PREDICTION OF ADHESIVE JOINTS STRENGTH BASED ON THE MODIFIED DE BRUYN METHOD USING THE NUMERICAL METHODS

Przewidywanie wytrzymałości połączen klejowych w oparciu o modyfikowaną metodę De Bruyna z wykorzystaniem metody numerycznej

Прогнозирование прочности клеевых соединений на основе модифицированной методы Де Брёйне с использованием номерического метода

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Abstract: The paper presents a numerical model, based on artificial intelligence, to predict the strength of adhesive joints on basis of the modified De Bruyn method. The model was built using the results of research on destructive force of adhesive joints of steel sheets. Input variables for the model were: the thickness of the materials to be joined, the length of the overlap, the geometrical development of the surface and the thickness of the adhesive layer. The obtained model was tested on correctness of representing of the impact of individual variables on the strength of the joint, represented by the value of stress from the destructive force of the adhesive joint in the combined material. Based on the obtained results, it was possible to extend this forecasting method with further factors affecting the strength of adhesive joints, including energy parameters.

Keywords: joint strength, adhesive joint, numerical model

Streszczenie: W artykule przedstawiono model numeryczny oparty na sztucznej inteligencji służący przewidywaniu wytrzymałości połączeń klejowych w oparciu o modyfikowaną metodę De Bruyna. Model ten zbudowano posługując się wynikami badań laboratoryjnych pomiaru siły niszczącej połączenie klejowe blach stalowych. Jako zmienne wejściowe przyjęto grubość łączonych materiałów, długość zakładki, rozwinięcie geometryczne powierzchni i grubość spoiny klejowej. Uzyskany model poddano ocenie poprawności odwzorowania wpływu poszczególnych zmiennych na wytrzymałość połączenia reprezentowaną przez wartość naprężenia w łączonym materiale pochodzącego od siły niszczącej połączenie klejowe. W oparciu o uzyskane wyniki stwierdzono możliwość poszerzenia tej metody prognozowania o kolejne czynniki mające wpływ na wytrzymałość połączeń klejowych w tym o parametry energetyczne.

Słowa kluczowe: wytrzymałość połączenia, połączenie klejowe, model numeryczny

Introduction

Technology of glue bonding plays a very big role in development of modern constructions. In many cases, it is an alternative to the so-far employed methods of joining, sealing or regeneration of parts of machines. Gluing creates the new possibilities in respect of combining materials with different physical and geometrical properties; it allows also linking the parts with different dimensions what contributes repeatedly to the simplification of their construction. Combination of gluing and other technologies e.g. riveting or welding allows obtaining joints with different properties, favourable for improvement of bearing capacity or tightness of joints. Such wide possibilities of adhesive bonding application cause the necessity of seeking for the optimum conditions for implementation of the discussed process and determination of factors, affecting significantly the resistance of adhesive joints.

The so-far employed single-factor models do not give a full image of the influence of independent variable on dependent variable, i.e. joint strength. The complexity of the discussed problem in combination with the expectations of the constructors causes the necessity of constructing a model which would consider the effect of the particular properties, relating to the way of formation of the upper layer state, including the energy properties as well as constructional parameters.

We still seek for better methods for forecasting the adhesive joint strength based upon the set of constructional and technological factors. The developed and published formulas of relationships between the independent parameters affecting the quality of joint, as obtained on the basis of empirical analyses, consider greater and greater number of factors. They are limited, however, by the interval of the values of variables in which they may be utilized. The alternative to such approach includes application of numerical methods, based on the artificial intelligence. The mentioned method gives a lot of new possibilities in respect of conducting the complicated analyses and construction of prognostic models. The ability of appropriate describing the state of the joint gives the possibility to improve the quality of the products as well as affects the lowering the cost of their manufacture owing to the limitation of technological operations to the indispensable minimum and their optimal selection. Apart from this, the application of numerical methods gives the possibility of constant improvement of the model.

The described above factors have caused that the attempts were undertaken to construct a prognostic model of joint strength based upon the modified De Bruyn method, with the consideration of the following initial parameters: length of the adhesive lap, thickness of adhesive joint, thickness of the joined materials, the square mean of coarseness profile ordinates.

Numerical analysis of the adhesive lap joints

A quick method for determination of the adhesive joints strength is facilitated owing to the modified De Bruyn method, presented in the paper [3]. As a result of the method's modification, the nomographs of the bearing capacity of the lap joints were created on the grounds of the experimental trials. In the submitted studies, the samples were made from the sheets of different thickness. They were joined, using different lengths of the laps and then, the level of tensions in the joined elements was determined at the moment of destruction of the joint (σ_0=P/δb), (where: P- force, d –thickness of sample, b-width of sample) (Fig. 1.) [3].

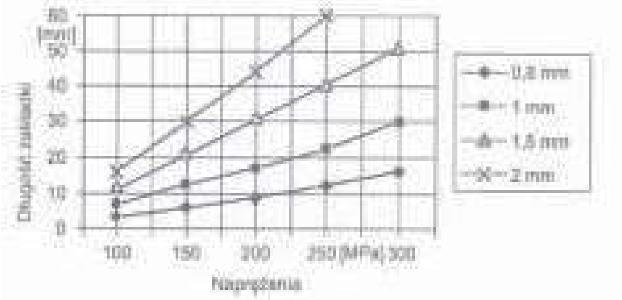

Fig. 1. Nomograph of single lap joints strength of PA7 sheets of four different thickness, joined using Epidian57 resin, cured by TECZA hardener at 328 K during 1,5 hour (surface of sheets cleaned with abrasive cloth, 80 Grit) [3]
Rys. 1. Nomogram nośności jednozakładowych połączeń blach z materiału PA7 o czterech grubościach, klejonych Epidianem 57 utwardzanym TECZA w temperaturze 328 K w czasie 1,5 h (powierzchnia blach czyszczona płótnem ściernym o ziarnistości 80) [3]

Nomograph in such form is true for the specified species of adhesive, the determined conditions of hardening the adhesive lap, the determined type of the joined material and a specified way of preparing the surface for joining as well as for the specified type of joint.

The set of the initial factors of the analysis of the adhesive joints strength was determined based upon the experimental data, as presented in the publications [5, 2, 6, 7, 8, 9, 13] and the noticeable relationship of the dispersive part of a free surface energy, determined by Owens-Wendt method [5, 14] and the strength of the joint.

To obtain the input data for construction of the numerical model, serving the forecasting of short term strength of adhesive joints, the trials of resistance of the lap adhesive joints to shearing force were carried out. The plan of the studies was based on the complete set, constituting a combination of the mentioned below input factors. Five repetitions of the strength measurement in the system were conducted. The tests were carried out on the basis of PN-EN 1465:2003 [11]. The joined elements included steel sheets, made of the steel 1.0330. The shape and dimensions of the samples, used in the tests are given in Fig.2.

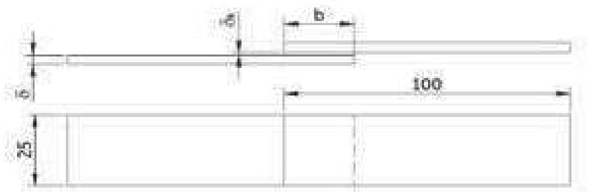

Fig. 2. Shape and dimensions of the test samples
Rys. 2. Kształt i wymiary próbek stosowanych do badań.

For the analysis of the obtained results and construction of the model, the artificial neuron nets were used. As a result of the conducted analysis of the effectiveness of the network's functioning it was found that the best prognostic model was obtained in the case of MLP network – Multilayer Perceptron with a structure (4:4-11-1:1). The mentioned network was learnt with utilization of algorithm CG - Conjugate Gradient Descent, with logistic function of activating neurons of the hidden layer and linear with the saturation with function of activation the input layer and output layer with the application of linear function of postsynaptic potential [1, 12].

The schematic plan of the model's construction is given in Fig.3.

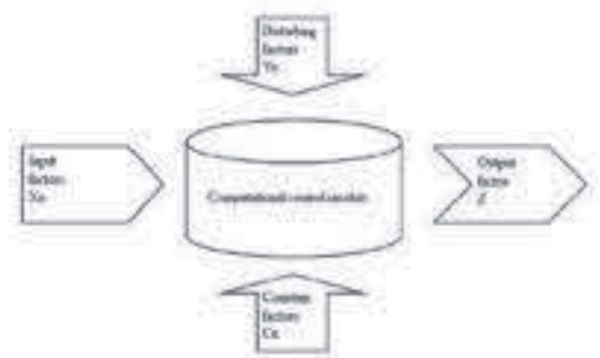

Fig. 3. Diagram of mathematical model of predicting strength of adhesive joint, based on modified De Bruyn method
Rys. 3. Schemat planu budowy modelu numerycznego do przewidywania wytrzymałości połączenia klejowego w oparciu o modyfikowaną metodę De Bruyna

Where:

Input factors:

X_1 – length of the lap (l – 5, 10, 15 [mm]),
X_2 – degree of geometrical development of surface (characterized by parameter R_q- 2.4, 1.9, 1.8, 2.4 [μm]),
X_3 – thickness of adhesive joint (δk – 0.06, 0.11, 0.17, 0.24 [mm]),
X_4 – thickness of joined materials (δ - 1, 1.5, 2 [mm])

Output factor:

Z – normal stress in the joined material (δ0 [MPa]).

Constant factors:

C_1 – type of joined material,
C_2 – time of hardening (72h)
C_3 – type of the applied adhesive (Epidian 57/PAC-100/80),
C_4 – type of degreaser Loctite 7061

Disturbing factors:
Y_1 – unrepeatability of the measurement conditions
Y_2 – unrepeatability of technology of joint performance
Y_3 – inaccuracy of measurements stands
Y_4 – inaccuracy of measurement

The conducted own studies allowed building – based upon the neural networks – of the multi-parameter model in a form of implicit function. When assuming the homeostasis of the selected input parameters, the discussed model gives also a possibility of constructing the three-dimensional nomographs. Such approach allowed extending the range of analysis and considering the effect of the changes in stereometric parameter Rq and thickness of adhesive layer δk on the adhesive joint strength.

Table 1 shows the results of regression statistics of MLP network, as given in Fig.4. Value of a strength, destructing P joint ([N] was presented here as an input variable.

Uc, P, Wa, P, Te, P – Information concerns, successively, the following sets: training dataset, validation data set and testing dataset, connected with the analysis of the destructive strength value P [N]

Tab.1. Regression statistics of destructive strength value for MLP network (4:4 – 11 – 1:1)
Tab. 1. Statystyki regresyjne wartości siły niszczącej P dla sieci MLP (4:4-11-1:1).

	Uc. P	Wa. P	Te. P
Mean	4668	4628	4418
Standard deviation	1914	1957	2139
Mean error	-6,6	41,9	-102,1
Error deviation	746,1	739,9	883,9
Mean absolute error	538,9	525,8	651,7
Deviation quotient	0,39	0,38	0,41
Correlation	0,92	0,93	0,91

Where:
Mean: the mean value of the input variable, calculated on the basis of the set values of the discussed variable, collected – respectively – in training dataset, validation dataset or test dataset.
Standard deviation: standard deviation, calculated for the set values of the input variable
Mean error: mean error (understood as module of difference between the expected value and the obtained output value
Standard deviation of error: standard deviation of errors for the output variable
The mean absolute error: the mean absolute error (difference between the set value and the obtained output value) for input variable
Quotient of standard deviations: quotient of standard deviations for the errors and the data. It is the main indicator of the quality, constructed by the network of regression model
Correlation: standard correlation of R Pearson correlation for the set value and the obtained output value

Fig.5 shows the surfaces of the responses if the net, as illustrated in Fig.4. The mentioned surfaces represent the stress in the joined material, corresponding to the stress destructing the adhesive joint, with the consideration of the changes in the length of the lap and the changes of the remaining input parameters.

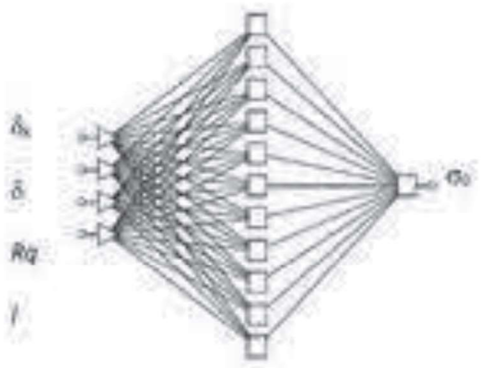

Fig. 4. MLP structural diagram (4:4-11-1:1)
Rys. 4. Schemat strukturalny sieci MLP (4:4-11-1:1)

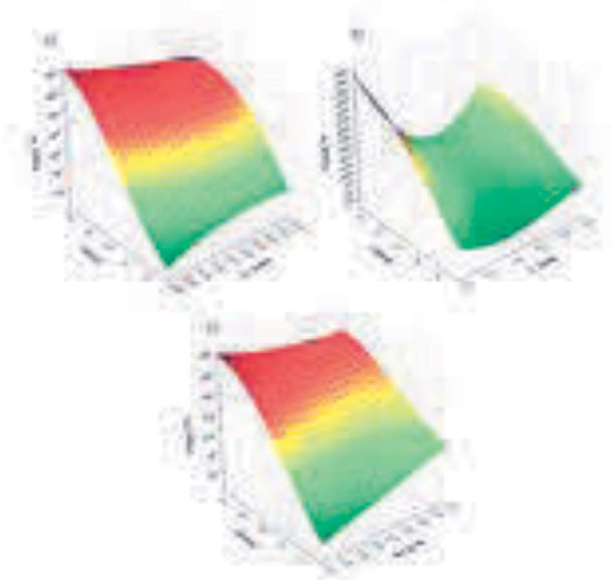

Fig. 5. Predicted change of stress in joined material depending on a) dk – l, b) d – l, c) Rq-l
for dk=0,1 [mm], d=2 [mm], Rq=2 [mm]
Rys. 5. Prognozowany przebieg zmian naprężenia w łączonym materiale w funkcji:
a) dk – l, b) d – l, c) Rq-l. Przypadek chwilowy dk=0,1 [mm], d=2 [mm], Rq=2 [mm]

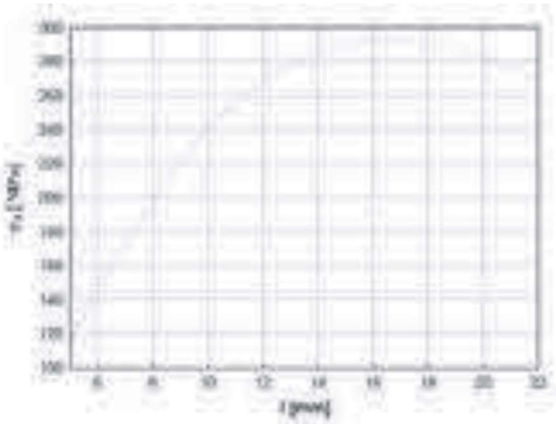

Fig. 6. Nomograph of single lap joints strength of d=1 [mm] thick sheets, where thickness of adhesive layer dk=0,1 [mm], parameter Rq=1,7 [mm], joined using Epidian 57/PAC/100:80
Rys. 6. Nomogram nośności jednozakładowych połączeń blach stalowych o grubości d=1 [mm], grubości spoiny klejowej dk=0,1 [mm], parametr Rq=1,7 [mm], klejonych klejem Epidian 57/PAC/100:80

The analysis of the mutual relations between the thickness of the joined elements and the length of the lap based upon the De Bruyn coefficient (4) does not impose any limitations concerning the increase of the lap's length. It has been revealed, however – as it is followed from the diagram on fig.6 – that the increase of the lap's length above a certain limitary value is aimless. It does lead to the increase of the joint strength. The obtained numerical model is deprived of the errors, resulting from the theory of Volkersen [10] which assumed omitting the deformations, resulting from the bending of the joined elements and the resulting normal stress.

Summary

From the presented effects of the model functioning, it is followed that the introduction of modifications in De Bruyn method gives the possibility of conducting the analysis of the strength of the lap adhesive joints as well as forecasting of their strength, described by normal stress, generated in the joined material, with the consideration not only of the lap's length and thickness of the joined materials but also including the thickness of the adhesive layer and geometric features of the joined surfaces. The run of the relationship, as being presented in the model corresponds to the current state of the knowledge on the effect of the analysed variables on value of the joint strength. When designing the adhesive joints, the consideration of the effect of the changes of the particular factors and their noticeable non-linear influence on bearing capacity of the joint gives the possibility to improve the quality of the joints as well as allows more precise forecasting of their strength.

Based upon the conducted analyses, we may formulate the following cognitive conclusions:

1. In the case of the length of the lap, the thickness of the joined materials as well as thickness of the adhesive layer, the non-linear effect of the mentioned factors on the strength of the adhesive joint has been revealed; the nature of the mentioned effect and by this, the run of the relationship function is changing together with the change of each of the input parameters.
2. The threshold length of the lap should not be determined with omitting of the geometric (stereo) features of surfaces of the joined materials in the site of joint. The results of analysis, using the artificial intelligence show that the real threshold length of the lap is higher than that one determined with the utilization of the known strength equations which are charged with the errors, resulting from the simplifications, adopted in the theory of Violkersen.
3. There is a possibility of optimizing the strength of the lap adhesive joint due to the thickness of adhesive layer, its length, geometric status of the surface for a specified adhesive (glue) and the joined material, with the set thickness of the joined materials and width of the joint.

The presented model may be further modified and improved owing to introduction of the successive parameters affecting the strength of the joint. Based upon the conducted research work, it may be supposed that the improvement of the quality of the model may be reached via introduction of the energy parameters, describing the state of the surface layer of the joined materials [5] as well as compositional elements of a surface free energy of the adhesive substance.

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