# Experimental investigation of adhesive layer properties

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**Abstract**

This paper dealing with investigations of adhesive layer characteristics and it is a part of our continuous research on adhesively bonded joints. Previous experimental analysis has shown that bonding of different adherend materials using the same adhesive leads to the different behaviour of adhesive. This effect is more evident in numerical modelling of adhesively bonded joints, especially in bonding of adherends of higher yield strength. To understand how adhesives work, it is necessary to understand their mechanical properties and the chemistry used to create those properties.
The object of present investigation is therefore to research cohesive and adhesive characteristics of chosen structural adhesives in correlation with adherend materials to be bonded. In particular, two-component structural epoxy adhesive and aluminium as adherend material have been tested. The knowledge of adhesive and cohesive properties of the adhesive is necessary in strength calculation of bonded joints, especially in application of numerical methods such is the finite elements analysis (FEA).

## 1 Introduction

Joint which connects two components together is a common technology for assembling structures, and is increasingly used in aerospace and automotive industries. 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 [1]. Even when relatively low modulus adhesives are employed, the stress is non-uniformly distributed through the bond-line. Therefore, an extensive research of 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.
Single lap joints are by far the most widely used adhesive joints and have been the subject of considerable research over the years. The loads in a single lap joint are not co-linear, a bending moment therefore exists which causes the joint to rotate. This consequently turns 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 both the adhesive and adherend may become plastic, particularly in the highly stressed regions. The commonly used metallic adherends used in single lap joints test are often found to have plastic deformation, due to yielding, before failure [2].
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, the objective of this investigation is to research cohesive and adhesive characteristics of chosen structural adhesive in correlation with adherend material to be bonded. In the work, two-component structural epoxy adhesive *Loctite 3421* and aluminium *Al99.5* as adherend material has been tested.

## 2 Experimental works

### 2.1 Mechanical characterization of adhesive

Flat tension specimens have been moulded aiming to test tensile mechanical properties of the adhesive chosen. Dimensions of the specimens (Fig. 1) are defined in ASTM D-638.

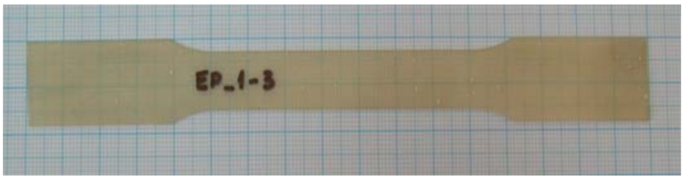


*Figure 1:* Adhesive tensile test specimen

An special mould was made for rectangular specimens production (Fig. 2).


*Figure 2:* Mould for rectangular specimen production

The mould consists of three steel plates in which the insertions were set. Insertions were set to obtain the specimens of various thicknesses. All of steel plates were dressed in tracing-paper, so adhesive were not adhere to steel plates. In the mould, the rectangular specimens were obtained. Afterward they were machined on high speed milling machine to reach their final dumbbell geometry. All tests were conducted on *WPM, VEB Thuringer Industriewerk Rauenstein* 2,5 kN, Typ 2092 tensile testing machine following the standardized procedure according to ASTM D-638. Stretching speed was set at about 0,05 mm/s. All tests are performed at room temperature. Fig. 3 shows a specimen clamped in tensile testing machine jaws.

*Figure 3:* Tensile test of an adhesive specimen

Experimentally obtained stress-strain curve (average value of 3 runs) is shown in Fig. 4.

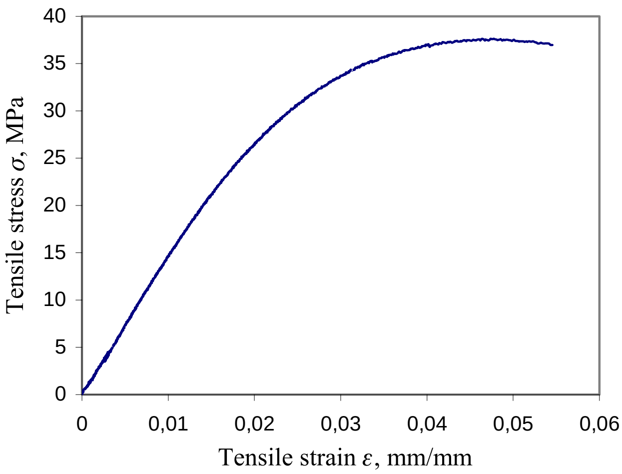


*Figure 4:* Tensile stress-strain curve of epoxy adhesive

## 2.2 Adhesive joint testing

The standard single lap bonded specimens for evaluating the load bearing characteristics i.e. strength of adhesively bonded joint have been prepared accordingly Fig. 5. Aluminium *Al99.5* as adherend material has been considered. Dimensions of such prepared rectangular adherend plates were $a \times b \times s$ = 30 × 90 × 1,95 mm. The adherends are cleaned by an appropriate surface preparation method [3].

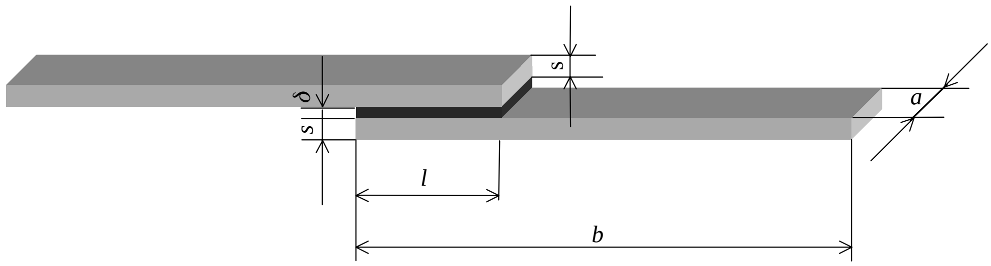


*Figure 5:* Single lap bonded joint specimen

The two-component epoxy adhesive *Loctite 3421* [3] is applied to 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 20 °C to reach maximum strength. The lap length has been varied in range from 15 to 60 mm (relative lap length ($l/a$) from 1/2 to 2). The all in this way prepared bonded joints have been stretched up to the break in the clamps of the tensile testing machine *Carl Schenk AG 1000 kN*.

## 3 Numerical analysis

In numerical analysis the commercial FEA code *ANSYS* [4] has been used. The same geometry of single lap bonded lap specimen as tested experimentally (Fig. 5) was numerically modelled by using two-dimensional 8-node isoparametric finite elements (*PLANE82*). 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 (Fig. 4) follows by linear discretization of the curves in several steps as shown in Fig. 6 and Fig. 7. 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.

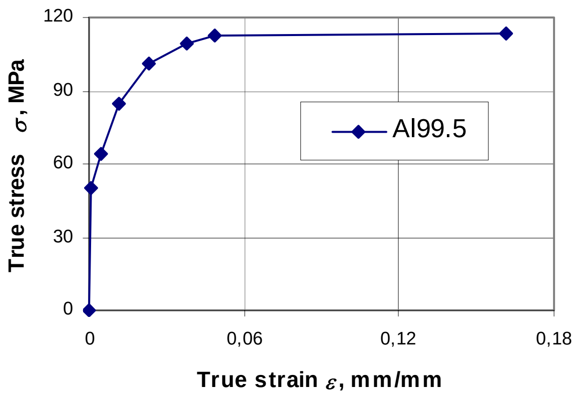


*Figure 6*: Discretized adherend (aluminium) stress-strain curve

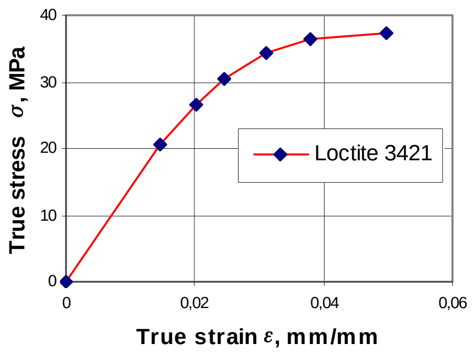


*Figure 7*: Discretized adhesive (epoxy) stress-strain curve

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

| Input data | |
|---|---|
| ADHESIVE | ADHEREND |
| $E_0$ = 1400 MPa<br>$\nu$ = 0,35<br>$\sigma_m \cong$ 38 MPa | $E_0$ = 70 000 MPa<br>$\nu$ = 0,3<br>$\sigma_m \cong$ 115 MPa |

## 4 Results and discussion

Comparisons of experimental and numerical results of stretching are shown on Fig. 8 – Fig. 12.

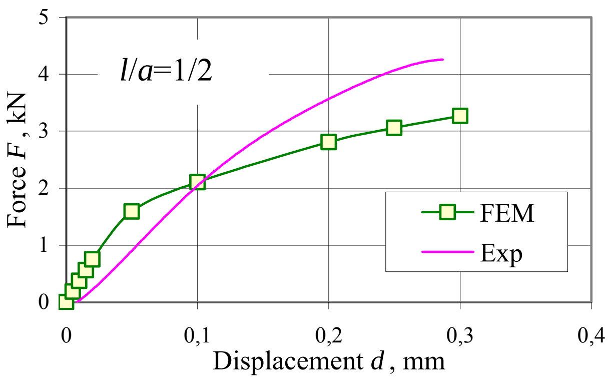


*Figure 8*: Comparison of experimental and numerical results (relative lap length, $l/a$ = 1/2)

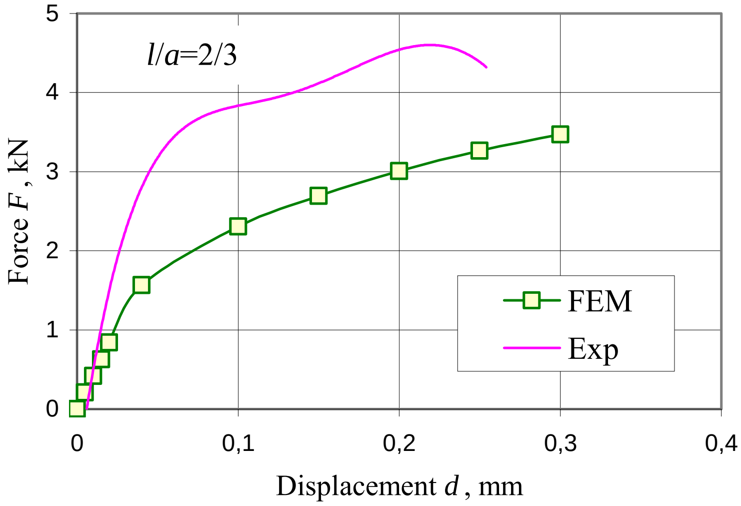


*Figure 9*: Comparison of experimental and numerical results (relative lap length, *l/a* = 2/3)

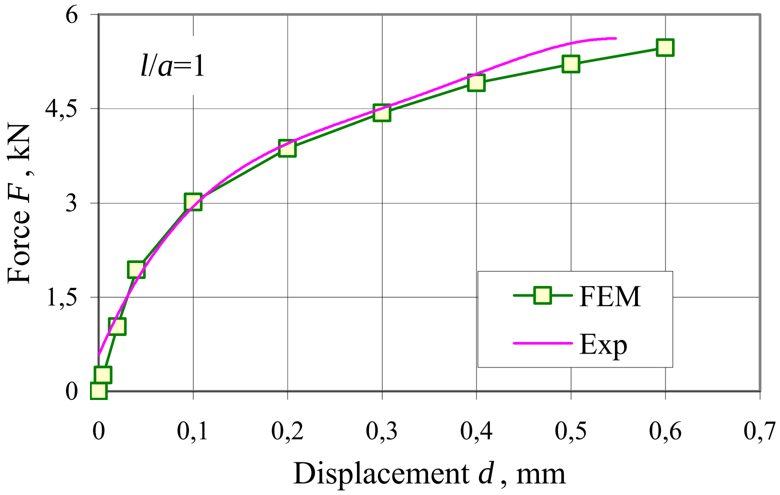


*Figure 10*: Comparison of experimental and numerical results (relative lap length, *l/a* = 1)

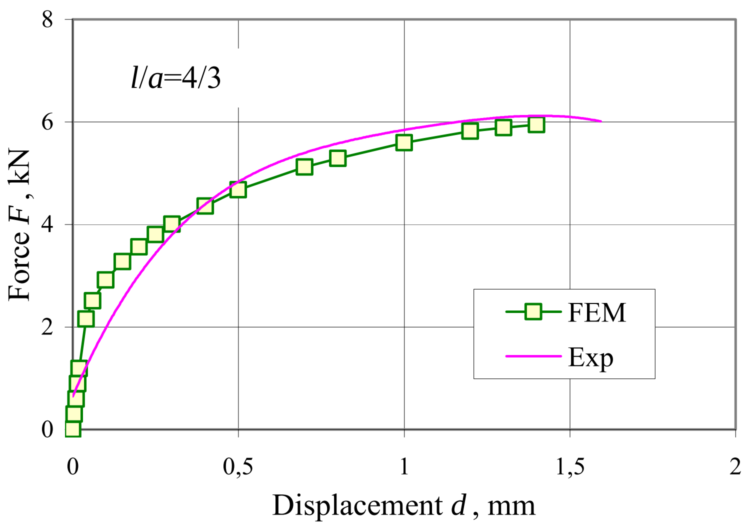


*Figure 11*: Comparison of experimental and numerical results (relative lap length, *l/a* = 4/3)

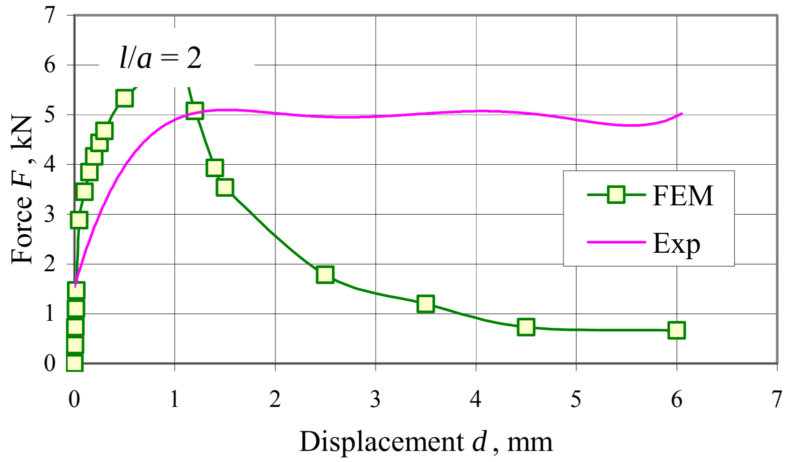


*Figure 12*: Comparison of experimental and numerical results (relative lap length, *l/a* = 2)

The results of numerical analysis correlate good with experimental ones in the cases of bonded joints of 1 and 4/3 relative lap length (Fig. 10 and 11). At small relative lap lengths (Fig. 8 and 9) the influence of the lap ending and adhesive layer imperfections strongly affects results and cannot be easily numerically simulated.

At high relative lap length (Fig. 12) a quite different numerical results (Fig 12) have been noted. The possible explanation for such behaviour rises from authors' previous paper [6], in which the optimal lap length for bonding was investigated. By increasing lap 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 lap lengths. At optimum lap length the maximum joint strength is reached [6]. Increase of the lap 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 continuously by increasing bonding area i.e. lap 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 [6]. 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 joint failure. However, at lower lap lengths at which the joint strength has not reached the yield strength of adherend, a mixed failure occurs in adhesive layer (Fig. 13).

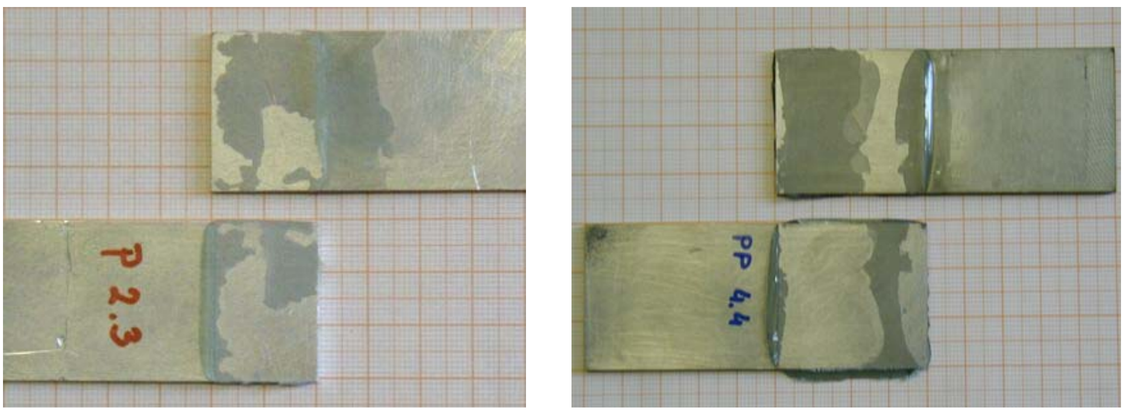


*Figure 13*: Mixed failure in bonded single-lap joints

It is also noted that experimentally recorded tensile strength of the joint at optimum lap length [6] matches with values of yield stresses of the adherends ($R_{p0,2}$), which also confirm theoretical considerations presented above. It also matches with stresses obtained in numerical analysis (Fig. 14).

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 lap lengths at which the adherend doesn't have an influence on load-bearing capacity of the bonded joint. Critical (optimal) lap length which enable that adhesive joint could transmit higher stresses as adherend could withstand, is leading parameter which initiates that MISO material model in FEA is not acceptable anymore. According to theoretical knowledge, the elastic-plastic material model should be used with creep.

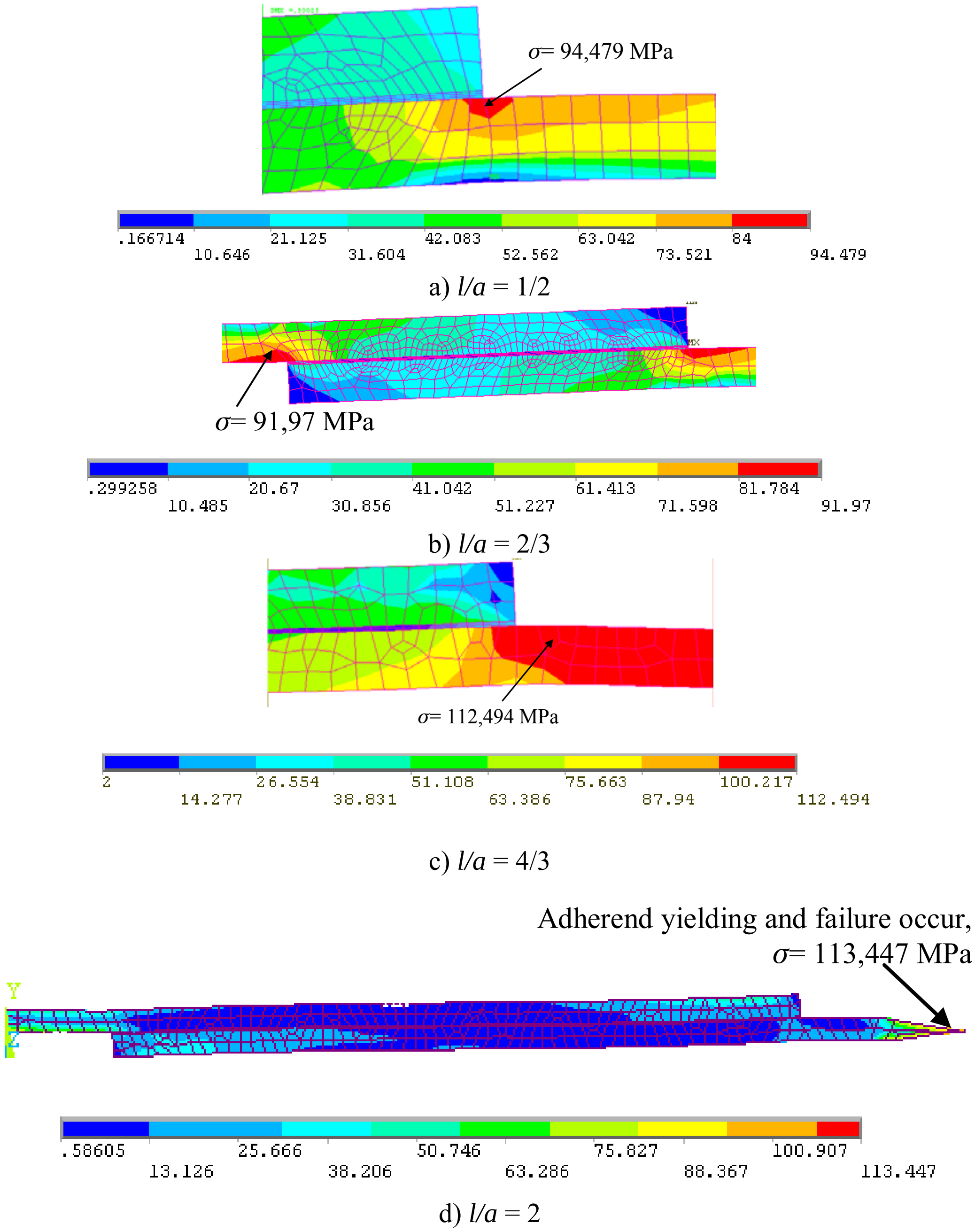


*Figure 14*: Numerically calculated von Misses stresses in aluminium adherends

Figure 14 presents von Misses stresses obtained in numerical simulation in a bonded joint of lap length, $l/a$ = 4/3. As displayed in Fig. 6 aluminium adherend has a yield point at 100 MPa true stresses. As adhesive joint transmits higher values of strength then adherend could withstand it begins to flow. This remark is confirmed in both experimental and numerical analysis (Fig. 14).

## 5 Conclusions

Bonding of different adherend materials using the same adhesive leads to the different behaviour of adhesive [5,6]. This effect is more evident in numerical modelling of adhesively bonded joints, especially in bonding of adherends with higher yield strength. To understand how adhesives work, it is necessary to understand their mechanical properties and the chemistry used to create those properties. Therefore, objective of this investigation was to research cohesive and adhesive characteristics of chosen structural adhesives in correlation with adherend material to be bonded.

Problems occurs the mostly in numerical research because mechanical properties of adhesive are unknown. Accuracy of adhesive properties data depend on reliable materials models that can be used to predict the strength of adhesively bonded structures. In particular, two-component structural epoxy adhesives (*Loctite 3421)* and aluminium (*Al99.5*) as adherend materials have been tested experimentally and numerically.

Simulation of stretching of joints with software based on FEM (Finite Element Method) is based on all lap length as performed in experimental analysis. Material model of adhesive and adherend was used as multi-linear isotropic (MISO). Used material model in numerical analysis was satisfied, and results obtained with them were in appropriate correlation with experimental for all lap length except for 60 mm of lap length. For given geometry of plates to be bonded, there has been an optimal lap length reached, and its value is 40 mm. 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 occurred that cannot be compensated by relatively rigid adhesive layer. This leads to failure inside the adherend. Adherend exceed into the plastic region. Critical (or optimal) lap length which enable that adhesive joint could transmit higher values of strength than stresses which adherend could withstand, is leading parameter which initiates that MISO material model in FEA is not acceptable anymore. The appropriate elastic-plastic material or creep models should be used.
In further work, it will be provide simulation with such approach. Also, there are plans to extend the numerical analysis on stainless steel adherends.

## 6 References


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