ICAS-88-5.10.3

# NEW DEVELOPMENTS IN ARALL LAMINATES


L.B. VOGELESANG, J.W. GUNNINK
D. CHEN, G.H.J.J. ROEBROEKS, A. VLOT

FACULTY OF AEROSPACE ENGINEERING
DELFT UNIVERSITY OF TECHNOLOGY
THE NETHERLANDS



## ABSTRACT

It is expected that a future cost effective aircraft structure should incorporate significant proportions of three potential aircraft materials:

- aluminium alloys (both new and conventional)
- composites
- ARALL Laminates (both with aramid fiber and glass fiber)

There is a strong need for new materials that combine high strength, low density and high modulus of elasticity with improved toughness, corrosion-resistance and fatigue properties. Carbon composites cover almost all those demands except for fracture toughness, which is and will be an important argument for using aluminium alloy in current, and aluminum alloy together with ARALL Laminates in future primary aircraft structures.
The unique set of ARALL Laminate properties match up well with existing structural integrity requirements and the more demanding performance needs of next generation aircraft. Through use of good design practices, goals of 30 - 40 percent weight savings and no-repair structure have been demonstrated to be within reach.
ARALL Laminates are now transitioning from the R and D stage to the commercialization stage with the event of flying articles.


## INTRODUCTION

The development of a new aircraft is significantly influenced by the introduction of new structural materials.

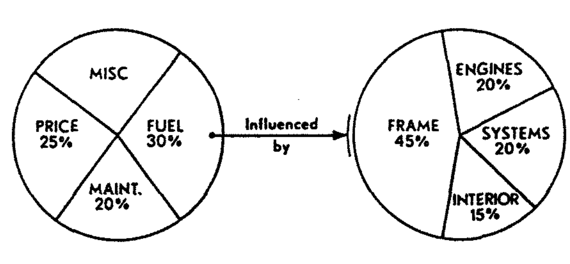



Fig. 1 The relation between DOC and aircraft empty weight



The driving force behind such developments is the everlasting incentive of reducing aircraft operating costs. In the future an increasing part of the operating costs will be spent on fuel and maintenance, see Figure 1. It will be cost effective if aircraft structures can be designed of new materials to obtain a lower weight and to require less maintenance. Based on about 400 kg weight reduction as today obtained on the Airbus A-310, a typical European operator with 500 nm flight distance and an utilisation of about 2000 to 4000 hrs/year, a fuel burn reduction of 8660-19400 USG and corresponding cost reduction of 10300-23300 US $ per aircraft per year has been calculated.[1] Maintenance is directly related with durability and damage tolerance, especially chemical corrosion has a high impact on it. The experience of some aircraft operators is that 80% maintenance costs are environmentally related.[3] Several materials should be considered for the future aircraft structure (excluding engines, landing gears and other systems). There are three potential families: aluminium alloys (both new and conventional), composites, and ARALL Laminates. It may be questioned whether there will be one single 'winning' material. In view of the variety of dominating requirements for different parts of the structure (Figure 2) it must be expected that different materials will be used to optimise structural weight and durability. Actually in the past there was not one single Al-alloy adopted for all components of the structure.

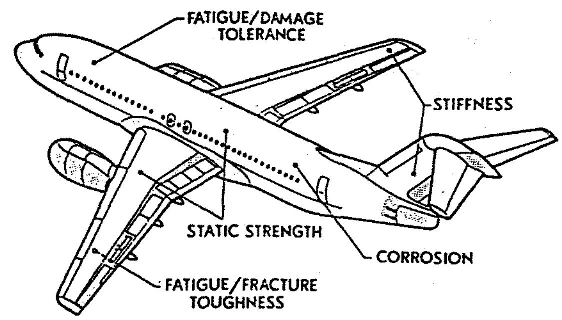



Fig. 2 Dominating design requirements

Higher yield stress alloys (7000 series) were preferred if static strength and stability (buckling) were the dominant criteria, whereas the lower strength 2024-T3 alloys was generally preferred for fatigue critical components. For Al-alloys the picture at this moment is not fully clear. The breakthrough of both Al-Li and powder metallurgy alloys is still uncertain. The large weight savings and extensive utilisation of composites also for primary parts of the structure, has been expected already for some decades. For several reasons it still is not yet realised for civil aircraft. Nevertheless for the 1985 generation of aircraft, weight savings are mainly achieved by the introduction of carbon and aramid composites. This is demonstrated by Figure 3 showing the introduction of composites on Airbus Industries aeroplanes. With today's technology the expected future composite structure weight percentage is about 20%. With new higher strain fibers and new resin systems like thermoplastics this percentage might be raised to 30%. A first important step for reducing the structural weight of an aircraft is to determine the essential design criteria for the separate components of the aircraft. Figure 2 illustrates the major requirements for fuselage, wing and tail. Optimal structural design with the new airworthiness requirements leads not only to the introduction of damage tolerant materials but also to damage tolerant structures.

Due to fatigue sensitiveness and the durability & damage tolerance assessments it turns out that allowable design stresses for aluminium alloys must be reduced by roughly 20%. For composites the allowable design strains are in the order of 0.25 - 0.4%, due to environmental effects, low tolerance to impact damage and low fracture toughness; the lower value is for compressive critical areas and the higher value for tension critical areas. Even with this drastic reduction of more than 50% in strain these materials are very attractive for aircraft structural use.

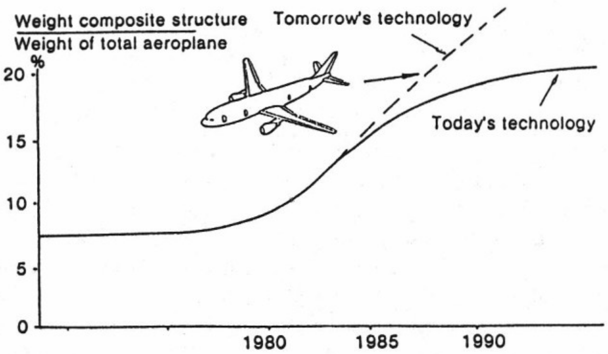



Fig. 3 Introduction of composites on Airbus Industries aeroplanes

***What do we demand from a material?*** There is a strong need for new materials that combine strength, low density and high modulus of elasticity with improved toughness, corrosion-resistance and fatigue properties. Carbon and Aramid composites cover almost all those demands except for fracture toughness, which is an important argument for using aluminium alloy 2024-T3 in today's aircraft primary structures. The new ARALL Laminate material, to be discussed in more detail in this paper, combines outstanding fatigue resistance and a high specific strength compared to existing Al-alloys. It appears to be a very attractive material for fatigue critical parts. Development work is now in full progress, in both Europe and the USA. Considering the 'best' properties of the three families of materials and some disadvantages as well it should be expected that a cost effective aircraft structure should incorporate significant proportions of the mentioned families of materials. At this moment it is still an open question which percentage will apply to each of them in the future.

## ARALL LAMINATES FOR FATIGUE AND IMPACT SENSITIVE STRUCTURES

### Development

ARALL Laminate developed by Delft University, is an adhesive bonded laminate which combines the advantages of high strength isotropic aluminium sheet with the fatigue and fracture resistance of aramid or glass fibers. The material is built up as laminated sheet material (Figure 4) with: thin high strength aluminium alloy sheets; strong unidirectional or woven aramid or glass fibers, impregnated with a thermoset or thermoplastic adhesive followed by (if desired) post-stretch of the material after curing, which results in a compressive residual stress in the metal sheets.

A cross-section of ARALL Laminate is shown in Figure 5. ARALL Laminate was developed principally to obtain a material with good fatigue strength, in which possible cracks would grow very slowly.[2,3]

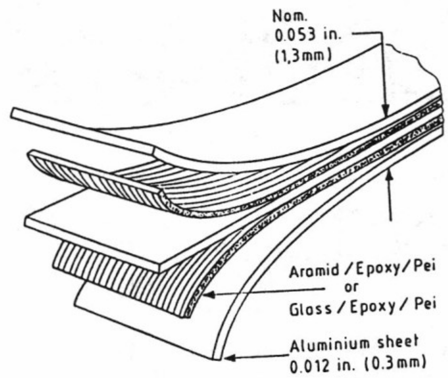



Fig. 4 Alcoa ARALL Laminates. Schematic of standard 3/2 lay-up

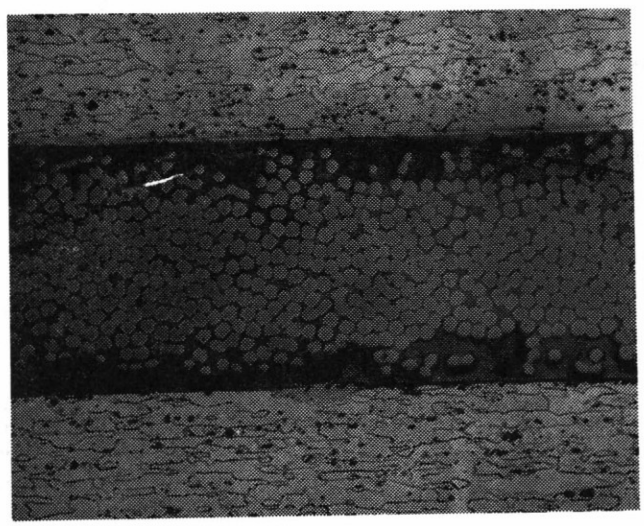


Fig. 5 Cross-section of ARALL Laminate

Design studies indicate that for fatigue critical areas, such as the lower-wing and the skin of a fuselage, ARALL Laminate is an attractive material. Weight savings of more than 20% are easily attainable. There is also potential for acoustic fatigue and noise damping applications. Preliminary tests have shown that ARALL Laminate has promising properties after impact.

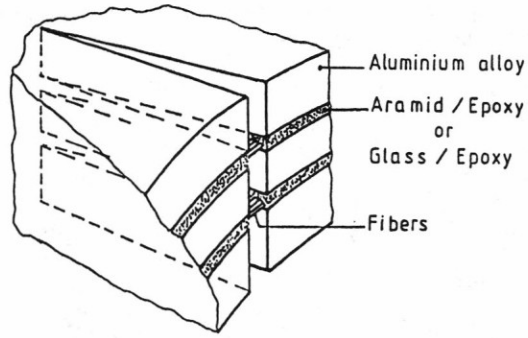



Fig. 6 Fatigue crack in ARALL Laminate

Fatigue cracks generally grow in a direction perpendicular to the maximum principal stress. For this reason a high percentage of the fibers should be orientated in the direction of the maximum principal stress. The action of the fibers is mainly to resist the crack opening. This produces a high degree of resistance to further crack growth (Figure 6). In this way ARALL Laminate combines the favourable static properties of high strength aluminium alloys with good fatigue resistance of fiber reinforced materials.

### Composition

ARALL Laminates are a new family of structural composite materials. The final properties are highly dependent on the variables of the material. So ARALL Laminates can be tailored for a lot of different applications by varying fiber-resin systems, aluminium alloys and sheet gages, stacking sequences, fiber orientations (such as uniaxial and cross-ply), surface preparation techniques and by the degree of post-cure stretching or rolling. Although several variations of these systems have been successfully fabricated, the four product variants listed in Table 1 have been standardized for commercial availability by ALCOA.[5]

TABLE 1 ARALL Laminate Commercial Product Forms[a]

| Description | Characteristics |
|---|---|
| ARALL-1 Laminate<br>Alloy 7075-T6 (b)<br>250°F (120°C) cure prepreg (c)<br>0.4% permanent stretch | Superior fatigue<br>High Strength |
| ARALL-2 Laminate<br>Alloy 2024-T3 (b)<br>250°F (120°C) cure prepreg (c)<br>with or without 0.4% stretch | Excellent fatigue<br>Increased formability<br>Damage tolerant |
| ARALL-3 Laminate<br>Alloy 7475-T76 (b)<br>250°F (120°C cure prepreg (c)<br>0.4% permanent stretch | Superior fatigue<br>Improved toughness<br>Good exfoliation<br>High strength |
| ARALL-4 Laminate<br>Alloy 2024-T8 (b)<br>350°F (175°C) cure prepreg (c)<br>with or without 0.4% stretch | Excellent fatigue<br>Elevated temperature |

(a) Also produced in a one side or two side clad condition for added corrosion protection.
(b) Bonding surfaces anodized and primed.
(c) With 50% by volume unidirectional aramid fibers.

A variety of lay-up sequences is available, ranging from 2/1 (two layers of aluminium alloy sheet bonded by one layer of aramid epoxy prepreg) to any number of layers. Present production is up to 5/4 (five layers of aluminium alloy sheet bonded by four alternate layers of aramid epoxy prepreg). The thickness of the 2/1 lay-up is 0.032 in. (0.8 mm). The thickness of the 5/4 lay-up is 0.092 in. (2.3 mm). The most commonly produced lay-up sequence is 3/2. It is 0.052 in. (1.3 mm) thick and is primarily used for test and evaluation programs at many aerospace companies.

Two new promising developments are in progress:

1. ARALL Laminates based on $S_2$ or R-glass fiber. Characteristics: excellent fatigue, very high strength, superior fracture toughness and impact.
2. ARALL Laminates based on a thermoplastic resin system. Characteristics: elavated temperature and increased formability.

The prepreg system used in all four standard products consists of thermoset adhesive with unidirectional aramid fibers and a fiber volume content of 47%. Prior to lay-up and cure, the aluminium unclad surfaces are anodized and primed to provide good bond integrity and to inhibit aluminium bondline corrosion in the event of moisture intrusion. A chromic acid or phosphoric anodizing treatment is used. For added corrosion protection, or polished sheet application cladding can be applied to the outer aluminium faces of the ARALL Laminate sandwich. During curing, due to the differences in termal expansion coefficients, a small tensile residual stress will occur in the aluminium sheets and a corresponding compressive stress in the aramid layers. This is called the 'as-cured' condition.

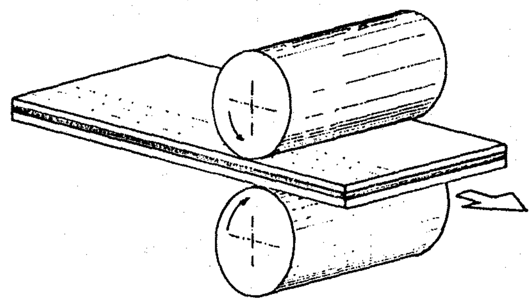


Fig. 7 Flat rolling of ARALL Laminates

However, the sign of the residual stresses can be reversed in a favourable way, by plastically deforming the material after curing. This is called 'post-straining'. Post-straining can be done in two ways:

1. By poststretching. The laminates are given a nominal 0.4% permanent stretch. 2. By rolling. The laminates are plastically deformed by flat-rolling under pressure (Fig. 7).

## PROPERTIES OF ARALL LAMINATES

The different types of ARALL Laminates are designated in the report by ABCD, with:

A = aluminium alloy sheets, f.i. 7 for the 7000 series, 2 for the 2000 series.
B = fiber, f.i. H for high modulus aramid fiber, R for R-glass fiber.
C = thickness of the separate aluminium layers in tenth of mm.
D = number of aluminium layers.

### Mechanical

Table 2 lists the mechanical properties of different types of ARALL Laminates along will those of 7075-T6, 2024-T3 and a typical grade of graphite/epoxy composite. As with most fibrous composite materials, ARALL Laminates properties are directional as dictated by fiber orientation.

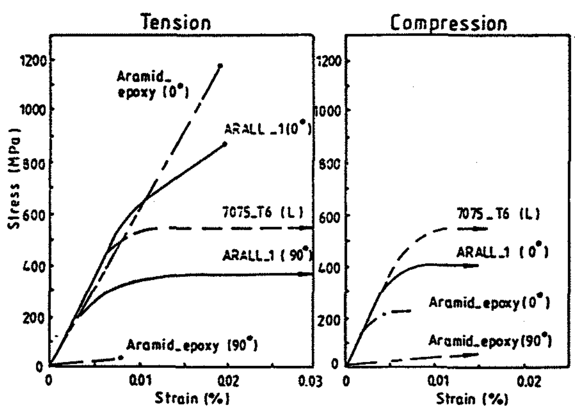
ARALL Laminate tensile ultimate strengths in the reinforcement direction are significantly better then those of the respective aluminium counterparts; also they are competitive with those of graphite/epoxy composite. This is especially true for ARALL Laminate with high strength glass fiber. Due to ineffectiveness of the fibers in bearing, the ratio of bearing strength/tensile strength is lower than that experienced by aluminium. The bearing strength is reasonably estimated by the summation of the bearing strength of the aluminium layers. Typical tensile and compressive stress-strain behaviours of 3/2 ARALL-1 Laminates and its constituents are given in Figure 8.

fatigue crack initiates and grows in the aluminium sheet(s), the

TABLE 2. Mechanical properties of some aircraft materials

| Property | Test Direct. | 3/2 ARALL laminate, 0.053 in (1.3mm) thick ARALL-1 | ARALL-2 | ARALL-3(b) | ARALL-4(b) | 2/1 ARALL laminate glass UD | glass 70/30 | Aluminium Alloy Sheet 0.063 in (1.6mm)thick 7075-T6 | 2024-T3 | Carbon Fiber Composite Typical Structure (d) |
|---|---|---|---|---|---|---|---|---|---|---|
| Tens. Ultimate | L | 116(800) | 104(717) | 120(828) | 106(731) | 160(1100) | 1145(1000) | 83(572) | 66(455) | 95(655) |
| Strength, ksi (MPa) | LT | 56(386) | 46(317) | 54(373) | 49(338) | 44(300) | 87(600) | 83(572) | 65(448) | 40(276) |
| 0.2% Off, Tens, Yld. | L | 93(641) | 52(359) | 85(587) | 54(373) | 54(370) | 44(327) | 74(510) | 52(359) | --- |
| Strength, ksi (MPa) | LT | 48(331) | 33(228) | 46(317) | 46(317) | 30(205) | 38(260) | 72(496) | 47(324) | --- |
| Tens. Elastic | L | 9.8(68) | 9.3(64) | 9.8(68) | 8.9(61) | 9.6(66) | 8.7(60) | 10.3(71) | 10.5(72) | 11.0(76) |
| Modulus, msi (GPa) | LT | 7.0(48) | 7.1(49) | 7.4(51) | 7.1(49) | 7.0(48) | 6.5(45) | 10.3(71) | 10.5(72) | 5.0(35) |
| Tens. Elong., % | L | 0.7(e) | 1.4(e) | 1.0(e) | 1.4(e) | 4 | 4 | 11 | 18 | --- |
| | LT | 7.1(e) | 12.0(e) | --- | 3.9(e) | >10 | 4 | 11 | 18 | --- |
| Tens. Tot. Strain | L | 1.9 | 2.5 | 2.2 | 2.6 | 5 | 5 | 12 | 19 | 0.5 |
| to Failure, % | LT | 7.9 | 12.7 | --- | 4.6 | >11 | 5 | 12 | 19 | 0.5 |
| Poisson Ratio | L | 0.33 | 0.32 | --- | --- | --- | --- | 0.33 | 0.33 | 0.48 |
| (Tension) | LT | 0.25 | 0.26 | --- | --- | --- | --- | 0.33 | 0.33 | 0.23 |
| 0.2% Off. Compr.Yld. | L | 54(372) | 38(262) | --- | --- | --- | --- | 73(503) | 44(304) | 95(655)(f) |
| Strength, ksi (MPa) | LT | 57(393) | 34(234) | --- | --- | --- | --- | 76(524) | 50(345) | 42(290)(f) |
| Compr. Elastic | L | 10.2(70) | 9.7(67) | --- | --- | --- | --- | 10.5(72) | 10.7(74) | 11.0(76) |
| Modulus, msi (GPa) | LT | 7.5(52) | 7.6(52) | --- | --- | --- | --- | 10.5(72) | 10.7(74) | 5.0(35) |
| 0.2% Off. Shear Yld. | L-LT | --- | 17(117)(g) | --- | --- | --- | --- | --- | 30(207)(g) | 37(255)(h) |
| Strength, ksi (MPa) | LT-L | --- | 16.5(114)(g) | --- | --- | --- | --- | --- | 30(207)(g) | --- |
| Shear Modulus | L-LT | 2.4(17)(g) | 2.5(17)(g) | --- | --- | --- | --- | 3.9(27) | 4.0(28) | 3.1(21) |
| msi (GPa) | LT-L | --- | 2.3(16)(g) | --- | --- | --- | --- | 3.9(27) | 4.0(28) | --- |
| Bearing Ult.Strength | L | 95(655) | 77(531) | --- | --- | --- | --- | 129(890) | 110(759) | --- |
| e/D=1.5, ksi (Mpa) | LT | 102(703) | 79(545) | --- | --- | --- | --- | 129(890) | 110(759) | --- |
| e/D=2.0, ksi (Mpa) | L | 107(738) | 82(565) | --- | --- | --- | --- | 166(1145) | 137(945) | --- |
| | LT | 105(724) | 79(545) | --- | --- | --- | --- | 166(1145) | 137(945) | --- |
| Bearing Yld.Strength | L | 85(586) | 56(386) | --- | --- | --- | --- | 110(759) | 78(538) | --- |
| e/D=1.5, ksi (Mpa) | LT | 88(607) | 56(386) | --- | --- | --- | --- | 110(759) | 78(538) | --- |
| e/D=2.0, ksi (Mpa) | L | 102(703) | 66(455) | --- | --- | --- | --- | 128(883) | 94(649) | --- |
| | LT | 97(669) | 64(441) | --- | --- | --- | --- | 128(883) | 94(649) | --- |

(b) Single laboratory lot
(d) Fiber orientations: 42% 0 degree, 50% ± 45 degree, 8% 90 degree.
(e) Plastic strain determined from test record by back extrapolating elastic slope from point of fracture.
(f) Compressive ultimate strength.
(g) Iosipescu shear test method; L-LT means fibers parallel to long specimen axis, LT-L means fibers normal to long specimen axis.
(h) In-plane shear ultimate.




*3/2 ARALL®-1 Laminate,
0.053 Inch (1.3 mm)

Fig. 8 Tensile and compressive stress-strain behaviours (Courtesy Alcoa)

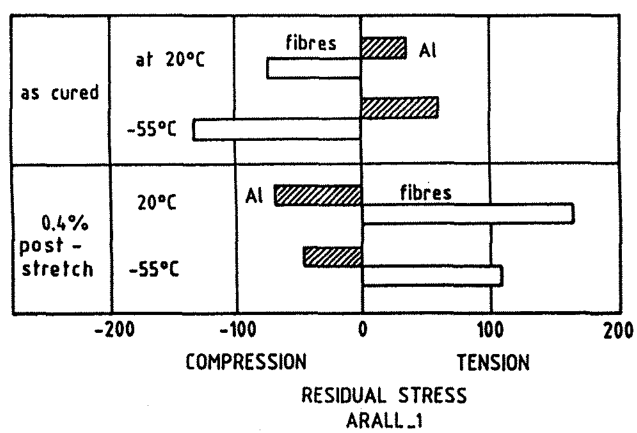



Fig. 9 Effect of temperature on residual stress in the laminate

Figure 9 shows the effect of service temperature on residual stress in ARALL-1 Laminate for as-cured and post-stretched material. The influence of the service temperature is not very strong, but have to be taken into account for fatigue live predictions.

### Fatigue

The reason for the extremely good fatigue properties of ARALL Laminates is the crack bridging function of the fibers. When a

fibers have to stay in tact, bridging the crack and thus lowering the stress intensity factor at the crack tip. Aluminium ply thickness and fiber properties play an important role in the optimization proces.

A nominal thickness of 0.3 mm has been chosen for the individual aluminium sheet layers together will a prepreg nominal thickness of 0.2 mm (Fig. 10). Due to the notch sensitivity at high K values, aramid or glass fibers has been chosen instead of carbon fibers (Fig. 11). Peak loads during flight simulation loading cause failure of the fatigue crack bridging carbon fibers. This is the result of a high stiffness combined with a low failure strain of the carbon fiber. For this reason high strength aramid- and glass fiber have been selected for use in ARALL Laminates. Figure 12 shows how stresses in the aluminium layers are effected by the amount of post-cure stretch (Fig. 12). ARALL Laminates in the as-cured state have excellent fatigue properties, but stretching operation makes ARALL Laminates practically insensitive to fatigue crack growth (Figures 13, 14and 15).

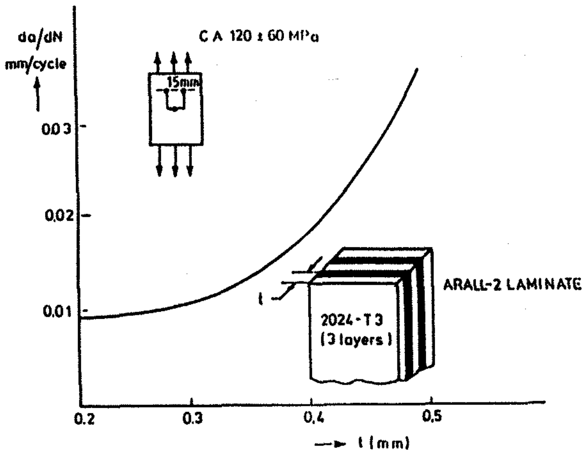



Fig. 10 Effect of aluminium ply thickness on crack growth rate

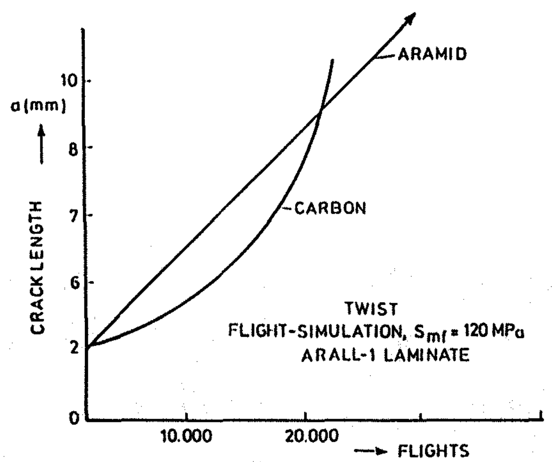



Fig. 11 Carbon fiber instead of aramid fiber

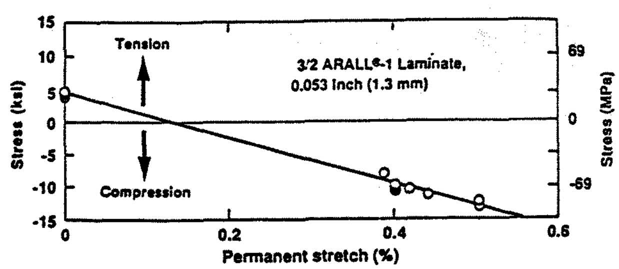



Fig. 12 Aluminium layer residual stress (Courtesy Alcoa)

The initial built in stresses of the fibers are of extremely importance whether fiber failure will happen or not. In the post-streched material the fibers are in tension while in the as-cured material the fibers are in compression. During flight-simulation and constant amplitude loading the fibers in the post- stretched material are fully tension-tension loaded, and no fiber failure will happen. This is also true for as-cured material under constant amplitude loading with minimum stress higher than zero. However for constant amplitude loading with minimum stress equal or smaller than zero, the aramid fibers will be cycled in compression,

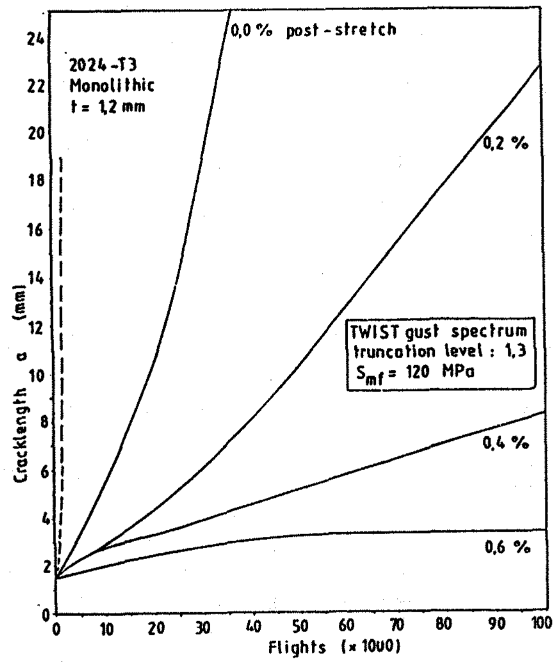



Fig. 13 Influence of post-stretch rate on flight simulation fatigue properties of ARALL Laminates

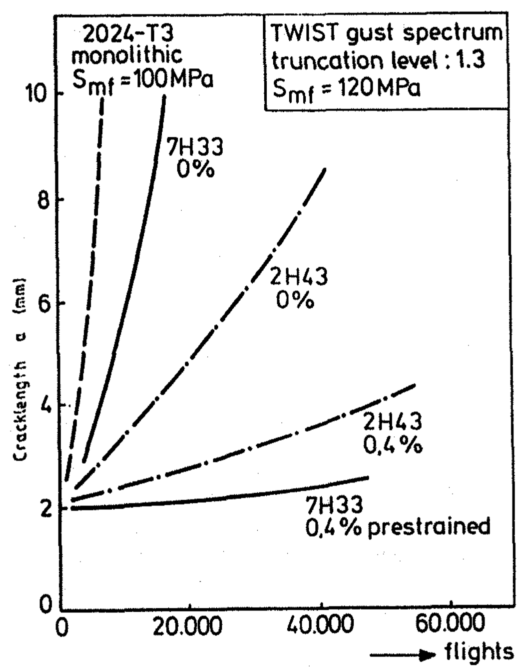



Fig. 14 Crack propagation rates in "standardized" ARALL sheet material

causing early fiber failure due to matrix cracking and subsequent fiber buckling (Fig. 16). The problem of fiber failure is even more serious for low frequenties. Tests at 0.02 Hz showed increased crack growth rates in comparison with 10 Hz. The length over which fibre failure occurred was greater at 0.02 Hz. A faster damage growth in the matrix material, for lower frequencies, causes the relative poor behaviour of as cured ARALL 2 Laminate at $R = 0$ constant amplitude fatigue.[7]

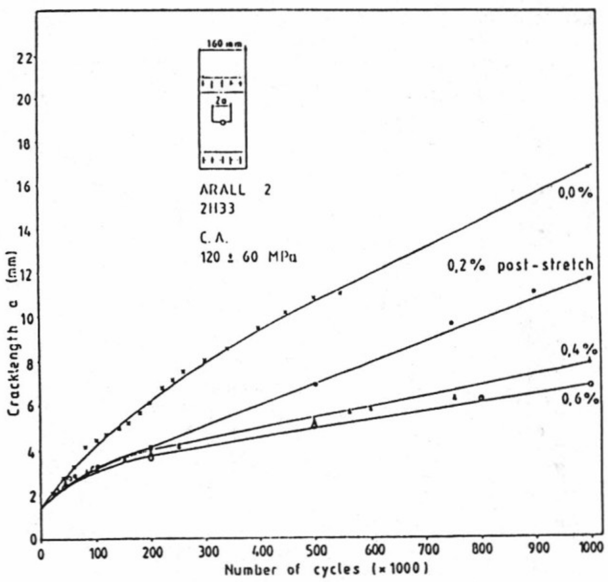



Fig. 15 Influence of post-stretch rate on constant amplitude fatigue properties of ARALL-2 Laminates

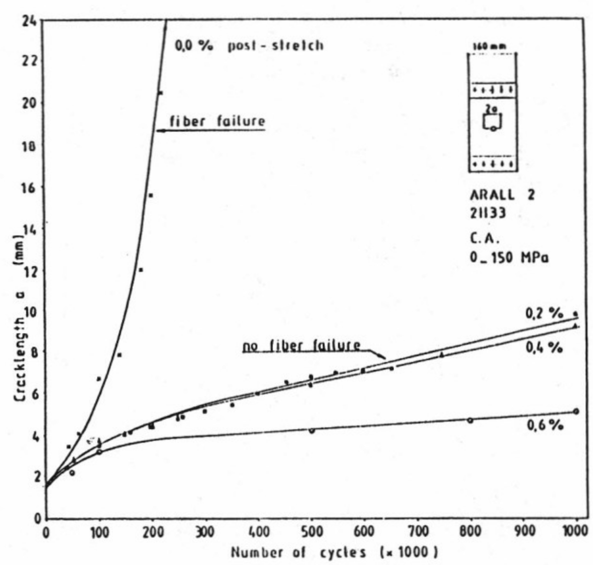



Fig. 16 Influece of compression-tension C.A. fatigue loads on the fatigue properties of as-cured and post-stretched ARALL-2 Laminate material

This is a problem for the application of as-cured ARALL Laminate in fuselage skins. To avoid a large number of tranverse joints, long sheets have to be produced with fibers in width direction. Post-stretching of such sheets is practically impossible, rolling might be possible.

The application of high performance glass fibers (S-glass, $S_2$-glass or R-glass) solves this problem. These materials have excellent compression-tension fatigue properties. ARALL Laminates, based on these glass fibers will not show fiber failure if used in the 'as cured' condition under $R = 0$ constant amplitude fatigue loading (Fig. 17).

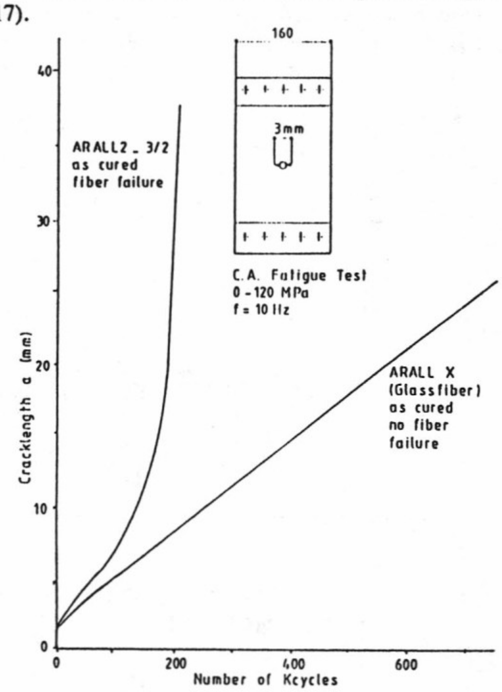



Fig. 17 Constant amplitude fatigue properties of ARALL Laminates with glass fibers

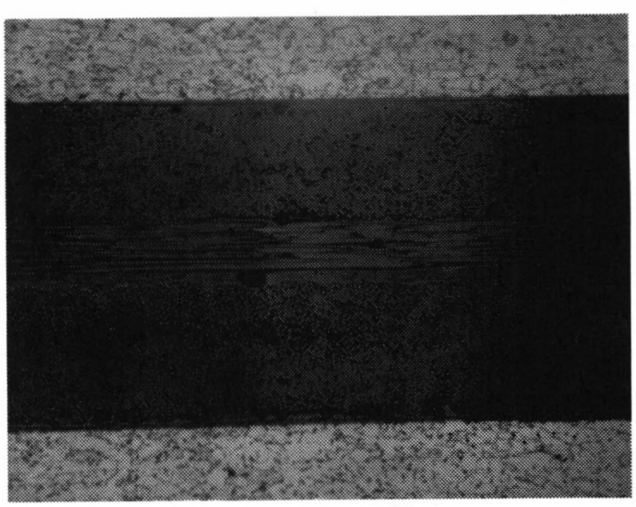


Fig. 18 Cross-section of ARALL-R-glass typical fuselage skin material

Because of this behaviour the ARALL Laminates based on glass fibers are thought to be extremely suitable for the application as a fuselage skin material. In the aircraft fuselage skin both stresses in the circumferential- and the longitudinal direction do occur (biaxial loading). A small amount of fibers in the longitudinal direction is therefore necessary to increase the fatigue life of the circumferential riveted lap joints. An ARALL Laminate based on R-glass fiber has been developed for this specific application. The fiber volume content of the composite layer is 60% with 70% of the fibers in circumferential and 30% of the fibers in longitudinal direction (Fig. 18). Excellent fatigue properties are observed for both fiber orientations (Fig. 19).

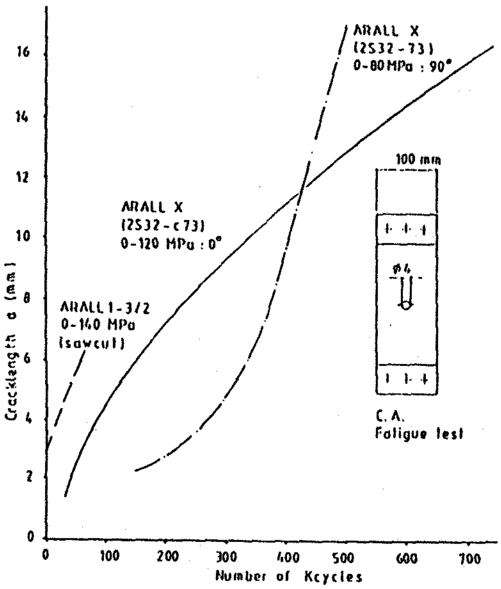



Fig. 19 Constant amplitude test results of ARALL-R-Glass fuselage skin material

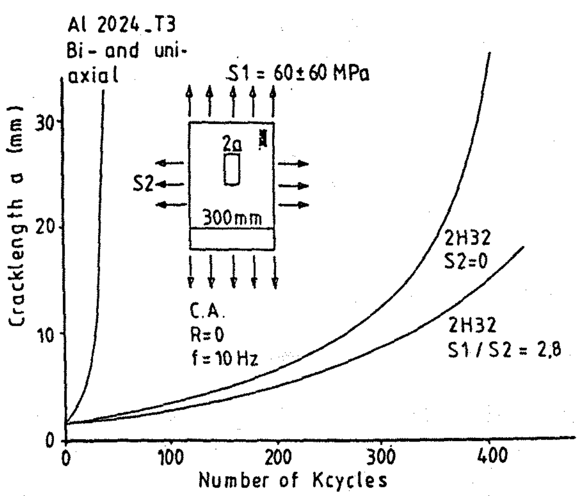



Fig. 20 Comparison of fatigue lives. Results of uni-axial and bi-axial constant amplitude tests on as cured ARALL-2 Laminate and monolithic 2024-T3 centre notched sheets

Two important aspects of designing aircraft fuselage structure are the biaxiality and the so-called bulge-out of the fuselage skin due to lateral pressurization of the fuselage. Both biaxial tests and fatigue test by pressurization of a fuselage section have been carried out using specially developed testing systems. As shown in Figure 20 biaxial stresses increase the fatigue life of ARALL 2 Laminate. Tests on curved specimens have shown that ARALL Laminates are favourably influenced by the so-called bulge-out effect even at a very low test frequency (1/12 Hz). Due to the lateral pressurization the bulge-out fenomenon seems to influence the fatigue behaviour of the ARALL Laminate sheet in a very positive way (Fig. 21).

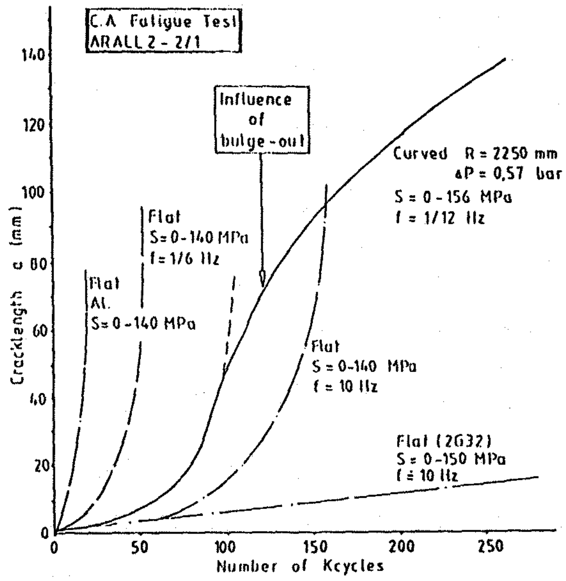



Fig. 21 Comparison of fatigue lives. Result of C.A. fatigue tests with flat and curved specimens

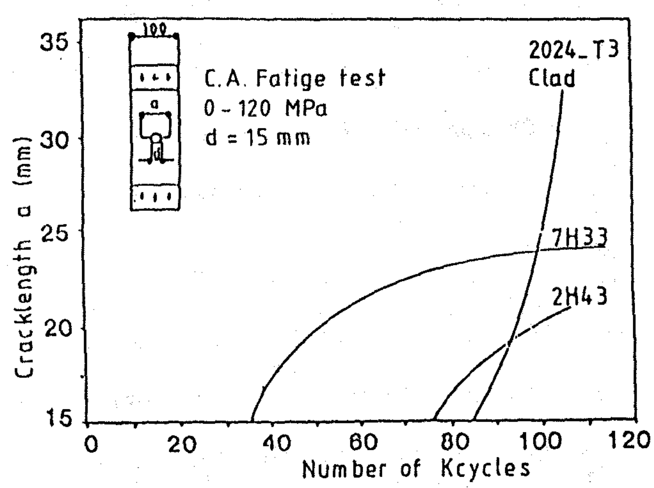



Fig. 22 Crack initiation and crack growth from open holes (chromic acid anodize layers)

It is evident that ARALL Laminates can be a strong candidate to be applied as an aircraft fuselage skin material.

Crack initiation from open holes starts sooner in ARALL Laminates compared to non anodized monolithic aluminium alloy due to microcracking of the anodize layer (Fig. 22). However in ARALL Laminate the crack growth rate is very small and the initiated cracks soon come to a standstill at an early stage of the fatigue life.. For crack initiation an advantage has been found of phosphoric acid anodize layers over chromic acid anodize layers.

transport aircraft wings show that the good properties of ARALL Laminates can not be used fully.
Mainly three reasons can be given:

1. Relative low shearmodulus G
2. Relative low bearing strength
3. It is in practice impossible to taper ARALL Laminates.

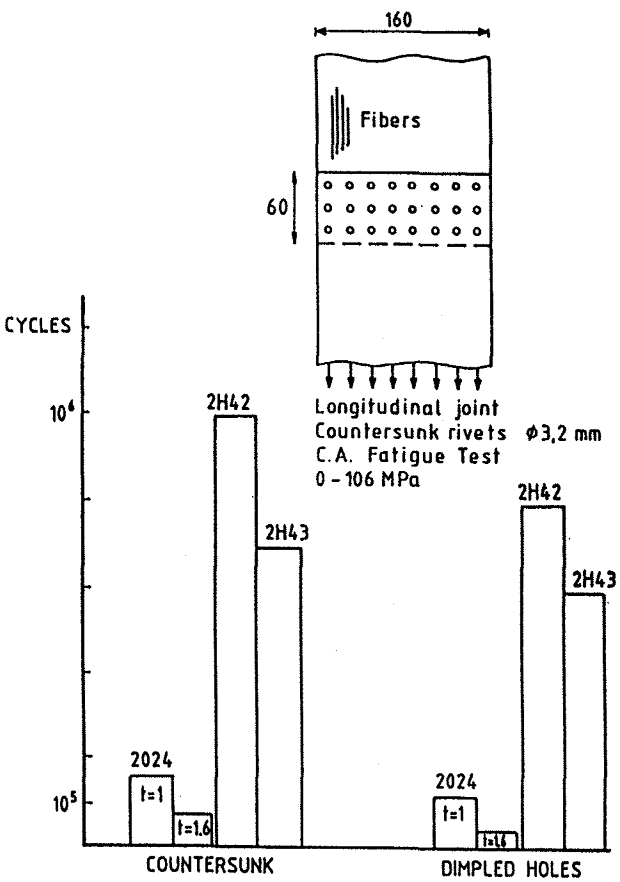



Fig. 23 Comparison of fatigue lives.
Results of C.A. tests on ARALL Laminate and monolithic 2024 T3 countersunk and dimpled riveted lap joints

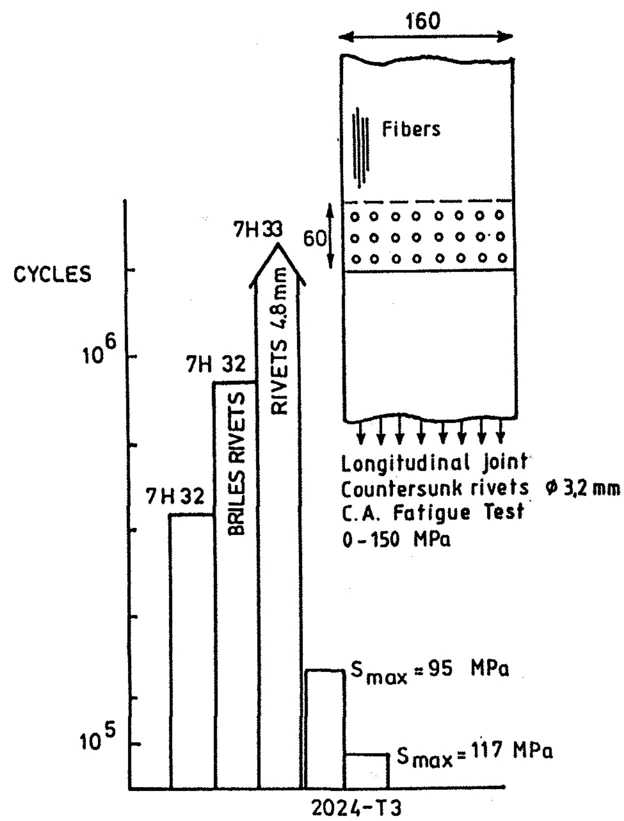



Fig. 24 Comparison of fatigue lives
Results of C.A. tests on ARALL Laminate and monolithic 2024-T3 riveted lap joints

Results of constant-amplitude and flight simulation fatigue tests on riveted and bolted joint specimens show highly superior fatigue properties in all cases for ARALL Laminates, as compared with monolithic aluminium alloy. Investigated is the influence of:

- countersinking and dimpling in combination with the sheet thickness (Fig. 23).
- Briles rivets and rivet diameter (Fig. 24).
- Fiber content in main loading orientation (Fig. 25).
- Ageing and corrosion, TWIST flight simulation loading (Fig. 26).
- FALSTAFF flight simulation loading (Fig. 27).
- Glass fiber instead of aramid fiber, fiber content in main loading orientation (Fig. 28).

Fatigue tests with ARALL Laminate lugs show highly attractive properties compared with monolithic and laminated aluminium alloy lugs (Fig. 29).
As will be discussed later on in this paper design studies of large

These three points can be improved and/or solved by using a modified ARALL Laminate sheet, consisting of a thick monolithic aluminium alloy core sheet with thin standardized ARALL Laminate sheets bonded to both sides of the core material (Fig. 30). The core material can be easily tapered for application in a wing skin structure. Table 3 demonstrates the mentioned property improvement.

TABLE 3

| | ARALL-1 Laminate | Mod-ARALL Laminate 2024-T3 | Mod-ARALL Laminate 7075-T6 | impr. |
|---|---|---|---|---|
| Shear modulus (GPa) | 17 a 18 | 23 a 25 | 22 a 24 | ~ 50% |
| Bearing strength ultimate (MPa) | 630 a 680 | 750 a 820 | 850 a 950 | ~ 40% |
| Bearing strength yield (MPa) | 480 a 520 | 550 a 590 | 660 a 730 | ~ 40% |
| Overall thickness (mm) | 6.8 | 7.0 | 7.0 | |

Preliminary tests results indicate that the fatigue properties of the modified ARALL Laminate are good and are situated between those of standardized ARALL Laminate and monolithic 2024-T3 (Fig. 31).

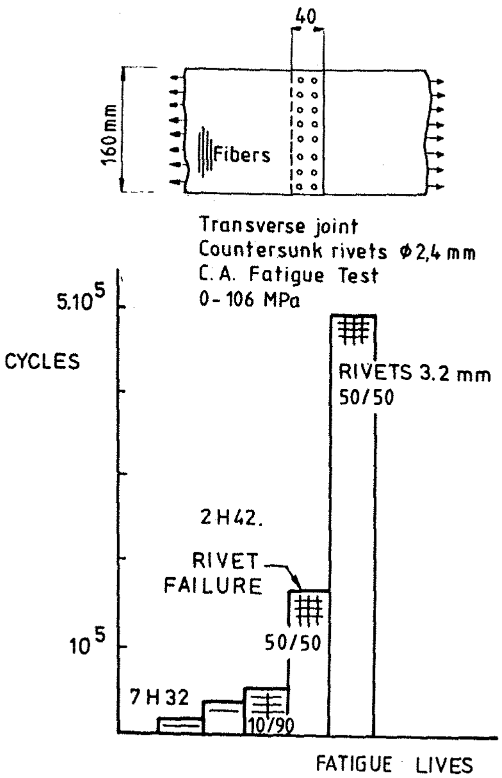



Fig. 25 Comparison of fatigue lives Influence of fiber content in main loading direction

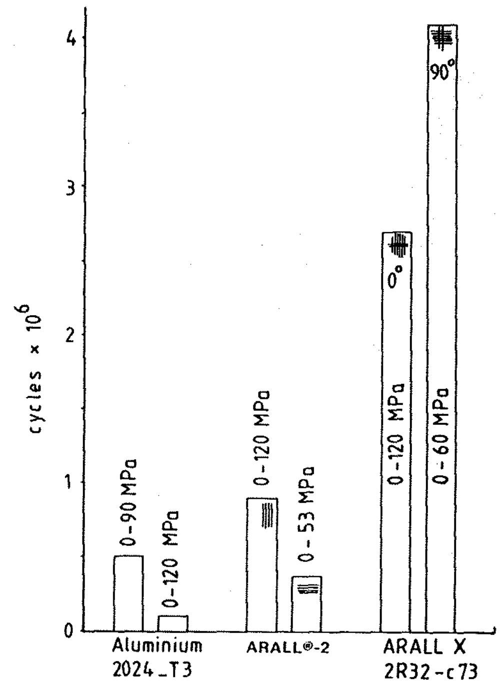



Fig. 28 Results of C.A. fatigue tests of riveted lap joints

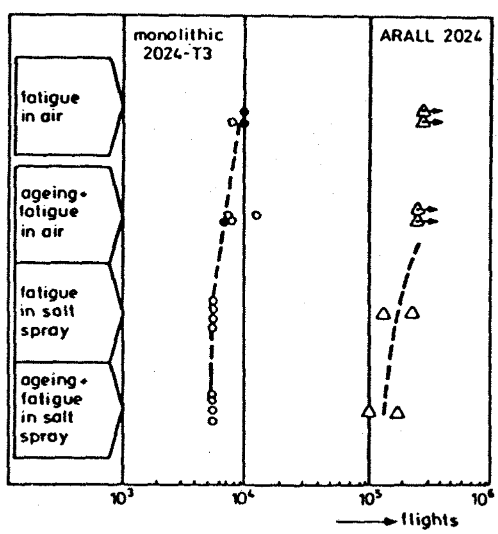



Fig. 26 Fatigue lives-until failure of bolted joint specimens under Mini-Twist gust spectrum with $S_{mf}$ = 100 MPa

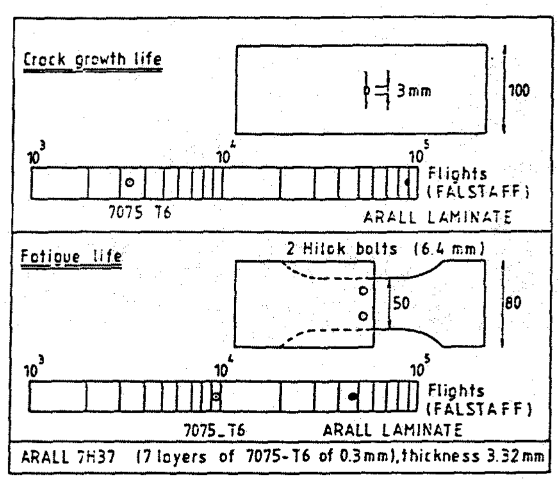



Fig. 27 Flight-simulation test results for ARALL Laminate (0.4% post-stretched) and aluminium 7075-T6

## Residual Strength

A reliable assessment of residual strength is required to verify that damaged safety-of-flight structural components made of ARALL Laminate are capable of sustaining fail-safe loads. While monolithic structures comform quite closely to the concepts of the engineering theory of fracture mechanics, this can not be expected for ARALL Laminate. Fracture toughness properties define the ability of a material to resist rapid fracture in the presence of fatigue cracks or other flaws. Typical aircraft panels of ductile materials tend to exhibit net section failure stresses approaching yield.

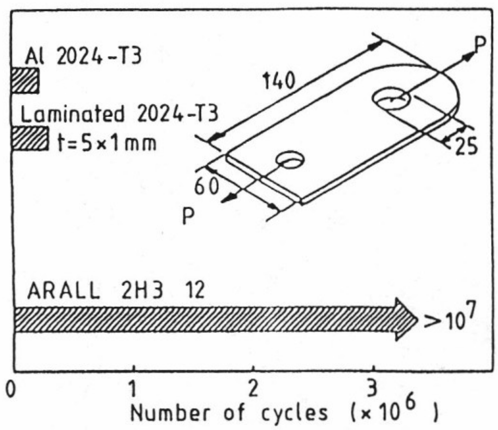



Fig. 29 Comparison of fatigue lives
Results of constant amplitude tests on lugs

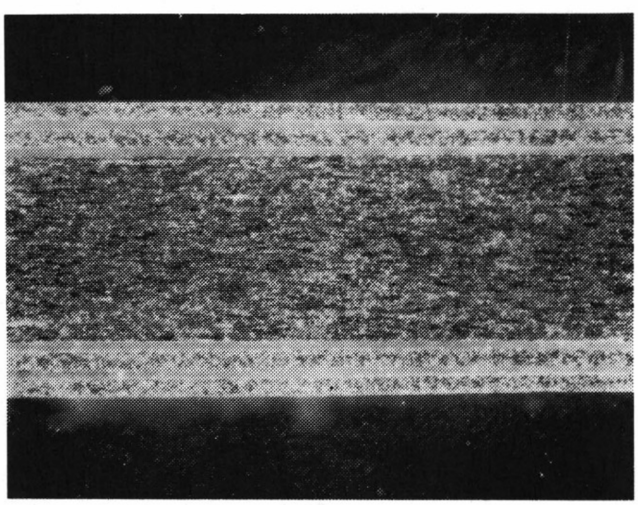


Fig. 30 Characteristic cross-section of a modified ARALL Laminate

Development of fracture toughness parameters for such alloys requires large test panels to validate complex structural designs. This is also true for ARALL Laminate based on aluminium 2024, so an extensive test program on large panels (width 500 mm) is executed. ARALL Laminate is a hybrid material, with its own typical residual strength behaviour. The low strain to failure of the aramid high modulus fiber has an unfavourable influence on the fracture toughness, especially in those cases where the fibers are cut. Fig. 32 shows the Feddersen diagram for 2024-T3, 7075-T6, ARALL-1 Laminate and ARALL-2 Laminate material. The fracture toughness of ARALL Laminate based on aramid fibers, with sawcuts is lower than that of monolithic 2024-T3. On the other hand the fracture toughness of ARALL Laminate based on aramid fibers and fatigue cracks is higher than that of 2024-T3, due to the unbroken fibers in the wake of the crack and the delamination zone around the crack, which effectively enlarge the 'strainlength' of the fibers (Fig. 33).

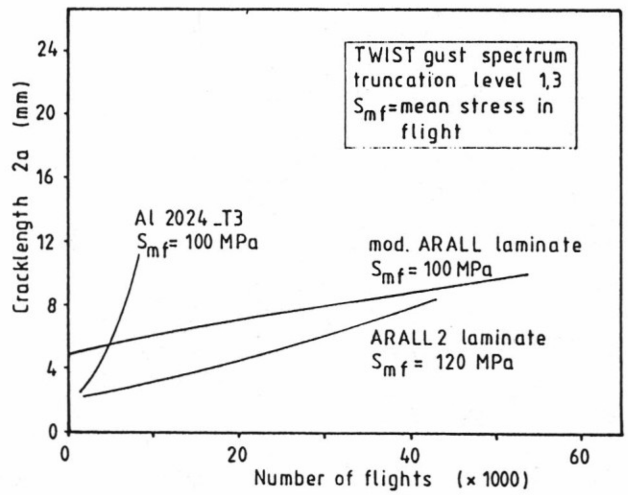



Fig. 31 Crack propagation rate in a modified ARALL Laminate sheets

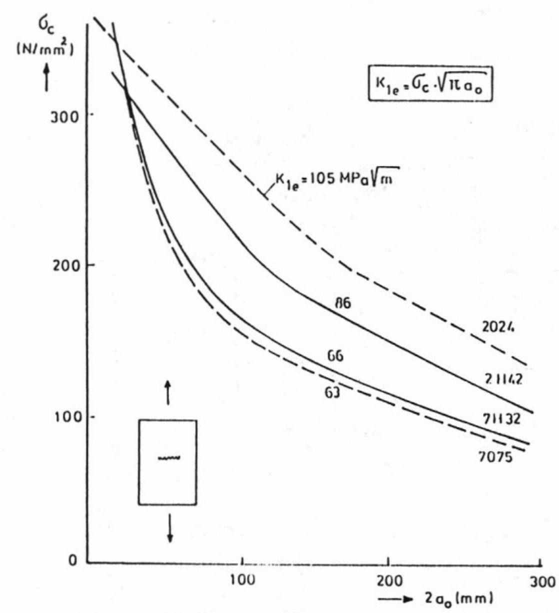



Fig. 32 Feddersen diagram
Panel width: 500 mm

To improve the residual strength of damaged (cut fibers) ARALL Laminate structures, a remarkable result can be obtained by using R-glass fibers instead of aramid fibers. Fig. 34 shows the residual strength of ARALL 2R32 Laminates in comparison with ARALL-1 Laminate, ARALL-2 Laminate and 2024-T3. ARALL Laminates based on R-glass show a superior fracture toughness behaviour

over most of the excisting structural sheet materials.
The effect of blunt notches on the static failure stress of ARALL Laminate sheet specimens of different grades has been investigated and is compared with monolithic 2024-T3 and 7075-T6 (Fig. 35).

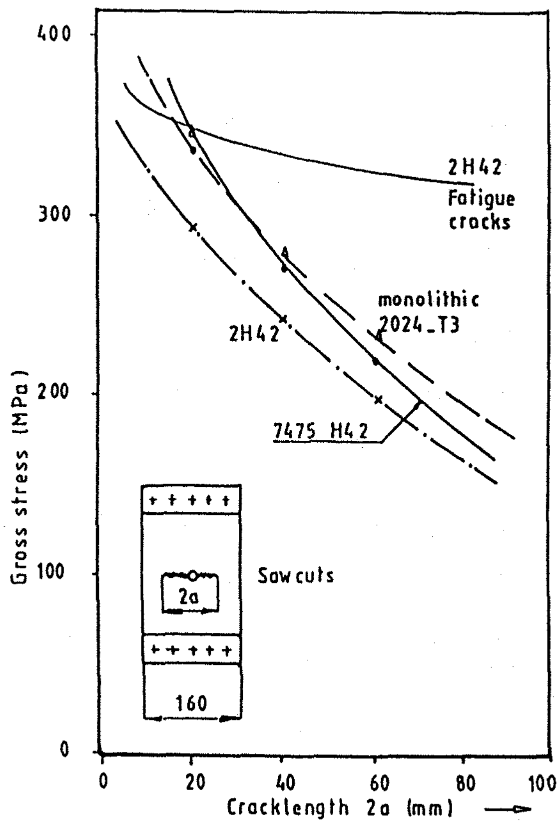



Fig. 33 Comparison of residual strength of unstiffened 2024-T3, ARALL-2 and ARALL-3 Laminate panels

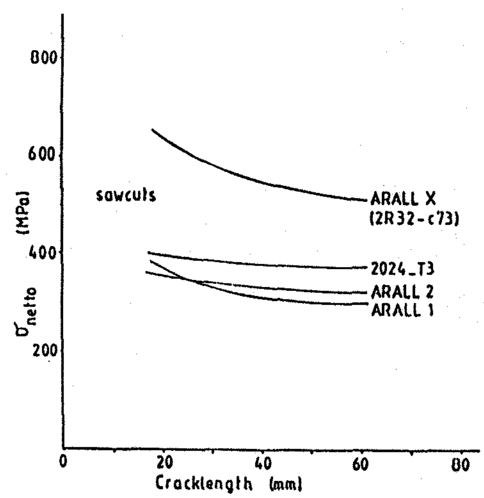



Fig. 34 Residual strength of unstiffened panels with a sawcut

The results imply that ARALL Laminate is relatively intolerant of blunt notches as far as static strength is concerned. This can be understood also by the small strain to failure of the fibers, a behaviour which is inherent in all fiber reinforced materials. Use of high strength glass fibers strongly improves the blunt notch strength. Extensive research work revealed that the notch strength of an ARALL Laminate is determined principally by the ultimate strength of the fiber.

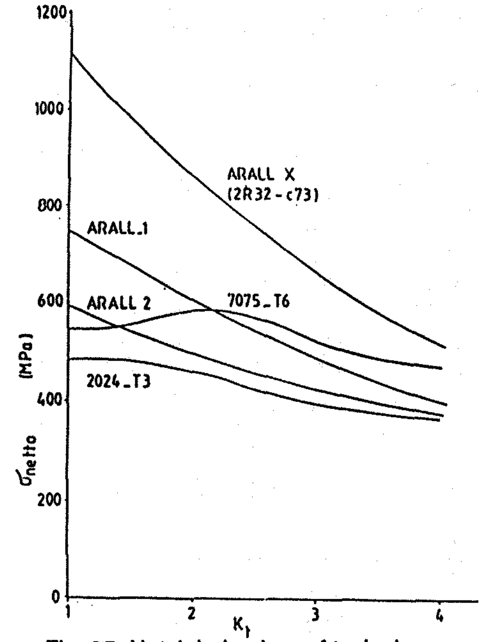



Fig. 35 Notch behaviour of typical fuselage materials

## Impact

The impact behaviour of materials has two aspects:

1. The impact phenomenon itself, the deformation process during the contact of projectile and plate, by which damage is induced.
2. The residual mechanical properties of the material after impact.

The impact tolerance of a material depends on the amount of damage that is obtained by an impact of a certain level, and the damage tolerance of the material. Impact tolerance is therefore a combination of damage resistance and damage tolerance. ARALL Laminate is a combination of monolithic aluminium, a damage resistant material, and fiber/adhesive layers which have to take care of the damage tolerance of ARALL Laminate, especially under fatigue loading.
The damage resistance of ARALL Laminate is relatively low compared with monolithic aluminium, but relatively high compared with pure composites.[8] The damage resistance of ARALL Laminate is limited by:

1. The relatively low flexural stiffness of ARALL Laminate, especially perpendicular to the fiber direction. This causes large deformations and therefore early failure of the fiber/adhesive layers, the aluminium layers, or both.
2. The low strain to failure of the fibers in ARALL Laminate.

In ARALL Laminate containing aramid fibers the fibers will be the weakest link. The fibers in the outer aramid layer of ARALL Laminate, opposite to the impact side will fail first. In general this will be immediately followed by failure of the aluminium layers, and a through crack will be created perpendicular to the fiber direction. In ARALL Laminate with glass fibers, the aluminium outer layer opposite to the point of impact will fail, creating a crack in fiber direction, the fibers will remain intact.

TABLE 4
Minimum energy needed to initiate cracking, impactor radius R = 7.5 mm
sheet thickness: 1.4 mm

| | |
|---|---|
| 2H33 | 4.4 (J) |
| 2H33/weave | 5.6 (J) |
| 2H33/crossed UD | 5.2 (J) |
| 2R33 | > 14.2 (J) |
| typical quasi isotropic carbon/PEI | 4.6 (J) |
| typical quasi isotropic aramid/PEI | 5.3 (J) |

The use of R-glass fibers improves the damage resistance significantly, but it can further be improved by using weaves instead of UD layers, or crossed UD layers as stated in table 4.
In ARALL Laminate no delamination was found after impact such as in pure composites. Impact damage in ARALL Laminate can easily be detected because of the dent in the outer aluminium layer.

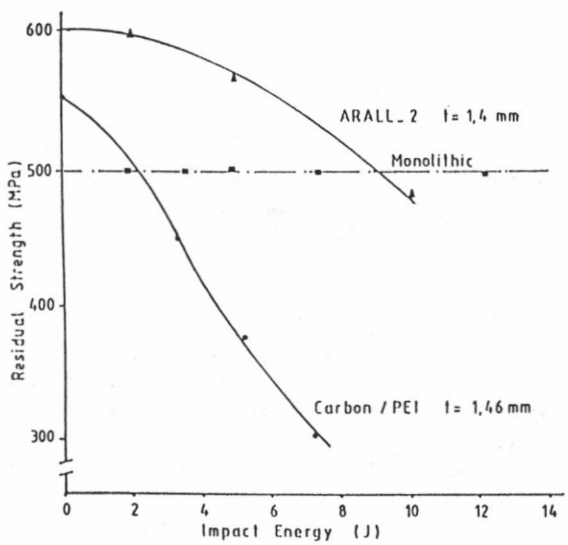



Fig. 36 The effect of impact damage on the residual strength
Impact mass 0.2 kg
Diameter of clamped plate 80 mm
Hemispherical projectile R = 7.5 mm

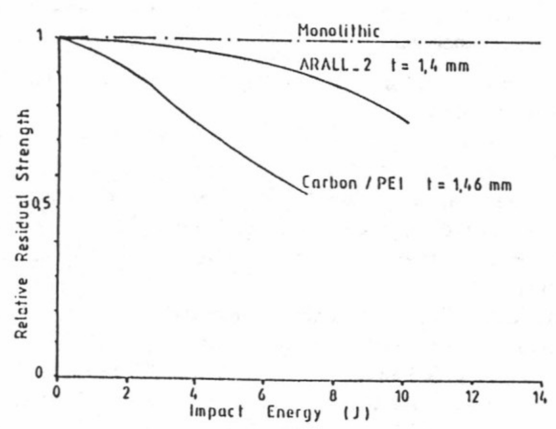



Fig. 37 The effect of impact damage on the relative residual strength

The damage tolerance of ARALL Laminate can be divided in fatigue properties and residual strength. A crack size caused by impact will be in the order of the dimension of the projectile that strikes the plate. In ARALL Laminate based on aramid fibers the impact damage will be a through crack transvers to the fiber orientation; in ARALL Laminate based on R-glass fibers the impact damage will be a crack in the aluminium layers parallel to the fiber orientation. Because of the excellent fatigue properties of ARALL Laminate in fiber direction, cracks will grow very slowly from this initial damage. The residual strength after impact of ARALL Laminate based on aramid fibers is compared with monolithic aluminium and carbon reinforced thermoplastics in figures 36 and 37. In this respect ARALL Laminate properties are between monolithic aluminium alloy and pure composites.

## Durability

Extensive durability programs are running both at Delft (Delft University together with AKZO) and at the ALCOA Laboratories in the USA. These programs include corrosion tests on ILS (interlaminar shear), Bell peel, wedge edge and delamination specimens in different environments (Fig. 38). Also the influence of temperature and humidity, the effect of static and dynamic loading on corrosion behaviour and the influence of pitting on fatigue crack initiation and growth (Fig. 39) are being investigated. Results available so far are good.[4]
With laminated materials the interfaces between the different components (fiber, adhesive and metal) can have a decisive effect on the behaviour of the material, especially under environmental action. The fiber/adhesive interface proved to be the weakest link for ARALL Laminate, especially when a mode I loading condition (loading perpendicular to the fiber orientation) is present.

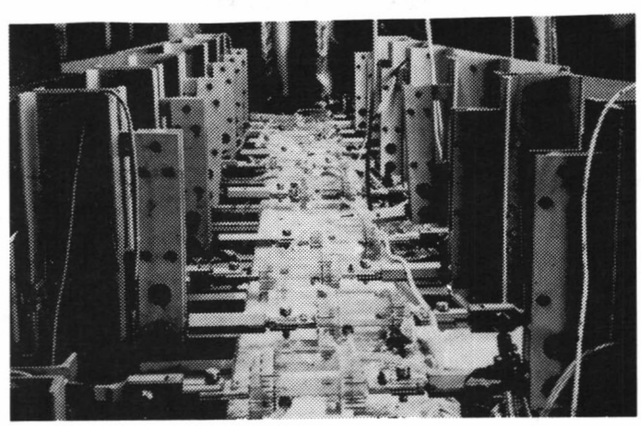


Fig. 38 Sustained load testing of ARALL Laminates in different environments

Inadequate adhesion between the aramid fiber and adhesive results in low peelstrength (Bell-peel test) and energy release rate (WTDCB-test) of the aramid prepreg. Actually this feature is not hampering the structural applications. Use of glass fiber instead of aramid fiber improves the peelstrength of ARALL Laminate due to the better adhesion of glass fiber and resin. A higher fiber volume content (60% instead of 47% for aramid) of the glass fiber layer can be used with sufficient peel properties.

## Workshop properties

Extensive work on ARALL Laminates has shown that the material can easily be cut, drilled, sawn and milled by normal workshop procedures.[3] Countersinking is also possible (Fig. 40). A second adhesive bonding treatment of ARALL Laminate sheets (involving pretreatments and high temperature curing) has been used. No degradation of properties and no relaxation of residual stress could be detected.Folding of ARALL Laminate requires some special attention, in view of the limited failure strain of the aramid fibers and the possibility of delamination due to the high shear stresses involved. An extensive program to determine the limitations, and most suitable technique for folding ARALL Laminate sheet reached success with the manufacture at the Fokker Papendrecht plant of different aircraft parts by modified rubber press and folding technique (Figures 41 and 42).

In addition peen forming has been tried out on ARALL Laminate to obtain double- curved parts. It turns out that this technique can also be used successfully.

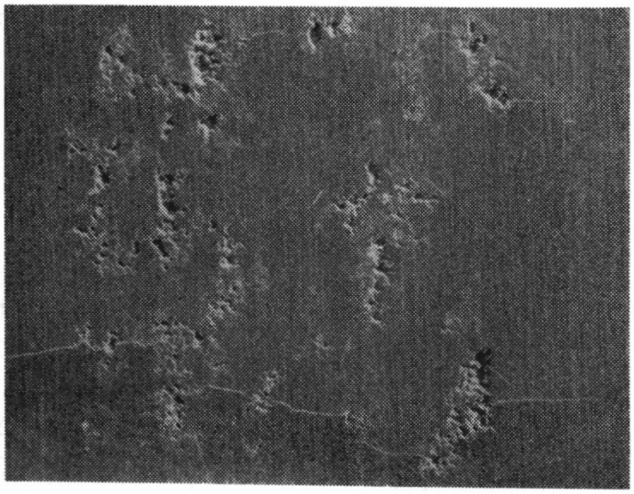


Fig. 39 Fatigue cracks initiated from corrosion pits

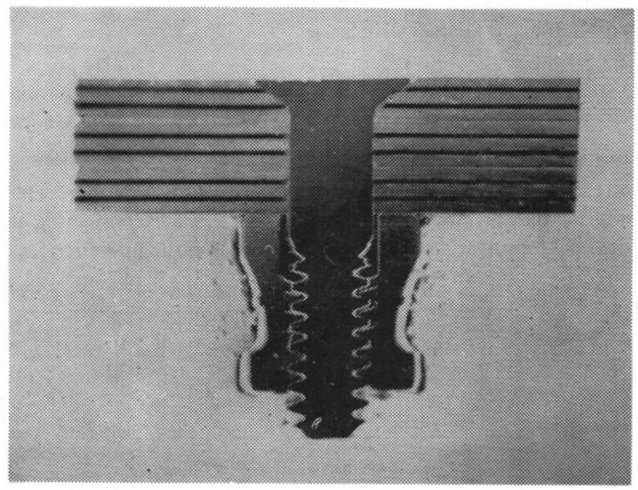


Fig. 40 Cross-section of ARALL Laminate countersunk Hi-Lok

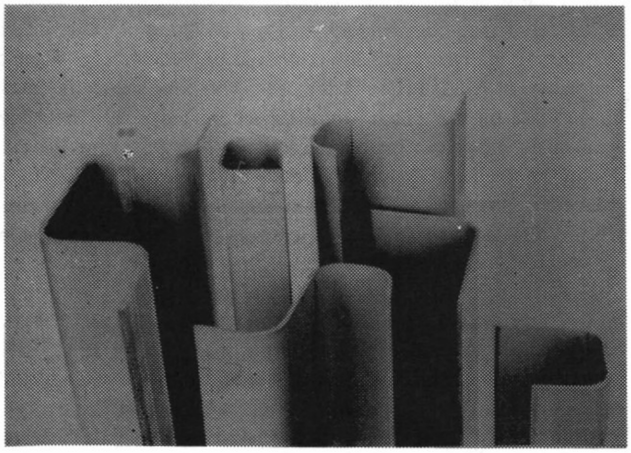


Fig. 41 Some ARALL Laminate stiffeners

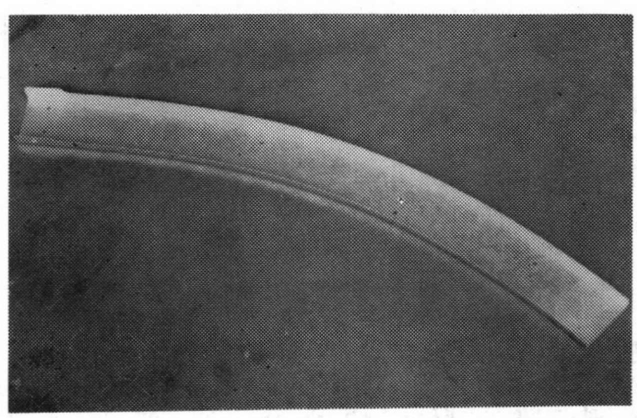


Fig. 42 ARALL Laminate fuselage bulkhead part

## STRUCTURAL APPLICATIONS

A number of applications of ARALL Laminates are considered during the past 10 years. A lot of design studies have been focused on application in primary structures of commercial transport aircrafts. However with growing confidence in the material and due to new developments also the military aircraft industry become more and more interested in ARALL Laminates. Outside the aircraft industry also a growing interest in the material can be observed. Due to its high strength, excellent fatigue and residual strength properties as well as anti-ballistic and acoustic characteristics ARALL Laminate turns out to be an interesting material for a wide range of applications like marine and off-shore structures, cars, containers, bridges, etc. However this section will be primarily focused on the application in aircraft structures.

### AIRCRAFT STRUCTURES

During the development of ARALL Laminates several design studies of primary aircraft structures in ARALL Laminates are performed.[9] It turns out that the impact of this material on primary aircraft structures is in the same order as the full composite materials. Its abilities are such that manufacturers are considering the material for primary structures of their existing and new aircrafts.

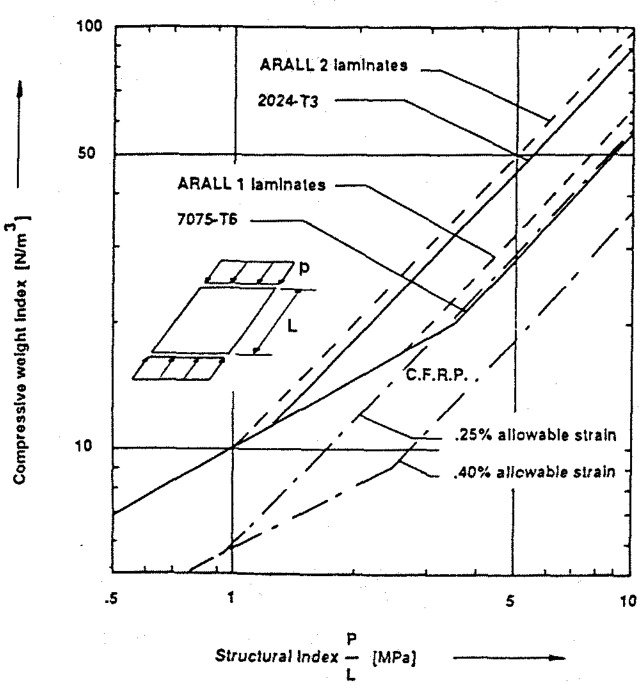



Fig. 43 Compression structural efficiency

General comparison of candidate materials for transport aircraft structures indicate that the most likely parts in which to use ARALL Laminates are the lower wing and the fuselage skin, speed brakes, ailerons or in general high fatigue and tension loaded components.[9] Fig.43 shows that compression critical components made of ARALL Laminates can hardly compete with their C.F.R.P. counterparts. In this case even aluminium alloys are slightly better.

It is common knowledge that for structural design several allowables are of primary importance: static strength (design limit and ultimate loads), durability and damage tolerance. Especially for military aircrafts an aspect of major concern is supportability. These aspects in relation to ARALL Laminates are discussed extensively[9,10] and are still under investigation.

The static strength allowable of ARALL Laminate is, like composites, determined primarily by the notch factor (Fig. 35). However the notch sensitivity of full composites is much more severe compared to the ARALL Laminates. On the other hand Fig. 35 shows also that ARALL Laminates based on glass fibers give significant improvement in static strength. Environmental effects, which are decisive for composite materials, are virtually absent in tests on ARALL Laminate specimens. Extensive durability tests have shown hardly any reduction in static strength and stiffness. The static strength of ARALL Laminates reduce 5 to 10% after fatigue loading to more than three times the aircraft life in agressive environments.

While for aluminium alloys durability is directly related to its fatigue and crack initiation behaviour, durability of ARALL Laminates is hardly influenced by these phenomena. It turns out that durablity of aircraft structures made of ARALL Laminates is primarily dictated by the damage tolerance characteristics of the structure. A structure is damage tolerant if it retain adequate strength and stiffness after damage has occured until detected through inspection. Residual strength, crack propagation and damage detection are the major aspects comprising damage tolerance. The relative importance of these aspects depends very much on the material used, the applied load level and the required aircraft life. These aspects are discussed in detail in ref. 9. This discussion showed that from residual strength viewpoint accidental damage (only if the fibers are broken!!) is the most critical damage. Due to the nature of ARALL Laminates fatigue crack growth is of hardly any importance, also the residual strength of fatigued specimens (fibers intact, thereby bridging the crack in the aluminium layers!!) showed a small reduction in static strength compared to the unfatigued specimen. Because ARALL Laminate structures will be designed taking into account the notch behaviour of the material, this reduction will be covered completely. Due to the fact that genuine cracks in ARALL Laminate structures will have extraordinary slow crack growth and finally arrest it seems justified to allow the structure to fly with small cracks. In that case the structure must be able to carry the design ultimate load with these cracks. It will be shown later on that this behaviour is observed at tests of full scale aircraft components.

Accidental damage can only occur in specific areas of the structure. In fact only the exterior of the aircraft is prone to foreign objects. The nature of ARALL Laminates, it will deform plastically due to impact, is a big advantage from inspection viewpoint. Especially accidental damage causing broken fibers will show severe deformation of the structure. Only in this case the residual strength will be reduced significantly. So the maximum damage of the structure will be dictated by this case. Also from supportability viewpoint the accidental damage is a critical factor. However it carries further, it also comprise the broad field of repairability. In this case repairability means the ability to repair the structure to the extend that it again can carry ultimate load as well as the easy way of repairing the structure and storage of the repair material. ARALL Laminates offer in this respect a big advantage over the existing C.F.R.P. materials. It can be stored and handled like the ordinary aluminium alloys. However it should be mentioned that the introduction of thermoplastic resins have given the C.F.R.P. materials the same advantages.

To prove the ability of ARALL Laminates in primary aircraft structures and to explore problem areas, several design studies on lower wing and fuselage structures are performed. To get full confidence beside small specimens also full scale aircraft structural components are tested, both with static and flight simulation loading. In the next sections the results of these investigations will be discussed. However, it is obvious that the investigation still continues.

## LOWER WING STRUCTURES

Several lower wing structures are investigated during the development of the ARALL Laminates itself. Two design studies and structural testings will be discussed briefly in this section. The lower wing of the Fokker F-27 and the lower wing of the McDonnel Douglas C-17.

### F-27 lower wing structure

During the first development phase of ARALL Laminates the lower wing structure of the Fokker F-27 was investigated. Several design studies of this specific structure were performed.[9] These overall design studies showed a significant improvement in fatigue life as well as a drastic reduction in weight of the structure (in the order of 30%). Due to these results it was decided to design in detail a fatigue critical part of this structure, but also to manufacture and test it. Fig. 44 shows the overall design of the panel. The design is performed using the CAD-system Medusa.[11,12] Overall and detail optimization of the structure is performed with the finite element code GIFTS (Graphical Interactive Finite element Total System).[11]

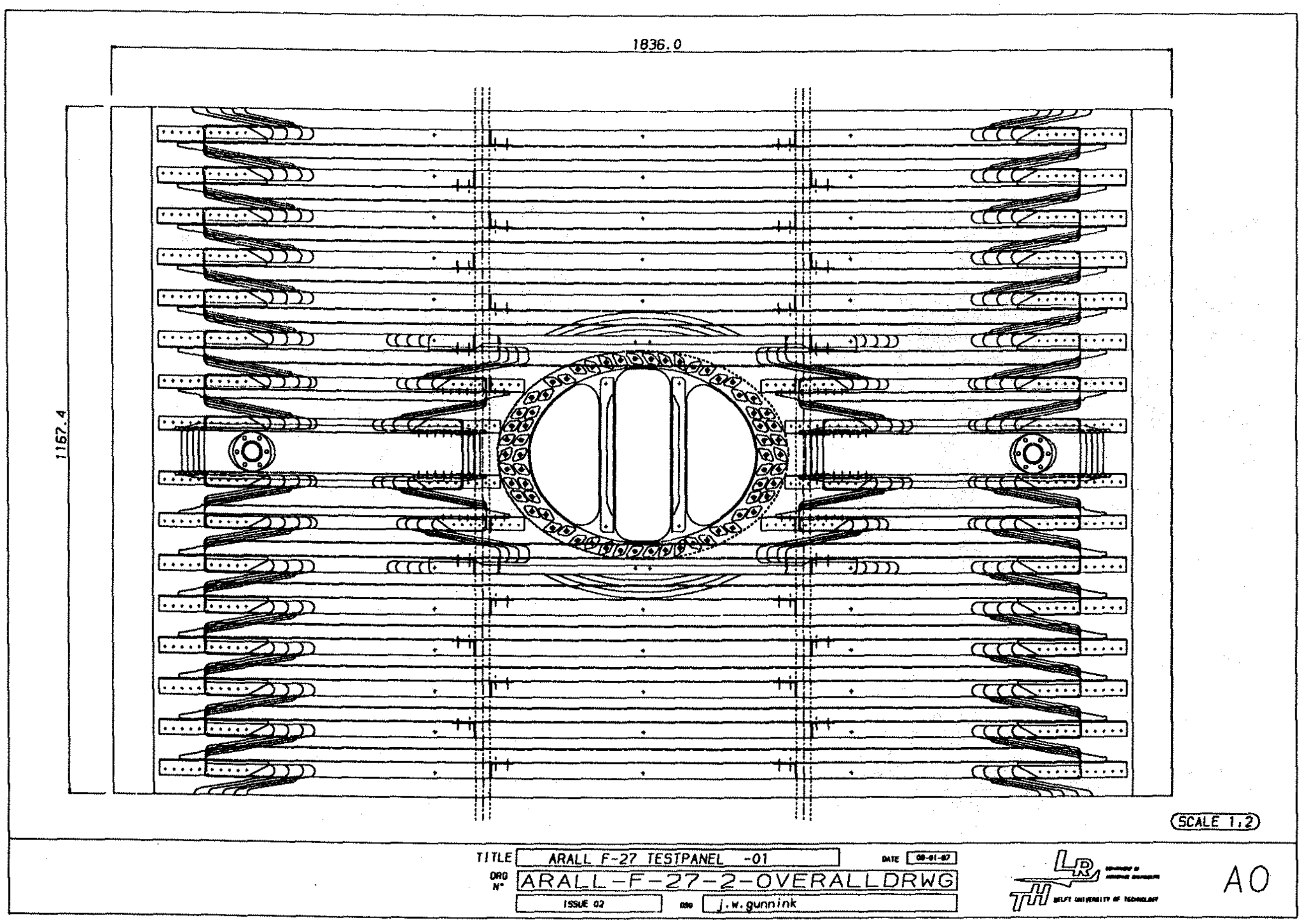



Fig. 44 Overall design of the ARALL F-27 lower wing panel

During the design procedure several detail structures have been tested. The most important tested structure was the endfitting panel, representing the load transfer at the inner-outer wing connection (Fig. 45 and 46). Four endfitting panels are tested in flight simulation loading up to three times the design life time of 90,000 flights.

the panels did not failed at the fatigue cracked area but failed over the center of the panel through the rivets which connect the rib-shear cleats to the stiffener. So in fact in the area with the smallest nett-section and the highest notch-factor. The failure load was about 5% above the design ultimate load.

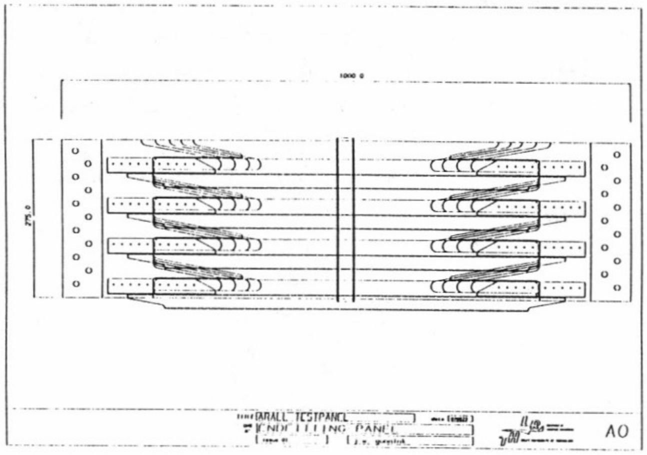


Fig. 45 Design of the ARALL F-27 endfitting panel

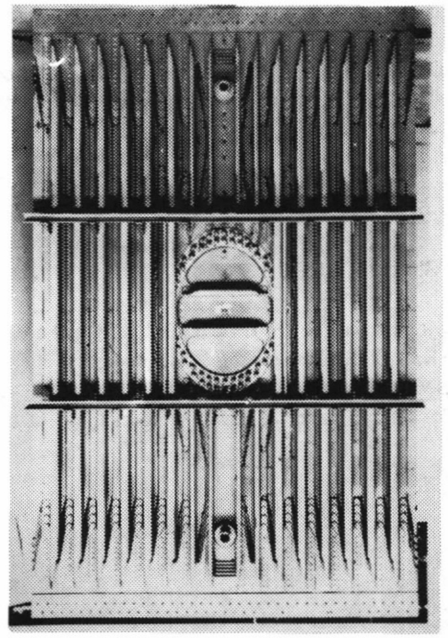


Fig. 47 ARALL F-27 lower wing panel

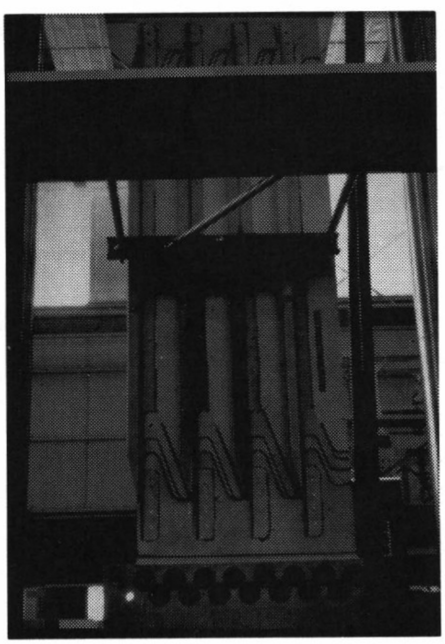


Fig. 46 Testing of the ARALL F-27 endfitting panel

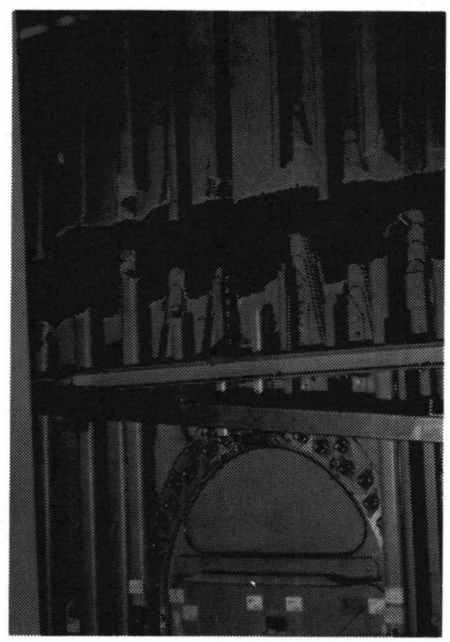


Fig. 48 Fracture of the ARALL F-27 lower wing panel in the residual strength test

Only small cracks are detected in the outer layer of the stiffener at the end of the fingertips. After 270,000 flights, two panels are tested in tension until failure. It was remarkable to observe that

These tests confirm the statement that the blunt notch figures of ARALL Laminates are one of the prime design allowables. These and related tests gave improved confidence in the design of the

overall panel. According to the design and the production drawings the ARALL F-27 testpanel was manufactured at Fokker (Fig. 47). Also the testing of the panel has been performed at Fokker.[12,13] It turns out that the panel has 33% less weight compared to the original aluminium Fokker panel.
Due to severe bending, after 20,000 flights some cracks are observed in the rebate of the manhole. Reanalyse of this area resulted in a local change of the structure.[11,12] Without any repair the panel was tested up to more than 270,000 flights. After fatigue testing the panel was tested in tension until failure. It failed at 1.42 times limit load.[13] Also in this case the panel failed at the rib-panel connection and not in the fatigue cracked area (Fig. 48). This means that also these tests confirm that the blunt notch figures are one of the most important design allowables. So it can be concluded from the results of this panel that ARALL Laminates are materials which offers the aircraft structure reduced weight and improved life.

### McDonnell Douglas C-17 wing structure

To explore possible problem areas in ARALL Laminate structures it turns out to be necessary to design the lower wing of a large transport aircraft apart from the small to medium size aircraft wing like the Fokker F-27 and Fokker 50. Special problems have to been solved with these types of aircrafts. Due to aeroelastic behaviour of the structure the stiffness characteristics turns out to be a major design parameter. Furthermore joining is rather difficult in ARALL Laminates due to its relatively low bearing strength properties. All these aspects are considered in a preliminary design study of the wing of the McDonnell Douglas C-17 aircraft in ARALL Laminates. Due to the formability characteristics of ARALL Laminates it turns out that ARALL Laminate stiffeners are hardly to manufacture for this type of structure. Together with the aeroelastic requirements this was the reason to adopt a sandwich skin (Fig. 49).

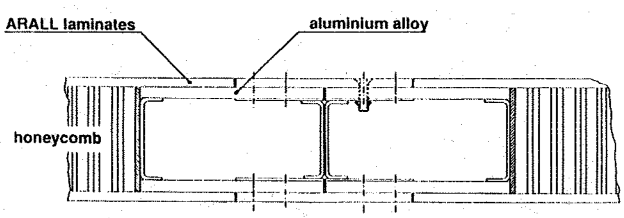



Fig. 49 ARALL Laminate wing joint of the McDonnell Douglas C-17

However like all sandwich structures the joining of this structure is rather difficult. In fact mechanical fastening was impossible without using bonding technology. So an optimized joint was designed by bonding a sheet of aluminium alloy with high bearing properties to the ARALL Laminate faces. In this specific aluminium sheet mechanical joining can be taken place. Fig. 49 shows the fundamentals of the joint. Static strength test of the joint have shown that this joint was able to transfer the design ultimate load. However from manufacturing as well as inspection point of view this type of joint is hardly to tolerate. Furthermore tailoring of ARALL Laminate in spanwise direction is with the existing material almost impossible. So a modified ARALL Laminate is developed (Fig. 30). This laminate contains ARALL Laminate facings and a thick aluminium core, which can be tapered to suit the load distribution. In addition the bearing strength properties as well as the shear modulus increase significantly (Table 4). Fatigue test results of this modified ARALL Laminate are still good as Fig. 31 shows.
In new preliminary design studies this modified ARALL Laminate is applied. Instead of sandwich structures stiffened panels are considered, using aluminium alloy stiffeners with the modified ARALL Laminate skin. In this particular case the same type of joining can be used as for the ARALL F-27 lower wing structure is developed (Fig. 46). Fatigue testing of these type of panels are under development.

## FUSELAGE STRUCTURES

It is widely known from conventional (aluminium) aircrafts that the normal differential pressure p in a pressure cabin can be regarded as the main fatigue initiator. Fatigue cracks will start from locations with relatively high stress concentration factors (riveted joints, frame skin connections, door areas, windows. etc.). Due to the internal pressure p the longitudinal lapjoint in combination with local stress concentrations is often the most fatigue critical area. However due to flight loadings and/or structural lay-out with its inherent stress concentration factors, other areas can become also fatigue criti cal. In this respect ARALL Laminates offers with their excellent fatigue behaviour great benefit. However as is mentioned previously ARALL 2 Laminates (in the as-cured condition) can obtain fiber failure under R=0 loading. Although still the fatigue life is better compared to aluminium alloy. On the other hand fatigue testing (R=0) of curved panels and biaxial loading show improved fatigue life and limited fiber failure (Fig. 20 and 21). Furthermore it should be realised that in case the fibers are broken the standardized ARALL Laminates have a relatively low residual strength . Taking into account that the damage tolerance requirements have the major effect on the design of aluminium alloy fuselages it can be expected that these requirements have an even larger effect on the ARALL Laminate fuselage design. The application of ARALL Laminate in fuselage structures and the consequences are extensively discussed in ref. 14. As expected it turns out that the residual strength characteristics of ARALL Laminates is one of the main design allowables for a large part of the fuselage cabin skin. In this respect the ARALL Laminates based on R-glass fibres are promising. They show a large increase in residual strength values, as followed from Fig. 34 and 35. The full consequence of the application of ARALL Laminates in fuselage structures can only be judged by designing the structure itself and testing of its essential components. In this way the effect of stiffeners, frames, windows, doors, joints and bulkheads as well as the load history can be incorporated. Already in an early stage of the ARALL Laminate development a preliminary design study of a significant part of the Airbus A-320 fuselage was performed for this reason. It shows significant weight savings for the fuselage skin, varying from 20% for the bottom part up to 40% for the crown. From this study can be concluded that the biaxial loading in the crown and the residual strength requirements are critical issues for an ARALL Laminate fuselage. The reduction in weight of the fuselage skin is partly due to the lower density but in general mainly due to the smaller skin thickness, which are obtained by the higher allowable fatigue loading in ARALL Laminate structures. However, this can have an effect on the aluminium frames and the frame-skin connections.[9] It turns out that the stresses in the frame can become too high. In this respect it must be

realised that fuselage frames are not so readily inspectible as the fuselage skin. For this reason operators require long inspection periods for these types of aircraft components. High stresses in the frames could obviously lead to a dangerous situation.
Due to questions of the aerospace industry a research project was carried out on ARALL Laminate crack-stoppers. In this project was investigated primarily the fatigue behaviour of aluminium alloy panels with crack-stoppers of different materials (Fig. 50). In this way aluminium sheet panels with ARALL 1 Laminate crack-stoppers are compared with aluminium sheet panels with crack-stoppers of aluminium alloys, titanium alloy and integrally stiffened sheet panels. Also riveting and bonding of the crack-stoppers was taken into account.

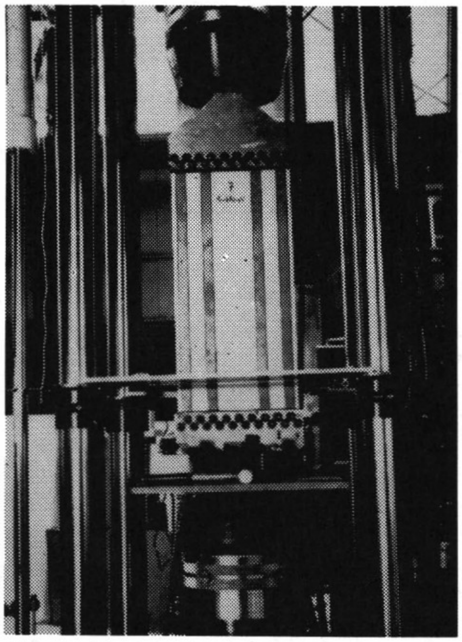


Fig. 50 Testing of a crack-stopper panel

For the riveted as well as the bonded crack-stoppers the ARALL Laminate crack-stoppers show significant better result compared to the alumium alloy crack-stoppers as well as the integrally stiffened panels. Even after total failure of the aluminium sheet the ARALL Laminate crack-stoppers are able to transfer the total panel load. This shows in fact the remarkable damage tolerance behaviour of the ARALL Laminate crack-stoppers. Comparison with the titanium crack-stoppers show a slightly different behaviour. Due to the higher stiffness of titanium alloy, the crack growth rate of the titanium crack-stopper panels was somewhat lower compared to the ARALL Laminate crack-stopper panels. However if a fatigue crack initiates in the titanium crack stopper the crack growth rate increase significantly, and will lead into total panel failure. On the other hand if the ARALL Laminate crack-stoppers are bonded to the aluminium panel with the unidirectional prepreg NPE 9055, the crack growth rate of these panels reduce significantly, and show even better fatigue life than the titanium crack-stopper panels. Whereby still the ARALL Laminate panels are able to transfer the panel load.

## SPECIAL APPLICATIONS

As said before ARALL Laminates can be taylored for a lot of different applications by varying fiber-resin systems, metal alloys and sheet gages etc. Figure 51 shows a thick ARALL Laminate plate as part of a very efficient anti- ballistic system. Figure 52 shows an ARALL Laminate tube. The current manufacturing techniques for metal tubes can not be used for ARALL Laminate tubes. A special manufacturing technique has therefore been developed for ARALL Laminate tubes. The high static strength combined with the excellent corrosion resistance makes it very interesting to use ARALL Laminate tubes for high pressure pipelines. ARALL Laminate tubes with R-glass fibers show a 60% improvement of the relative pressure over aluminium alloy tubes. Much research is done to develop ARALL Laminates based on thermoplastic adhesive. Special attention is given to the resin-metalsurface adhesion.

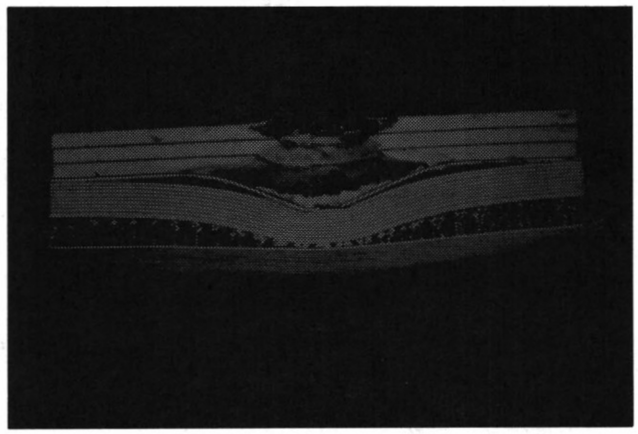


Fig. 51 Cross-section of an anti-ballistic ARALL Laminate sheet after high velocity impact

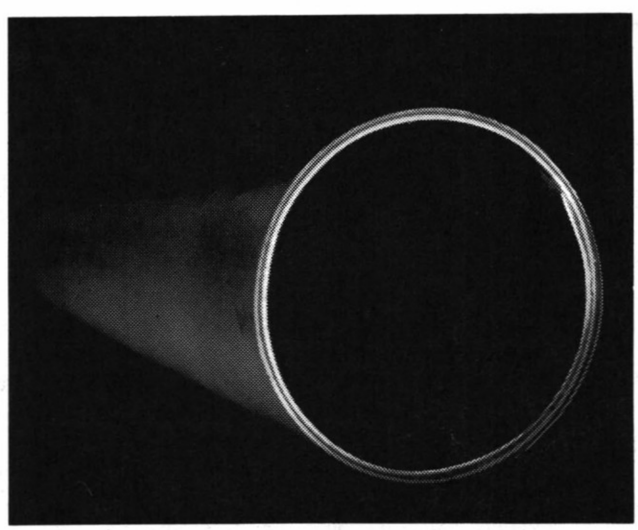


Fig. 52 ARALL Laminate tube

Promising results are obtained with an ARALL Laminate consisting of thin creep resistant titanium layers with intermediate unidirectional siliconcarbide layers for high temperature applications.

## Conclusions

The high fatigue resistance, high strength and low density of ARALL Laminate make it a very promising candidate for an aerospace material. ARALL Laminates are notch sensitive. However up to a notch factor of 4 the strength of the four standardized grades of ARALL Laminates is higher than monolithic 2024-T3. The application of glass fiber instead of aramid fiber improves the notch strength considerably. ARALL Laminates based on glass fiber also show excellent fatigue properties under cabin pressure simulation fatigue loading.
It is shown that the unique set of ARALL Laminate properties match up well with existing structural integrity requirements. Flying with small fatigue cracks does not harm the ARALL Laminate structure. Weight savings of more than 30% are within reach.

## Acknowledgement

The authors gratefully acknowledge the assistance of F. Oostrum, C.G. Paalvast, J. de Vries, ir. R.P. Notenboom, Prof. dr. A. Rothwell, prof. dr. ir. J. Schijve, Ms. I.C. Eggens-Dijkshoorn and all the students participating in the ARALL Laminate project. Especially acknowledged are the many contributions by ALCOA, in particular dr. R.J. Bucci and dr. L.N. Mueller.

## REFERENCES

1 Koshorst, J. How one A/C manufacturer transits to composites, Airbus Industrie, Toulouse, Jan. 1985.

2 Marissen, R and Vogelesang, L.B., Development of a new hybrid material: ARALL, Internat. SAMPE Conference, Cannes, France, Jan. 1981.

3 Vogelesang, L.B. and Gunnink, J.W., ARALL: A material challenge for the next generation of aircraft, Materials and Design, Vol. 7, no. 6, Nov. 1986.

4 Verbruggen, M.L.C.E., ARALL adhesion problems and environmental effects, Report LR-504 and LR-505 (PhD-thesis), Faculty of Aerospace Eng., Delft Univ. of Techn., The Netherlands, Febr. 1987.

5 Bucci, R.J., Mueller, L.N., Vogelesang, L.B. and Gunnink, J.W., ARALL Laminates properties and design update, 33rd Int. SAMPE Symp., Anaheim, California, March 1988.

6 Chen, D., Design and evaluation of a new biaxial testing method for sheet material, Report LR-548, Faculty of Aerospace Eng., Delft Univ. of Technology, The Netherlands, Dec. 1987.

7 Roebroeks, G.H.J.J., Constant amplitude fatigue of ARALL-2 Laminates, Report LR-539, Faculty of Aerospace Eng., Delft Univ. of Technology,The Netherlands, Oct. 1987.

8 Vlot, A., Impact tests on aluminium 2024-T3, aramid and glass reinforced aluminium laminates and thermoplastic composites. Report LR-534, Faculty of Aerospace Eng., Delft Univ. of Technology, The Netherlands, Oct. 1987.

9 Gunnink, J.W., Design studies of primary aircraft structures in ARALL Laminates, Report LR-520, Faculty of Aerospace Eng., Delft Univ. of Technology, The Netherlands, June 1987, will be also publ. in the Journal of Aircraft.

10 Gunnink, J.W., Damage tolerance and supportability aspects of ARALL Laminate aircraft structures, presented at a workshop on Supportability of Composite Airframe Structures, Glasgow, August 1987, will be also publ. in the journal Composite Structures.

11 Baten,T.J. van, Gunnink, J.W., Design and Analysis of ARALL Laminate Wing panels, paper at the conference COMPOSITE-88, Nice, France, June 1988.

12 Gunnink, J.W. and Schee, P.A. van der, Design of the ARALL F-27 lower wing fatigue panel, COMPOSITE STRUCTURES, Proceedings of the 4rd International Conference on Composite Structures, Scotland, July 1987.

13 Veggel, L.H. van, Jongebreur, J.J., and Gunnink, J.W., Damage tolerance aspects of an experimental ARALL F-27 lower wing skin panel, 14th ICAF Symposium, Ottawa, June 1987.

14 Honselaar, C.H. and Gunnink, J.W., Design aspects of ARALL Laminate fuselages, Report to be published, Faculty of Aerospace Eng., Delft Univ. of Technology, The Netherlands, 1988