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ARALL, A LIGHT WEIGHT STRUCTURAL MATERIAL FOR IMPACT AND FATIGUE SENSITIVE STRUCTURES

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Abstract

A new hybrid material is obtained by incorporating 'high modulus' fibres into the bondline of laminated sheet material. This material is called ARALL (Aramid Reinforced Aluminium Laminate). Principally ARALL was developed to obtain a material with very good fatigue properties, in which possible cracks would grow very slowly. However, it turns out that ARALL is also a strong material with relatively low density.

Preliminary tests have shown that the material also has promising impact and energy absorbing properties, which may qualify it as an interesting material for those applications where a high degree of ballistic tolerance is required. Aircraft design studies have indicated that, especially for fatigue sensitive areas such as the lowerwing and the skin of a pressure cabin, ARALL is an attractive material. Weight savings of more than 30% should be attainable in practice.

This paper gives a survey of the ARALL production process, and the properties of the material including mechanical properties, durability and some workshop aspects. Properties of joints and some applications of the material are also discussed. However, to understand the behaviour of ARALL some more basic considerations must be first presented.

1. Introduction

An important step towards the further development of laminated sheet material is the addition of 'high modulus' fibres into the bondline. It has been shown that a completely new hybrid material, with superior properties, can be obtained by optimisation of the amount of fibres and fibre orientation in relation to the thickness and the type of alloy of the metal sheets, and by prestraining of the material after curing to introduce a favourable residual stress system in the fibres (in tension) and the sheet (in compression).

The material is called ARALL (Aramid Reinforced Aluminium Laminate) and is now being developed by the Department of Aerospace Engineering of Delft University of Technology in co-operation with ENKA (producer of aramid fibres), 3M (producer of adhesives), ALCOA (producer of aluminium alloys), the Dutch National Aerospace Laboratory (NLR) and the Fokker Aircraft Company.

ARALL is built up as laminated sheet material with:
- thin high strength aluminium alloy sheets
- strong unidirectional or woven aramid fibres, impregnated with metal adhesive.

followed by:
- prestrain of the material after curing, which results in a compressive residual stress in the metal sheets.

A cross-section of ARALL is shown in Figure 1.

ARALL was developed principally to obtain a material with good fatigue strength, in which possible cracks would grow very slowly[1]. Design studies indicate that for fatigue critical areas, such as the lower-wing and the skin of a fuselage, ARALL is an attractive material. Weight savings of more than 20% are easy attainable.

Preliminary tests have shown that ARALL has promising impact and energy absorbing properties which may qualify it also as an interesting material for applications requiring high ballistic tolerance.

ARALL may be considered, structurally, a composite material, because it is composed of at least two different phases, while the structural performance is superior to the performances of the separate phases. It is a family of materials in view of the fact that it can be built up in a number of different ways. The final properties are highly dependent on the variables of the material (types of aluminium alloy, adhesive system, fibres, thicknesses etc.). The optimisation of these properties, the cost-effectivity of the material as applied in a structure as well as the processing of the material, are part of an extensive research program.

2. ARALL material-basic considerations

Basically ARALL is built up as a laminated sheet material of high strength aluminium alloy with aramid fibre, mostly uni-directional, in the bond layers. Fatigue cracks generally grow in a direction perpendicular to the maximum principal stress. For this reason a high percentage of the fibres should be orientated in the direction of the maximum principal stress. The action of the fibres is mainly to resist the crack opening, this produces a high degree of resistance to further crack growth. In this way ARALL combines the favourable static properties of high strength aluminium alloys with good fatigue resistance of fibre reinforced materials.

The main variables in the optimisation of the material itself are:

- sheet material, i.e. type of alloy and sheet thickness.
- residual stress system
- type of fibres
- adhesive bonding system

The effect of these variables is discussed in detail in ref. 1. The main conclusions will be summarized here, also some new results will be referred to.

One of the main reasons that aramid fibres are chosen is their relatively high elongation, which gives the possibility to create a semi-ductile material. A disadvantage of aramid fibres is their low compressive strain to failure. In spite of this, the compressive strength of ARALL remains good, due principally to the aluminium layers.

The adhesive used is 3M AF 163-2. This meets the requirements of good adhesion between both anodized aluminium and aramid fibres, and good durability. It turns out that a unidirectional aramid/metal adhesive layer with a thickness of 0.2 mm (0.0079") and with a fibre/adhesive ratio of 50/50 by weight gives the best configuration for the aramid layer.

During curing, due to the differences in thermal 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. However, the sign of the residual stresses can be reversed, in favourable way, by plastically deforming the material after curing. This is called "prestraining".

With this in mind, two standard types of ARALL are defined:

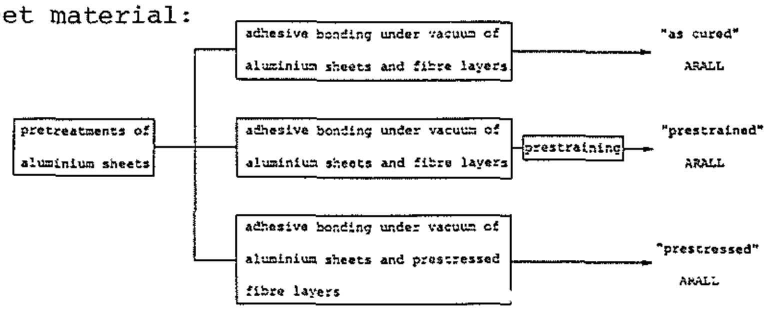
- ARALL 7075 (prestrained) based on Al 7075-T6
- ARALL 2024 (as-cured) based on Al 2024-T3

for which standardised aluminium thicknesses are, respectively, 0.3 mm and 0.4 mm.

However, further improvement in properties can be expected by use of Al 7475 or the new aluminium-lithium alloys. This arises from the excellent fracture toughness (AL 7475) and the high Young's modulus, low density and good corrosion properties (aluminium-lithium) of these alloys.

3. Fabrication process

The following flow chart depicts a typical production sequence for ARALL sheet material:



Prior to assembly the aluminium alloy sheets are pretreated as follows: alkaline degreased, pickled in chromic-sulphuric acid, chromic acid anodized and primed with a corrosion inhibiting primer. Curing is performed in an autoclave or press with a temperature and pressure dependent on the adhesive used.

4. Properties of ARALL

Four types of ARALL material are being investigated. These types are designated 7HXY, 7IXY, 2HXY and 2IXY, with 7 = 7075-T6 sheets, 2 = 2024-T3 sheets, H = high modulus aramid fibres, I = intermediate modulus aramid fibres, X = thickness of the separate aluminium layers in tenth of mm and Y = number of aluminium layers.

4.1. Mechanical and physical properties

Typical mechanical and physical properties of some combinations of ARALL in comparison to those of the monolithic 2024-T3 and 7075-T6 aluminium alloys are summarised in the table below.

		ARALL				Aluminium	
		7H32 pre-strained	2H42 as cured	7I32 pre-strained	2I42 as cured	2024-T3	7075-T6
tensile stress	MPa(ksi)	735(107)	590(86)	785(114)	610(88)	470(68)	560(81)
0.2% yield stress	MPa(ksi)	635(92)	380(55)	530(77)	340(50)	360(52)	480(70)
Young's modulus	MPa(ksi)	69000 (10005)	70000 (10150)	63000 (9135)	64700 (9380)	72000 (10440)	72000 (10440)
proportional limit in compression	MPa(ksi)	355(52)	255(37)	325(47)	240(35)	270(39)	480(70)
elongation	$^o/_o$	1.9	2.4	3.5	4.2	17	11
thermal expansion *coefficient*	$* 10^6/^oC$	17				23	
density	kg/m^3	2450				2800	

4.2 Fatigue properties

Results of constant-amplitude and flight-simulation fatigue tests on lugs, centrally cracked specimens and on bolted and riveted joint specimens show highly superior fatigue properties in all cases for ARALL, as compared with monolithic aluminium alloy (Figures 2 - 6). Cracks initiating from open holes were arrested after a small amount of crack growth, or grew very slowly, depending on the loading condition (Fig. 7)

Test data indicate significant improvements in the fatigue properties of ARALL as compared to monolithic aluminium alloys. Especially when a favourable residual stress system is introduced in ARALL, it becomes almost fatigue insensitive. This behaviour can be understood because fibres in the wake of the crack, even for very minute cracks, exert a significant crack opening restraint. In the extreme case crack opening may even be prevented. In other cases the stress-intensity factor K is greatly reduced. This mechanism works only if fibre failure does not occur. It appears that a certain amount of "self-controlled" delamination occurs between fibres and adhesive, and as a result the fibres in the wake of the crack are not loaded to the point of failure. Further analysis indicates that the load in those fibres will be approximately constant.

4.3 Residual strength properties

A reliable assessment of residual strength is required to verify that damaged safe-of-flight structural components made of ARALL are capable of sustaining specified fail-safe loads. While monolithic structures conform quite closely to the concepts of the engineering theory of fracture mechanics, this can not be expected for ARALL.

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. Development of fracture toughness parameters for such alloys requires large test panels to validate complex structural designs. This is also true for ARALL based on aluminium 2024, so an extensive test program on large panels (width 500 mm) is in execution.

ARALL is a hybrid material, with its own typical residual strength behaviour. The low strain to failure of the aramid high modulus fibre has an unfavourable influence on the fracture toughness, especially in those cases where the fibres are cut. Figures 8 and 9 show results of residual strength tests on 160 mm (6.3") and 500 mm (20") wide unstiffened panels, made of monolithic 2024-T3 and 7075-T6 sheet material and ARALL 2H42, 7H32 and 7I32, with saw cuts and fatigue cracks. The fracture toughness of ARALL with fatigue cracks is higher than that of monolithic 2024-T3 and 7075-T6, due to unbroken fibres in the wake of the crack and the delamination zone around the crack, which effectively enlarge the "strainlength" of the fibres. ARALL with saw cuts shows a comparable or worse fracture toughness behaviour compared with 7075-T6 and 2024-T3, respectively. This disappointing behaviour of ARALL can be improved by use of intermediate modulus aramid fibres instead of the high modulus fibres (Fig. 9) and by use of the 7475-T761 alloy instead of the 2024-T3 (Fig. 10). The effect of blunt notches on the static failure stress of sheet specimens of ARALL of different grades has been investigated and is compared with monolithic 7075-T6 and 2024-T3 (Fig. 11). The results imply that ARALL 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 aramid fibres, a behaviour which is inherent in all fibre reinforced materials. Use of intermediate modulus fibres improves the residual strength. This effect is also expected for the use of 7475 alloy. However, in the K_t range from 1 - 2.5 ARALL still has a superior behaviour to monolithic aluminium alloys.

4.4 Incidental damage

From tests performed by Fokker it appears that damage caused by lightning strike is limited to a small degree of burning in localised spots and slight delamination areas[2]. Initial testing by NLR of the impact strength of ARALL sheets indicates a behaviour superior to carbon fibre sheets[3]. C-scan pictures show no delamination for impact energies of 0.56 Joule. In impact tests at 7.86 Joule a small crack develops in the lower aluminium sheet, attended by a small delamination zone. Preliminary tests on a special type of ARALL have shown that ARALL has promising impact and energy absorbing properties, which may also qualify it as an interesting material for armour applications (Fig.12).

4.5 Durability

Extensive programs are running both at Delft (Delft University together with ENKA) and at the ALCOA and 3M laboratories in the USA. These programs include corrosion tests on I.L.S. (interlaminar shear) Bell peel, wedge edge and delamination specimens in different environments (Fig. 13). Also the influence of temperature and humidity, and the effect of static and dynamic loading on corrosion behaviour are being investigated. Results available so far are encouraging[4].

With laminated materials the interfaces between the different components (fibre, adhesive and metal) can have a decisive effect on the behaviour of the material, especially under environmental action. The fibre/adhesive interface proved to be the weakest link for ARALL, especially when a mode 1 loading condition (loading perpendicular to the fibre direction) is present. Inadequate adhesion between the aramid fibre and adhesive results in low peelstrength (Bell-peel test) and energy release rate (W.T.D.C.B. test) of the aramid prepreg. Actually this feature is not hampering the structural applications.

4.6 Cutting, jointing and sheet forming

The material can easily be cut, drilled, sawn and milled by normal workshop procedures. Tests also show that countersinking is possible (Fig.14). A second adhesive bonding treatment of ARALL 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 requires some special attention, in view of the limited failure strain of the aramid fibres and the possibility of delamination due to the high shear stresses involved. An extensive program to determine the limitations, and the most suitable technique for folding ARALL sheet reached success with the manufacture at the Fokker Papendrecht plant of different aircraft parts by a modified rubber press and folding technique (Fig. 15 and 16). In addition peen forming has been tried out on ARALL to obtain double-curved parts. It turns out that this technique can be used successfully.

5. Applications of ARALL in aircraft structures

In ref. 1 a rather basic comparison is made between aluminium alloy, various forms of carbon fibre reinforced plastics and different grades of ARALL (see Table 1 and Fig. 17 and 18, which summarize this comparison). This data shows clearly that ARALL is a promising material for aircraft use, and it is deduced that among the most likely parts in which to use ARALL are the lower wing and the skin of a pressure cabin (Fig. 19). Design studies in ARALL of both of these will be discussed briefly in the following sections.

It is well known[5] that for these structural parts a material is needed which has:

- high static strength
- high fatigue strength
- slow crack growth rate
- good exfoliation and stress corrosion resistance
- good stiffness
- good fracture toughness

In the previous sections it was shown that ARALL meets all, or almost all, of these requirements. However, some special attention must be given to fracture toughness.

As already mentioned in section 4.2, the crack growth rate of ARALL under severe fatigue loading is extremely low and in certain cases crack arrest can even occur. This means that ARALL structures will have a very good fatigue life. In fact the fatigue life of all grades of ARALL structures is expected to be far superior even to structures of 2024-T3 aluminium alloy. However, Fig. 8 and 9 show a remarkable difference in residual strength for ARALL panels with through-cracks (meaning here cracks in which the fibres are also broken, such as by a sawcut) in comparison with ARALL panels with genuine fatigue cracks (fibres intact). It turns out that the residual strength of panels with fatigue cracks is an order of magnitude greater than panels with through-cracks. It becomes clear that the residual strength of ARALL structures with fatigue cracks is extremely good, but on the other hand the residual strength of ARALL structures with through-cracks (in practice these could only be caused by accidental damage) is comparable to structures made of conventional aluminium alloy. With this difference in behaviour it is now doubtful if, for residual strength calculations, the same crack length should be used for (as implied by JAR and FAR airworthiness requirements) fatigue cracks as for cracks caused by accidental damage. This is especially the case as the accidental damage crack is much more visible than the fatigue crack, due to the local deformation around the crack, whereas a fatigue crack is hardly visible without careful inspection. Actually these arguments are to a large extent true for aluminium alloy structures as well. So some reconsideration of the design requirements in this respect would be in order, and perhaps even essential.

5.1 The ARALL F-27 testpanels

The lower skin of the outer wing of the Fokker F-27 Friendship has been selected as a good example for re-design in ARALL. The reason for choosing this particular structure was that all the essential information of the existing F-27 wing structure was readily available[1]. Furthermore, a major component of the existing structure of the Fokker F-27 lower wing, has been extensively tested in fatigue[6].

Some preliminary structural design of the lower wing structure (sta. 4155 - 10030) has already been completed. This indicates that, in this example, a weight saving of 30% is within reach. This means that, by comparing the ARALL structure with the F-27 testpanels, a good assessment can be made of the performance of ARALL in realistic structures, as far as mechanical loading is concerned.

The structure tested extensively by Fokker is a double version of a representative part of the wing structure, station 4155 - 5075 (Fig. 20). In principle the design of the ARALL F-27 testpanels will follow the general structural lay-out of the F-27 lower wing design mentioned above.

The aim of the ARALL F-27 testpanels can be described as :

The investigation of ARALL in a realistic aircraft structure (under static and fatigue loading) by comparing testresults with results on a comparable aluminium alloy structure.

In the tests on the ARALL structure, the following targets have been set[7]:

- a 1-g stress level $\sigma_{1-g} = 100\ \mathrm{N/mm}^2$
- an average weight for the ARALL panel about 25% less than that for aluminium panels
- a fully successful panel should demonstrate:
  - a crackfree life of 30.000 flights
  - a life without repairs of 100.000 flights
  - an economic fatigue life of 200.000 flights
- a residual tensile strength 1.1 times the limit load

Before the final design of the ARALL F-27 test panels could be completed several structural details had to be designed and/or tested, for example the endfittings, the reinforcements around the access hole, tank cover and the rib-skin connections. However, the design of the endfittings has now been completed; also a first panel to test these endfittings has been manufactured (Fig. 21). Fatigue and static tests of the endfittings are under way. As expected, preliminary static tests on this first endfitting panel have shown relatively high bending stresses in the panel. These bending stresses will be reduced in the ARALL F-27 testpanel, by lateral support of the panel, provided by simulation of ribs. Because the endfitting panels and the ARALL F-27 testpanels will have the same average design and fatigue stresses it can be expected, that if the behaviour of the endfitting panels is satisfactory, the endfittings in the ARALL F-27 testpanels will cause no problem.

5.2 Fuselages (Airbus A-320)

As already stated, the skin of the cylindrical part of a pressure cabin is a major structural area which could well be designed in ARALL. In general the most important loading, especially for fatigue, is the normal differential pressure p. However, the upward- and downward bending moments can also have a significant effect on the design of the pressure cabin, especially in the region of the fuselage-wing intersection. This structural area is considered in an ARALL design study, in which a scheme for the Airbus A-320 fuselage section just aft of the frame connected to the rearspar of the wing is considered. The fuselage structure is in general designed according to the FAR/ JAR 25 airworthiness requirements. It turns out, as shown in ref.1 (see also Fig. 22), that, due to the difference in stress level between the stiffeners and the skin, the stiffeners can still be made of conventional aluminium alloy, whereas the skin should be made of ARALL with the fibres (mainly) in circumferential direction.

The bottom part and the crown of the fuselage are two areas being given special attention. The bottom part is both fatigue and compression critical, i.e. fatigue critical in the circumferential direction and compression critical in the axial direction. The crown of the fuselage is mainly fatigue critical in both directions. However, some compressive stress can occur in the axial direction, due to upward bending moments.

Due to the special properties of ARALL - good fatigue resisance - it is possible to increase the fatigue stress level of the skin, and to use thinner skins as compared to fuselage skins of aluminium alloy. However, this has an effect on the aluminium frames and the frame- skin connection, as can be deduced from Fig. 23 . It appears that the skin-frame connection should be a flexible connection, because if it is rigid the frame stresses become too high. Furthermore, it must be realised that frames are not so readily inspectable 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, so flexible connections are preferred.

Comparison of the preliminary results of the different designs shows that weight savings for the ARALL parts are large, varying from 20% (bottom part) to 40% (crown). However, it also appears that, in order to meet the existing damage tolerance requirements, a critical aspect of ARALL 7075-T6 and ARALL 2024-T3 will be their fracture toughness. This is especially (probably only) true in the case of cracks due to accidental damage (through cracks). This argument underlines again the statement made in the introduction to this section, concerning the necessity to reconsider design requirements in this respect. While it is clear that the residual strength of ARALL structures must be a major aspect of further investigation, the preliminary results, shown in section 4.3, are better than expected, especially those for ARALL 7475.

6. Conclusion

An attractive hybrid material for light weight structures can be obtained by adhesive bonding together of a number of thin aluminium alloy sheets with thin aramid layers. ARALL shows very favourable fatigue crack growth properties, and high static strength, compared to conventional aluminium alloys. This is particularly true if a favourable residual stress system is introduced, and an optimum metal sheet thickness is chosen.

The static strength of notched ARALL for $K_t < 2.5$ is higher than that of monolithic aluminium alloys in general. However, for higher K_t values the opposite is true. On the other hand the residual strength of ARALL with fatigue cracks is much higher than that of monolithic aluminium alloys, while the residual strength of ARALL with artificial cracks (fibres cut) is somewhat lower (ARALL 2024 and ARALL 7075). An improvement can be obtained by the use of the 7475 alloy.

In spite of the introduction of structural fibres into the laminate, nearly all the advantages of metals over pure composites are preserved, such as: plasticity, impact strength, lightning resistance, easy machining, etc. Special types of ARALL appear to be promising for armour plating.

An extensive durability program still in progress shows remarkably good results. It indicates that no problems of long term durability are to be expected.

It seems therefore that ARALL is a very attractive material, especially for fatigue critical components. Design studies on a lower wing and a pressure cabin of an aircraft have confirmed this. Weight savings of the order of 30% are likely. These studies also show that for regions of lower loading aluminium alloy can still be used. This is also the case for the stiffeners in a pressure cabin. On the other hand, it appears that the same may not be true for the frames, which need further attention.

7. References

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	σ_t/ρ 10^3 Nm/kg	E_c/ρ 10^6 Nm/kg	$\sqrt{E_c}/\rho$ $\sqrt{N}m^2$/kg	σ_c/ρ Nm/kg
Aluminium alloy	70 - 115	26	100	165
C.F.R.P.	140 - 240	37 - 58	150 - 190	150 - 230
ARALL	200	29	110	145

Table 1 Strength and stiffness to weight ratios of different aircraft materials (based on design stresses)

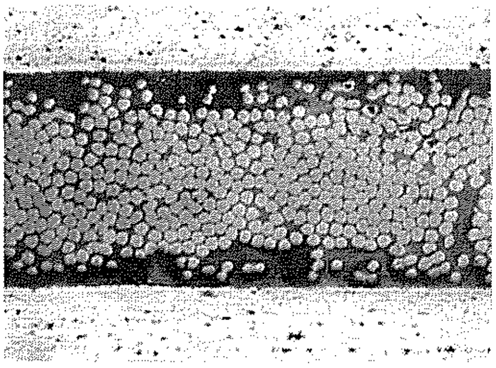


Fig. 1 Cross-section of ARALL sheet material

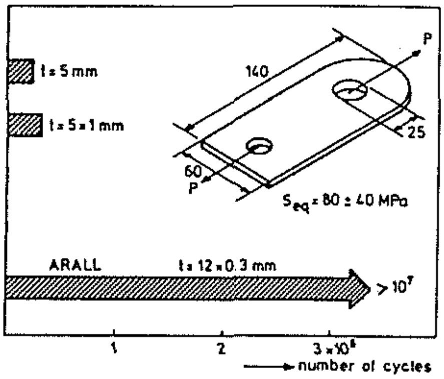


Fig. 2 Comparison of fatigue lives
Results of constant-amplitude tests on lugs
Material: 2024-T3, laminated and ARALL

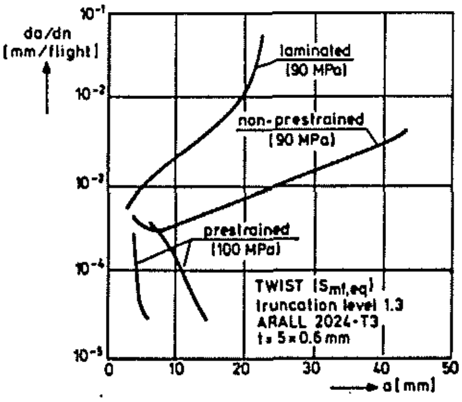


Fig. 3 Crack propagation rates in 2024-T3
laminated material and ARALL
TWIST flight simulation loading

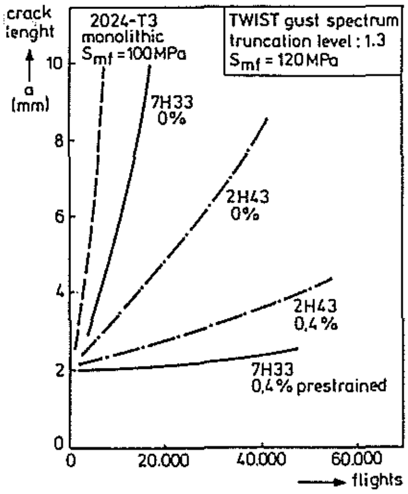


Fig. 4 Crack propagation rates in standardized ARALL sheet material

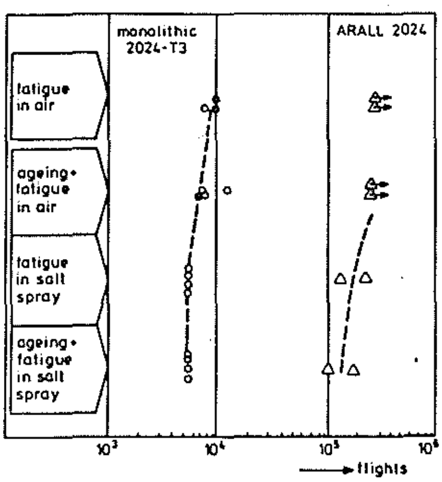


Fig. 5 Fatigue lives until failure of bolted joint specimens under MINI TWIST gust spectrum with S_{mf} = 100 MPa

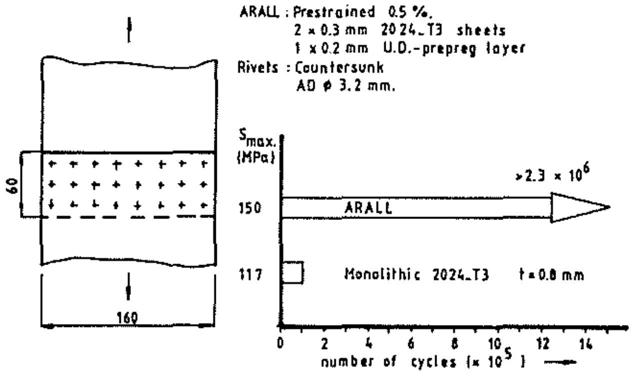


Fig. 6 Comparison of fatigue lives
Results of constant amplitude tests on ARALL and monolithic 2024-T3 riveted lap joints

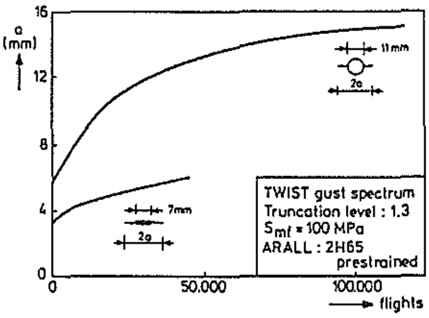


Fig. 7 Crack growth from a sawcut and a circular hole in ARALL sheet material

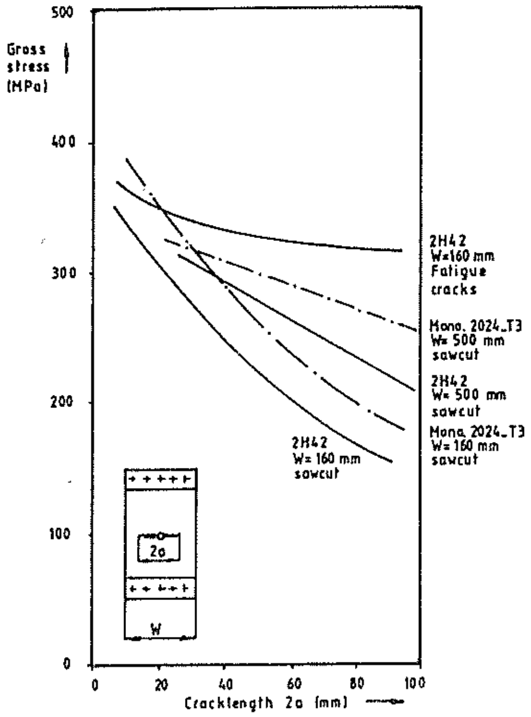


Fig. 8 Residual strength of unstiffened ARALL 2024 panels with sawcuts and fatigue cracks

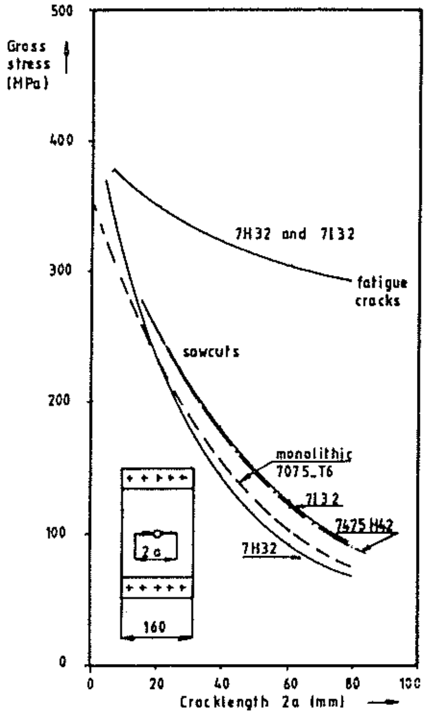


Fig. 9 Residual strength of unstiffened ARALL 7075 panels with sawcuts

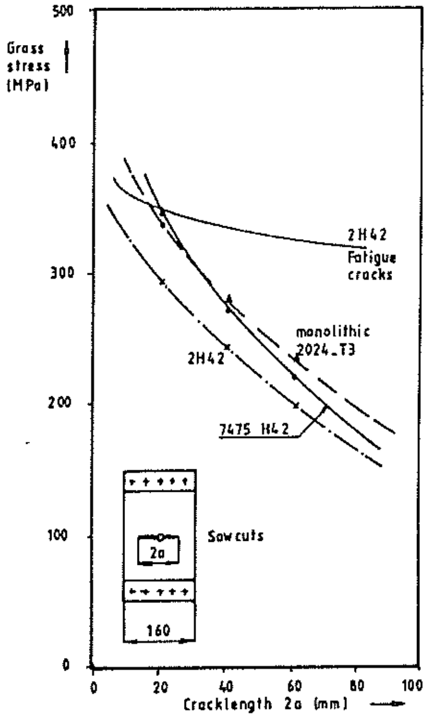


Fig. 10 Comparison of residual strength of unstiffened 2024-T3, ARALL 2024 and ARALL 7475 panels

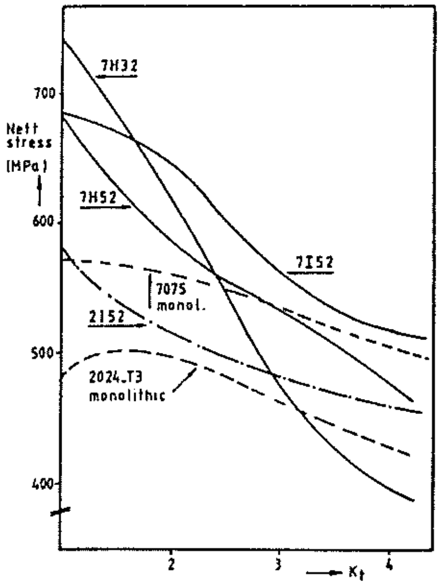


Fig. 11 Static strength of hole notched specimens with different stress concentrations

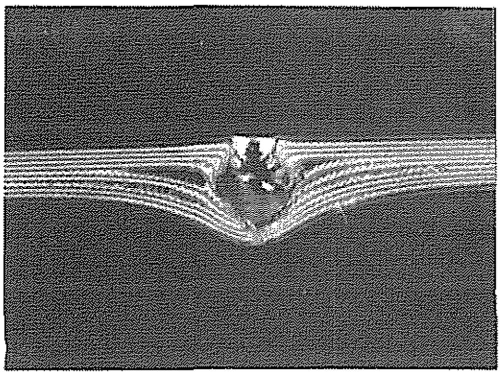


Fig. 12 Cross-section of "ARALL" sheet specimen after bullet impact

Fig. 13 Sustained load testing of ARALL delamination specimens in different environments and temperatures

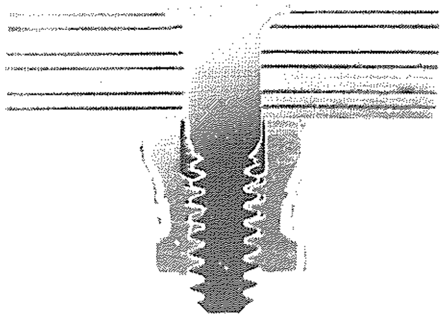


Fig. 14 Cross-section of ARALL countersunk Hi-lok joint

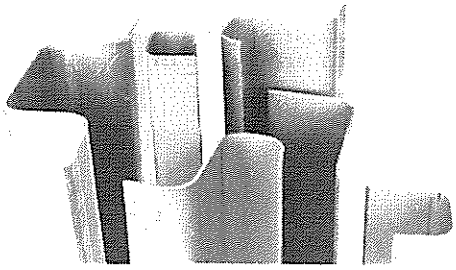


Fig. 15 Some ARALL stiffeners

Fig. 16 ARALL fuselage bulkhead part

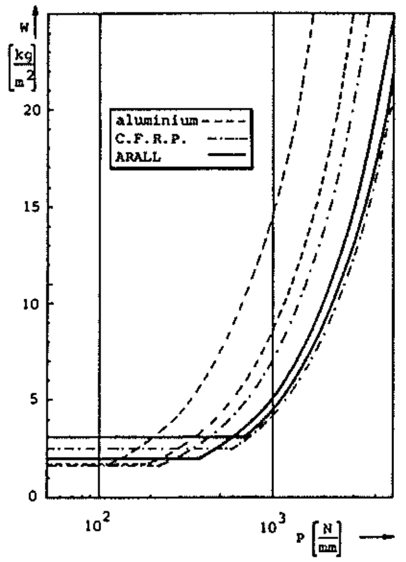


Fig. 17 Tensional structural efficiency W of different aircraft materials

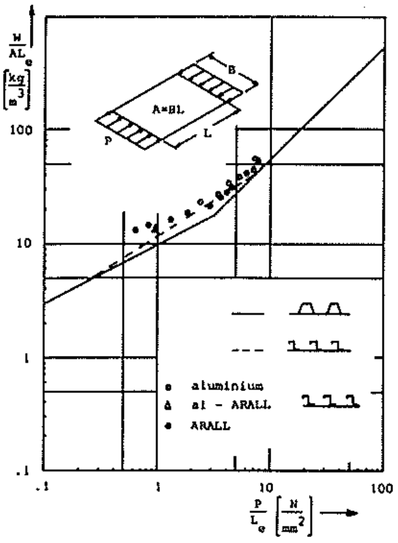


Fig. 18 Compression structural efficiency of Z-stiffened panels

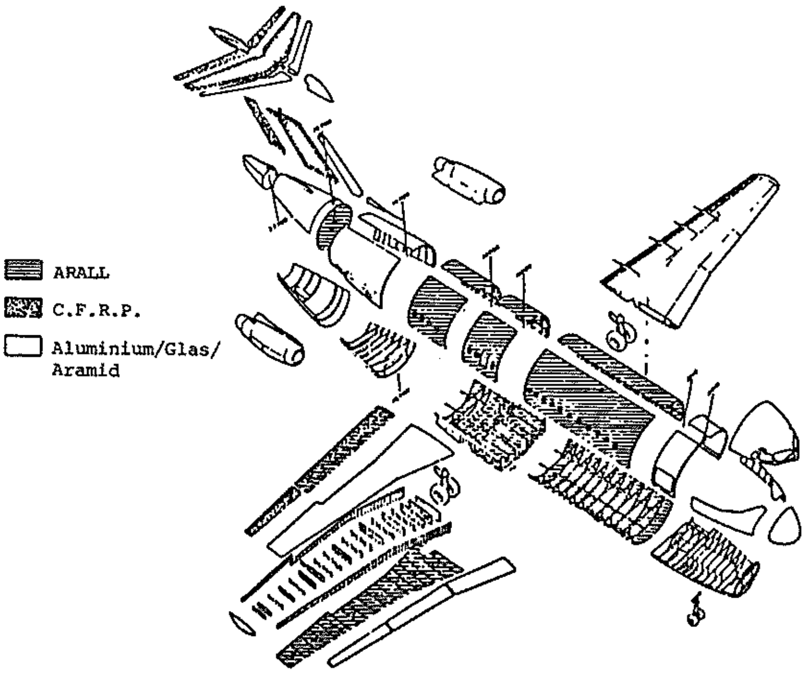


Fig. 19 Material "selection" for aircraft structural components

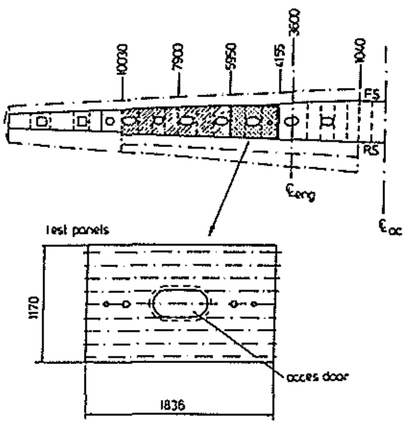


Fig. 20 The lower skin of the outerwing of the Fokker F-27

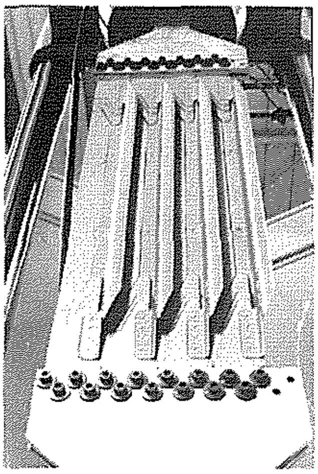


Fig. 21 ARALL F-27 endfitting testpanel

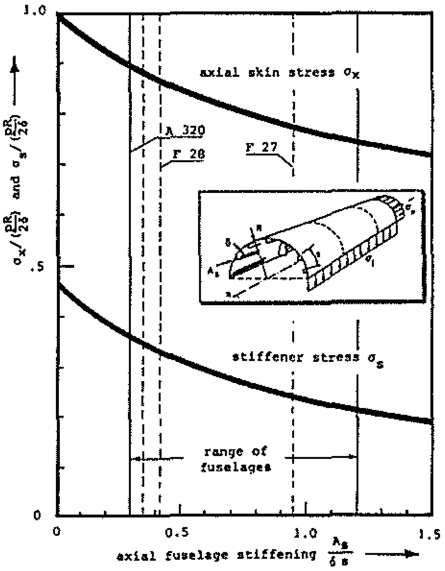
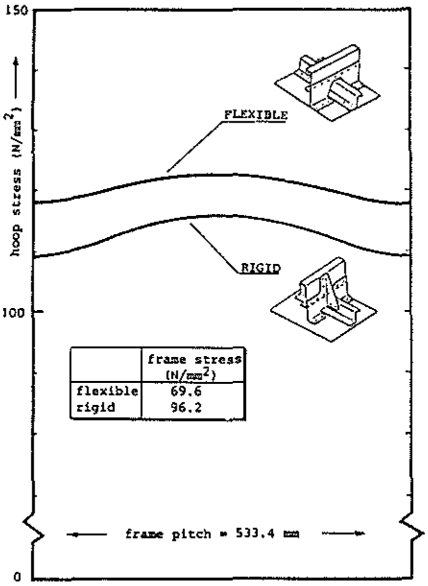


Fig. 22 Influence of the axial fuselage stiffening on the axial skin and stiffener stress in a pressure cabin



	frame stress (N/mm^2)
flexible	69.6
rigid	96.2

Fig. 23 Influence of the frame skin connection on the hoop stress and the frame stress in a pressure cabin