Fatigue Crack Growth Predictions in Aramid Reinforced Aluminum Laminates (ARALL)

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Aramid reinforced aluminum laminates (ARALL) consist of thin sheets of high-strength aluminium alloy that are laminated using a structural adhesive and high-strength aramid fibers. ARALL is extremely fatigue resistant because the aramid fibers remain intact if fatigue cracks occur in the metallic component. The crack growth rate in the aluminium sheets is reduced considerably due to crack bridging by the fibers. 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 that is able to calculate the fatigue crack growth rates in ARALL for different constant-amplitude fatigue loadings is presented.

Introduction

DURING aircraft service, fatigue stresses occur in the material of the structure as a consequence of cyclic loadings. Fatigue stresses may cause the initiation and propagation of cracks in the structure. Consequently, a potential risk of a final catastrophic failure of the structure is present. The risk is kept low by inspections and repair of the aircraft. These aspects are especially relevant because fatigue stresses and cycle numbers in modern aircraft are high as a consequence of the need for weight savings in the structure. Weight savings are important 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 aluminum alloys. Unfortunately, the strongest conventional aluminum alloys usually show only moderate fatigue performance; 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: 1) the resistance against the initiation of fatigue cracks and 2) the resistance against the growth of fatigue cracks. The initiation of 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 the scatter in the fatigue crack initiation behavior, 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 (aramid reinforced aluminum laminate) combines good strength properties and very slow fatigue crack growth rates; thus, it is especially suitable for use in fatigue-critical aircraft structures.

Description of ARALL

ARALL is a hybrid composite material developed to replace conventional aluminum 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 aluminum alloy sheets (about 65% in volume, ≈80% in weight), 2) a structural adhesive (about 17% in volume, ≈10% in weight), and 3) high-strength aramid fibers (about 17% in volume, ≈10% in weight). The aluminum alloy is the "body" of the material; to a large extent, it determines the (static) mechanical properties of ARALL. The main function of the fibers is to bridge the fatigue cracks in the aluminum, thus reducing the crack growth rates. The function of the adhesive is to impregnate the fibers and to bond them to the aluminum sheets.

The laminate buildup is shown in Fig. 1. The fibers 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 fiber 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 increased). However, this is achieved at the penalty of higher material costs. A good compromise is achieved at a thickness of 0.3–0.5 mm for the aluminum sheets and of 0.2–0.3 mm for the fiber/adhesive combination layers.

ARALL contains unfavorable residual stresses if a normal curing process is performed (tensile stresses in the aluminum 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: prestraining and prestressing.

The prestraining technique is applied after the curing of the laminate. A small plastic strain of 0.5–0.7% in the tensile direction is applied on the laminate and the fibers remain elastic. After elastic unloading, a part of the tensile stress remains in the fibers and, consequently, the aluminum sheets are loaded by compressive residual stresses.

The prestressing technique is applied during the curing of the laminate. The fibers are loaded in tension before the autoclave pressure is applied and the curing temperature is reached. The tensile stresses on the fibers are kept constant during the whole curing process. After the curing and unloading of the fibers, a part of the tensile stresses remains present in the laminate; consequently, compressive residual stresses occur in the aluminum sheets. Figure 2 shows tensile residual stresses in the aluminum sheets and compressive stresses in the fiber/adhesive layers. These stresses are denoted here by $S_{r,al}$. The residual stresses are introduced at the ends of the laminate by an interlaminar shear stress field (see Fig. 2). More detailed descriptions of these techniques may be found in Refs. 2–5.

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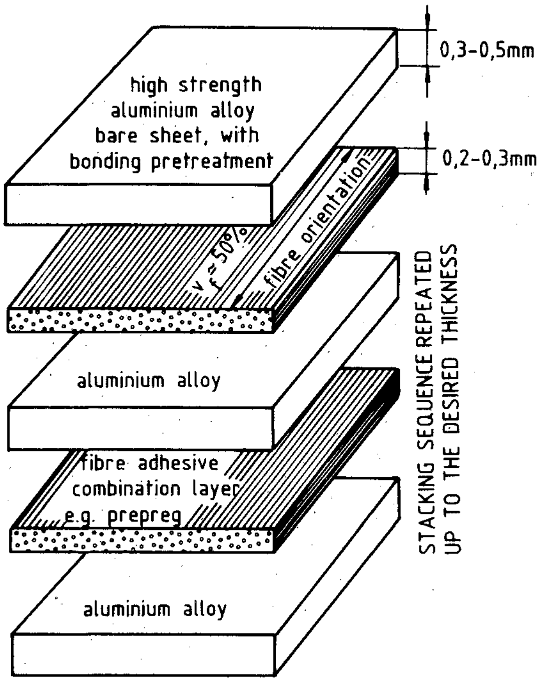

Fig. 1 Laminate buildup of ARALL.

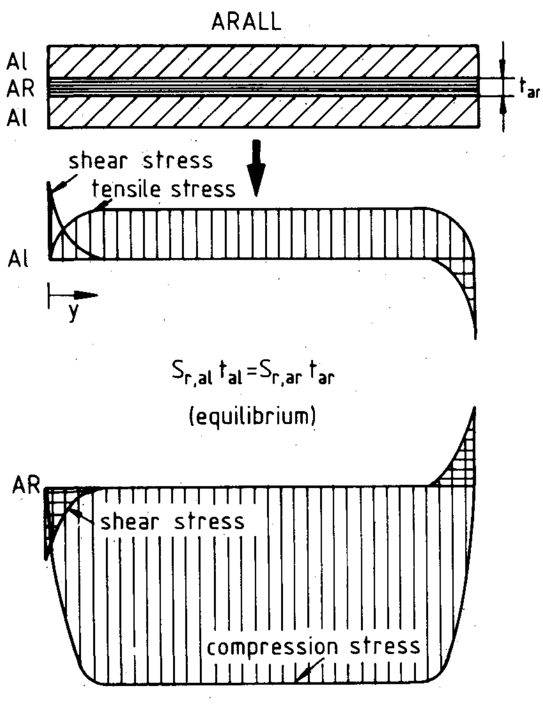

Fig. 2 Schematic presentation of the residual stress system in ARALL after curing.

An optimized ARALL type such as has been described offers improvements of the fatigue crack growth rates by a factor of 100 and more as compared to conventional damage-tolerant aluminum alloys. The crack bridging in ARALL is so efficient that the metallic component may be chosen using 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, compared to conventional aluminum alloys, weight savings of about 30% are possible for fatigue-critical aircraft structures if they are designed with ARALL.

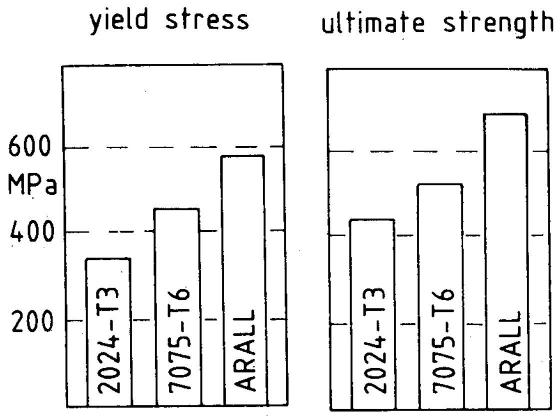

Fig. 3 Tensile properties of ARALL vs conventional aluminium alloy sheets.

Technological Behavior 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 to shape 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 (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 in an autoclave or press. The similarity between the technological properties of ARALL and conventional metallic sheet materials is an advantage for aircraft manufacturers, because no new large investments are necessary for material processing when ARALL structures are manufactured. At present, different kinds of ARALL are commercially available from ALCOA in the form of flat sheets.

Application of ARALL

ARALL is a material showing very good static and fatigue properties in one direction (the fiber direction) and good static properties in all other directions, due to the high content of isotropic aluminum alloy. In Fig. 3, static tensile properties in the fiber direction of ARALL are compared to the properties of conventional aluminum sheets. ARALL may be applied favorably in structural components, which require nearly isotropic stiffness properties but are fatigue loaded in one direction. The lower-wing skin of an aircraft may be an important example of such an application. The cyclic bending of transport aircraft wings caused by gust loads creates a fatigue loading on the skin of the lower wing. The fatigue stresses are in the span direction. The fibers of ARALL must also be oriented in this direction. The requirements of bending and torsion stiffness result in the need for a nearly isotropic structural material (see Fig. 4). The nearly isotropic properties of ARALL are achieved by the high aluminum content. In Fig. 5, the fatigue behavior of ARALL is shown under the standardized TWIST flight simulation fatigue spectrum. TWIST simulates the fatigue due to gust loads of the lower skin of a transport aircraft. The results of Fig. 5 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 (see Refs. 8 and 9). Thus, truncation yields a more conservative spectrum with higher crack growth rates.

Figure 5 reveals the great difference in fatigue crack growth rates between nonreinforced material (two upper curves) and ARALL types with different levels of residual stresses. Figure 5 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 used. This behavior is typical for ARALL; it correlates with the decreasing crack growth rates with increasing crack length. This latter effect occurs in ARALL because the amount of crack-bridging fibers increases if the crack grows away from the notch. Such a behavior is unusual in nonreinforced materials; it is normal in ARALL. The TWIST spectrum contains tensile overloads and compressive underloads. It can be observed in Fig. 5 that ARALL resists this complex type of loading quite well. A more detailed description of ARALL under TWIST flight simulation loading is presented in Ref. 10. Finally, it should be noted that the load level chosen for the tests in Fig. 5 is about 50% above the value representative for current aircraft designs. Consequently, weight savings of about 30% are anticipated in the tests. Still, the fatigue life of ARALL extended far beyond the expected commercial life of an aircraft.

Fatigue Mechanisms in ARALL

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

1) Delamination: The adhesive interface between the fibers and aluminum 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 fiber stresses are transferred over the adhesive into the aluminum 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. 6. The fatigue behavior of ARALL is characterized by the growth of two damage systems: crack growth in the aluminum and delamination growth between the aluminum and fibers. Both growth rates are interrelated during the fatigue of ARALL.

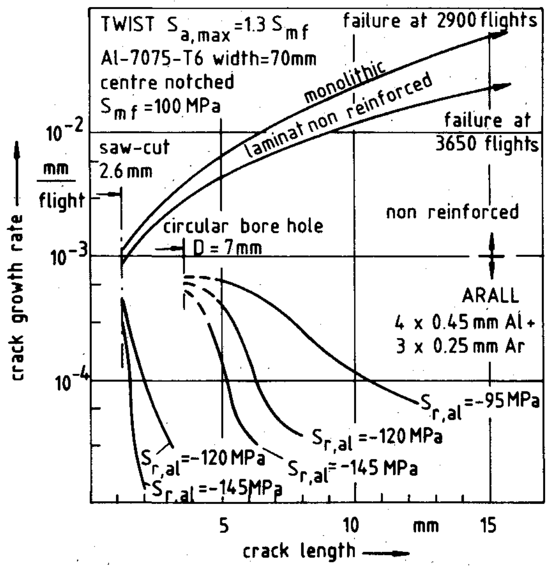

Fig. 5 Comparison of the fatigue crack growth rates of ARALL and nonreinforced materials under the standardized TWIST flight simulation program.

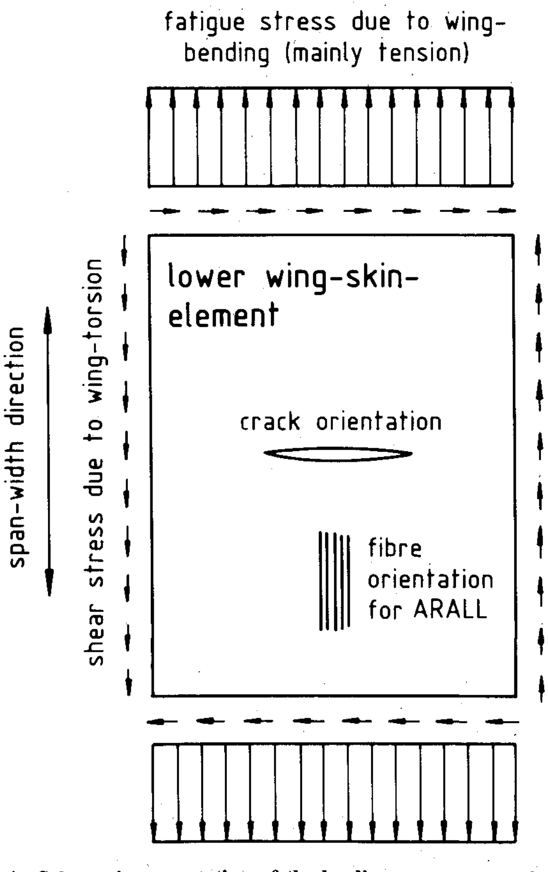

Fig. 4 Schematic presentation of the loading system on a wing tension skin.

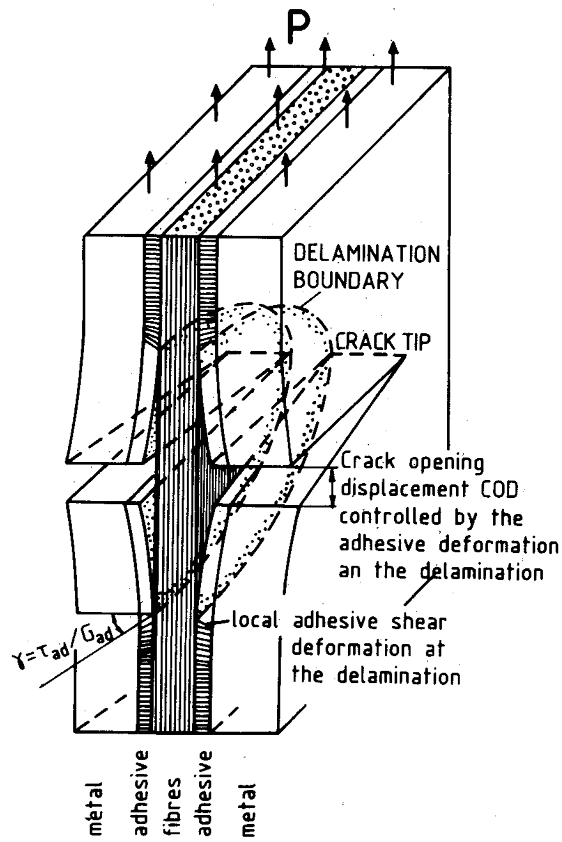

Fig. 6 Schematic presentation of the mechanical situation in cracked ARALL.

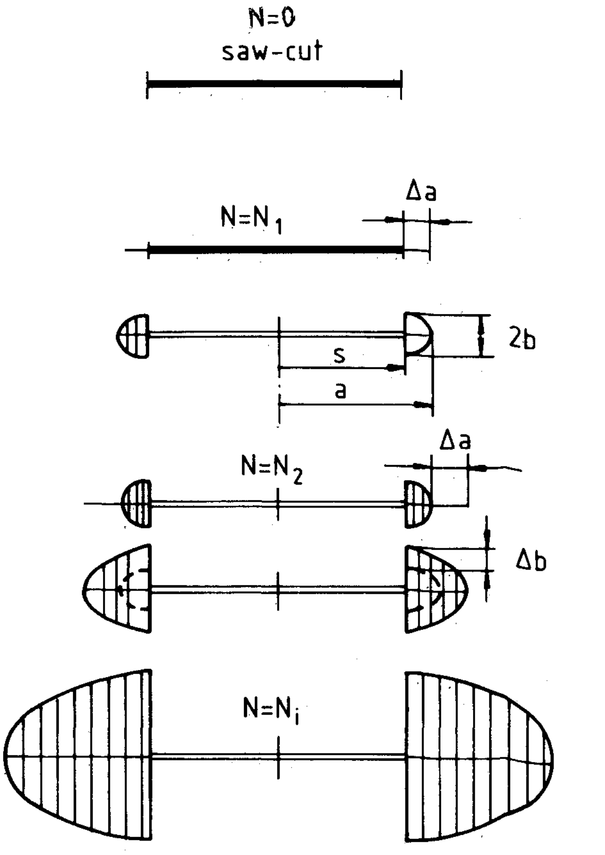

Fig. 7 Iterative routine for the computation of the crack growth and delamination growth rate in ARALL.

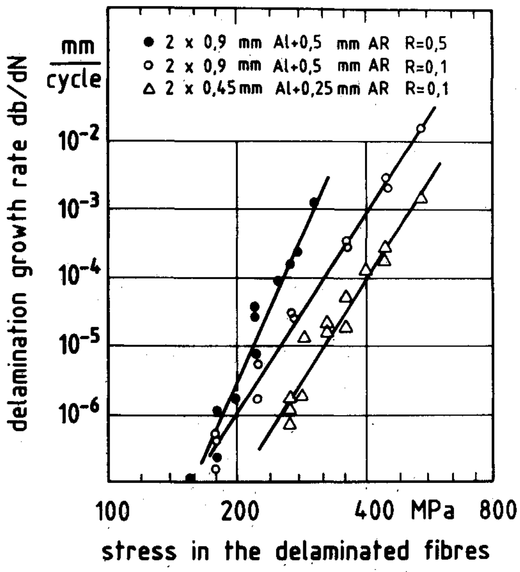

Fig. 8 Delamination growth rates as a function of the crack-bridging fiber stresses.

Described here is a method developed to predict the growth of the two damage systems. The first step is the calculation of the mechanical boundary conditions, as presented in Fig. 6. The second step is the calculation of the growth of the crack and the delamination caused by the mechanical boundary conditions. The geometry changes, however, after some growth of the crack. The delamination area and 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 presented. 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. 7.

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 behavior. As a consequence, the calculation of the mechanical boundary conditions has to be repeated often. This requires a calculation approach that is not too complicated.

Problems related to the mechanical behavior in Fig. 6 are treated by Ratwani,[11] Rose,[12] and Roderick.[13] The methods are finite element, analytic, or hybrid. Because of the typical features of the present problem (high residual stresses, the presence of a notch, finite width, the combined occurrence of delamination, and adhesive deformation), a new analytical method has been developed. A main feature of this method is the assumption that the crack-bridging stresses are constant along the crack flanks. This assumption is supported by a typical feature of the behavior 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 fibers 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 section 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 cannot be presented here explicitly. A complete description of the model has been published previously[14] and only some general terms are presented here.

The crack growth rate in the aluminum is dependent on the effective cyclic stress intensity factor,[8]

$$\frac{da}{dN} = C \cdot \Delta K^n_{\mathrm{eff}} \tag{1}$$

and $\Delta K^n_{\mathrm{eff}}$ depends on the fatigue loading, damage state, and type of laminate, as

$$\Delta K = f(a, b, \Delta P, \mathrm{lam}) \tag{2}$$

where a is the half-crack length, b the half-delamination distance at the crack center, ΔP the fatigue load level, and lam refers to the geometrical parameters and type of laminate. Equation (1) may be established empirically by crack growth measurements on nonreinforced 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. 8. 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 the fibers and the aluminum. This is one reason for the higher crack-bridging efficiency in laminates built up from thinner sheets. Figure 8 also shows the influence of the stress ratio R. Higher stress ratios cause higher delamination growth rates.

The influence of the different laminate parameters can be accounted for, to some extent, by a correlation of the delamination growth rates to the energy release rate for delamination. The behavior shown in Fig. 8 may be described by the following equation:

$$\frac{db}{dN} = q \cdot \Delta G^m \text{ (at the same } R \text{ value)} \tag{3}$$

In cracked ARALL, ΔG depends on the mechanical boundary conditions

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

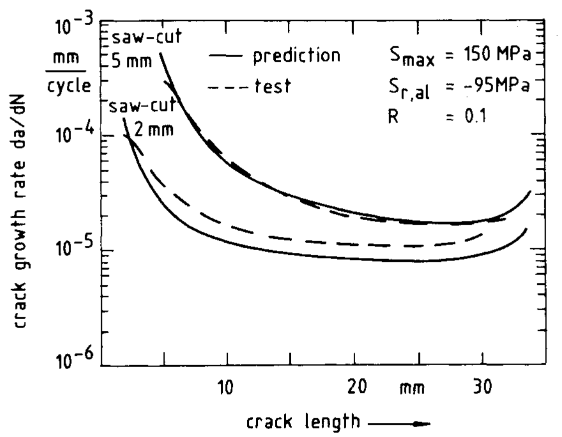

Fig. 9 Comparison of experimental fatigue crack growth rates in ARALL to numerical predictions.

The functions $f(a,b,\Delta P,\text{lam})$ and $g(a,b,\Delta P,\text{lam})$ are presented in Ref. 14. As so far discussed, the model is based on linear elastic material behavior. Elastic deformations do indeed represent the main deformation component; however, some significant plasticity and viscoelastic behavior occurs in the adhesive. These effects are currently being investigated and will be published in future.

Figure 9 shows a comparison of some experimental crack growth results of ARALL (under constant-amplitude fatigue loading) with 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, so it may be concluded that the mechanical behavior of ARALL is quite well understood.

Crack Initiation Behavior in ARALL

The main advantage of ARALL is its superior crack growth behavior. The initiation of cracks may be assumed to be governed by the (local) stresses in the aluminum sheets at notch. These stresses are hardly different for ARALL and monolithic aluminium at the same external load level; also, the number of fatigue cycles up to crack initiation are similar. However, the crack initiation fatigue cycle number is not well defined. Cracks may initiate very early in the fatigue life, but they can 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 growth of short cracks is incorporated in this crack initiation criterion; thus, the favorable 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 thus less influenced. This behavior is contrary to that of monolithic structures where cracks may grow through the thickness rather early. The crack barrier effect of the nonreinforced adhesive layers is already recognized earlier (e.g., see Ref. 15). However, the influence is much more pronounced for ARALL. A nearly complete decoupling of the initiation behavior of the different sheets has been observed, where each sheet initiated individually at its own "weakest location."

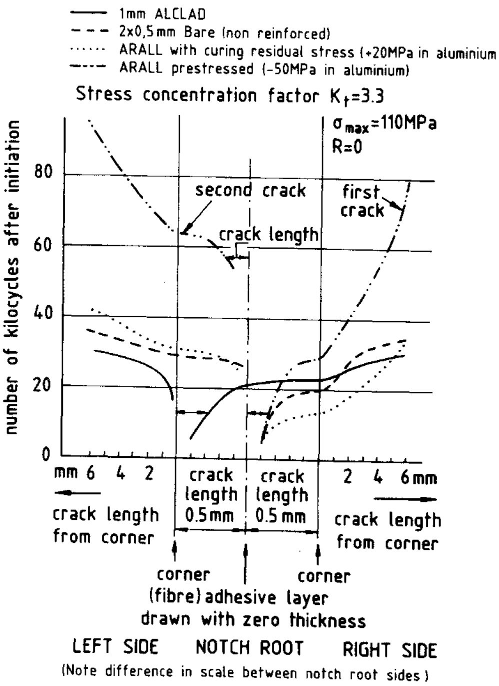

Fig. 10 Crack initiation behavior of ARALL as compared with nonreinforced materials.

Figure 10 shows the behavior of different types of ARALL as compared to nonreinforced laminated and monolithic materials. 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 the scale differences). It can be observed in Fig. 10 that the total fatigue life up to the initiation of an engineering crack is increased for ARALL, especially if favorable residual stresses are present. More detailed discussions about the growth of small cracks in ARALL are presented in Ref. 16.

Conclusions

1) ARALL is a hybrid material that may replace conventional aluminum alloys in fatigue-critical aircraft structures. Weight savings of about 30% are possible.

2) The mechanical behavior of ARALL is understood and can be predicted numerically for constant-amplitude fatigue loading. The behavior of ARALL under flight simulation loading can be explained qualitatively.

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