CRACK BRIDGING EFFECT IN HYBRID REINFORCED FUSELAGE STRUCTURE

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Abstract: The A400M fuselage main frames at the wing-to-fuselage interface have the function of introducing the wing loads into the fuselage.
The loads that are introduced by the wing are pre-dominantly tension, which results in an in-plane bending moment in the frame due to their curved shape, especially on the rear wing attachment.
These fuselage frames are primarily sized by fatigue and damage tolerance requirements. In order to avoid heavy weight impact these frames have been reinforced by adhesively bonded GLARE® straps. The development of the design principles, using bonded reinforcements have been presented in the ICAF conference in 2009.
This paper now continues and closes this circle by presenting the outcome of the detailed analysis and test campaign that was done in frame of the development, comprising of component testing and full-scale fatigue testing. It outlines the different aspects of assessing a full-scale fatigue test result. A correlation is provided of this design with main focus on the crack bridging effect of the bonded GLARE® strap. Finally the initial assumptions are compared to the latest outcome confirming the crack bridging ability of the GLARE® reinforced frame.

Keywords: Fuselage frame, GLARE®, crack growth correction function

INTRODUCTION

The A400M is a military transport aircraft launched by Airbus in 2003. Performing its first flight in 2009 it is thought to replace the aged fleet of the C-160 Transall and the C130 Hercules. A payload of 37 tonne can be carried up to a maximum of 1780 nautical miles. The aircraft can operate as tanker, tactical aircraft including areal delivery and as military transporter of paratroopers, tanks, helicopters and medical evacuation.

The fuselage is divided into three sections: nose/forward fuselage, centre fuselage and rear fuselage and has a length of 45 metres. Wing span is 42 meter which positions the aircraft in the middle size area. However its size to payload ratio is unmatched in the landscape of military transport aircraft. Having a high-wing attached to the fuselage the centre part is characterized by a cut out, see Figure 1.

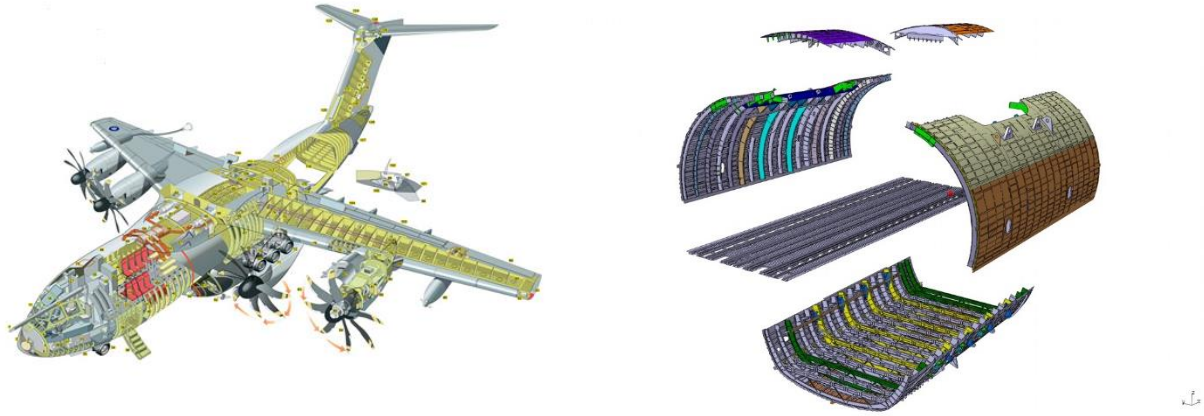

Figure 1: A400M structure overview

Wing and main landing gear are both attached to the fuselage centre section and the loads coming from the wing are introduced by twelve attachments into the fuselage. The main loads in global z-direction are introduced into the four so-called main frames. These wing loads create for the main part of the fatigue spectrum tensional stresses in these frames. Due to this load introduction and the curvature of the frames, the inner flange has to carry high tensile loads. This fact is making the main frames to some of the most vital parts inside the fuselage structure sized by fatigue reasons.

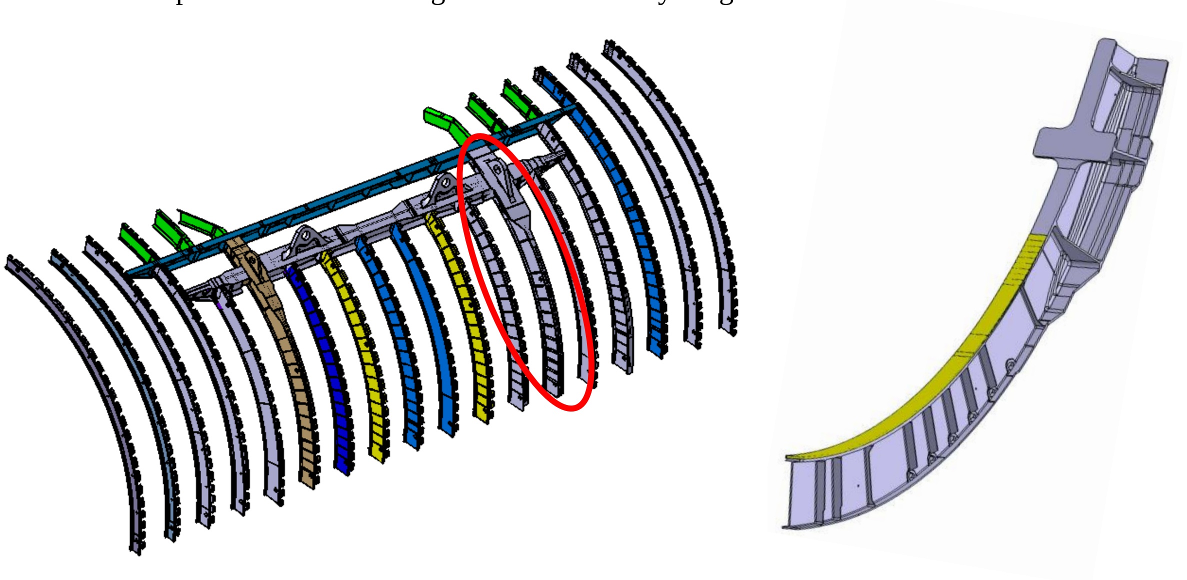

Figure 2: Main Frame of wing load introduction

In an extensive study of various design concepts, which is described in Ref. [1] the idea of a damage containment feature by bonding a GLARE® strap onto the inner flange has been found the best solution in terms of F&DT performance vs. weight as well as production and in-service costs.

The main idea behind this was to have the GLARE® strap bridging any inner flange fatigue crack and in parallel to offer a second load path with an outstanding damage tolerance behaviour.

For this reinforcement the existing GLARE® manufacturing techniques are used to mill straps out from a GLARE® sheet. The Tartaric Sulphuric Acid anodised (TSA) frames are finished with a primer. Supported by several tests it was found that the interface between frame and strap should contain one adhesive film and two pre-preg layers to provide the best structural behaviour. This is mainly due to the fact that such design principle prevents an early cracking of the first GLARE® layer. A schematic view of the interface can be seen in Figure 3. After laminating and curing the GLARE® sheet is inspected by means of ultrasonic through transmission.

In a second bonding cycle the GLARE® strap is then bonded to the inner flange and the assembly is finally inspected by manual ultrasonic through transmission. The maximum allowable defect levels were part of the structural qualification tests.

The complete process is schematically shown in Figure 3.

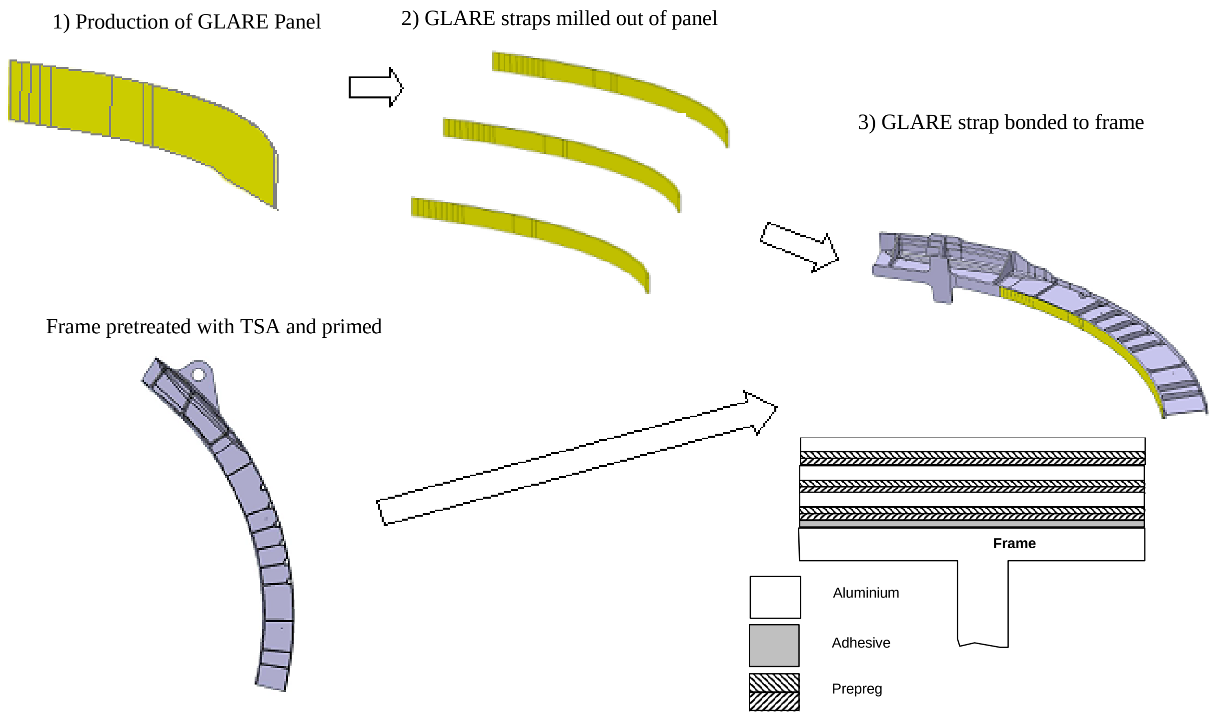

Figure 3 GLARE® Strap manufacturing

By time of the A400M type certification the fatigue and damage tolerance justification of this design principle was primarily supported several coupon and sub-component tests. Significant attention was given during these tests to the crack bridging capability of the GLARE® strap, see Figure 4.

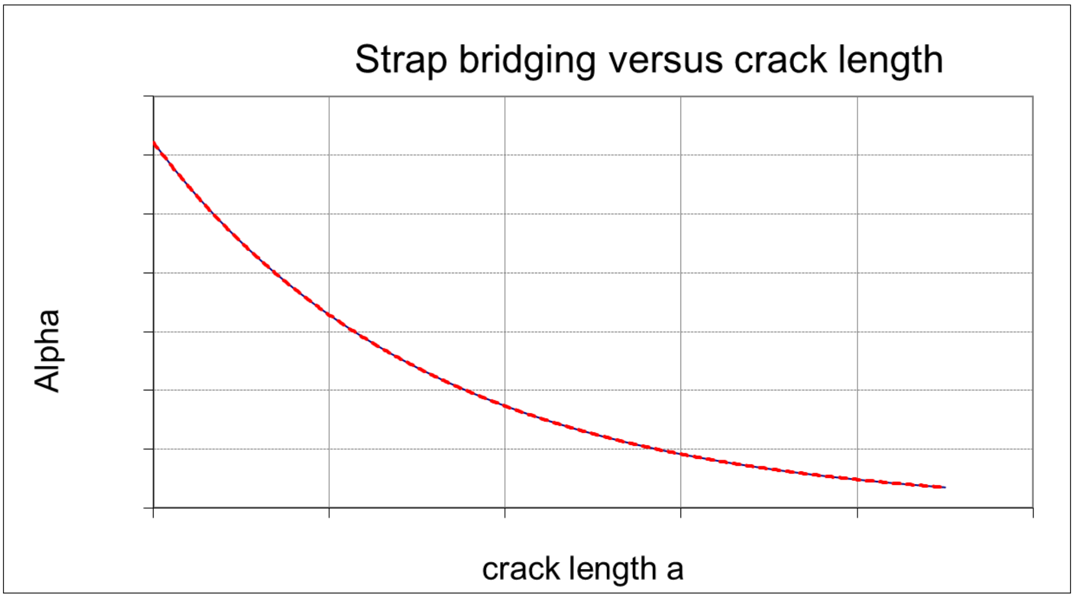

Figure 4 Crack bridging correction used in design phase

The limiting factor by that time was the fact that coupons were used to determine the crack bridging correction, but the influence of other parameters, like the presence of a frame web or system installation brackets was not captured in detail.

The A400M FSFT offered the first chance to extend the accuracy this bridging effect by including these factors.

FULL SCALE FATIGUE TESTING

Being at the top of the testing pyramid, the A400M Full Scale Fatigue Test (FSFT) has been carried out as part of 'Means of Compliance' (MoC) with Type Certification (TC) requirements to provide evidence of metallic structural behaviour in response to fatigue loading.

Concepts of such tests varied over the years, ranging from specimen separation into different sections like in case of the Airbus single aisle aircraft family up to testing complete aircraft structures. The A400M Full Scale Fatigue Test belongs to the second group.

Considering all necessary steps and activities its overall timeframe was from 2009 till 2015, while main testing activities have been carried out between 2011 and 2014. It has always been general Airbus aim to reflect not only the minimum requirement of two times Design or Extended Service Goal (DSG/ESG) but to go significantly beyond it. So it was done as well in case of the A400M were 27500 flights respectively 2.75 times DSG have been simulated.

The usual structure of an Airbus FSFT comprises the following phases (see also Figure 5, Ref. [2])

1. Test Preparation
2. Calibration
3. Fatigue Test Phase
4. Damage Tolerance (DT) Test Phase
5. Residual Strength Test Campaign
6. Tear Down & Storage

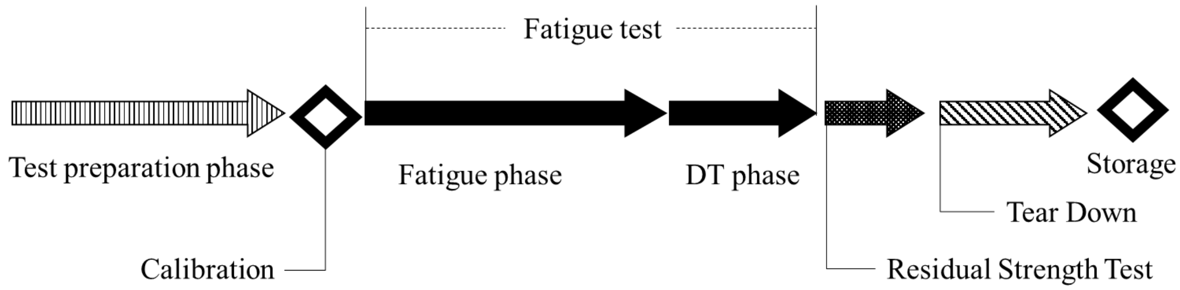

Figure 5: Description Airbus FSFT procedure

Test Preparation Phase

The preparation phase is laying the basis for a successful test. In this stage several key aspects are being defined like:

- Development of proper test spectra, where the theoretical analysis spectrum is being simplified in order to allow efficient testing.
- Loading program definition, which means that the theoretical load application is adjusted to meet the constraints of the physical test setup.

Already during this phase setting the test prerequisites for the GLARE® reinforced frames manifested to play a quite important role. Therefore it was only a logical consequence that loading as well as spectra could be defined almost perfectly representative for them. Both only led to a slight overtesting by 1-2% depending on the detailed area.

The design representativeness is as well a very important aspect when it comes to testing. Here special care has to be given to select all the different contributors to the fatigue criticality. It goes without saying that primary structural parts always should be implemented according to serial aircraft design. Secondary structures and system attachment are not scope of the test, but may have stiffness influence on the primary structure or lead to parasitic loading that can influence the test result. To include these structures is a trade trade-off between test representativity and manufacturing effort. Being one of the highest stressed parts for the GLARE® reinforced mainframe it has been decided to install all the system installation brackets as well into test. This was done not necessarily to introduce system loads but rather to have all the structural discontinuities included. The system installation was generally only installed on one side of the aircraft to limit the cost and still have tested the local effects at the other side.

Being a new design concept also artificial damages like disbondings between the GLARE® and the frame had been introduced.

Especially when it comes to new technologies, the instrumentation of the structural hot spots is of great importance. In case of the GLARE® reinforced frames special care was given first to the inner flanges and was extended to the upper web part of the frames in the course of the test.

Test Execution Phases

The so-called Fatigue Phase of the test aims first at fulfilling the requirement of simulating two full service lives. During this period the fatigue loading program is applied as defined during the preparation and constant monitoring and inspection of the test specimen ranging from general visual up to special detailed is undertaken. Furthermore an extensive amount of measurements of the installed instrumentation is collected.

In the case of the GLARE® reinforced frames this period was used once more to confirm the test representativeness. Figure 6 shows the almost perfect match in the comparison between finite element model-based strains and measured strains in the frame inner flange.

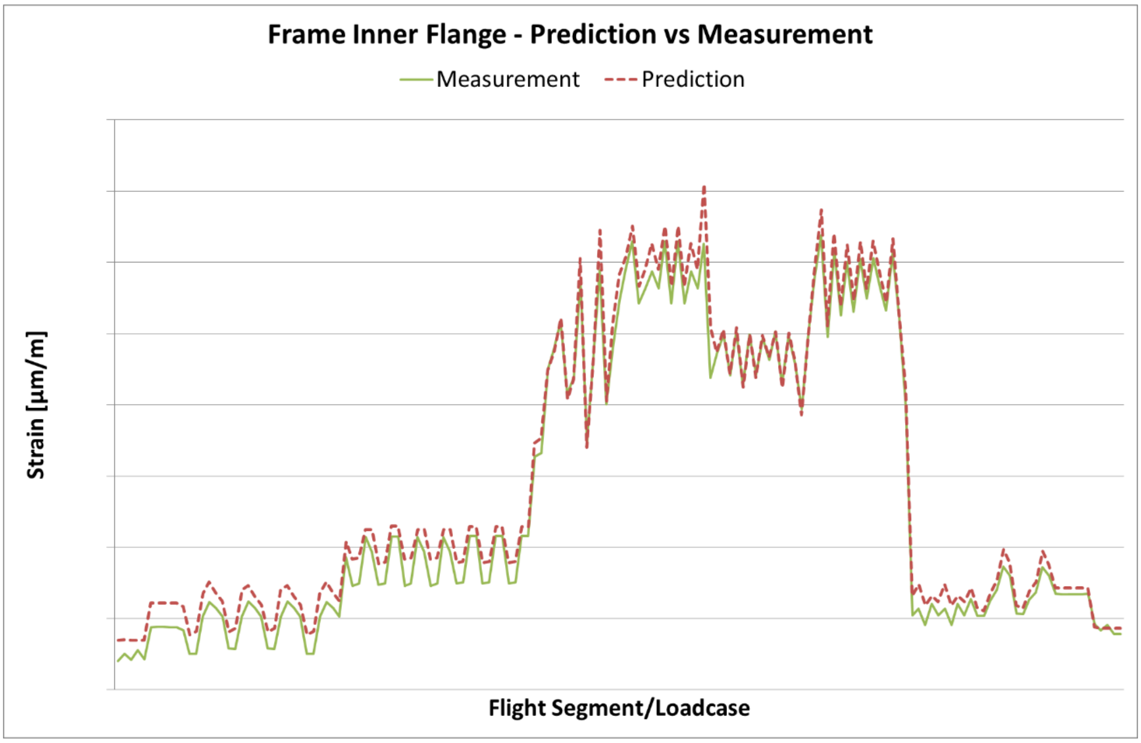

Figure 6: Strain measurements vs prediction comparison

At a late stage in the test the presence of natural crack initiations was detected. In course of the subsequent damage tolerance and residual strength phase this opportunity has been used by the installation of further instrumentation to assist as good as possible the test damage assessment, which is discussed on the following pages of this paper.

Consequently, it was first decided to go for more comprehensive measurements to determine the stress distribution along the frame, see Figure 7 and Figure 8. The frame chosen for this exercise was a neighboured frame which is sufficiently similar at a location free of damages.

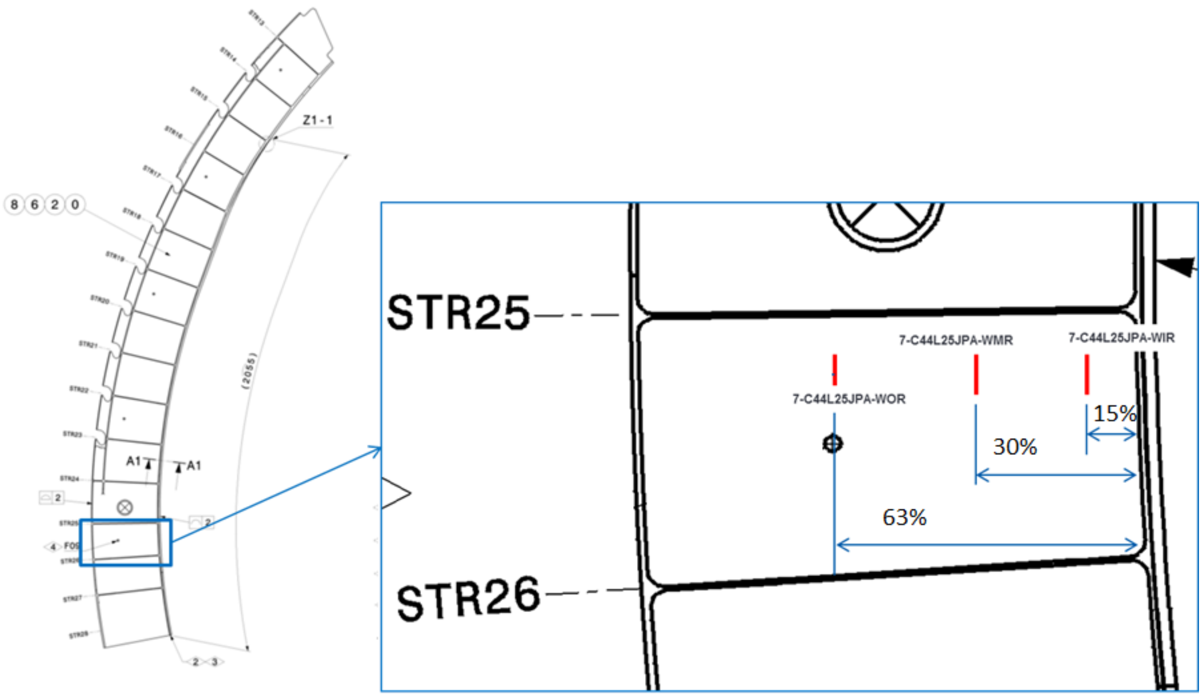

Figure 7: Strain gauge installation in frame web

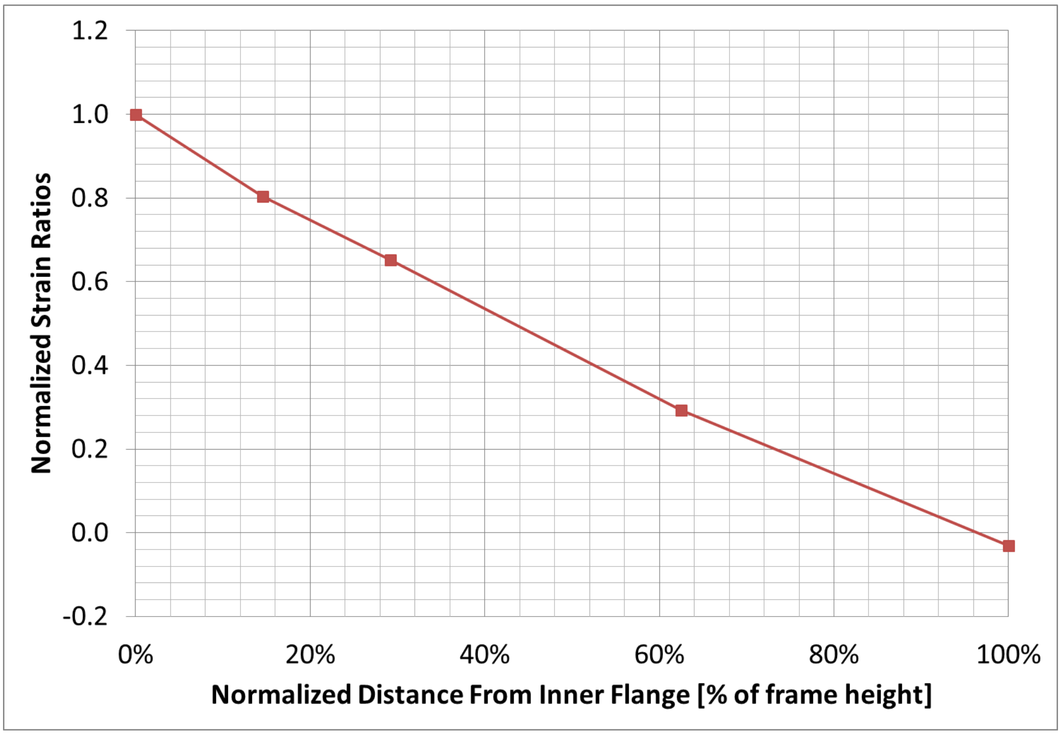

Figure 8: Strain measurements in frame web

The propagation of the found crack initiations at the damaged frame was monitored automated via crack wire installations. This approach allowed a cost, time and safety efficient continuation of the test and at the same time retrieve the maximum of information of the damage evolution.

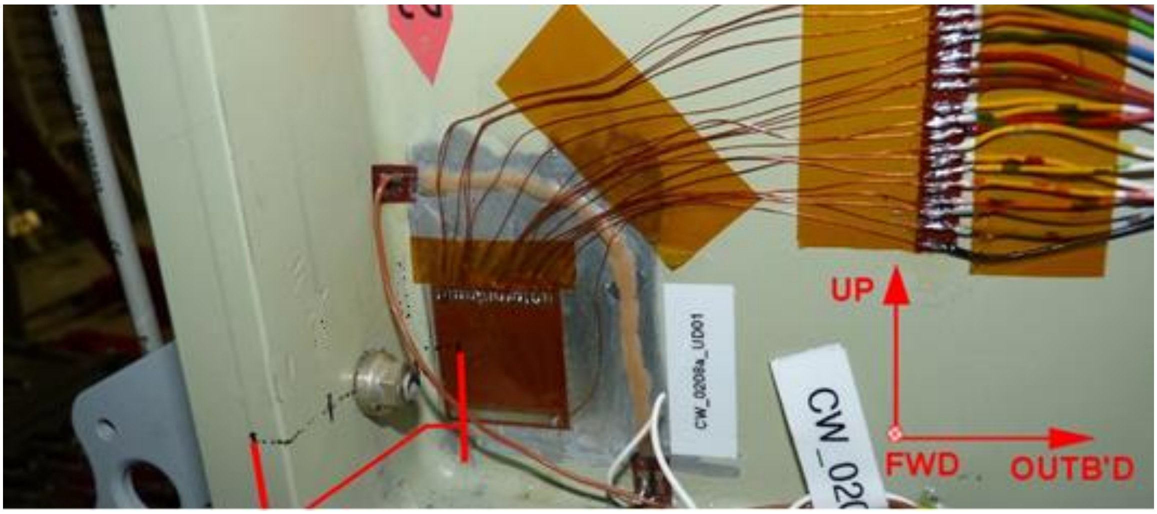

Figure 9: Crack wire installation

This installation was also kept during the residual strength phase were the frame was stressed up to its in-service limit load without prior repair. This residual strength test has been passed successfully.

Post Testing

During the tear down phase which is usually the last stage of the FSFT all GLARE® reinforced frames were inspected in disassembled condition. This was then providing a significant clearer and more detailed view on the damages themselves and supported the assessment of their propagation which is explained in the following.

ASSESSMENT OF CRACK GROWTH

The assessment of the crack growth data that was obtained from the test damages has been carried out in order to estimate the crack bridging effect on the frame inner flanges reinforced by GLARE® straps. The benefit of the GLARE® reinforcement on crack bridging has been investigated by comparing the natural damage outcomes of metallic frames with and without GLARE® straps.

A damage was found in the test in the reinforced frame inner flange at the location of a system installation bracket. The damage was found with crack initiations on both sides of the fastener hole and propagated later through the flange edge and into the frame web (Figure 10).

The measurements (see Figure 10, no 4-6) on the web region have been performed using crack wires while the opposite side is measured manually. Each arrow on Figure 10 represents a measurement point on a specific simulated flight number during FSFT. This explains why the propagation into the web is more refined compared to the measurements towards the frame edge.

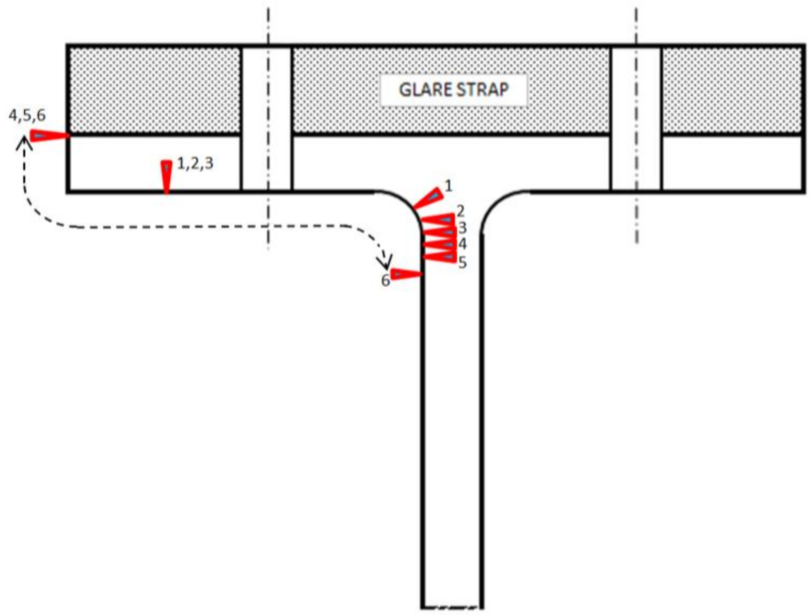

Figure 10: Measurement Points of the relevant damage during FSFT

The crack growth assessment of the damage has been performed using analytical models under the consideration of linear elastic crack growth approach. In order to generate a realistic outcome from these models, the crack propagation scenario is divided into several steps which are consistent with the measurement data points given in Figure 10 and summarized below:

(a) Step 1: Two-sided flaw.
(b) Step 2: Two-sided crack through the thickness
(c) Step 3: A through the thickness crack through the web.

At first step the crack is modelled as two sided flaw initiating from hole to frame edge and web (Figure 11, (a), (b)). After it reached to the point where the crack turned into an edge crack, the same conversion was also made on the analytical crack model (Figure 11, (c)). The fastener is considered as unloaded which is in line with FSFT.

The geometry factors, ß-factors that are used in the 3 steps of the crack growth analysis, follow analytical crack models and are originating from the common text books or relevant manuals. These factors represent the geometrical difference of the crack and cracked geometry. Since the studied damage is located in the metallic frame that is reinforced using a glare strap, the bridging effect of the strap has been considered as an additional ß-factor and derived via an iterative process using the FSFT outcomes (Figure 12).

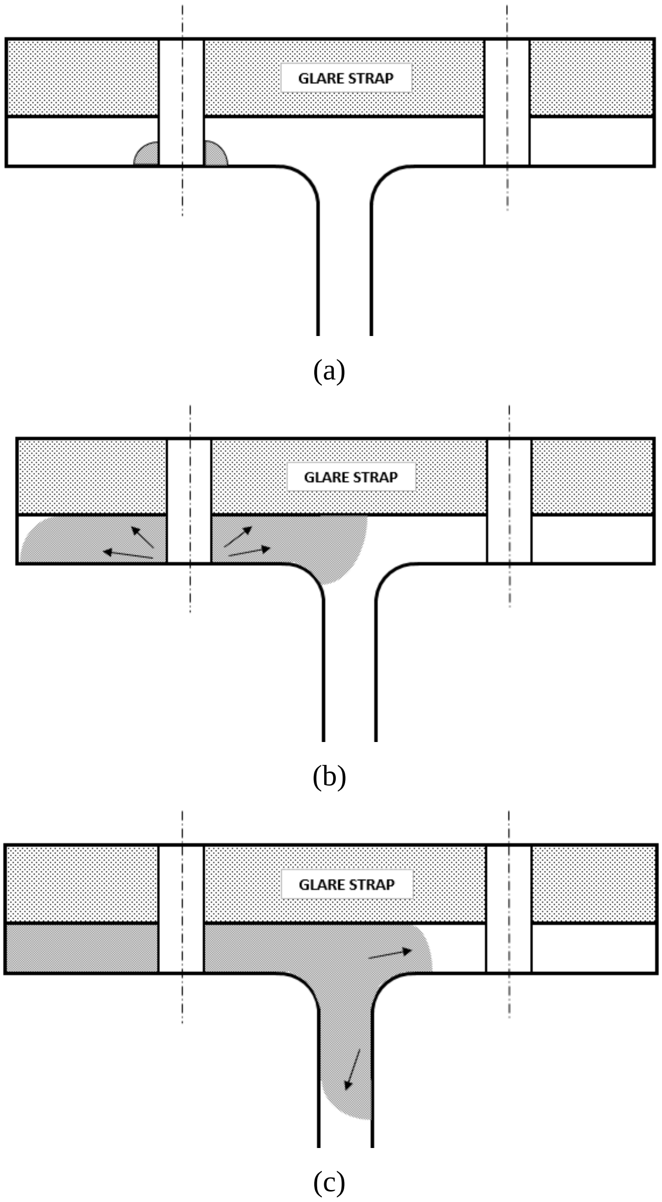

Figure 11: Crack Growth Scenario

Figure 12 shows the crack growth analysis and test measurements of the damage detected on the inner flange of the frame with the glare strap. The curves highlighted as “Analytical Calculation” and “FSFT Measurement” are calculated crack growth result and measurement data points of the natural crack respectively. The vertical axis “Simulated Flight Cycles” at the left side of the diagram, relates to these two curves in Figure 12.

The correction factors obtained for the bridging effect have been compared with the correction factors which are generated for the natural damage detected on the inner flange of a metallic frame without glare strap. These factors are shown as the curves of “Correction Factor for Bridging Effect” and “Correction Factor for non-glare Metallic Frame” in Figure 12. The vertical axis “Correction Factors” at the right side of the diagram, relates to these two curves is.

As seen in Figure 12, the correction factors for metallic frame without GLARE® has a constant value along the different crack lengths. The bridging effect, due to the presence of the GLARE® strap, is varying along with the crack propagation. Starting from the early stages of the crack, the bridging effect of GLARE® is present but its effect increases after the crack reaches a longer length and the growth rate reduces. This behavior was already discovered during the initial studies described in Ref. [1].

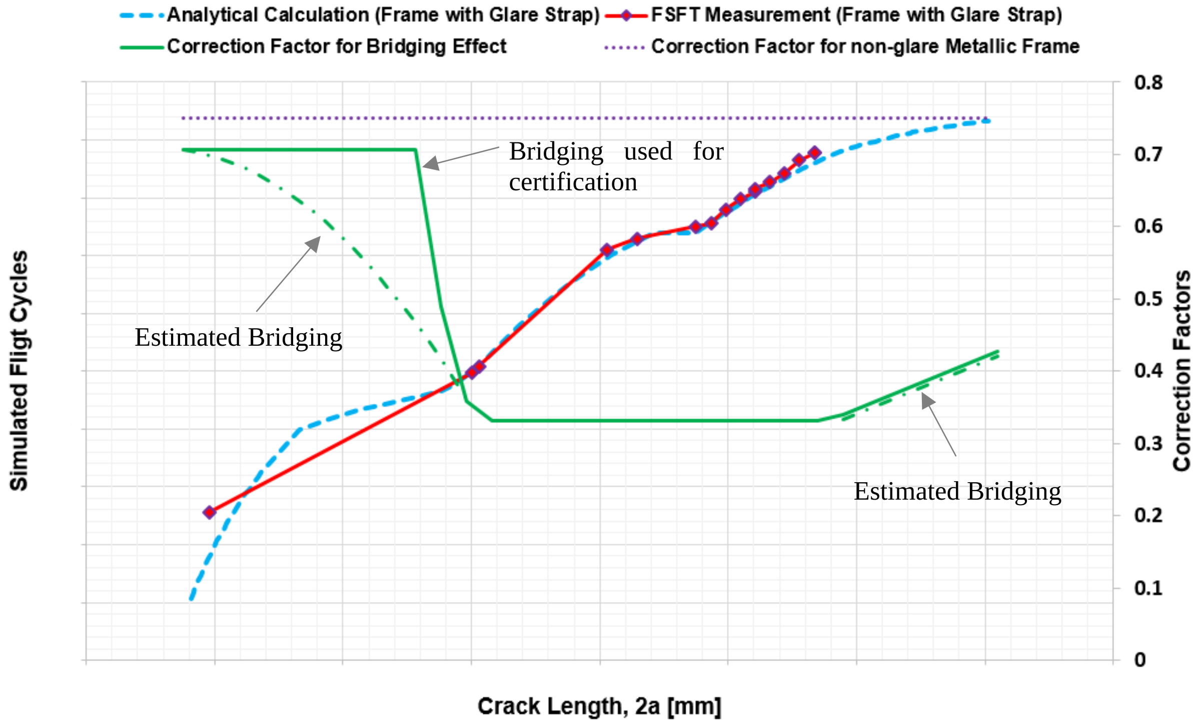

Figure 12: Crack growth result vs bridging capability of GLARE®

For rather small cracks the factors generated for bridging effect were kept relatively high on purpose since there is not sufficient information from FSFT, which is shown by the solid line "bridging used for certification". Due to lack of measurement data at the early stage of the crack, the full crack bridging effect could not be used for certification. Based on previous experience the bridging effect in this area is estimated to gradually increase with the crack length as sketched by the green dash-dotted line in Figure 12. Therefore it was decided to conservatively consider for small cracks a faster crack growth.

Furthermore, correction factors for the bridging effect have been conservatively increased for the last stage of the crack growth analysis where the crack is already propagating deep into the frame web. Although crack growth data in this stage is rather limited, a decrease of bridging effect is already indicated by the final measurements and therefore it is expected that it will further drop down while the crack grows further away from the GLARE® strap (Figure 12).

CONCLUSION

As described in the article, the expected outstanding benefit of the adhesively bonded GLARE® strap, reinforcing the main frame inner flange of the A400M could be confirmed.

The derivation of the crack retarding feature, due to the bridging effect of the bonded GLARE® strap has been illustrated by the example of the assessment of the damage that was found in the full-scale fatigue test.

The full-scale fatigue test revealed that detailed design features, like presence of the frame web and bracket installation, have an important influence and needed to and could be considered by means of the FSFT. The FSFT showed that the potential crack bridging effect could not be used to its full potential, due these design features.

Furthermore, the FSFT showed that the finite element modelling and resulting stress predictions from the certification exercise, were matching the strain gauge measurements well. This provides confidence in the simulation capabilities for these structures at the same time.

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