FATIGUE CRACK GROWTH PREDICTIONS IN ARAMID REINFORCED ALUMINIUM LAMINATES (ARALL)

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Abstract

ARALL consists of thin sheets of high strength aluminium alloy, which are laminated using a structural adhesive and high strength aramid fibres. ARALL is extremely fatigue resistant, because the aramid fibres remain intact, if fatigue cracks occur in the metallic component. The crack growth rate in the aluminium sheets is reduced considerably due to the crack bridging by the fibres. The mechanical properties of ARALL are discussed and some potential applications for ARALL are presented. The fatigue mechanisms in ARALL are explained and a model is presented, which is able to calculate fatigue crack growth rates in ARALL for different constant amplitude fatigue loadings.

1. Introduction

During the use of an aircraft cyclic loadings occur on many structural components. These cyclic loadings cause corresponding cyclic material stresses. These stresses may cause the initiation and growth of fatigue cracks in the structure. Consequently a potential possibility of a final catastrophic failure of the structure due to fatigue damage is present. This aspect is especially relevant, because the fatigue stresses in modern aircrafts are high and the number of fatigue cycles is great. The high fatigue stresses are caused by the necessity of weight savings in the construction for reasons of economy (fuel consumption) and aircraft flight performance. Improvements of aircraft designs become possible, if stronger and lighter materials with a good fatigue resistance become available.

Presently the bulk of an aircraft construction consists of different aluminium alloys. Unfortunately, the strongest conventional aluminium alloys usually show only moderate fatigue performance and for fatigue critical aircraft components the designer must choose other more fatigue resistant alloys. The fatigue resistance of a metallic material can be classified by two properties:

- the resistance against the initiation of fatigue cracks
- the resistance against the growth of fatigue cracks.

The initiation of the fatigue cracks often takes place at notches in the structure, because the stresses in the notch root are higher than in the rest of the structure. Due to the great number of notches in an aircraft structure, and due to scatter in the fatigue crack initiation behaviour it is impossible to prevent the initiation of cracks with enough certainty, at an acceptable weight of the aircraft structure. Hence the safety of an aircraft has to be obtained with a damage tolerance approach (fail safe structure). Consequently the fatigue crack growth properties of a structural material are of major importance. Cracks have to be found before they become dangerous, so materials showing slow fatigue crack growth rates are required.

The hybrid material ARALL combines good strength properties to very slow fatigue crack growth rates and it is especially suitable for the application in fatigue critical aircraft structures.

2. Description of ARALL

ARALL is a hybrid composite material, which is developed to replace conventional aluminium alloy in fatigue critical aircraft structures. It was invented at the Technical University of Delft, The Netherlands.(1) ARALL consists of three components:

1. Thin high strength aluminium alloy sheets (about 65 % in volume ≈ 80 % in weight).
2. A structural adhesive (about 17 % in volume ≈ 10 % in weight).
3. High strength aramid fibres (about 17 % in volume ≈ 10 % in weight).

The aluminium alloy is the "body" of the material, it determines the (static) mechanical properties of ARALL to a large extent. The main function of the fibres is to bridge fatigue cracks in the aluminium, thus reducing the crack growth rates. The function of the adhesive is to impregnate the fibres and to connect them to the aluminium sheets.

The laminate build up is shown in Fig. 1. The fibres are orientated into the direction of the main fatigue load. The laminate is cured at 120 °C at curing pressures of up to 10 bar (depending on the kind of fibre adhesive combination layers). The crack bridging efficiency and the fatigue crack growth rates become better, if the thickness of the individual layers is decreased (and their number is increased). However, this is achieved at the penalty of higher material costs. A good compromise is achieved at a thickness of 0.3 to 0.5 mm for the aluminium sheets and of 0.2 to 0.3 mm

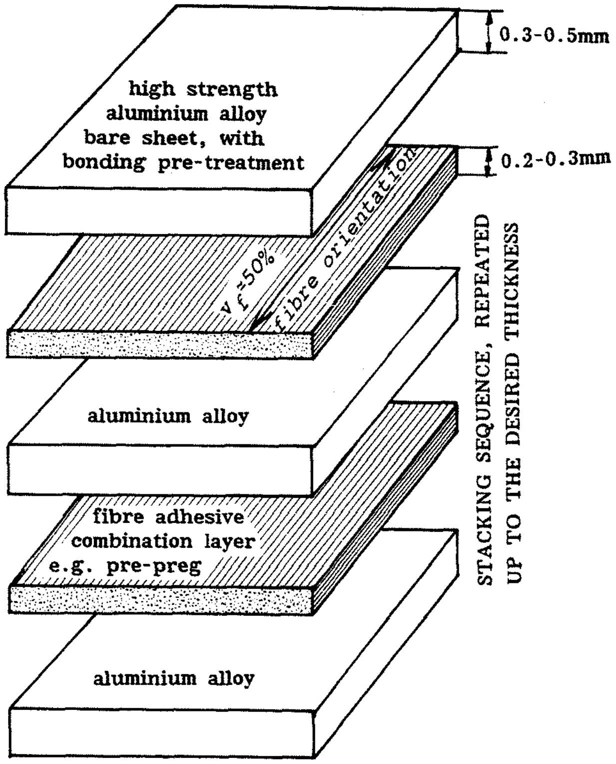


Figure 1. The laminate build up of ARALL

for the fibres adhesive combination layers.

ARALL contains unfavourable residual stresses, if a normal curing process is performed (tensile stresses in the aluminium sheets and compressive stresses in the aramid sheets). These stresses reduce the effect of the crack bridging mechanism to some extent. However, this residual stress system may be reversed, thus causing an additional improvement of the material properties. Two methods may be used to reverse the residual stress system: They are denoted as 1) pre-straining and 2) pre-stressing.

The pre-straining technique is applied after curing of the laminate. A small plastic strain of 0.5 - 0.7 % in the tensile direction is applied on the laminate, the fibres remain elastic, and after elastic unloading a part of the tensile stress remains in the fibres, and consequently the aluminium sheets are loaded by compressive residual stresses.

The pre-stressing technique is applied during the curing of the laminate. The fibres are loaded in tension, before the autoclave pressure is applied and the curing temperature is reached. The tensile stress on the fibres is kept during the whole curing process. After curing and unloading of the fibres a part of the tensile stresses remains present in the laminate and consequently, compressive residual stresses occur in the aluminium sheets. These stresses are denoted here with $S_{r,al}$. The residual stresses are introduced at the ends of the laminate by an I.L.S. field (compare Fig.2). Some more detailed descriptions of these techniques may be found in (2,3,4,5).

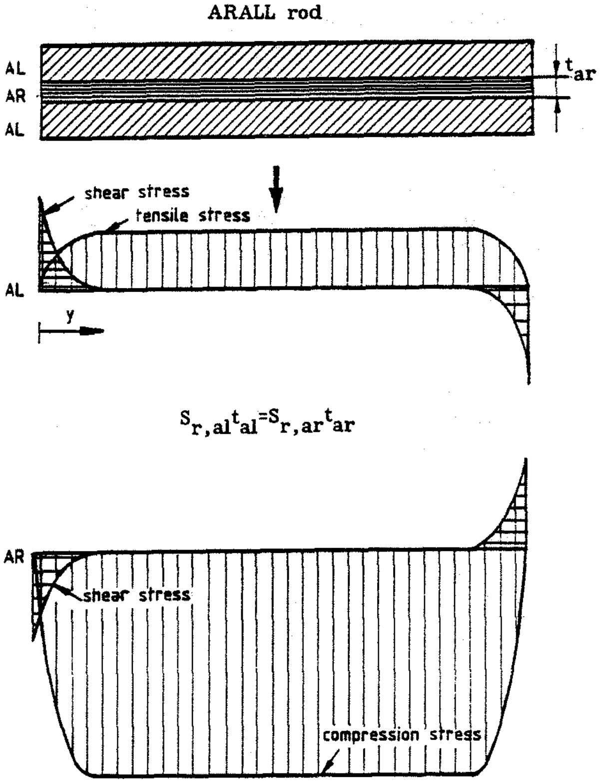


Figure 2. Schematic presentation of the residual stress system in ARALL after curing

An optimized ARALL type as described above offers improvements of the fatigue crack growth rates by a factor of 100 and more, as compared to conventional damage tolerant aluminium alloys. The crack bridging in ARALL is such efficient that the metallic component may be chosen after strength criteria. The crack growth properties of the metallic component are of secondary importance. Thus a high static strength may also be achieved for ARALL. Due to the improved properties as compared to conventional aluminium alloys, weight savings of about 30 % are possible for fatigue critical aircraft structures, if they are designed in ARALL.

3. Technological Behaviour of ARALL

For the building of an aircraft structure from sheet material several production processes are necessary. Conventional metallic sheets are formed by bending, milling, drilling, etc. and then joined by riveting, bolting, or bonding. Pure composites are formed already in the autoclave, deformation after curing is usually impossible and not necessary. Then after some cutting or milling the components are joined by bolting or bonding.

The properties of ARALL are most similar to those of metal. ARALL may be formed using a cold bending process.(5) All workshop techniques like drilling, milling, etc. are possible on ARALL with normal sharp tools. (The well-known difficulties in milling a pure aramid composite do not exist for ARALL). Then ARALL may be riveted or bolted, similar to conventional monolithic materials.(6,7) However, it is also possible to some extent to form curved ARALL components already in an autoclave or press. The similarity between the technological properties of ARALL and conventional metallic sheet materials is an advantage for aircraft manufactures, because no new high investments are necessary for material processing when ARALL structures are manufactured. At present, different kinds of ARALL are commercially available at the ALCOA company in the form of flat sheets.

4. Application of ARALL

ARALL is a material showing very good static and fatigue properties in one direction (fibre direction) and good static properties in all other directions, due to the high content of isotropic aluminium alloy. ARALL may be applied favourably in structural components, which require about isotropic stiffness properties, but which are fatigue loaded in one direction. The lower wing skin of an aircraft may be an important example of such an application. Cyclic bending of the wings of transport aircrafts due to gust loads causes a fatigue loading on the lower wing skin. The fatigue stresses are in the span direction. The fibres of ARALL must also be orientated into this direction. Requirements of bending and torsion stiffness result in the need of a nearly isotropic structural material (compare Fig. 3). The nearly isotropic properties of ARALL are achieved by the high aluminium content. In Fig. 4 the fatigue behaviour of ARALL is shown under the standardized TWIST flight simulation fatigue spectrum. TWIST simulates the fatigue of the lower skin of a transport aircraft due to gust loads. The results of Fig. 4 are obtained with a truncated TWIST spectrum. In the original spectrum the maximum amplitude $S_{a,max}$ is 1.6 times the mean stress in flight S_{mf}. The present spectrum was truncated to $S_{a,max} = 1.3\ S_{mf}$. High peak loads cause decreasing crack growth rates due to an increase of the crack closure level (compare (8,9)). Thus truncation yields a more conservative spectrum with higher crack growth rates.

Figure 4 reveals the great difference in fatigue crack growth rates between non-reinforced material (two upper curves) and ARALL types with different levels of the residual stresses. Figure 4 also shows that the size of the starter notch influences the crack growth rate in ARALL during the entire fatigue life. Lower crack growth rates occur, if smaller notches are applied. This be-

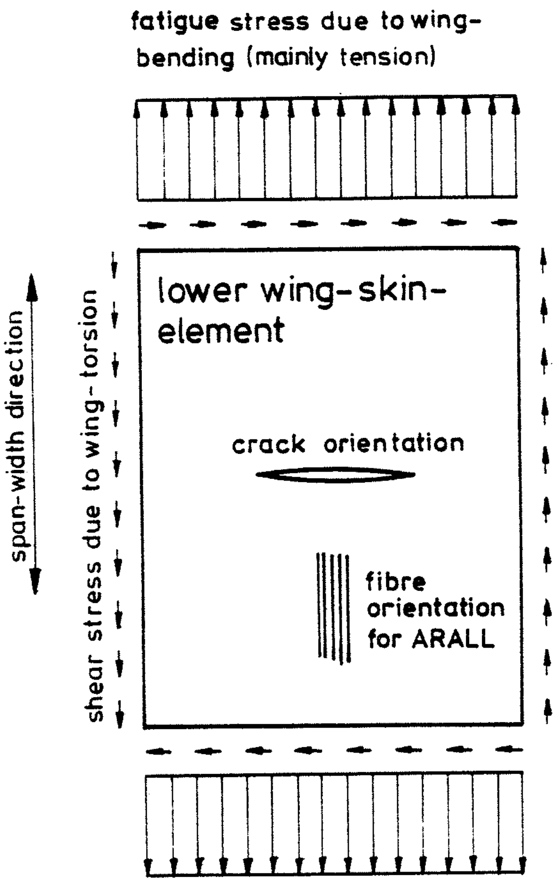


Figure 3. Schematic presentation of the loading system on a wing tension skin

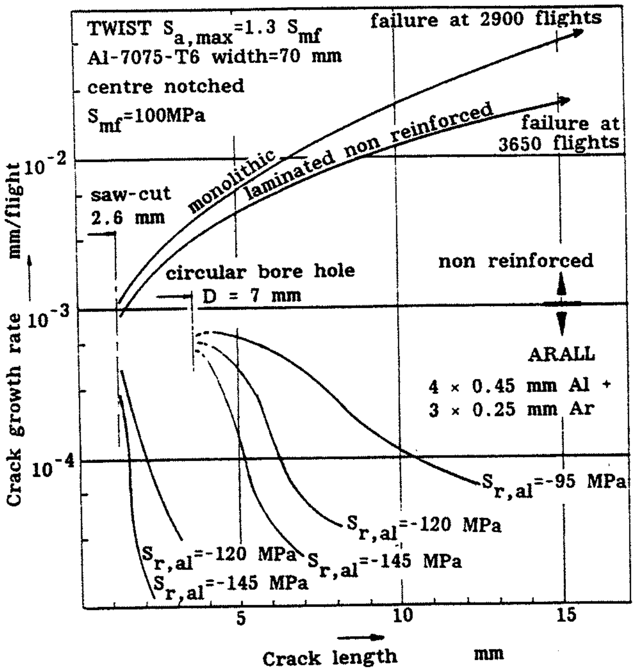


Figure 4. Comparison of the fatigue crack growth rates of ARALL and non-reinforced materials under the standardized TWIST flight simulation programme

haviour is typical for ARALL, it correlates with the decreasing crack growth rate with increasing crack length. This latter effect occurs in ARALL, because the amount of crack bridging fibres increases, if the crack grows away from the notch. For non-reinforced materials such a behaviour is unusual, in ARALL it is normal. The TWIST spectrum contains tensile overloads and compressive underloads. It can be observed in Fig. 4 that ARALL resists this complex type of loading quite well. A more detailed description of ARALL under TWIST flight simulation loading is presented in(10).

5. Fatigue Mechanisms in ARALL

The fatigue behaviour of ARALL is mainly dependent on the efficiency of the crack bridging mechanism. The crack bridging mechanism is influenced by the laminate construction parameters and by the type of the fatigue loading. Fortunately, these numerous parameters become active in the form of two basic mechanisms only:

1. Delamination
   The adhesive interface between fibres and aluminium in the environment of the crack is severely loaded by fatigue, thus some local cyclic debond occurs, which reduces the crack bridging efficiency.
2. Adhesive shear deformation
   The crack bridging fibre stresses are transferred over the adhesive into the aluminium sheets, at the delamination boundary some crack opening is allowed by the corresponding adhesive shear deformation and the crack bridging efficiency is reduced.

These two mechanisms are schematically illustrated in Fig. 5. The fatigue behaviour of ARALL is characterized by the growth of two damage systems:

1. Crack growth in aluminium.
2. Delamination growth between aluminium and fibres.

Both growth rates are interrelated during the fatigue of ARALL.

In the following part a method is described, which is developed in order to predict the growth of the two damage systems. The first step is the calculation of the mechanical boundary conditions, as presented in Fig. 5. The second step is the calculation of the growth of the crack and the delamination as caused by the mechanical boundary conditions. However, the geometry changes after some growth of the crack and the delamination area and the mechanical boundary conditions are also changed. This problem is solved by the application of an iteration routine. The calculation is started for the beginning of the fatigue loading (the cycle number N is zero), a small increment of crack and delamination growth is calculated, and a new geometry is present. The calculation of small increments of damage growth is repeated for the latter geometry, again resulting in a new geometry. This routine is illustrated in Fig. 6.

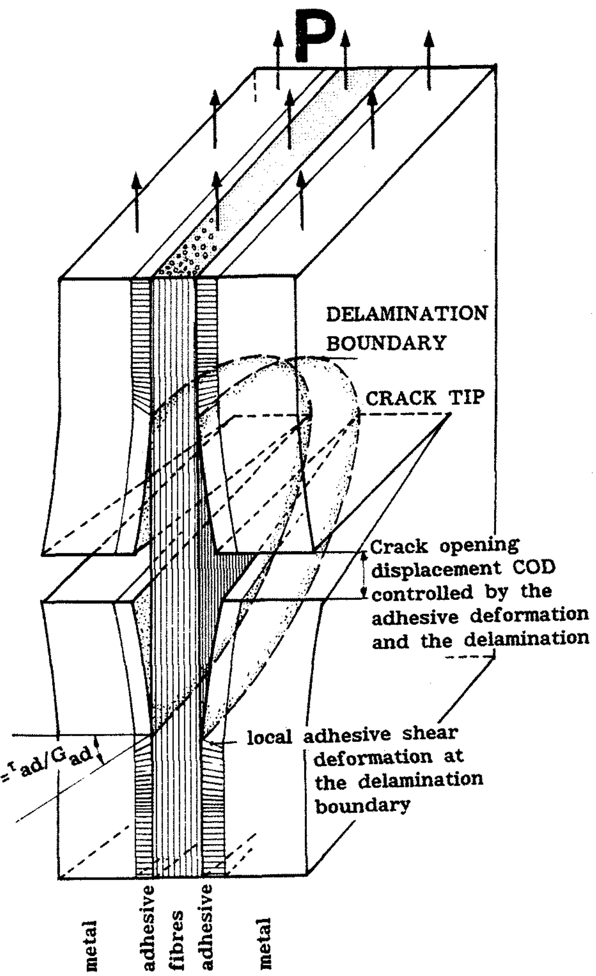


Figure 5. Schematic presentation of the mechanical situation in cracked ARALL

This approach allows for a calculation of the fatigue crack growth rates during the entire fatigue life. The increments have to be small for a realistic simulation of the fatigue behaviour. As a consequence the calculation of the mechanical boundary conditions has to be repeated often. This requires a calculation approach which is not too complicated.

Problems which are related to the mechanical behaviour in Fig. 5 are treated by Ratwani(11), Rose(12) and Roderick(13). The methods are of the Finite Element type, or analytic, or hybrid. Because of the typical features of the present problem (high residual stresses, presence of a notch, finite width, combined occurrence of delamination and adhesive deformation) a new analytical method is developed. A main feature of this method is the assumption that the crack bridging stresses are constant along the crack flanks. This assump-

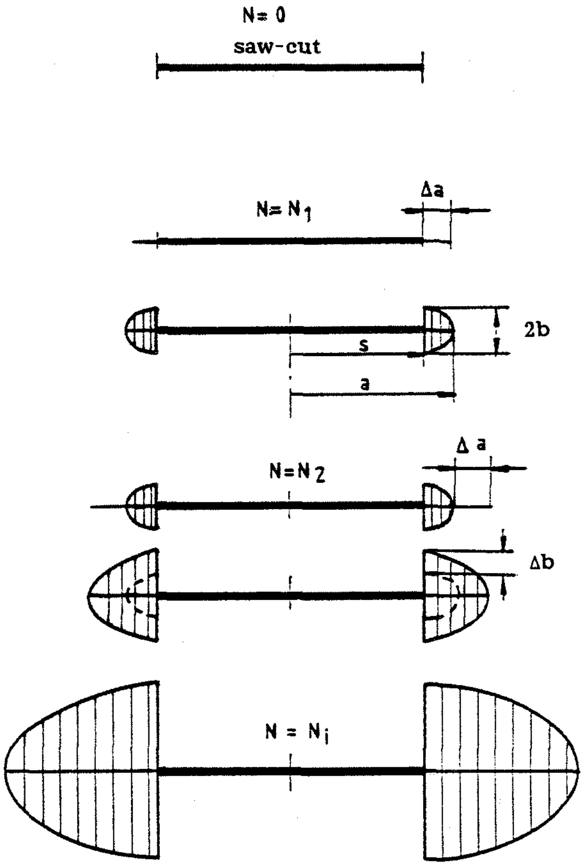


Figure 6. An iterative routine for the computation of the crack growth and delamination growth rate in ARALL

tion is supported by a typical feature of the behaviour of ARALL:

If the crack bridging forces are higher at some location, the delamination rate is increased at that location, the free length of the elongated fibres is increased, and the strain and stress due to crack bridging is decreased. This mechanism is very efficient, because the delamination rate is very sensitive to the crack bridging stress. (It will be shown in a later part that the delamination rate is about proportional to the tenth order of the crack bridging stress). In spite of this simplification the analytical model is rather complicated and it cannot be presented here explicitly. A complete description of the model is published before.(14) However, some general terms are presented here.

The crack growth rate in the aluminium is dependent on the effective cyclic stress intensity factor(8)

$$da/dN = C \cdot \Delta K_{eff}^{n} \qquad (1)$$

and ΔK depends on the fatigue loading, the damage state, and the type of laminate

$$\Delta K = f(a,b,\Delta P,lam) \qquad (2)$$

where 'a' is the half crack length, 'b' is the half delamination distance at the crack centre, ΔP is the fatigue load level, and the symbol 'lam' refers to geometrical parameters and the type of laminate.

Equation (1) may be established empirically by crack growth measurements on non-reinforced material in the usual way.

Delamination growth tests on ARALL specimens with a through crack allowed for an empirical correlation of the delamination rates to the crack bridging stresses. Some results are presented in Fig. 7. It can be observed in this figure that the delamination rate is slower, if the thickness of the individual layers is smaller. This is explained by the smaller load transfer per adhesive interface between fibres and aluminium. This is one reason for the higher crack bridging efficiency in laminates built up from thinner sheets (compare section 2). Figure 7 also shows the influence of the stress ratio R. Higher stress ratios cause higher delamination growth rates.

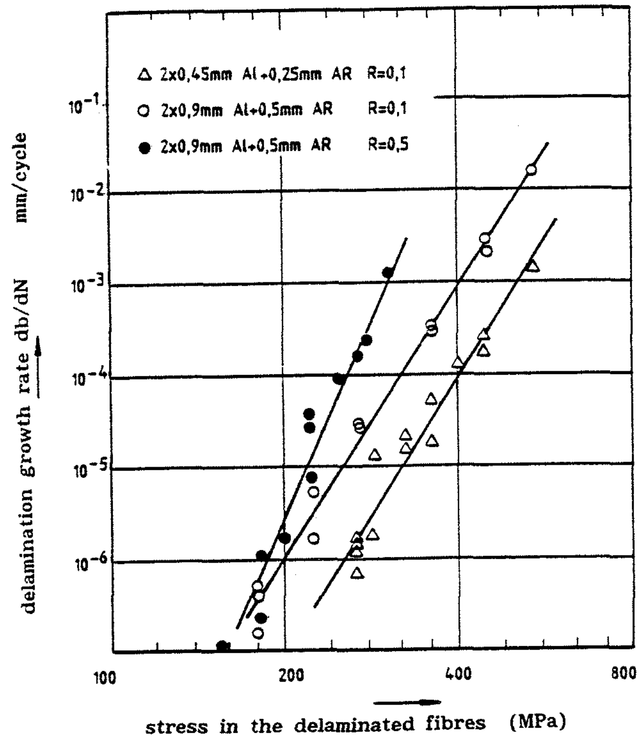


Figure 7. The delamination growth rates as a function of the crack bridging fibre stresses

The influence of the different laminate parameters could be accounted for, to some extent, by a correlation of the delamination growth rates to the energy release rate for delamination and the behaviour of Fig. 7 may be described by the following equation:

$$\frac{db}{dN} = q \cdot \Delta G^m \tag{3}$$

(at the same R-value)

In cracked ARALL ΔG depends on the mechanical boundary conditions.

$$\Delta G = g(a,b,\Delta P,lam) \tag{4}$$

The functions $f(a,b,\Delta P,lam)$ and $g(a,b,\Delta P,lam)$ are presented in$^{(14)}$. The model as it is mentioned so far is based on linear elastic material behaviour. Elastic deformations do indeed represent the main deformation component, however, some significant plasticity and some visco-elastic behaviour occurs in the adhesive. These effects are currently being investigated and will be published in future.

Figure 8 shows a comparison of some experimental crack growth results of ARALL under constant amplitude fatigue loading, and numerical crack growth calculations. Such comparisons were performed for different types of ARALL under different constant amplitude fatigue loadings. An acceptable correlation between the tests and the calculated results was found and it may be concluded that the mechanical behaviour of ARALL is quite well understood.

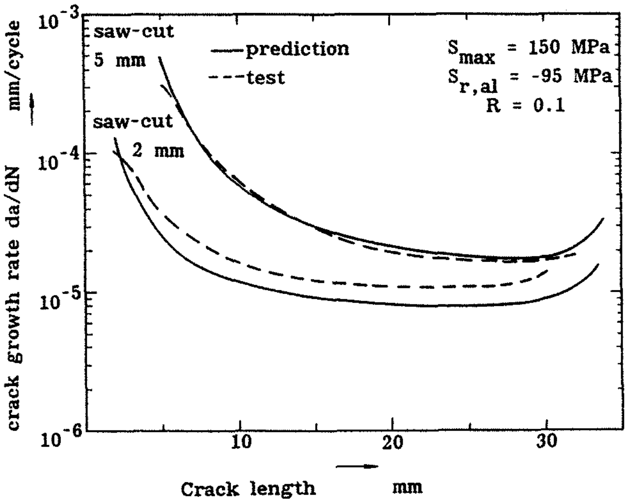
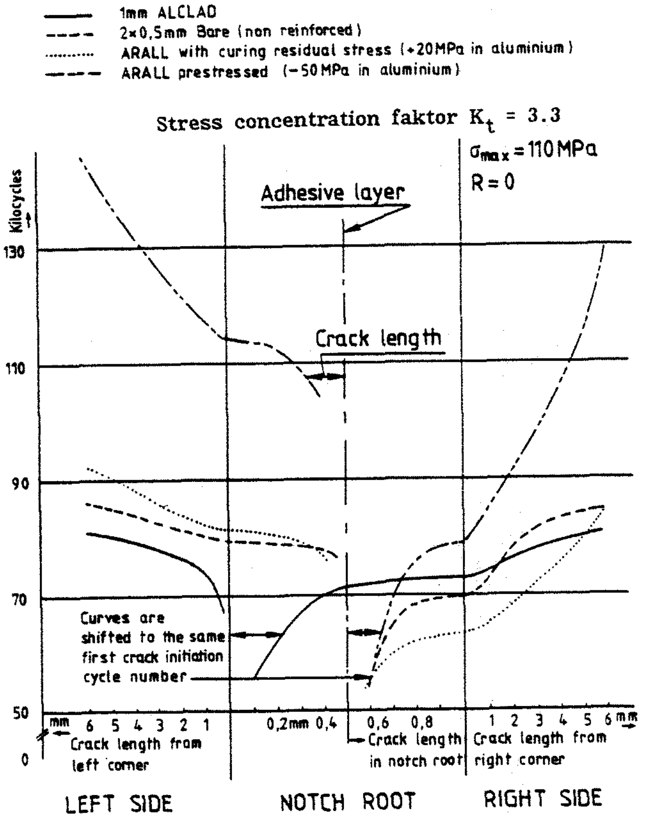


Figure 8. Comparison of experimental fatigue crack growth rates in ARALL to numerical predictions

6. Crack Initiation Behaviour in ARALL

The main advantage of ARALL is its superior crack growth behaviour. The initiation of cracks may be assumed to be governed by the (local) stresses in the aluminium sheets at notches. These stresses are hardly different for ARALL and for monolithic aluminium at the same external load level and the number of fatigue cycles up to crack initiation is similar. However, the crack initiation fatigue cycle number is not well defined. Cracks may initiate very early in the fatigue life, but remain undetectable by most inspection techniques for a long time due to their small size. The strength of the structure is not affected by those small cracks. The definition of the crack initiation fatigue number is strongly dependent on the inspection technique. The detection techniques in service are not as sensitive as in laboratories, and the fatigue life up to a crack length of some millimeters may be interpreted as an engineering fatigue crack initiation life.

Some crack growth of short cracks is incorporated in this crack initiation criterion, and the favourable crack growth properties of ARALL may already be present to some extent. Moreover, it is observed that the reinforced adhesive layers are an efficient barrier for the growth from one sheet into another. The cracks may remain "part through" cracks for a long period. Thus, an additional decrease of the crack growth rates may be achieved, and the structural strength is less influenced. This behaviour is contrary to that of monolithic structures, where cracks may grow through the thickness rather early. The crack barrier effect of the non-reinforced adhesive layers is already recognized earlier, e.g. $^{(15)}$. However, for ARALL the influence is much more pronounced. A nearly complete decoupling of the initiation behaviour of the different sheets has been observed, where each sheet initiated individually at its own "weakest location".



(Note difference in scale between notch root and sides)

Figure 9. The crack initiation behaviour of ARALL as compared to non-reinforced materials

Figure 9 shows the behaviour of different types of ARALL as compared to non-reinforced laminated and monolithic material. The crack lengths in the notch and at the sides of the specimens are plotted as a function of the number of fatigue cycles (note scale differences). It can be observed in Fig. 9 that the total fatigue life up to the initiation of an engineering crack is increased for ARALL, especially if favourable residual stresses are present. More detailed discussions about the growth of small cracks in ARALL are presented in (16).

7. Conclusions

1. ARALL is a hybrid material, which may replace conventional aluminium alloys in fatigue critical aircraft structures, weight savings of about 30 % are possible.
2. The technological properties of ARALL are similar to those of monolithic aluminium alloy sheets. Manufacturing of aircraft components from ARALL sheets does not require great new investments.
3. The mechanical behaviour of ARALL is understood and can be predicted numerically for constant amplitude fatigue loading. The behaviour of ARALL under flight simulation loading can be explained qualitatively.

Acknowledgment

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8. References

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