory of interaction of material’s development, which considering different factors, is very relevant. Nowadays, many authors think that numerical modeling is the most relevant method to study the bond strength of materials.

Along with a large number of methods for the study of coupling, a phenomenological approach of mathematical analysis of experimental results based on a number of simplifying prerequisites has found wide application in science. At the same time, it became possible to study in depth the interaction of concrete and reinforcement. To date, the interaction of materials is considered schematically based on numerical methods [3,4].
2. Research objective
The distribution of stresses in the early stages of pulling is uneven, but becomes almost uniform at the limit state. Therefore, the expression of the maximum coupling force is considered as the average coupling stress between the concrete and the reinforcement [5-7]. This method of calculating the value of $\tau_{bs}$ provides a practical approach to determining the bond strength of concrete to reinforcement, but it does not reflect the real state of the structure, since it does not take into account such factors as the formation of cracks from stress, local crushing, support reaction, etc. It is necessary to obtain an analytical model using artificial neural networks (NN), which helps to determine the final bond strength based on average values of shearing stress.

3. Description of investigations
For researching was made 220 samples (Fig. 1). The Studies on pulling were carried out according GOST 31938-2012 [8]. The prism samples reinforced on the center, in a square with a section of 10 $\times$ 10 cm and the ratio of the length to anchoring depth $l/d = 5$ were used. As a reinforcement was used a 10 mm diameter’s rebars. The study of the process of bond strength of concrete to reinforcement occurred under various loads and external conditions. Two types of a periodic profile reinforcement was used:
- Steel reinforcement class A400, steel grade 25G2S which has a yield point.
- Fibre-reinforced plastic rebar, which has no physical yield stress.
In this model used 6 critical parameters, such as the compressive strength of a concrete prism, the tensile strength of concrete, the elastic module of concrete, anchorage depth, the profile and material of reinforcement. These prognostic parameters were used to develop the model as an estimate of the final bond strength of concrete to reinforcement [9]. For the modeling of bond strength, the database was arbitrarily divided into three parts: training, control and testing. At the same time, 15% of the experimental data was used for testing, another 15% for control, and the remaining 70% for network training. As a result of the control, the risk of network retraining was reduced. The training database was used to develop a prediction model, while a test database was used to monitor the repeatability and reliability of the proposed NN models.

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Figure 1. Sample’s general view of the pull-out test.

Figure 2. Sample’s scheme of the pull-out test.

Therefore, the value $\tau_{bs}$ was calculated from the average shearing stress and determined from the ratio:
where N is applied effort; l is anchorage depth; P is perimeter of a circle.

Artificial neural networks (NN) are designed on the principle of biological neural networks in the body, which is a simplified mathematical model. The application of NN in construction problems is a new area of research that is just beginning to develop. In this article presents the results of a NN-based model in Matlab.R2014a, using the nnstar tool.

The NN architecture at the input level has six nodes corresponding to six prediction factors, eight nodes in the hidden layer and one in the output layer corresponding to the ultimate bond strength \( \tau_{bs} \). Therefore, to build a model based on NN, an architecture of 6-3-1 NN was obtained (Figure 3). The NN model used in this study may simply be expressed by eq. 2 - 4.

\[
\tau_{bs} = \frac{N}{lP} \quad (1)
\]

\[
\tau_{bs} = \text{Bias}_{\text{output}} + \sum_{j=1}^{s} w_k F(U_k) \quad (2)
\]

- where Bias = - 0.0967797406340369 is output layer;

\[
\tau_{bs} = g(-0.0967797406340369 + 0.415257533499754 \cdot th(U_1) + + 0.353067120271963 \cdot th(U_2) + 0.158184154640520 \cdot th(U_3)) \quad (3)
\]

where \( th(U) = \frac{2}{1-e^{-2U}} - 1 \) is activation function (hyperbolic tangent) of first layer; \( w_{ij} \) – bond weight of first NN layer; \( g \) – de-normalization function; \( I_i \) - normalized values of input data.
\[
W_j = \begin{bmatrix}
5.190788147878 & 2.70834614124 & -5.06624074036 & 3.34590341286 & 0.37560050362 & 0.41946252795 \\
2.30147485801 & 2.70834614124 & 3.211775097304 & -5.00584872238 & -1.1041294545 & -17.2678192617 \\
-1.7149527701 & -2.942424536 & 19.9794765231 & -1.4924299751 & 2.183544601584 & 18.81724270846
\end{bmatrix}
\]

\[
I_j = \begin{bmatrix}
-1.72184452651361 \\
-1.45840212371189 \\
12.0538659352713
\end{bmatrix}
\]

(4)

\[
W_j = \begin{bmatrix}
5.190788147878 & 2.70834614124 & -5.06624074036 & 3.34590341286 & 0.37560050362 & 0.41946252795 \\
2.30147485801 & 2.70834614124 & 3.211775097304 & -5.00584872238 & -1.1041294545 & -17.2678192617 \\
-1.7149527701 & -2.942424536 & 19.9794765231 & -1.4924299751 & 2.183544601584 & 18.81724270846
\end{bmatrix}
\]

(5)

Figure 4. Network Learning Outcomes.

Figure 5. The state of the artificial neural network in the learning process.
A comparison of the prediction results obtained using the NN model and the experimental data obtained from the coupling tests is shown in figure 5. Correlation coefficients of 0.969 and 0.969 were achieved for the control and test database, respectively. Based on the work done, it can be concluded that the NN model is characterized by the reliability of the results and reliability.
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