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Modeling Adhesive Strength of Corroded Rods in Reinforced Concrete Structural Elements Using a Genetic Algorithm

V.P. Yartsev*, A.N. Nikolyukin, T.M. Pluzhnikov

Tambov State Technical University; 112D, Michurinskaya St., Tambov, 392032, Russia

* Corresponding author. Tel .: +7 4752 63 03 80. *E-mail*: kzis@nnn.tstu.ru

Abstract

We developed an analytical model to describe the behavior of the tangential stresses of the reinforcement adhesion τ_{ad} in the anchoring zone, taking into account the influence of various parameters (concrete strength, rod corrosion, etc.). Under normal conditions, the development of such a model is a long process. The “Genetic Algorithm” (GA) of soft computing, being a powerful tool for evolutionary modeling of complex technical problems, was used to simplify and accelerate this process.

Keywords

Reinforced concrete; core reinforcement; adhesive strength; corrosion; experimental data; approximation; mathematical model; genetic algorithm.

Introduction

To speed up the construction of a building or structure, precast concrete elements have been widely used in construction practices. The formation of a unified structure occurs with the help of butt joints produced, as a rule, in the form of inserted (overlapped) rod bars, subsequently bonded in butt joints [1–5]. Under the influence of external loads or due to precipitation of the base, axial tensile and transverse shear forces occur in the butt joints of the structure (Fig. 1); this leads to the formation of cracks or various defects in the bonded joint. As a result, rod reinforcement of the structure is subjected to corrosion while in operation [6–11].

Consequently, when designing precast concrete structures special attention should be paid to the development of rod joints. In this case, it is necessary to take into account such parameters as limiting the width of crack opening and determining the area of the reinforcement anchoring in concrete.

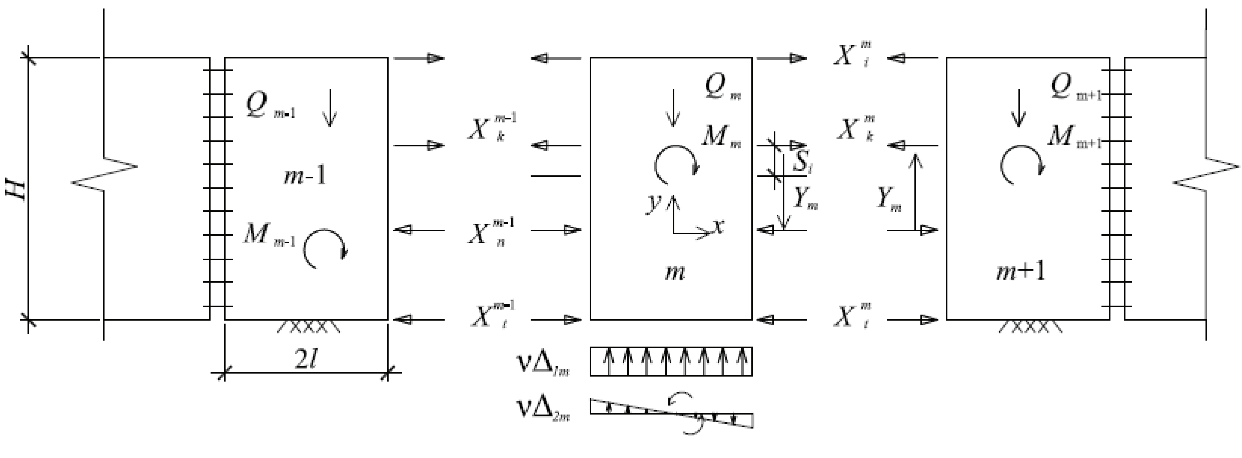


Fig. 1. Diagram of forces acting on a separate block of butt joint

For a long time, S.A. Mariupolsky was engaged in the study of this area. In his work, he described the main types of butt joints, which were done using reinforcing rods, subsequently bonded in the place of installation [11]. The author noted that one of the reasons for the premature destruction of structures is the insufficient strength of construction joints.

However, the destruction of the joints may occur due to the ductility of joints which is not taken into account during their construction, as well as the occurrence of transverse and longitudinal deformations of free ends of reinforcing rods in the concrete joints as a result of various factors. Therefore, the joints should not be considered as an absolutely stiff structure. In order to control displacements (cracks) in the joints, one should perform the selection of the number and diameter of the rods in the assembly, as well as specify the calculation of stresses and attenuation of the joint section caused by joint action of the structure elements [8].

Studying the issue of design modeling of butt joint destruction requires solving a number of important general problems related to the action of reinforcing elements in concrete under longitudinal and transverse loads, as well as setting physical parameters characterizing the mutual action of concrete and steel through different means of stress application [12].

Thus, in order to solve this problem, in this paper, we propose to use genetic algorithms (**GA**) in order to establish the relations between the input parameters and final shear stresses of the reinforcing rods, occurring in the joints while in operation.

Therefore, when building the model, six parameters were taken: compressive strength, concrete sample dimensions, reinforcing rod profile, reinforcing rod diameter, embedment depth, corrosion degree, maximum adhesive strength. On the basis of the obtained experimental data [13–30], the dependence was established between the input parameters and the final shear stress.

Experimental

To build the model, experimental data were used from [13–30]. Six critical parameters, which are presented in Table 1, were used.

These parameters were used to estimate the final adhesive strength between the corroded reinforcing rod and the concrete. In pulling tests, concrete cubes 150×150×150 mm in size were used with reinforcing rod of A400-A240class.

Table 1

Parameters

Parameters	Designations in the formulas	Designations in the expression tree
Compressive strength	R_b	d0
Concrete sample dimensions	c	d1
Reinforcing rod profile	S_p	d2
Rod diameter	d	d3
Embedment depth	l_{depth}	d4
Corrosion degree	K_m	d5
Maximum adhesive strength	τ_{ad}	y

As the adhesion value, τ_{ad} was used to describe the average stress values throughout the sample anchoring zone

$$\tau_{\text{ad}} = \frac{N_{\max}}{A}, \tag{1}$$

where $N_{\max}$ is ultimate load (N) in pull-out-test (kN), A is contact area (cm^2).

To model adhesion properties, the database was arbitrarily divided into two parts, namely, training and testing. Among these experimental data, 10 % were used as a test base (26 sets), while the remaining 90 % were used to train the model (225 sets). The training database was required when developing a prediction model, while the test database monitored the repeatability and reliability of the proposed model.

Gene Expression Programming (GA)

Genetic programming (GA) proposed by J.R. Koza [31], essentially is the application of genetic algorithms for computer programs. Gene expression programming (GA) was introduced by C. Ferreira [32], and it can be viewed as a natural development of genetic algorithms and genetic programming. GA creates computer programs of various sizes and shapes encoded in linear chromosomes of a fixed length. The GA algorithm begins with the random generation of chromosomes of a fixed length for each individual for the initial population. The chromosomes are then expressed and the suitability of each person is evaluated based on the quality of the solution they represent. An important characteristic of GA is that it allows you to accurately derive the phenotype based on the sequence of the gene and vice versa, which is called the Karva code.

GA parameters used for the derivation of mathematical models were listed earlier (Table 1),

$$\tau_{ad} = \sigma_1 + \sigma_2 + \sigma_3 + \sigma_4 + \sigma_5 + \sigma_6, \quad (2)$$

where τ_{ad} is final adhesive strength between the reinforcing rod and concrete; functions $\sigma_1, \ldots, \sigma_6$.

In the present study, the GeneXproTools 5.0 application package was used to determine the functions $\sigma_1, \ldots, \sigma_6$ in equation (2). The GA parameters used for the derivation of mathematical models are listed in Table 2.

In this case, the genetic algorithm is designed to approximate experimental data and build dependency functions. The complexity of the function being optimized is determined both by the number of variables for which optimization is carried out and by the presence of local extremes. This, in turn, with a large area of research can lead to almost a huge number of solution options, so it is impossible to prove that the solution found with the help of GA is the best. However, such proof in this case is not required, it is only important that the installed function satisfies the required conditions for the convergence of the model.

The parameters presented in Table 2 were derived from a preliminary study to maximize correlation and minimize error.

Table 2

GA parameters used to build the model

Parameters GA	Values
Fundtions	+, –, *, /, ^, ln, exp, cos, sin, tg, ctg, log, x^1/3, x^2, x^1/4, x^1/5
Chromosome	30
Population size	8
Functions relation	Addition
Number of genes	0.045
Inversion	0.1
One-point and two-point recombination rate	0.3
Gene recombination and gene transfer rate	0.1
Number of genes	6
Number of generations	1864590

To implement the exact model various mathematical operations were used. During training, it was found that the software can sometimes ignore some input variables due to a minor external impact on the overall model. In this case, the GA model presented in this study used each of the input parameters at least once. As a result, the following dependencies were obtained:

$$\sigma_1 = \left((\mathrm{G1C7} - K_m) R_b - \mathrm{G1C0} - \frac{1}{\cos K_m^{1/3}} \right)^{1/3}; \quad (3)$$

$$\sigma_2 = \frac{\mathrm{G2C4}}{\mathrm{G2C0} - R_b + c} - \sqrt{K_m} + \mathrm{G2C1}; \quad (4)$$

$$\sigma_3 = \frac{\ln\left((\exp(R_b)^{1/4} + (R_b + \mathrm{G3C5})\ \mathrm{G3C1}) - d \right)}{\ln 10}; \quad (5)$$

$$\sigma_4 = \cos(l_{\mathrm{depth}} - \cos S_p - K_m\ \mathrm{G4C0}) - c; \quad (6)$$

$$\sigma_5 = \frac{1}{\mathrm{tg}\left(R_b + l_{\mathrm{depth}} + \mathrm{G5C1} - K_m + d \right)^{1/3}} + c; \quad (7)$$

$$\sigma_6 = \ln\left(\frac{c}{d} \exp\left(\sin(\mathrm{G6C5} + l_{\mathrm{depth}}) \right) \right), \quad (8)$$

where the constants:

G1C0 = –35.6765470119042;
G1C7 = 2.6195898035416;
G2C1 = 6.61345964007763;
G2C4 = 5.41190574148063;
G2C0 = 7.07966697155402;
G3C1 = –8.92397791683817;
G3C5 = 4.84969634083071;
G4C0 = 0.563865309919699;
G5C1 = 6.18578923675139;
G6C5 = 7.1938173760206.

The most recurring input parameter in the model was the corrosion degree and the concrete strength (it was repeated five times), while the size of the concrete sample was the least used (it was repeated only once). This may be due to the significance of the input parameters selected for modeling.

For example, frequent repetition of concrete strength and the corrosion degree of the reinforcing rod can be explained by the fact that these parameters have a great influence on the amount of adhesion, since the amount of adhesion of the cement gel between the reinforcing rod and the concrete mass increased with an increase in strength.

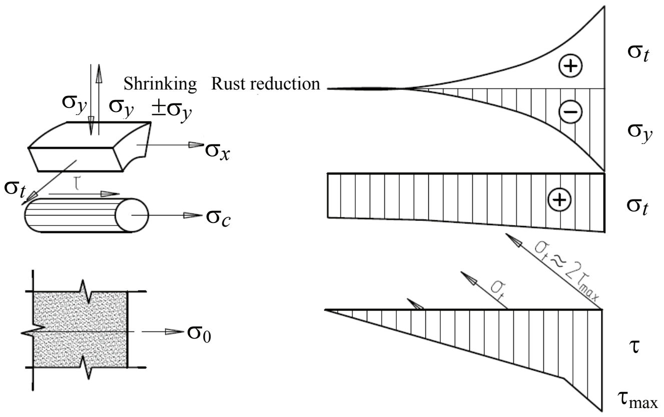


Fig. 2. Stress-strain state between reinforcing rod and concrete in pull-ou-test

With a low degree of corrosion, an increase in the adhesion strength occurred until the formation of cracks in the concrete mass as a result of a change in the surface properties of the reinforcing rod. In this case, an increase in the magnitude of the friction force between the surfaces was observed. At the same time, the filling of the layer between the reinforcing rod and the concrete formed by rust led to a more dense combination of materials (Fig. 2). However, the occurrence of cracks and reduction in the cross section of the rod (at a higher degree of corrosion) resulted in a decrease in the amount of adhesion, which contributed to premature loss of bearing capacity.

The low importance of such a factor as the profile frequency was due to the insufficient number of reinforcement profiles in the presented sample to fully reflect the model.

As can be seen from equation (3), trigonometric functions are included in the proposed GA model. Preliminary studies showed that equations (3) – (8) with the parameters of the GA were the optimal characteristics for obtaining the best prediction model with the available data set.

Models developed by software in its native language can be automatically analyzed for visually attractive expression trees, thus allowing them to understand their mathematical logical complexity faster and more completely. Fig. 3 shows the expression tree for terms used in the formulation of the GA model.

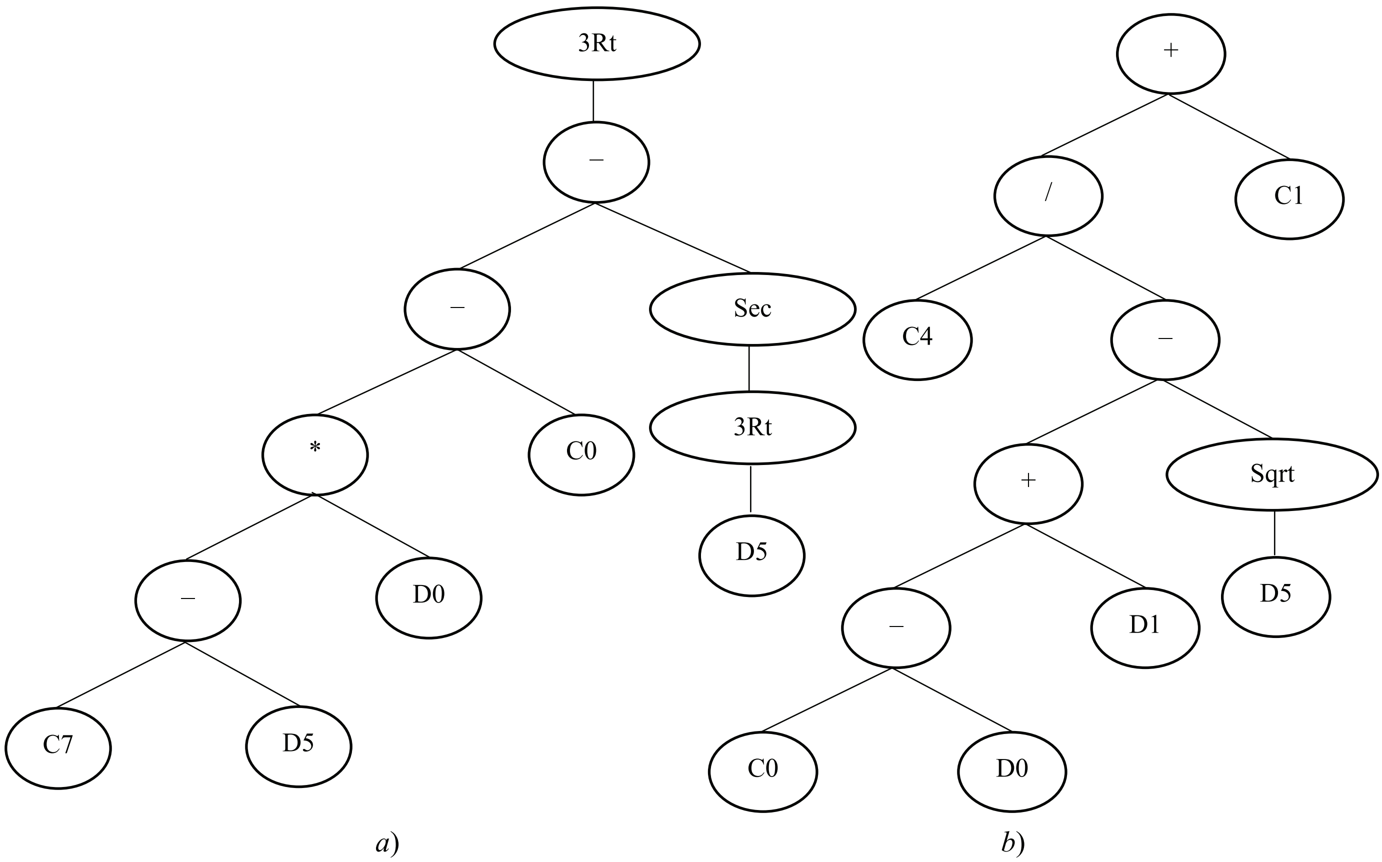


Fig. 3. Expression tree for the model:
a – Sub-ET1; *b* – Sub-ET2
(D0 is the compressive strength of concrete; D1 is the dimensions of the concrete sample; D2 is the reinforcing rod profile; D3 is the reinforcing rod diameter; D4 is the embedment depth; D5 is the corrosion degree; C0 – C7 are constants)

Some mathematical operations from the expression tree were simplified in equation (8). The comparison of the experimental and predicted bond strength is graphically illustrated in Figs 4 and 5. The model was evaluated using the correlation coefficient *R* (equation (9)), which describes the correspondence between the curve of the output variables of the model and the actual variable of the test output curve. A higher *R* coefficient indicates a model with better ability

$$R = \frac{(m_i - m_{\text{mean}})(p_i - p_{\text{mean}})}{\sqrt{\sum(m_i - m_{\text{mean}})^2 \sum(p_i - p_{\text{mean}})^2}}, \qquad (9)$$

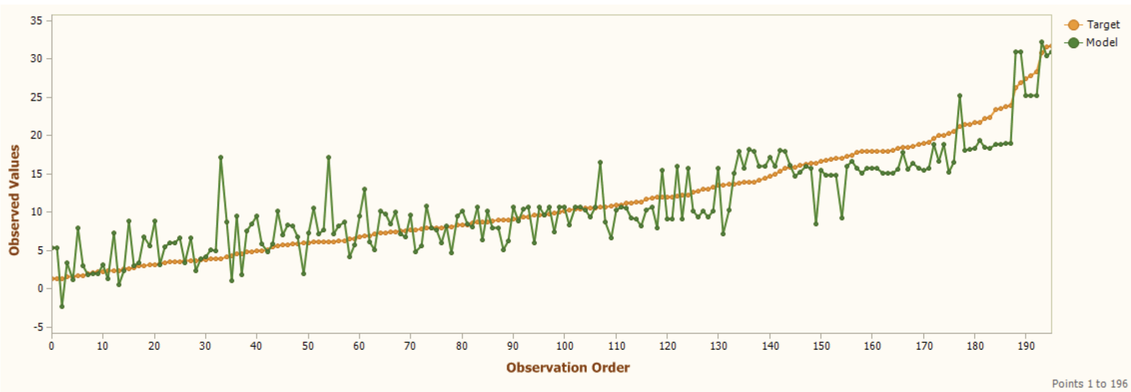
where m_0 and p_0 are mean values of measured m_i and predicted p_i values, respectively.

As can be seen from Fig. 4 and Fig. 5, the trend of changing training data was better than that of testing. The calculated correlation coefficients (*R*) were 0.890 and 0.9 for the training and test databases, respectively. This can be viewed as the evidence that there was a satisfactory correlation between actual and predicted values. Moreover, close values of the correlation coefficients can be considered as an indicator of the reliability and appropriate suitability of the proposed GA model.

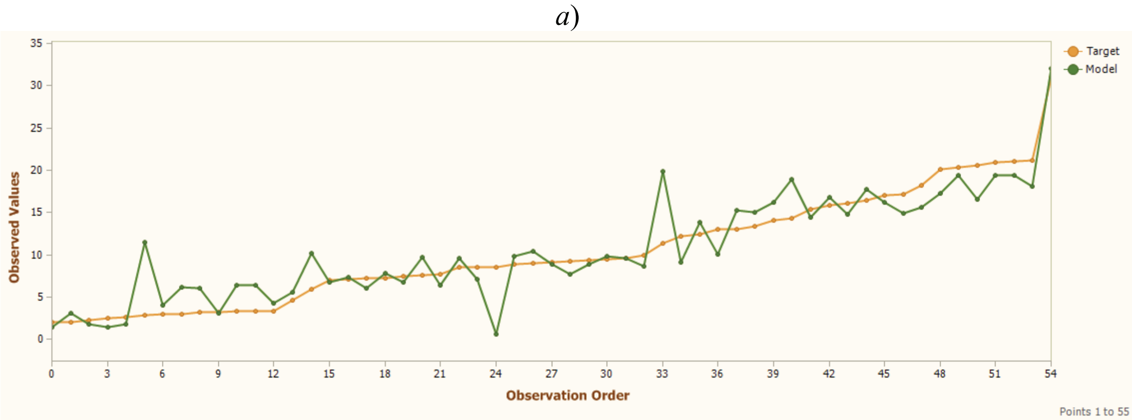
Analysis of the obtained correlation

To assess the possibility of predicting the proposed model, the normalized results were calculated, calculated by dividing the predicted results by actual ones (Fig. 6). In addition, for further comparison of the proposed models, Fig. 7 presents the estimation errors and the frequency of the corresponding data.

Considering the normalization of the predicted data, the ideal estimate was 1.0, which indicated that the predicted and observed values were exactly the same. As can be seen from Fig.6, the closest trend in the change of normalized values for this model was about 1.0. The normalized values of τ_{ad} ranged from 0.48 to 7.12 for the model with test data, while for the training database, the range of values was from 0.22 to 4.72. However, observing the trend of distribution of normalized results together with the errors presented in Fig. 8, one can notice that the greatest fluctuations occurred for the actual adhesion strength of less than 5.0 MPa. Figs 6 and 7 show that most of the data exceeded this value and the estimation errors became relatively low as the adhesion strength values increased.



a)



b)

Fig. 4. Comparison of the obtained values using the model with the experimental:
a – training data set; *b* – tesingt data set

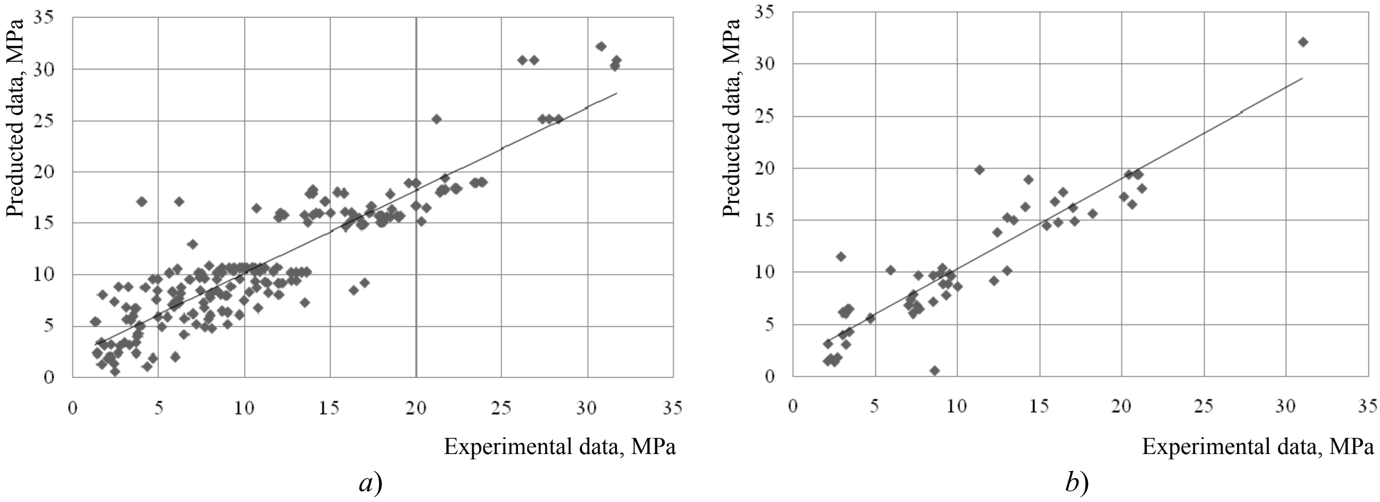


Fig. 5. Regression analysis of the model:
a – training data set; *b* – testing data set

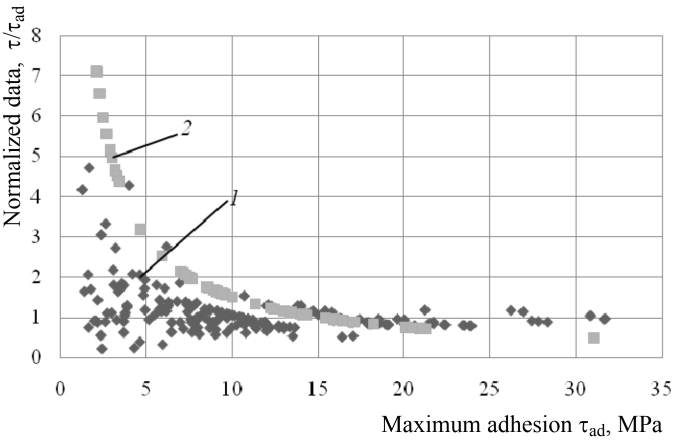


Fig. 6. Comparison of the effectiveness of the proposed model for training and testing data sets:
1 – training data set; *2* – testing data set

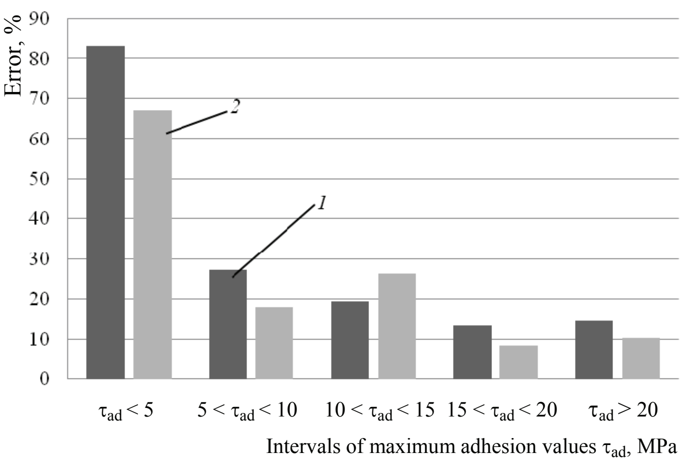


Fig. 7. Error analysis of the proposed GA model for training and testing data sets:
1 – training data set; *2* – testing data set

The fluctuation of normalized data usually tends to re-evaluate for the GA model in the training array. Sufficiently high errors occurred for the GA model with overestimated data. The number of confirmed or understated data obtained for the model in the test database is much less. Considering that most of the data, the values of τ_{ad} which exceeded 5.0 MPa, the average value of the absolute error was about 10 and 20 % for the proposed GA models, respectively.

The predicted values obtained for the GA model indicate an underestimate. For a more detailed test of the prediction capabilities of the proposed data set models, a statistical analysis was also conducted. The following statistical parameters were calculated using equations (10) – (12) and are presented in Table 3.

Mean Absolute Percentage Error:

$$\mathrm{MAPE} = \frac{1}{N}\sum_{j=1}^{n}\left|\frac{m_i - p_i}{m_i}\right|100\,\% \;; \tag{10}$$

Mean Square Error:

$$\mathrm{MSE} = \frac{\sum_{j=1}^{n}(m_i - p_i)^2}{n} \;; \tag{11}$$

Root Mean Square Error:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{j=1}^{n}(m_i - p_i)^2}{n}} \;, \tag{12}$$

where *m* and *p* are measured values (m_i) and predicted values (p_i), respectively.

Table 3

Statistical parameters of the proposed models

Model	MSE	RMSE	MAPE	RSE	RRSE	RAE	*R*	R^2
Training	9.242286	3.040113	2.400503	0.19611	0.442844	0.429236	0.896753	0.804167
Testing	7.319179	2.705398	1.941344	0.176835	0.420518	0.367689	0.909323	0.826869

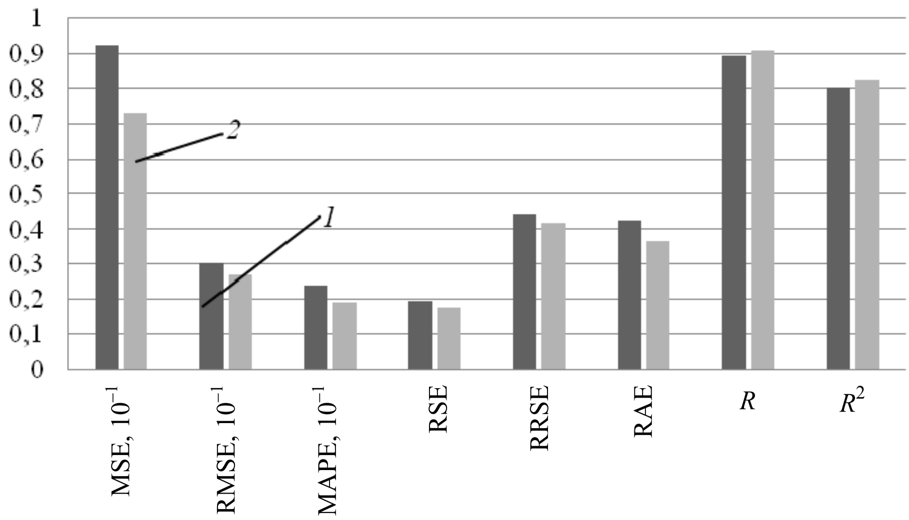


Fig. 8. Histogram of model regression analyses:
1 – training data set; *2* – testing data set

As can be seen from Table 3 and Fig. 8, the lowest errors were observed for the proposed model, especially for the training database. However, the statistical errors calculated for the testing database were also close to the training database. Error analysis, shown in Figs 6, 7 and Table 3, proves that the proposed model, in terms of accuracy and efficiency of prediction, works within an acceptable range.

However, for low experimental values of τ_{ad} up to 5 MPa, the average error between the predicted and experimental data was significant compared with other ranges. According to the observed correlations and determination, the reliability of the proposed models can be considered satisfactory and higher for values of τ_{ad} more than 5 MPa. The correlation coefficients for the database of training and testing were 0.9 and 0.89, respectively. In addition, for testing databases, correlation coefficients of 0.89 were achieved for the first and 0.9 for the latter stages. Although the database for testing was not used for training, a high level of prediction was obtained for both the training data sets and for testing ones, which was caused by a low average absolute error rate and high correlation coefficients.

The statistical analysis based on the MAPE and MSE values also showed that the proposed wording of the testing data set had relatively lower errors than the training set. Observing the general trend of efficiency evaluation, it turned out that the GA-based model can be considered as the preferred prediction model.

Therefore, soft computing methods can be handy tools for processing empirical data and determining the final adhesion strength of specimens susceptible to corrosion. All predicted values were valid and comparable with the observed ones. Therefore, we can conclude that both proposed models can be considered as useful systems with satisfactory prediction ability.

This study focuses on predicting the adhesive strength between concrete and reinforcing rod, subject to varying degrees of corrosion. From the point of view of practice, the use of models on structural elements is quite relevant. For example, the ultimate strength of adhesion is necessary to calculate the length of the anchoring [5]. In this case, the rod perceives the force acting upon pulling out if the value of l_d is sufficient:

$$l_d = \frac{R}{4\tau_{ad}} d \ , \qquad (13)$$

where R is design yield strength of reinforcing rod, τ_{ad} is ultimate adhesive strength and d is a rod diameter. In the future, the considered value of R and the estimated value of τ_{ad}, the proposed empirical models, as well as the depth of embedding of structural elements can be calculated in more detail.

Conclusion

Adhesion is the ability of concrete to resist slipping of reinforcing rods under load in concrete products. “Reinforced concrete” is considered as a single composite material until such time as there is adhesion along the contact surface between the reinforcing rod and concrete. In operation, the metal reinforcing rod is subject to structural degradation of the surface (corrosion). Therefore, special attention should be paid to the process of breaking the interaction of reinforcing rod with concrete due to corrosion. For evaluations of this interaction, a soft computing method based on the genetic algorithm programming was used.

The application of the GA model is convenient for the user, since it receives data without normalization. However, if predicting accuracy is more important with new parameters and in a different range of specified parameters, the use of the existing models becomes incorrect. GA computing on the basis new empirical data will result in retraining the model or correcting the existing one.

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