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CONTROLLING THE DAMAGE WITH FIBER METAL LAMINATE STRUCTURES

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Abstract. *In order to extend the excellent safety record of civil transport aircraft on the one hand and to provide structural improvements on the other, Fiber Metal Laminates (FML) have been brought from laboratory to industrial status. This group of hybrid materials has some key features in common with monolithic alloys, i.e. the potentials to yield, to absorb energy, to oxidize, to fatigue and the electrical conductivity . These characteristic properties made it obvious to qualify and certify FML structures as metallic structures. The Metal Volume Fraction method as specified in MIL-HDBK-5 (metallic) has been validated for Standard-GLARE®, the material type applied in large quantity on the A380.*

However, the composite part of the hybrid, i.e. the fibers embedded in the resin film, have the important task to control any kind of damage on both, material and structural level – with other words to contribute to Damage Tolerance. The presence of the fiber- prepregs as joining medium for the metal sheets added some composite typical items to the metallic certification.

1 CERTIFICATION ASPECTS FOR FIBER METAL LAMINATE STRUCTURES

The invention from ARALL towards GLARE®[1] happened in the same period as the aeronautic community learned about the significance to control Multiple Site Damage Fatigue (MSD) because of the ALOHA incident[2]. It took a few more years until a manufacturing process has been developed, which made the production costs of FML panels attractive although the thin sheet width was (and is) limited to 1.5m. The introduction of "Standard-GLARE®", the FML- member which contains 2024T3 metal foils, combined the advantages of the high alloy ductility and fatigue resistance with the proven reliability of metal bonding under inclusion of a reinforcement, i.e. the glass fibers embedded in the resin. The structural development with FML's took benefit from the lessons learned of 55 years metallic jetliner operation, but with a special attention to the MSD phenomenon. The aim of Fiber Metal Laminate design is to extend the safety record of the metallic transport fleet, explicitly the concept of Continued Airworthiness according to JAR25.1529, and to provide performance improvements nevertheless. A long list of FML-topics has been discussed between the Airworthiness Authorities, Airbus and it's Dutch development partners from 1999 to 2003. A few of them will be discussed in this section.

1.1 Brittle or ductile ?

The question had to be answered whether GLARE® would behave as ductile as a monolithic aluminium in case of a dynamic impact under loading. Several indications have been present to expect a ductile behavior of the material in that particular case. First, the MVF in practical FML panels is always above 0.65, i.e. at minimum 65% of the hybrid consist of metal. Thus one may expect that the failure mode in case of a dynamic impact will be metal dominated. Thanks to the fibers supporting the metal, "Standard-GLARE®" has a significant capacity to transform energy into plastic deformation (see linear behavior in stress-strain diagram, figure 1, consider that the energy absorption capability is related to the area included by the curve). However, it has to be realized that the stress-strain curve is dealing with the ideal, non-damaged case. May be a better indication for the material ductility is the similar behavior of monolithic aluminium and FML's in case of residual strength experiments[3] (R-curve). In order to answer the a.m. question finally, Airbus performed harpoon tests with a series of stiffened Standard-GLARE® panels, which have been kept under maximum tensile fatigue load (of the A380 fuselage) when the sword impacted. Figure 2 shows one panel after impact from both sides. The aluminium sheets of the hybrid skin deformed and plastified, allowing no sharp notch to develop and the damage not to increase under load. Because the maximum possible impact energy lead to smaller damages than expected, some panels have been even impacted a second time at the same location in order to extend the damage. The physical behavior remained the same. Obviously FML's behave as ductile as the metal component in it.

1.2 Second load path material

The strength justification must distinguish between damage scenarios with broken fibers (e.g. impact) and damages where the fibers are not or just to a small fraction damaged. To the latter we count scratches, lightning strikes and scribe marks. These are surface damages which may or may not – depending on the damage depth – influence the fiber layers. In the fatigue case however, which is mainly linked to riveted joints, all fibers have to be intact until fatigue cracks in the aluminium layers will be detected and corrective actions can be taken. This design principle (of the material) has been verified for the FML types qualified at Airbus. The property provides that the second load path, i.e. the fibers, are present and that the residual strength of the structure can be predicted at any time. Fiber Metal Laminates are in itself a multiple load path structure, with the advantage that the fatigue approach can be integrated in the strength justification[4] (see figure 3).

1.3 Environmental considerations

Environmental topics for a FML type certification are linked to corrosion thermal exposure and potential effects of moisture absorption in the resin. The corrosion behavior of the hybrid is of course dependent on the applied metal. However, it is known that the corrosion extension in depth direction is stopped by the first fiber prepreg.

The evaluation of thermal influences on a metal/fiber hybrid requires more complex analysis than the corrosion task. Material properties and design allowables must be available for all static and fatigue cases. Especially the experimental investigation of realistic influences of thermal cycling on crack initiation and fatigue crack propagation is time consuming.

Experience from the composite community has been provided when the discussion started about realistic accelerated ageing. An process is in place to simulate the condition of a composite part at the end of the operational life of a commercial transport aircraft. The accelerated process is linked to in-service evaluations, i.e. it was investigated how deep moisture can penetrate into the thickness of a composite part during the aircraft life. The moisture absorption into the prepreg of a Fiber Metal Laminate is limited to the holes and cut-out edges, since the far field is protected by the outer aluminium layers. Although in the shortness of time for the A380 certification all required material properties and design values have been determined with the accelerated ageing procedure in place for composites, the question remained whether the composite approach wouldn't be too conservative for FML. Delft University started an extensive outdoor exposure program at the end of 1999, with Standard-GLARE® specimens being exposed in the tropic area of Queensland / Australia. The program includes both mechanic tests (after natural ageing) and moisture absorption measurements. Special specimen have been developed for this purpose, i.e. FML specimens with a high Fiber Volume Fraction, closed edges and drilled holes[4]. The specimens are painted in dark blue in order to attract temperature, which leads to high moisture absorption rates. Fortunately also specimen with paint but without holes are exposed, since it turned out that the chemical processes in the paint dominated the diffusion process during the first 12 month. Figure 4 is presenting the weight gain results for 57 month exposure. Specimens 8-1-P and 8-2-P indicate the diffusion behavior of the paint alone. Specimens 8-3-PH and 8-4-PH indicate the diffusion behavior of both the paint and the prepreg through the drilled holes. The seasons in Queensland can be easily identified. Obviously moisture is taken up by the prepreg during the wet season but it is diffusing out during the hot season. The absolute maximum moisture level in the GLARE® prepreg is significantly lower than obtained with the standard accelerated ageing process.

1.4 Special condition

The A380 fuselage including the Standard-GLARE® panels is certified under JAR25 without any special condition.

2 CONTROLLING THE DAMAGE ON MATERIAL LEVEL

The effectiveness of the crack bridging mechanism in Fiber Metal Laminates is dependent on the particular damage case, i.e. how far the fibers themselves are damaged as well. It is distinguished between fatigue cracks (just the alloy is damaged), through-the-thickness cracks and part-through-the-thickness cracks. The latter two conditions are related to accidental damages like scratches, scribe marks, dents and lightning strikes.

2.1 Riveted joints

As addressed in section 1, a main criterion for a FML is the rule “No fiber failure under fatigue conditions until the damage is detectable”. This criterion leads to an almost constant fatigue crack propagation rate for practical applications, which makes it easy to control. Numerous publications are available which deal with this fatigue topic. For the interested reader the authors will add a comparison of crack propagation rates of various materials under variable amplitude conditions (figure 5). It allows to calculate the demanded inspection intervals for the monolithic alloys, where as the GLARE® cracks do not even reach the detectable crack length within a multiple of an aircraft life.

Concerning both metal and FML riveted joints it shall be reminded on the local plastification effects for the ultimate strength justification. The load distribution in a three rivet row aluminium lap joint for instance is easily calculated because the outer rivet rows escape from the load after yielding and before failure all rivet rows carry the same load. This principle holds for FML’s as well, however, the ultimate load capability is driven by the fiber strength. Ultimate strength and residual strength can be easily predicted using the blunt notch material property.

2.2 Scratches and scribe marks

Surface damages like scratches are classified according to the number of effected layers. To be distinguished is whether and how much fiber layers are effected. Figure 6 shows two scratches in a GLARE® panel which both effect the first metal and the first prepreg layer. As indicated in figure 7, the residual strength is still larger/equal the blunt notch strength, which is a major design parameter. However, the damaged location must be protected against environmental influences. Fatigue investigations with damage scenarios as shown in figure 6 justify no damage growth for more than 300000 flights.

The blunt notch strength becomes a sizing parameter in case a riveted repair is required. Obviously the riveted repair, i.e. the presence of drilled holes, would decrease the residual strength of a GLARE® panel in some cases below the strength level of the to be repaired structure. For this reason the certification of a primary structural bonded repair is desired.

3.3 Dents

The robustness of a structure against impact may be specified as it’s sensitivity to demand an immediate repair or not. Important in this consensus is the capability of the structure to provide Large Damage Capability (LDC), which is further discussed in the next section. However, it has to be considered that small but significant damages do usually not effect the structural integrity of an aircraft, but it is nevertheless common sense to repair them soon. Reasons are such as noise (continuous airflow through hole in pressurised fuselage) potential environmental influences on the open structure and optical appearance. Figure 8 shows a severe dent in a GLARE3-2/1-.3 test panel, which provided more than the required ultimate strength. The advantage of Fiber Metal Laminates is the no- or very slow growth of damages according to figure 8.

For the establishment of SRM handbook data specific attention has to be paid to the relation between impacts evaluated with small test specimen and those on a real structure. Standardized impact tests provide a relatively rigid suspension, which results in relatively high local deformations and – above a certain energy level – to cracks in the non-impacted side aluminium layer. The associated delamination sizes between the aluminium layers are relatively small. In the aircraft structure, however, impact energy levels factor 3 to 6 higher than those applied on a coupon are necessary in order to get the same deformation. Cracks did never occur but the associated delaminations are larger than obtained with coupon tests. The reason for this behavior is the flexibility of the large aircraft structure which distributes the impact energy to a larger area than this is possible in a small coupon. A tentative SRM diagram for dents in GLARE® is provided in figure 9. It is taken advantage of the investigations which verified that delaminations in FML's do not grow under practical conditions.

3 CONTROLLING THE DAMAGE ON STRUCTURAL LEVEL

Saving weight in aircraft structures is usually a mix of two measures, i.e. the application of materials with lower density and increased the stress levels. In order to avoid that the increase of stress levels in contradiction with the demand to maintain/extend the safety level provided by the previous aircraft generations, it is required to design consequently for Large Damage Capability. Damages which may be present or even increase on/from small scale – let's take some bullet hits between stiffeners - must be controlled not just on the material level, but also on the larger, structural scale. It is talked at this point about the transition from "material properties" to "design values". The differential character of the laminated hybrids allow to design consequently for LDC by using the metal and prepreg lay-up's in the most suitable way (for safety and weight saving). An example is the local increase of Fiber Volume Fraction in order to turn a long crack for the sake of a controlled decompression in a pressurized fuselage. In a cylindrical fuselage large longitudinal cracks (representing any kind of large damage) tend to turn if the hoop to flight direction stress ratio of 2:1 because of the internal pressure changes towards the opposite in the vicinity of a stiffener. This behavior may not be present in a non-cylindrical fuselage, as the A380, where local loads due to frame bending are superposed with the internal pressure loads. Dedicated stiffness changes have to be designed into the fuselage skin panel in order to secure a crack turning or crack arrest capability. In FML's a large through-the-thickness crack can be forced to turn by increasing stiffness locally with additional fiber bundles. The principle is shown in figure 10, the design is designated "GLARE3improved" at Airbus. There is no design value cut-off level required for this design.

4 EXTENDING THE FIBER METAL LAMINATE FAMILY

Actual research for the extension of FML family members include hybrids composed with aluminium-lithium foils, aluminium magnesium scandium foils, different resin and fiber types. In any case the compositions have to be specified with care in order to maintain the certification envelope of material- and structural behavior as agreed with the Airworthiness Authorities for Standard-GLARE®. Aluminium-lithium foils, for instance, shall provide a measurable density advantage and similar material properties and design values relevant for sizing as obtained from Standard-GLARE®. Extensive screening investigations using 1441-FML's alloy are on the way, shared between Airbus and Dutch and Russian research partners. 1441 aluminium has been selected because it's density of 2,60 kg/dm^3. Good crack initiation and crack propagation properties have been reported, i.e. the weight saving potential may balance the costs. Some preliminary results are presented in the following. One demand to qualify as a FML is a fiber dominated tensile failure. If the stiffness and failure loads of both the metal and the fibers do not match, the final tensile failure may be metal driven, which means the fibers are not really the second load path any more. Figure 11 indicates the static tensile behavior of 1441-FML. It is known from Standard-GLARE® that the stress-strain curve ends at 4.5% strain because the S-glass fibers reach their ultimate strain[1]. Similar values are obtained with 1441-FML, obviously the requirement is fulfilled. A second property of importance on elementary level is the fatigue crack initiation life. Because of the curing stresses and the stiffness ratios between both metal and fiber prepreg, crack initiation lives in the aluminium layers of FML are significantly lower compared with monolithic aluminium of the same kind at similar gross stress levels. It is desired to decrease this property not further by selecting fatigue sensitive alloys. The results provided in figure 12 confirm the results known from monolithic aluminium, i.e. the crack initiation life in 1441-FML is not worse compared with Standard-GLARE®.

Particular properties have been investigated after 1000 hours artificial ageing of the 1441-FML, since the alloy is supposed to be not thermally stable. The expectations could be confirmed that the thermal sensitivity of the alloy plays has a negligible influence on the FML.

5 FIGURES

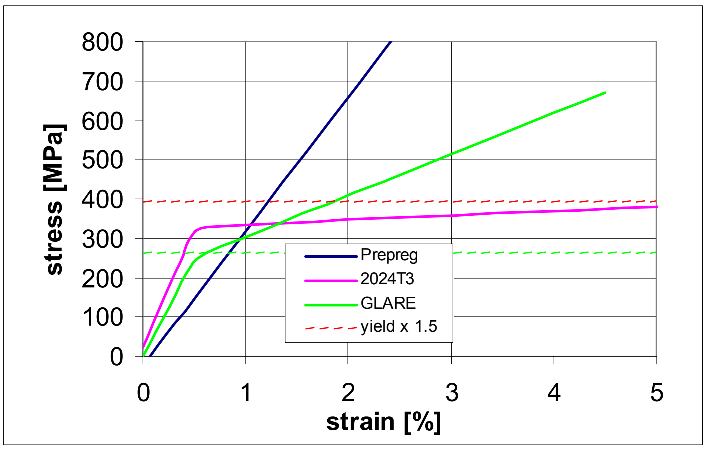

Figure 1: Stress-strain diagram Standard-GLARE

Figure 2: Standard-GLARE® panel impacted under tensile load

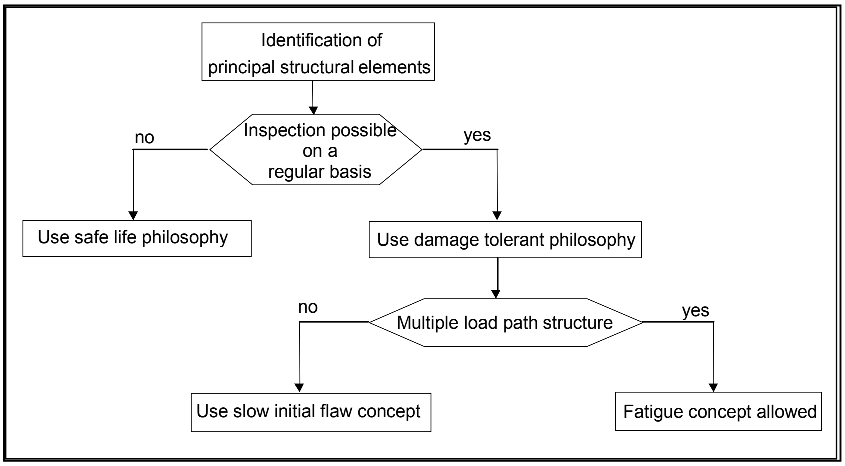

Figure 3: Applicable fatigue and damage tolerance philosophy

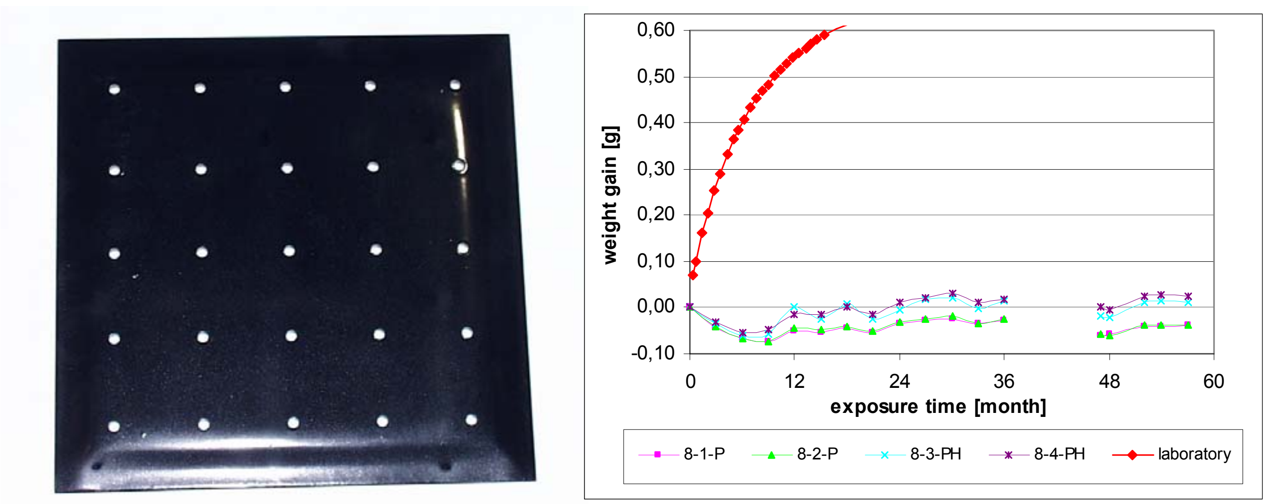

Figure 4: Outdoor weight gain specimens[4], painted (P) and painted and drilled (PH) specimen

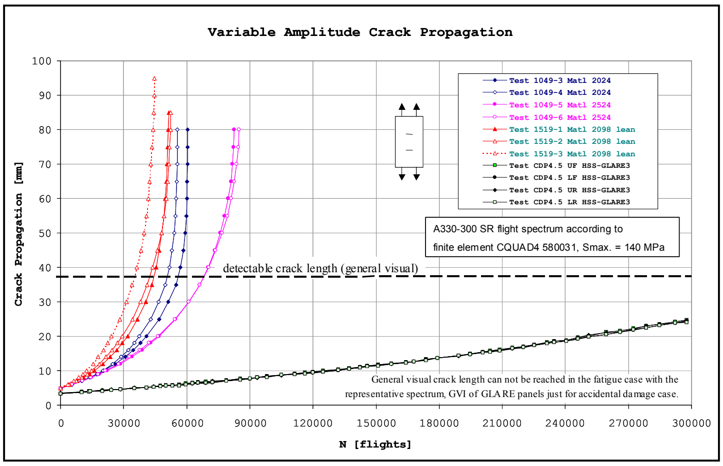

Figure 5: Fatigue crack propagation comparison

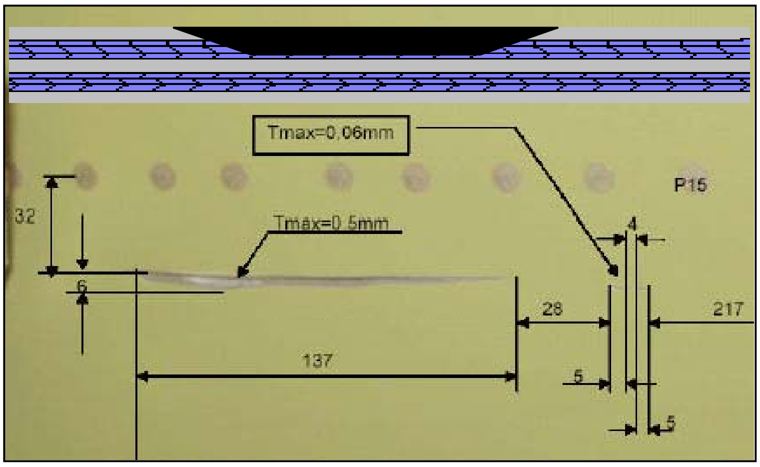

Figure 6: 0.5mm and 0.6mm scratch on GLARE® surface

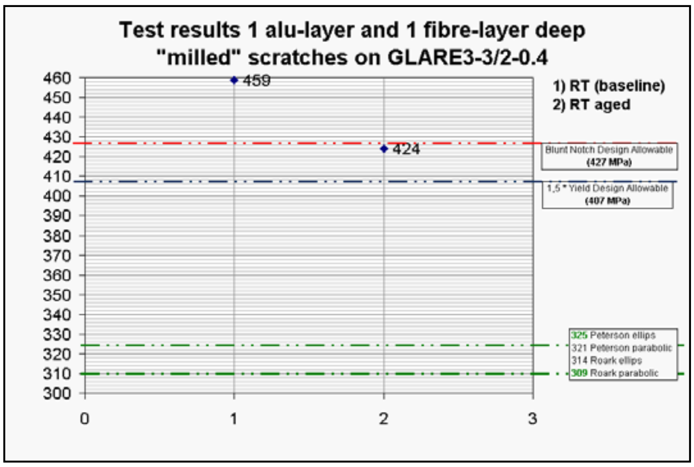

Figure 7: Tensile test results with scratches in Standard-GLARE3-3/2-.4

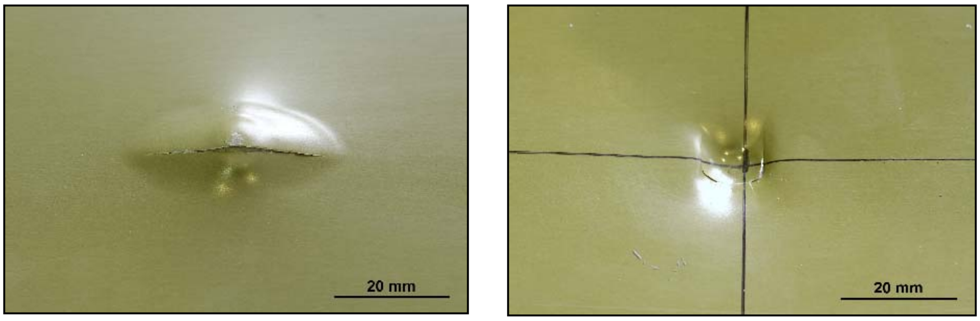

Figure 8: Impact damage on GLARE3-2/1-.3 panel, rear side (left) and impact side (right)

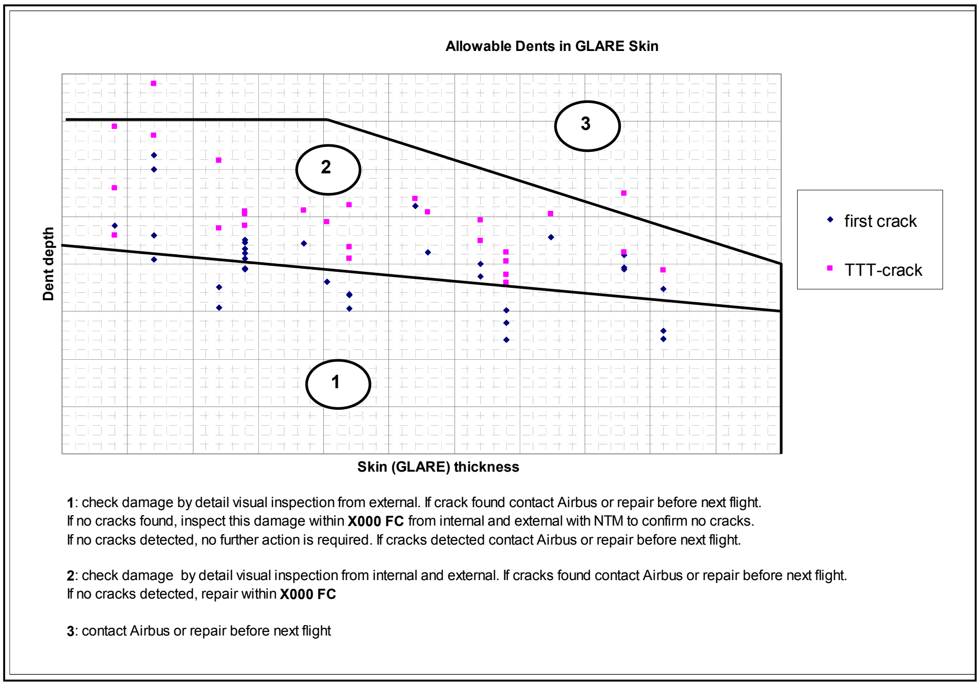

Figure 9: Tentative SRM dent diagram for GLARE® fuselage skin panels

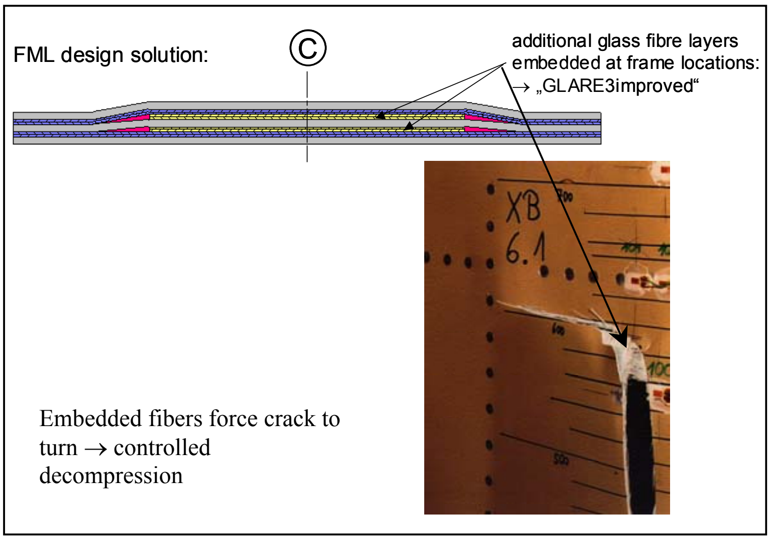

Figure 10

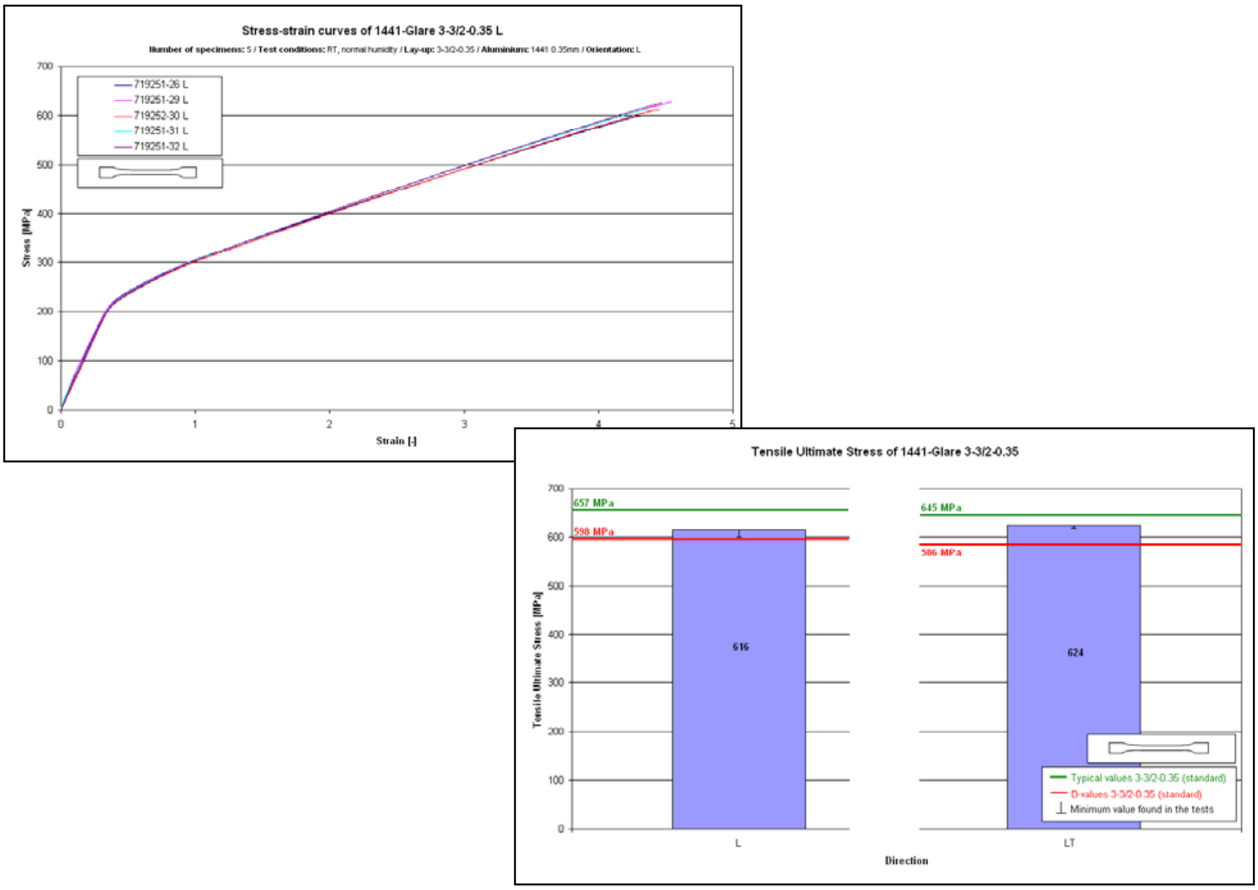

Figure 11: Stress-strain curves (left) and tensile ultimate results (right) for 1441-FML (source: TU Delft)

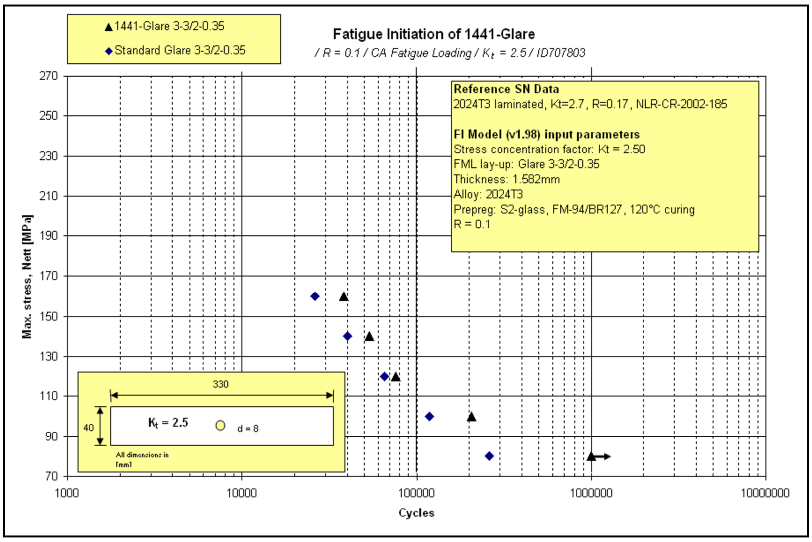

Figure 12: Fatigue crack initiation in Standard-GLARE and 1441-FML (source: TU Delft)

6 CONCLUSIONS

- Fiber Metal Laminates take advantage of the alloy capability to plastify. The embedded fibers allow to increase the failure stress.
- Damage Tolerance capability is provided by both, the material and the design. The Damage Tolerance feature on material level is the fiber acting as second load path. It controls the damage locally. On structural level Damage Tolerance and Large Damage Capability can be easily designed into the hybrid structure by local tailoring of both, metal foils and fiber prepregs.
- Standard-GLARE®, the member of the FML family composed of 2024T3 metal sheets and FM94/S-glass prepreg, has been qualified and certified for the A380 under FAR25, no Special Condition is required.
- Two FML types are qualified at this moment by Airbus in cooperation with Fokker. They are put into the basket of options for future applications together with monolithic aluminium alloys and various composite materials.
- Research continues to add laminates with new material compositions.

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