HOW THE HOLISTIC APPROACH FOR GLARE DEVELOPMENT STILL BRINGS BENEFITS

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Abstract: This paper presents the approach for the FAR26.21 Widespread Fatigue Damage (WFD) compliance demonstration for GLARE® skin panels of the A380-800. In 1999, Airbus decided to apply this Fibre Metal Laminate (FML) as a novel structural material for the fuselage skin panels of the A380-800. GLARE® is developed with the target to complement the advantages offered by metals, i.e. stability, ductility, isotropy, etc., with the high-strength properties of glass fibres. As a result, a multiple load path structural material is developed, which exhibits excellent damage tolerance and residual strength capabilities. WFD was covered in the F&DT calculations already for the Type Certification (TC). Several requirements, which drove the GLARE® development, resulted in a structure, which exhibits MSD scenario, but cannot lead to a critical WFD scenario.

Keywords: Widespread Fatigue Damage, GLARE®, Fibre Metal Laminates

INTRODUCTION

This paper presents how the holistic approach from the GLARE® development, simplified the FAR26.21 Widespread Fatigue Damage (WFD) compliance demonstration for the A380-800 GLARE® skin panels. In 1999, Airbus decided to apply this Fibre Metal Laminate (FML) as a novel structural material for the fuselage skin panels of the A380-800 (Figure 1). GLARE® is developed with the vision to combine the high-strength properties of glass fibres with the advantages offered by metals, i.e. stability, ductility, isotropy, etc. As a result, a structural material is developed, which exhibits excellent damage tolerance and residual strength capabilities.

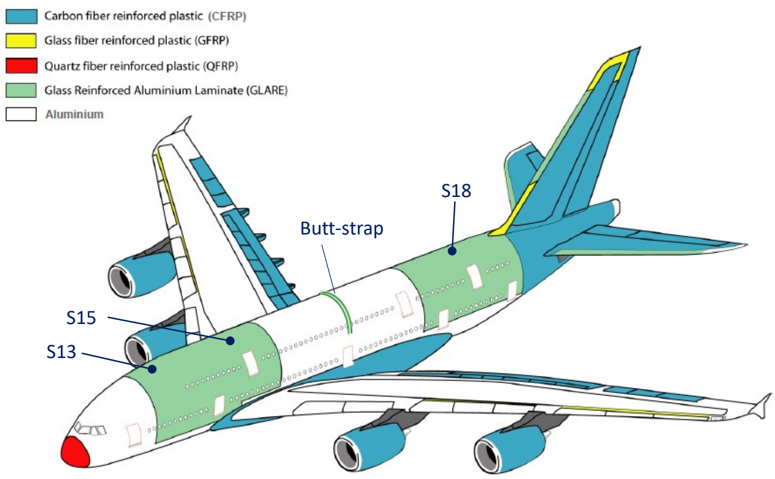

Figure 1, Application of GLARE® to the A380 fuselage

Figure 2 presents an overview of the FAR26.21 WFD compliance demonstration campaign for the A380 fuselage of Section 13, 15 Forward Upper Unit (FUU), S18 and the GLARE® butt-strap in S15, in which the GLARE® skin is applied. In these sections, GLARE® covers ~60% of the skin surface.

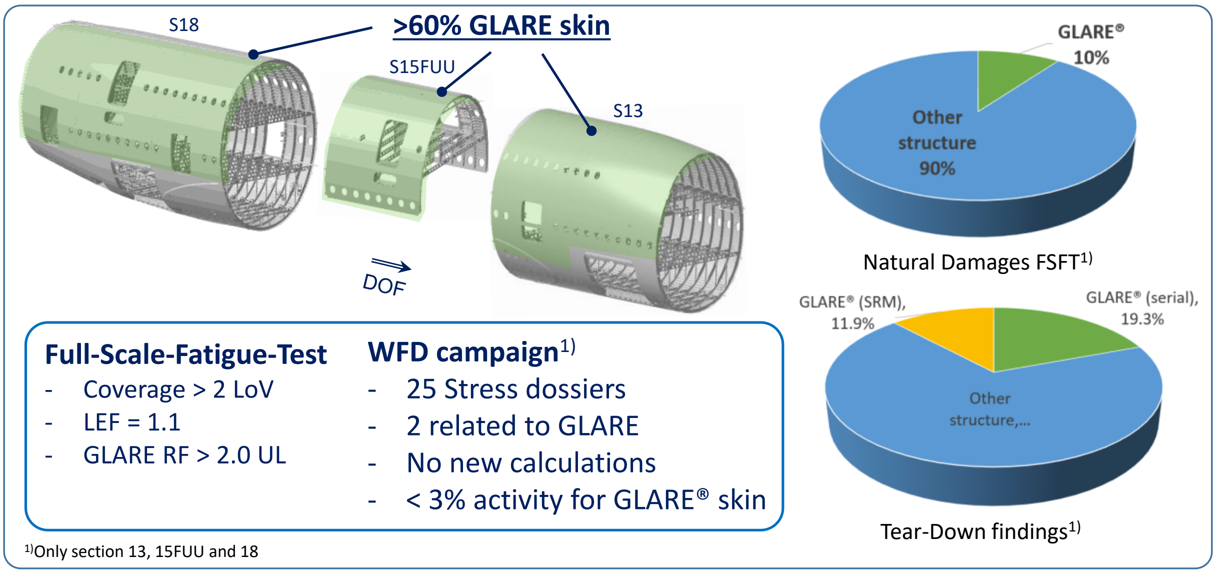

Figure 2, Dashboard WFD campaign for A380-800 Section 13, 15FUU and 18

The WFD scenario is a characterised by 2 phenomena, fatigue damage initiations at multiple locations simultaneously and these damages are not detectable during normal maintenance before a critical scenario occurs. WFD is separated in 2 damage scenarios, i.e. Multiple Side Damage (MSD) and Multi Element Damage (MED). MSD is the scenario where multiple damages occur in the same area of the same part, e.g. multiple cracks initiated in a fastener row of a lap-joint. MED is the scenario where multiple adjacent elements develop fatigue damages simultaneously, e.g. the failure of multiple frames in a row. This has the potential that multiple elements fail at the same time resulting in a catastrophic situation, before the damage can be detected during normal maintenance. Two prerequisites are needed for both scenarios: the design is similar, and the load at the different areas is similar.

For the scope of this paper only MSD is relevant, because the GLARE® parts are the fuselage skin. The fastener rows of the fuselage skin are typically assessed on occurrence of MSD, e.g. in the fastener rows of the longitudinal or orbital joint, or a repeating features with similar designs, like the pax window frames.

GLARE® DEVELOPMENT A HOLISTIC APPROACH

GLARE® is an FML, build up from Glass fibre layers and aluminium layers (Figure 3). FML's are developed from the vision to combine the high strength properties from fibres and the ductility of metals to create a material with superior damage tolerance behaviour. The driver is to solve at one side the un-preferred failure mode of composites, i.e. brittle failure and complex impact behaviour, and at the other side the potential fatigue failure in metals.

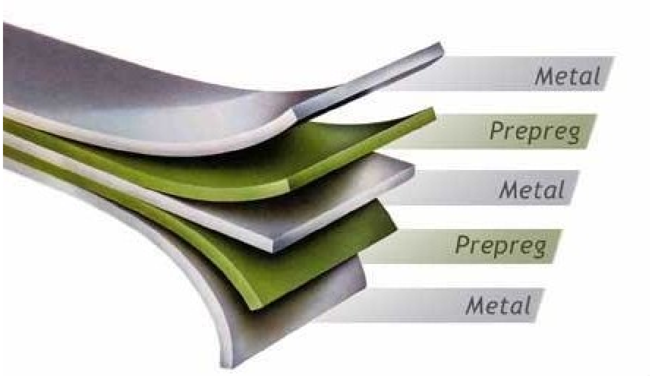

Figure 3, GLARE® laminate build up

During the development of FMLs always all requirements are kept in view, which are relevant for an aerospace application, i.e. structural, production, in service, certification, etc. As example, operational requirements, mean that the structure is inspectable and reparable with conventional methods.
Another example to simplify the certification, is the definition of 6 GLARE® types. By limiting the lay-up possibilities the test matrix is significantly reduced, which reduces the certification effort. From all considered requirements, the following 6 aspects are most relevant for this paper.

1: Fatigue crack initiation
2: Damage tolerance
3: Residual strength
4: Detectability of fatigue cracks
5: Multiple Side Damage (MSD)
6: Splice concept

<u>The fatigue behaviour of GLARE</u>
The fatigue crack initiation behaviour of GLARE® is reduced compared to monolithic aluminium structures. This is caused by 2 mechanisms:

1- Fatigue initiation occurs earlier in thin sheets than in thick sheets.
2- GLARE® exhibits tensile residual stress in the aluminium layer as a result of the manufacturing process. GLARE® is manufactured in an autoclave process, during which the material is heated to enable the bonding and curing process of the adhesive prepreg. Due to the different Coefficient of Thermal Expansion (CTE), tensile residual stresses exist in the metal layers at operational structural temperatures.

The reduced fatigue crack initiation behaviour is compensated by 2 effects:

1- The reduced fatigue initiation behaviour is compensated by the low propagation rates once a crack length of ~1.0 mm is exceeded.
2- The discrete layers prevent a crack to continue from one metal layer to the other metal layer (Figure 4). In general a crack starts at the metal surface layer, because of secondary bending effects. After that it takes a significant amount of time to initiate in the second aluminium layer. Moreover, the glass layer acts as a fence for the metal layers below, because it carries a significant part of the load from the cracked layer.

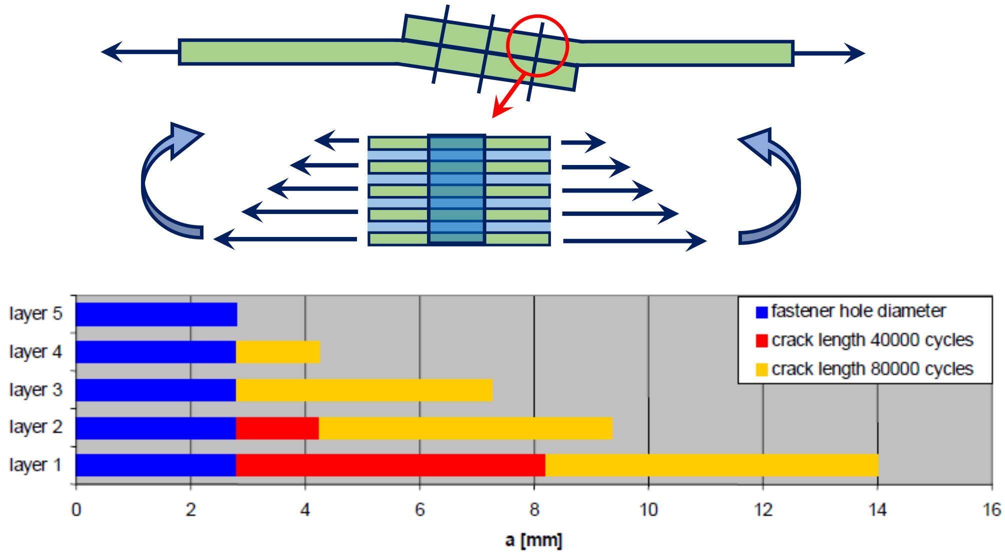

Figure 4, Crack growth through thickness example

<u>Damage tolerance behaviour</u>

GLARE® exhibits exceptional Damage Tolerance capabilities due to low and constant crack propagation rates [4]. This behaviour is a result of the fibres bridging the fatigue crack in the metal. This reduces the Stress Intensity Factor (SIF) at the crack tip, and prevents an exponential increase of the SIF as function of the crack length. The crack propagation rate remains low and constant up to ~90% of a full cracked part or critical crack length. It must be noted that in many cases the fully cracked part has still limit load capabilities by the glass fibres only.

<u>Residual strength capabilities</u>

As mentioned above, the bridging fibres result in a high residual strength capability. The fibres remain intact and bridge the metal damage in case of typical operational damage types, e.g. standard crack propagation scenario, impact damages, lightning strike and corrosion. This margin is so large, because on stiffened panel level, the high residual strength capabilities are driven by the worst-case damage scenario of a cracked skin over a broken frame, e.g. as a result of a fan-blade penetrating the fuselage after a Fan-blade-Off event. In such event both metal and fibres are broken, and the remaining structure must ensure limit load capability. As a result of this large damage capability requirement, a fatigue crack (all fibres intact) will never reach a critical crack length. All A380 GLARE® panels are designed to withstand the so-called “two-bay-crack” damage.

Scheduled fatigue inspections

It was an important design criterion for the A380 GLARE® structure to design riveted joints against ultimate load capability at DSG, with the dedicated reserve factors applied on the full scale test results. Practically, the validation of this criterion does not require any dedicated fatigue inspection of the riveted/bolted GLARE® structure.

Integration of MSD in F&DT analysis

WFD for GLARE is taken into account at the Type Certification (TC) of the A380 for GLARE®. WFD is included by performing a MSD scenario analysis for the calculation of fatigue crack initiation, and fatigue crack growth. This is performed using a Monte Carlo analysis. Consequently, the TC F&DT analyses already include the WFD scenario, which provides a robust baseline for the WFD compliance activity.

It must be reminded that at the TC of the A380, the FAR26.21 was under discussion, but not published yet. However, during the development of GLARE® it was recognised that WFD is a failure mechanism for aircraft structures, which cannot be ignored. By taking this requirement already into the TC analysis, a good foundation is created for WFD justifications performed after TC is created.

Splice concept

The width of thin aluminium sheets limits the size of the fuselage skin panels and thus increases the number of longitudinal joints required. To reduce manufacturing costs and weight, the splice concept is developed (Figure 5). The splice concept joins the different aluminium sheets together, whereas the glass fibre layers continue over the splice.

The longitudinal joints are prone to MSD. By substituting the riveted longitudinal joints by an integral splice of GLARE®, the MSD feature is removed.

Still the requirement exists to enable the installation of fasteners in the splice area. First, some stringers are installed by fasteners in the splice area. Secondly, in case of an in-service repair, the working party does not know the location of the splice, which could result in fasteners from the repair in the splice area.

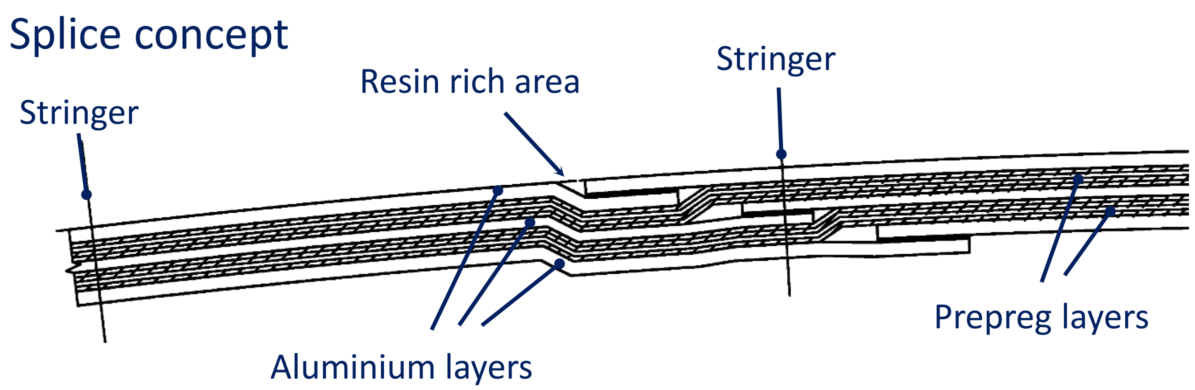

Figure 5, Example of a splice design

WFD COMPLIANCE APPROACH

To show compliance FAR26.21 (WFD) for all GLARE® parts, following steps are followed in accordance with the FAA Advisory Circular No 120-104 [3]:

- Select all WFD candidate structures
- Evaluate the WFD susceptibility for each candidate
    - Evaluate the stress mapping
    - Evaluate the damage findings in the Full-Scale-Fatigue-Test (FSFT)
    - Evaluate the Tear-down results from the FSFT
- Determine the Inspection Starting Point (ISP) for the WFD Susceptible areas;
    - Evaluate the TC analysis results
    - In case of FSFT findings, factorise the life based on the stress.
    - Compare the ISP with the Limit of Validity (LoV)
- Determine the Structural Modification Point (SMP) for areas with ISP < LoV
- Define the maintenance program for areas with ISP < LoV
- Define Modification Service Bulletin (MSB) if required
- Define the binding schedule for areas with SMP < LoV

WFD candidate selection

Seven WFD candidates related to the GLARE structure are selected:

- Orbital joints (skin & butt-strap)
- Longitudinal Joints
- Door surrounds
- Window surrounds
- GLARE® splices
- Pressure bulkhead – skin interface

These areas are selected based on the mandatory list provided by the Advisory Circular AD 120-104 [3] and the experience obtained from the FSFT.

RELEVANT TEST RESULTS

Many fatigue tests on GLARE® are performed in the test pyramid for the certification of the A380-800. The top of the test pyramid is an FSFT, which is performed on a complete fuselage structure. The test covered 60800 Simulated Flight cycles (SF), which covers over 2 times the Limit of Validity's (LoV), i.e. 28000 FC or 206300 FH. The structure was cyclic loaded by mechanical and pressure loads. A Load Enhancement Factor of LEF = 1.1 is applied to all loads. Consequently, the coverage of the DSG and LoV is significantly higher than the values provided above.

The fatigue loading phase was followed by a limit load campaign. Several limit load cases were applied to the full structure to demonstrate limit load capability after aged structure.

Artificial Damages (AD) are introduced in areas with critical loading conditions, or critical design features. These ADs are introduced from the beginning of the test, during the fatigue phase and before the limit load campaign.

During the fatigue phase of the FSFT, inspections were performed to monitor the health of the test specimen. From all findings in the A380 fuselage, only a very low % are related to the GLARE® skin.

After the test, the test specimen was dismantled and Tear-Down (TD) inspections are performed. Moreover, coupon specimens have been extracted from damaged areas, to confirm the residual strength.

Orbital joints
No damages were detected in the orbital joints during the fatigue phase of the FSFT. After the test more than 50% of the orbital joints were subjected to TD inspections. Only few cracks were detected, from which the largest crack only had a length of 7 mm (Figure 6). All cracks are located in the top area of the rear fuselage, which corresponds to the highest loaded area of the fuselage in longitudinal direction.

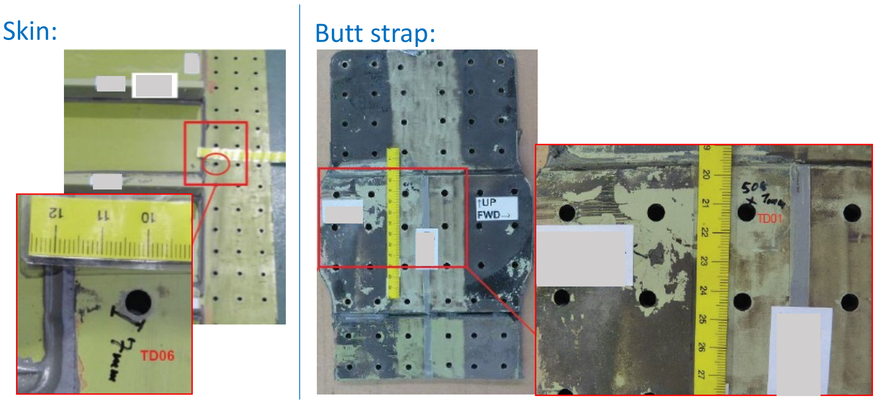

Figure 6, Crack finding in orbital joint

The residual strength test coupons were extracted from 9 different areas of the orbital joints. The selected areas cover all critical areas, including the highest loaded area in longitudinal direction at the top of the rear fuselage. The lowest measured reserve factor is RF = >1.5

Longitudinal Joints
No damages were detected in the longitudinal joints during the fatigue phase of the FSFT. More than ~90% of the longitudinal joints are inspected during TD. In total >100 cracks were detected, from which 95% exhibited a crack length below 3.0 mm. The longest crack detected is 16.0 mm (Figure 7). All cracks are surface cracks and no link-up is observed.

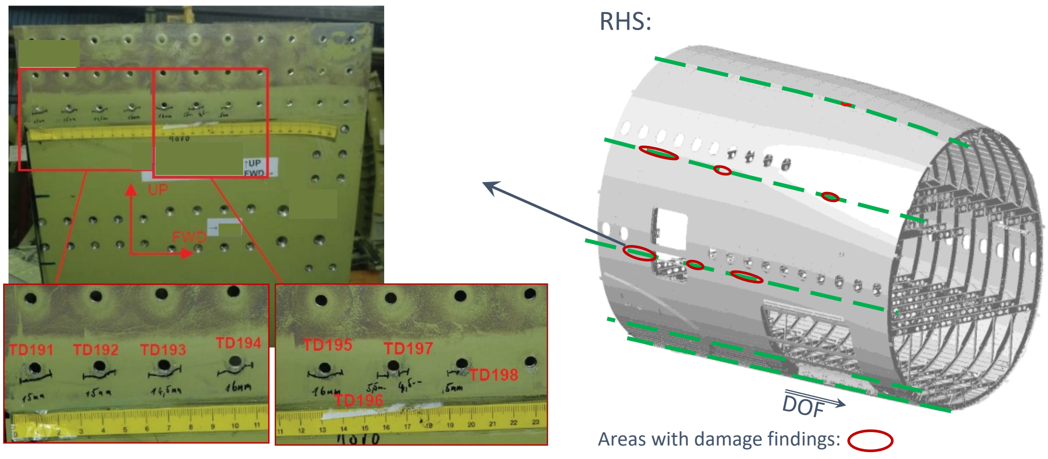

Figure 7, Example of crack findings in longitudinal joint

Residual strength test coupons were extracted from 7 different areas of the longitudinal joints. The selected areas cover all critical areas, including the area with longest detected cracks (Figure 7). The lowest test validated reserve factor is RF >1.5 against ultimate load.

Door surrounds

No damages were detected in the door surrounds during the fatigue phase of the FSFT. All door surrounds were subjected to TD inspections. This includes the skin below the door beam and door frames, the doublers and the back-up structure. In total >100 cracks were detected distributed over 10 doors (Figure 8). The cracks are located mainly below the door beam and at the door corners with high stress gradients. In general the group of cracks are situated around a limited amount of fasteners. The maximum detected crack length is 8.0 mm.

The crack propagation direction is perpendicular to the expected principle stress direction (Figure 8). Consequently, cracks growth parallel to each other in succeeding fasteners. Because of this behaviour, no link-up can occur between the cracks from different fasteners.

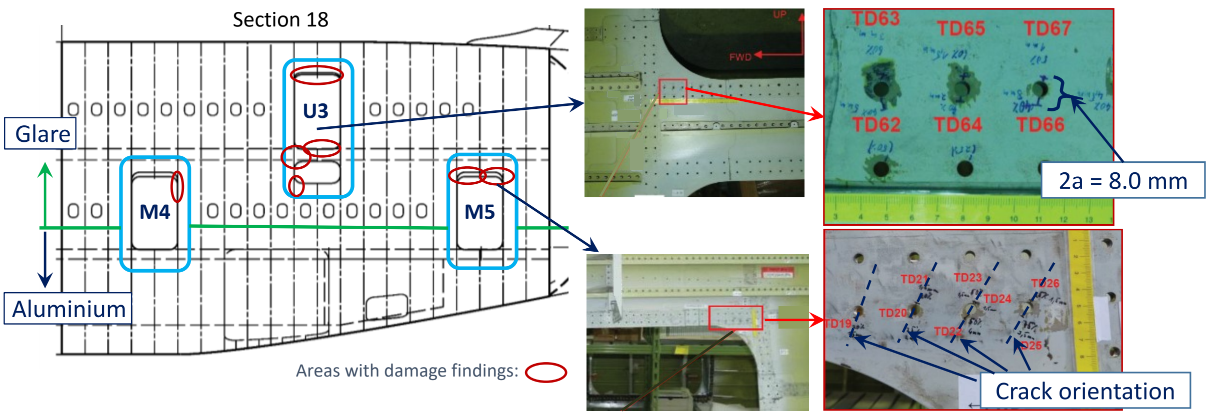

Figure 8, Example cracks at door surrounds

Passenger window surrounds

Only in the surrounding of 3 windows, damages were detected during the fatigue phase of the FSFT. These 3 windows are located below doors, and thus affected by the stress gradient around the door cut-out. Moreover, one window exhibited a cracked window frame, which was repaired earlier in the test. All damages were detected after 2/3rd of the FSFT fatigue phase. The longest crack length at the end of the test in the GLARE® skin is only 12 mm. Conservatively, the window frame situated at the window with the largest crack, is cut completely and the remaining structure sustained the complete limit load campaign well.

On 43 from 120 windows TD inspections are performed. several dozens of additional damages were detected at 3 window locations. These window locations correspond to the windows with damages detected during the fatigue phase or windows with artificial damages. The maximum detected crack length is 7.0 mm.

GLARE® splices

After 80% of the fatigue phase of the FSFT, several cracks in the resin rich area of the splices are detected (Figure 9). These resin cracks are situated between the run-out of the outer aluminium layer, and the resin rich layer of the splice. The cracks are detected on multiple locations of the same splice. The cracks propagate along run-out of the aluminium layer.

Residual strength test coupons are extracted from the splices with the largest damages. The coupon tests showed that the damages did not lead to knock-down in the load carrying capabilities of the skin. The lowest measured reserve factor is RF >1.5.

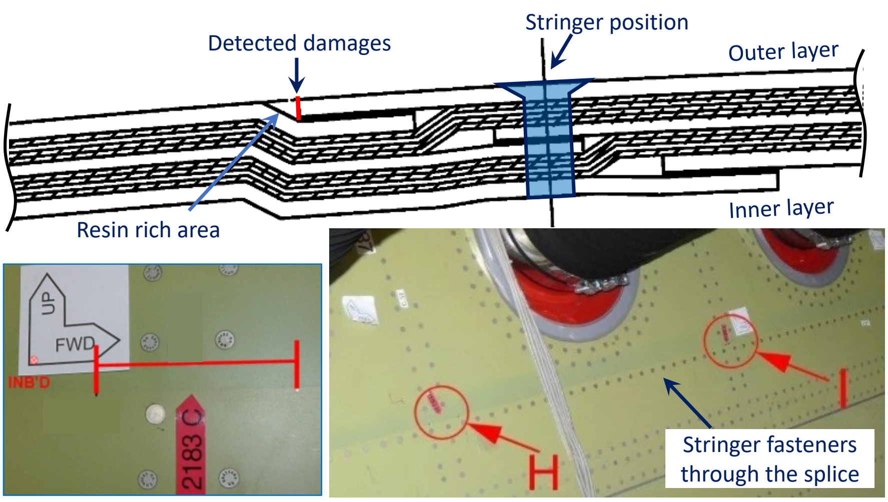

Figure 9, Examples of damages in the splice areas

<u>Pressure bulkhead – skin interface</u>

Surface cracks are detected during the fatigue phase of the FSFT at the stringer-frame intersections in the upper shell in front of the Rear Pressure Bulkhead (RPD) (Figure 10). The RPB is connected to the skin and stringers through struts. These struts are positioned every 2nd stringer. As a result, the skin is pulled inward at the strut locations, and pressed outside by the internal pressure in-between these positions. The resulting out of plane bending is the root cause of these damages. The damages are detected at 10 stringer positions. These damages were not repaired and sustained the limit load campaign very well.

During inspection of the damages, and in the TD inspections, ultrasonic inspection detected delamination's below the cracked areas. The delamination was arrested by the next fastener row.

The WFD analysis resulted in an ISP larger than LoV. Therefore, no inspection or modification is required for this area before LoV.

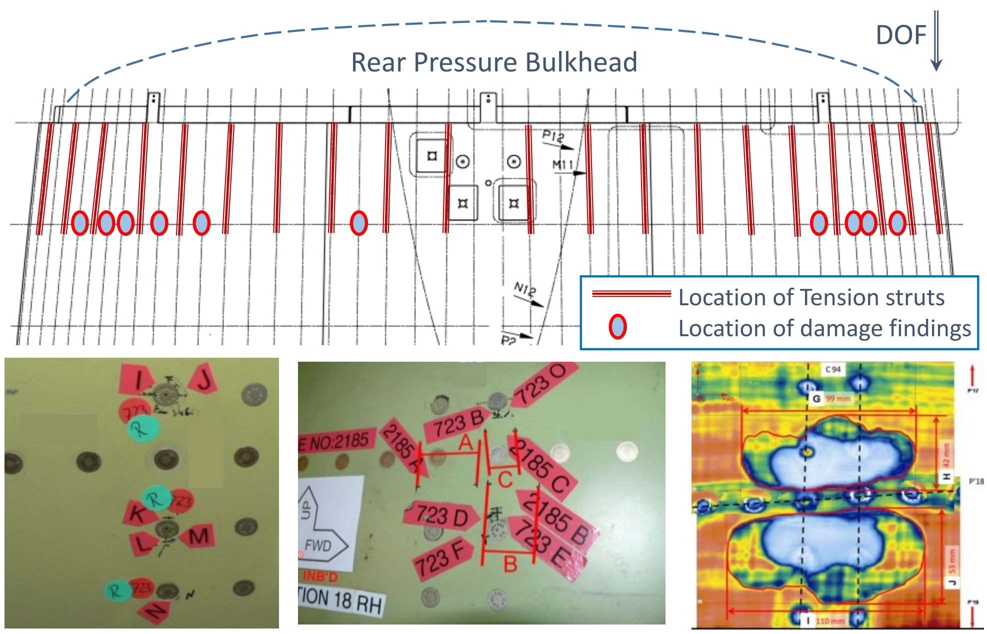

Figure 10, Example of damages at Pressure bulkhead – skin interface

WFD EVALUATION

Orbital joints (skin & butt-strap)
The TC F&DT analysis for the orbital joints is based on a Monte-Carlo analysis of 200 different MSD scenario's. The crack initiation result show that the orbital joint at rear frames exhibited the lowest initiation life. This correspond to the location where the (few) cracks are detected. The calculated damage tolerance life is infinite for all orbital joints, except one, which exhibits a DT life > 100 * DSG. Infinite life means that the fully cracked structure is able to carry limit load by the glass fibres only. Consequently, it is concluded that the orbital joints can develop MSD, but will never become critical.

Longitudinal Joints
The TC F&DT analysis for the Longitudinal joints is based on a Monte-Carlo analysis of 200 different MSD scenario's. All calculated DT life result for the longitudinal joints are infinite. Consequently, also the longitudinal joints have limit load capability in case of a fully cracked structure. The reserve factor from the coupon tests is significantly larger than UL, which confirms the high residual strength. Consequently, it is concluded that the orbital joints can develop MSD, but will never become critical for a WFD.

Door surrounds
The cracks detected in the door surround, exhibit a damage scenario where local link-up is not possible, i.e. all cracks propagate parallel (Figure 8). Consequently, it is concluded that the doors are not WFD susceptible, i.e. MSD cannot occur. Off course, the fatigue cracks can develop further, but that is covered by the standard F&DT analysis scenario of a single crack propagating form the door corner into the next frame bay. It is also excluded that a global MSD scenario can occur from damages from different doors. As GLARE® provides a constant crack growth and no crack tip interaction, it cannot happen that crack from different doors interfere and develop a critical crack length, before the cracks are detectable.

Window surrounds
Like the doors, the cracks detected at the window surrounds are propagating parallel from the different fastener holes. Therefore, no local MSD scenario can develop. No link-up with cracks from the neighbouring windows is possible, as the cracks develop from the same diagonal opposite corners for all windows in the same area, i.e. the crack propagation paths are parallel. The scenario of a crack propagation from the window is covered by the F&DT analysis performed at TC. Consequently, the windows are not WFD susceptible.

GLARE® splices
The damages in the GLARE® splice represent an MSD scenario. Because the resin cracks are between the aluminium layer run-out and the resin rich area, there is not detrimental effect on the strength capabilities (Figure 9).

The TC F&DT analysis of the splice is based on a splice with fasteners in the splice area. This analysis is based on a Monte-Carlo analysis of 200 different MSD scenarios. The resulting damage tolerance life is infinite, as the full cracked splice still exhibits limit load capability. This is supported by the tested residual strength. Consequently, it is concluded that the splices are WFD susceptible in the form of MSD, but not WFD critical.

Most small cracks are detected in the forward section instead of the rear fuselage sections. This is caused by a relative thin skin in the forward section. Consequently, secondary bending plays a larger role in the forward splices than in the rear fuselage splices.

Pressure bulkhead – skin interface

The root cause of the damage is related to the design of the rear pressure bulkhead connection to the skin (Figure 10). The out of plane deformations, result in significant local damages at several stringer positions. The ISP > LoV is calculated based on the FSFT damage findings. Therefore, no inspection or modification is required in frame of the WFD compliance demonstration.

This approach is conservative, because the damages, if any, will be detected in an early stage. For WFD, these damages will never result in a critical situation. Even without repair, the damages will never link-up and result in a critical WFD scenario before the damages are detected.

Overall result and conclusion

As a result of the WFD compliance campaign, no modifications or maintenance tasks are required

WFD SUSCEPTIBILITY OF GLARE®

GLARE® skin is susceptible to WFD, because the MSD scenario can occur. This is shown by the damage patterns in the longitudinal joints (Figure 7). However, the MSD scenario will never result in a critical situation of WFD. The design of GLARE® exhibits several characteristics, which provides an intrinsic not WFD critical skin material:

- Delayed initiation in adjacent metal layers
- Constant crack propagation rate without crack tip interaction (also in MSD scenario)
- Low crack propagation rate
- Large damage tolerance capability

Delayed crack initiation in adjacent metal layers

Due to the delayed fatigue crack initiation in lower metal layers, there is a significant time before the GLARE® part is fully cracked (Figure 4). Link up of cracks in the surface layer have therefore no significant detrimental effect. This behaviour is confirmed by the FSFT findings, because most cracks are only limited to the surface layer.
The effect described here occurs mainly in areas with secondary bending. For the skin structure, all critical areas exhibit secondary bending, i.e. lap joints, butt-strap joints, splices, skin to frame or stringer connections, etc.

Constant crack propagation rate without crack tip interaction

The effect of MSD scenario is that undetected cracks exhibit instable crack propagate, due to interaction between the cracks. This scenario is not possible, as the crack propagation rate is constant and will not become instable before 90% of the net section is fully cracked. Consequently, cracks are detectable by visual inspections, before any crack interaction can occur.

Low crack propagation rate

The low fatigue crack propagation rates lead to a long fatigue life before the cracks become detectable – as explained above in any case with ultimate load capability provided (F&DT design criterion). Therefore, the threshold inspection is beyond the DSG for potential riveted/bolted fatigue SSI's.

Significant residual strength capability

The residual strength test performed after the tear down of the FSFT specimen, show a significant high residual strength of the significantly damaged structure (>>1.0 UL). As mentioned earlier in this paper, the large damage capability resulted in a structure where a fully cracked GLARE® skin is still capable of Limit Load capability.

From the above evaluation it is concluded that the GLARE® skin is susceptible for an MSD scenario, but these cracks will never develop a critical WFD scenario.

HOW THE HOLISITC APPRAOCH GLARE® SUPPORTED THE WFD CAMPAIGN

The initial vision, to combine the strength of fibres and the ductility of metals is the baseline for many capabilities which are combined in GLARE®. The unique combination of fibres with aluminium layers, results in the slow and constant crack propagation, which gives GLARE® its superb damage tolerance performance, i.e. inspection intervals with good damage detectability.

Two characteristics highlight the how the holistic approach supported the WFD campaign for the A380-800:

- The MSD scenario as baseline for the TC F&DT analysis avoided the need to perform the MSD scenario for all joints in frame of the WFD campaign. Consequently, no new MSD calculations or fatigue calculations were necessary to show FAR26.21 WFD compliance.
- The limit load capability of a fully cracked structure, simplified the WFD campaign, as no area could develop undetected critical cracks, no matter how many damages are detected, limit load is always protected. Consequently, no inspections have to be defined, and no special procedures are required to detect the damages.

CONCLUSIONS

Following conclusions are highlighted from the previous paragraph:

- The holistic approach by taking all requirements into account from the beginning, i.e. manufacturing, costs, damage tolerance, reparability, etc, for a new material development, saves significant effort and costs later in the life of the program.
- GLARE® is WFD susceptible, as MSD can occur in the structure. But this MSD damage can never lead to a WFD critical scenario.
- By including the MSD scenario in the design principles, the F&DT TC analysis includes already the WFD criteria. Therefore, no additional analysis work was required for the WFD campaign.
- By applying all requirements to all design solutions, it is ensured that the whole structure exhibits same standard and no weaknesses are created.

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