UDK 519.61/.64:669.018.95
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 47(4)417(2013)

DETERMINATION OF THE MECHANICAL PARAMETERS OF A BONDED JOINT BETWEEN A METAL AND A COMPOSITE BY COMPARING EXPERIMENTS WITH A FINITE-ELEMENT MODEL

DOLOČANJE MEHANSKIH PARAMETROV SPOJA MED KOVINO IN KOMPOZITOM S PRIMERJAVO PREIZKUSOV IN MODELOM KONČNIH ELEMENTOV

Petr Bernardin[1], Josef Vacík[1], Tomáš Kroupa[2], Radek Kottner[3]
[1]University of West Bohemia in Pilsen, Department of Machine Design, Univerzitní 22, 306 14 Plzeň, Czech Republic
[2]University of West Bohemia in Pilsen, Department of Mechanics, Univerzitní 22, 306 14, Plzeň, Czech Republic
[3]University of West Bohemia in Pilsen, European Centre of Excellence, NTIS – New Technologies for Information Society, Faculty of Applied Sciences, Univerzitní 22, 306 14, Plzeň, Czech Republic
berny@kks.zcu.cz

Prejem rokopisa – received: 2012-09-01; sprejem za objavo – accepted for publication: 2012-11-16

The main goal of this work was to evaluate the application of a cohesive surface-based contact for bonded joints between rotational parts. The numerical simulations were realized using the commercial finite-element software Abaqus. The mechanical properties of the joint were identified using the gradient-optimization method implemented in the OptiSLang software. The identification was performed by minimizing the difference between the force-displacement diagram obtained from the numerical analyses and from the experiments. The shapes of the specimen and the bonded joint were designed in accordance with joints commonly used in the machine industry.

Keywords: joint, bond, composite, metal, finite element, optimization, damage modelling, identification

Glavni cilj tega dela je oceniti uporabo spoja na osnovi kohezivnega stika površin med rotacijskimi deli. Numerične simulacije so bile izvršene z uporabo komercialne programske opreme končnih elementov Abaqus. Mehanske lastnosti spoja pa so bile ugotovljene z uporabo gradientne optimizacijske metode, uporabljene s programsko opremo OptiSLang. Ugotavljanje je bilo izvršeno z zmanjšanjem razlike med vrednostmi na diagramu sila-raztezek, dobljenem z numerično analizo, in preizkusi. Oblike vzorcev in spojev so bile izvedene skladno s spoji, ki se pogosto uporabljajo v strojništvu.

Ključne besede: stik, vez, kompozit, kovina, končni element, optimizacija, modeliranje poškodb, identifikacija

1 INTRODUCTION

Composite materials are being used in different industrial fields. The number of applications in the machinery industry is also increasing very quickly. Most constructions usually consist of more than one material, which places severe demands on the inter-part connections, for example, a metal-to-composite joint. Adhesive bonding is a suitable option for such joints. For the purpose of numerical simulations, the proper finite-element model should be selected. There are many possibilities for bonded joint modelling. The components of the joint can be represented by 3D elements, whereas the adhesive layer substitutes the system of spring elements with a specific stiffness for each direction.[1] The most innovative and recently the most used approach utilizes cohesive elements, i.e., the damage and cohesive surface behaviour[2] (stiffness and maximum nominal stress), to define the material properties.[3] These parameters are not usually provided by the manufacturers of adhesives, since the parameters strongly depend on the type of the bonded joint. The main goal of this work is the determination of the specific values of these parameters on the basis of tensile tests. A special optimization cycle compares the results of the experiments and the FE analyses and minimizes the difference.[4]

2 EXPERIMENT

The experiments were performed on specimens consisting of two parts made of steel (**Figure 1** – part #1 and #3) and composite material (**Figure 1** – part #2). The shape of the specimens and the bonded joint was designed by respecting the normal joints used in the machinery industry. The outer diameter of the composite

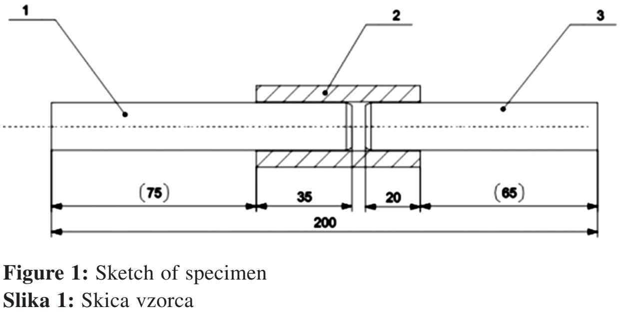

Figure 1: Sketch of specimen
Slika 1: Skica vzorca

Table 1: Material properties of the composite pipe
Tabela 1: Lastnosti materiala kompozitne cevi

Matrix		V_m
Epoxy resin		0.29
Fibre		V_f
T700		0.71
E_1/MPa	E_2/MPa	E_3/MPa
167662	6627	6627
ν_{12}	ν_{23}	ν_{31}
0.329	0.326	0.013
G_{12}/MPa	G_{23}/MPa	G_{31}/MPa
5116	2498	5116

pipe was D = 30.32 mm and the thickness was t = 6.328 mm. The properties of the composite pipe are shown in **Table 1**.

The assembly arrangement is shown in **Figure 1**.

The description of the layers, the fibre orientation and the thickness of particular layers in the composite pipe are shown in **Table 2**.

Table 2: Description of layers
Tabela 2: Opis plasti

Layer number	Thickness (mm)	Fibre Orientation (°)
1	0.677	18.79
2	0.638	–20.09
3	1.320	0.00
4	1.320	0.00
5	0.577	0.00
6	0.228	87.17
7	0.228	87.22
8	0.453	87.26
9	0.453	87.35
10	0.454	87.43

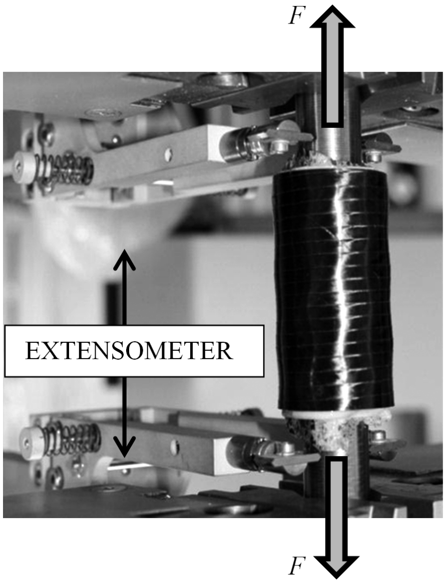

Figure 2: Specimen testing using the Zwick Roell Z050 (Load in F direction)
Slika 2: Preizkus vzorca z Zwick Roell Z050 (obremenitev v smeri F)

Four specimens were analyzed during the determination of the cohesive parameters. An epoxy adhesive Spabond 345 LV[5] was used to join the two cylindrical surfaces of the specimens. The specimens were then tensile loaded until failure using a Zwick Roell Z050 universal testing machine. The method of loading and the location of the extensometer are shown in **Figure 2**.

2.1 Finite-element analysis

The finite-element models were created in the commercial software Abaqus/CAE 6.11-1. All the parts were modelled in accordance with the sketch in **Figure 1**. They were uniformly meshed except for the contact surfaces. These surfaces were covered with a finer mesh. Parts #1 and #3 were made of steel. Part #2 was made of composite material. The idealization of the adhesive layer was realized using surface-to-surface contact with defined cohesive and damage behaviour. To simulate the loading, the coupling function on both frontal surfaces and the reference points was applied. The boundary conditions were set on the reference points. The loading was defined by the velocity v_y = 0.033 mm/s. The 3-D finite-element model is shown in **Figure 3**. Four particular specimens were modelled because of the different size of the active surface of the bonded joint.

The surface-to-surface-contact with the defined cohesive and damage properties was used for the modelling. The cohesive properties of the bonded joint are characterized by the cohesive stiffness in three directions (k_{nn}, k_{ss}, k_{tt}). A damage-modelling option was used for the simulation of the degradation and the eventual failure of the joint. The mechanism of failure consists of a damage-initiation criterion and the damage-evolution law.

The damage initiation refers to the beginning of the degradation when the maximum contact stress defined by user (t_n, t_s, t_t) and the nominal traction stress are equal, and the maximum contact stress ratio reaches the value of one. This state describes the equation:[2]

$$\max\left\{\frac{\langle t_n \rangle}{t_n^0} \quad \frac{t_s}{t_s^0} \quad \frac{t_t}{t_t^0}\right\}=1 \qquad (1)$$

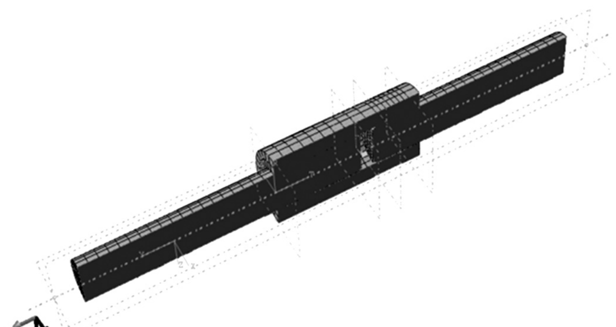

Figure 3: 3-D meshed model
Slika 3: 3-D model mreže

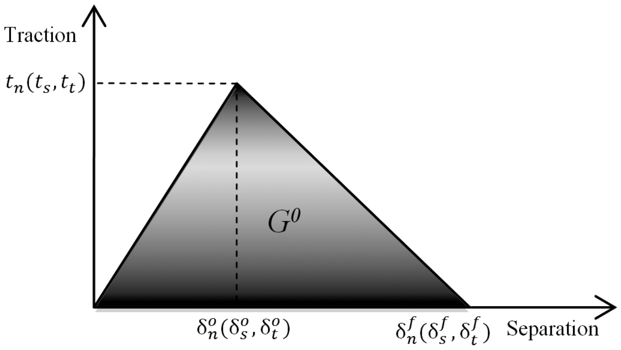

Figure 4: Linear damage parameters
Slika 4: Linearni parametri poškodbe

The damage evolution can be defined either by an effective separation during complete failure or by the energy that dissipates during the failure. The separation (δ) is described in **Figure 4**, while the energy (G^0) is represented by the area under the curve in **Figure 4**.

The relationship between the above-mentioned parameters is described by equation:[3]

$$t=\begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix}=\begin{bmatrix} K_{nn} & K_{ns} & K_{nt} \\ K_{ns} & K_{ss} & K_{st} \\ K_{nt} & K_{st} & K_{tt} \end{bmatrix}\begin{Bmatrix} \delta_n \\ \delta_s \\ \delta_t \end{Bmatrix}=K\delta \qquad (2)$$

2.2 Identification

The cohesive and damage properties of the bonded joint were identified using the optimization method implemented in OptiSLang software. The cohesive and damage parameters (δ, k_{nn}, k_{ss}, k_{tt}, t_n, t_s, t_t) were set as the input parameters. The identification was performed by minimizing the difference between the force-displacement diagram obtained from the numerical analysis and the experiment:

$$r_g=\sum_{i=0}^{n}\frac{(F_{FEA}^i-F_{\exp}^i)^2}{\max\limits_i(F_{\exp}^i)} \qquad (3)$$

where F_{FEA}^i is the force obtained by the experiment and $F_{\exp}^i$ is the force obtained by the analysis. The difference marked as r_g is the objective function and was tracked at particular points of two curves. This is the model parameter to be minimalized.

3 DISCUSSION

The curves shown in **Figure 5** describe the relationship between the force and the displacement of all four specimens. These values were obtained during the testing. The reason for the disagreement between the curves was the different area of the active bonding surface. The real bonding surface area was influenced by the shrinkage of the adhesive, which occurs within the curing process. Another reason could be the errors caused by the imperfect manual preparation of the test specimens. Thanks to the particular ruptured specimens it was possible to find the different widths of the bonded joint surface, which was implemented in the 3D-model.

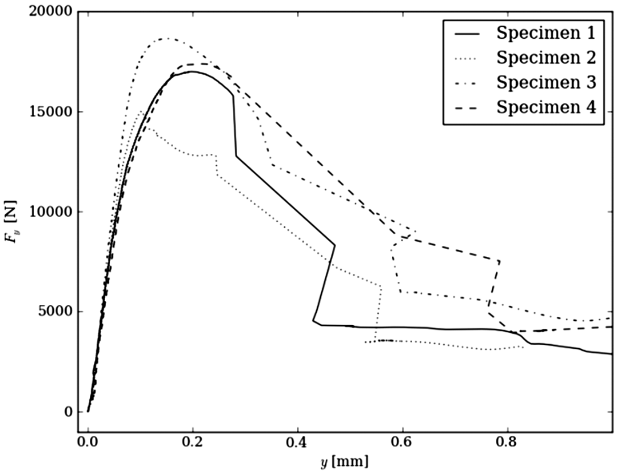

Figure 5: Comparison between four tested specimens
Slika 5: Primerjava med štirimi preizkušenimi vzorci

Using the optimization process, the necessary parameters for all the bonded joints were found for the tested specimens (**Table 3**).

Table 3: Cohesive and damage parameters
Tabela 3: Parametri kohezije in poškodb

Parameters	1	**2**	**3**	4
δ/mm	0.75	**0.89**	**0.95**	0.97
K_{nn}/N/mm	1254.0	**1158.0**	**1193.0**	1194.0
K_{ss} /N/mm	1212.0	**1179.0**	**1112.0**	1112.6
K_{tt} /N/mm	1000.0	**6648.0**	**6007.0**	850.9
t_n /MPa	30.0	**30.0**	**30.0**	30.0
t_s /MPa	30.0	**30.0**	**30.0**	30.0
t_t /MPa	30.1	**27.8**	**30.6**	31.2
r_g	41.19	**11.7**	**4.1**	16.8

Table 3 describes the cohesive and damage parameters obtained during the optimization process for four specimens. In the ideal state, the found parameters had to be the same, but some differences emerged, especially in the value of K_{tt}. The specimens #1 and #4 show similar values, as well as #2 and #3. This might be caused by a different mechanism of failure during the test. With the 1st and 4th specimens, the pull-up of the fibre, not the

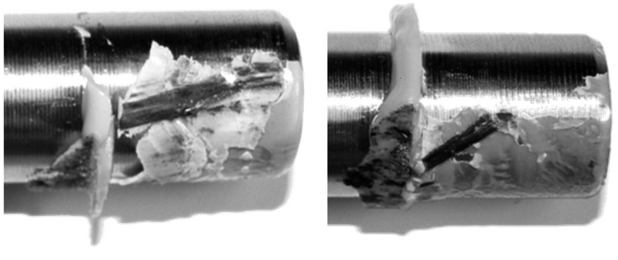

Figure 6: Specimens 1 and 4
Slika 6: Vzorca 1 in 4

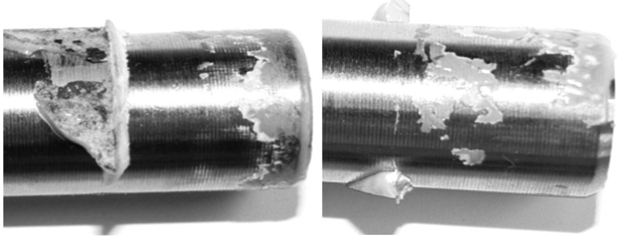

Figure 7: Specimens 2 and 3
Slika 7: Vzorca 2 in 3

adhesive failure, occurred. The failures of the specimens #2 and #3 were located in the layer of the adhesive. The properties gained from these specimens (bold text in **Table 3**) are really describing the cohesive and damage behaviour of the adhesive. These parameters do not differ by more than 10 % and the r_g ratio is also low. The mechanism of the failure is shown in **Figures 6** and **7**.

The fitting of the interpolation curves of the experiment and the FE analyses are shown from **Figures 8** to **11**.

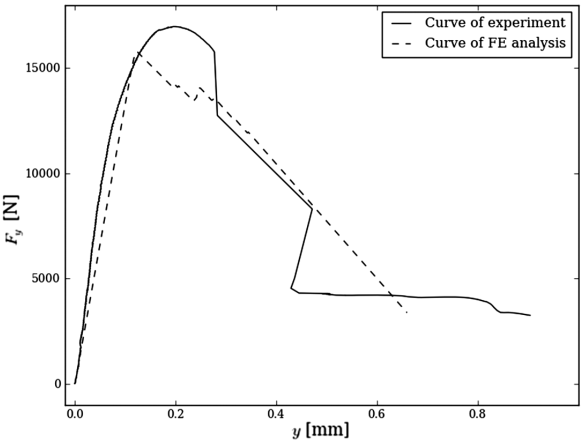

Figure 8: Specimen 1
Slika 8: Vzorec 1

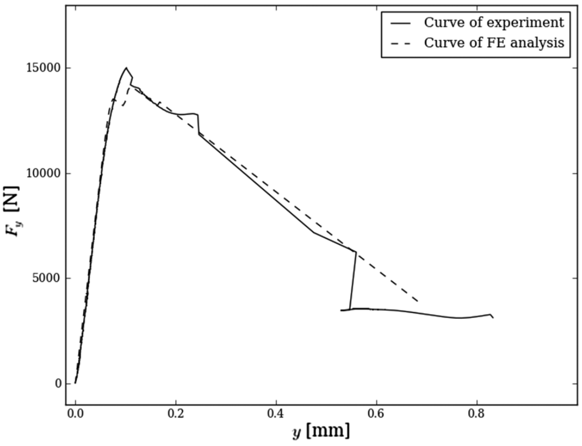

Figure 9: Specimen 2
Slika 9: Vzorec 2

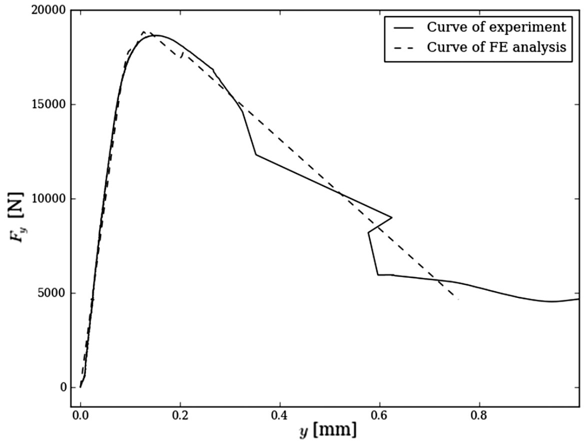

Figure 10: Specimen 3
Slika 10: Vzorec 3

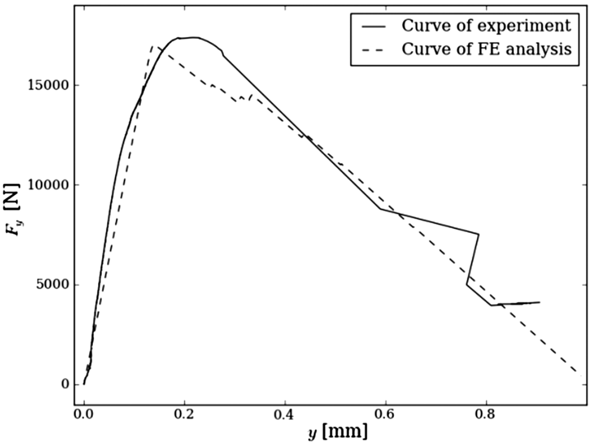

Figure 11: Specimen 4
Slika 11: Vzorec 4

The behaviour of the curves of the experiment and the FE analyses differs after the 0.8 mm value of the displacement and the curves were fitted up to this value. After this value, the force obtained by the experiment had a constant value, which was caused by the friction, although the adhesive was already ruptured. The friction was not taken into account in the FE models; therefore, the force decreased to zero in the numerical simulations. As is implied by the optimization process, the parameters of δ, k_{tt}, t_t have the largest influence on the shape of the curve, while the other parameters have smaller influences (k_{nn}, k_{ss}, t_n, t_s). The datasheet shear stress value of the Spabond 345 LV[5] is in the range between 29 MPa and 37 MPa, which corresponds well with the observed values.

4 CONCLUSION

A series of tensile tests was performed on specimens consisting of steel and composite material. Particular parts of the specimens were joined by the Spabond 345 LV[5] adhesive and loaded using the Zwick Roell Z050 universal testing machine. The objective function was minimized with the help of the OptiSLang software. The damage and cohesive parameters of the cohesive surface-based contact were determined. The analyses successfully confirmed the suitability of the experimental data fitting for the identification of the cohesive parameters. Nevertheless, further investigations should follow in order to optimise the parameters, e.g., testing according to ASTM standards.

Acknowledgement

The work has been supported by projects ME 10074 and GA P101/11/0288.

5 REFERENCES

[1] F. P. Tahmasebi, Finite Element Modeling of an Adhesive in a Bonded Joint, NASA Goggard Space Flight Center, 1999

[2] M. L. Benzeggagh, M. Kenane, Measurement of Mixed-Mode Delamination Fracture Toughness of Unidirectional Glass/Epoxy Composites with Mixed-Mode Bending Apparatus, Composites Science and Technology, 56 (**1996**) 4, 439–449

[3] P. P. Camanho, C. G. Davila, Mixed-Mode Decohesion Finite Elements for the Simulation of Delamination in Composite Materials, NASA/TM-2002-211737, 2002

[4] P. Janda, M. Kosnar, T. Kroupa, V. Lašová, J. Vacík, Využití programů ANSYS a OPTISLANG v konstrukci výrobních strojů, Frymburk: ANSYS konference, 2010

[5] Spabond, Epoxy Adhesive System, Newport Isle of Weight, 2004, Available: http://www.gurit.com/files/documents/Spabond_345_v7.pdf. [cited 12 June 2012]