Comparative Static and Fatigue Tests of Laminate-to-Aluminum-Alloy Adhesive Joints

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1. Introduction

Adhesive bonding can be succesfully applied to modern fibreglass structures when laminate-to-metal joints are employed. The metal-to-metal adhesive bonding processes are well known. Many different synthetic adhesives have been investigated and have found wide application in aluminium alloy aircraft structures.

There are, however, reasons to suppose that the adhesive laminate-to-metal bonding may introduce some new problems if the types of adhesives for metal-to-metal bonding are used. One has to, take into account that laminates consist of two different materials, the synthetic resin and the reinforcement. The adhesion of adhesives to each component can be different, therefore both static strength and fatigue properties of the joints can be different too and will depend on the resin-to-reinforcement ratio on the surface of laminate.

2. Programm of Investigations

The investigations reported were intended to compare static strength and fatigue life in normal temperature of adhesive laminate-to-al-alloy joints represented by lap joint specimens.

It was decided to test two adhesives which were radically different as regards chemical properties, shear strength, and shear modulus of elasticity. It was also decided to examine different methods of laminate surface pretreatment, intending to determine the influence of simple mechanical pretreatment and use of abrasive paper. Comparative fatigue tests were carried out for those speciments having the highest static strength.

The type of specimen (Fig. 1) composed of aluminium alloy sheet and fribreglass sheet was selected considering the results of other similar experiments. The specimens were designed to avoid high stress comentration in the adhesive and were accepted as the standard specimens for adhesive joint testing.

The thickness of laminate as well as aluminium alloy resulted from the following asumption:

$$E_L \cdot \delta_L = E_A \cdot \delta_A$$

where:

- Young's modulus of laminate
- Young's modulus of al-alloy
- thickness of laminate sheet
- thickness of al-alloy sheet.

The adhesives were selected from two groups which had already been applied in metal-to-metal bonding of thin-sheet al-alloy structures. The representative rigid adhesive was ME-1, based on an epoxy resin and evaluated several years ago in Poland. Shear modulus of elasticity of the adhesive at normal temperature ist $G \approx 400$ [MPa] and the shear strength in metal-to-metal bonding is $\tau_S \approx 40$ [MPa] when thickness of the adhesive film is about $\delta = 0{,}2$ mm. The representative elastic adhesive was WK-3, based on a phenol-formaldehydic resin and evaluated in USSR. Shear modulus of elasticity of the adhesive is $G \approx 6$ [MPa] and the shear strength in metal-to-metal bonding is $\tau_S \approx 20$ [MPa] at the same conditions as mentioned above.

Adhesion of both adhesives to al-alloy is good when the surfaces are adequately prepared, for instance the 'picling process', is applied and when other technical requirements are met. There are two requirements which are particularly important: heating up to the temperature of 165 ÷ 170°C and compression up to about 0,5 ÷ 0,8 [MPa]. The problems are, whether the strength of fibreglass will decrease in such conditions and how to prepare the surface of laminate for good adhesion.

In order to reduce the heat treatment influence on the strength of the laminate the following fibreglass was selected for testing:

- epoxy resin Epidian 53 with hardner MM – 40%
- glass roving ER 2003 – 60%

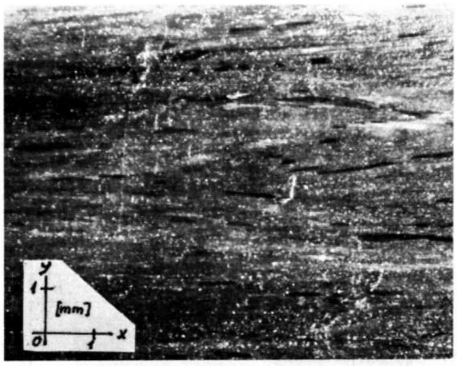

Fig. 2 Surface of laminate sheet after A-method pretreatment.

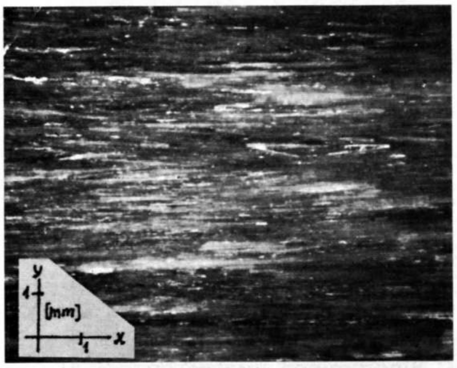

Fig. 3. Surface of laminate sheet after B-method pretreatment.

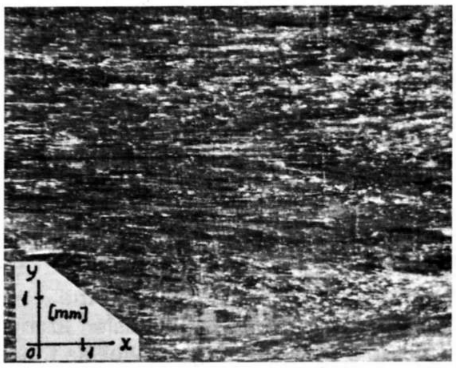

Fig. 4. Surface of laminate sheet after C-method pretreatment.

The laminate after additional hardening at a temperature of about 180°C has good static strength at elevated temperatures up to about 70°C.

Three following methods of laminate surface preparation were utilised:

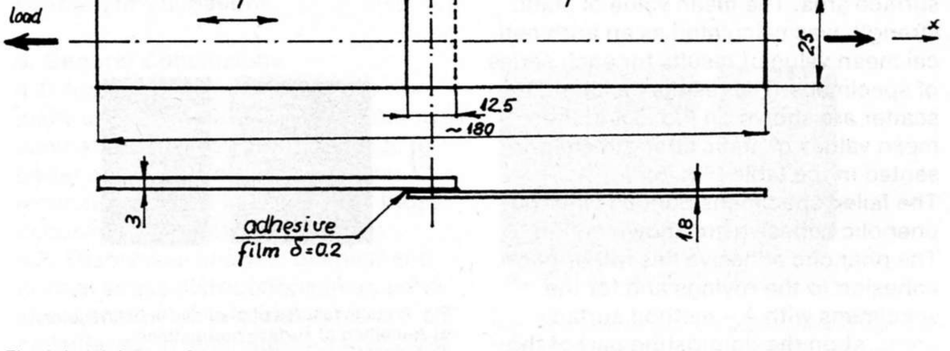

Fig. 1. Lap joint specimen
1. Fibreglass: Roving ER 2003 – 60%, Epidian 53+MM – 40%. 2. Al-alloy (Al-Cu-Mg)

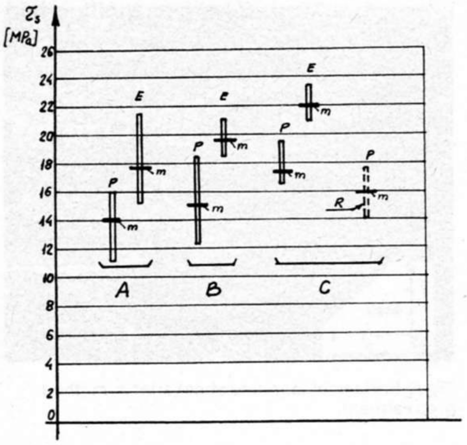

Fig. 5. Results of static shear strength investigations.
E – epoxy adhesive, P – phenolic adhesive; m – mean value of strength; R – residual static strength; A, B, C – Methods of surfaces preparation.

A. Washing in the solutions
1. based on benzine,
2. based on acetone.

B. Fine-grained abrasive paper 220 treatment in line with rovings + Washing as in A.

C. Fine-grained abrasive paper 220 treatment perpendicularly to rovings + Washing as in A.

Aluminium alloy sheet surfaces were prepared by the 'pickling process'. When method A was applied the cleaning of surface did not result in any change of surface structure (Fig. 2). Method B caused the grinding of external layer of resin (Fig. B) allowing better adhesion to the external rovings. However method C (Fig. 4) caused additionally the grinding of not only the resin but also some parts of the external rovings making the intrusion of the adhesive into the laminate easier. In this way the external rovings as well as the glass filaments lying under the external rovings were bonded with the adhesive.

3. Method and Results of Investigations.

3.1. Static investigations.
Static shear strength of all types of specimens was investigated using a Pauenstein machine. Not less then ten specimens of each type were tested. The static shear strength τ_s was calculated as the quotient of the force causing failure and the true value of bonding surface area. The mean value of static strength was calculated as an arithmetical mean value of results for each series of specimens. The results including the scatter are shown on Fig. 5 and the mean values of static strength are presented in the table (Fig. 6).

The failed specimens bonded with the phenolic adhesive are shown on Fig. 7. The phenolic adhesive has rather poor adhesion to the rovings and for the specimens with A – method surface preparation the dominating part of the failure is of an adhesion type. The best results arose when C-method was applied, due to the greater number of rovings bonded with the adhesive film. The failed specimens bonded with the epoxy adhesive are shown on Fig. 8. Here the dominating part of the failure is that of the rovings. The best results arose, as previously, when using C-method of surface preparation. Comparing all the results one can state that the strength of specimens with A or B or C-method of surface preparation was always better when the specimens were bonded with the epoxy adhesive than with the phenolic one. Based on the results of microscopic analysis one can also state that about 70% of the surface consists of rovings when C-method is used. Another observation is that the epoxy adhesive, which during the bonding process changes into a high viscosity liquid, adheres very well to the glass filaments. The joints of glass filaments and phenolic adhesive are clearly worse because this adhesive remains as an elastic film during the bonding process.

static shear strength				residual strength
	τ_s [MPa]			
surface preparation	A	B	C	C
epoxy adhesive	17.7	19.5	22.0	-
phenolic adhesive	14.0	15.1	17.8	15.9

Fig. 6 Table of the mean values of static shear strength.

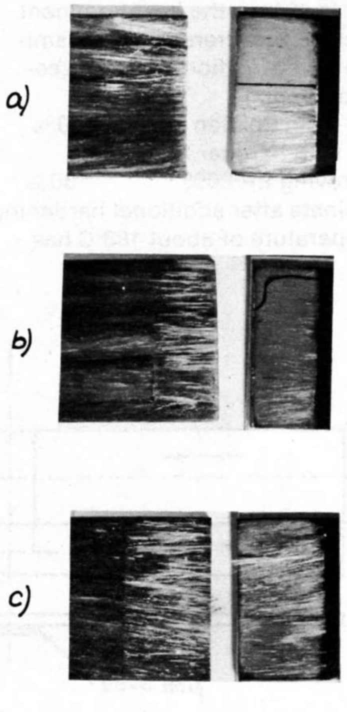

Fig. 7. static failures of phenolic adhesive joints.
a) A-method of surface pretreatment;
b) B-method of surface pretreatment;
c) C-method of surface pretreatment.

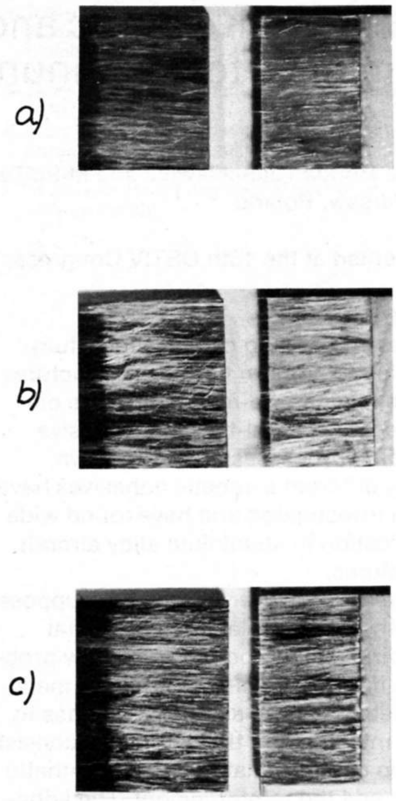

Fig. 8 static failures of epoxy adhesive joints.
a) A-method of surface pretreatment;
b) B-method of surface pretreatment;
c) C-method of surface pretreatment.

The main conclusions resulting from the investigations are the following.
1. The static shear strength of laminate-to-al-alloy adhesive joints depends basically on the adhesion of the glass filaments to the adhesive and on the strength of the filaments as well.
2. Shear modulus of elasticity and static shear strength of adhesive measured on metal-to-metal joints have no significant meaning for the static strength calculations of laminate-to-metal joints.

3. When only chemical pretreatment of laminate surfaces is applied, it leads to a higher scatter of results and lower values of static shear strength, due to non-uniform roving/resin ratio on the surface.
So it becomes clear that the inclusion of abrasive paper treatment in the surface preparation should lead to increased static strength and also decreased scatter of results.

3.2. Fatigue investigations.
According to the static tests results the simplified fatigue test program was carried out. Two series of specimens were tested, being respectively epoxy adhesive joints and phenolic adhesive joints, with C-method of surface preparation. A fatigue load cycle of constant mean load value, corresponding to $^1/_3$ of static shear strength, was chosen. The program was carried out using mechanical fatigue test machines.
The results of the tests are presented as fatigue curves in absolute coordinates

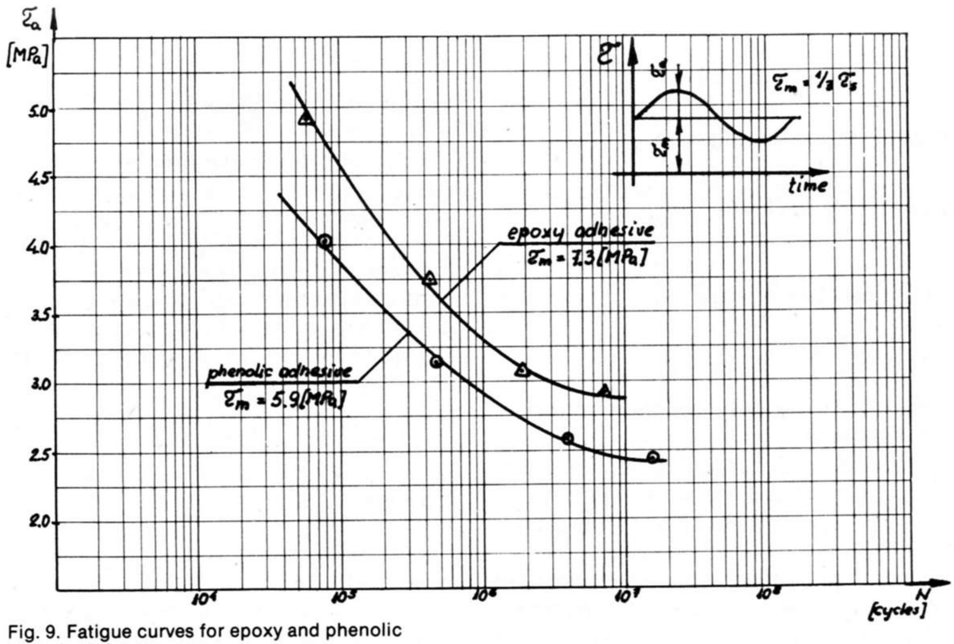

Fig. 9. Fatigue curves for epoxy and phenolic adhesive joints.

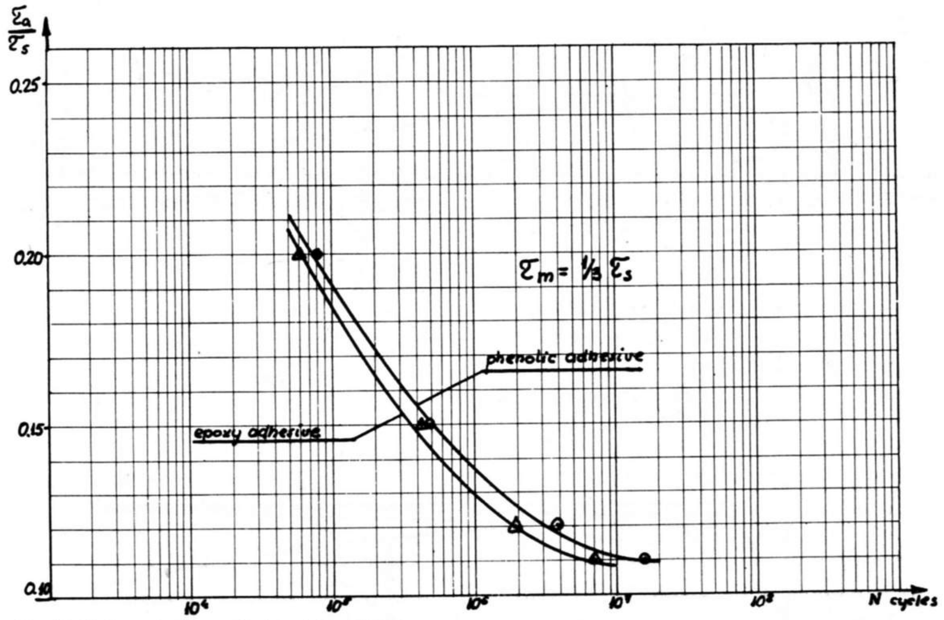

Fig. 10. Fatigue tests results in relative stress amplitude coordinate.

(Fig. 9) and also as ratios to static strength (Fig. 10). The specimens bonded with the epoxy adhesive failed similarly to those statically tested (Fig. 11). This means that the fatigue properties of adhesive are higher than those of the glass filaments in the particular composition tested. Failures of the phenolic adhesive bonded specimens occur also inside the adhesive (Fig. 12) and on the laminate surface (adhesion type) so it can be concluded that the fatigue properties of phenolic adhesive are simmilar to these of glass filaments in the composition tested. It also means that the fatigue properties of the adhesion of phenolic adhesive to filaments and resin are lower than those of the epoxy type.

Some of the specimens bonded with phenolic adhesive did not fail up to N = 10^7 cycles when $\tau_a \approx 0{,}1\ \tau_s$. In such cases the fatigue tests were stopped and the specimens were tested statically in order to check the residual static shear strength. The results are presented in table (Fig. 6) which shows that the residual static shear strength decreases to about 85% of the initial value. On the photograph (Fig. 13) of failed specimen one can see two different types of failure, cohesive failure of adhesive caused by fatigue, and static failure simmilar to that found in static strength investigations.

4. General Conclusions.

4.1. Application of the adhesives normally used in metal-to-metal bonding in laminate-to-al-alloy bonding leads to better static and fatigue properties of laminate-to-metal bonding than those occurring with resin adhesives.

4.2. Theoretical analysis of shear and normal stress distributions in an adhesive when metal-to-metal joints are considered, in laminate-to-metal joints analysis application leads to incorrect results because of the different type of adhesion between the adhesive and the laminate.

The conclusions support continuation of the investigations and carrying out a theoretical analysis.

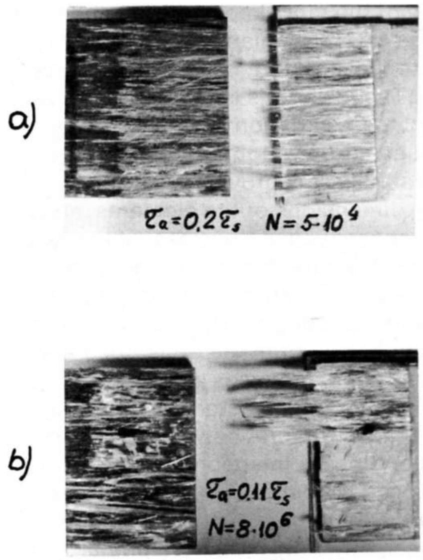

Fig. 11. Fatigue failures of epoxy adhesive joints: a) low fatigue life; b) high fatigue life.

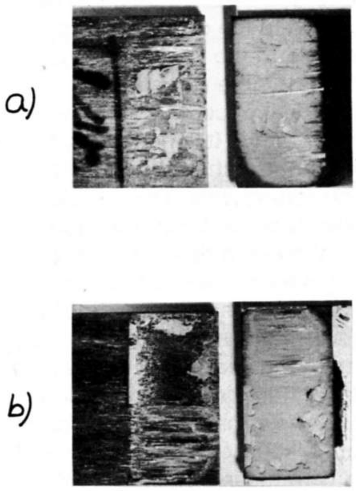

Fig. 12. Fatigue failures of phenolic adhesive joints: a) low fatigue life ($\tau_a = 0.2\ \tau_s$, N = $8 \cdot 10^4$); b) high fatigue life ($\tau_a = 0.12\ \tau_s$, N = $1.7 \cdot 10^7$).

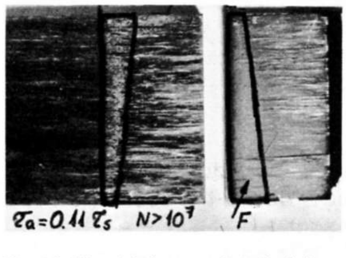

Fig. 13. Mixed fatigue and static failure of specimen after residual shear strength testing.
F → part of joint failed during fatigue testing.