3D NUMERICAL INVESTIGATION OF TENSILE LOADED LAP BONDED JOINT OF AIRCRAFT STRUCTURE

Agnieszka Derewońko, Tadeusz Niezgoda

Military University of Technology
Faculty of Mechanical Engineering
Department of General Mechanics
2 Kaliskiego Street, 00-908 Warsaw, Poland
tel.: +48 022 683 90 39, fax: +48 022 683 94 61
e-mail: a.derewonko@wme.wat.edu.pl, t.niezgoda@wme.wat.edu.pl

Jan Godzimirski

Military University of Technology
Faculty of Mechatronics
2 Kaliskiego Street, 00-908 Warsaw, Poland
tel.: +48 022 683 95 75, fax: +48 022 683 75 81
e-mail: Jan.Godzimirski@wat.edu.pl

Abstract

Adhesive bonding is becoming one of the most popular joining techniques in automotive and aircraft industry. The adhesively bonded joints need to be designed to minimize tensile stress. The most widely used method of an adhesive joint strength test is the lap-shear test. Single lap joints create bending loads in the adherends and tensile stress in the adhesive. The mechanism of shear deformation of the adhesive and adherend layers and separation occurring at the adherend/adhesive interface are discussed in this paper.

Uniaxial tensile test of a lap bonded joint and numerical simulations were carried out. 3D numerical model of single lap bonded joint consists of three components described as separate solids. Glue contact is defined between the joined layers. This approach allows to determine and compare stress distribution along the adhesive and the adherend bondline.

Experimental data are used to establish the engineering stress-strain curves for the aluminium adherends and the epoxy adhesive. Two step loadings are applied.

The results of laboratory tests compare favourably with VG and Reissner closed-form solutions and numerical simulations.

Non-linear analyses of a 0,03 mm thick adhesive layer show that the shear stresses along the adhesive bondline exceed stresses along the adherend line by 1% to 50%.

Keywords: adhesive bonded joint, FEM, non-linear

1. Introduction

Adhesive-bonding is a joining process similar to welding as far as the function it performs is concerned. This process allows to hold together metals to themselves and to ceramics or composite materials by the surface attachment of adhesives. Bonding has increasing importance in the sheet metal or aircraft industry due to cost and mass reduction. The advantage of an adhesive joint is that the stresses are distributed throughout the joint in a way relatively more uniform than with other localized methods (spot welding, riveting, bolting etc.), although existing stresses concentrate at the borders of the joint. The design of safe and cost effective joints is a major challenge. It

demands on the engineer to have a good understanding of the influence of material and geometric parameters on the joint strength.

Numerical analyses of adhesively bonded joints usually are performed for 2D models due to the computer processing time. Major differences between the adhesive's and the adherend's thickness impose mesh dimension and consequently the model size. In this study, analyses of three-dimensional models are considered. This kind of model is processor time consuming but allows to check the strain and stress distribution across the overlap. Uniaxial tensile test of the lap bonded joint and numerical simulations were carried out. Finite element analysis allowed to predict the failure behaviour in bonded structures. The predicted performance was compared with the experimental data.

2. Lap Shear Test

The most widely used method of an adhesive joint strength test is a lap-shear test. The figure below shows a single-lap joint in which the eccentric forces acting on the joint induce a bending moment. The bending moment causes additional tensile (peel) stresses to be induced in the adhesive layer, concentrated at the ends of the joint.

The shear test was performed for a single lap specimen consisting of two aluminium adherends bonded by an epoxy adhesive. The adherends had the same dimension shown in Fig. 1. The length of the clamped region was 28.75 mm, and the length of the overlap was 12.5 mm. Two thickness of the adhesive layer (δ_k) were considered: 0.2 mm and 0.03 mm. The total length of the joint was 127.5 mm.
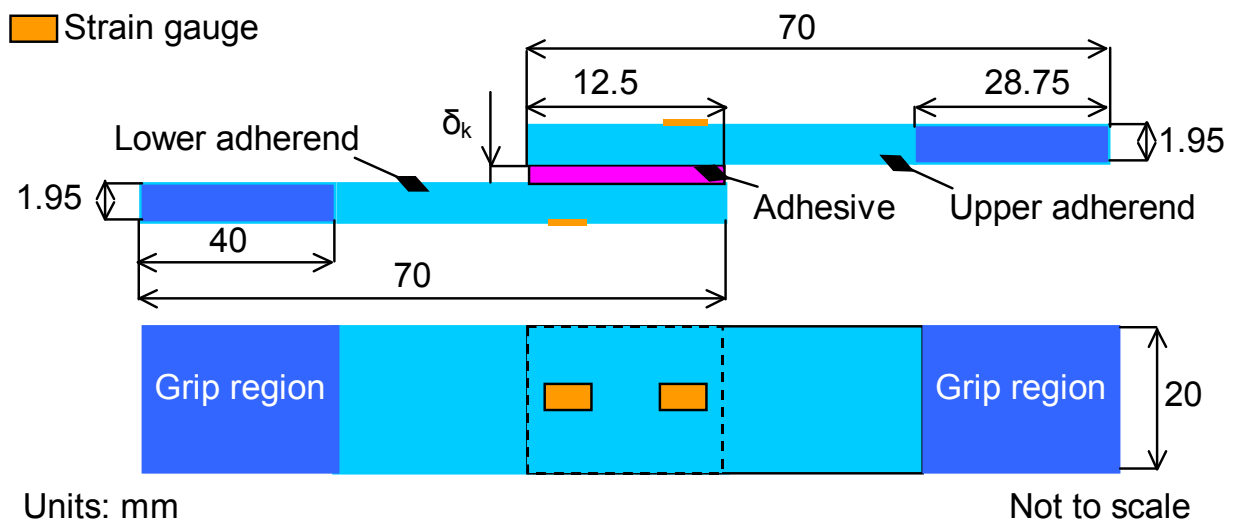

Fig. 1. Specimen dimensions

The adhesive and adherends were modelled with an elastic-plastic material models with stress-strain curves as shown in Fig. 2. The material for adherend was aluminium with Young's modulus E = 72 052 MPa and Poisson's ratio ν = 0.3. The material properties of the adhesive were E = 2083 MPa and ν = 0.35.

The main goal of the shear test was to obtain the value of the failure force for each adhesive thickness which caused plastic strain. Therefore, the material test were performed for the whole strain range [1].

The epoxy properties were determined from a compression test. This test was a more useful procedure than tension test for the adhesive [2]. A compression test was performed for the cured adhesive. The cured state of the adhesive layer in the adhesive joint was similar to that of the bulk adhesive specimen.
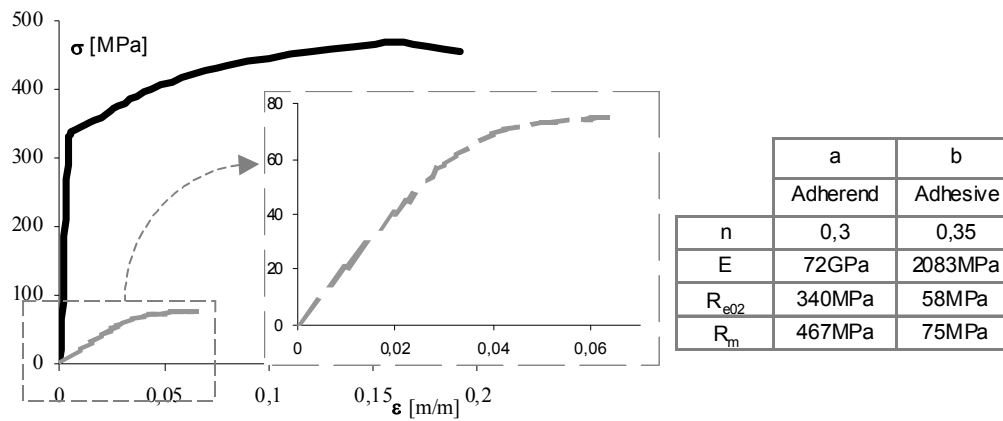
		a	b
		Adherend	Adhesive
n		0,3	0,35
E		72GPa	2083MPa
R_{e02}		340MPa	58MPa
R_m		467MPa	75MPa

Fig. 2. Strain-Stress Curves: a) adherend; b) adhesive

Two strain gauges were mounted to the centre of the adherends' surfaces in the overlap regions (Fig 1 and 3a). The effective strain length of gauges was 3 mm. The gauges were placed parallel to the applied loading.
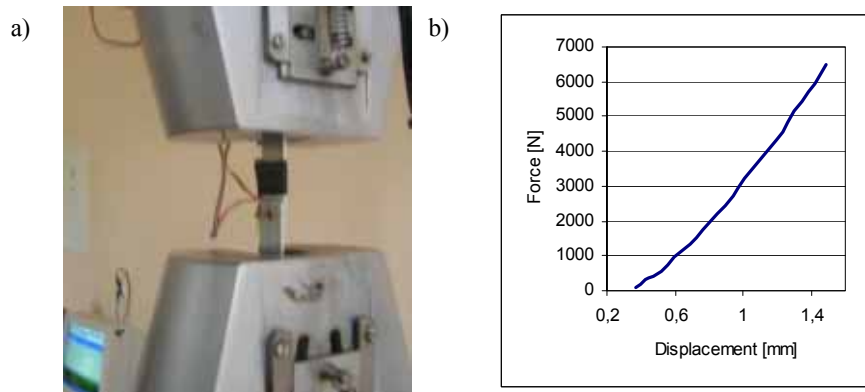

Fig. 3. Lap Shear Test

The force versus the upper adherend displacement for a 0,2 mm adhesive thickness is shown in Fig. 3b.

3. Numerical Model

The MSC.Marc code was used to perform the non-linear stress analysis. The implementation of equations governing mechanics allowed to solve non-linear problems due to material behaviour, large deformation and boundary conditions. To perform the contact analyses presented below the penalty method was used [3].

The discrete model of the investigated single lap bonded joint consisted of three solids. Three-dimensional, eight-node elements (HEX8) were used to discretize the whole joint. Authors aimed to create cubical elements near the ends of the adhesive. Therefore, the mesh density depended on the number of elements throughout the thickness of the adhesive.

All nodes on the adhesive and adherends contacting surfaces in the overlap regions were coupled. A multipoint constraint (called tying) was automatically imposed and such constraint expression was formed, that no relative motion occurred. This type of contact is called a "glue" in MSC.Marc. Such an approach allowed to determine and compare the stress distribution along and across the adhesive and adherend bond lines.

Two uniform thickness of the adhesive δ_k were modelled: 0.2 mm and 0.03 mm and two different loading schemes were applied. The grip region of lower adherend was fully supported. The effect of the adherend bending did not reflect in the first scheme of analysis. Therefore the uniform tensile loading was applied to the grip region of upper adherend in the FEA analysis. Two-step loading was performed in the second scheme. Uniform displacement V along the transverse direction in the grip region of the upper adherend was applied as the first step loading. V was equal 1.953 mm for the adhesive thickness $\delta_k = 0.03$ mm, and 2.15 mm - for $\delta_k = 0.2$ mm. This step was called an alignment. The uniform pressure was applied to the upper adherend (Fig. 4) in the second step. Pressure value gradually increased until the joint failed due to large plastic deformation.
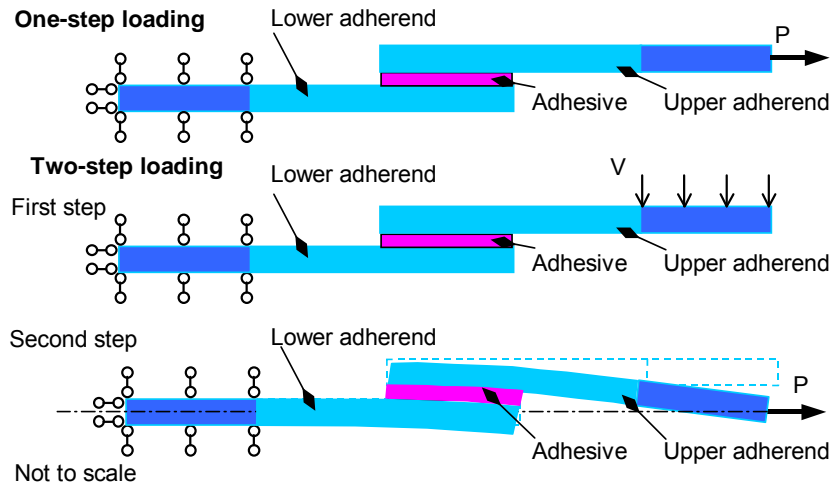

Fig. 4. Loading scheme

4. Results

Four lines and four surfaces were considered as shown in Fig. 5. Lines A-D and A-B were along and across the interfaces between the lower and the upper adherend and the adhesive, respectively. Four surfaces shown in Fig. 5. belong to the lower adherend (index 1), the adhesive (lower – index 2, upper – index 3) and the upper adherend (index 4).
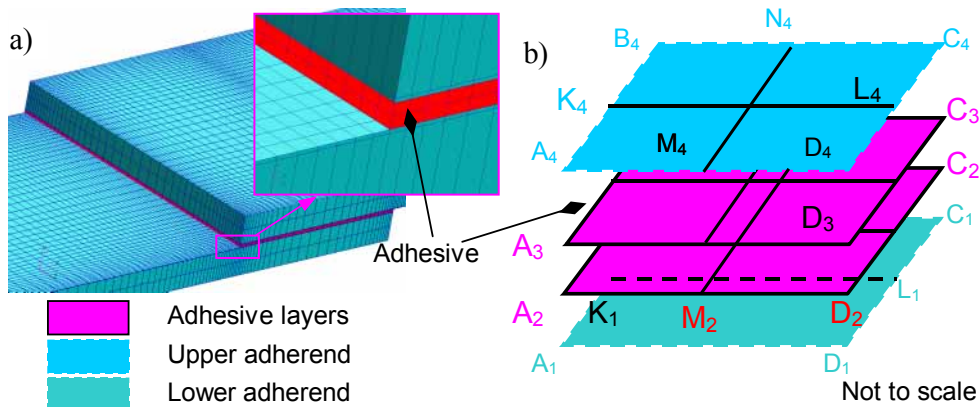

Fig. 5. Labelling of lines and surfaces

Finite element models were validated with a lap shear test. Comparison of FEA and experimental results for the 0.2 mm thickness was performed. Force versus longitudinal strain curves for gauge on the upper and lower adherend (Fig. 1) are shown in Fig. 6, respectively.
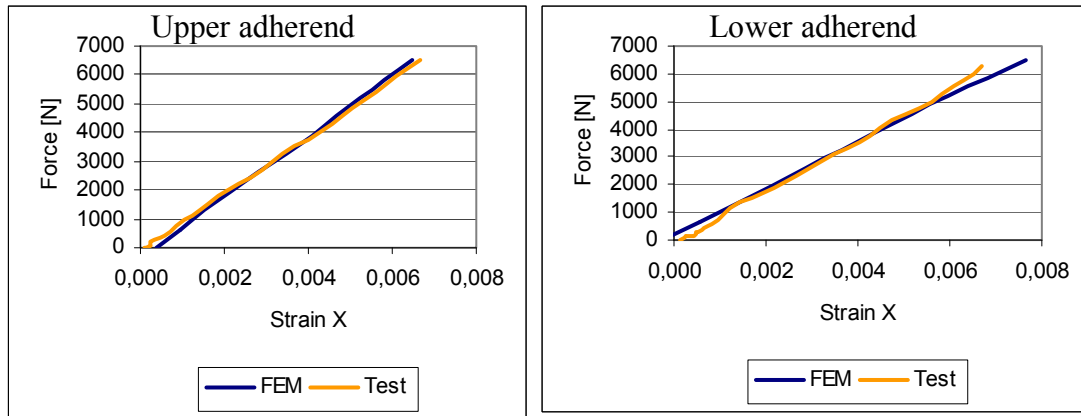
Fig. 6. Force versus longitudinal strain curve for the gauge on the upper adherend

Results of numerical analyses for the adhesive thickness of 0.2 mm and 0.03 mm yielded maximum failure loads of 6500 N and 4800 N, respectively. The first one was equal to the test failure load of an aluminium single lap joint. The second one was lower than the test value, which was 6860 N. In this case, the analysis failed to converge before the critical value was reached due to improper number and dimension of finite elements. Further analyses will be carried out.
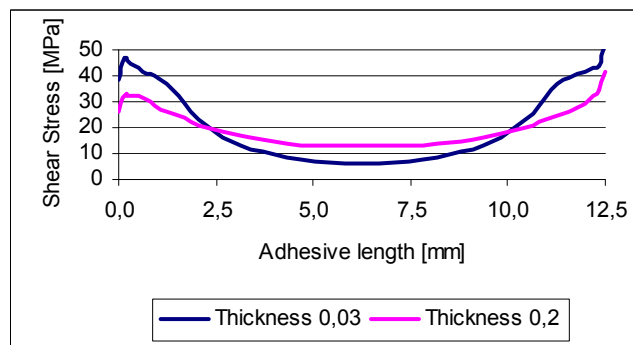

Fig. 7. Distributions of shear stress along the adhesive for the thickness of 0.03 mm and 0.2 mm
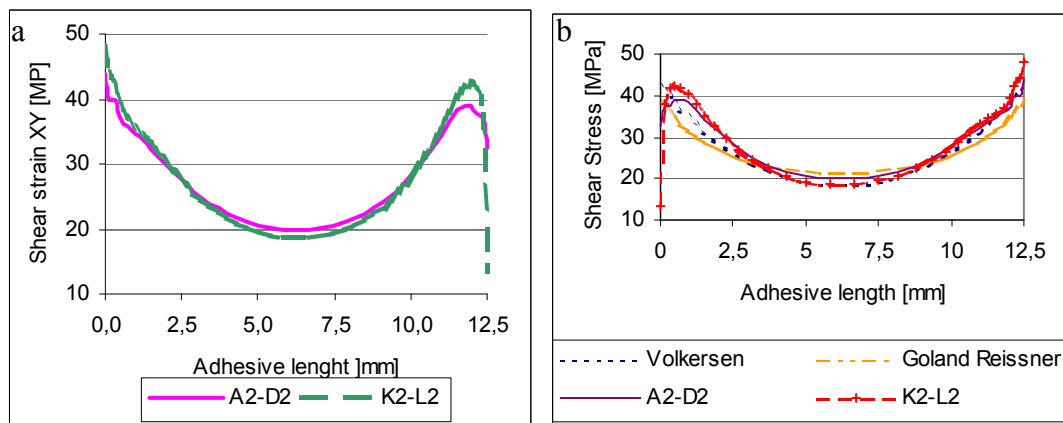

Fig. 8. a) Shear stress along the adhesive bondline
b) Comparison of numerical results and closed-form solutions

65

Shear stress for two adhesive thickness for the load of 4500 N were compared (Fig. 7). The difference between the highest and the lowest value of the shear stress for the thickness of 0.03 mm was equal 46 MPa and for the thickness of 0.2 mm was 29 MPa. This indicated that failure could appear for joint with adhesive thickness 0.03 although strength of this joint was higher then for the adhesive thickness of 0.2 mm.

Shear stress distribution along the edge A_2-D_2 in Fig. 5a of the adhesive lower bonding surface A_2-B_2-C_2-D_2 shown in Fig. 8a, agreed with the results from literature [4]. The closed-form expressions, e.g. Volkersen and Goland – Reissner [5], were used to obtain stress distributions in the adhesive bondlines of a conventional single lap (Fig. 8b). Noted that there was no symmetry in the shear stress distribution along the adhesive bondlines (Fig. 8a). The peak shear stress at the adhesive edge bondline (A_2-D_2, Fig. 5b) occurred at the left end and was equal 44,2 MPa. It was lower than at the overlap centre (K_2-L_2, Fig. 5b), which was equal 48 MPa.
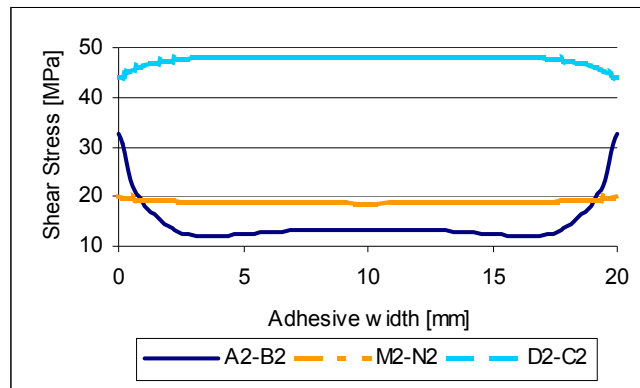

Fig. 9. Shear stress across the adhesive bondline

The shear stress distribution was symmetric across the overlap. Fig. 9 shows that the shear stress in the middle of the width (10 mm) of the left edge of the overlap A_2-B_2 is equal 13.4 MPa and is lower than the corresponding one on the right boundary edge D_2-C_2 (52,5 MPa).
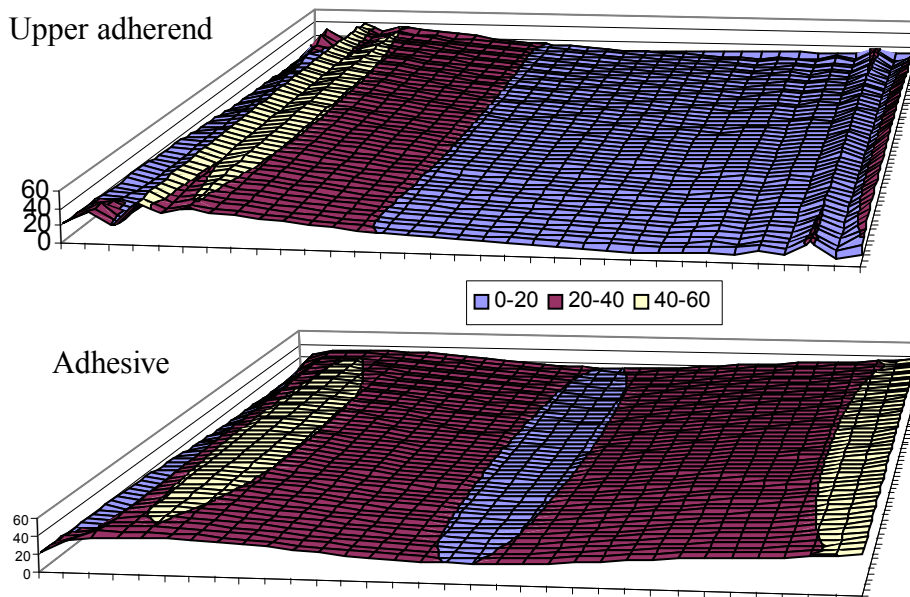

Fig. 10. Shear stress distribution on the upper adherend surface A_4-B_4-C_4-D_4 and adhesive surface A_3-B_3-C_3-D_3

Shear stress distribution at the upper adherend overlap surface A_4-B_4-C_4-D_4 and adhesive surface A_3-B_3-C_3-D_3 shown in Fig. 10 indicate large shear stress difference, especially at the free edges across the overlap.

Application of two surfaces of nodes as the bonding surface allowed the shear stress comparison in the adhesive and adherend. The shear stress along the adhesive and lower adherend bondlines are shown in Fig. 11a. It enabled to compare the strain energy density in pure shear for each of the bondlines. Strain adhesive density for the adhesive at the left free end of the overlap was 80 times higher than the strain energy density for the lower adherend (Fig. 11b).
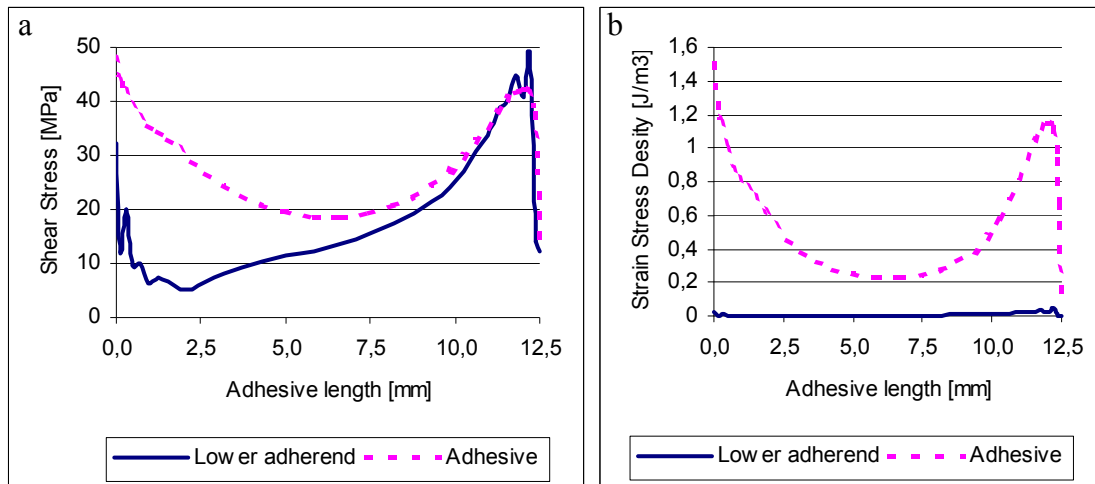

Fig. 11. a) Shear stress along the adhesive and the lower adherend
b) Strain energy density for the adhesive and the lower adherend

Shear stress distribution across the overlap for the adhesive and the lower adherend indicated that the highest value occurred in the adhesive (Fig. 12a).

The difference of shear stress for a line across overlap was more regular than along the overlap and was equal to 16 MPa at the centre of this line (Fig. 12a). Maximum values appeared at the boundaries of the overlap and were equal 35 MPa. Strain energy density distributions across the overlap for the adhesive and adherend surfaces are shown in Fig. 12b.
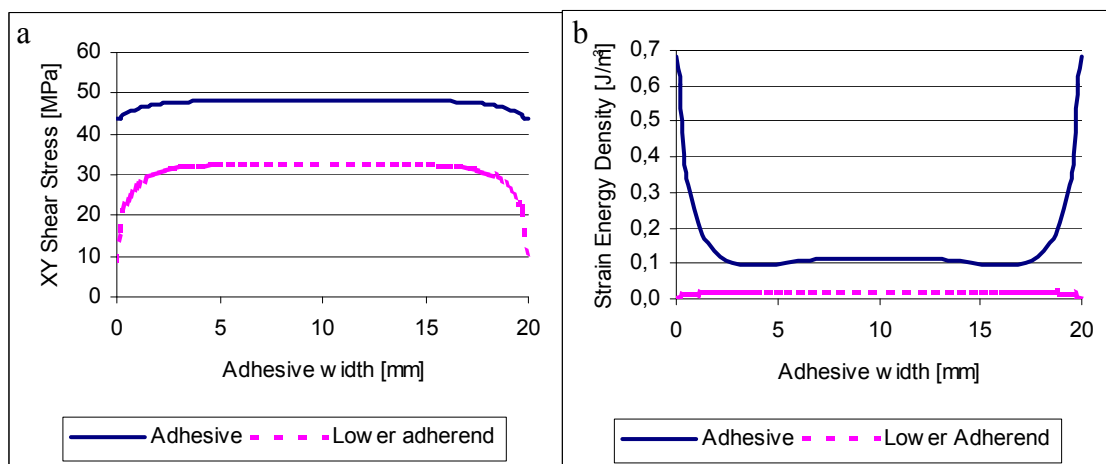

Fig. 12. a) Shear stress across the adhesive and the lower adherend
b) Strain energy density for the adhesive and the lower adherend

5. Conclusions

The following main conclusions may be drawn from the presented analyses:

- Analyses were carried out using a three-dimensional (3D) model which allowed determine the stress distribution across the overlap.
- Closed-form solutions predict symmetry of the shear stress distribution along the adhesive with the maximum value occurring at the overlap ends. Non-linear finite element analyses shown that the maximum shear stress occurred at one of the free edges and increased in the middle of the overlap width.
- Full calculation for the model with the adhesive thickness of 0.2 mm indicated that results of numerical analysis corresponded to the experimental test results. If analysis failed to converge before a critical force was reached, remeshing of model should be made.
- Separated solids, as models of adherends and adhesive, increase the numerical model size but allow to determine the stress and strain at the adhesive and adherend bonding surface.
- Failure of the single lap adhesively bonded joint occurred at the point where the strain energy density between the adhesive and adherends was maximum.
- The maximum strength of the adhesively bonded single lap joint increased with the decreasing adhesive thickness.

References

[1] Godzimirski J., Tkaczuk S., *Numeryczne modelowanie spoin klejowych połączeń obciążonych na ścinanie*, Biuletyn WAT Nr 4, Warszawa 2005.
[2] Godzimirski J., Tkaczuk S., *Określanie właściwości mechanicznych spoin klejowych*, Technologia i Automatyzacja Montażu 3, 4/2004.
[3] *MSC.Marc Volume A: Theory and User Information.*, Version 2005.
[4] *Zhu Y.*, Kedward K., *Methods of analysis and failure predictions for adhesively bonded joints of uniform and variable bondline thickness*, DOT/FAA/AR-05/12, U.S. Department of Transportation, Federal Aviation Administration, 2005.
[5] Godzimirski J., *Wytrzymałość doraźna konstrukcyjnych połączeń klejowych*, WNT, 2002