Mechanistic aspects of fatigue crack growth in ARALL

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G.H.J.J. Roebroeks, J.C. in 't Velt

TU Delft
Faculty of Aerospace Engineering
Delft University of Technology
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Summary

If for the ARALL 2 series (not prestrained) a central notched fatigue specimen is used and only low fatigue loads are applied, fibre failure in the wake of the crack in the aluminium can occur. This failure initiates from the starter notch in the prepreg, due to the high stress level in this area. Near the crack tip in the prepreg, shear stresses will load the prepreg material in an unfavourable way. At a certain stress intensity splitting of the prepreg in the longitudinal direction will occur, which will cause crack arrest in the prepreg. The prepreg stresses are now too low to cause further fibre fatigue failure.
Introduction

The crack growth properties of laminated aluminium sheet material can be improved by adding unidirectional continuous aramid fibres in the adhesive. This has resulted in a new material developed at the Delft University of Technology. The material is called ARALL, and it has outstanding crack growth resistance during cyclic loading (ref.1). The desired retardation of crack growth (fig.1) is achieved by crack bridging of the aramid fibres in the wake of the crack. The fibres are supposed to bridge the crack in the aluminium, which will cause high stresses in these fibres.

In the past it turned out that fibre failure can occur under certain test circumstances. One explanation for fibre failure is related to the residual stress distribution over the material thickness after curing (tensile stress in the aluminium layer and compressive stress in the aramid prepreg). The compressive stresses in the aramid layer might cause initial damage by micro-buckling of the filaments (ref.2). However, new observations of the delamination surface around the fatigue crack, indicate that other mechanisms must be active. In this report an alternative explanation for fibre failure in the wake of the fatigue crack in the aluminium is presented.
Observations

Until now, two standardized ARALL materials are produced and investigated: 1 - The prestrained material based on 7075-T6 aluminium sheet material (7H3x where x indicates the number of aluminium layers)

2 - The "as cured" material based on 2024-T3 (2H4x)

Both materials have been fatigue tested in the past. Flight simulation spectra were applied because the material was expected to be extremely efficient in the lower skin and stiffeners of the aircraft wingbox. The load history is a gust dominated wing bending, superimposed on an average one-g-level. Each "flight" contains a ground-air-ground cycle. In these spectra rather rough flights, corresponding with bad weather conditions, do occur. It has been shown that the very high tension loads have a favourable influence on the crack growth behaviour of monolithic aluminium (ref.3). Plastic deformation at the crack tip, resulting in compressive stresses afterwards, considerably delay crack growth through the plastic zones.

As a supplement to the flight simulation tests, constant amplitude tests at severe cyclic loads were also carried out, for instance at $S_m + S_0 = 120 \pm 60$ MPa. Many constant amplitude test results for ARALL are available now. All results showed a satisfactory crack growth behaviour. Since ARALL is also considered for the skin of aircraft fuselages, the material now is more often tested under R=0 cyclic loads. Although the crack growth properties of unprestrained ARALL 2H4x are still far better than those of 2024-T3, the enormous advantage of ARALL becomes smaller in R=0 tests. The maximum stress in these constant amplitude fatigue tests is significantly lower than the maximum stress (truncation level) in the flight simulation spectra.

In view of the application of ARALL as a fuselage skin material, fatigue tests at R=0 and a maximum stress ranging from 80 to
120 MPa were carried out. It has turned out that fibre failure does occur at low $S_{\text{max}}$ - values. In the work of Mattheij (ref.2) a possible explanation for this fibre failure is proposed. Residual compressive stresses in the aramid fibres of the 2H4x material, originating from the curing process, will cause compression loads (at least during a part of the cycle) in the prepreg layer in a test at $R=0$ ($S_{\text{min}} = 0$). It was thought that the compression loads, combined with a small delamination length between prepreg and aluminium sheets, will result into some compressive failure of the aramid filaments (fig.2). This local damage, together with tensile fatigue loading, would finally lead to fibre failure.

fig.2: Possible explanation of fibre failure in ARALL

fig.3: Local prepreg damage
The local damage of the prepreg in the wake of the crack in the aluminium, is shown on the surface of the delaminated area (fig.3). Visual observation of the prepreg surface reveals a line perpendicular to the fibre orientation consisting of aramid filaments pulled out of the prepreg layer for about 1mm (it has the yellow colour of the unimpregnated aramid filaments) (fig.3). The scanning electron microscope confirms this observation (fig.3). Fibre pull-out, fibre failure and some fibrillation in this area are observed.

![Diagram showing fibre isolated in the resin-rich layer](image)

**fig.4: Cross-section of ARALL**

This small prepreg damage is the result of the isolated position of some fibres in the resin-rich zone (fig.4). If normal delamination occurs, a matrix bridging delamination front (cohesive delamination) should develop (fig.5a). However, another possibility is a more or less continuous delamination front (fig.5b), which leaves the outer fibre in its isolated position. Delamination around the full periphery of this fibre is possible, but it might well meet with
more "resistance". Because delamination growth occurs both in the crack growth direction and in the fibre direction, the isolated fibre, in view of its lesser extent of delamination, will carry a higher crack bridging force. As a result isolated fibres near the aluminium sheet may fail, which explains the local prepreg damage.

fig.5a: Delamination front which will cause no fibre damage

fig.5b: Delamination front resulting in fibre failure

Initially the crack in the prepreg layer in the middle of the specimen coincides with the damaged area (point A in fig.6). However, after a certain crack growth a deviating path is followed. The cracks in the aluminium sheets and in the prepreg do not coincide (point B). This indicates that it is not only the initial prepreg damage which is responsible for prepreg fatigue failure.

fig.6. Difference in crack growth path between prepreg and aluminium
In order to study crack growth in the prepreg, a delamination specimen as shown in figure 7 was tested. The aluminium sheets are cut over the full width and the prepreg has a central crack starter. The specimen was tested at a cyclic load with a maximum stress equal to 86 MPa (based on the total ARALL thickness) and R=0. The prepreg stresses at the interrupted aluminium layers in this specimen (330 MPa) will correspond with the stresses in the delamination area around a fatigue crack in a central notched specimen at which a fatigue load with a maximum stress of 120 MPa and R=0 is applied (specimen in figure 3). In view of the type of delamination specimen, residual compressive stresses of the curing cycle can not occur at the tip of the initial crack. As a consequence compressive stresses will not be present in this area during cyclic loading. The result of cyclic loading is shown in figure 8.

The fatigue crack grows through the unidirectional aramid layer. Apparently it is possible to cause crack growth in the prepreg layer of ARALL as a result of:
- a cyclic stress in the prepreg far below the fatigue limit of this material, combined with
- an initial crack in the prepreg.
From this observation it should be concluded that fatigue crack growth in the prepreg of a central notched ARALL specimen, will also be possible if a similar severe stress field is present in the prepreg. This may well occur at the central notch and later when fatigue crack growth in the prepreg occurs. It should be explained why fatigue crack growth in the prepreg does not occur when ARALL is loaded at higher stress levels. This will now be discussed.

Further studies of the delamination surfaces of fatigue loaded ARALL specimens have revealed another essential failure mechanism. Figure 9 shows the typical delamination area as found for specimens of the ARALL 7 series (prestrained material), but also for the ARALL 2 series (as cured) on which a cyclic load of 120 ± 60 MPa has been applied. Figure 10 shows the delamination surfaces of a specimen of the unprestrained ARALL 2 series tested at a much lower cyclic load (60±60 MPa).

In these figures longitudinal splitting of the aramid prepreg can be observed. For the ARALL 7 series, and also for highly stressed ARALL 2 series, this splitting occurs at the tip of the saw-cut. For low
stresses in the ARALL 2 series (fig.10), laminate splitting occurs only if the crack in the prepreg layer has become relatively large. Also the amount of delamination seems to be important. (The relation between these two parameters and laminate splitting is still investigated now. The results will be presented in a later report.) Large delaminations and long cracks in the prepreg will increase the stress intensity at the crack tip in the prepreg. It implies that high shear stresses at the crack tip will occur in the prepreg. The high shear stresses are responsible for prepreg splitting in the fibre direction. It should be expected that it requires some critical stress intensity to reach a critical shear stress (mode II) for this type of failure at the tip of the crack in the unidirectional prepreg. In the prestrained ARALL 7 series, the unloaded material has tensile stresses in the prepreg layer and compressive stresses in the aluminium sheets. If this material is loaded in tension, the tensile stresses in the prepreg are considerably higher than those in the prepreg of unprestrained material. Therefore, the external load of the prestrained material at which prepreg splitting occurs, will be considerably lower than for the unprestrained material.

**Consequences of fatigue crack growth in the prepreg and prepreg splitting.**

Some consequences of fatigue crack growth in the prepreg and prepreg splitting can be indicated:

- In a centrally cracked ARALL 2H4x specimen (as cured) with a through crack, fibre failure is possible and an increasing crack growth rate will be observed (fig.11). However crack growth in a more relevant specimen with an open hole shows an essentially different behaviour, see the results from ref. 4 in fig.11. The decreasing crack growth rate indicates that filament failure did not occur. Apparently a critical tensile stress-level necessary for fibre failure was not attained and some controlled delamination and active crack bridging could occur. Figure 11 thus illustrates two
essentially different types of crack growth behaviour. As a consequence it is necessary to consider the relevance of the starter notch if the practical significance of ARALL crack growth results for aircraft structures is evaluated.

Fig. 11 Influence of specimen geometry on crack growth results for as cured ARALL 2H42.

- Whether prepreg splitting will occur in ARALL (2H4x) depends on the stress distribution around the (starter) notch and on the maximum stress of the fatigue load. Because prepreg splitting is obviously important for the subsequent crack growth resistance, test results from one type of specimen and its type of fatigue load cannot directly be generalized to other conditions. Even in a qualitative way it might be misleading.
- Biaxial tensile loading may be an interesting case. Biaxiality could improve the fatigue properties of ARALL. At the crack tip not
only shear stresses originating from the longitudinal load are present, but also fibre splitting forces due to the transverse load. Prepreg splitting at the crack tip may occur at a lower longitudinal stress because of the biaxiality. It should be studied whether there is a beneficial effect.

Conclusions

1. Fatigue crack growth in the prepreg layers of ARALL can occur under cyclic tension-tension load in these layers. It will be the result of high cyclic stresses at the tip of the crack (or starter notch). However, if longitudinal prepreg splitting does occur the stress singularity has vanished and crack arrest in the prepreg layer will occur. This is favourable for subsequent crack bridging effects.

2. Prepreg splitting will be initiated if some critical shear stress at the tip of the crack in the prepreg is exceeded. As a consequence it is depending on the maximum stress of the fatigue load. This is particularly relevant to flight-simulation tests and other tests with a high $S_{\text{max}}$. Biaxiality may also enhance prepreg splitting.

3. Because the occurrence of prepreg splitting is sensitive to $S_{\text{max}}$ and the type of notch, the selection of relevant test conditions should be done with great care. More research with respect to the significance of prepreg splitting should be considered.
References.


