THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE XIV MECHANICAL ENGINEERING, ISSN 1224-5615
2005

EXPERIMENTAL-COMPUTATIONAL DETERMINATION OF EPOXY RESIN MECHANICAL PROPERTIES, USED IN ASSEMBLY APPLICATIONS

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ABSTRACT

A wide use of adhesive substances and especially of epoxy resins in metal structures with elevated strength is registered during the last years. Epoxy resins possess enhanced mechanical, chemical and physical properties, i.e. increased shear and compression strength, resistance in solvents, as well as at high temperatures.In the present paper, two-components of epoxy resin were tested through a developed experimental apparatus, applying tensile stress loads. Rolls and aluminum pipes, as well as further specimens were used. The specimens were cemented under constant temperature and humidity conditions. The experimental results were simulated with the aid of FEM-based procedures. The stress–strain curves of epoxy resins derived from previous works, were considered. The results revealed that the resins fail mainly due to poor adhesion with the cemented surfaces and not owing to cohesion release.

1. Introduction

Epoxy resins have been extensively examined as far as their physical and chemical properties in [1, 2, 3]. The present paper investigates the mechanical properties during static tensile loading of epoxy resins. This procedure was performed by means of an apparatus, able to apply tensile loads on the cemented specimens and record at the same time the tension force versus the displacement of the cemented specimen, up to the ultimate fracture of the resin. The specimens used in the tensile experimental procedures are made of aluminum tubes.

Various epoxy resin failure modes are elucidated through improved FEM simulation models. For every experimental procedure, the corresponding FEM simulation models are created considering the specimen geometry and the mechanical properties of specimen and epoxy resin materials. A comparison of the experimental results to the analytically determined ones showed that the epoxy resin fracture is initiated, due to poor adhesion of the soldered faces.

2. The experimental and FEM procedure to determine the stress strain curve of epoxy resin

The determination of the main mechanical properties of the investigated epoxy glues was determined by means of nanoindentation test device and FEM simulations. The upper part of figure 1 shows the experimental indentation depth versus penetration load curve, which represents the mean curve of the twenty trials during the experimental procedure. This curve is used as input data to FEM modeling in order to determine the elasticity modulus, yield strength and stress-strain curve of the investigated epoxy glue. In order to proceed

with the simulation procedure using the finite element method, this curve is digitalized in small steps. The very first region of this curve represents the elastic behavior of the examined material, where only elastic deformation occurs into the material by the indenter penetration.

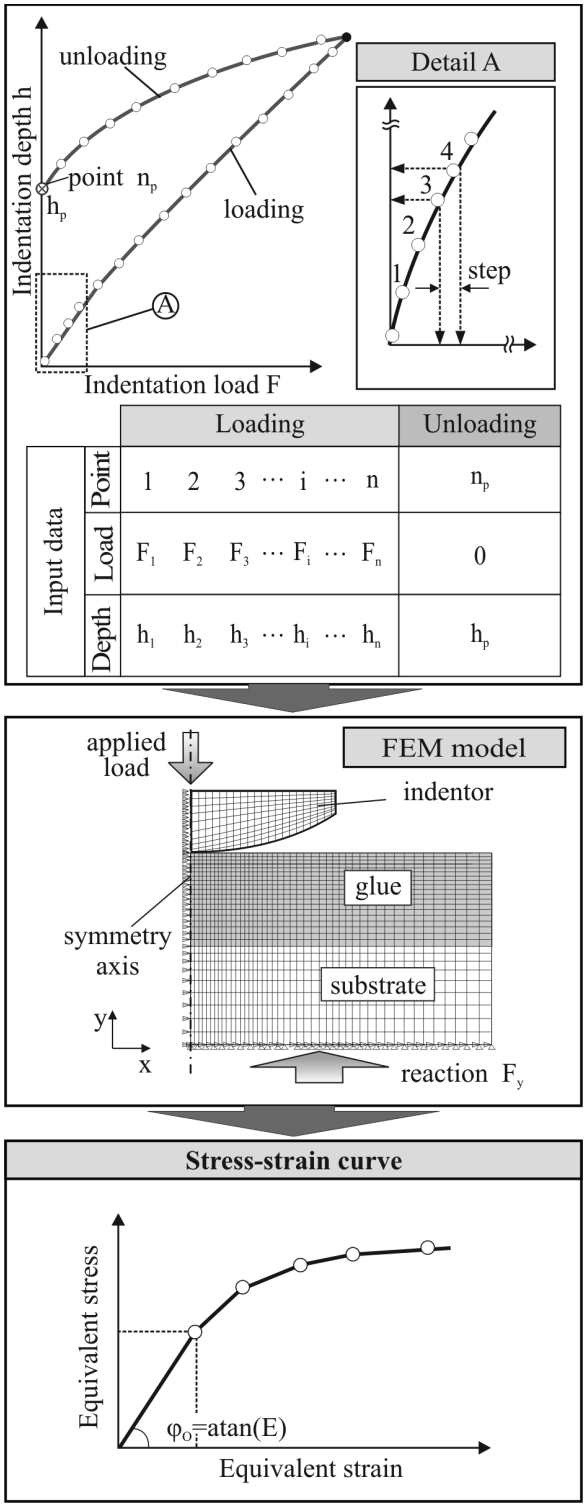
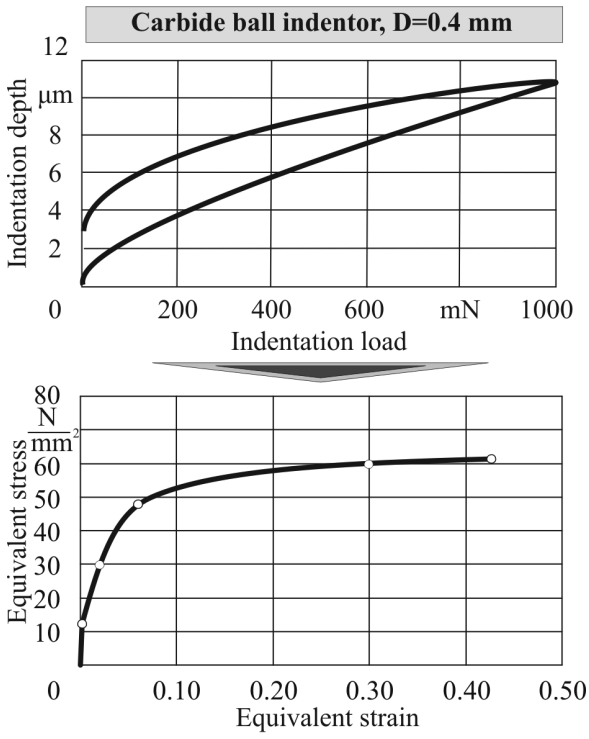


Fig. 1. The experimental indentation depth – penetration load curve and the FEM procedure for the determination of the stress – strain curve

A further penetration of the carbide indenter leads to the elastic – plastic flow of the examined material at the contact area beneath the indenter.

The applied axisymmetric FEM model, used for the determination of the mechanical properties of the epoxy glues, is illustrated in the middle part of figure 1. The penetration depth versus indentation load curve of the investigated material is used as the input data to the FEM model. The solution of this FEM simulation gives the load F_y, which is the reaction load occurring as the carbide ball penetrates into the glue material. For each specified glue type, there is only one penetration depth – penetration load experimental curve, derived direct from the nanoindentation test. Therefore only one stress-strain curve gives the same, through FEM procedure, analytical results, identical to the experimental ones [4,5].



	E (N/mm²)	R_E (N/mm²)
Epoxy resin	5500	14.0

Fig. 2. Experimental and analytical curves of the investigated epoxy resin

The elasticity modulus and yield strength can be determined using the experimental data of the first area of penetration depth - indentation load

curve. This can be succeed by inserting small penetration depth into the FEM model and compare the output results with those of the first elastic area of the aforementioned curve. The whole stress-strain curve of the investigated glues is determined by the continuous FEM simulation of the penetration of the indenter into the material. The final stress – strain curve is illustrated at the bottom part of the same figure.

The application of the above mentioned analytical – experimental procedure on the epoxy resin as well as the experimental and stress – strain curves, are illustrated in figure 2. The diameter of the carbide ball during the nanoindentation procedure was 0.4 mm. The maximum penetration load during the investigation of these glues was 1000 mN [6]. The determined stress – strain curve are illustrated in the middle part of the same figure.

3. Static tensile loading of epoxy resin

An important property of epoxy resin materials is their strength under static tensile loading. This behavior is due to adhesion between the epoxy resin and the glued material. The static tensile loading behavior of epoxy resins is detected using the experimental set-up shown in figure 3. The operation of the experimental apparatus is numerically controlled. The application of the operational parameters and experimental data acquisition are explained in [5].

This apparatus has the capability of measuring the applied force and the occurring elongation of the glued specimens at the same time. The maximum available tensile load is 10000 daN. Elongation measurement is achieved with an inductive sensor, with accuracy less than 1 μm. The examined specimens are rectangular rods of 25 x 8 mm mm^2 glued with various types of epoxy resin materials [4,7,8].

In the right part of figure 3, a typical glued specimen as well as the applied tensile force is shown. The thickness of the epoxy resin between the glued surfaces is 0.1 up to 0.4 mm. The lower part of the specimen is

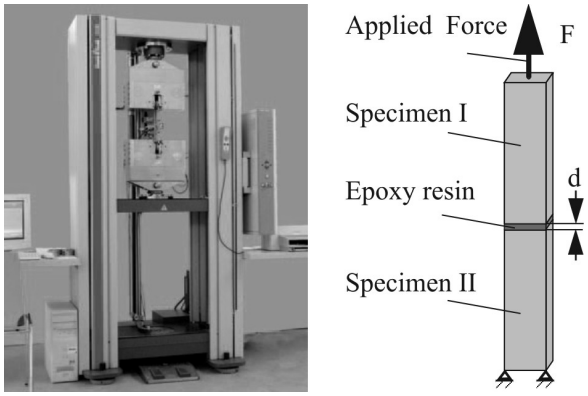


Fig. 3. Experimental device for the tensile loading of glued specimens by epoxy resin

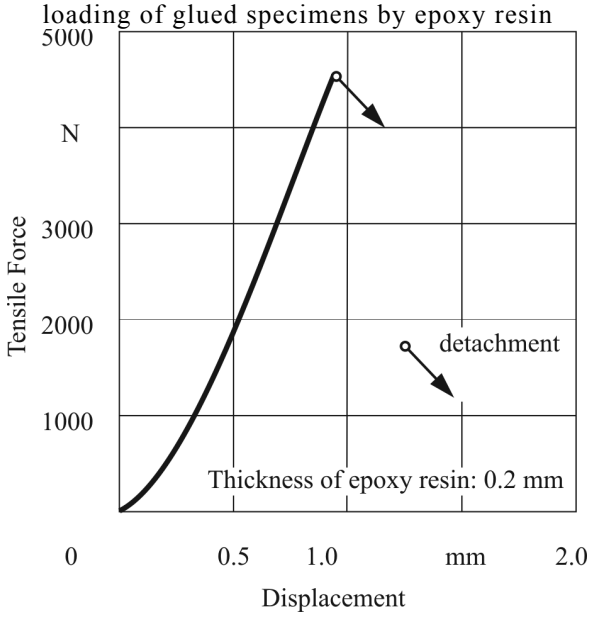


Fig. 4. Experimental results from the tensile tests

founded to the tester base, while the upper part is mounted to the piston pin of the experimental device and follows its movement.

The applied tensile force versus the relative elongation of the epoxy resins are illustrated in figure 4 for the examined epoxy resin types. The end point of each curve refers to the separation of the glued specimens. It is evident, that the tested epoxy resin withstands a tensile separation force up to 4554 N, before any separation between the rods occurs.

In that case, the maximum elongation before the epoxy resin failure is 0.8 mm, as shown at the lower part of figure. Through the deformation increasing, an epoxy resins ductility deterioration occurs, leading to an abrupt fracture, after a steep tensile force growth.

The failure of the epoxy resins and the consequent separation of the glued cylinders can be elucidated through a FEM simulation

model of the static tension test. This model is presented in figure 5. A cross-section of the glued rectangular specimens is illustrated in the left part of this figure. The FEM simulation model is shown at the right part of the figure, where the elements discretization and the axis of symmetry are demonstrated. Mechanical properties and especially the stress-strain curves of the examined epoxy resins and the aluminum specimen, are used as input data in this FEM simulation model.

The occurring experimental data described in figure 2 are processed with the FEM simulation model and the failure modes of the epoxy resin are determined which can be either cohesive or adhesive.

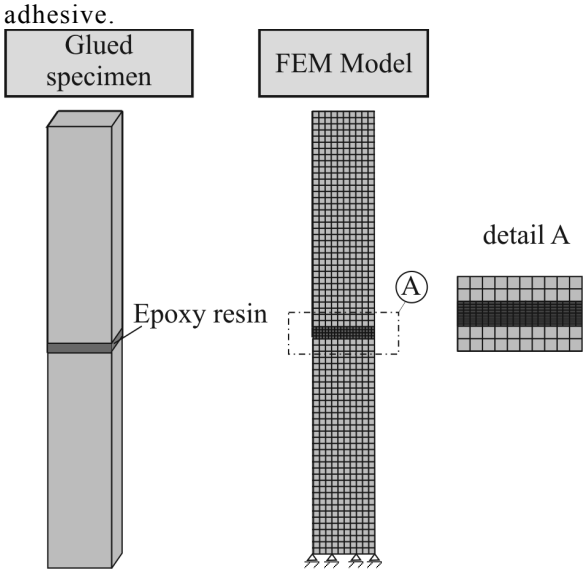


Fig. 5. FEM simulation model of the glued cylinders' tensile test.

The FEM-determined results of the epoxy resin are given in figure 6. Equivalent stress distributions in the interior of the aluminum rectangles and the epoxy resin are presented. Apparently, the maximum stresses causing the failure of the epoxy resins are observed at the interface between the two materials, the epoxy resin and the rectangular specimen. A poor adhesion between the two materials is responsible for the early loss of bonding between the glued rectangles, which is verified by the occurring stresses in the epoxy resins, since these stresses are below their stress limits.

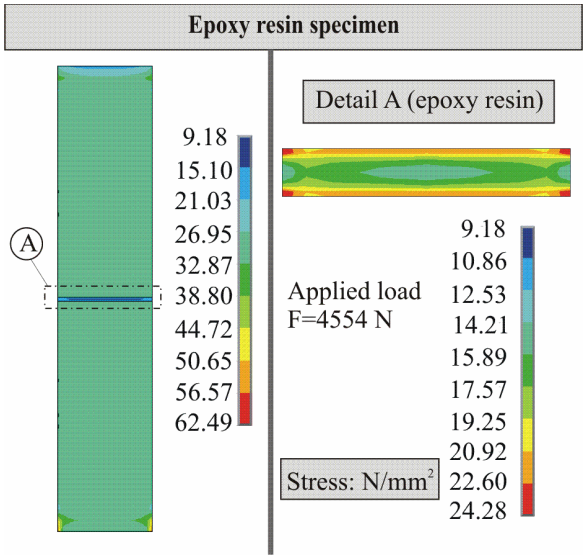


Fig. 6. Typical FEM simulation results of the tensile loading for the cylinders bonded with epoxy resin.

4. Experimental procedure for the tensile testing of aluminum tubes glued by epoxy resin

The goal of the present experimentation is to determine the elasticity modulus and the tensile strength of various epoxy resins applied on aluminum tubes, representing actual glued assemblies in real conditions.

Special attention is taken into account in the proper placement of the specimens on the holding table, aiming to keep the load parallel to the epoxy resins during the tests, in order to avoid shear loading of the resin. The experiments are performed in the Laboratory of Machine Tools and Manufacturing Engineering of the Aristoteles University of Thessaloniki, using a tensile device.

4.1 Description of the proper preparation of the specimens and the test device

The examined case is a two aluminum tubes assembly subjected to tensile loading. Steel cylinders are constructed and placed inside the aluminum tubes, as shown in figure 7. The steel cylinders' length is longer than the tubes by 5 mm and its diameter smaller by 0.8 mm than the inner diameter of the aluminum specimen, in order to reduce their deformation during the loading stage and not affect the measurements. Threads are constructed in the center of the upper and lower surface of the steel studs, in order to install them on the experimental device.

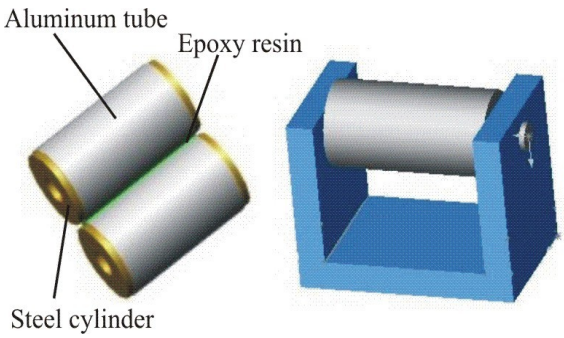


Fig. 7. Glued specimens of the tensile strength and holding rig of the tested specimens

A significant part of the experimental procedure is the proper holding of the assembly on the test apparatus. The upper part of the holding rig consists of a metal Π shape base with holes on its lateral sides in order to fasten with screws the top part of the assembly (see figure 7). On the metal holding base of the dynamometer, an identical metal Π shape base holds the lower part of the specimen.
The experimental set-up for tension tests is based on the one presented in figure 3, taking into account the aforementioned speculations for the suitable seating of the specimens on the holding table. Figure 8 illustrates clearly the herein developed experimental set-up.
The tested specimens are all glued in the same way. After the previously mentioned preparation, the specimens are placed on the holding device, and a strain gage is properly connected. Moreover, displacement is applied by means of a pneumatic piston and the tensile force is measured.

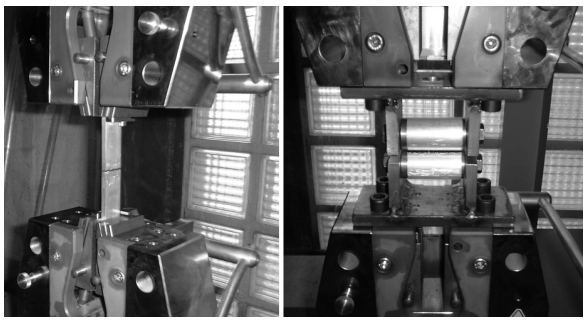


Fig. 8. Tensile tests on the experimental device

4.2 Conduction of the test procedure and respective results

Figure 9 presents the experimental results of specimens glued by epoxy resin subjected to tension.

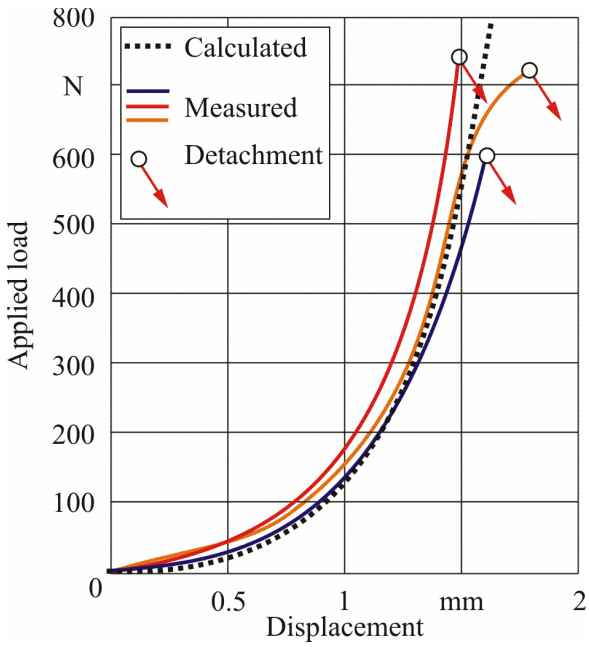


Fig. 9. Theoretical and measured results of the epoxy resins under tension

The range of the force values that lead to fracture of the glued specimen varies between 600 N and 742 N, while the epoxy resin displacement on the specimen before the fracture is in the range 1.48 mm to 1.83 mm. The FEM calculated curve is also shown in this figure. The good approximation between the theoretical and the measured curves is owed to the appropriate determination of material mechanical properties used in the FEM simulation.
Furthermore, the specimens' behavior is stronger affected by the adhesive bonds evolved between the glued surfaces, along with the proper application of the loading, to avoid shear effects. The combination of shear and tensile stresses leads to critical reduction of the load, where failure occurs. The dispersion of the experimental results is due to the adhesive bonds developed on these surfaces.

5. FEM Simulation Model Of Tensile Loaded Aluminum Tubes Glued By Epoxy Resin

In order to determine epoxy resins' failure mechanisms that lead to bonding loss of the glued cylinders, experimentally examined in the previous paragraph, FEM simulation models of the tensile loadings are herein developed.
The investigated problem is the join of two tubes for tensile loading, as illustrated in figure 10. In the two tubes system the tubes are joined together along a line. To avoid local overloading of the tubes, the forces are applied

on a steel tube placed inside the aluminum tube. In this way, the distribution of the force is uniform on the left tube face, while the boundary conditions imposed on the lower line, prevent the motion at the vertical axis.

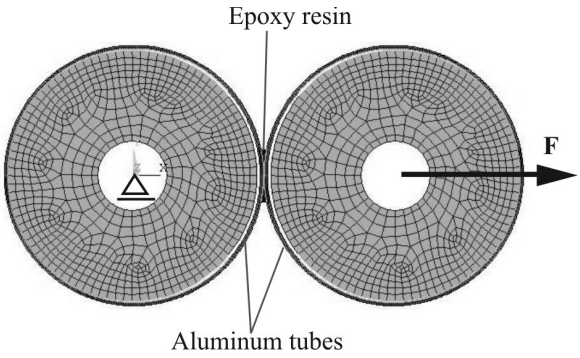


Fig. 10. FEM model of the glued tubes assembly

In the FEM model, the finite element size of the resin, the aluminum tube and steel cylinder is created different, as shown in figure 11. Contact elements are also used between cylinder and tube interface [9, 10, 11].

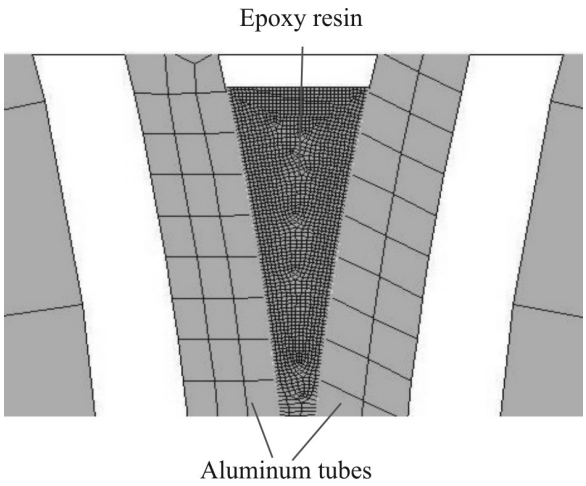


Fig. 11. Detail of the FEM model in the region of the resin and aluminum contact

5.1. FEM results of the glued specimens tensile test

The abovementioned FEM simulation results are shown in figure 12. The von Mises equivalent stress distribution inside the epoxy resin and the maximum value for the various loads are presented in this figure. These results exhibit that large portion of the resin remains unloaded and they are below fraction limit which is 60 N/mm2.

Considering the above, a different developed FEM model is created, by removing the inner not loaded resin region. The results are shown in figure 13. A very small variation of the occurring stresses occurs, in comparison to the previous ones with the full resin form case.

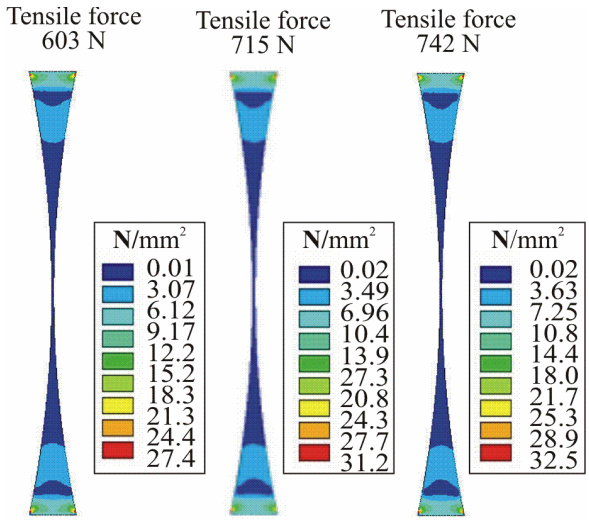


Fig. 12. von Mises equivalent stress distribution under 603, 715 and 742 N

Figure 14 exhibits the maximum occurring equivalent stresses for various removed resin region cases. It can be observed for removed region widths of 1 up to 4 mm that the maximum equivalent stress remains constant.

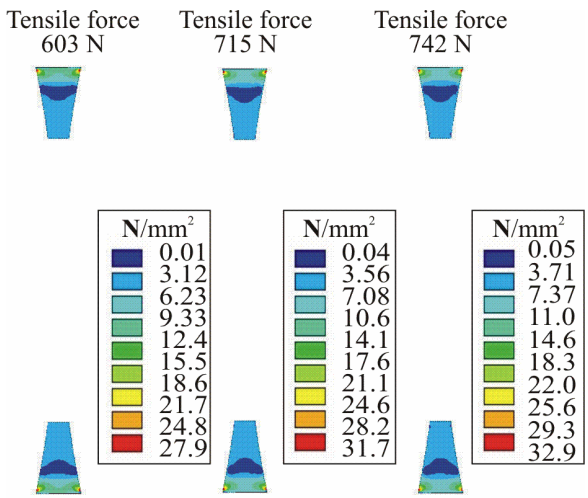


Fig. 13. von Mises equivalent stress distribution under 603, 715 and 742 N, and removed resin region of 4 mm

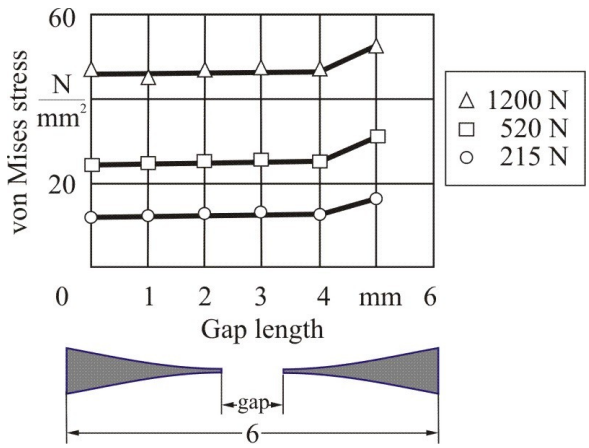


Fig. 14. The maximum developed von Mises equivalent stress for removed resin region 0 up to 5 mm at various loads 215, 520 and 1200 N

6. Conclusions

In the present paper the determination of the epoxy resin behavior considering tensile loading is explained. This resin is used to glue aluminum cylindrical specimens. The experimental results are simulated by means of developed FEM models, concerning the stress – strain curves of the involved materials. The results illustrate that the epoxy resin failure occurs due to bad adhesion of cemented surfaces and not by exceeding the ultimate stress limit.

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