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Damage Tolerance aspects of ARALL fuselage skin structure

(Philosophy and experiments)

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DAMAGE TOLERANCE ASPECTS OF ARALL® FUSELAGE SKIN STRUCTURE (PHILOSOPHY ANDEXPERIMENTS)[1]

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INTRODUCTION

Since the introduction of ARALL® Laminate materials at the end of the 70's, ARALL® Laminates (ARamid ALuminium Laminate) have been widely regarded as a family of highly damage tolerant materials with a high weight saving potential. Damage tolerance design of full scale ARALL® aircraft lower wing structures has been achieved with weight savings of more than 30% [Ref.1]. Attention is now focused on the application of ARALL® Laminates as an aircraft fuselage skin material. Yet, several questions concerning the basic design principles and material properties have to be answered. First of all, fatigue properties of the material under realistic fuselage loading conditions, such as, the effects of biaxiality, internal pressurization, curvature, etc, have to be investigated. Secondly, design of the joints is an important factor for the fuselage skin structures. And the last and certainly not the least question is how to certificate an ARALL® fuselage skin structure according to the airworthiness regulations.

To answer these questions, various realistic experimental set-ups have been designed. A wide range of test data for various materials have been obtained. As a final conclusion, it may be concluded that ARALL® Laminate material is an excellent candidate for fuselage skins of modern transport aircrafts.

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PROBLEM AREAS

During the last decade much attention was paid to the damage tolerance evaluation of the aircraft fuselage structure, particularly in pressurized fuselage shell structures. Since the design of the first jet transport aircraft, tangential loading of the fuselage shell structure has more than doubled due to the increase of the fuselage diameter and higher cabin pressures. One of the most important aspects of designing an aircraft fuselage shell structure is to consider skin cracks resulting from fatigue and to choose material and stress level in such a way that the cracks will be discovered within a certain inspection period prior to reaching a critical crack length.

Since ARALL laminates are considered to be a very damage tolerant material under certain load conditions, for instance if the material is loaded in the fiber direction, it may be a good candidate for the fuselage applications.

It is well known that the stress conditions in a modern pressurized fuselage skin structure are rather complicated due to the internal pressurization of the structure and secondary effects associated with this internal pressurization, such as the bulge-outs, biaxial stress, bending, etc. For the application of a new fuselage skin material, it is very important to know if those effects contribute to the crack growth behaviour of the material under service load conditions.

At the present time, fracture mechanical analyses, especially the crack growth mechanism of ARALL laminates are studied in the Structures and Material Laboratory of the Faculty of Aerospace Engineering at the University of Technology of Delft, The Netherlands. Several crack growth models concerning different aspects of crack growth behaviour of the material exist. Unfortunately, it is still difficult to account for the secondary effects such as the bulging-effects, frequency effects, biaxial stress field and bending effects in those models. It is thus essential to do experimental work to investigate the influences of those effects before designing an ARALL fuselage skin structure.

EXPERIMENTS AND TEST RESULTS

(i) Biaxiality

As mentioned above, aircraft fuselage skin structures of modern transport aircrafts are loaded both in the longitudinal direction (axial loading) as well as in the circumferential direction (hoop stress) of the fuselage. The influence of those biaxial stress fields on the fracture mechanical properties of engineering materials is still a hot topic of fracture mechanics research. Analytical methods exist for calculating the influence of the biaxial stress fields, but unfortunately, non of them seems to be useful in practice. Contradictory results of experimental works on biaxial fatigue tests were reported. Cruciform shaped specimens are often used for static tests of monolithic sheet materials. Complications occur when these specimens are used for fatigue investigations (fatigue crack development from the corners of the specimen).

To overcome these problems, a new biaxial testing method for sheet materials, the so-called "SUPERBAT" (Specimen Using Poisson's ratio Effect Restraining for Bi-Axial Testing) (see Fig.1) has been developed in the laboratory [Ref.2]. The principal feature of this method is to restrain the lateral contraction of a sheet material, which is induced by the Poisson's ratio effect, in the direction perpendicular to the loading direction of the specimen. Depending on the Poisson's ratio of the material, a biaxial stress ratio of $\lambda = 30\%$ can be created in the center of the specimen. In the present test set up the lateral restraint is obtained by heavy steel strips (fig.1).

Two uniaxial tests and two biaxial tests have been carried out on both 1.20 mm thick Al 2024-T3 and 0.82 mm thick ARALL (ARALL 2 2/1 lay-up) specimens. The test results are summarized in fig.2. A difference between the crack growth behaviour of the Al 2024-T3 sheets under uniaxial and biaxial load conditions could not be observed. On the other hand, the ARALL specimens loaded under the biaxial stress field show much longer fatigue lives than the uniaxially loaded specimens. After microscopic studies on the delamination area of the specimens, it is clear, that more fiber splitting occurs in the delamination area when the specimens are loaded biaxially, which results in a redistribution of the stress field, delaying fiber failure in the delamination area. Stress biaxiality works thus in favor of ARALL laminates. More transverse loading on ARALL material will promote more fiber splitting in the

delamination area, lowering fatigue crack growth rate.
Because of the orthotropic character of ARALL laminates, fatigue properties in the transverse direction is comparable to the aluminium alloy sheets of the same thickness. A very high transverse loading will obviously force the crack to grow in the fiber direction of the laminate. It is thus very important for a designer to put the fibers in the most heavily loaded direction of the structure. For the aircraft fuselage skin application, most upper skin sheets are loaded in tension-tension with a biaxiality of $\lambda \cong 30\%$ (taking into account the loads carried by the stiffeners and the frames). For these areas, the fiber orientation of the material must be chosen to be in the circumferential direction of the fuselage. The stress biaxiality will only work in favor of the material. In the compression dominating areas, such as the lower fuselage skin sheets, fibers must still be put in the circumferential direction of the fuselage, leaving the stiffeners for taking the transverse loads. In the crown section area, where an equal-axial stress field exists, uniaxiality of ARALL laminates may give some problem. To the authors opinion, this problem can be overcome by careful detail design or using ARALL laminates with fibers in both directions, which are now developed in our laboratory.

(ii) Bending Effects

During the assembling of an aircraft fuselage, the skin sheets are usually bent to take the local curvature of the fuselage. This process introduces a bending stress field in the fuselage skin sheets. For a conventional aluminium alloy skin sheet, this bending stress field will increase the stress intensity factor when a crack is present [Ref.3]. This results in a higher crack growth rate and reduces the fatigue live of the structure. To investigate this effect, a test set-up called "CETS" (Curvature Effect Test System) has been developed in our laboratory. A sketch of the set-up is given in Fig.3. An originally flat sheet can be forced to take a predetermined curvature by placing the sheet between a curved block and two press-rolls. To eliminate the friction force, some thin flexible teflon papers are fixed between the press-rolls and the block. The width of the blocks is 180 mm, so the specimens of 160 mm in width can be tested. Four blocks were made. The radii of the blocks are 130mm, 375mm, 750mm and 1500mm respectively. The diameter of the press rolls is 70mm and the distance between them is 220mm.

Two materials (ARALL 1 2/1 lay-up non-stretch and ARALL 2 2/1 lay-up non-stretch) are tested. The thickness of the specimens is 0.82 mm. The specimens are originally flat. Starter-notches are simulated by narrow saw-cut (width 0.3 mm) with a half-crack length of 1.5 mm and are always perpendicular to the fiber direction of the specimens. The specimens are then placed in the test fixture and a constant amplitude fatigue load of σ=75±75 MPa is applied. The residual strengths of the specimens are then determined in the same test fixture after the fatigue tests. The test results are given in Fig.4 and Fig.5. In contrast with the fatigue test results of Al.2024-T3 in the same test fixture, higher initial bending stress (smaller radii of curvature) leads to a lower crack growth rate of ARALL specimens. But no influence of the initial bending stress on the residual strength of the specimens was observed.

Further examination of the delamination area of the ARALL specimens has shown that partial fiber failure occurs when the specimens are loaded in CETS, which can be considered as the result of an extra tensile stress in the material introduced by the bending moment. This partial fiber failure reduces the crack growth rate in two ways: the fibers take a part of the tensile load from aluminium layers, and the fibers prevent the "out-of-plane" deformation of the crack edges (the so-called "Bulge-out effect"), which usually increases the stress intensity factor of the crack tips of an aluminium sheet. Thus the curvature has a positive influence on the crack growth behaviour of ARALL laminates.

It is thus desirable for ARALL fuselage skin sheets not to be rolled into the curvature of the fuselage when it is not necessary. For a conservative design parameter study, bending effect on ARALL laminates may thus be ignored. Results of coupon tests on flat tensile specimens can thus be adopted which leads to a significant simplification to the calculation procedure for the design engineers.

(iii) Bulge-out Effects

"Bulge-out" is a phenomenon which becomes more and more interesting for the aircraft designers because of the increasing demand on the safety of aircraft structures. Calculations on this effect are mainly based on empirical formulas (T.Swift, P.Kuhn etc). A complete understanding of this very complicated phenomenon is not yet available. Very limited experimental work has been done [Ref.4].

In order to investigate the possibility of applying ARALL laminates as pressurized fuselage skin material, an unique realistic pressurized aircraft fuselage skin structure test system is developed in our laboratory (see Fig.6). In this test system, a curved fuselage skin structure can be cyclically tested with a realistic internal air pressure. Based on a modern wide-body transport aircraft, tests have been carried out on both Al.2024-T3 and ARALL sheets of 1000 × 500 mm. A summary of the test results is given in fig.7. Again, ARALL laminates show an excellent fatigue behaviour. For the ARALL laminates with 3/2-lay-up, bulging of the fatigue cracks does not occur. The fatigue growth rate of this type of ARALL laminates tested in this condition is almost identical to the test results of flat ARALL specimens with a same tensile load. For the ARALL laminates with 2/1-lay-up, limited fiber failure does occur. Due to the internal pressurization, most of the fibers remain intact. As a consequence, the crack growth rate decreases with an increasing crack length.Better fatigue results of 3/2-lay-up ARALL laminates can be expected where the outer fiber layer of the material is put in tension when the laminate is bent to take the curvature of the fuselage. Because of the same reason, crack growth rate of a 3/2-lay-up ARALL laminate tested in a curved condition is even lower than the same material tested in a flat condition. A 2/1-lay-up ARALL laminate with R-glass fibers instead of aramid fibers show even better fatigue behaviour with severer load conditions (see fig.7). In general, R-glass fibers do not fail during the fatigue tests. As a consequence, a better fatigue performance and a better residual tensile strength of ARALL laminates with R-glass fibers are found [Ref.5].
The fatigue behaviour of ARALL laminates in this load condition is thus comparable to or even better than they will behave under flat tensile load conditions with comparable tensile stresses in the fiber direction of the material. A conservative design of ARALL fuselage skin structure can be achieved by adopting fatigue test results of flat coupon tests under comparable test conditions. In contrast with aluminium alloy skin sheets, where bulging still plays an important roll during the design procedure, this result will make the damage tolerance analyses of ARALL fuselage skin structures more straight forward, if not easier.

ABOUT DAMAGE TOLERANCE

For aircraft structural design, several allowables are of primary importance, especially the so-called damage tolerance design principals, which are laid down in the Federal Airworthiness Regulations (FAR) part 25 and in the Joint Airworthiness Requirements (JAR) 25.

In general, damage tolerance consists of the following three aspects: crack propagation, residual strength and damage detection, which are strongly associated to one another. It was shown in the previous paragraphs that ARALL laminates have excellent fatigue properties even under very severe loading conditions. The secondary effects, such as biaxial loading, bending effect and bulge-out effect which play an important role in designing monolithic aluminium alloy fuselage skin structures, are in favour for ARALL laminates. The residual strengths of the material remain excellent, especially when R-glass fibers are used. In contrast with monolithic aluminium fuselage skin structures, conservative stress analyses can easily be achieved by ignoring these secondary effects, which lead to more straight forward design procedures. It is the author's opinion that both the slow crack growth criterion and the two-bay fail-safe criterion can be applied to ARALL fuselage skin structures. Accidental damages may give some problem for aramid based ARALL structures due to a large drop of the residual strength of the material when fiber-cut occurs. Nevertheless, with the introduction of the R-glass fiber based ARALL laminates, it will also be of little concern for the aircraft designers.

Due to its excellent fatigue and residual strength after fatigue, it is believed, that ARALL structures should be allowed to continue to fly with fatigue cracks of the order of 5-10 mm [Ref.6]. Combined with the excellent fatigue and residual properties, it will certainly result in a very long inspection intervals and less expensive inspection methods. It can be concluded that due to its excellent engineering properties, static as well as dynamic, certification of ARALL fuselage skin structures under the current damage tolerance requirements is very well possible with a large weight-saving and service-cost reduction.

CONCLUSIONS AND REMARKS

In contrast with monolithic aluminium alloy sheets, ARALL laminates show very good fatigue and static test results under test conditions which can be regarded as severe and very realistic. Both "bulge-out" and bending, which are known to have a very unfavorable influence on the static and fatigue performance of monolithic aluminium alloy sheets, turned out to be favourable for ARALL laminates. A biaxial stress field gives a better fatigue performance of ARALL laminates. Tests on ARALL laminates with R-glass fibers show even better results. In short, ARALL laminates are very good candidates for the pressurized fuselage skin application. High weight-savings, especially for ARALL with R-glass fibers can be achieved. Damage tolerance requirements can easily be satisfied. Further investigations are being done in the laboratory on the technologies of joints and ARALL laminates with fibers in both directions. Possibilities of biaxial testing on joints are studied now. It is also desirable to do full scale fuselage testing on ARALL fuselage structures in the near future.

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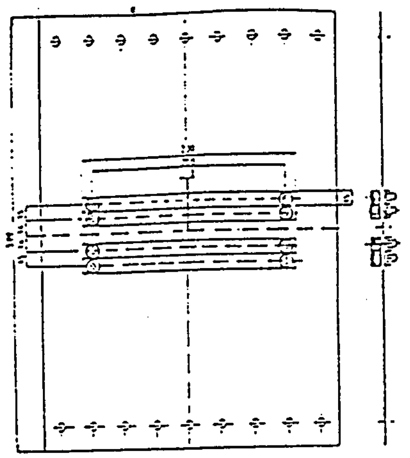

Fig.1 Biaxial fatigue test specimen (SUPERBAT)

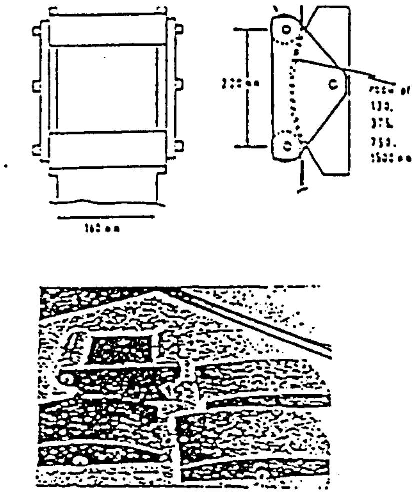

Fig.3 Curvature Effect Test Sysytem (CETS)

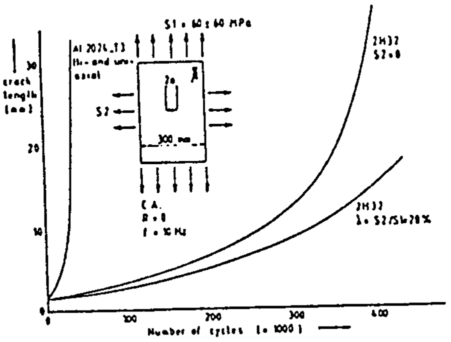

Fig.2 Biaxial fatigue test results

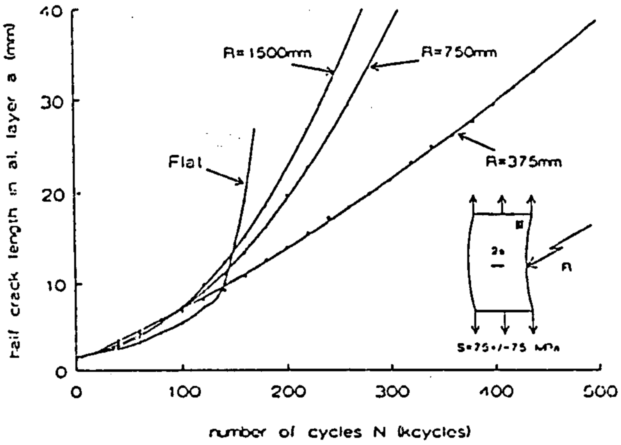

Fig.4 CETS fatigue test results

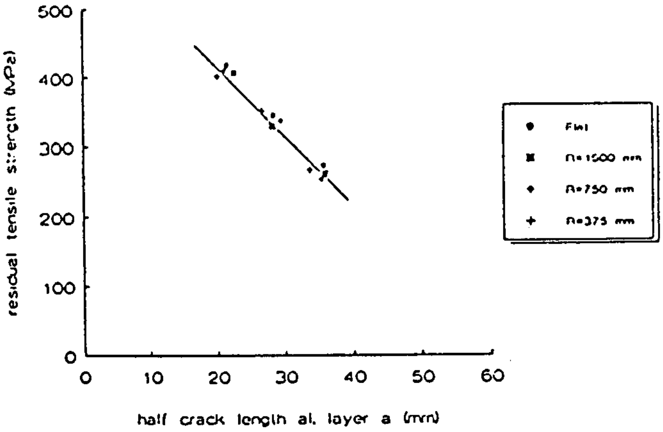

Fig.5 CETS residual strength test results

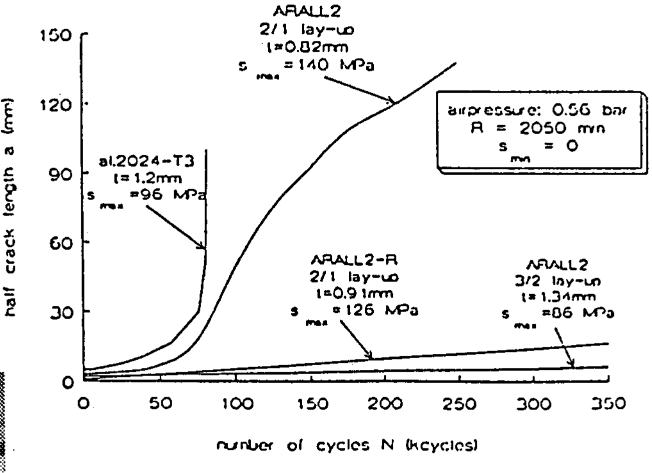

Fig.7 Test results obtained with the test system of figure 6

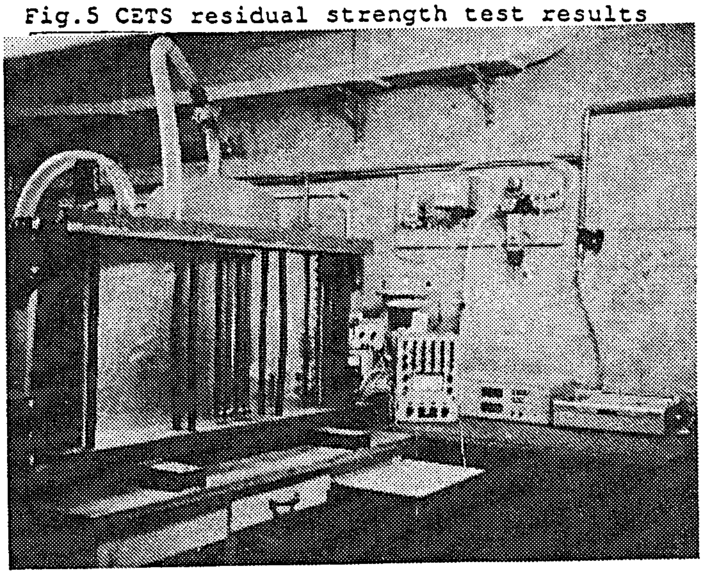

Fig.6 The test system for fatigue simulation of the skin structure of a pressurized fuselage