TOWARDS TECHNOLOGY READINESS OF FIBRE METAL LAMINATES

Glare Technology Development (GTO) 1997-2000

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Abstract

Fibre Metal Laminates (e.g., Glare) are composed of a bonded structure of metallic layers and fibre reinforced adhesive layers and were developed by laboratory testing and design during the last fifteen years. The Glare Technology Development (GTO) has been aiming at final technology readiness for application in aircraft design, production and service. The current paper gives an overview of the work that was done in this large project.

0 Introduction

Fibre Metal Laminates were developed at Delft University of Technology in The Netherlands by prof. L.B. Vogelesang and his team as a family of hybrid materials that consist of bonded thin metal sheets and fibres embedded in adhesive, i.e., rubber toughened epoxy (see Fig.1). The variant with glass fibres is called 'Glare'. The laminated layout creates a material with excellent fatigue, impact and damage tolerance characteristics and a low density. The bondlines with fibres ('prepreg') act as barriers against corrosion of the inner metallic sheets, whereas the metal layers protect the fibre/epoxy layers from picking up moisture. The laminate has an inherent high burn-through resistance as well as good damping and insulation properties. The material can be produced as semi-finished sheet material. Like monolithic aluminium, this sheet can be machined and formed into products. However, the laminate can also be cured in an autoclave into a complete structure, e.g., large curved panels with co-cured doublers and stiffening elements. The so-called 'splicing concept' (see Fig.2) makes a larger panel size possible compared to conventional aluminium structures, and consequently it reduces assembly costs. The prospect of a possible 20% weight reduction for aircraft structures was the prime

Figure 1. Typical Fibre Metal Laminate lay-up.

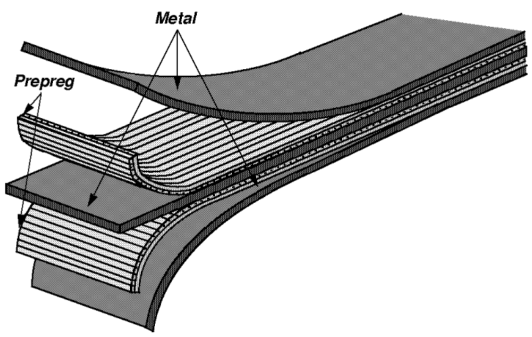

Figure 2. Splicing concept.

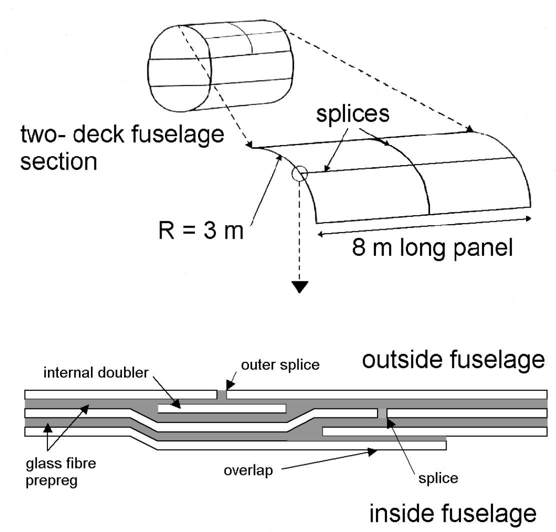

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Table 1. Available Glare grades.

Grade	Aluminium layers		Fibre layers	
	Alloy	Thickness per layer (mm)	Orientation	Thickness per layer (mm)
Glare 1	7475-T761	0.3 – 0.4	Unidirectional	0.25
Glare 2	2024-T3	0.2 – 0.5	Unidirectional	0.25
Glare 3	2024-T3	0.2 – 0.5	Cross-ply (50%-50%)	0.25
Glare 4	2024-T3	0.2 – 0.5	Cross-ply (67%-33%)	0.375
Glare 5	2024-T3	0.2 – 0.5	Cross-ply (50%-50%)	0.5

driver behind the Glare development.

Several Glare grades are commercially available (see Table 1). Every grade can be built up in many different thicknesses, e.g., the lay-up of a Glare 3 variant with a so-called ‘3/2 lay-up’ as is shown in Fig.1 is:

[2024-T3/0° glass/90° glass/2024-T3/90° glass/0° glass/2024-T3]

in which the 0°-direction is the L-direction (i.e., the rolling direction) of the aluminium layers.

In August 1997 a large project was initiated in The Netherlands by Structural Laminates Industries to fill in the technology gaps between laboratory material development and large-scale application in aircraft design, production and airline operation: the Glare Technology Development (GTO). This large project was a co-operation of several European partners and was mainly carried out in The Netherlands. The project was funded by the Dutch Ministry for Economic Affairs via the Netherlands Agency for Aerospace Programs (NIVR). At the end of 1999 a substantial part of this project was finished. The project counted over eighty sub-projects that were distributed over the following seven working groups: 1. Qualification, Properties & Design Allowables, 2. Calculation Methods, 3. Design Concepts and Certification Aspects, 4. Basic Manufacturing & Processing Technology, 5. Specialties, 6. Spin-off and 7. Maintenance Support.

It is impossible to treat all the research that was done in detail here. This paper only provides a broad overview of the work that was carried out in the subsequent working groups.

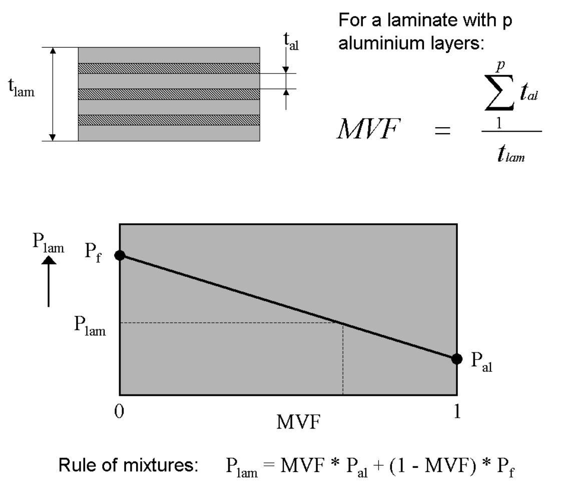
1 Qualification, Properties & Design Allowables

The objectives of this first working group were (1) the qualification of Glare material and components, (2) the generation of material property data and design allowables, and also (3) the determination of the properties of spliced laminates.

For the airlines the lack of standardisation in composites is a burden which tempers their enthusiasm for composite materials. The aim for the development of Glare was to avoid this problem. Complete Glare grades and not only their constituents are qualified, like for conventional aluminium alloy sheets, which assures standardisation of the material and also reduces costs. A qualification strategy for Glare was discussed between the partners and was initiated. The grades Glare 2, 3 and 4 were considered. Batches of Glare were defined. The Glare constituents (aluminium, prepregs, primer) were qualified. All the processes needed to produce Glare were covered in the qualification: deoxidising, anodising, priming and bonding. Essential for the qualification of the Glare grades were the definitions of the batches on the basis of the various constituents, the relevant mechanical tests, the test conditions (as received, exposed at low and high temperature) and the number of tests that had to be carried out per batch. For each of the three

Glare grades (2, 3 and 4), qualification tests will be carried out on a laminate with a particular lay-up, i.e., one Metal Volume Fraction (MVF). The properties of laminates with other lay-ups will be determined with the so-called ‘Metal Volume Fraction Approach’. This is a ‘kind of rule of mixtures’ (see Fig.3), which assumes that the properties of a Glare laminate depend linearly on its Metal Volume Fraction. The validity of the Metal Volume Fraction Approach was proven, for several mechanical properties, during the project. For example, it was shown that the strength of a Glare lay-up is linearly dependent on the Metal Volume Fraction (see Fig.4). Also the qualification of components was performed using fuselage demonstrator panels.

Figure 3. Definition of the Metal Volume Fraction Approach.

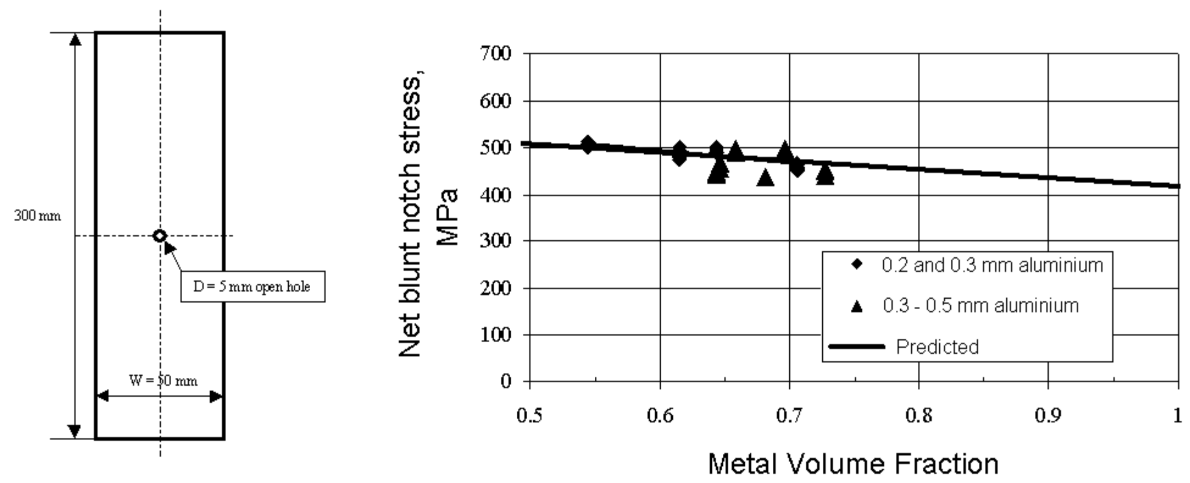


Material properties and design allowables are essential for the design of aircraft structures. A database with design allowables will be determined using the qualification test data and the Metal Volume Fraction Approach to calculate allowables of specific lay-up of the qualified Glare grades.

The influence of multiple curing cycles, needed for example to bond stringers on the panels, was determined. No effect was found. A stress-strain calculation program was developed as a material design tool to calculate stress-strain curves of an envisioned Glare grade from the properties of the constituents. An extensive environmental durability test program was carried out to determine the effect of temperature and moisture on the basic material properties (e.g., tensile strength) and on properties of structural details (e.g., riveted lap and butt joints). Effects of initial flaws and damage due to impact and scratches were taken into account in this program. Only limited strength reductions were found after long time environmental exposure.

The third part of this working group was the research into the properties of spliced Glare. The objective was to determine the properties of spliced Glare as compared to those of the basic laminates. These data will also be used to qualify the splices. The splices were divided into separate details (‘building blocks’) like the

Figure 4. Blunt notch strength as a function of the MVF.



outer splice (see Fig.2 and 5) for which the properties were determined. A detailed finite element analysis was performed for several splice details to study the interaction between these splice details and to prove that this interaction is negligible.

2 Calculation Methods

The objective of this second working group was to provide the aircraft designer with analysis methods for Glare structures that are validated by tests. The conventional design principles and methods available for aluminium were taken as a starting point, and were adapted for the specific features of Glare such as anisotropy and elastic fibre layers. This ensured a better acceptance of these methods and principles by the aircraft industry. Many methods for Glare already existed, because they were part of the material development that was carried out in Delft by MSc- and PhD-students during the last fifteen years. It had to be proven that these structural analysis methods were accurate and reliable for industrial application as well.

The calculation methods comprised, a.o.:

- basic material properties: stress-strain curves, blunt notch strength and shear yield strength,
- stability: compression, shear and combined shear/compression,
- residual strength: unstiffened panels, stiffened panels, Foreign Object Damage in combination with Widespread Fatigue Damage and crack stoppers,
- fatigue crack propagation: through cracks, surface cracks and crack initiation.

As for the basic material properties, the Metal Volume Fraction Approach was proven to be valid for shear stiffness and blunt notch and yield strength.

Well-known and accepted analytical design methods, for post-buckled stiffened panels, like

Figure 5. Definition of an outer splice as a building block of the total splice (see also Fig.2).

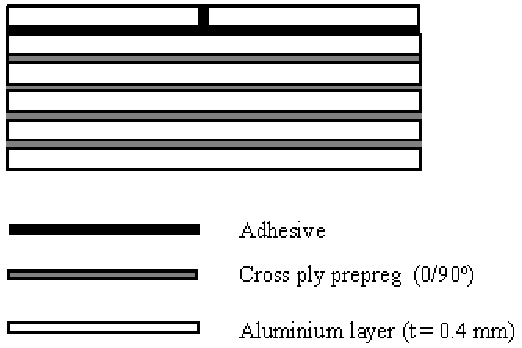
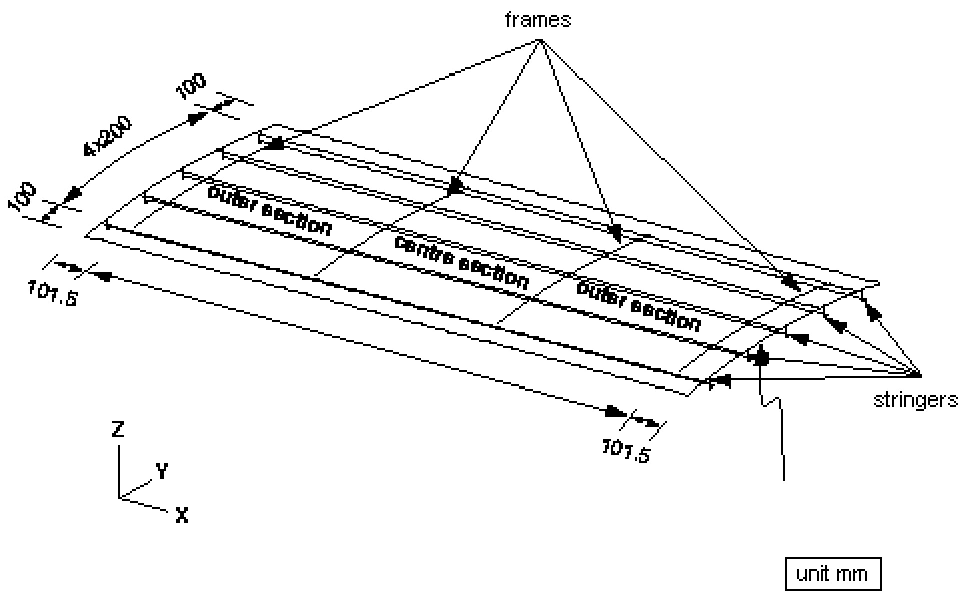


Figure 6. Geometry of the tested compression panels.



the Euler-Johnson method for compression loading and Kuhn's method for shear loading, were modified and supported by finite element calculations. For compression two panels such as indicated in Fig.6 were designed and tested. Also large (1 x 1 m^2) shear panels were designed and tested using a picture frame test (see Fig.7). Both the compression and the shear behaviour could be accurately predicted by finite element calculations.

A total of 48 flat unstiffened panels of different Glare grades and lay-ups were tested for residual strength (see Fig.8). Force, elongation, crack opening displacement, crack tip opening angle and strains were measured. From these measurements R-curves were derived in much the same way as for monolithic aluminium alloys (see Fig.9). The Metal Volume Fraction Approach was proven to be valid for residual strength as well (see Fig.10). The R-curves can be used as input for an analytical design tool to predict residual strength of a stiffened Glare panel with a two bay crack and a broken central stiffener. The

Figure 7. Picture frame test set-up.

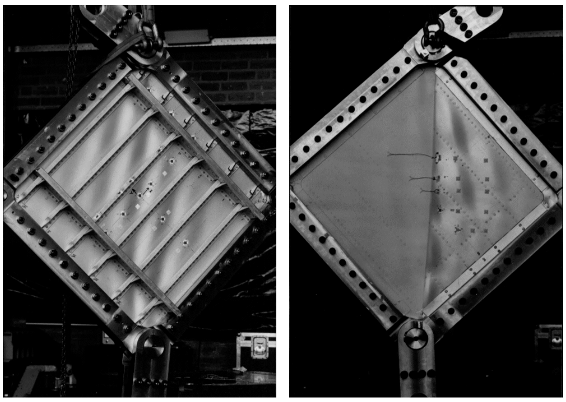


Figure 8. Geometry of the tested flat unstiffened panels.

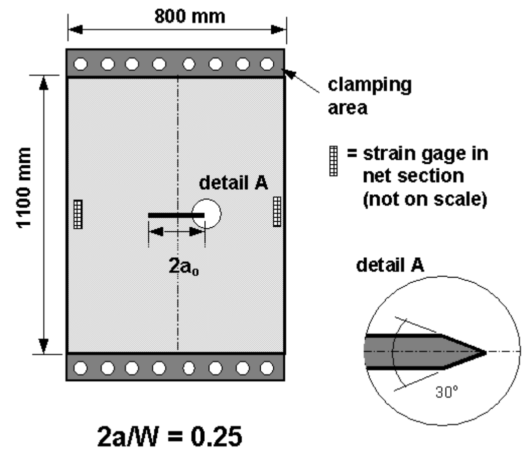
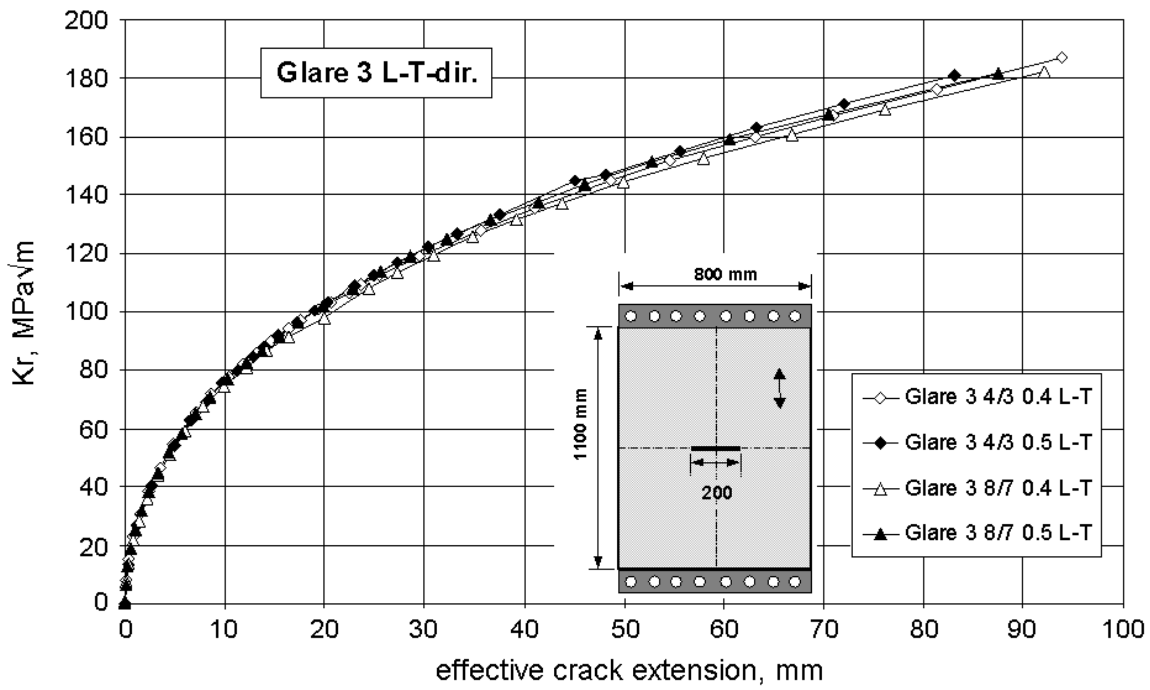


Figure 9. Typical R-curves derived from flat unstiffened panel tests.



analytical design tool was based on the proven displacement compatibility method. Four large stiffened Glare panels were tested, each with five riveted or bonded stringers. The results were used to verify the design tool. Also the effect of small cracks emanating from rivet holes simulating multiple site fatigue damage, on the residual strength with Foreign Object Damage was determined.

A total of 78 specimens of different grades and lay-ups with an initial through-the-thickness central saw cut were tested under fatigue, to verify and to determine input parameters for a design tool. After an initial more rapid growth immediately after initiation, the crack growth rate decreases until it reaches a constant value

Figure 10. MVF Approach for residual strength properties.

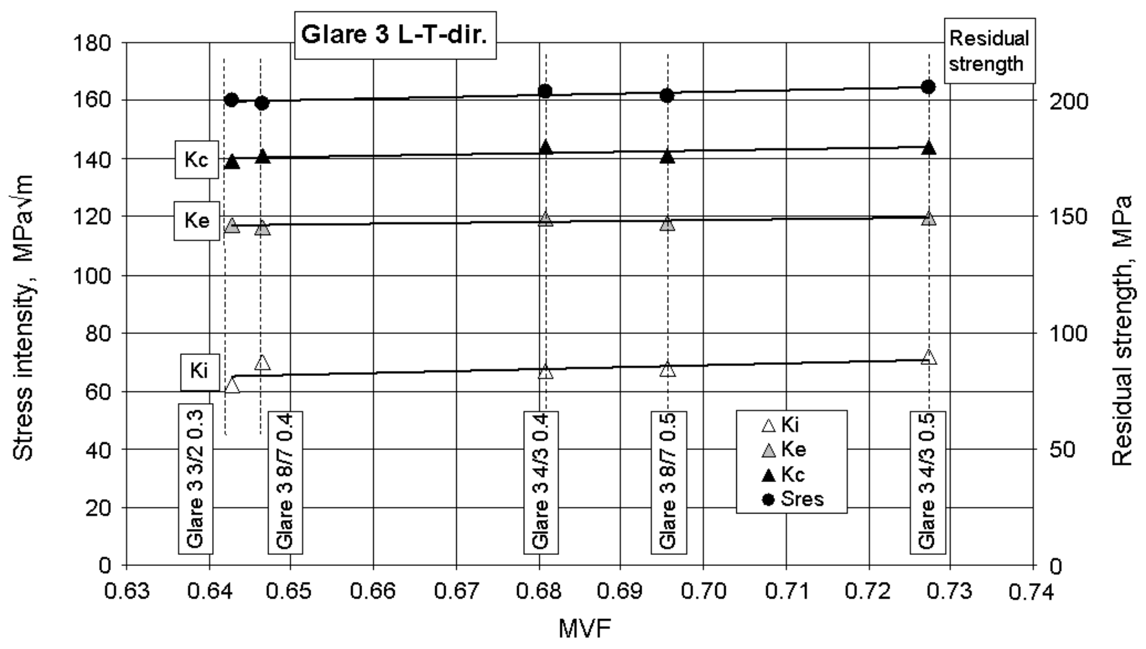
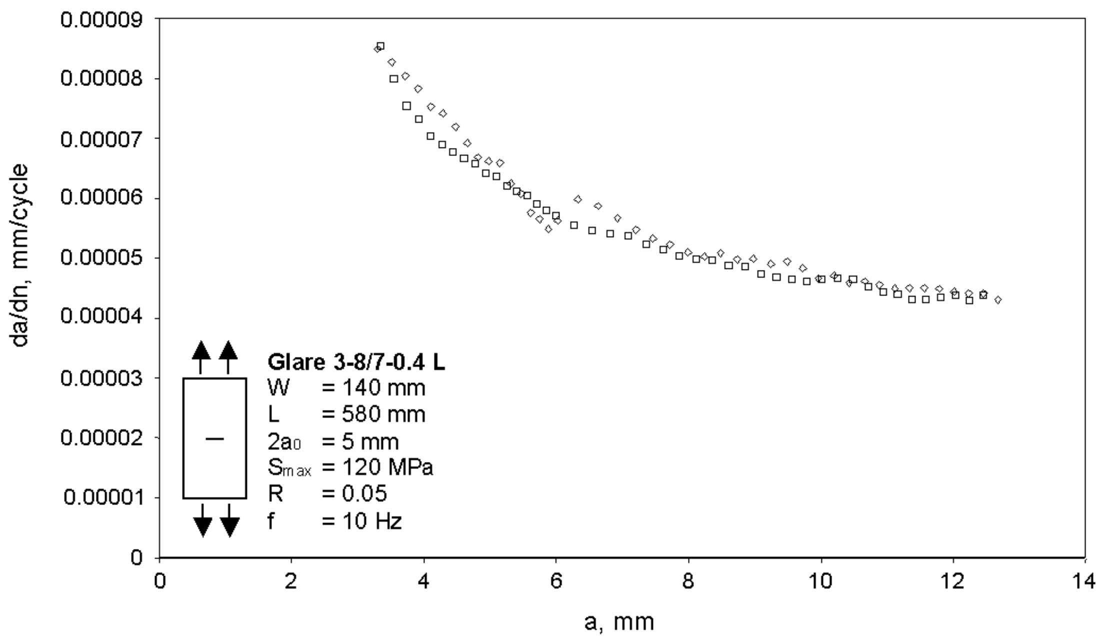


Figure 11. Crack growth rate in Glare becomes approximately constant.



for a large part of the life (see Fig.11). This implies that a certain crack length of several millimetres is needed before the fibres become fully effective. In general cracks in Glare structures will initiate as surface cracks in one layer only as a result of bending present in the structure, e.g., at riveted lap joints. Therefore a test program on crack growth in the outer aluminium sheets was carried out. It was proven that also in this case the crack growth rate is constant. The database of determined constant crack growth rates for different stress levels will be implemented in a design tool later. For the prediction of the initiation life of cracks starting from a hole, it was shown that the existing methods based on S-N-curves of the aluminium alloy in Glare can be used.

The fatigue crack growth of part-through cracks was found to be constant for a certain maximum stress level S_{max}. Curves could be generated for a specific Glare variant, lay-up, rolling direction of the aluminium layers and MVF that give a relation between crack growth rate and S_{max}. By taking into account the residual stresses that are left in the laminate after the curing cycle, the amount of curves can be reduced to one single curve for every Glare variant and loading direction (see Fig.12).

The overall conclusion of this working group was that the existing methods for aluminium can be modified, implemented and used to design Glare structures.

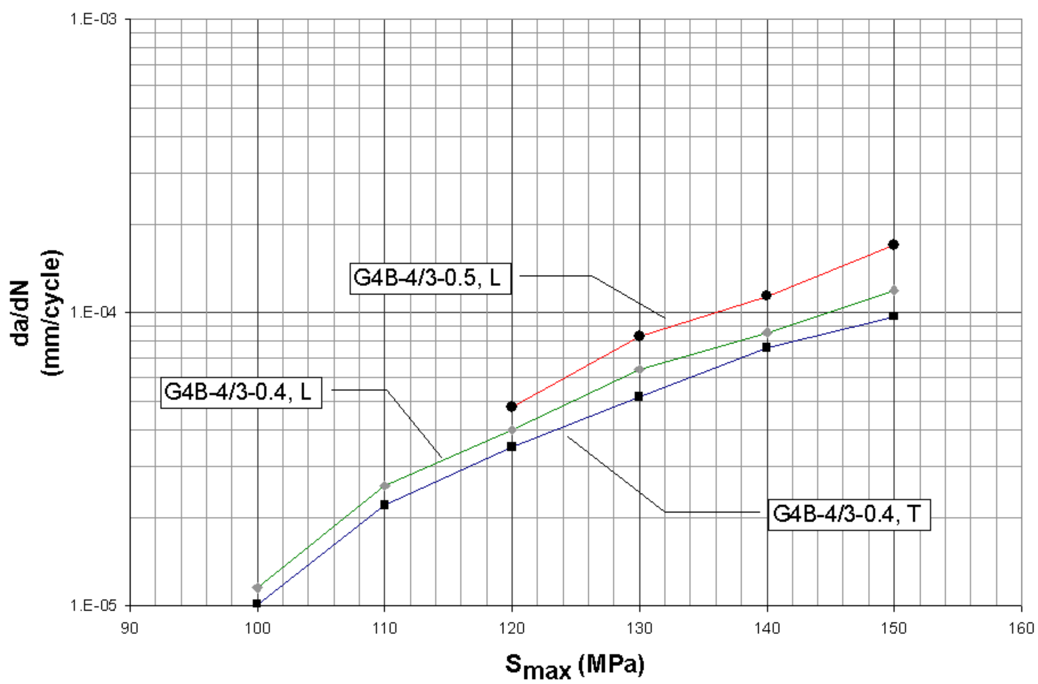
3 Design Concepts and Certification Aspects

The Glare Technology Project mainly focused on fuselage applications. To ensure a proper detail design of the fuselage, adequate design concepts (e.g., stringer types, frame/skin-attachment concept) have to be available. With these concepts the methods resulting from the previous working group can be used for dimensioning the chosen structural concept. Because Glare is neither a metal nor a composite material, also the certification philosophy needs adjustment to ensure airworthiness of the designed Glare structure.

This working group covered the following aspects:

- panel arrangement of an envisioned aircraft fuselage,
- use of a preliminary design tool for Glare fuselages,
- stiffener concepts,

Figure 12. Crack growth rate as a function of the maximum stress level for different Glare variants and loading directions.



- joints,
- door and window cut-outs,
- specific features of the Glare design concepts, e.g., splices,
- certification aspects.

A panel arrangement study aimed at a technically and economically feasible panel distribution over an envisioned fuselage. Available autoclave sizes for curing Glare panels, available sizes of automatic drilling and riveting machines, transport limitations on the panels, etc., were considered. A minimal number of panels is desirable to minimise the necessary number of circumferential and longitudinal joints in the fuselage.

Preliminary designs were made to determine the locations with the expected critical allowables for Glare (blunt notch strength, stability, residual strength or fatigue) for the different load cases of the aircraft. Fig.13 shows a typical plot of the stresses in the fuselage for one of these load cases. The bending of the fuselage is clearly visible. It causes large stresses in the top of the fuselage at the location of the wing.

Several stiffener concepts were studied from a manufacturing and structural efficiency point of view (stability) for the various regions of the fuselage, i.e., in front of the wing, at the wing and aft of the wing. Especially for the last two locations stability may be the design driver. In the top of the fuselage section at the wing, large fatigue loads may occur which may be critical for the stringer design.

The longitudinal and circumferential joints of the stiffened Glare panels of the fuselage will be made using rivets or hi-locks. In a fuselage structure these joints are the most likely locations for fatigue damage to occur. The residual strength of 2024-T3 and Glare riveted lap joints after fatigue is shown in Fig.14. The Glare lap joint displays a better behaviour over the aluminium lap joint combining high initial residual strength with slow strength reduction. Cracks initiate in one aluminium layer at the mating surface and remain limited to this layer for a long portion of the life. Ultimate load carrying capability is required and proven with these cracks. The 2024-T3 riveted lap joint shows fast strength decrease once fatigue cracks have initiated. Relatively short inspection intervals are required for aluminium to prevent a situation in which unstable crack extension and reduced residual strength will occur. The results of the Glare joints indicate that fracture of a riveted lap joint as a result of fatigue damage will never occur under realistic conditions. Damage tolerance is built into the material instead of having to rely on adequate inspection. Currently a design tool is being developed to

Figure 13. Axial stresses in the fuselage for a 2.5G pull-up load case.

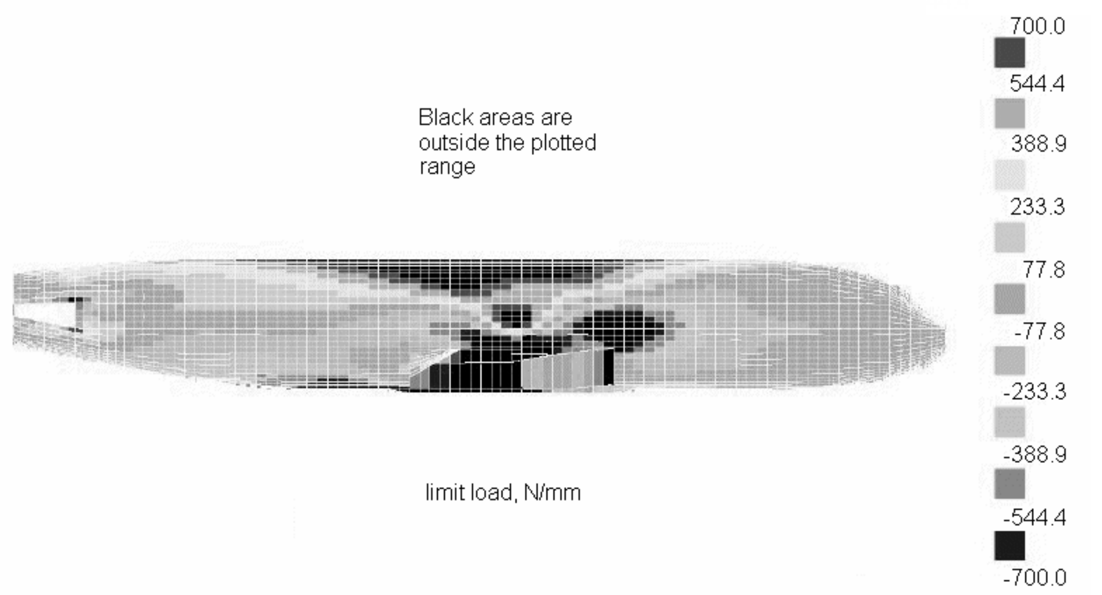
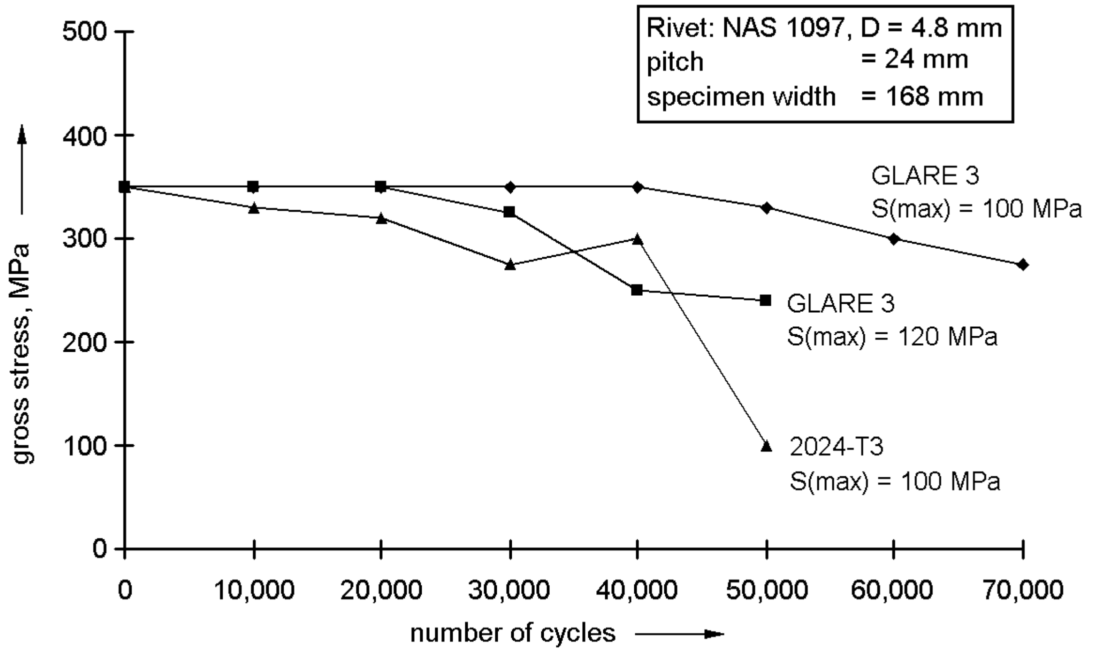


Figure 14. Residual strength of Glare and 2024-T3 riveted lap joints.



cover prediction of crack initiation, crack growth and residual strength using the constant crack growth rate and the crack initiation method found in working group 2 (Calculation Methods) as input.

Door and window cut-outs are critical locations in aircraft fuselages. This is also true for Glare because of its anisotropic nature and lower stiffness and the high shear loads that have to be transferred over the cut-outs. Limitations are set on the deformations of the cut-out because of the doors. High stress concentrations at the corners and large deformations are prevented by a complex set of doublers around the cut-out. The design concept for these doublers had to be established.

The splice concept has a lot of inherent design freedom (e.g., splice gap width, overlap lengths, etc.). Design rules had to be formulated to give the designer guidelines for his decisions. Also for ply drop-offs due to thickness changes in Glare, design concepts had to be derived and verified by testing.

An initial certification philosophy for a Glare structure has been documented. The proposed approach is under further discussion, also with representatives of airworthiness authorities.

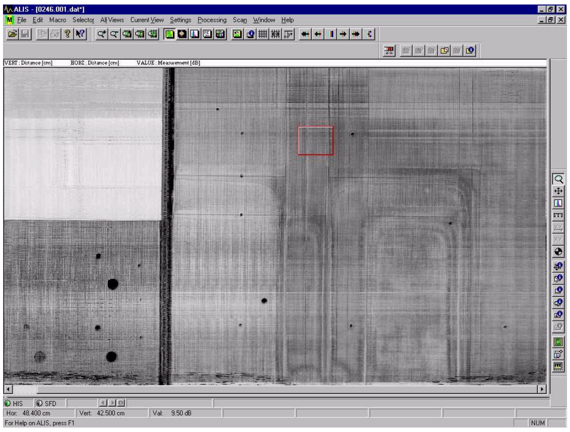
4 Basic Manufacturing & Processing Technology

Glare is an excellent material because of its material properties, but low-risk and cost-effective manufacturing techniques are vital to make this material truly successful. Upscaling from laboratory production in Delft to large-scale industrial application was necessary. This working group was divided into the following subjects:

- development of details of the necessary procedure in the manufacturing process (e.g., lay-up of splices, double-curved panels),
- manufacturing trials under semi-industrial conditions.

Fokker Aerostructures produced test panels for the entire Glare Technology Project on an industrial basis. C-scan quality control was done, using the method that was especially developed for Glare at the Delft University. The 600 m^2 of Glare sheet produced this way was essential in providing valuable production experience and to establish a large database for quality control. A typical C-scan plot is shown in Fig.15.

Figure 15. Typical C-scan plot for the quality control of Glare panels.



Several large panels with details, such as doublers around cut-outs, splices, and second cure bonded stiffeners, were produced and checked. This included several large panels to practise the lay-up of splices and the accurate handling and positioning of thin sheets, prepregs and adhesive layers (see Fig.16). A method for curing Glare in a double-curved mould was developed. Double-curved panels with a radius of 20 m in the one direction and 1.6 m in the other and including splices were produced. These double-curved panels demonstrated that Glare is suitable for use in fuselage panels close to the cockpit and toward the tail of the aircraft.

5 Specialties

The working group Specialties was meant for items that not yet covered in one of the other groups. So far only the subject of fire, smoke and toxicity was treated.

The problem with the burn-through aspects is that at this moment no regulations exist for fuselage skin material as for cabin interior materials. The only existing requirement is that in case of an emergency the passengers must be able to leave the aircraft within 90 seconds. Recent experience showed that the fuselage should preferably be more fire-resistant to increase survivability. This is in particular true for high-capacity aircraft. The skin acts as a first barrier against the fire.

Under normal conditions aluminium shows burn-through within a minute. Glare has excellent burn-through characteristics (see Table 2). Burn-through tests were carried out on small samples with various compositions as well as on large panels. Fig.17 shows typical measured temperatures during a burn-through test on small samples of 105 x 105 mm. The tested materials were Glare 4-3/2-0.5, a 2.1 mm thick biaxial fuselage material composed of a 3/2 lay-up with 0.5 mm thick 2024-T3 layers and

Table 2. Results of burn-through tests (flame temp. 2500 °C).

Glare type	Thickness (mm)	Burn-through time (s)
Glare 2-2/1-0.3	0.85	89
Glare 3-3/2-0.3	1.4	111
Glare 3-4/3-0.2	1.55	144
Glare 4-3/2-0.3	1.65	185
Al 2024	1	5
Al 2024	1.3	8

Figure 16. Large fuselage panel.

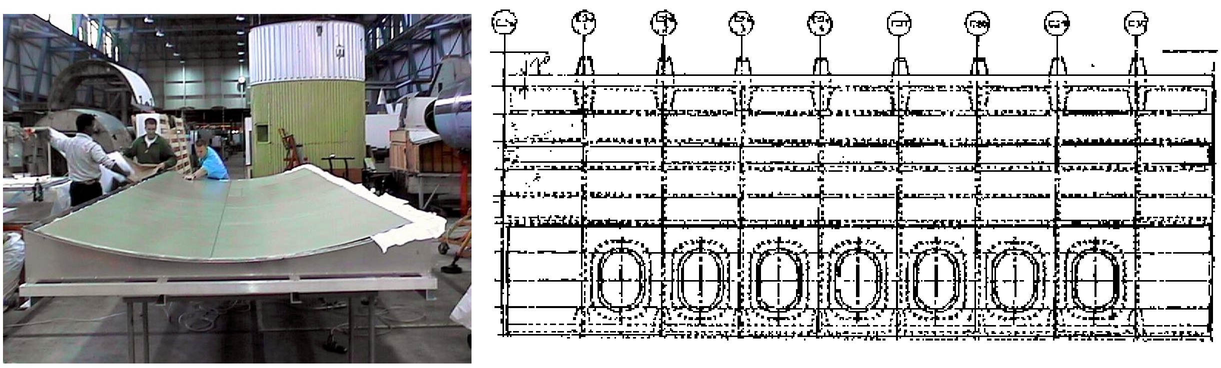
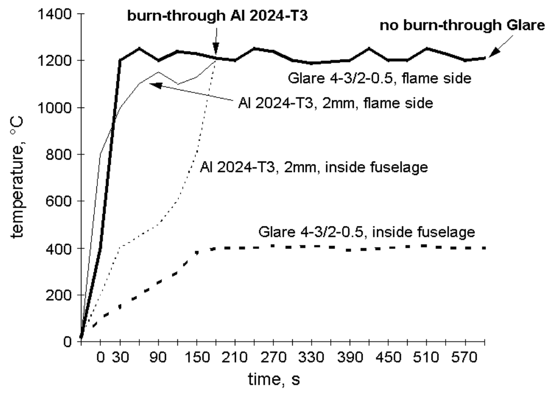


Figure 17. Measured temperature during burn-through tests on Glare 4-3/2-0.5 and 2024-T3.



stacking order [2024-T3/0°/90°/0°/2024-T3/0°/90°/0°/2024-T3], and 2 mm thick 2024-T3. A heat flux of 204 kW/m^2 and a temperature of 1150 °C both typical for a kerosene fire, were applied. The temperature was measured at the centre of the specimen at the flame side and the opposite side. The thin outer aluminium sheet of Glare melted immediately, after which the glass/epoxy layers acted as a fire barrier. Due to the high melting temperature of the glass fibre (1500 °C) the fibres remained intact, whereas the epoxy burned and formed a carbon layer around the fibres. Delamination of the laminate took place, which caused a very effective insulation as can be seen in Fig.17. No flame penetration was observed for Glare after 10 minutes, whereas the 2024-T3 samples showed burn-through within 100 sec at approximately 1150 °C.

6 Spin-off

Once this new material has been accepted and applied in aerospace industry, it can be expected that applications outside aerospace will be possible too. To anticipate this, a separate working group studied possibilities for these so-called 'spin-off' applications.

As Glare is initially developed for *primary* aircraft structures like fuselage panels, the spin-off working group also considered *secondary* aircraft applications, e.g., cargo floors and engine cowlings. This may function as a 'bridge' between aerospace and non-aerospace applications. The application of Glare in secondary aircraft parts is mainly driven by the good impact behaviour of the material (especially Glare 5) and its fire resistance. The use of Glare in cargo bays (floors and liners) was already extensively evaluated by test installations at various airlines and with success. Engine cowlings were studied in this project. In the past, fan cowl doors were made of aluminium whereas currently they are made of impact prone composite sandwiches. Glare seems superior because it combines the impact resistance and reparability of aluminium with the low structural weight of composites. Preliminary design studies also covering possible production techniques, were done for this promising application. Another spin-off application is the Glare production that started in 1999 for the Glare cargo container of the Galaxy Scientific Corporation. This was the only container that passed the severe FAA blast resistance test (see Fig.18).

A special forming technique was studied for the use of Glare in secondary structures: explosive forming (see Fig.19). It was shown that this technique offers unprecedented opportunities for this material but further study is still needed. Another special technique that was developed, was a method for producing seamless Glare tubes (see Fig.20).

Compared to competing materials, the advantages of Glare in the spin-off area are its

Figure 18. Glare cargo container after FAA blast resistance test (courtesy Galaxy Scientific Corporation).

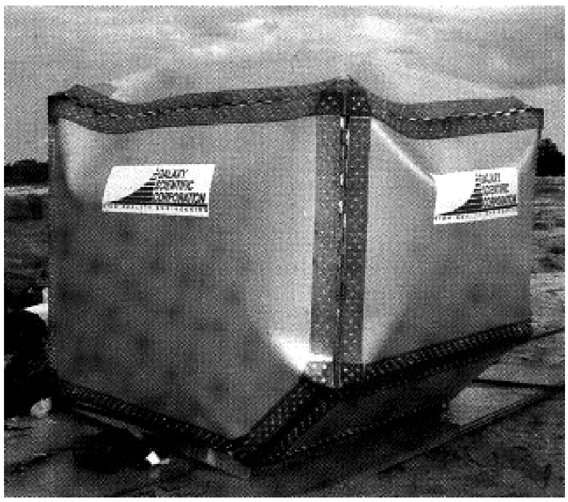


Figure 19. Experimental study of explosive forming for the production of a Glare antenna mirror.

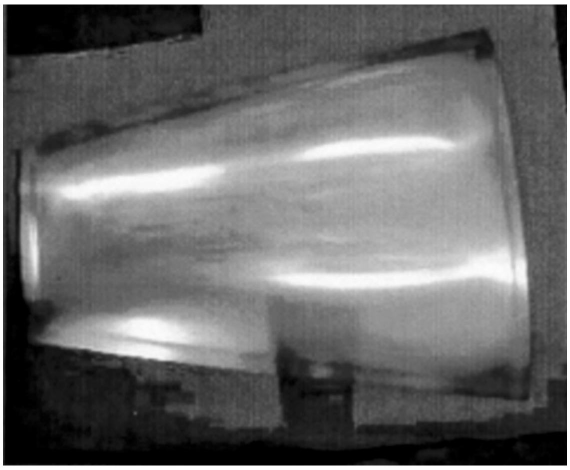


Figure 20. Seamless Glare tubes.

fatigue, impact and fire resistance. Possibilities were investigated for the use of Glare, e.g., for application in luxury yachts, defence and automotive applications. The reduction in material costs appears to be essential for the viability of Glare during spin-off. Cheaper aluminium alloys, pretreatments and production techniques are now being studied and developed.

7 Maintenance Support

'Last but not least' is in particular true here. As the maintainability of Glare structures is crucial for airline acceptance it is of utmost importance for the applicability of Glare. This working group identified many questions raised by the airlines and also studied the current practices in the maintenance of aluminium structures. The main target of this working group was to prove that Glare structures can be maintained using conventional repair and inspection procedures, such as are currently in use for monolithic aluminium structures. The following maintenance related aspects were identified and covered: impact damage resistance; lightning strike damage; corrosion; environmental influence on damage growth, such as moisture, temperature cycles and chemicals (e.g., skydrol); inspection techniques; corrosion removal; removal of scratches; paint stripping and repair types, such as flush repairs and small and large repairs.

The impact damage resistance of Glare is better than that of an aluminium structure. It was proven that no debonding occurs due to impacts with no visible dent. The debond size is always smaller than the dent size. This ensures a general visual inspectability of the impact damage. Very high residual strengths were found after impact. Even with the most severe impact damage riveted lap joints are still able to carry ultimate load after fatigue cycling up to the design life. Also the worst thinkable case of in-flight inflicted hail damage will not cause debonding of Glare.

Lightning strike was simulated according to specifications on large Glare specimens and structural details (e.g., splices and lap joints). Aluminium 2024-T3 was taken as reference material. For Glare lightning strike damage was found to be restricted to the outer aluminium layer at the impact side and only a small zone of debonding was observed (see Fig.21). During fatigue tests on the damaged Glare specimens no fatigue initiation occurred. In 2024-T3 holes were created during the simulated lightning strike (see Fig.21).

During accelerated corrosion tests the only corrosion attack observed in Glare once again was in the outer (0.4 mm thick) aluminium layer. The corrosion resistance of the thin 2024-T3 sheet layers of Glare was shown to be superior to that of a thicker (4 mm thick) panel of the same alloy. Finally, during stress corrosion tests no stress corrosion problems were observed for Glare.

To study the possible debonding of Glare at high temperatures, specimens were exposed to temperatures ranging from 190 °C to 300 °C. For exposures up to 255 °C no debonding was found. Indeed these high temperatures may occur accidentally, e.g., when a fuselage skin is exposed to the APU exhaust of a neighbouring aircraft. To simulate the latter situation, some Glare panels were located behind a running APU of a Boeing 747 (see Fig.22). No debonding was observed. Also it was found that temperatures caused by an APU exhaust, in reality do not exceed 200 °C.

Possible defects in Glare that have to be detected during inspections include surface cracks, sub-surface cracks and debonding. Flat-bottomed hole specimens were produced to simulate debonding at different positions in the laminate (see Fig.23). It was proven that debonds can be found in service, even in thick

Figure 21. 2024-T3 and Glare after simulated lightning strike tests.

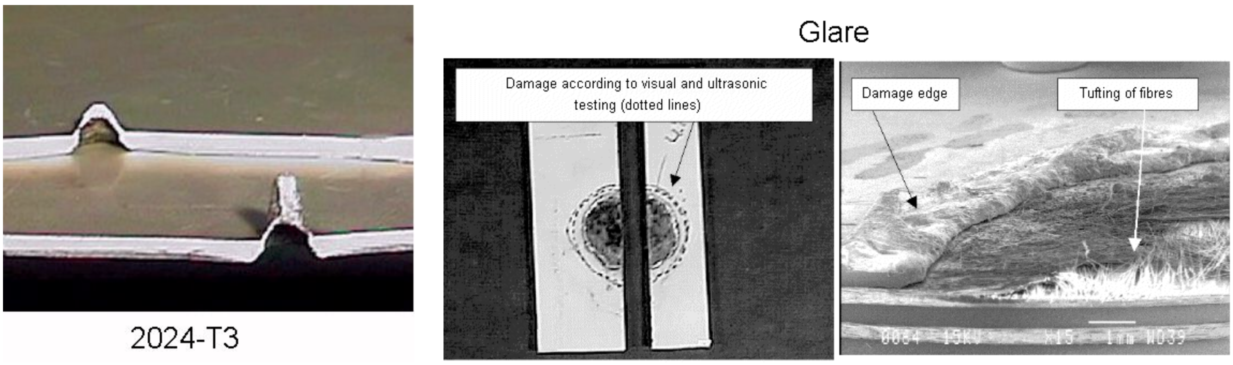


Figure 22. Test set-up for APU exhaust exposure tests of Glare panels.

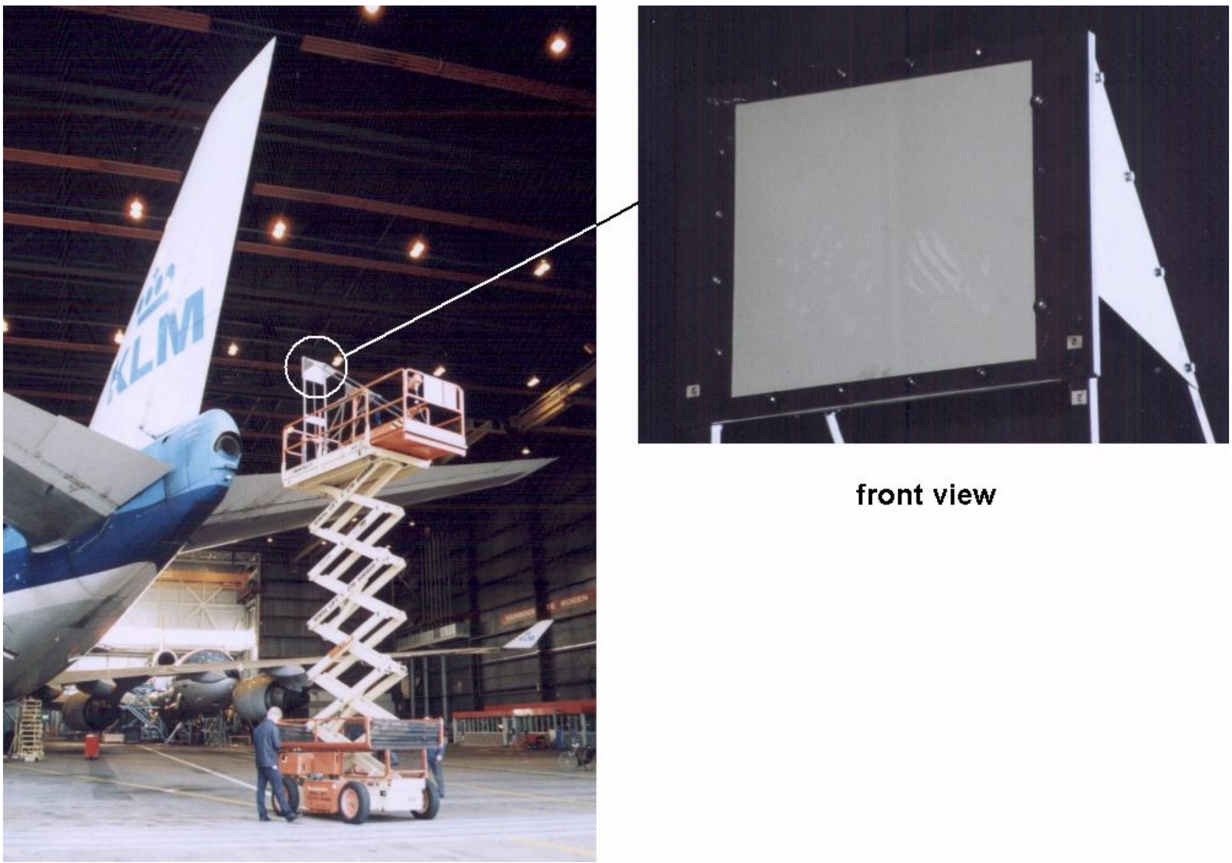
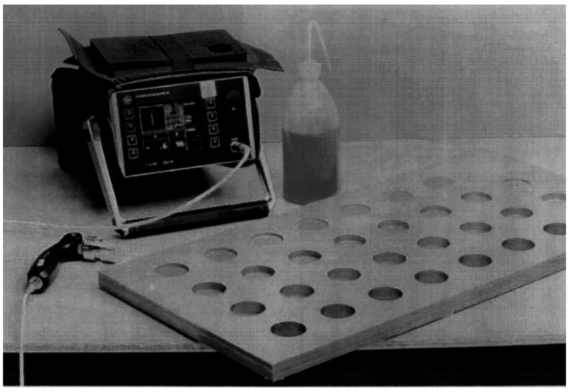


Figure 23. Fokker Bondtester equipment with flat-bottomed hole test panel.



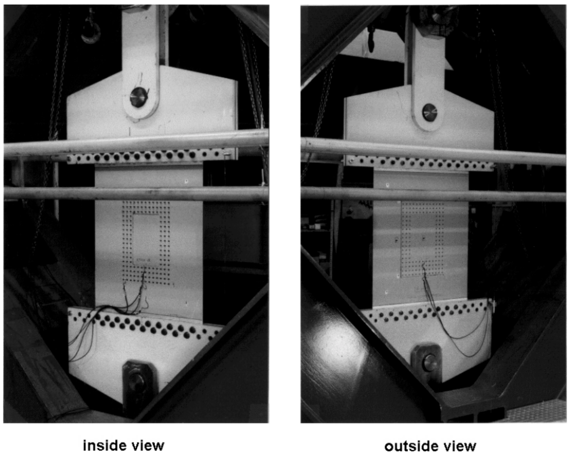
Glare lay-ups with standard inspection techniques. For the detection of surface cracks Eddy Current inspection and Magneto Optic Eddy Current Imaging were studied. Eddy Current inspection also proved suitable for tracing sub-surface cracks in Glare.

Possible corrosion of Glare, which is limited to the outer sheet, can be removed with the regular abrasives that are also used for aluminium structures. Also the use of conventional methods of paint strippers to remove the paint layer showed no risk of debonding of Glare or degradation of the bondlines of the splices.

Conventional repair techniques were applied to the repair of Glare panels with bonded stringers, e.g., drilling, cut-out of corners, cutting, grinding to remove lower stringer flanges, alodine application and riveting. It was proven that conventional repair methods can successfully be applied. Glare test panels were made with riveted repair patches made of both Glare and monolithic aluminium. These panels were subjected to a fatigue cycling simulating a period of up to three times the design life of a typical fuselage (see Fig.24). Only moderate reductions in strength were found. It was proven that Glare can be repaired with riveted aluminium patches.

It can well be expected that the evidence provided by this working group will help to ensure airline acceptance of Glare. No new investments for special tooling, inspection techniques or repair material are required.

Figure 24. Test set-up for fatigue testing of Glare panel with riveted repair.



8 Conclusion

The gap between laboratory testing and application, production and use of fibre reinforced bonded laminated metallic structures was filled up to a large extent by the Glare Development Program. A wide range of properties was covered and the upscaling of the production of the laminate was successful.