APPLICATION OF FIBRE METAL LAMINATES TO AIRCRAFT STRUCTURES

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OVERVIEW

The application of fibre metal laminates to the A380 marks the mayor milestone after a ten years taking research and development phase. This article gives an overview how this class of materials has been introduced in service. It covers aspects on the material qualification and the assessment of material parameters for the different combinations of the material. Based on the fuselage's design requirements global and local sizing methods are described. Its implementation into the sizing process is shown with some comparison to designing of metal structures. Some detailed design issues are addressed and their solution is shown especially in the light of design optimisation. The article is completed with an outlook on future development possibilities based on improvement of the material's constituents and new design principles.

1. FIBRE METAL LAMINATES

The design of the Airbus A380 has led to many innovations. One of those is the application of so-called fibre metal laminates to aircraft structures. Fibre metal laminates consist of thin aluminium layers (AL 2024) that are bonded by fibre reinforced prepregs, FIG 1. Dependent on the material of the fibre different types of fibre metal laminates can be distinguished. When aramid fibres are used the material is called ARALL™. Actually applied in the Airbus A380 is the material GLARE® with glass fibre reinforced aluminium sheets. Other applications currently use so called Titan-Graphite Laminates with titan layers instead of aluminium layers.

FIG 1. Photo of aluminium layers (green) and prepreg layers (white) of a fibre metal laminate.

It is the basic idea of fibre metal laminates that cracks occurring in metal sheets will be bridged by the fibres of the prepreg layers. If the fibre direction coincides with the main loading direction crack propagation is significantly lower compared to homogeneous metallic materials. This principle is shown schematically in FIG 2. Either the growth of an accidental damage that penetrates through the whole thickness of the material is significantly decelerated when the crack reached the zone with intact fibres [1]. Or fatigue damage which occurs at the surface or within the layers is decelerated by crack bridging fibres. In FIG 3 a photo shows this effect, that is combined with a plastic zone of the metallic sheets at the crack tip [8].

The comparison of the crack propagation between aluminium and GLARE® is outlined in FIG 4. It is shown that GLARE® can take between three to four times more load cycles to reach the same crack length as aluminium could.

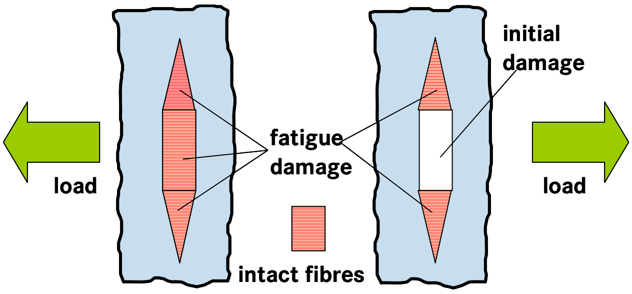

FIG 2. Sketch of the basic principle of fibre metal laminates, with fibres bridging a possible crack and assuring load transfer cross the crack.

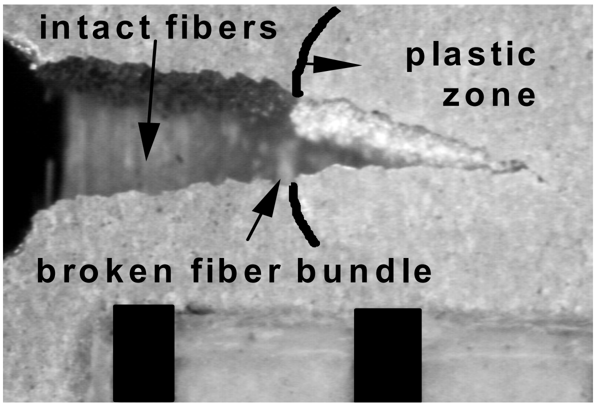

FIG 3. Principle idea of fibre metal laminates

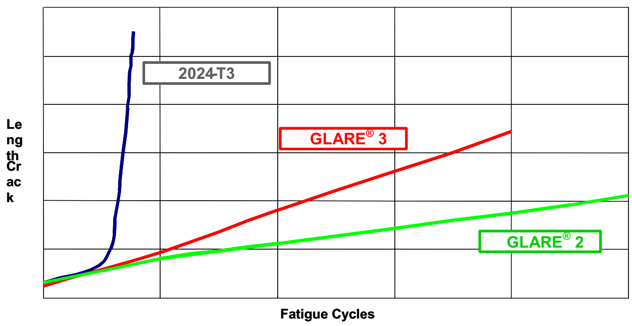

FIG 4. Comparison of the crack propagation between aluminium 2024 and GLARE®

Or at a give number of load cycles the crack length in aluminium would lead to fatal damage while GLARE® could still take the loading.

Originally the development of fibre metal laminates has started with the material ARALL™. However, this material has shown fast crack propagation with high cycles fatigue loading. This has been caused by the poor load transfer between resin and aramid fibres. As result the fibre type has changed to glass fibres for which this deficiency has been solved. This new material is called GLARE®.

Next to the superior fatigue characteristics other advantages have been found:

- Less maintenance efforts due to slow crack propagation
- Repair methods similar to those applied for aluminium structures
- Production of integrated structures possible within one autoclave step
- Tailoring of the materials to structural/loading needs
- Superior burn through characteristics compared to homogeneous aluminium or composite materials
- Superior impact behaviour with high impact energy
- Good lightning strike characteristics
- Highly damage tolerant
- 10% lower density compared to aluminium
- Good corrosion characteristics

Unfortunately, some drawbacks occur for GLARE® which influence the sizing and the design of the fuselage:

- Temperature dependent material characteristics with a degradation of material characteristics at high temperatures
- Lower stiffness compared to aluminium leads to load redistribution
- Possible delaminations at production and assembly
- Free edges sensible to damages
- Open hole strength lower compared to aluminium
- Higher material costs

As examples the penetration by corrosion is shown in FIG 5. For GLARE®, corrosion penetrates on the (mostly the outer) aluminium layer only. It is retarded by the prepreg layer and will not penetrate through the whole thickness of the material. In contrast monolithic aluminium will be penetrated over the whole thickness by corrosion. The crack or even hole that is created by this penetrated will significantly reduce the structural integrity of the aluminium structure. Next to this, the comparison of impact energy between composite, aluminium and GLARE® is shown in FIG 6. It can be concluded that

FIG 5. Comparison of corrosion penetration in GLARE® (left) and aluminium (right)

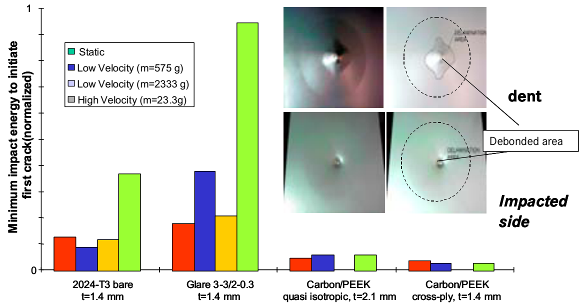

FIG 6. Comparison of impact energy for different materials

GLARE® absorbs much higher energy for similar damages compared to aluminium or composites.

As mentioned, it is the possibility of GLARE® to tailor the material according to the structural needs. As design parameters the number of layers, the thickness of the aluminium layers, the thickness of the prepreg layers and the fibre orientation in the prepreg layers can be varied. Typically five different types of GLARE® are known; GLARE®2, GLARE®3, GLARE®4 (a and b) , GLARE®5 and GLARE®6. These types vary in the number and orientation of the prepreg layers between the aluminium layers. The fibre orientation of the prepreg layers in measured relatively to the rolling direction of the aluminium sheets. GLARE®2 is composed of two prepreg layers between the aluminium layers. Both fibre directions are oriented into the 0 degree direction, denoted as 0/0. Also GLARE®3 is composed of two prepreg layers. However, the fibres of one layer are oriented into 0 degree and the fibres of the other layer are oriented perpendicular into the 90 degree direction, denoted as 0/90. GLARE®4 is made of three prepreg layers between two aluminium layers. Two of the prepreg layers are oriented into the 0 degree orientation and one into the 90 degree orientation, denoted as 0/90/0. This material is named GLARE®4a. If the fibre orientation is changed into a 90/0/90 combination the material is called GLARE®4b. GLARE®5 is composed of four prepreg layers between two aluminium layers. They are either oriented as 0/90/90/0 or 90/0/0/90 and are called GLARE®5a or GLARE®5b, respectively. Finally, GLARE®6 is composed like GLARE®3 of two prepreg layers. However, the fibre orientation is +45/-45 degrees.

The thickness of the aluminium layers is either 0,2[mm], 0,3[mm], 0,4[mm] or in some cases 0,5[mm]. In most applications the number of aluminium layers ranges between three and six. Based on this a certain nomenclature has be derived to describe GLARE®. As example a GLARE®4a-4/3-[0,4/0,3/0,3/0,4] describes GLARE® with four aluminium layers. The outer aluminium layer has a thickness of 0,4[mm], the following two layers have a thickness of 0,3[mm] and the last one a thickness of 0,4[mm] again. Between the four aluminium layers we find three combinations of prepreg layers. For GLARE®4a each of these combinations consists of three individual prepreg layers that are oriented into 0/90/0-direction. The different grades of GLARE® are collected in TAB 1.

Grade	No. of prepreg layers	Direction of fibres	Design feature
GLARE®2A	2	0° / 0°	uniaxialx-loads
GLARE®2B	2	90° / 90°	uniaxialy-loads
GLARE®3	2	0° / 90°	biaxial xyloads
GLARE®4A	3	0° / 90° / 0°	biaxial loads with main componentin x axis
GLARE®4B	3	90° / 0° / 90°	biaxial loads with main componentin y axis
GLARE®5	4	0° / 90° / 90° / 0°	high biaxial xy-loads, high impact resistance
GLARE®6	2	+ 45° / - 45°	shear loads

TAB 1. Collection of different GLARE® types that are currently applied.

2. OVERALL FUSELAGE DESIGN

The material selection of the fuselage material is a strategic decision for which several technical aspects and criteria classes must be taken into consideration. Focussing on the technical criteria, these are the load distribution and the load density, the temperature and the environment and its impact on strength and on stiffness, production methods and capabilities, fatigues loading, fracture toughness and residual strength of the materials and the impact of corrosion.

FIG 7. Design parameters for the fuselage design

To prepare the materials selection of the Airbus A380 numerous studies have been carried out. Some of these are displayed in FIG 8, [3]. In these studies different material scenarios have been investigated. These scenarios were heavily impacted by the results that were derived from a test program that was carried out in parallel to the design studies. The test findings led to iterations in the material selection due to different findings. This test campaign has covered basic material tests for the determination of basic material parameter, over to subcomponent tests and compression/shear panels. Prior to the design of the A380 several full barrel test, FIG 9, have been carried out in which different material combinations and design feature were intensively assessed and compared [9]. The test campaign has delivered the input for the different sizing criteria that determine the dimensions (e.g. thickness of the skin and stringer).

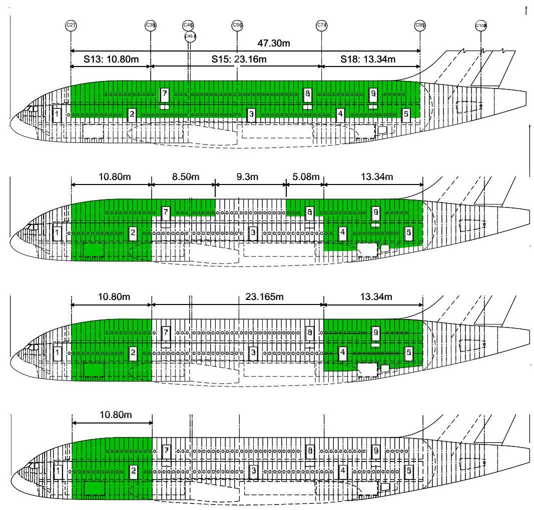

FIG 8. Different scenarios for the application of GLARE® to the A380 fuselage.

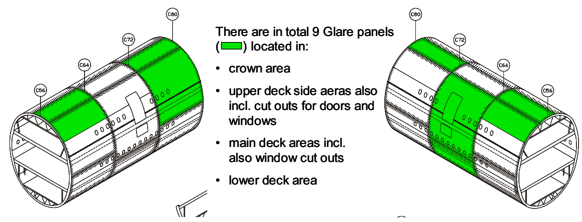

FIG 9. GLARE® panels in the mega liner barrel

The sizing methods cover a wide range of different analysis and failure criteria that are taken into account for sizing:

- Buckling analysis
- Panel analysis (Compression/Shear)
- Blunt notch analysis
- Tension analysis
- Fatigue analysis
- Residual strength and damage tolerance analysis
- Yield and ultimate analysis
- Bearing analysis
- Circumferential buckling analysis
- Shear analysis

Overall more than twenty-five sizing criteria are addressed.

The loads analysis is carried out taking into account several load cases. They range from ground load cases over manoeuvre load cases, internal pressure, gust loads, fatigue and aero-elastics and special failure load cases.

Based on the geometrical conditions and especially of the lofting of the fuselage the finite element model of the A380 is created. As basic element serve shell elements representing the skin, beam elements representing the frames and rod elements representing the stringers of the fuselage. A sketch of the finite element discretisation is shown in, FIG 11. The finite element discretisation leads to the overall mesh of the fuselage and the aircraft that is shown in FIG 13. The finite element description of GLARE® is based on an orthotropic shell applying a classical laminate theory. When certifying the structure this approach must find its equivalent in the qualification process for the structural element in which these GLARE® grades are applied. A similar line of reasoning required a significant change in the justification procedure that is carried out as a very extensive post-processing step after the finite element calculation. This post-processing is based on the analytical and half-analytical description of the skin-stringer combinations and of the skin-frame combinations. For isotropic materials a lot of sizing methods have been derived. A huge collection can be found e.g. Euler-Johnson, and Kuhns method and are collected by Niu and Bruhn, [4],[1]. In FIG 13 a typical compression-shear diagram is shown.

For sizing, the range of the application of these methods must be extended to Fibre Metal Laminates for which their orthotropic character and temperature dependency must be taken into account. In particular, the stress-strain relation can be setup according to the method by Verolme [4] in which the direction dependent stress-strain relation can be accounted for by the application of the different material parameters. At Airbus Hamburg a highly specialised software is applied to carry out the stress analysis and the post processing of the finite element results. This software ISSY has been developed over the last twenty years and summarised the experience of fuselage sizing.

Resulting from the loading a typical distribution of the bending moment is shown in FIG 10. In the rear fuselage the bending moment is much higher than in the forward fuselage. Consequently, the longitudinal tension forces in the rear fuselage and thus the fatigue loading is higher in the depicted rear components. In contrast compression loading due to breaking and landing cases dominated the forward fuselage. Since this is also the dominating load case for the lower fuselage welded aluminium shells have been selected for the lower shells. The final material selection for the fuselage is shown in FIG 15.

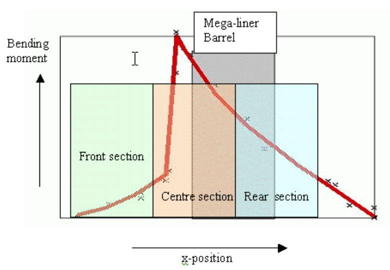

FIG 10. Bending moment

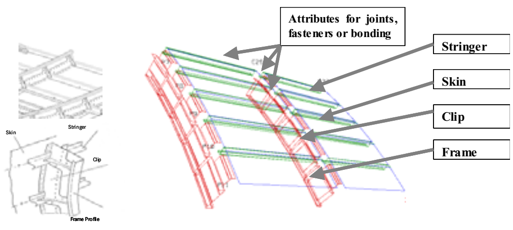

FIG 11. Principle sketch of the finite element discretisation

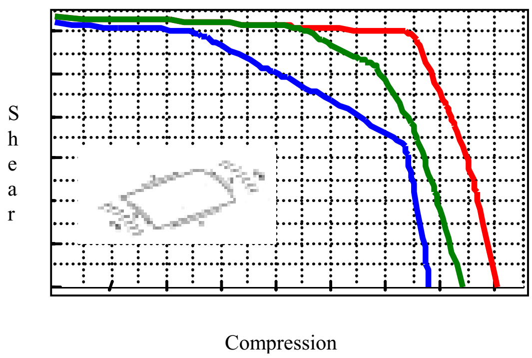

FIG 12. Typical stress-strain relation for combined compression shear loading

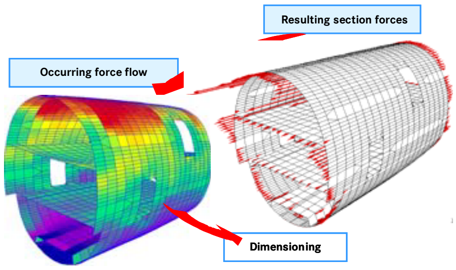

FIG 13. Typical stress-strain relation for combined compression shear loading.

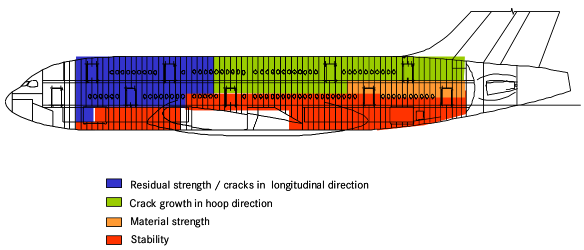

FIG 14. Schematic distribution of the dimension criteria. This picture does NOT reflect the real sizing criteria and is just a schematic sketch !

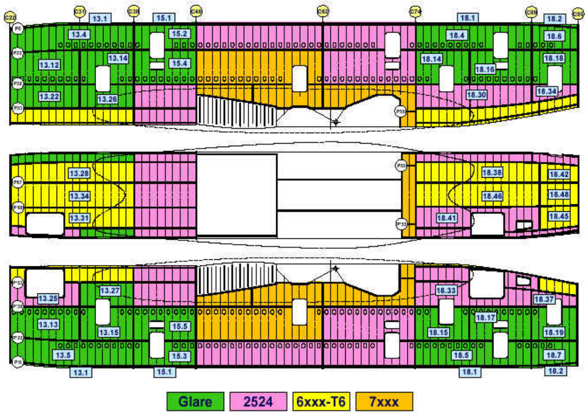

FIG 15. Final distribution of materials in the A380.

3. DETAILED DESIGN STUDIES

The selection of a GLARE® type does not necessarily mean that the skin has the same thicknesses and lay-up at all positions of the panel. At the boundary of the panel we find lap joints and butt joints. Load is transferred from one panel to another. Because of the riveting in these regions they are typically sensible to fatigue loading. Therefore, the thickness at the boundary is slightly higher than in the rest of the panel. With GLARE® this is accomplished with so-called interlaminar doublers. These doublers consist of one or more separate aluminium layers that are inserted into the lay-up of the material, FIG 17.

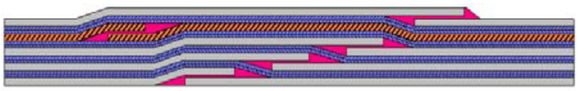

FIG 16. Schematic sketch of an interlaminar doubler combined with a splice

Another important feature of GLARE® is the so-called splice. Normally, the width of the panel is limited by the width of the aluminium layers. The smaller the aluminium layers the more lap joints are required and the heavier will be the structure. By overlapping the aluminium layer and bridging prepreg layers the width of the GLARE® panels can be significantly increased. By that the number of lap joints can be reduced and the weight of the structure can be reduced significantly. The principal idea of the splicing technique is shown in FIG 17.

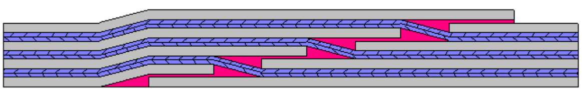

FIG 17. Schematic sketch of a splice in GLARE.

In some cases the transition from one type of GLARE® to another type of GLARE® may be required due to the design requirements. In these cases prepreg layers added or removed so that a switch from one type to the other type is achieved see FIG 18.

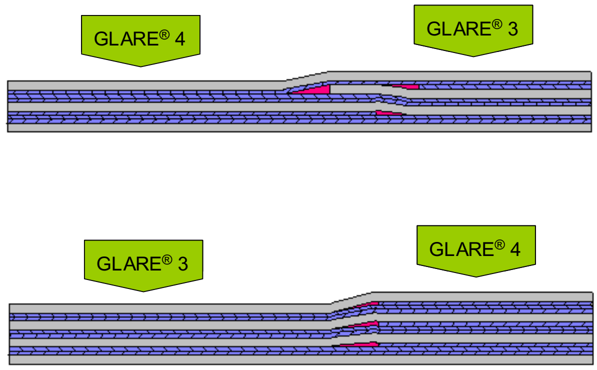

FIG 18. Schematic sketch of the transition from one GLARE® type to the other

In areas in which the hoop stress is the critical design parameter like the forward section that is less sensitive to manoeuvre loads but to the internal pressure or residual strength criteria, the combination of basic GLARE® with circumferential strap is a design feature that significantly reduces weight for the whole panel by reinforcing in areas where load carrying capacity is necessary. Since this type of GLARE® is an important design feature the GLARE® type with those reinforcement straps is called GLARE®3 improved, as depicted in FIG 19.

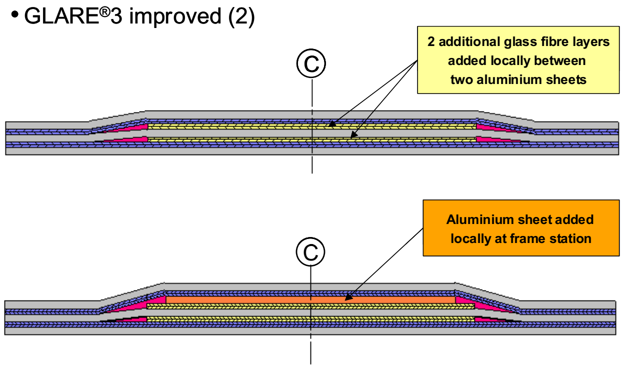

FIG 19. Schematic sketch of an interlaminar doubler combined with a splice.

Taking these design feature into account a typical lay-up of a GLARE® panel is shown in FIG 20. The yellow areas represent the splice areas. The green and the red areas are the butt joint areas. Special areas of the fuselage are all kinds of cut-outs like windows, doors, cargo doors or hatches. These design features disturb the load flow. This leads normally to an increase of the thickness in the surrounding of the cut-out. The number of interlaminar doublers that can be applied is limited. However, if the thickness required is not met with interlaminar doublers so-called internal doublers are applied. These internal doublers are separate parts that are produced like normal GLARE® sheets. In a second autoclave cycle these internal doublers are bonded to the panel in a second autoclave cycle. In general when designing GLARE® skins a continuous step from the basic thickness to the required thickness must be considered. A sketch of a GLARE® panel with a door surrounding is displayed in FIG 20.

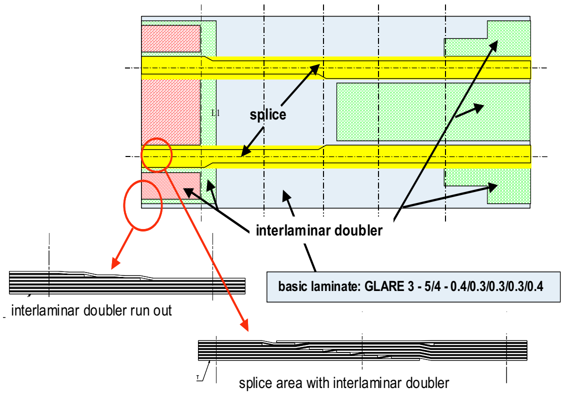

FIG 20. Schematic sketch of a GLARE® panel

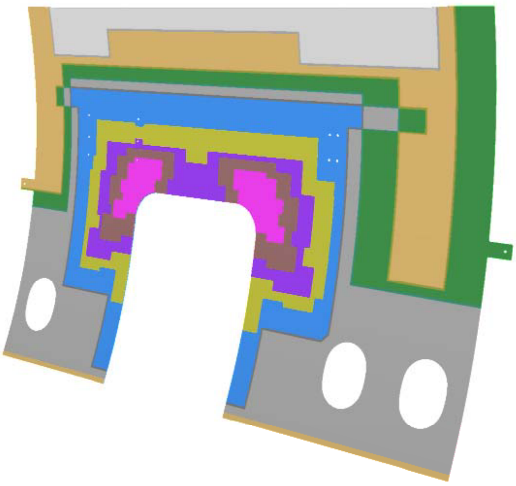

FIG 21. Schematic sketch of a GLARE® panel with interlaminar and internal double

Generally, the design process for GLARE® panels follows a certain methodology. First the basic GLARE® that best fits the global sizing requirement must be chosen. Then the splice area will be defined as well as the location of the interlaminar doublers. Since these design features lead to slightly varying thicknesses over the panel a harmonisation of the thickness will be applied. This thickness harmonisation shall avoid joggling of the supporting back-up structure like stringers and clips. As a special design step the location of rivets must be combined with the thickness steps. For this design special design rules have been derived during the materials qualification and testing phase. In the case that internal doublers are applied to the panel the process continues with the definition of the position of the internal doublers. For this definition the same design requirements apply especially when the position of the rivets are defined. In total the design process of a GLARE® panel is a highly iterative procedure.

When the definition of the panel is completed and has reached final maturity the definition dossier is composed. It consists of the 3D model in a CAD system. In this the digital mock-up, the machining of the contour, the drilling positions of the holes and the machining of the cut-out is defined. In the layer model the flattened aluminium sheets and the laser projection onto the sheet is stored. In the 2D drawing a general description of the panel is presented. Additionally, section drawings and a ply book are defined. Finally, the quality requirements sheet is defined.

4. MATERIAL QUALIFICATION/CERTIFICATION

For the introduction of a new material several requirements must be met. To shown compliance with these requirements the following topics must be studied in the qualification process:

- Material qualification process to assess the material parameter and their tolerances
- Material properties and design allowables
- Production process of GLARE® panels including their inspection process and quality control
- Proof of structure, maintenance and in-service inspection techniques
- Repair methods
- Assessment of the impact of lightning strike
- Fire resistance, fire, smoke and toxidity
- Corrosion resistance
- Emergency conditions for fuselages made of GLARE®

The legal framework of the qualification process is set in several top level requirements like FAR/JAR requirements. Formally, the qualification is a highly administrative process which leads to a high number of documents (more than 120 official documents) in which all results are formally stored.

The material properties of the raw material serve as basis for the definition of the material parameters. For designing and sizing several design allowables (e.g. yield strength, tension strength) must be defined. In this framework the so-called metal volume fraction method [7] has been derived to calculate the material design allowables of each GLARE® grade. The input for the calculation method is taken from the basic material parameters of the input constituents aluminium and prepreg. Additionally, to these basic design allowables blunt notch and bearing allowables are derived. These design allowable are partly taken from sub-component test and are described in a similar manner with the metal volume fraction method.

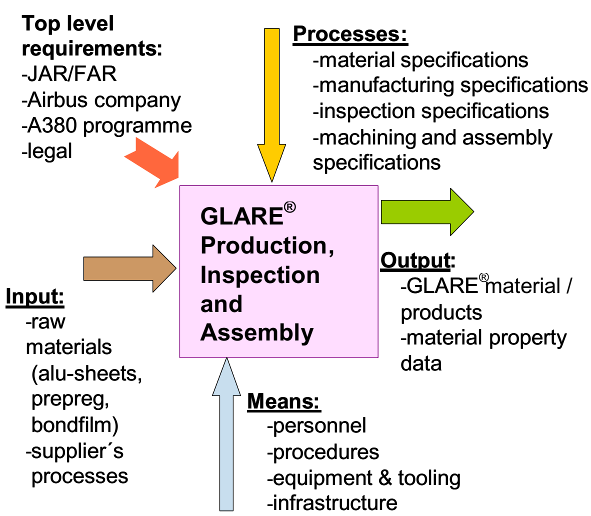

FIG 22. Parameters for material qualification, [3]

5. PRODUCTION PROCESS AND REPAIR

The production process consists of several steps. The aluminium coils are delivered and stored. In the first step they are decoiled and cutted up to the required length. In the next step the contour of the sheets is milled. Afterwards the aluminium sheets are stored in a frame and prepared for the chemical treatment of the aluminium sheets. The bonding primer is added in the following step. After chemical treatment and application of bonding primer the prepared coils are rolled up and stored. In the next step the lay-up is composed. For this the mould is filled with the aluminium coils and the prepreg layers, see FIG 23.

The mould with the lay-up is moved in the autoclave and cured at a temperature of 120°C and a pressure of approx. 10 bar. In the following the panel is inspected with a C-scan method. After accepting the panel the contour and the cut-out of the panel are milled. The production is completed with finishing possible small repairs and the application of alodine to the free edges of the panel.

Next to the many design aspects the customer requirements of the airline must be taken into account when a new material is applied. The repair methods and processes are an important issue for the airlines' acceptance of a new technology. Therefore, special care has been given to defining these repair techniques [4]. The big advantage of GLARE® is that similar if not the same repair methods can be applied as for monolithic aluminium structures. In FIG 24 the process steps of a repair is shown for a GLARE® panel.

FIG 23. Lay-up of a GLARE® panel.

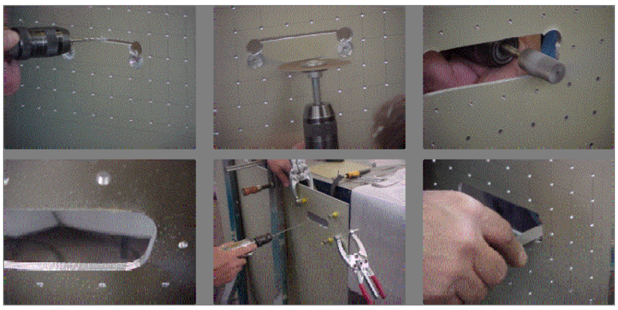

FIG 24. Repair of a GLARE® panel.

6. SUMMARY

The paper gives a short summary about the introduction of the fibre metal laminate GLARE® to the fuselage structure of the Airbus A380. It described the basic idea, advantages, drawbacks and outlines some design studies that have been carried out in the definition of the material. Some detailed design features are presented and the principle lay-up of GLARE® panels is described.

With the current application of GLARE® to the A380 a first step in the introduction of the technology has been reached. However, this technology is further improved. Instead of 2024 aluminium 7475 aluminium sheets are applied in areas with significant static loading requirement like side shells. Additionally, further design features like waffle plates are introduced. Furthermore, new aluminium sheets like aluminium lithium alloys are studied for a potential application. Also new prepreg material is studied for the application in GLARE®.

7. REFERENCES

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