Jakub Szabelski[1], **Jacek Dominczuk**[2]

PREDICTING THE STRENGTH OF LAP ADHESIVE JOINTS BASED ON MULTIDIMENSIONAL ANALYSIS OF MEAN DESTRUCTIVE SHEAR STRESSES

The theoretical analysis of the strength of lap adhesive joints based on mean destructive shear stress is presented in the paper. Based on the concept of forecasting the strength of adhesive joints with mean destructive shear stress, the results of experimental research on determining the strength characteristics of the above joints are presented. The results obtained revealed the dependence of the strain from the de Bruyne's coefficient, the findings were analysed and discussed.

Keywords: *strength, adhesive joints, destructive stresses, neural network.*

Якуб Шабельський, Яцек Домінчук

ЕКОНОМІЧНЕ ПРОГНОЗУВАННЯ МІЦНОСТІ КЛЕЄВИХ З'ЄДНАНЬ ВНАКЛАДКУ НА ОСНОВІ БАГАТОВИМІРНОГО АНАЛІЗУ СЕРЕДНІХ РУЙНІВНИХ НАПРУЖЕНЬ

У статті подано теоретичні основи аналізу міцності клеєвих з'єднань внакладку, проведеного з використанням середніх значень руйнівних дотичних напружень. Використовуючи представлену ідею прогнозування міцності клеєвих з'єднань на основі середніх руйнівних напружень клеєвих швів, наведено результати експериментальних досліджень з визначення міцнісної характеристики випробовуваних швів. Подано отримані результати та аналіз залежності напруження від коефіцієнта де Бройна.

Ключові слова: *міцність, клеєві з'єднання, руйнівні напруження.*
Форм. 8. Рис. 6. Літ. 19.

Якуб Шабельский, Яцек Доминчук

ЭКОНОМИЧЕСКОЕ ПРОГНОЗИРОВАНИЯ ПРОЧНОСТИ КЛЕЕВЫХ СОЕДИНЕНИЙ ВНАХЛЕСТКУ НА ОСНОВЕ МНОГОМЕРНОГО АНАЛИЗА СРЕДНИХ РАЗРУШАЮЩИХ КАСАТЕЛЬНЫХ НАПРЯЖЕНИЙ

В статье представлены теоретические основы прочностного анализа клеевых соединений внахлестку, проведенного с использованием средних значений разрушающих касательных напряжений. Используя представленную идею прогнозирования прочности клеевых соединений на основе средних разрушающих напряжений клеевых швов, представлены результаты экспериментальных исследований по определению прочностной характеристики исследованных швов. Представлены полученные результаты и анализ зависимости напряжения от коэффициента де Бройна.

Ключевые слова: *прочность, клеевые соединения, разрушающие напряжения.*

1. Introduction

The strength of adhesive joints has been a widely discussed problem (Osnes, Andersen, 2003; Porebska, Skorupa, 1993; Chen, Adams, Lucas, da Silva, 2011). It lacks, however, the multidimensional analysis which could allow better understanding of the simultaneous influence of various factors on the joints quality known better as its static strength. The overall strength of adhesive joints depends on a number

---

[1] Assistant, Lublin University of Technology, Poland.
[2] PhD, Senior Lecturer, Lublin University of Technology, Poland.

of technological as well as constructional factors. The conducted analysis of the energetic properties of the surface layer (Dominczuk, Szabelski, 2010; Dominczuk, 2012; Zenkiewicz, Golebiewski, Lutomirski, 1999) allows distinguishing factors which have the essential influence on the strength of lap joints from the adhesive properties perspective. These are: the thickness of joined materials δ, the thickness of the adhesive δ_k, the stereometric properties of the surface described by root mean squared of the roughness R_q and finally – the length of the joint l. The influence of abovementioned factors is not linear and depends on the assumed system of the nodal values. Forecasting strength of joints becomes difficult for large number of data.

Often the adhesive joints are overdesigned. Joints become larger, overall cost of preparation of surfaces increases, joining them requires larger quantity of adhesive material. With regard to safety coefficient – joints are designed much larger than actually needed – due to problems with estimating their actual strength. All that increases the final cost of adhesive joints and decreases the potential application of adhesive techniques. On the other hand, failing to meet the strength conditions of the joint is also unacceptable due to potential breakdown of the designed article followed up by often even more costly consequences. Therefore a tool for finding the best solution between the lowest cost (Gola, Swic, 2011) of preparation of joint, on the one hand, and assurance of meeting the functional requirements set by the designer on the other – seems to be necessary.

There are several traditional procedures for analysing the strength of adhesive joints: destructive and non-destructive (analytic methods (Dominczuk, 2010), strains analysis methods (Dominczuk, 2011; Kuczmaszewski, Dominczuk, Rudawska, 2001), FEA method (Rudawska, Debski, 2011; Sadowski, Knec, Golewski, 2010; Xiaocong, 2011) etc.). The method based on forecasting of the static strength of adhesive joints using the mean destructive strains is one of the most applied ones. Being extremely widespread, the wider analysis of the influence of selected constructional and technological factors on the value of these strains seems to be reasonable. In order to build the multidimensional regression model of dependence using the neural network, the research on strength of lap adhesive joints of steel sheets (DC01 – 1.0330 acc. to. DIN EN 10130) has been conducted for adhesives: Epidian 57/PAC-100/80. Sheet metal samples were subjected to abrasive machining using 80, 120, 320 and finally 500 abrasive paper and degreasing process using Loctite 7061 cleaning agent. Research tests were conducted according to PN-EN 1465:2003 Standard (Polish Standards: PN-EN 1465:2003).

2. Forecasting the strength on the basis of mean destructive stresses of adhesive joints

The method of forecasting the strength of adhesive joints on the basis of mean destructive stresses of adhesive joint was formulated after experimental obtaining those mean destructive stresses of the modelled adhesive joint (Godzimirski, Roskowicz, 2002; Godzimirski, 2002). The strength of the same type joint, prepared with application of the same exact technology but different in dimensions can be defined as:

$$P=\tau_{mean}A\varphi, \tag{1}$$

where: τ_{mean} – mean destructive stresses, A – area of adhesive joint, φ – coefficient describing the real dimensions of an adhesive joint.

De Bruyne's conducted the first tests (Snedon, 1961) of strength of lap adhesive joints based on the Volkersen Theory, wider presented in (Godzimirski, 2002).

In case of joining elements of equal tensile rigidity and the length of joint almost the border length of lap — the stresses concentration coefficient has been defined as the relation of maximum to mean stresses:

$$n = \frac{\tau_{\max}}{\tau_{avg}} \tag{2}$$

after modifications it becomes:

$$n = \sqrt{\frac{G_k l^2}{2\delta_k E\delta}}, \tag{3}$$

where: G_k — modulus of elasticity of adhesive (adhesive joint), E — modulus of elasticity of joined materials, l — length of lap, δ_k — thickness of adhesive layer, δ — thickness of joined materials.

Assuming that E, G_k and δ_k values are constant for the defined joint, the dimensions of the lap joint are characterized by the lap length and the thickness of joined elements. The relation $\sqrt{\delta}/l$ is called the joint coefficient, the geometrical coefficient of joints or the de Bruyne's coefficient (Godzimirski, 2002; Kuczmaszewski, 1995). The stresses concentration coefficient equals now:

$$n = \frac{Cl}{\sqrt{\delta}}, \tag{4}$$

where: C — is constant.

The shear strength of the lap joint equal to mean stress in the moment of joint destruction ($\tau_{mean}=R_t$) can be obtained using the research methods. Knowing that destruction of the joint begins when the maximum stress reaches the value of destructive stress ($\tau_{max}=\tau_{des}$) (Godzimirski, 2002):

$$\tau_n = \tau_{mean1} n_1 = \tau_{mean2} n_2 = \ldots = \tau_{mean\_i} n_i \tag{5}$$

Knowing the mean value of destructive stresses for one joint, it is possible to evaluate the value of mean stresses for different dimensions joint:

$$\tau_{avg\_i} = \frac{n_n \tau_{mean\_n}}{n_i} = \tau_{mean\_n} \frac{l_n}{l_i} \sqrt{\frac{\delta_i}{\delta_n}}, \tag{6}$$

According to the above equation, mean shearing stresses is connected with the joint coefficient (Godzimirski, 2002):

$$\tau_{mean} = f\left(\sqrt{\delta}/l\right) \tag{7}$$

This dependence between a selected adhesive and the type of joined materials can be presented on graph. The mean shearing stresses relation to the de Bruyne's coefficient is introduced in Figure 1.

The strength of the adhesive joint can be forecasted for joints of known value of coefficient of stresses concentration on the basis of the relation below:

$$P=\tau_{mean} jb, \tag{8}$$

where: j — lap length, b — lap width.

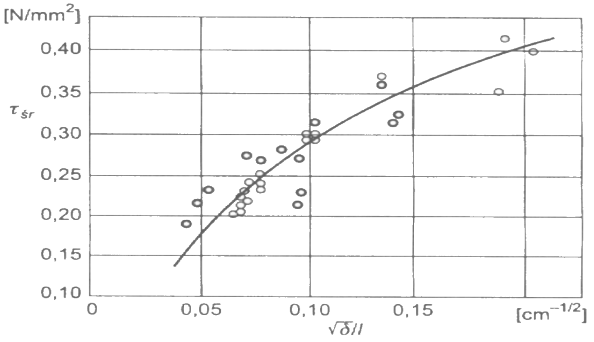

Figure 1. **The dependence of mean shearing stresses destroying the joints and the coefficient of the connection for metal sheet samples joined using the Araldit adhesive** *(Godzimirski, 2002)*

3. The model for forecasting the strength on the basis of mean shearing stresses destroying the adhesive joints

The general concept behind forecasting the strength of adhesive joints using the mean destructive stresses is based on experimental obtaining of the mean destructive stresses of the modelled adhesive joint (Kuczmaszewski, 2006) and an assumption, that the strength of joint of the same type, prepared with application of identical technology but different in dimensions can be described by Equation 1.

The research conducted by the authors allowed qualifying the relation between the mean shearing stress damaging the joint and the coefficient of connection for steel samples joined using Epidian 57/ PAC/100:80 adhesive according to the planned agenda of the research.

The study was conducted following the static, multifactorial research plan. 144 arrangements combining 4 independent input values and 5 repetitions were conducted, which resulted in 720 single measurements in total. The mean destructive stress was the outputs size. The object of investigations with indicated input parameters, disturbing factors and constant values is introduced in Figure 2.

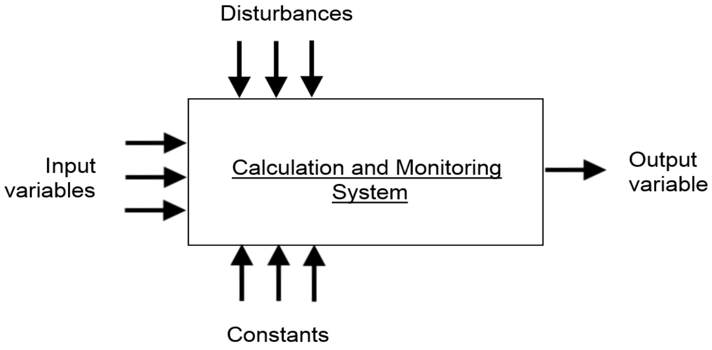

Figure 2. **The plan of multifactorial experiment for investigation of the influence: the lap length, the stage of surface layer development, the thickness of adhesive layer and thickness of joined materials on final strength of lap adhesive joints**

where:

Input variables:

- X1 – de Bruyne's coefficient

(for combination of l = 5, 10, 15 [mm] and δ = 1, 1.5, 2 [mm]),

- X2 – the geometrical development of surface layer (R_q – 2.43, 1.94, 1.86, 2.43 [μm]),
- X3 – thickness of adhesive layer (δ_k = 0.06, 0.11, 0.17, 0.24 [mm]),

Output values:

- Z – mean destructive stresses (τ_{mean} [MPa]).

Constants:

- C1 – type of joined material

(steel DC01 – 1.0330 acc. to. DIN EN 10130; 100x25xδ sheet),

- C2 – curing time (72 h),
- C3 – type of adhesive (Epidian 57/PAC-100/80),
- C4 – temperature conditions during test (20±2 [^{0}C]),
- C5 – humidity conditions during test (40±5 [%]),
- C6 – cleaner/degreaser type (Loctite 7061).

Disturbances:

- Y1 – unrepeatability of measurement conditions,
- Y2 – unrepeatability of preparing the joint,
- Y3 – inaccuracy of measuring tools and equipment,
- Y4 – measuring inaccuracy.

The neural network was used as a tool for the statistical and prognostic analysis (Dominczuk, Kuczmaszewski, 2008). The graph of MLP networks outputs of the defined structure (Figure 3), used a conjugate gradient (CG) method for the temporary parameters: $\delta_k=0,1[mm]$; $R_q=2[\mu m]$ and were presented in Figure 4.

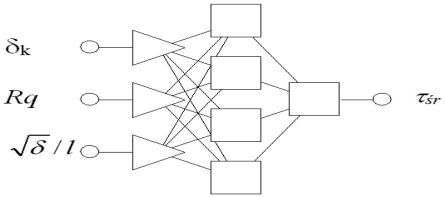

Figure 3. **The diagram of MLP Network (3:3-4-1:1)**

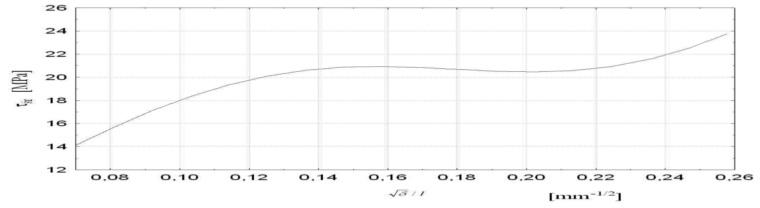

Figure 4. **Relation between the mean destructive shear stresses and the connection coefficient for steel samples joined using Epidian57/PAC/100:80 adhesive** *(based onDominczuk, Kuczmaszewski, 2008)*

The surfaces of networks outputs for selected initial values of input parameter δ_k are presented in Figure 5, and for selected initial values of input parameter R_q in Figure 6.

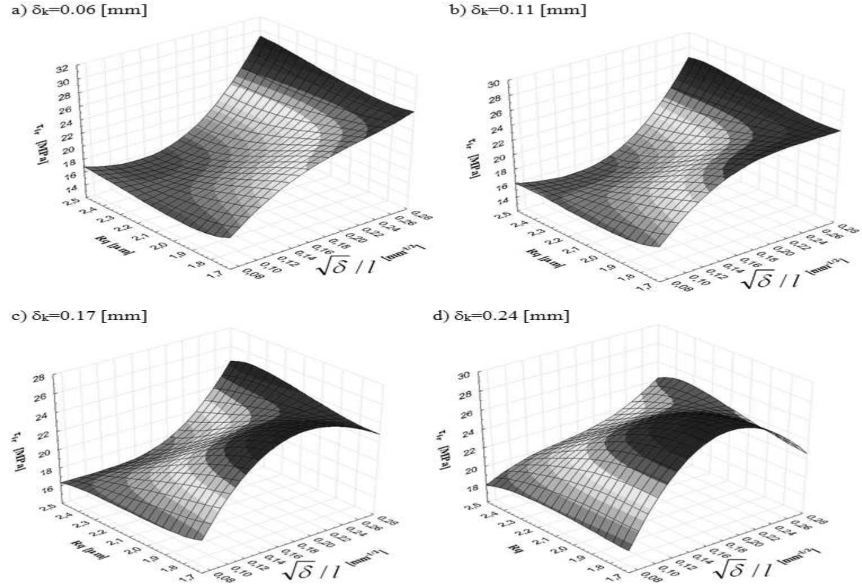
a) δk=0.06 [mm]
b) δk=0.11 [mm]
c) δk=0.17 [mm]
d) δk=0.24 [mm]

Figure 5. **The output surfaces of MLP network (3:3-4-1:1) fed using the CG method for input parameter δ_k**

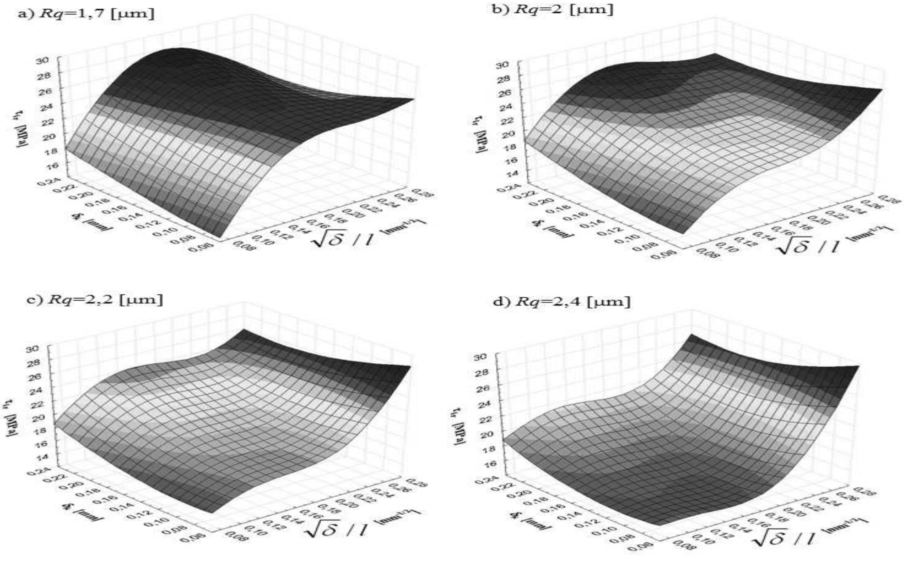
a) *Rq*=1,7 [μm]
b) *Rq*=2 [μm]
c) *Rq*=2,2 [μm]
d) *Rq*=2,4 [μm]

Figure 6. **The output surfaces of MLP network (3:3-4-1:1) fed using the CG method for input parameter R_q**

The given research analyses prove that the real relation between the mean shear stress of joints and the connection coefficient, for examined steel samples, only in certain range meets the theoretically obtained curve (Eq. (7)). The approximation test conducted using the neural network also allows broadening the knowledge of the range and type of influence of the thickness of the adhesive joint layer and parameters related to the root mean squared of the roughness – R_q, on the forecasted strength of joints of the de Bruyne's coefficient values.

4. Summary

The analysis of mean destructive shear stress in the adhesive joints allows to make a conclusion that for the research plan the experimental dependence of the mean shear strain from the de Bruyne's coefficient answers the theoretical curve only partially. For the examined case of the material coefficient: 0.16 / 0.22 the stabilization of mean shear stress was observed.

Applying the Equation 7 is not recommended in forecasting of the strength of adhesive joints in case of the connection coefficient above 0.16 (Figure 4). Significant drop of mean shear stress or its stability on the defined level in certain range of geometrical coefficients, observed on strength graphs, is a result of decrease of influence of external bending moments affecting the joints due to the plastic deformation of the joint.

Also the thickness of the adhesive layer as well as stoichiometric state of the surface layer have significant influence on the value of mean destructive shear strains. As it was proven in the research studies, with the increase of R_q parameter, the value of the maximum destructive shear stress moves in the direction of larger values of the de Bruyne's coefficient (Figure 6). It was demonstrated that using the neural networks one can estimate the variation of the mean shear stress in function of stress concentration coefficient and keep the input parameters which allow for wider utilization dependence applied so far.

References:

Dominczuk, J., Kuczmaszewski, J. (2008). Modelling of adhesive joints and predicting their strength with the use of neural networks. ELSEVIER. Computational Materials Science, pp. 165–170.

Dominczuk, J., Szabelski, J. (2010). Surface layer energy state and its influence on adhesive strength. Monografia: Edited by: Jozef Jonak: Aspects of fracture and cutting mechanics of materials. Lubelskie Towarzystwo Naukowe. Lublin, pp. 89–100.

Dominczuk, J. (2010). Prognozowanie wytrzymalosci polaczen klejowych przy wykorzystaniu sieci neuronowych. Technologia i Automatyzacja Monta?u. Instytut Mechanizacji Budownictwa i Gornictwa Skalnego. Warszawa, pp. 41–47.

Dominczuk, J. (2011). Wlasciwosci adhezyjne warstwy wierzchniej materialow konstrukcyjnych. Postepy nauki i techniki, pp. 28–37.

Dominczuk, J. (2012). Wplyw stanu energetycznego warstwy wierzchniej na wytrzymalosc polaczenia adhezyjnego. Postepy nauki i techniki, pp. 30–36.

Godzimirski, J., Roskowicz, M. (2002). Wytrzymalosc dorazna i dlugotrwala oraz pelzanie kleju "Epidian 57". Polimery, pp. 721–726.

Godzimirski, J. (2002). Wytrzymalosc dorazna konstrukcyjnych polaczen klejowych. WNT, Warszawa.

Kuczmaszewski, J., Dominczuk, J., Rudawska, A. (2001). Ocena wlasciwosci adhezyjnych warstwy wierzchniej stopow aluminium. Eksploatacja i Niezawodnosc – Maintenance and Reliability, pp. 9–17.

Kuczmaszewski, J. (2006). Fundamentals of metal-metal adhesive joint design. Lublin University of Technology: Polish Academy of Sciences. Lublin Branch.

Kuczmaszewski, J. (1995). Podstawy konstrukcyjne i technologiczne oceny wytrzymalosci adhezyjnych polaczen metali. WU Politechnika Lubelska.

Osnes, H., Andersen, A. (2003). Computational analysis of geometric nonlinear effects in adhesively bonded single lap composite joints. Composites, pp.417—427.

Polish Standards: PN-EN 1465:2003. Kleje. Oznaczanie wytrzymalosci na scinanie przy rozciaganiu polaczen na zakladke materialu sztywnego ze sztywnym.

Porebska, M., Skorupa, A. (1993). Polaczenia spojnosciowe. PWN. Warszawa.

Rudawska, A., Debski, H. (2011). Ocena wytrzymalosci polaczen klejowych blach ze stopu aluminium z wykorzystaniem analizy numerycznej MES. Eksploatacja i Niezawodnosc — Maintenance and Reliability, pp. 4—10.

Sadowski, T., Knec, M., Golewski, P. (2010). Experimental investigations and numerical modelling of steel adhesive joints reinforced by rivets. International Journal of Adhesion & Adhesives, pp. 338—346.

Snedon, I. N. (1961). The distribution of stress in adhesive joints. Oxford University Press. Oxford, pp. 207—253.

Xiaocong, He. (2011). A review of finite element analysis of adhesively bonded joints. International Journal of Adhesion & Adhesives, pp. 248—264.

Chen, Z, Adams, R. D., Lucas, da Silva, F. M. (2011). Prediction of crack initiation and propagation of adhesive lap joints using an energy failure criterion. Engineering Fracture Mechanics, pp. 990—1007.

Zenkiewicz, M., Golebiewski, J., Lutomirski, S. (1999). Doswiadczalna weryfikacja niektorych elementow metody van Ossa-Gooda, Polimery, pp. 212—217.

Gola, A., Swic, A. (2011). Computer-Aided Machine Tool Selection for Focused Flexibility Manufacturing Systems Using Economical Criteria. Actual Problems of Economics, 10(124): 383—389.

Стаття надійшла до редакції 17.07.2013.