Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 37 (1982)

Artikel: Fatigue characteristics of adhesive joints between aluminium alloys

Autor: Istafanaous, A.A.

DOI: https://doi.org/10.5169/seals-28982

Fatigue Characteristics of Adhesive Joints between Aluminium Alloys

Caractéristiques de fatigue d'assemblages collés entre alliages d'aluminium

Ermüdungseigenschaften geklebter Verbindungen bei Aluminiumlegierungen

A.A. ISTAFANAOUS
Dr. Eng.
Military Technical College
Cairo, Egypt

SUMMARY
This paper deals with an experimental study of the fatigue characteristics of a set of adhesive-bonded single lap joints. The joints were produced from aluminium alloys bonded with an epoxyde adhesive. The study of the joint fatigue behaviour considered the influence of geometric parameters, overlap lengths and metal sheet thickness. In addition the influence of the number of fatigue cycles on adhesive constants and optimum overlap length was investigated.

RESUME
Cet article traite d'une étude expérimentale sur les caractéristiques de fatigue d'une série de joints collés avec recouvrement simple. Les assemblages sont réalisés entre des alliages d'aluminium au moyen d'une colle epoxy. L'étude du comportement à la fatigue des assemblages prend en considération l'influence des paramètres géométriques tels que la longueur de recouvrement et l'épaisseur des tôles métalliques. On a en plus étudié l'influence du nombre de cycles de fatigue sur les caractéristiques de la colle et sur la longueur de recouvrement optimale.

ZUSAMMENFASSUNG
Der Beitrag behandelt experimentelle Studien auf dem Gebiet geklebter Verbindungen mit einfacher Überlappung. Die Leichtmetallbleche wurden mit einem Epoxi-Klebstoff geklebt. Die Studie untersucht den Einfluss geometrischer Parameter wie Überlappungslänge und Blechstärke auf die Ermüdungsfestigkeit der Verbindungen. Zusätzlich wird der Einfluss der Lastwechselzahl auf die Eigenschaften des Klebstoffes sowie auf die optimale Überlappungslänge betrachtet.

1. INTRODUCTION

The development of adhesives, having improved mechanical properties, had increased their importance as joining materials. The adhesive bonding technique had found many applications in the industry of automobiles, aeronautics and constructions in general. However, lack of design information, control of manufacturing variables, and quality control experience are prime factors for the rather hesitant acceptance of this technique. In particular, informtion about the fatigue behaviour of bonded joints is lacking. This paper presents the results of our experimental study of single lap bonded joints as a contribution to the fatigue characteristics of such joints.

2.DESIGN AND PRODUCTION OF TEST SPECIMENS

The fatigue tests were carried out on single lap bonded joints produced from sheets of different thicknesses of material 2024 T3 clad aluminium alloy used for aeronautics. The joints were bonded by the adhesive Redux 609 . The form of joints is shown on Fig.1. During fatigue tests it was studied the influence of two geometric parameters:
-overlap length, (it was used l_o = 25,20,15,10 mm)
-metal sheet thickness, (it was used t= 1,3,5 mm)
It was decided to use fixed width for all joints (25 mm) taking into account that it has no effect on the fatigue strength of the joint

To produce the bonded joints, the surfaces were firstly pretreated by degreasing, mechanical etching and finally pickling in a solution of sulphuric acid and sodium bichromate. Then the adhesive was applied under pressure $10 N/cm^2$ and temperature 120°C for 60 minutes.

3.TESTING PROGRAM

The tests were carried out on three groups of joints. The first group included the joints produced from emtal sheet thickness t=1 mm. The second and third groups had sheet thickness 3 and 5 mm respectively.Each group included several subgroups with different values of overlap length.

Tensile axial loading was used for all tests with a ratio of minimum to maximum load in the fatigue cycle R=0,1. The value of maximum stress in fatigue loading cycle (σ_{max}) was changed such that σ_{max} would be in the order of (50-15)% σ_{st} (where σ_{st} was the strength corresponding to static failure of joint). The tests were stopped when the number of loading cycles was reaching N $=10^7$ cycles without failure of joint and the corresponding value of stress was considered as fatigue limit σ_f. During all tests the temperature was kept as ambiant one.

The testswere carried out on fatigue testing maching Vibrophore Amsler with high frequency, type 10 HFP 422. The used testing frequency was depending on sheet thickness as shown:

t	|mm|	1	3	5
f	|Hz|	91	100	125

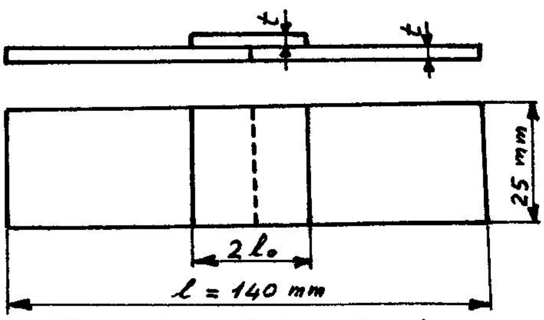

Fig.1 Form of Test Specimen

4. TEST RESULTS AND DISCUSSION

4.1. Results and Types of Failure

From the results of fatigue tests, it was plotted the fatigue curves for each parameter as shown in figures 2,3 and 4. These curves gave us the possibility of better comparison of results.

The joints failure was either in the metallic sheet or in the adhesive layer.The metallic failure occured always in the middle of the cover plate. The metallic failure occured when we were near to fatigue limit (at $N=10^7$ cylces) in case of small thickness and great overlap (t= 1 mm, l_o= 20 mm) . For the joints with greater thickness all failures were in the adhesive only because the sheets are more rigid and they resist fracture.

4.2. Effect of Overlap Length

Fig.2. shows that the fatigue strength σ_{max} increases as the overlap length increases. For smaller values of N (at $N=10^5$ cycles), the fatigue strength increases by 50% and 100% as l_o increases to 15 mm and 20 mm respectively. For greater values of N (at $N=10^7$ cycles), the increase in fatigue strength is not so great.

The joints with thickness t= 3 mm (Fig.3) give the same type of results, the fatigue strength increases with the overlap. The joints with l_o=25 mm has better strength for small N but starting from $N=1,5 \times 10^6$ cycles their strength is smaller. For t=5 mm (Fig.4), the joints with l_o= 25 mm have smaller strength starting from $N=1,5 \times 10^5$ cycles. Then the great values of overlap are prefered only for small endurance ($N < 10^5$ cycles). The overlap l_o=10 mm gives a very high resistance which signifies that at great thickness and at great N, the increase of overlap is not able to cause an increase in fatigue strength. This shows that the effect of stress concentration became very great.

Then it can be concluded that the fatigue strength is higher, at high endurances, if the overlap length is decreased as the thickness increases.

4.3. Effect of Thickness of Metal Sheet

If we compare the influence of thickness on the fatigue strength for the same value of overlap, we see from Fig.5 that the strength is higher when t decreases. It must be noted that the increase of strength for t= 1 mm is relatively great in comparison with the increase obtained for t=3 mm. This is explained by the fact that the role of bending moment and stress concentration is very weak for the joints with small thickness.

4.4. Variation of F_{max}

It is plotted Fig.6 to give us the possibility to make a comparison from the point of view of fatigue force acting on the joint, F_{max}. It can be seen that for smaller endurance ($N < 10^5$ cycles) F_{max} increases when t decreases, while for higher endurance ($N > 10^5$ cycles) F_{max} increases when t increases too.

4.5.Variation of Ratio ($\sigma_{max}/ \sigma_{st}$)

The fatigue test results were represented in another dimensionless scale ($\sigma_{max} / \sigma_{st}$) and due to this representation the curves were more separated at hight endurance (see Fig.7). The ratio $\sigma_{max}/ \sigma_{st}$ indicates the dynamic efficiency of the joint related to its static characteristics. The figure show that at high endurance ($N > 10^5$ cycles) the joint efficiency is great for smaller overlap while at small endurance ($N < 10^5$ cycles) the joint efficiency is great for greater overlap.

It was used the same representation to determine the effect of thickness for a given value of overlap (Fig.8). It is seen that for high endurance the joint efficiency increases with the thickness and for small endurance the joint

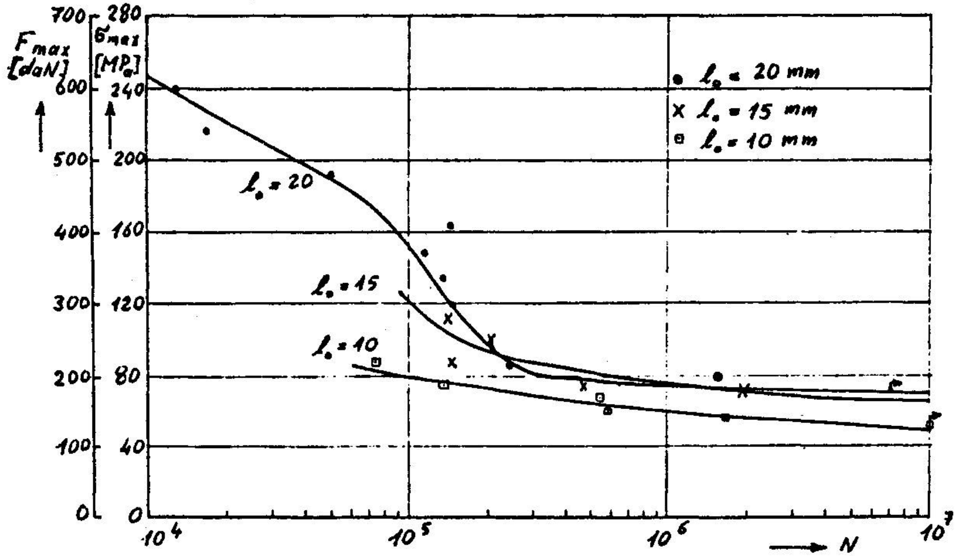

Fig.2 Fatigue Curves for Joints with t=1mm and Different l_o

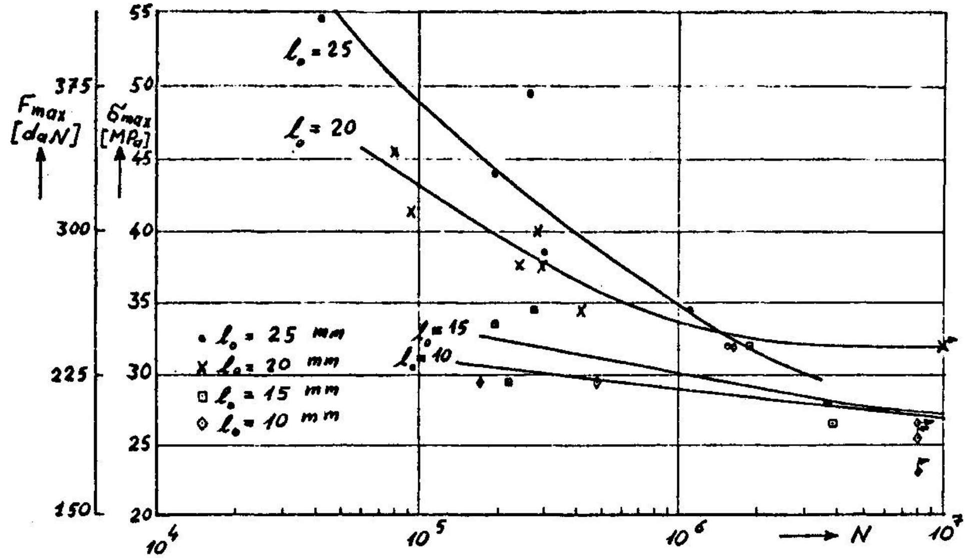

Fig.3 Fatigue Curves for Joints with t=3mm and Different l_o

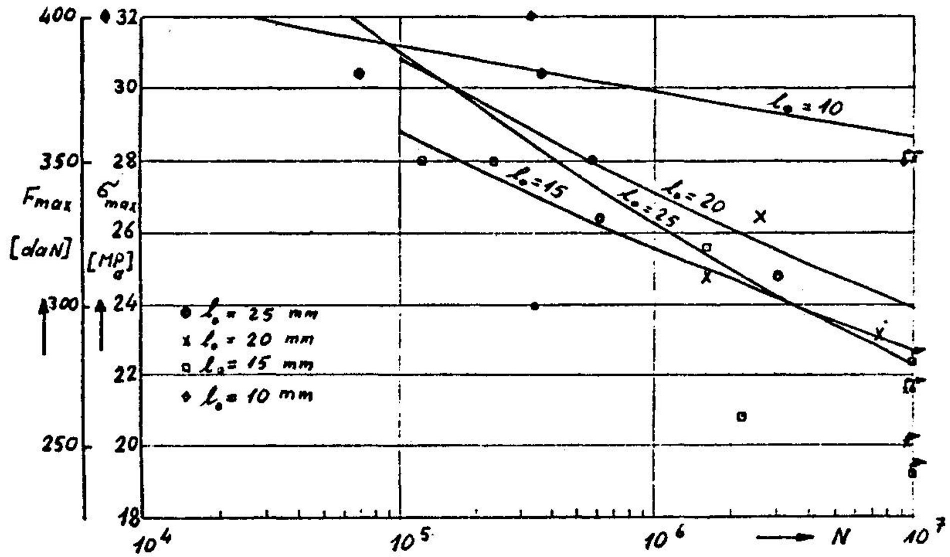

Fig.4 Fatigue Curves for Joints with t=5mm and Different l_o

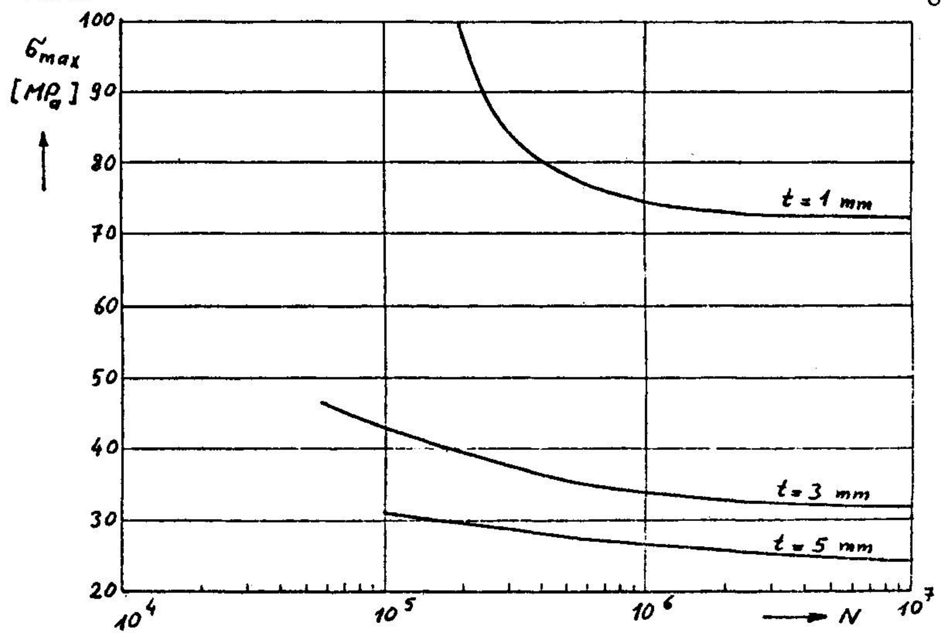

Fig.5 Influence of Sheet Thickness on Fatigue Strength for l_o = 20 mm

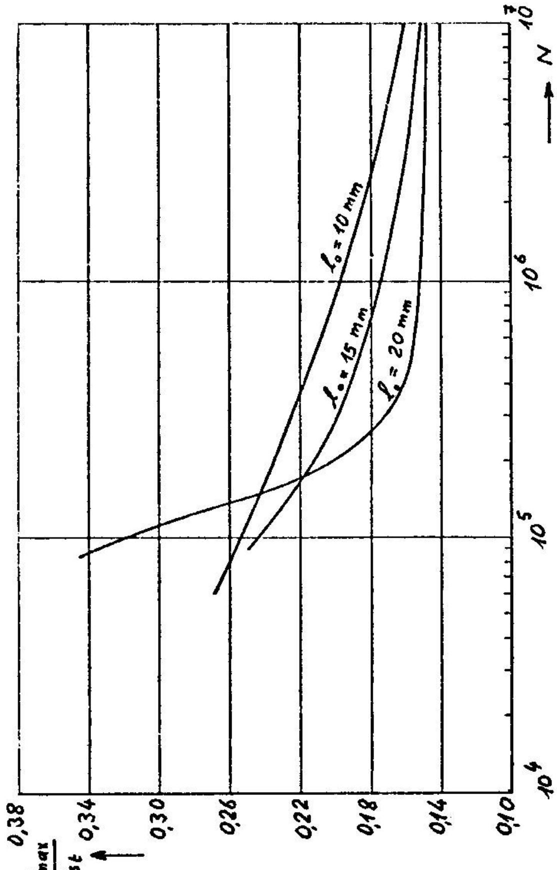

Fig.7 Influence of Overlap Length on ratio $\frac{\sigma_{max}}{\sigma_{st}}$ for t=1mm

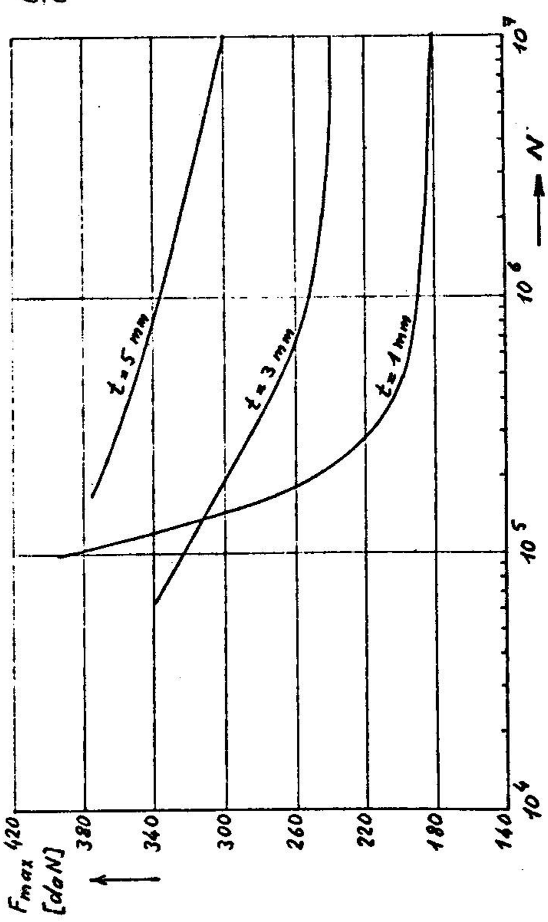

Fig.6 Influence of Sheet Thickness on Fatigue Force for l_o=20mm

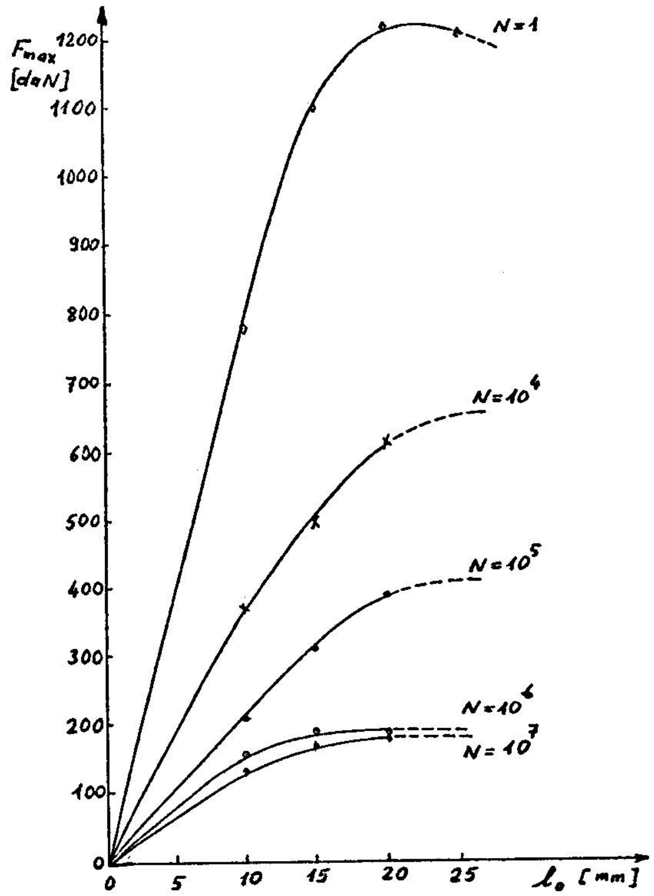

Fig.9 Variation of Fatigue Force with l_o for Different Endurances, t=1mm

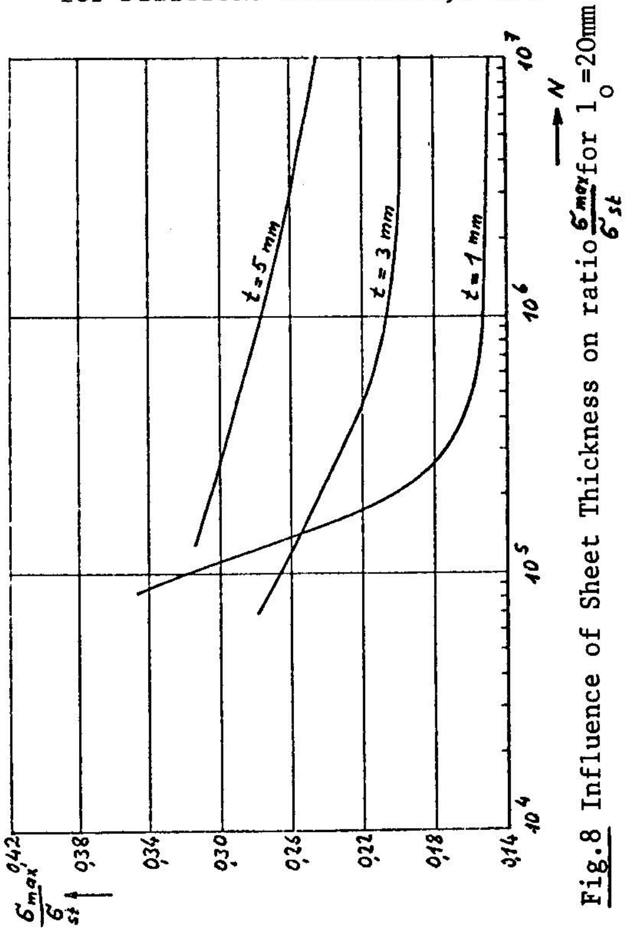

Fig.8 Influence of Sheet Thickness on ratio $\frac{\sigma_{max}}{\sigma_{st}}$ for l_o=20mm

efficiency is higher for smaller t.

5. EFFECT OF (N) ON THE ADHESIVE CONSTANTS τ_o AND C

In reference [1], Szépe had concluded that the value of maximum shear stress in an elastic adhesive layer assuming plates of unit width is :

$$\tau_{max} = \tau_{avg} \left(1 + \frac{Cl_o^2}{6Et}\right) \qquad (1)$$

It can be assumed that failure occurs in an adhesive layer when τ_{max} reaches the shear strength of the adhesive, τ_o. i.e., when $\tau_{avg} = \tau_u$

According to formula (1), the average ultimate shear stress of the adhesive-bonded lap joint can be calculated from the following formula:

$$\tau_u = \frac{\tau_o}{1 + Cl_o^2/6Et} \qquad (2)$$

and the ultimate load (F_u) of the bonded joint can be calculated:

$$F_u = \tau_u l_o = \frac{\tau_o}{\frac{1}{l_o} + \frac{Cl_o}{6Et}} \qquad (3)$$

In formula (3), there are two unknowns, τ_o and C, which can be regareded as adhesive constants . In order to determine the two unknowns, two equations are required. These may be obtained from tests on two joints with two different lengths of overlap.

In our case , from the fatigue curves shown in Fig. 2, it can be obtained the curves giving F_{max} as a function of l_o for different endurances, as it is shown on Fig. 9 [see references 3 and 4]. Applying formula (3) taking into account F_u as F_{max}, at each curve given in Fig. 9 it can be calculated the adhesive constants corresponding to each endurance. The result is drawn in Fig.10 which shows that τ_o decreases with number of cycles while C is not affected by it.

6.EFFECT OF (N) ON THE OPTIMUM OVERALAP LENGTH

In formula (3), the ultimate load will be maximum ($F_{u\,max}$) when the denominator is minimum. In this case the length of overlap is denoted by l_{opt}, where

$$l_{opt} = \frac{1}{\sqrt{\alpha}} \quad , \quad \alpha = \frac{C}{6Et} \qquad (4)$$

Substituting this in formula (3), $F_{u\,max}$ becomes

$$F_{u\,max} = \frac{1}{2}\,\tau_o\, l_{opt}$$

Hence, the optimum overlap length l_{opt} is

$$l_{opt} = \frac{2F_{u\,max}}{\tau_o}$$

In our case $F_{u\,max}$ can be considered as the maximum value of the force reached at each endurance (see Fig.9). The calculated values of l_{opt} are given in Fig.11 which shows that the required value of optimum overlap length is smaller as the endurance increases.

7. CONCLUSIONS

From the previous discussion, it can be concluded the following:
- To have a better fatigue strength of adhesively bonded joint, at high endurance,

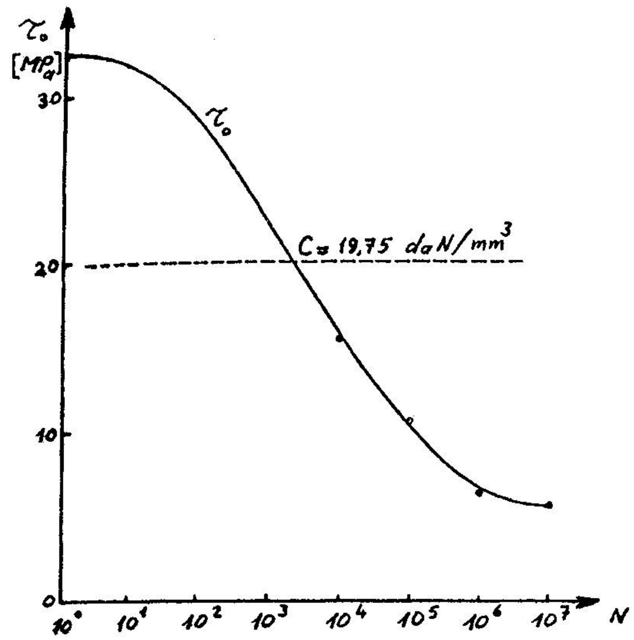

Fig.10 Variation of Adhesive Constants with Number of Cycles (Adhesive Redux 609)

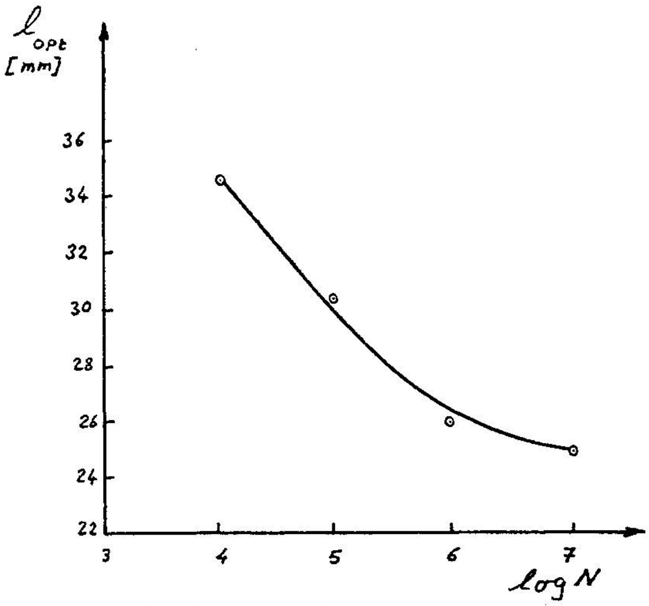

Fig.11 Variation of Optimum Overlap Length with Number of Cycles

it must be decreased the overalp length when the metal sheet thickness is great (Fig.4).

-For higher endurances ($N > 10^5$ cycles): use greater thickness and smaller overlap length . In spite of the great thickness decreases the fatigue strength (Fig.5), but the joint efficiency (Fig. 7 and 8) and fatigue force (Fig.6) are higher.

-For lower endurances ($N < 10^5$ cycles): use smaller thickness and greater overlap. This is the best solution from point of view of joint efficiency , fatigue force and fatigue strength.

-From point of view of fatigue strength: the use of thickness t=1 mm is the best for all endurances whatever the value of overlap.

-With increasing the number of fatigue cycles, the shear stress of the adhesive τ_o decreases while the adhesive constant C does not change and the required value of optimum overlap length is smaller.

NOTATIONS

l_o overlap length
t metal sheet thickness
σ_{max} fatigue strength
F_{max} fatigue force
N number of cycles to failure
E elastic modulus of the adherend
C constant of the adhesive, theoretically C= G/d

G shear modulus of adhesive
d thickness of adhesive
τ_{max} maximum shear stress in adhesive layer
τ_{avg} average shear stress
τ_u average ultimate shear stress
τ^o shear stress of the adhesive
F_u^o ultimate load of joint

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