Design Studies of Primary Aircraft Structures in ARALL Laminates

Jan Willem Gunnink*
Delft University of Technology, Delft, the Netherlands

Comparison of ARALL laminates with other aircraft materials at the structural level shows that ARALL laminate is a very attractive material, especially for fatigue-dominated parts of the aircraft such as the lower wing skin and the pressure cabin. To investigate the potential of the material, some preliminary design studies are carried out on these parts, resulting in a weight savings of more than 25% for the lower wing skin as well as for the pressure cabin.

Introduction

AFTER more than five years of extensive testing, ARALL laminates have developed into commercially available materials. Tests show that ARALL laminate is highly insensitive to fatigue, has high strength, and outstanding durability.[1-3] However, to verify the excellent behavior of the material, it is necessary to design, manufacture, and test realistic structural components. This paper will concentrate mainly on the first step in this process. After a brief review of the properties of ARALL laminates, aircraft design allowables will be discussed specifically with regard to ARALL laminate material. This will be followed by a more general comparison of candidate aircraft materials to identify the most suitable locations for ARALL laminates in aircraft structures. Finally, some results of preliminary design studies on these structures will be discussed.

ARALL Laminates

ARALL is a laminate consisting of thin layers of aluminum alloy and (unidirectional) aramid fibers bonded together to form a sheet material. Two standardized types of ARALL laminate have been defined:[1-3] ARALL-1 laminate (post-stretched, based on aluminum 7075-76, and ARALL-2 laminate (as cured), based on aluminum 2024-T3.

Optimization of ARALL laminates has shown that the maximum aluminum layer thicknesses for ARALL-1 and -2 laminates are 0.3 and 0.4 mm, respectively. Although further improvements in the properties of ARALL laminates, for example, by using other grades of aluminum alloy, are expected (and already demonstrated in some preliminary tests[1]), the only materials considered in this paper will be the standardized ARALL laminate materials currently available.

Mechanical Properties

Table 1 compares the mechanical properties of the two standardized ARALL laminates with the ordinary aluminum alloys 7075-T6 and 2024-T3. The ultimate tensile strength of both types of ARALL laminate is far superior to that of the corresponding aluminum alloys. However, the compressive strength of ARALL-2 laminate is somewhat lower than that of 2024-T3 aluminum alloy, whereas for ARALL-1 laminate it is somwhat higher. For both types of ARALL laminates, the compressive strength is lower than that of 7075-T6 aluminum alloy. Young's moduli of both types of ARALL laminates are in the fiber direction approximately 3% lower than Young's moduli of the aluminum alloys. Perpendicular to the fibers, Young's moduli of ARALL-1 and -2 are 25% lower. To complete the comparison, the properties of unidirectional carbon-fiber-reinforced plastic (CFRP) are also given. However, these values for CFRP will be reduced drastically in real structural applications, as will be shown later.

Fatigue Properties

Extensive fatigue tests on ARALL-1 and -2 laminates, both at constant amplitude and in flight-simulation tests, have been performed. These tests include lugs, centrally cracked plate specimens, and bolted, riveted, and bonded joints. Comparison with the ordinary aluminum alloys shows significant improvement in fatigue life even at much higher stress levels.[1] The most significant aspect of the fatigue behavior of ARALL laminates is shown in Fig. 1. This shows that, even at a high fatigue stress level, propagation of the crack is slow. Under most practical conditions crack arrest occurs.

Residual Strength and Blunt-notch Properties

A wide range of tests have been and are still being performed to determine the fracture toughness of ARALL laminates. However, a remarkable difference in residual strength for ARALL laminate with through-cracks (i.e., cracks in which the aluminum layers as well as the fibers are broken, such as by a sawcut) and ARALL laminate with genuine fatigue cracks (fibers intact) has been found. It has been found that the residual strength of plate specimens with fatigue cracks is much greater than for specimens with through-cracks. Figure 2 shows this behavior. Also directly related to fracture toughness is the blunt-notch behavior of the material. As Fig. 3 shows, ARALL laminates are relatively intolerant of blunt notches as far as static strength is concerned. At a stress-concentration factor $K_t = 3$, the static strength of ARALL-1 and -2 laminates is reduced to 65 and 75% of its original value, respectively. Similar behavior is observed for residual strength after impact. Preliminary tests show that the residual strength of ARALL-1 and -2 laminates after impact is reduced to about 60 and 80% of its original value, respectively.[1]

Durability

Extensive durability programs have been performed at the Delft University of Technology.[4] These programs, which are

Received Jan. 12, 1988; revision received April 18, 1988.

*Associate Professor, Aircraft Structural Design, Faculty of Aerospace Engineering.

still running, include corrosion tests on interlaminar stress, Bell peel, wedge edge, and delamination specimens in different environments and at different temperatures. Results to date are encouraging. However, relatively poor adhesion between the aramid fiber and the adhesive results in low peel strength (Bell peel test) and low energy release rate wide tapered double cantilever beam (WTDCB) test of the aramid prepreg. In fact, it was found that this feature does not impair performance in structural applications.

Sheet Forming

Forming in the direction perpendicular to the fiber can be achieved by means of a modified rubber press and folding technique.[1] The bend radii are about the same as for ordinary aluminum alloys of the same thickness. Figure 4 shows some ARALL laminate stiffeners obtained by this modified technique. Delft University of Technology has performed these tests together with the Papendrecht plant of Fokker Aircraft, whereas Alcoa is continuing the tests for a wider range of ARALL laminate layups.[5] In addition, peen forming has been found to be a successful technique.

Machining and Joining

Extensive work on ARALL laminates has shown that the material easily can be cut, drilled, sawn, and milled by normal workshop procedures. Fastening can be accomplished by riveting as well as by adhesive bonding, while countersinking and dimpling are also possible.

Primary Design Allowables

It is well accepted that for aircraft the following design allowables are of primary importance: static strength (limit and ultimate design stresses), durability, and damage tolerance. This can be deduced from the Federal Airworthiness Regulations (FAR) Part 25 and also the Joint Airworthiness Requirements (JAR) Part 25, both as requirements and design guidelines to achieve structural integrity. For structural integrity, it is necessary to determine as accurately as possible the load history of the structure, as well as the limit and the ultimate loads. In this section, the definition of design allowables will be considered. It is obvious that the above-mentioned design allowables for ARALL laminates cannot be determined in the same manner as for ordinary aluminum alloys or for composites.[1] Strength allowables for composites are determined primarily by the notch factor (holes, flaws, etc.) and environmental effects, and for ordinary aluminum alloys mainly by material characteristics.

In many publications, durability and damage tolerance are treated as separate items. In fact, durability is concerned with the economic life and serviceability of the airframe, whereas damage tolerance is defined as the ability of the structure to retain adequate strength and stiffness after some damage has occurred. Since "damage" includes fatigue and corrosion as well as accidental damage, this generally means that the durability requirements also include damage tolerance. In practice, the durability "allowable" is related to crack initiation (fatigue) for aluminum alloys (in different environments) and to compression fatigue, holes, and delaminations together with environmental effects for composites. On the other hand, the "damage tolerance" allowable for aluminum alloys is dictated primarily by crack propagation, residual strength, and inspectability. In the case of composite structures, this allowable is dominated by residual strength, especially in compression loading of impacted structures. To define suitable allowables for the ARALL laminates, much research has been undertaken and is still continuing.[1-5] From the results thus far, it can be concluded that ARALL laminates behave, in one respect, similar to a metal, and, in another respect, similar to a composite. At the same time, the material also has its own characteristics, which cannot be related directly to either metals or composites. Presently, not all the data necessary to define satisfactory the design allowables are available. However, with the data that is so far available, reasonable values can be determined for the preliminary design of aircraft structures.

Static Strength

The allowable static ultimate strength of ARALL laminates is, like a composite, determined primarily by the stress-concentration factor, as shown in Fig. 3. When the stress-concen-

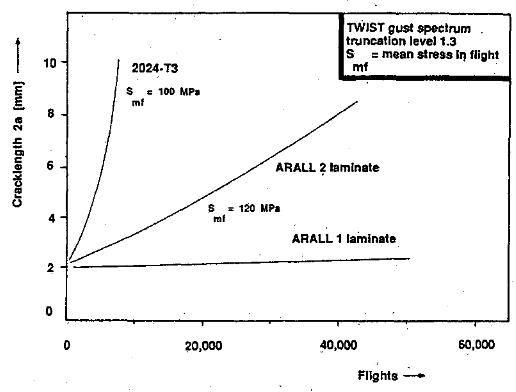

Fig. 1 Crack propagation rates in ARALL laminate materials.

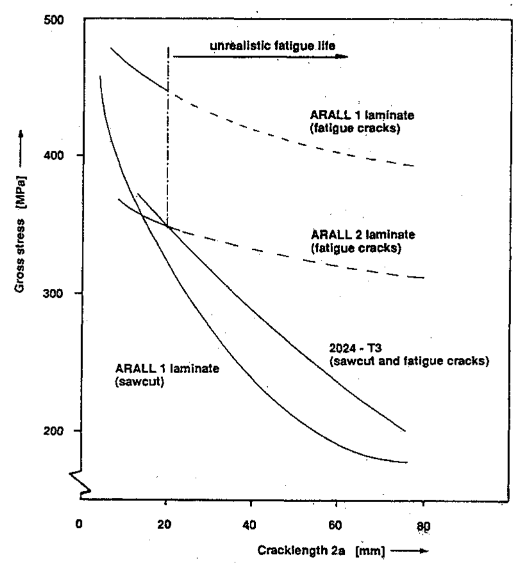

Fig. 2 Residual strength of unstiffened panels (panel width is 160 mm).

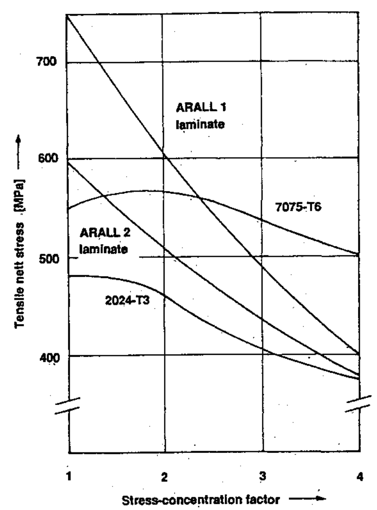

Fig. 3 Notch behavior of materials.

tration factor is increased, the static strength of the ARALL laminates decreases substantially. For example, for an open hole, the strength of ARALL-1 laminate reduces to 65% and for ARALL-2 laminate to 75% of the unnotched strength. Similar behavior, with the same order of magnitude, is observed from preliminary tests on low-energy-impacted ARALL laminates.[1] On the other hand, environmental effects, generally decisive for advanced composite materials, virtually are absent in tests on ARALL laminate specimens, even in very aggressive environments.[4] From the available data, it is concluded that the allowable static tensile strength is dependent primarily on the stress-concentration factor for ARALL laminates. Presently, the static compressive strength allowables are not defined well enough. However, preliminary figures for the buckling behavior and compressive yield strength indicate that buckling stresses are approximately 15% lower than for the corresponding aluminum alloys, whereas the compressive strength is approximately 25% lower. The relationship between buckling, compressive yield stress, and the structural index of the load in stiffened plates is given in Fig. 5, where p is the compressive loading per unit width of the stiffened plate, and L is the effective length of the plate.

Durability

In the previous section, the durability of ARALL laminates was mentioned briefly. From the extensive durability tests,[4] it is found that different temperature ranges in combination with all possible types of aggressive environments show hardly any degradation in strength and stiffness (approximately 5%) even after exposure of more than 60 weeks.

For aluminum alloy, durability is related directly to its fatigue and crack-initiation behavior. Fatigue cracking has been found to be the most prevalent form of degradation for aluminum structures. Environmental effects have a substantial and even dominant influence on fatigue behavior. Crack initiation occurs in the outer aluminum layer of ARALL laminates at about the same number of load cycles as for a related aluminum alloy. However, subsequent growth to macrocracks does not occur in ARALL laminates, or occurs at much higher fatigue stress levels and at a much greater number of load cycles than for the aluminum alloys. In most cases, it is even followed by complete crack arrest. Tests have shown that the maximum tensile strength of ARALL laminates is scarcely affected after fatigue testing (even in very aggressive environments) to more than three times the aircraft life. The reduction is not more than 5–10%. It can be concluded from these tests that crack initiation is not the decisive factor for the durability of ARALL laminates. It will be shown in the next section that damage tolerance will primarily dictate the durability of aircraft structures in ARALL laminates.

Damage Tolerance

As stated earlier, damage tolerance is the ability of a structure to sustain loads after fatigue, corrosion, and accidental damage until detected through inspection and repaired in such a way that the structure is again able to sustain the design ultimate load. Damage tolerance comprises, in fact, three aspects:[6,7]

1) *Residual strength* – the maximum damage, including the possibility of multiple cracks, that the structure can withstand under specified fail-safe load conditions.

2) *Crack propagation* – the time period in which a crack grows from a defined, detectable length to the allowable length determined by the residual strength requirements.

3) *Damage detection* – inspection methods and intervals to ensure timely detection of cracks and other damage.

The relative importance of these aspects depends very much on the material used, the load level of the structure, and the required life of the aircraft. Before discussing these aspects further, different types of damage will be discussed. Very extensive fatigue and corrosion testing has been performed on ARALL laminates.[1,4] A fatigue crack starts at a stress concentration after about the same number of fatigue cycles both in aluminum alloy and ARALL laminates. However, the crack in ARALL laminates stays primarily in the outer layer, propagates very slowly, and, in most cases, crack-stop is observed. The crack length at which this occurs depends on the fatigue stress level. For practical applications, the crack length is found to be on the order of 2–5 mm. Preliminary residual strength tests on these fatigue specimens (fibers still intact) show a very small reduction in strength compared with unfatigued panels, on the order of 10% for both grades of ARALL laminate material (Fig. 2).

Corrosion tests also show that ARALL laminates behave very satisfactorily; in fact, the aramid layer acts as a barrier so that only the outer aluminum layer shows some pitting corrosion, whereas ordinary aluminum alloys are fully corroded in the same test period. Reduction in static strength due to corrosion is small, on the order of 5%. Fatigue testing of corroded ARALL laminates shows the same behavior as for the uncorroded material. The most critical type of damage seems to be accidental damage (with broken fibers). For this type of damage, the static strength of an unnotched specimen decreases substantially. Preliminary low impact energy tests on ARALL laminates, when the fibers are broken in the damaged area, show a reduction in strength of 25–40% in comparison with undamaged specimens.[1] In fact, this reduction is of the same order of magnitude as – or even slightly better than – the already mentioned notch effect in ARALL laminates (Fig. 3). However, fatigue crack growth of these impact-damaged ARALL laminate specimens shows the same behavior as for the above-described damage types.[1,8]

From the results thus far, it is worth repeating that accidental damage is the most critical type of damage, from the residual strength point of view. In fact, the crack growth rate for all types of damage shows about the same type of behavior in

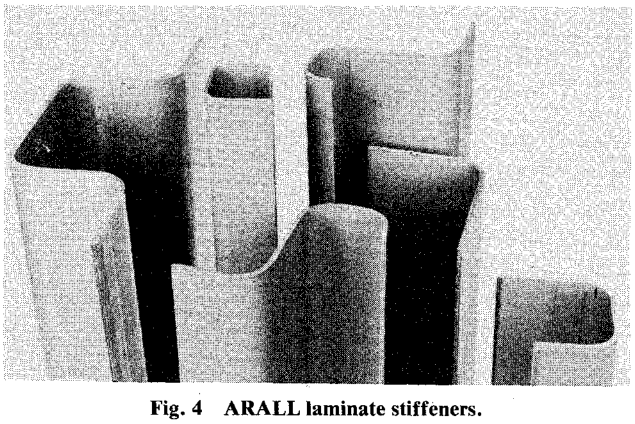

Fig. 4 ARALL laminate stiffeners.

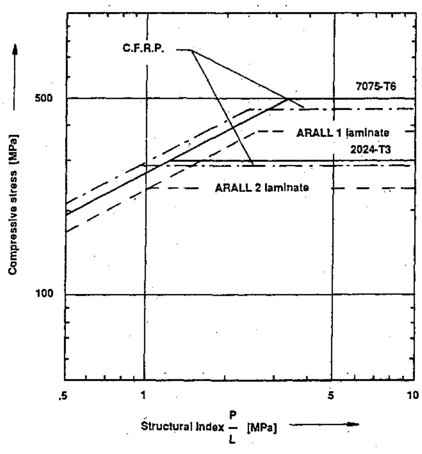

Fig. 5 Structural ultimate compressive strength.

practical types of application, crack extension on the order of 5 mm combined with a decreasing crack growth rate, and, in most cases, crack arrest even occurs. The reduction in strength after further fatigue, compared to the initial (accidental damage, corroded, or notched) state is very little, about 10%.

Some preliminary conclusions can be drawn from this. First, crack propagation is of little significance for ARALL laminate structures. Second, the residual strength of damaged ARALL laminate structures is important only in case of accidental damage. The static notch factor has a large enough effect on ARALL laminates that the small, further reduction due to fatigue crack growth after damage of all types seems adequately covered. In fact, the results thus far indicate that the further reduction in the strength of structures with fatigue cracks is so small compared to the unfatigued structure that it still can carry the ultimate design load, which means that ARALL laminate structures should be allowed to continue to fly with fatigue cracks (in which only the outer aluminum layers contain a crack). Usually these cracks will be on the order of 5–10 mm. On the other hand, due to the notch sensitivity of ARALL laminates, accidental damage is the decisive factor from the damage-tolerance point of view, i.e., it gives, in principle, the maximum allowable initial crack length due to impact of foreign objects. However, it must be realized that the corresponding load is a well-defined residual strength load, mostly taken as 1.0 times limit load. This means that after such a crack is detected, it must be repaired in such that the structure is capable of sustaining the design ultimate load. Because accidental damage can occur only in specific areas, primarily in the external parts of the structure, inspection of ARALL laminate structures seems to be much easier than for aluminum structures.

Overall Comparison of Materials

The prospects for ARALL laminates for application in aircraft structures in relation to other (possible) aircraft materials will be discussed in general terms in this section. The comparison will be restricted to ordinary aluminum alloys, carbon-fiber-reinforced composites and ARALL laminates. The mechanical properties of these materials are given in Table 1. However, for CFRP, the unidirectional properties will be reduced substantially as a result of different fiber orientations in the structure. Even these reduced properties will not be the design allowables, as pointed out in the previous section. Environmental effects have a considerable influence on aluminum alloys as well as on CFRP. This, together with fatigue cracking, dominates the behavior of aluminum alloy structures; whereas, for CFRP, the low-impact resistance, sensitivity to stress concentrations, and poor repairability together with environmental effects are the essential issues reducing significantly the ultimate design strains. According to today's practice, the allowable compressive strain for CFRP is on the order of 0.25–0.4%, and the tensile strain is on the order of 0.4–0.5%.[9] Because fatigue cracking dominates the design of aluminum aircraft structures, the design life is an important parameter in the design of the structure. Simons et al.[10] have given a general relationship between the ultimate gross area stress and the fatigue life for aluminum transport aircraft. It is obvious that by increasing design life the allowable gross area stress reduces (Fig. 6). As already discussed, the allowable tensile design strength for ARALL laminates is governed primarily by the stress-concentration sensitivity of the material. As a result, the designer's level of experience plays an increasing role in designing aircraft structures with these types of materials. On the other hand, it should also be pointed out that the notch sensitivity of CFRP is even more pronounced. Based on test results for ARALL laminate structures, the preliminary

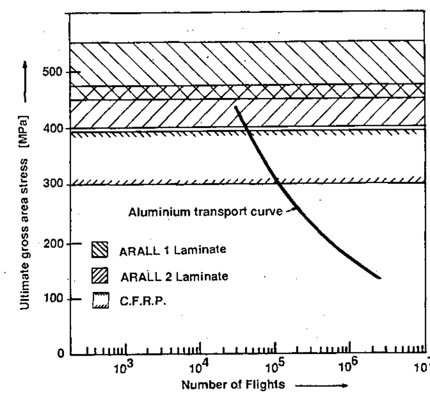

Fig. 6 Relation between gross area stress and transport aircraft life.

Table 1 Mechanical properties of aircraft materials

Average properties		ARALL-1 laminate	ARALL-2 laminate	7075-T6	2024-T3	CFRP unidirectional
Tensile ultimate strength, MPa	L	772	703	572	455	1240
	LT	379	317	572	488	55
Tensile yield strength, MPa	L	655	351	510	344	NA
	LT	324	234	496	310	NA
Compressive yield strength, MPa	L	365	240	503	297	1240[a]
	LT	379	270	524	338	207[a]
Elongation percentage	L	0.6	1.3	11	18	NA
	LT	6.3	12.4	11	18	NA
Elastic tensile modules, GPa	L	69.6	70.2	71.0	72.4	145
	LT	52.1	52.9	71.0	72.4	12
Ultimate strain percentage	L	1.7	2.5	12	19	0.9
	LT	7.8	13.6	12	19	0.47
Blanking shear, MPa		262	248	345	290	–
Density, g/cm^3		2.29	2.29	2.78	2.78	1.6

L = in fiber direction (ARALL laminates and CFRP) or rolling direction (aluminum alloys);
LT = perpendicular to fiber direction (ARALL laminates and C.F.R.P.) or rolling direction (aluminum alloys).

conclusion is that a practical range of notch factor is 2.5–3.5. However, recent results of tests on large structural components indicate that the upper part of this range is more appropriate. Also, preliminary results for repaired ARALL laminate structures show that the strength of repaired structures is covered by use of the upper range of these notch factors. This means that repairability will have a relatively small influence on a structure designed with this notch factor.

In Fig. 6, the corresponding range of tensile strength is plotted, together with the previously mentioned range for CFRP (based on strain values). In this figure, the general comparison of aircraft materials, for the lower wing skin application, shows the beneficial tensile strength of both grades of ARALL laminates over aluminum alloys as well as over CFRP. Comparison of compressive strength shows a different behavior. The maximum compressive stresses of both grades of aluminum alloy (7075-T6 and 2024-T3) are higher than the corresponding ARALL laminates. The maximum compressive strength of CFRP depends on the allowable compressive strain, which, because of impact sensitivity, depends on the thickness. As shown in Fig. 5, the maximum compressive strength of CFRP lies in the same range as aluminum alloys and ARALL laminates. However, if the materials are compared with each other in relation to their density, the differences are more pronounced. Because aluminum alloys are very fatigue sensitive, comparison of fatigue- and tensile-dominated structural components has to be done in terms of the design life of the aircraft. A range of 30,000–100,000 flights is taken for this purpose. The fatigue tensile structural efficiency curves (Fig. 7) show clearly that ARALL laminates are promising aircraft materials for this type of application. The comparison shows also that CFRP and ARALL laminates are, from the structural viewpoint, genuine competitors. This means that other considerations also become important. In this respect, economics (the cost of the structure) is an important factor. However, this subject is beyond the scope of this paper. The comparison of compressive structural efficiency (Fig. 8) shows clearly that both types of ARALL laminate and their corresponding aluminum alloys have about the same efficiency, whereas CFRP behaves much better in almost all respects.

Primary Aircraft Structures

The material comparison of the previous section gives a general impression of the suitability of the materials considered for aircraft applications. The next step in the process is to carry out a preliminary design of structures with these materials, and to compare them with each other. A very important aspect – in the author's opinion, the most important aspect of structural design – is the detail design. This counts for structural optimization, but will also influence the damage tolerance and durability of the structure. Of course, comparison on a structural level makes sense only if the results of the previous section show an advantage for the new materials over existing aluminum alloys. This leads to the conclusion that primarily fatigue- and tensile-dominated structures have to be considered for ARALL laminates. The most likely primary structural parts in which to use ARALL laminates are the lower wing skin and the skin of a pressure cabin. Both structures will be discussed briefly.

Lower Wing Structure

Alongside the development of ARALL laminates themselves, structural design studies also have been performed at Delft University of Technology on the wing of the Fokker F-27 Friendship. This aircraft was chosen mainly because the structural layout and wing loading were readily available.[11] The lower skin of the outer part of the wing of this aircraft was selected for design in ARALL laminates (Fig. 9). If the results are satisfactory, the detail design of the wing is such that this part can quite easily be replaced (due to its attachment conditions) by the ARALL laminate structure. However, it was the conviction of Delft University that the effectiveness of the ARALL laminate structure must be proved by manufacturing and testing the structure. Also, in this respect, the selected part of the structure has advantages, since Fokker Aircraft has tested extensively in fatigue as well as statically a major part of the structure.[12] It is then only necessary to design in detail, manufacture, and test the related ARALL laminate structure. As previously mentioned, several such design studies were performed during the development of the ARALL laminates.[13,14] All of these studies came to the same overall conclusion: ARALL laminates show significant weight savings for the Fokker F-27 lower wing structure. A weight saving of approximately 30% is found to be within reach. On the other hand, the designs show another remarkable effect. The lower wing skins of small-to-medium-size aluminum alloy transport aircraft are, in general, fatigue- and tensile-strength-designed, i.e., the 1-*g* load level and the maximum positive gust loading are the decisive factors. The ARALL laminate lower wing structure is indeed critical in tension outboard of station 6000 (ARALL-1 laminate) or station7000 (ARALL-2 laminate) but inboard of this station becomes compression critical (Fig. 10). This means that the negative loading is the decisive load case for a major part of the ARALL laminate lower wing structure. This behavior can be explained partly by the almost fatigue-insensitive behavior of ARALL laminates and the increased allowable

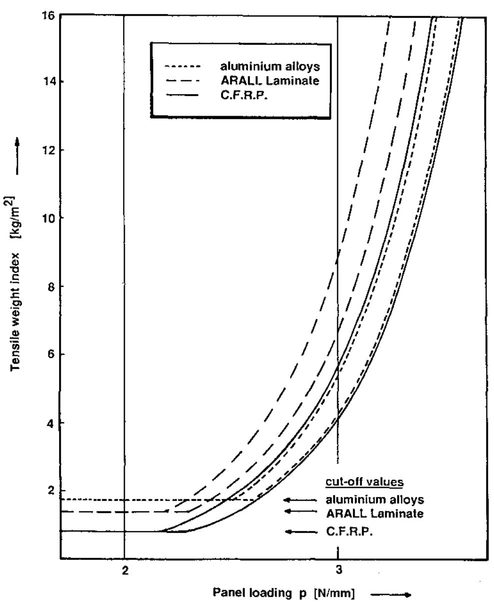

Fig. 7 Fatigue-tensile structural efficiency.

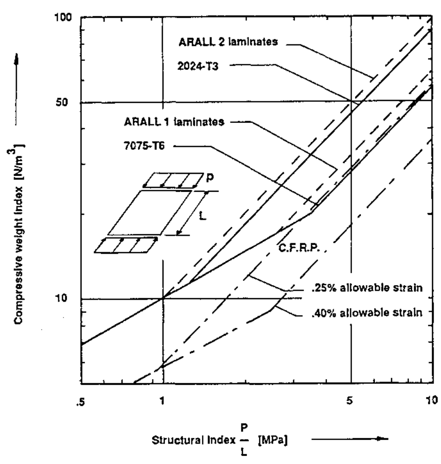

Fig. 8 Compression structural efficiency.

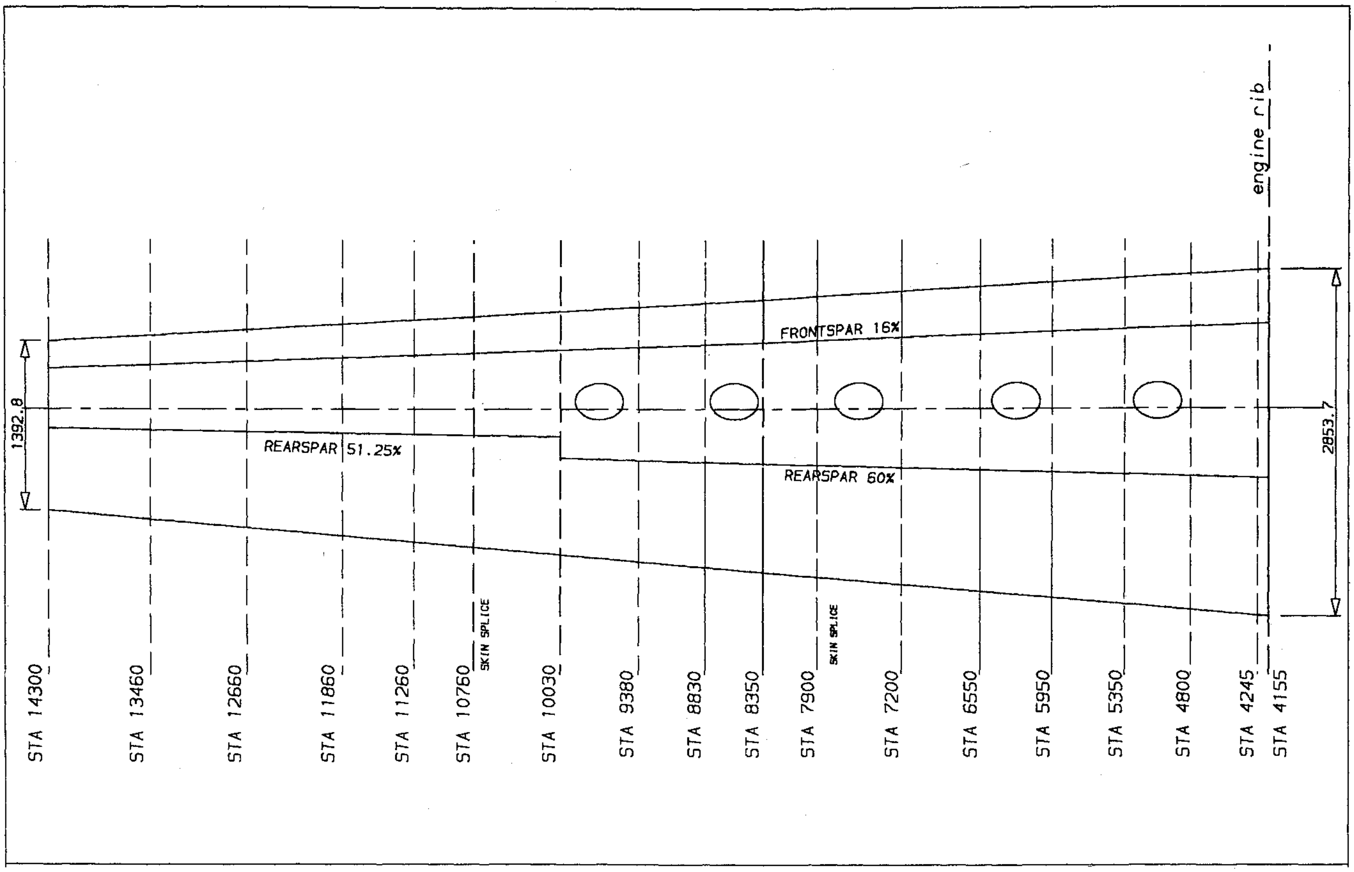

Fig. 9 Layout of the lower skin of the outer wing of the Fokker F-27.

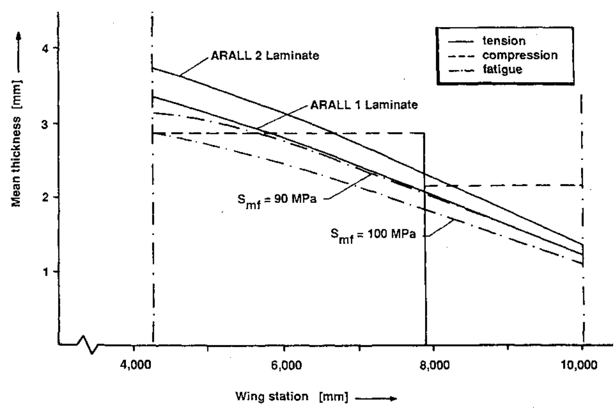

Fig. 10 Necessary thickness of the lower wing of the Fokker F-27.

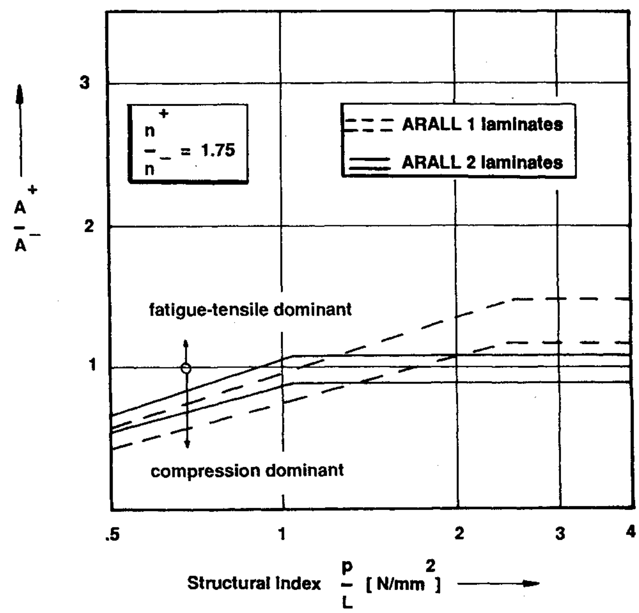

Fig. 11 Ratio of minimal cross-sectional areas for the lower wing of a relative low wing loaded aircraft.

tensile strength, and by the small reduction in allowable compressive strength of ARALL laminates compared to the aluminum alloys. However, a very important parameter is the ratio of the positive to the negative load factor. This, together with the material characteristics, explains the surprising change in critical load case, as will be shown next. The structural index of the lower skin of the outer wing of the Fokker F-27 is in the range of 0.5 to 1.5 N/mm^2. This results in an allowable compressive stress in the range of 150 to 270 N/mm^2 for ARALL-1 laminate and 150 to 240 N/mm^2 for ARALL-2 laminate (see Fig. 8). The ratio of the positive to nagative load factor, n^+ and n^-, respectively, is on the order of 1.75 for the Fokker F-27. With these figures, a rough estimate of the ratio of minimum necessary cross-sectional areas for the positive (A^+) and negative (A^-) load cases can be made. Using the tensile design strength figures, related to the previously defined range of notch factors, the ratios of necessary cross-sectional areas for ARALL-1 and ARALL-2 laminates are shown in Fig. 11. This figure corresponds well with Fig. 10 for the structural index range of 0.5 to 1.5 N/mm^2 for the Fokker F-27. It also shows that the wing structure in the ARALL-1 laminate is more compression sensitive than the wing structure in the ARALL-2 laminate. An important factor in this consideration is the ratio of the positive to negative load factor. In this respect, it must be realized that the Fokker F-27 is primarily a gust-critical aircraft.

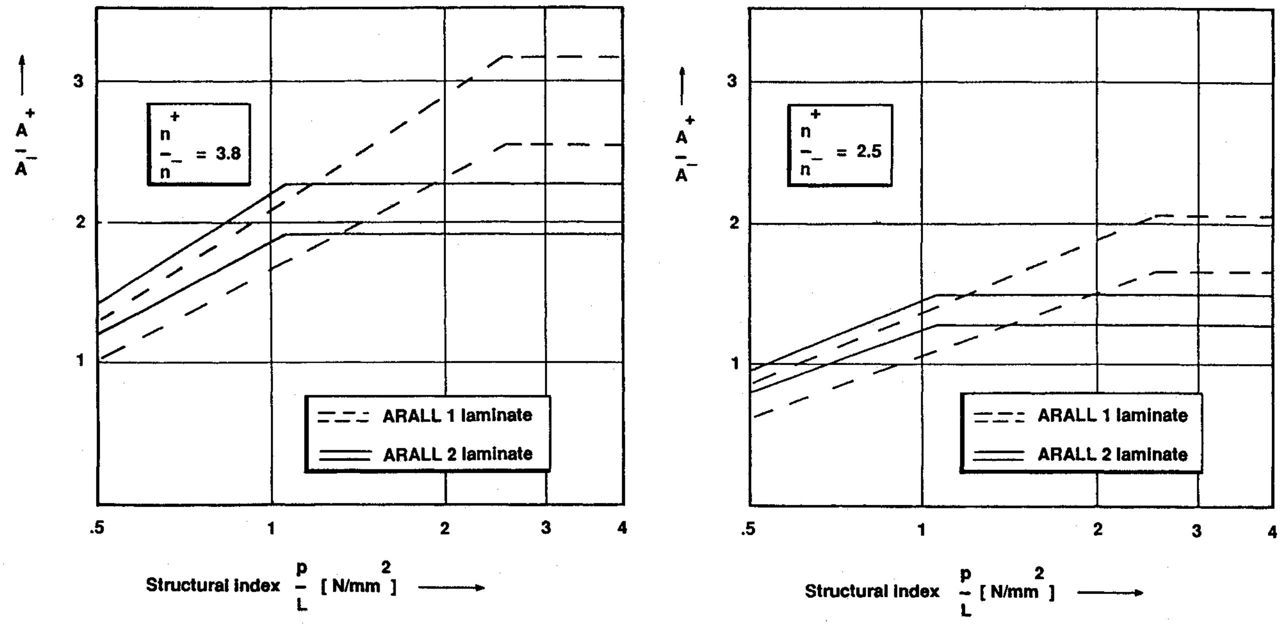

Fig. 12 Ratio of minimal cross-sectional areas for the lower wing of a relative high wing loaded aircrafts.

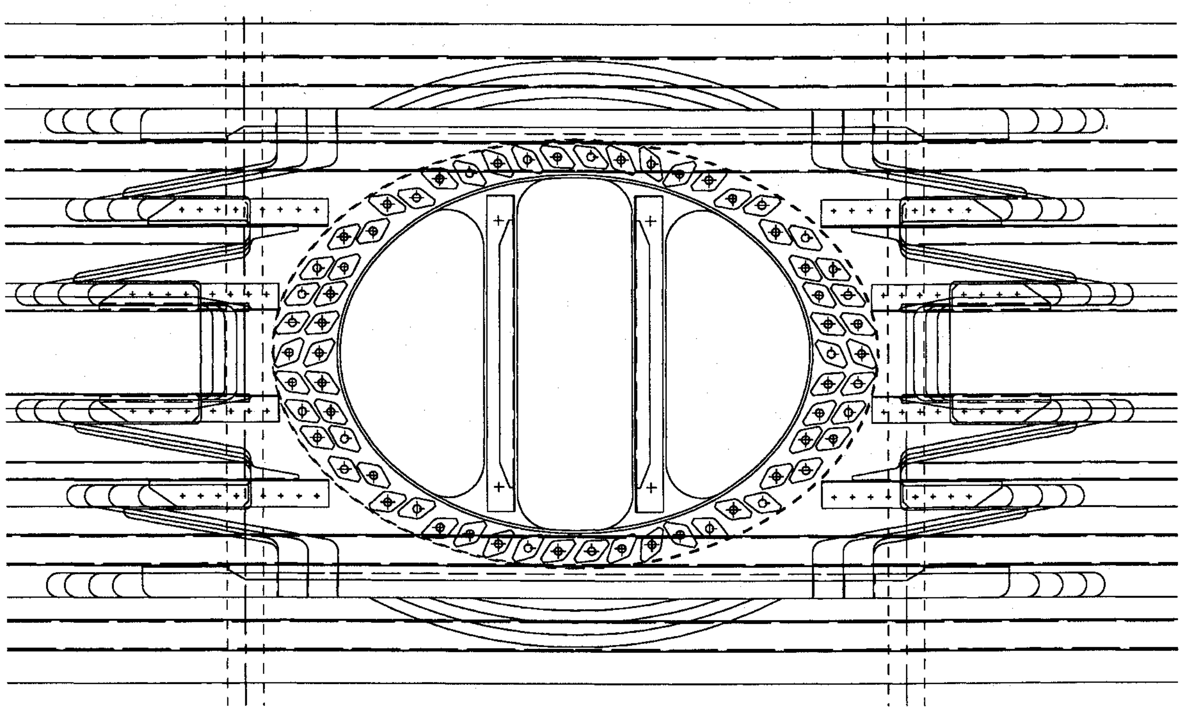

Fig. 13 Design of the manhole area of the Fokker F-27.

By increasing the wing loading, an aircraft becomes maneuver critical, which means that the ratio of positive to negative load factor increases to between 2.5 and 3.8. Mostly also the structural index can increase to a maximum of about 4.0 N/mm^2. Both ratios are shown in Fig. 12. Comparison with Fig. 11 shows that, in general, the lower wing skin of a maneuver-critical aircraft is less compression critical than the lower wing skin of a gust-critical aircraft. As a consequence, the biggest weight savings can be expected with maneuver-critical aircraft.

Special Aspects of the Design of the Fokker F-27 Lower Wing

As mentioned earlier, during the development stage of ARALL laminates, several preliminary design studies were performed on the lower skin of the outer wing of the Fokker F-27 Friendship. An additional study also included the Fokker-50.[15]

The lower wing structure can be seen as a collection of holes. It contains many manholes, bolt holes, rivet holes, and two drainholes. Fortunately, most of the holes are concentrated in a specific area that is centered, more or less, around the 40% chordline of the lower wing (Fig. 9). In this respect, the lower wing structure can be subdivided into three basic parts in the chordwise direction: the access panel with the manholes, bolt holes and reinforcements, and two "side" panels, which are basically undisturbed. The structure of the access panel can be treated as a full load-carrying structure or as an almost nonload-carrying structure. In fact, this is governed primarily by whether a load-carrying or a nonload-carrying tank cover is used. In practice, this means either a bolted tank cover or a tank cover that is only liquid-tight but hardly transfers axial loads. Both structural concepts have their advantages and disadvantages. The load-carrying access panel gives full use of the total cross-sectional area of the lower wing skin, whereas the

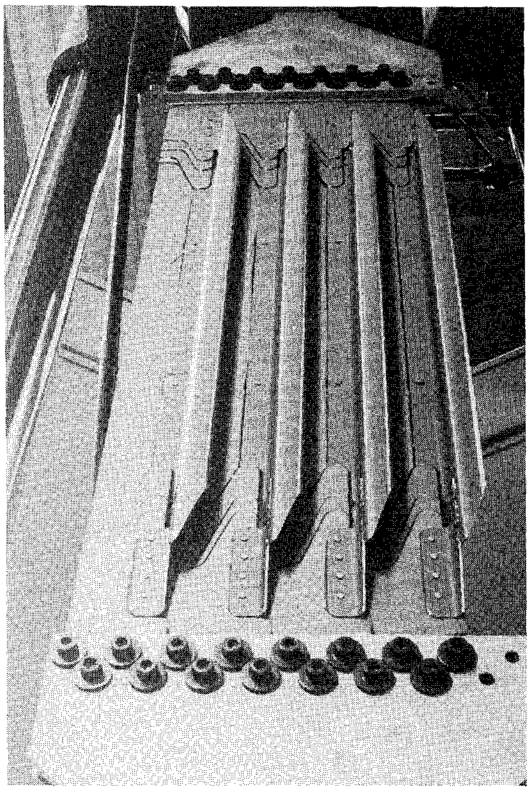

Fig. 14 Inner-outer wing connection of ARALL laminates for the Fokker F-27.

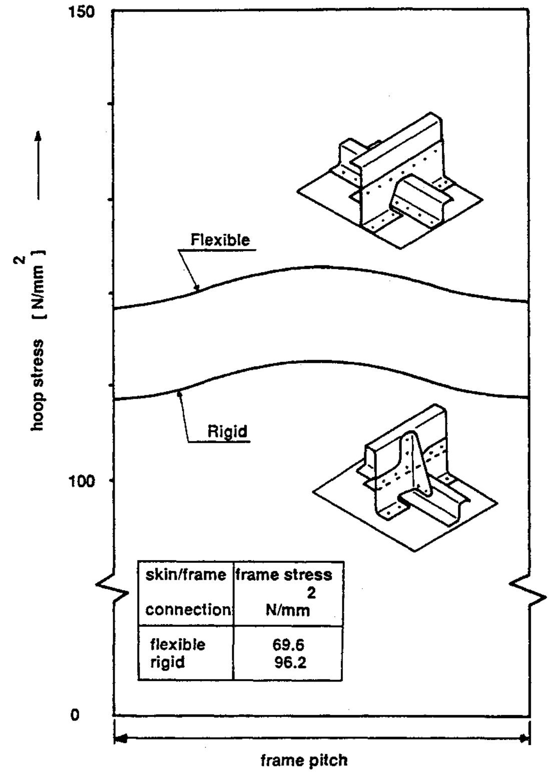

Fig. 16 Influence of the frame-skin connection on the hoop and frame stress in a pressure cabin.

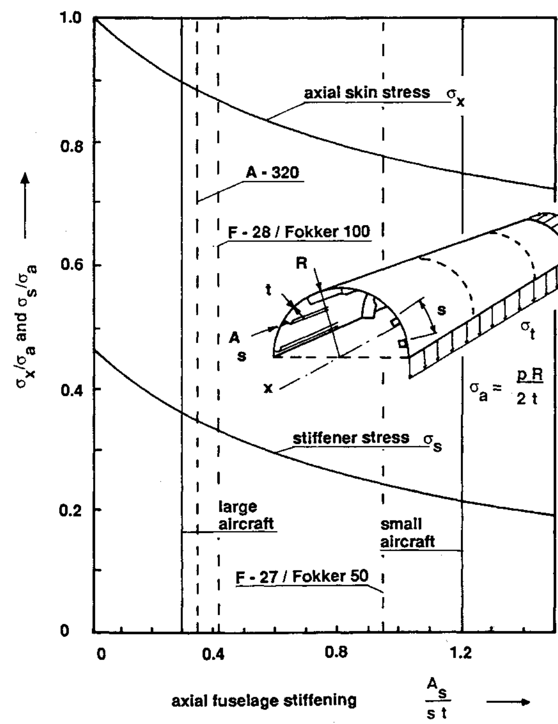

Fig. 15 Influence of fuselage stiffening on axial stresses in a pressure cabin.

nonload-carrying access panel relies on the side panels of the structure. On the other hand, the full load-carrying access panel has been found, in practice, to be more stress-concentration sensitive. Both structures are designed in more detail to make a good decision possible. Because of the negative load cases, it was found that the nonload-carrying structure was heavier than the load-carrying structure. To prevent premature buckling, it was necessary to reinforce the access panel locally. To avoid increasing the spanwise stiffness of the access panel, these reinforcements have to be placed in the chordwise direction. In fact, this means adding material to the structure that primarily is not used for carrying load. It is obvious that this can affect the weight of the lower wing structure significantly.[14] In the case of the Fokker F-27, the width of the access panel is more than one-third of the total width of the lower wing panel. This relatively large ratio also has a negative influence on the nonload-carrying access panel. Taking into account all of the above-mentioned effects, a "semi"-load-carrying access panel was chosen. This means a load-carrying tank cover whereby the cross-sectional areas of the access panel and the tank cover are taken to be as small as possible, resulting in a low load transfer through the tank cover as well as around the tank cover. The shape of the manhole is taken to be elliptical. The background to this decision is primarily the reduction of stress-concentration effects at the critical (minor) axis of the manhole. For further reduction of the stress concentration, the stiffeners on the tank cover should be placed in the minor axis direction (Fig. 13). In fact, this was done in the design of the ARALL F-27 lower wing test panel.[16]

Other important structural details that have been investigated are the connections between two or more structural parts. Examples are the inner-outer wing connection, stiffener run-outs, rebate-tank-cover connections, etc. In all of these cases, in addition to bonding, mechanical fasteners are used. This means that the bearing strength of the material and the strength of the riveted joints must be known. For this purpose, some introductory research has been performed.[17,18] The results of these investigations indicate that the bearing strength of ARALL laminates can be estimated from the bearing strength and the content of the aluminum alloy in the ARALL laminates. It is deduced that the strength of riveted joints in ARALL laminate can be determined from the ordinary rivet tables of *Military Handbook 5*.

These results are used in the previously discussed redesign of the lower wing structure of the Fokker F-27, as well as in the design of a test panel for testing the inner-outer wing connection with stiffener runouts of the Fokker F-27 lower wing in ARALL laminates (Fig. 14).[1,2] Finally, comparing the weight of the ARALL laminate structure with the existing lower wing structure, it is found that, by use of the ARALL laminate material, a weight reduction of 33% could be obtained for the lower skin of the outer wing of the Fokker F-27 Friendship.

Fuselage Structure

It is widely known that, for conventional (aluminum) aircraft, the normal differential pressure p in a pressure cabin is the main fatigue initiator. Fatigue cracks will start from locations of relatively high stress concentration. This means that fatigue cracks will occur at riveted lap joints, frame-skin connections, doors, windows, and, of course, the front and rear bulkheads. Fatigue cracks start mostly at the longitudinal lap joints of the pressure cabin because the hoop stress due to the internal pressure p is about two times the axial stress. However, reinforcement of the shell by axial stiffeners and frames can change the stress distribution substantially. Due to upward, downward, and sideways bending moments, the fuselage must be reinforced longitudinally, and frames are necessary to prevent buckling as well as to support the floor. Figure 15 shows the influence of axial stiffening of the fuselage. It is clear that, in the conventional range of axial fuselage stiffening, the stress in the skin due to the internal pressure p is more than two times the stress in the stringers. For reference, lines for some conventional aircraft are indicated in this figure. From the figure, two preliminary conclusions can be drawn: first, the skin of the pressure cabin should be made of ARALL laminates with the fibers in the circumferential direction; second, the stringers still can be made of ordinary aluminum alloy. However, in fuselage sections with high bending stresses, it is possible that the fatigue stresses in the axial direction could become critical. A possible solution to this last problem is the use of 0-deg as well as 90-deg aramid fibers in the ARALL laminate. This would result in a reduction in the fatigue life of the fuselage structure compared to a structure made of the standard ARALL laminates. Nevertheless, the fatigue life of this modified ARALL laminates would remain an order of magnitude greater than the aircraft design life.

The favorable properties of ARALL laminates allow the fatigue stress level of the skin to increase significantly and to use thinner fuselage skins compared to aluminum alloy. However, this has a major effect on the aluminum alloy frames and the frame-skin connection. Figure 16 shows the hoop stress distribution in the skin between two frames, as well as the effect of rigid and flexible frame-skin connection on the hoop stress and on the stress in the frame. This figure is based on a fuselage design study of the Airbus A-320 in ARALL laminates.[19] It appears that the stresses in the aluminum frames become too high, certainly in the case of a rigid frame-skin connection. Furthermore, it must be realized that frames are not as readily inspectable as the fuselage skin. For this reason, airliners require long inspection periods for these types of aircraft components. High stresses in the frames lead to the danger of a fully cracked frame. Making the frames of ARALL laminate can solve this problem. However, due to the rather complex shape, manufacture of an ARALL laminates frame is quite difficult. Research on this is already underway. Figure 17 shows the first result of cold forming a part of a fuselage frame in ARALL laminate.

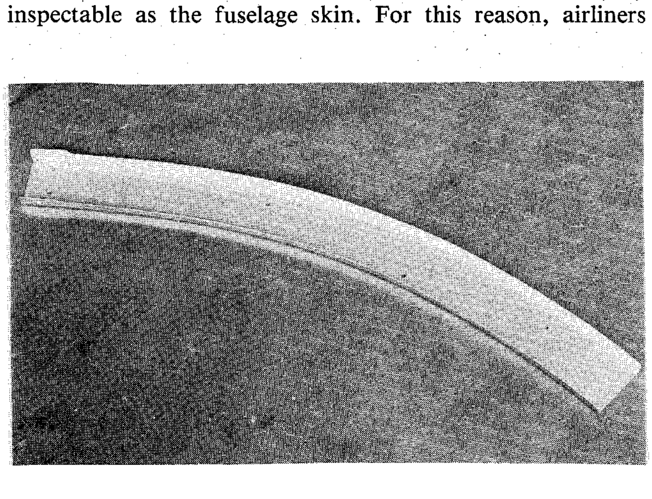

Fig. 17 Fuselage frame of ARALL laminate.

Reduction of frame stresses also can be obtained by the use of crack stoppers (may be better called "stress reducers"). These stress reducers act similar to frames with a rigid frame-skin connection. At the same time, investigation of several types of (true) crack stoppers on aluminum alloy skins shows considerable advantage in the use of ARALL laminates for the crack stopper itself, compared with aluminum alloy and titanium alloy crack stoppers.[20] Fatigue tests show that a crack in the fuselage skin propagates toward the crack stopper. A small crack is initiated in the ARALL laminate crack stopper. However, after a few millimeters, the crack does not propagate further in the crack stopper. On the other hand, the crack in the aluminum alloy fuselage skin continues to grow, but with passing the ARALL laminate crack stopper (which remains intact) the crack propagation rate slows down. This means for fuselages made of conventional aluminum alloy that the use of ARALL laminate crack stoppers can improve the damage-tolerance behavior substantially. The design study referred to is for a fuselage section just aft of the frame, making the connection to the rear spar of the wing. This is a heavily loaded section of the fuselage, the upward and downward bending moments having their maxima in this region. Two areas are studied in more detail: the bottom and the crown of the fuselage. The bottom of the fuselage is both fatigue and compression critical, fatigue critical in the hoop direction and compression critical in the axial direction. The crown of the fuselage is mainly fatigue critical in both directions. Preliminary results show that weight savings using ARALL laminates are large, varying from 20% (bottom) to 40% (crown). It appears that, in order to meet the damage-tolerance requirements, a critical aspect of ARALL-1 and -2 laminates will be their fracture toughness, in particular, for accidential damage when the fibers are broken. For genuine cracks (mostly fatigue cracks), the (residual) strength of ARALL laminates is hardly affected. This subject needs further attention in relation to damage-tolerance requirements.

Conclusions

As must be expected from the preceding discussion of primary aircraft allowables, the large weight savings that would follow from simply the initial static strength of ARALL laminates cannot be obtained in practice. Primarily, it is the notch sensitivity and the fracture toughness of the material that result in a reduced allowable strength. However, even with the reduced ARALL laminate figures, the general comparison of candidate materials shows clearly that ARALL laminate is competitive with or better than carbon-fiber-reinforced plastic, especially for fatigue-critical components. Furthermore, the preliminary design studies of the lower wing skin and fuselage structure confirm that ARALL laminate material has the ability to reduce the weight and increase the life of an aircraft structure significantly. Weight reductions of more than 25% are within reach.

The lower wing skin design study also shows that, because of the excellent tensile and fatigue behavior of ARALL laminates, this structure can become compression critical. Investigation of aircraft loading indicates that this effect will occur primarily for aircraft with relatively low wing loadings. It is deduced that the greatest weight savings will be obtained for aircraft with high wing loadings.

Apart from the significant weight reduction, use of ARALL laminate in pressure cabin structures also shows some other interesting results. Because of the use of relatively thin ARALL laminate skins, the stress in the aluminum frames increases substantially. In many cases, this increase would be unacceptable, especially from an inspection point of view. Possible solutions for this problem are indicated, such as application of flexible frame-skin connections, ARALL laminate crack stoppers, or ARALL laminate frames.

Another, rather obvious, result from the fuselage design study is the conclusion that, from the stress point of view, the stiffeners in the fuselage can be made of ordinary aluminum alloy. The ARALL laminate fuselage design also shows clearly that the further definition and implementation of airworthiness requirements for damage tolerance are urgent subjects for discussion.

Acknowledgment

The assistance of A. Rothwell in preparing this article is gratefully acknowledged. This paper was presented at the Sixth International Conference on Composite Materials combined with the Second European Conference on Composite Materials held July 20–24, 1987, London, England, UK.

References

[1]Vogelesang, L. B. and Gunnink, J. W. "ARALL: A Materials Challenge for the Next Generation of Aircraft," *Materials and Design*, Vol. 7, Nov.–Dec. 1986.

[2]Gunnink, J. W., Verbruggen, M. L. C. E., and Vogelesang, L. B., "ARALL, A Light Weight Structural Material for Impact and Fatigue Sensitive Structures," *Vertica*, Vol. 10, No. 2, 1986, pp. 241–254.

[3]Bucci, R. J., Mueller, L. N., Schultz, R. W., and Prohaska, J. L., "ARALL Laminates – Results from a Cooperative Test Program," Alcoa Labs., presented at Advanced Materials Technology '87, *32nd International SAMPE Symposium and Exhibition*, Anaheim, CA, April 1987.

[4]Verbruggen, M. L. C. E., "Aramid Reinforced Aluminium Laminates: ARALL Adhesion Problems and Environmental Effects," Faculty of Aerospace Engineering, Delft Univ. of Technology, the Netherlands, Repts. LR-504 and LR-505, Nov. 1986.

[5]"Alcoa ARALL Laminate Sheet", Alcoa Aerospace Tech. Fact Sheet, 1986.

[6]Hall, J. and Goranson, U. G., "Structural Damage Tolerance of Jet Transports," *Boeing Airliner*, Jan.–Mar. 1984.

[7]Schoevers, H., "Development of Structural Maintenance," *Proceedings of the International Federation of Airworthiness*, 15th Annuial Conference IFA, Amsterdam, Nov. 1985.

[8]Johnson, W. S., "Impact and Residual Fatigue Behaviour of ARALL and AS6/5245 Composite Materials," NASA TM-89013, Oct. 1986.

[9]Riedinga, L. A. and Waraniak, J. M., "Application and Integration of Design Allowables to Meet Structural Life Requirements," *Proceedings of the 14th Congress of the International Council of the Aeronautical Sciences*, Toulouse, Vol. 2, 1984, pp. 914–921.

[10]Simons, H., Rhodes, J. E., and James, A. M., "Strain Barrier Ultimate Cut-off for Aircraft Structures," presented at International Conference on Composite Materials (ICCM-3), Paris, Aug. 1980.

[11]"Type-Record Fokker F-27 Friendship."

[12]van der Schee, P. A., "Outerwing Lowerskin Fatigue Testing as a Part of the Continuing Airworthiness Programme of the Fokker F-27" *Proceedings of the 10th International Conference on Aeronautical Fatigue*, Brussels, 1979.

[13]Heydra, J. J. and Venselaar, C. F., "An ARALL Lower Wing Skin for the F-27" (in Dutch), M.S. Thesis, Faculty of Aerospace Engineering, Delft Univ. of Technology, the Netherlands, April 1981.

[14]Hegemans, G. and Racke, R., "Application of ARALL Sheet Material in the Lower Wing of the Fokker F-27" (in Dutch), Faculty of Aerospace Engineering, Delft Univ. of Technology, the Netherlands, Sept. 1982.

[15]Gunnink, J. W., "Introductory Re-design of the Lower Wing of the Fokker F-27," Faculty of Aerospace Engineering, Delft Univ. of Technology, to be published.

[16]Gunnink, J. W. and van der Schee, P. A., "Design of the ARALL F-27 Lower Wing Fatigue Panel," *Composite Structures 4*, Vol. 1, Elsevier Applied Science, London, 1987, pp. 1.162–1.177.

[17]Dames, R. A. C., "Design, Production and Fatigue of ARALL Lugs" (in Dutch), M.S. Thesis, Faculty of Aerospace Engineering, Delft Univ. of Technology, the Netherlands, April 1983.

[18]Gunnink, J. W. and Rothwell, A., "An Assessment of the Static Strength of Flush-head Aluminium Alloy Rivets in Two Grades of ARALL-Sheet," Faculty of Aerospace Engineering, Delft Univ. of Technology, the Netherlands, Rept. LR-391, 1983.

[19]Schijve, W., "Investigation of ARALL in the Fuselage Structure of the Airbus A-320" (in Dutch), M.S. Thesis, Faculty of Aerospace Engineering, Delft Univ. of Technology, the Netherlands, Aug. 1983.

[20]de Kruijff, R., "ARALL as Crack Stopper Materials," M.S. Thesis, Faculty of Aerospace Engineering, Delft Univ. of Technology, the Netherlands, Oct. 1985.