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Investigation of aluminum single lap adhesively bonded joints

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Methodology of research

ABSTRACT

Purpose: The purpose of research was to find an optimum overlap length ensuring the settled bearing performance of adhesive bonded joint. At the optimum overlap length it is possible to reach a maximum load bearing capacity using a minimum quantity of applied adhesive.
Design/methodology/approach: In accordance with experimental test results, an optimum overlap length was achieved. In numerical analysis, the proposed material model (MISO) fits well in simulations.
Findings: Mechanical properties of adhesive which are often public unknown have very strong influence on reliability of material models used in numerical analysis. Therefore, it was crucial decision of research to made an adhesive specimen for tensile testing.
Research limitations/implications: At the overlap lengths above critical (optimal) ones, the usage of a MISO material model in FEA is not acceptable any more. In further work is of great interest to verify simulation with other materials model approaches.
Practical implications: Maximal strength of joint might be reached if optimal overlap length of joint is applied, nevertheless if less adherend material is consumed.
Originality/value: Originality is in true stress/strain diagram of adhesive which is based on experimental testing of adhesive specimen. Material model in numerical analysis is based on true stress/strain diagram.
Keywords: Adhesive joint analysis; Adhesive modeling; Single lap joint

1. Introduction

The use of adhesive bonded joints in load-bearing structures is of great interest to the aerospace, automotive industry and to machine tools modules development as well [4]. Time and cost savings, high corrosion and fatigue resistance, crack retardance and good damping characteristics are the major advantages of these joints.

Altering the geometry of a bonded joint will invariably cause changes in the stress and strain distribution. These differences can also have a profound effect on the stress concentrations and consequently the load-capacity and long-term performance of the joint. In adhesive bonding, the load is transmitted from one adherend to another adherend smoothly through the adhesive layer in the overlap region, i.e. the adhesive serves as a medium for load transmission [3].

Single lap joints are over the years the most widely used adhesive joints and have been the subject of considerable research. Simplicity and service efficiency of the single lap design is exploited for determining the mechanical properties of adhesive joints and the adhesives as well [3]. Even when relatively low modulus of adhesives are employed, the stress is non-uniformly distributed through the bond-line. The loads in a single lap joint are not co-linear, what produce a bending moment which causes

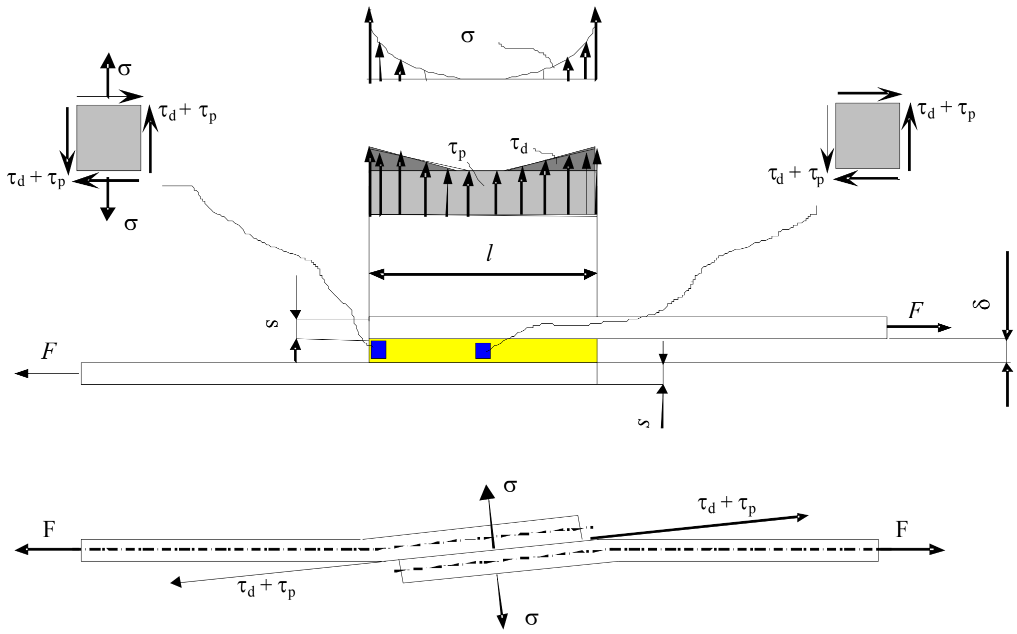

Fig. 1. Stresses in single lap adhesive bonded joint: τ_p – shear stresses which are parallel to bonded area caused by moving parts that are bonded; τ_d – shear stresses which are parallel to bonded area caused by deformation of bonded parts; σ - tensile stresses, perpendicular to bonded area caused by bending momentum [1]

the joint to rotate. This consequently expose the adhesive layer into shear, and peeling stresses. The adherends are similarly at the same time subjected to tension and bending. It is quite possible that deformation of both of adhesive and adherend may become plastic, particularly in the highly stressed regions. The commonly used metallic adherends used in single lap joint tests are often found to have plastic deformation, due to yielding, before failure [1].

Accuracy of the numerical analysis depends strongly on selection of adequate material model (constitutive law) used to predict the strength (e.g. load bearing capacity) of adhesively bonded structures as well as existence of accurate and reliable material properties data, both for adhesives and adherends. Unfortunately, it is mainly not the case in the practice.

Therefore, an extensive research of adherend and adhesive mechanical properties is essential to collect accurate material data, especially in implementation of numerical methods (e.g. finite elements analysis - FEA) in designing of bonded joints.
In the paper, two-component structural epoxy adhesive *Loctite 3421* and aluminum *Al99.5* as adherend material and joints made of them have been tested.

In order to satisfy safety and durability requirements while using properties of adherend close to maximum, stress analyses have to be conducted in joint design.

2. Problem statement

In adhesive bonding joint, the load is transmitted from one adherend to another adherend through the adhesive layer in the overlap region.

When two mating parts assembled through adhesive bonding are loaded in the direction of bonding joint plane or parallel planes, a mixed state of stresses develops, which is combination of shear stresses parallel to bonded surfaces and tensile stresses perpendicular to them (Fig. 1).

This stress combination in the single lap joint arises as a result of non-co-linear tensile forces. During the continuously increasing of stretching force, all stresses superimpose in the overlap boundary region up to the point when a critical stress are reached, which causes adhesive layer failure [1].

It is possible to increase the strength of bonded joint with enlarging overlap length, i.e. providing acceptance of major loads. However, there are bounds which depends on stress concentration at the ends of single lap adhesive bonded joints in increasing of overlap length.

The influence of overlap length on adhesive joint strength could be theoretically described. With exposing of joint to force *F,* plastic deformations of adherends occur if the strength of bonded joints is larger then proportional limit of adherend. Thereby, the stresses occurring in adherend in failure free service can be increased up to the strength of joint.

At small overlapping, bonded area is reduced. Joint is exposed to shear stresses induced with adherend moving and to small values of stresses caused by bending momentum. With increasing of load applied to lap joint, stresses can overcome the elastic limit values in adhesive/adherend interface. Therefore failure initiation and crack propagation starts at overlap region. This is the leakest loading region in joint. Failure of joint occurs even if the stresses of adherend is less than proportional limit of adherend.

By increasing of overlap length stresses through the overlapping region are decreased. Loading stresses in adherend can lead to elastic or elastic/plastic limit and even can match proportional limit of adherend caused by transmitted load through the overlapping region. Values of stresses in adhesive/adherend interface at the ends of overlapping region came up to values characteristic for such elastic deformation associated with already existing normal stress caused by bending.

With additional increasing of overlap length plastic deformation and stretching of adherend occurs mostly initiated at the overlapping ends while adherend in overlapping region is passed over [1]. Stresses in adhesive/adherend interface varied through overlapping region, and are the highest at the overlapping ends (cumulated tension and shearing stresses).

Optimal joint strength value occurs when the balance between load transmitted to the adherend in elastic region and stresses of adhesive/adherend interface in overlapping region is achieved. Experimental research was provided to obtain the optimal value of overlap length by keeping other parameters constant.

The validity of failure criterion has been assessed by comparison of numerical and experimental results.

3. Experimental research

The standard single lap specimens for evaluating the load bearing characteristics i.e. strength of adhesively bonded joint have been prepared according Fig. 2. Dimensions of prepared adherend plates were $a \times b \times s = 30 \times 90 \times 1{,}95$ mm. The adherends were cleaned by an appropriate surface preparation method [8]; degreasing (Loctite 7061) and mechanical grinding.

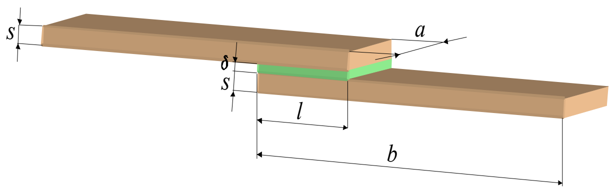

Fig. 2. Single lap joint specimen

The two-component epoxy adhesive *Loctite 3421* [8] was coated over the region to be lapped. The thickness of the adhesive layer is settled to 0,15 mm by using an appropriate fixture device and allowed to cure for 72 hours at room temperature to reach maximum strength. The overlap length has been varied in range from 15 to 60 mm (relative overlap length (l/a) from 1/2 to 2).

All the specimens were tested at average displacement rate of jaws 0,2 mm/min, with an *Carl Schenck AG 1000 kN* tensile testing machine (Fig. 3). To avoid dynamic displacement and jaws tugs during testing and to ensure acceptably reliable quasy-static conditions, initial loading rate was adapted on remainder values. The displacement rate of jaws was continuously increased after described short-term tug to reach up settled value (0,2 mm/min). Tug of jaws is insignificant (comparing with displacement essential for testing) and is consequence of PID (proportional/integral/derivate) device regulation under displacement control. To ensure symmetric loading, inserts with thickness equal to the sum of adhesive thickness and metal plate thickness were inserted into both upper and lower jaws (Fig. 3).

Displacement measuring device (Epsilon extensometer) was used with a gage length of 25 mm to measure joints elongation. Once all the specimens had been tested, the loading data from the data acquisition computer were stored on a diskette for data analysis.

3.1. Investigation of surface roughness influence on load bearing capacity

For each overlap joint length, three specimens where prepared. Procedure of thin surface layer removal with grinding was conduct manually, in accordance with standard specimen procedure preparing [8]. Measuring of surface roughness parameters before bonding procedures was provided by Taylor-Hobson Surtronic 3+ perthometer. Two measurements (for both before and after preparing of plates for bonding, grinding and degreasing) on each aluminium plate are performed (Fig. 4).

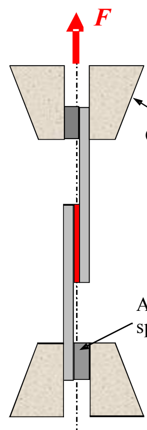

Fig. 3. Specimen in the clamps of testing machine

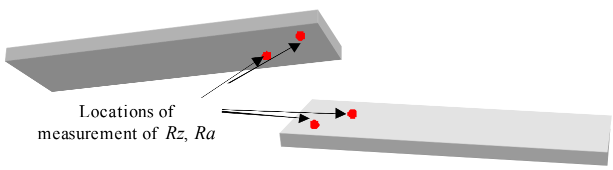

Fig. 4. Locations of measurement of R_z, R_a on specimens

The average surface roughness, R_a value, which was used for comparison purposes, is defined as follows

$$Ra = \frac{1}{L_m} \int_{x=0}^{x=L_m} |y| dx \tag{1}$$

where L_m is the total scanned length in the x (horizontal) direction (Fig. 5).

The Taylor-Hobson perthometer also provides mean roughness depth, *Rz* values. The *Rz* value is the arithmetic mean from the peak-to-valley heights of five successive sampling lengths (Fig. 6).

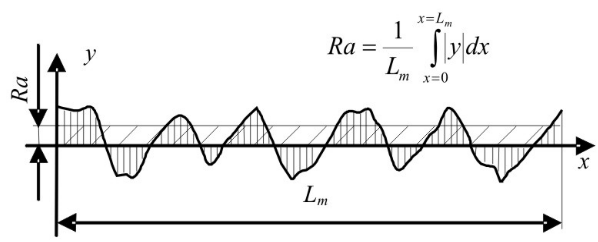

Fig. 5. Calculation of the average surface roughness R_a [2]

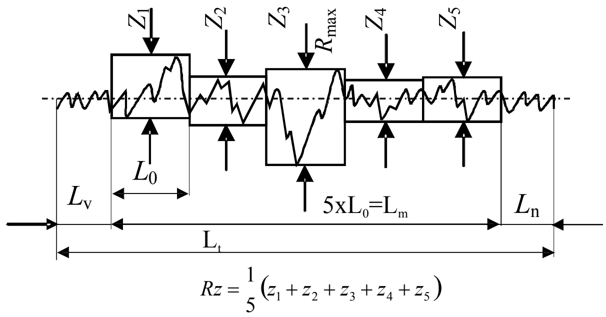

Fig. 6. Calculation of the mean roughness depth R_z [2]

4. Numerical analysis

The commercial FEA code *ANSYS* [6] has been used in numerical analysis. Geometry of single lap bonded lap specimen tested experimentally (Fig. 2) was numerically modeled by using of plane models with two-dimensional 8-node isoparametric finite elements (*PLANE82*) which discretize geometry of models with triangular or/and rectangular elements.

Simulations of axial stretching of the bonded joints have been carried out under the same boundary conditions as in experimental work.

Numerical implementation the experimentally obtained tensile stress-strain curves of adherend [5] and adhesive [9] follows by linear discretization of the curves in several steps as shown in Fig. 7. and Fig. 8. Such multi-linear isotropic (MISO) material model was used in all numerical calculations.

Characteristics of the materials (Table 1) of adherend and adhesive are given in input file.

Plane stress finite element model is composed of 2307 nodes and 708 elements. With intension to collect as possible larger number of data during numerical simulation of joint displacements, more steps are given in solution phase, depending on displacement. First displacement was given as 0,005 mm with displacement control up to 6 mm. This is also important for resumption of better stability of calculation and better control over data.

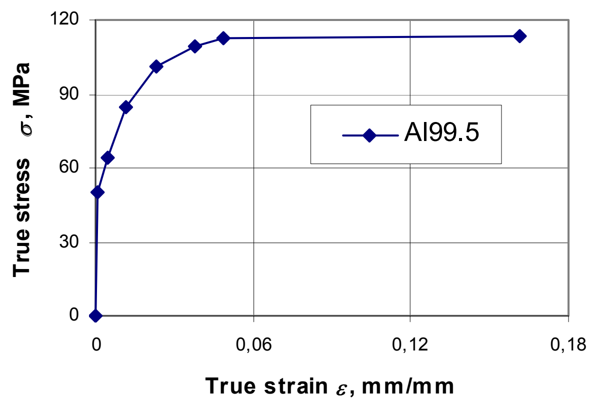

Fig. 7. Discretized adherend (aluminum) stress-strain curve

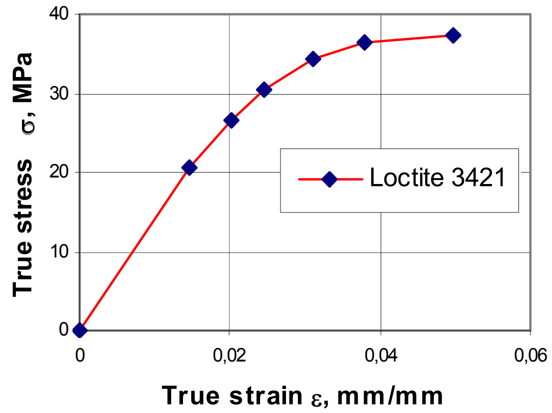

Fig. 8. Discretized adhesive (epoxy) stress-strain curve

Table 1.
Mechanical properties data of the materials used for numerical simulation

Input data	
ADHESIVE	ADHEREND
E_0 = 1400 MPa	E_0 = 70 000 MPa
ν = 0,35	ν = 0,3
$\sigma_m \cong$ 38 MPa	$\sigma_m \cong$ 115 MPa

5. Results and discussion

The adhesive shear strength (τ_a) has been calculated as a maximum shear stress achieved in an adhesive layer, based on recorded maximum tensile forces for each tested joint:

$$\tau_a = \frac{F_{max}}{l \cdot a} \quad (2)$$

and a joint tensile strength (σ_s) as a maximum tensile stress transferred crossover the joint:

$$\sigma_s = \frac{F_{max}}{s \cdot a} \quad (3)$$

The values of joint tensile strengths are calculated by using the equation (3) and they show load-bearing capacity of the bonded joint. It is easy to note from Fig. 9 that the joint strength strongly depend on overlap length. By increasing overlap length, joint strength increases because of increase of the bonding area. However, strength curve has reached its maximum at certain overlap length.

At this optimum overlap length the maximum joint strength is reached (Fig. 9). Increase of the overlap length over this optimum value leads to decrease in load bearing properties of the joint.

Decreasing of adhesive shear strength (fig. 10.) confirms the theoretical consideration of stress distribution through the overlap region (given in fig. 1 and eq. 2), since the ratio of tensile stress and overlap length increase is higher for larger overlap length. An explanation of this effect arises from the theoretical considerations from [1].

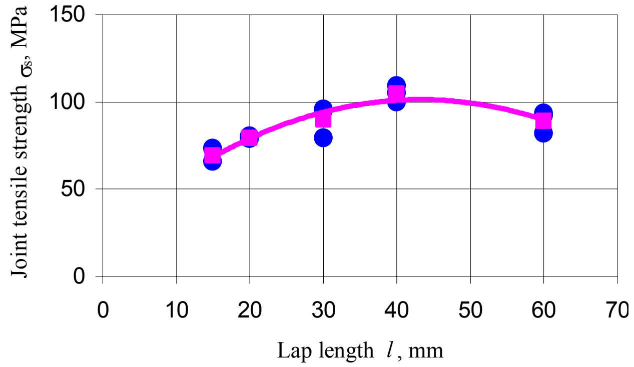

Fig. 9. Joint tensile strength vs. overlap length (experimental results)

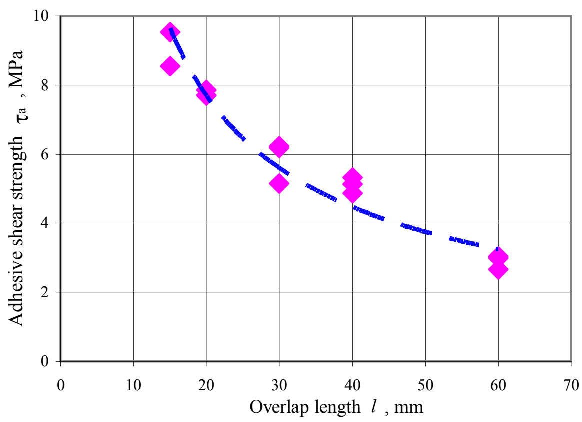

Fig. 10. Adhesive shear strength vs. overlap length (experimental results)

In accordance with equation (2), maximum tensile force (F_{max}) increases by increasing bonding area i.e. overlap length. However, increase of the maximum tensile force is possible only up to the point of reaching yield point of adherend. At this point equilibrium between stress in adherend and strength of the adhesive/adherend interface through the overlapping region is achieved [11]. Beyond this point an excessive deformation of the adherends occurs that cannot be compensated by relatively rigid layer of adhesive. This leads to crack initiation and consequently joint failure inside the adhesive layer, spreading from overlap ends towards inside. Therefore, maximum tensile force F_{max} decreases.

Also, it is noted that experimentally recorded tensile strengths of the joints at optimum overlap lengths match with values of yield stresses of the adherends ($R_{p0,2}$), which also confirm theoretical considerations presented above.

Theoretically, it is possible to calculate an optimum overlap length (l_{opt}) by equalizing the maximum tensile force (F_{max}) calculated from equation (2) with one calculated from equation (3) and including $l = l_{opt}$ and $\sigma_s = R_{p0,2}$ [1]:

$$\tau_a \cdot l_{opt} \cdot a = R_{p0,2} \cdot s \cdot a \quad (4)$$

This leads to:

$$l_{opt} = \frac{R_{p0,2} \cdot s}{\tau_a} \quad (5)$$

Some deviations between experimental and theoretically calculated optimum overlap length arise from the assumption of pure shear state of adhesive during tensile loading of the joint. However, it is not quite true since the applied tensile force tends to be linear through the joint specimen, what leads to bending at the lap ends.

If it is accepted for criteria in designing of single lap adhesive joints that joint strength should trace yield stresses of the adherends ($R_{p0,2}$), then those criteria for metal bonded joints could be satisfied by using of optimal overlap length. Thereby, the thesis of loading metal materials in elastic region is satisfied. In practical design the proportional limit of 0,2 % is taken as upper level of loading, and in the same way for calculating of optimal overlap length. This overlap length presents certain security from unintentional overloading.

The results of both surface roughness for untreated and for treated specimens are shown in table 2.

Table 2.
Results of surface roughness measuring before bonding

Specimen mark	A				b			
	Ra, µm		*Rz*, µm		*Ra*, µm		*Rz*, µm	
	1	2	1	2	1	2	1	2
P 1.1	0,92	1,06	5,8	6,9	1,16	1,46	7,5	8,6
P 1.2	1,50	0,88	10,6	6,3	1,18	1,06	8,3	6,8
P 1.3	1,46	1,1	8,4	7,3	1,12	1,24	8,3	8,4
P 2.1	0,98	1,30	7,3	10,9	1,34	1,96	10,3	13,4
P 2.2	1,10	0,98	9,9	7,3	1,26	1,10	9,5	8,5
P 2.3	1,06	1,80	6,8	14,2	1,08	1,46	7,8	8,7
P 3.1	0,52	0,52	3,0	2,6	1,18	0,92	6,1	7,5
P 3.2	1,28	0,54	6,0	4,0	0,58	0,62	4,0	3,9
P 3.3	0,46	0,46	3,9	3,6	1,54	0,48	9,5	3,2
P 4.1	0,66	0,48	4,3	3,7	0,82	0,60	4,5	3,8
P 4.2	0,44	0,68	3,8	5,3	0,60	0,56	4,6	3,6
P 4.3	0,74	1,02	4,9	8,1	0,73	1,02	5,1	7,8
P 5.1	0,96	0,90	7,6	6,9	0,84	0,96	6,8	7,0
P 5.2	1,02	0,88	6,4	6,7	1,08	0,92	7,2	7,5
P 5.3	1,14	1,26	7,8	9,7	0,98	1,22	5,8	8,7
Mean value	0,95	0,92	6,43	6,90	1,03	1,04	7,02	7,16
Before treatment: *Ra* = 0,19 µm; *Rz* = 1,8 µm								

As can be found from the table 2 the average surface roughness values for the untreated aluminium plates are Ra=0,19µm, Rz = 1,8 µm; and after treating Ra=0,986µm, Rz = 6,878 µm.

From the measured results it is obviously that the difference between surface roughness before and after treating was remarkably. This leads to the conclusion that preparing of soften materials like aluminium has more moment on surface roughness values, which is in correlation with forces transferred crossover the joints.

Figures 11-15 shows the results of experimental tensile testing of prepared joints for aluminium-epoxy combination and for all values of overlap length compared with numerical results of stretching.

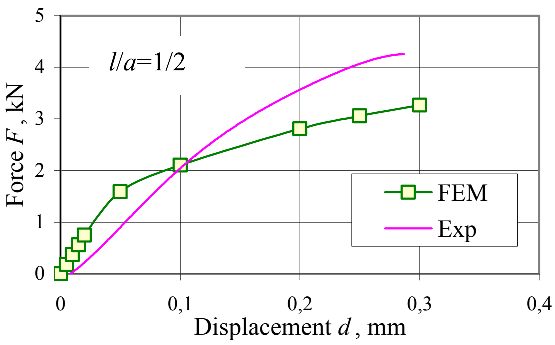

Fig. 11. Comparison of experimental and numerical results (relative overlap length, $l/a = 1/2$)

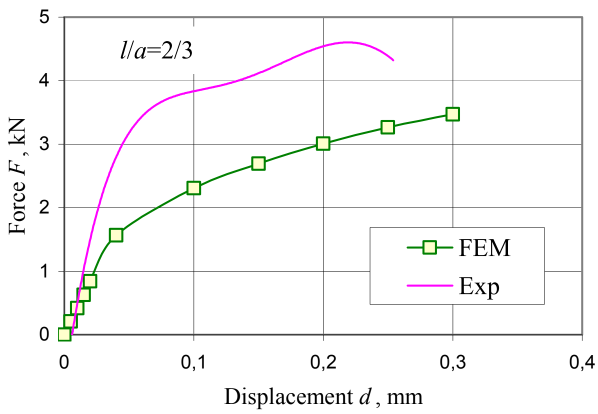

Fig. 12. Comparison of experimental and numerical results (relative overlap length, $l/a = 2/3$)

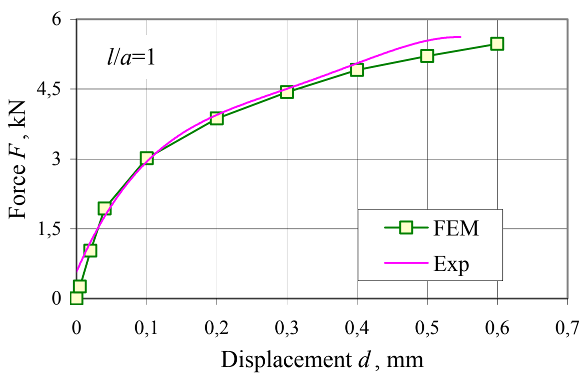

Fig. 13. Comparison of experimental and numerical results (relative overlap length, $l/a = 1$)

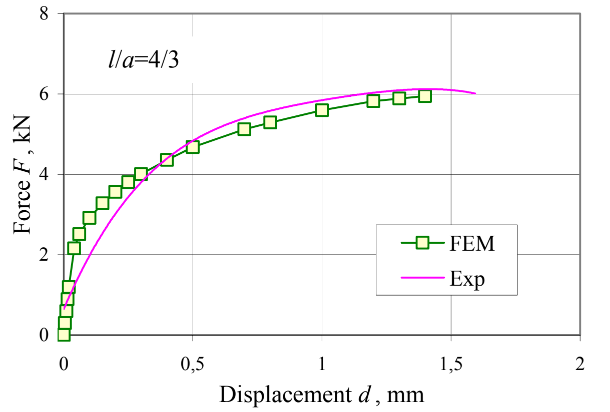

Fig. 14. Comparison of experimental and numerical results (relative overlap length, $l/a = 4/3$)

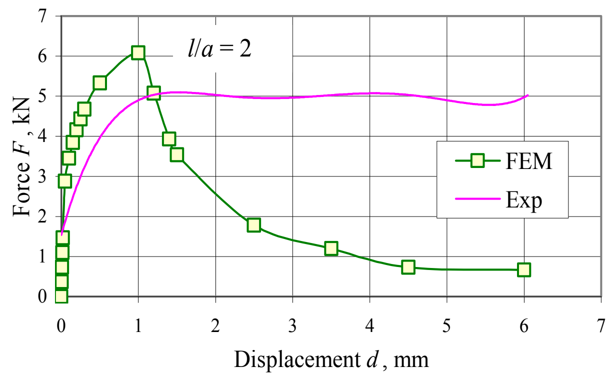

Fig. 15. Comparison of experimental and numerical results (relative overlap length, $l/a = 2$)

Figure 16 presents relations between *Rz* and *Ra* parameters. It can be seeing that the *Rz* values are approximately seven times higher than *Ra* values.

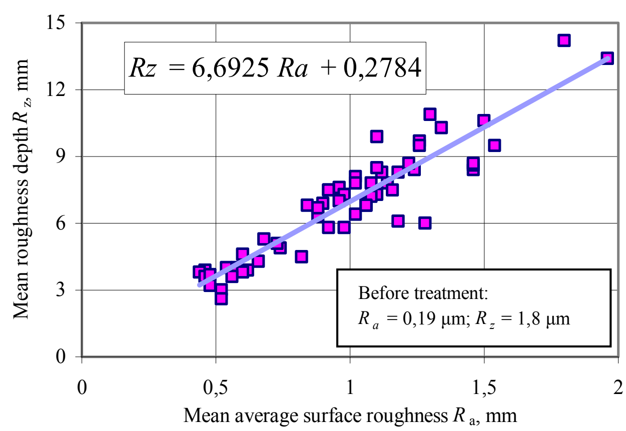

Fig. 16. Experimental results of surface roughness measuring

The fig. 17 presents the influence of surface roughness on joint tensile strength for aluminium as adherend. Analysis of results gives a following note: surface roughness doesn't have significant influence on achieved values of joint tensile strength at given overlap length (Fig. 17. a, b).

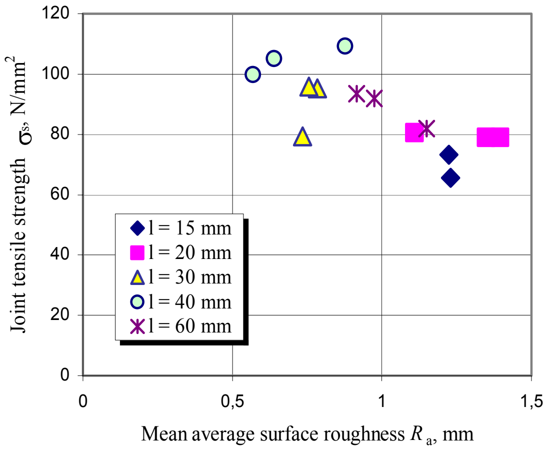

Fig. 17. a) Joint tensile strength vs. surface roughness

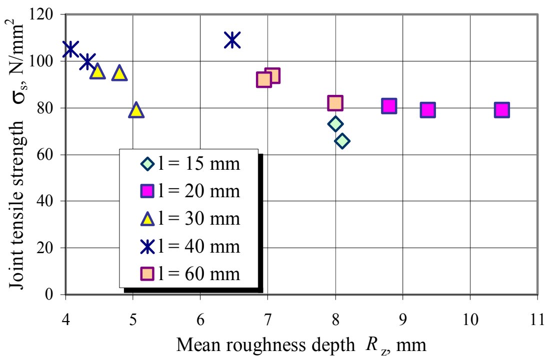

Fig. 17. b) Joint tensile strength vs. surface roughness

For every group of results for the same overlap length, it could be drawn straight line parallel with abscissa. Every line would present the strength value for group of specimens. With this approach it can be seeing that different values of surface roughness in observed interval lead to the same values of joint strength at given overlap length.

For joints with aluminium as adherend material R_a was measured from 0,6 to 1,4 µm, respectively. Comparing the recommended range (0,8 to 3,2 µm) [7] of surface finishing, with values of surface roughness parameters reached during experimentation one can conclude that they correlate well. The similar fact arises for R_z: measured values are 4 to 10,5 µm, respectively, and recommended are 6 to10 µm [7].

The results of numerical analysis correlate good with experimental ones in the cases of bonded joints of 1 and 4/3 relative overlap length (Fig. 13 and 14).

At small relative overlap lengths (Fig. 11 and 12) the influence of the overlap ending and adhesive layer imperfections strongly affects on results and cannot be easily numerically simulated.

At high relative overlap length (Fig. 15) a quite different numerical results (Fig. 15) have been noted. The possible explanation for such behavior arises from authors' previous paper [10], in which the optimal overlap length for bonding was investigated. By increasing overlap length overall joint strength, e.g. its bear loading capacity (usually identified by maximal tensile force, F_{max}) increases because of increasing of the bonding area. However, strength curves reach their maximum at certain overlap lengths, in this case at l/a = 4/3 [10] (Fig. 14). At this optimal overlap length the maximal overall joint strength is reached [10]. Increase of the overlap length over these optimum values leads to decrease in load bearing properties of the joint, and adherend exceeds into the plastic region. Maximal tensile force (F_{max}) increases by increasing bonding area i.e. overlap length.

However, increase of the maximum tensile force is possible only up to the point of reaching yield point of adherend. At this point equilibrium between stress in adherends and strength of the adhesive joint is achieved [10]. Beyond this point an excessive deformation of the adherends occurs, which cannot be compensated by relatively rigid adhesive layer. This leads to failure inside the adherend. Therefore, maximum tensile force F_{max} decreases. Experimental observations in this work confirm such model of bonded joint failure (Fig. 20 b). However, at lower overlap lengths at which the joint strength has not reached the yield strength of adherend, a mixed failure occurs in adhesive layer (Fig. 18 a).

From the fig 18 b) one can be note: the adhesive distribution is not quite regular; actually it is unintentional. Adhesive layer is not laminated; thereby the layer is hold on only on one side of adherend. It confirms that the adhesion forces in small lapping cases are the most important and have the major rule in failure.

It is also noted that experimentally recorded tensile strength of the joint at optimum overlap length [10] matches with values of yield stresses of the adherends ($R_{p0,2}$), which also confirm theoretical considerations presented above [10].

It also matches with stresses obtained in numerical analysis. Figures 18 (a,b) and 19 (a,b) show von Misses stresses in bonded joints of various overlap length numerically calculated at last step of loading.

As clearly could be noted from Fig. 7 aluminum adherend has a yield point at 115 MPa true stresses. Because of the bonded joint transmits overall higher values of stress then adherend could withstand, it begins to plastic deform. This is confirmed in both experimental and numerical analysis (Figs. 15. and 20.b).

From the discussion above, there is an important conclusion to be pointed out. Single lap bonded joints could be successfully numerically simulated by applying a multi-linear isotropic material model for all overlap lengths at which the adherend doesn't have any influence on load-bearing capacity of the bonded joint.

At the overlap lengths above critical (optimal) ones (which enable that bonded joints transmit higher stresses as adherend could withstand) the usage of a MISO material model in FEA is not acceptable (Fig. 14). The appropriate elastic-plastic or creep models might be and should be used.

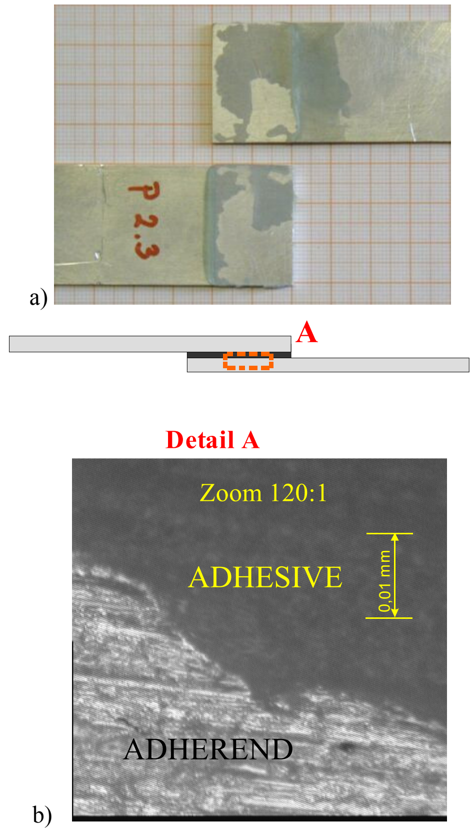

Fig. 18. a) Mixed failure in bonded single-lap joints, b) Distribution of adhesive through the adherend

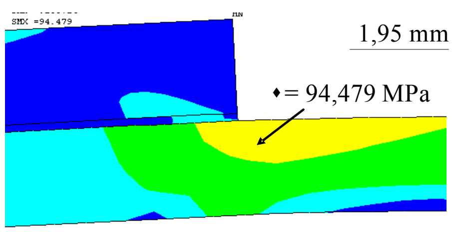

Fig. 19. a) Numerically calculated von Misses stresses in aluminum adherends on small lapping area, *l/a* = 1/2

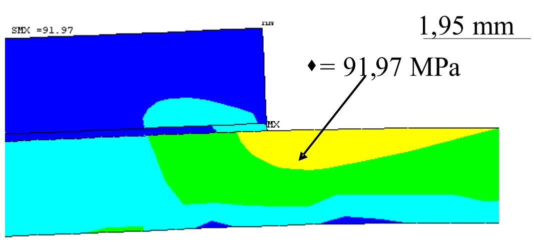

Fig. 19. b) Numerically calculated von Misses stresses in aluminum adherends on small lapping area *l/a* = 2/3

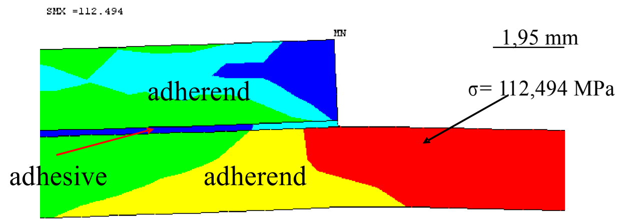

Fig. 20. a) Numerically calculated von Misses stresses in aluminum adherends *l/a* = 4/3 (FEM)

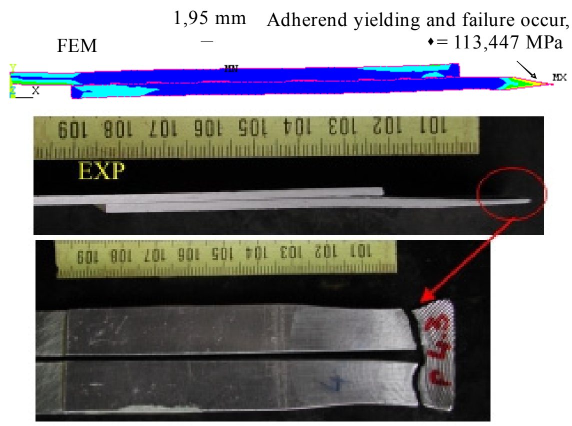

Fig. 20. b) Numerically calculated von Misses stresses in aluminum adherends *l/a* = 2 (FEM / EXP comparison)

6. Conclusions

One of the most managing factor in single lap adhesively bonded joint design is overlap length which affect the joint strength beside other factors, like adhesive properties, properties of the adherends, bonding procedure, joint design and loading conditions. Design of joint with optimal overlap length facilitate that maximum load bearing capacity using a minimum quantity of applied adhesive and adherend is possible to be reached. It was also noted that the influence of the adherend elastic/plastic behavior is very significant for joint strength.

To determine the importance of adhesives in joint strength, it is necessary to be familiar with their mechanical properties and the chemistry which creates those properties. The most of problems in numerical analysis are addressed to mechanical properties of adhesive which are often public unknown. Cohesive characteristics (tensile strength) of chosen structural adhesives in our work were determined applying the tensile test on specimen made of pure adhesive material. Nevertheless, reliability of materials models is influenced with accuracy of adhesive properties.

Experimental investigation confirmed theoretical consideration of significant influence of the considered parameter (overlap length) on strength of the joints. The optimal overlap length has been achieved.

It is important to note that joint preparation procedure on soft materials like aluminium results with increasing of existing adherend surface roughness values. Thereby, final adherend roughness influenced with joint preparation procedure could affect joint strength. However, the experimental results don't prove significance of surface roughness influence on strength characteristic of the joints in observed range of surface roughness. Materials model used in numerical simulation allows predicting the strength of adhesively bonded structures. In our work, two-component structural epoxy adhesives (*Loctite 3421)* and aluminium (*Al99.5*) as adherend materials have been tested experimentally and numerically which are performed in experimental analysis. Materials model of adhesive and adherend was multi-linear isotropic (MISO) and was acceptable within experimental range. The FEM results doesn't fits the experimental well for overlap lengths $l/a = 2$.

Simulation of stretching of joints with software based on FEM (Finite Element Method) is applied on several overlap lengths
At the overlap lengths above critical (optimal) ones (which enable that bonded joints transmit higher stresses as adherend could withstand), the usage of a MISO material model in FEA is not acceptable any more.

In our further work, it is of great interest to verify simulation with other materials model approaches.

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