Stress-Strain Analysis of Single-Lap Tensile Loaded Adhesive Joints

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Abstract. Both, experimental investigation and finite element analysis of single-lap adhesive joints subjected to tension have been done to find out an optimal overlap length. As the adherend material aluminum was considered with the two component high-strength engineering adhesive for the bonding of the layers. The thickness of the sheet metal layer was 1,95 mm, while adhesive was 0,15 mm thick. The width of all thin plates was 30 mm, but the overlap length varied as 15, 20, 30, 40 and 60 mm. Real mechanical properties of all materials in the joint have been determined experimentally. Obtained results proved that the overlap length affects directly the joint tensile strength, where an optimum value of overlap length can be defined. Finite element analysis of stress and strain fields could help to determine the moment when the crack initiates at the joint overlap end. In such a manner, complex mechanisms of failure of adhesive joints could be better understood.

Keywords: Single-Lap Adhesive Joints, Tensile Loading, Experiment, Finite Element Analysis, Optimal Overlap Length.
PACS: 81.40.Np

INTRODUCTION

Adhesive bonding is a widely used joining process in world-wide production of engineering products. It forms an essential part of the laminating process in multi-material sandwich structures and it is also used for structural connections between multi-material components. Adhesive joints are the most using for bonding of automotive and airplane parts, but also in everyday life (industry of shoes, bookbinder, household appliances etc.) [1]. A lot of influencing factors affect the load carrying capacity of an adhesive joint. The geometrical configuration of bonded parts is essential to obtain enough structural strength. Even joints having same adhesively bonded area, they might have different joint strength according to the bonded configuration. The adhering conditions are also important to attain the joint strength (e.g. the surface roughness of adhering surface, the thickness of the adhesive layer, the pressure applied to adhesive resin and its holding time, and curing conditions of adhesive resin are substantial factors affecting the joint strength). Adhesive strength is affected by the many physical and chemical factors [2]. Hence, the knowing of the strain-stress distribution through the adhesive joint might be of great help to designer by integrity assessment of the engineering component [3]. In accordance with the fact that aluminium has a wide application for many engineering components, adhesive joints of aluminium as adherend sheet material have been focused here.

This paper deals with 2D and 3D approach to finite element modelling of single lap bonded joints. True physical characteristics of adhesive and adherend have been considered and overlap length has been changed. Comparison of the results (applied force vs. end displacement) obtained by plane stress finite element models related to those recorded by test served as starting point for the further numerical investigation.

The aim was actually to determine the tensile stress σ_x, shear stress τ_{xy}, and Mises equivalent stress σ_{eq} distribution in adherend and adhesive as well for different designs of single-lap joint.

EXPERIMENTAL INVESTIGATION

Adhesive joints of aluminium as adherend sheet material have been considered in this work.

Thin plates from aluminium with dimensions: $a \times b \times s$ = 30 x 90 x 1,95 mm were bonded with two-component epoxy adhesive Loctite 3421 (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 20 °C to reach maximum strength). The adherends are cleaned by an appropriate surface preparation method [4]. The overlap length *l* has been varied in the range from 15 mm up to 60 mm (Figure 1). Prepared joints have been stretched up to the break in the jaws of the tensile testing machine. The aim of the testing was to determine the joint tensile strength of the single-lap adhesive joints with different geometries. The main goal of performed investigation was to find out an optimal overlap length from obtained results. Generally, increasing of the overlap length leads to the increasing of the joint strength due to increased area of bonding. However, it was shown that after some amount of the overlap length increasing an optimum overlap length can be defined, what means that after that point load capacity of the joint decreases. It should be pointed also that an optimal design of the bonded joint depends not only on the overlap length, than also on the applied adherend and adhesive material.

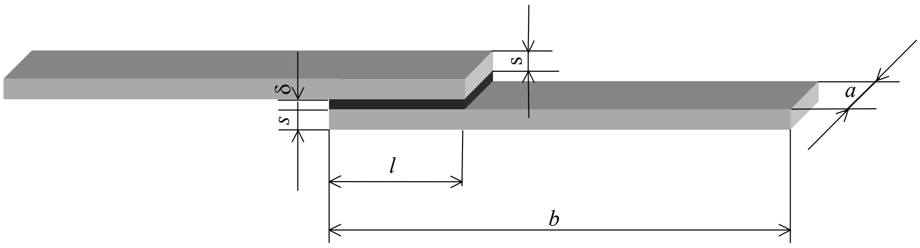

FIGURE 1. Geometry of the single-lap adhesive joint.

NUMERICAL ANALYSIS

Numerical simulation of the tensile testing of single-lap adhesive joint is cost-effective and time-consumed procedure to get an insight into stress and strain distribution in the adhesive and adherend materials. Both 2D and 3D non-linear finite element (FE) analysis were done and compared. An example of 3D finite element mesh is presented on the Fig. 2. All five plane geometries of the considered adhesive joints are presented in the Fig. 3.

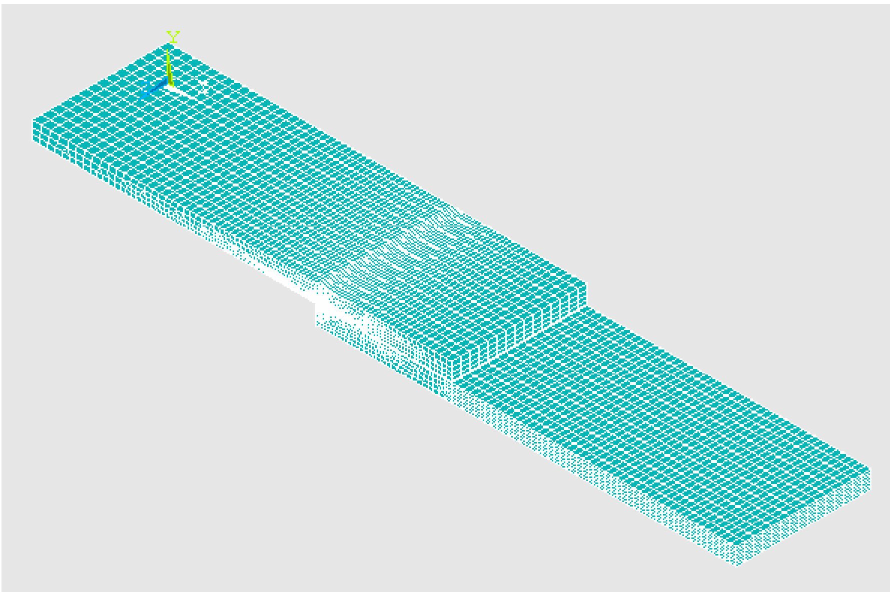

FIGURE 2. 3D finite element mesh of the single-lap adhesive joint (*l*=30 mm).

Comparing plane stress results with those obtained by spatial model it has been conformed that there is no need for 3D models, because sheet metals are relatively thin, where plane stress state is appropriate. True stress – true strain diagrams were defined for both materials in the joint (Fig.4 - for adherend and Fig.5 - for adhesive). Such multi-linear isotropic material model was used in all numerical calculations.

Characteristics of the materials (Table 1) of adherend and adhesive are given in input file. The material non-linearity, which is based on the real uniaxial stress-strain behaviour, increases the accuracy of obtained results by finite element calculations. Standard quadrilaterals 8-node isoparametric elements were used which are collapsed into triangle in the point where stress concentration was assigned. Free meshing technique was used with the size of 50 μm for the first row of elements around the stress concentration point. An iterative procedure of load increasing with small increments was applied to make the calculation stable and precise.

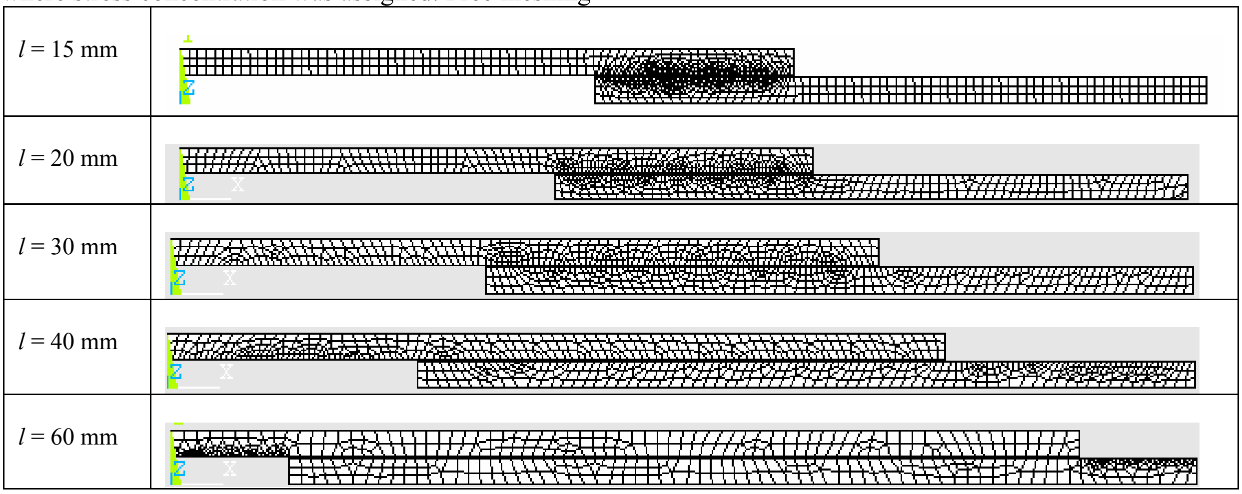

FIGURE 3. Finite element meshes for different geometries of the adhesive joint.

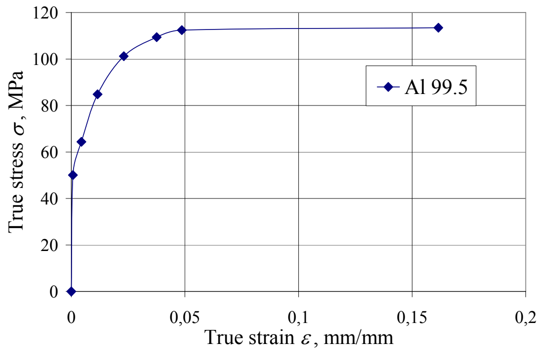

FIGURE 4. Discretized adherend (aluminium) true stress-strain curve used for finite element calculations.

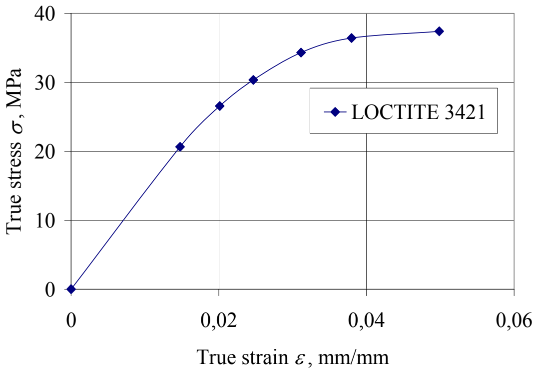

FIGURE 5. Discretized adhesive (epoxy) true stress-strain curve (marked points used for finite element modeling).

TABLE 1. Mechanical properties data of the materials used in finite element calculations.

ADHESIVE	ADHEREND
E_0 = 1400 MPa	E_0 = 70 000 MPa
ν = 0,35	ν = 0,3
$R_{p0,2} \cong$ 27 MPa	$R_{p0,2} \cong$ 100 MPa
$R_m \cong$ 38 MPa	$R_m \cong$ 115 MPa

All bonded joints were exposed to the same loading level, which was given as displacement of 0,295 mm on the right side of the joint.

RESULTS AND DISCUSSION

By increasing of 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. This is obvious on the Figure 6, where experimental results in the form of joint strength for different overlap lengths were given. However, strength curves reach their maximum at certain overlap lengths, in this case for about l = 40 mm. This optimal overlap length leads to the maximal overall joint strength. Increasing of the overlap length over this optimum value has for the consequence a decreasing in load bearing properties of the joint, and adherend exceeds into the plastic region.

Maximal tensile force (F_{max}) increases continuously as bonding area i.e. overlap length increases. 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. 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.

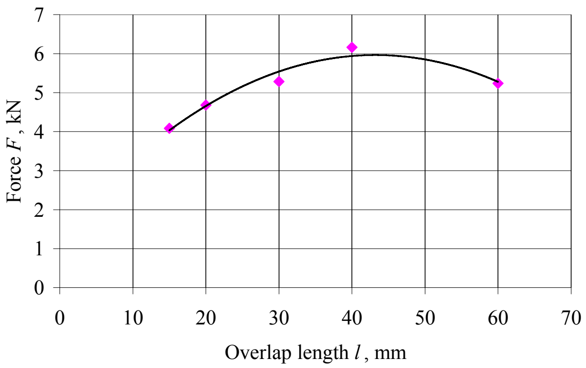

FIGURE 6. Joint strength of adhesive lap-joints with different overlap lengths (obtained experimentally)

However, some differences from theoretically considerations [3] arise from an assumption of pure shear state of adhesive during tensile loading of the joint. It is not quite true since the applied tensile force attempt to be linear through the joint specimen, what leads to bending at the lap ends. It is especially expressed in adhesive joints with a little overlap length in numerical analysis (15 and 20 mm of overlap length, Figure 8). The stress concentrations are very high at the ends of the overlap, but are relatively small around the middle. For this reason, the failure starts at the ends. A similar phenomenon was also recorded during the tensile testing in experimental investigation, what can be seen from the Fig. 7.

FIGURE 7. Failure starts at joint overlap end.

In order to determine the effects of overlap length on the strength of a single lap joint, detailed FE study has been carried out to determine the magnitude and distribution of the stresses σ_x, τ_{xy} and σ_{eqv}, similar as in [6]. Magnitudes of extreme values of analyzed stresses are given in the Table 2. for all considered bonded joint geometries. Spreading of the stresses is presented in the vicinity of the most critical adhesive joint place for the ranges of overlap lengths as above mentioned. It could be concluded from the stress fields depicted on the Fig. 8 that overlap increasing causes that adherend materials are more subjected to pure tension, without effects of joint ends bending. Maximum value of equivalent stress is more or less constant for any overlap length.

TABLE 2. Extreme values for analyzed stresses for different overlap lengths.

	***l*=15 mm**	***l*=20 mm**	***l*=30 mm**	***l*=40 mm**	***l*=60 mm**
Axial stress σ_x, MPa	-69,95	-63,09	-4,17	-5,02	-9,73
	+111,06	+117,1	+115,96	+111,93	+113,67
Shear stress τ_{xy}, MPa	-14,9	-19,11	-13,61	-18,01	-20,24
	+6,9	+15,68	+7,83	+5,38	+2,89
Equivalent stress, MPa	112,365	112,46	112,44	110,16	112,66

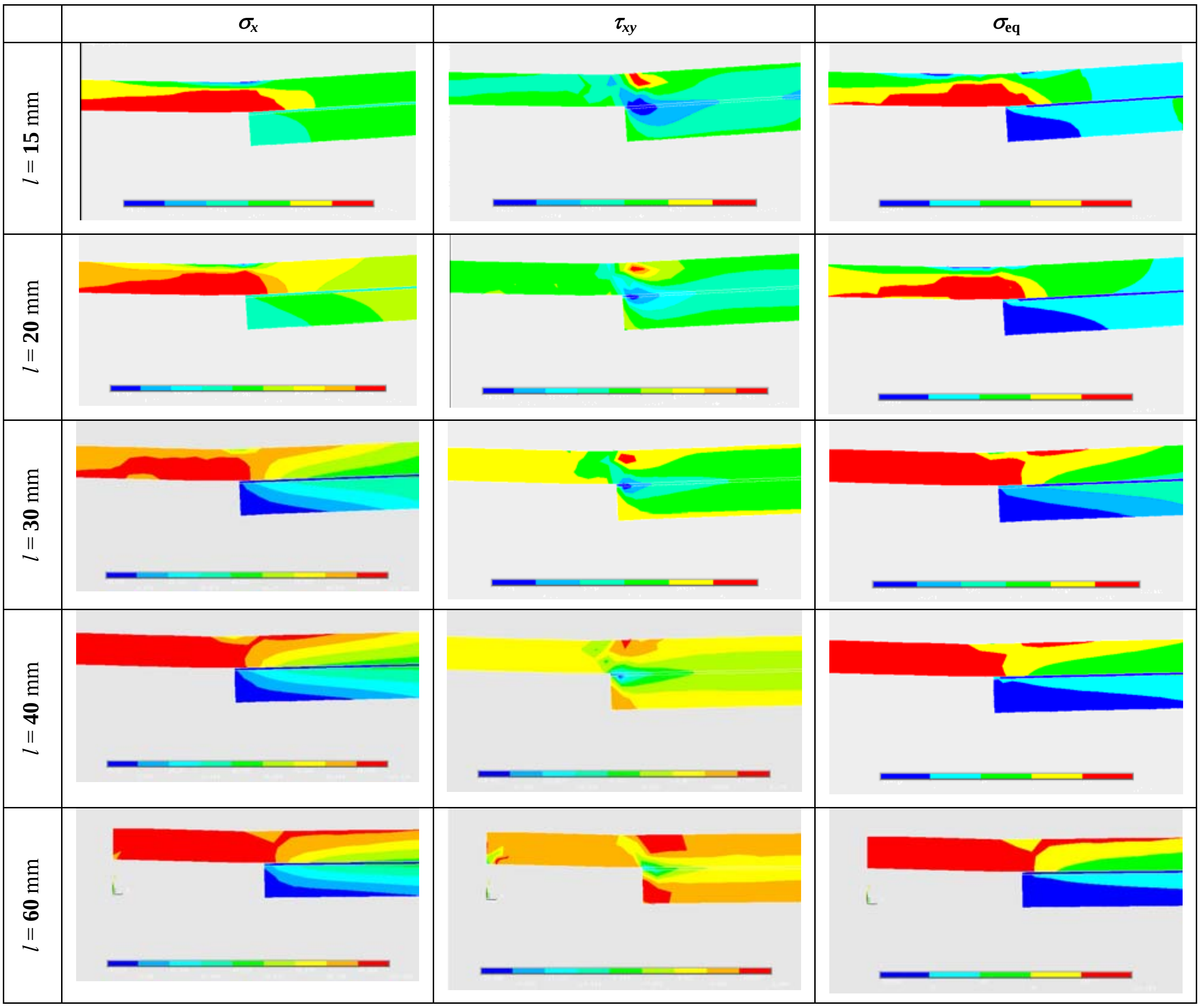

FIGURE 8. Axial, shear and equivalent stress distribution in the vicinity of the most critical adhesive joint place.

Strain analysis shown that total strain magnitude decreases rapidly with the increasing of overlap length. Finite element results for total strain values are given in the Table 3. It is obvious from the Fig. 9 that most deformation is concentrated in the adhesive material, for the case of overlap length with amount of 15 mm.

TABLE 3. The FE results of maximum value for total strain depending on the overlap length.

Overlap length l, mm	ε_{pto}
15	0,984
20	0,476
30	0,252
40	0,157
60	0,071

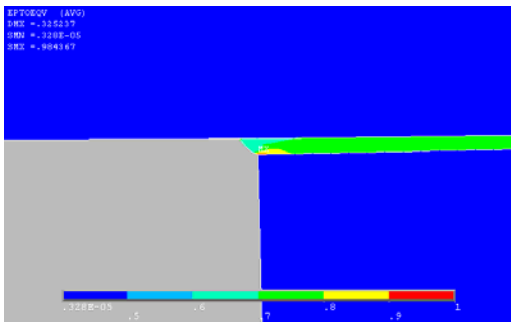

FIGURE 9. Total strain enlarged for adhesive material (overlap length is equal to 15 mm).

CONCLUSIONS

Experimental investigation and finite element analysis of single-lap adhesive joints subjected to tension have been carried out with the aim to define an optimal overlap length. Aluminum as the adherend material and two component high-strength engineering bonding as adhesive were considered. The thickness of the sheet metal layer was 1,95 mm, while adhesive was 0,15 mm thick. The width of all thin plates was 30 mm, but the overlap length varied as 15, 20, 30, 40 and 60 mm. True stress and true strain relationship for the materials in the joint have been determined experimentally. Obtained experimental results proved that the overlap length affects directly the joint tensile strength, where an optimum value of overlap length can be defined. Detailed numerical study has been performed to estimate axial, shear and equivalent stress for the same loading level (displacement of the right joint end amount as 0,295 mm). Magnitudes of the stresses were compared for the different values of joint overlap. It has been concluded that maximum value of equivalent stress is practically constant for all geometries, while axial stresses reduce significantly in the adherend materials for the greater overlaps. Characteristic for the adhesive joints with lower overlaps is also bending of the ends, what is obvious from the given figures. Shear stress is several times lower than axial stress and its influence is more present in the adhesive material. Total strain magnitude decreases rapidly with the increasing of overlap length and it is concentrated mainly in the adhesive material.

ACKNOWLEDGMENTS

Authors would like to thank to the Ministry of Science, Education and Sports of Republic of Croatia for the support realised through financing of the projects: *Advanced technologies of direct manufacturing of polymeric products* (Project code: 152-1521473-1474) and *Analysis and fracture assessment of the constructions made from anisotropic materials* (Project code: 152-1201910-1909).

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