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THE DEVELOPMENT OF CENTRAL

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Abstract: *A new material concept is developed for metallic lower wing structures. It combines 1 to 4 mm thick laminated aluminium and Glare layers, bonded together using a new high strength glass fiber prepreg based interface. It provides superiour fatigue crack growth properties, high strength and strait forward manufacturing for thick material.*

1 INTRODUCTION

Aluminium alloys have been used for over 50 years in aircraft structures. Both the thin fuselage skin and the much thicker structure of the wing panels have been made out of various alloys. Driven by the required high compression yield strength, the upper wing panels have traditionally been made of 7000 series aluminium. For the lower wing panels aluminium 2000 series alloys are generally used. A large resistance to crack growth is required for this part of the structure that is generally dominated by tensile fatigue loading conditions. Weight saving of the total wing structure (that is for both the lower and upper wing skin) is feasible, if the fatigue stress level in the lower wing skin could be increased. This has initiated the development of CentrAl, a material that combines various material and structural solutions used in the past.

2 HISTORY

In order to improve the lower wing skins fatigue performance, solutions like Glare could be considered. The fatigue crack growth rates in Glare are significantly lower in comparison with aluminium. Figure 1 shows the benefit for Glare 1 and 2 over aluminium 2024-T3 under mini-TWIST fatigue loading. This improved fatigue behaviour motivates the application of Glare as lower wing skin material, in combination with aluminium upper wing panels. The combination of Glare and aluminium does not give the large difference in Coefficient of Thermal Expansion (CTE) and stress-strain relation as for the aluminium CFRP material combination. A comparable CTE for upper and lower wing material prevents unfavorable internal stress in the wing. The comparable stress-strain relation for Glare and aluminium results in comparable design rules (based on the materials yield and strength values, not on a low maximum allowable strain level as for CFRP). A significant number of additional benefits could be provided by Glare to the lower wing structure (such as strength after fatigue, impact behaviour, ease of repair and corrosion resistance). However, especially for single aisle and larger aircraft with relatively thick (>8mm) lower wing skin, several manufacturing issues arise from the use of Glare in this part of the structure.

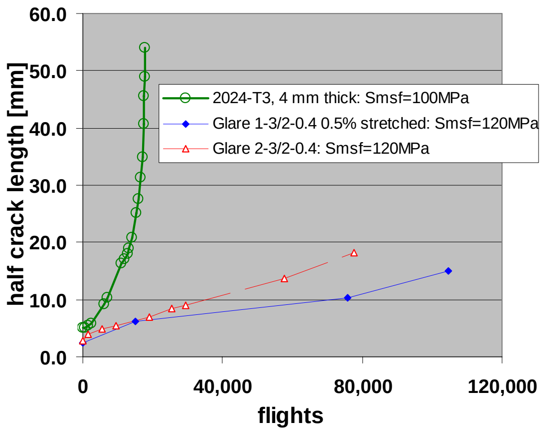

Figure 1: Fatigue crack growth in aluminium and Glare under spectrum loading

A large part of the production process of Glare fuselage panels (A380) consists of thin sheet milling, pre-treatment, storage and lay-up. During lay-up the metal sheets are accurately positioned in a curved bond tool together with the S2-glass prepreg layers.

The labor associated with the production of Glare fuselage panels is largely related to the handling activities of these thin layers. The thickness of the largest area of a Glare fuselage skin is generally relatively small (between 1.0 and 3.5 mm). This limits the configurations of Glare to approximately 6/5 lay-ups (6 metal sheets with 5 fiber prepreg layers in between).

For wing panels the thickness is significantly larger. The lower wing panel for a single aisle size aircraft between fuselage and engine mount, may be as thick as 10 to 15 mm. For a Glare 2 material, this would result in a 20/19 lay-up. Such configurations would significantly increase the amount of labor associated with preparation, handling and lay-up of thin metal and prepreg layers. The production of CFRP structures benefits of full automation using tape layers; a manufacturing method that could not be realized so far for Glare.

The manufacturing of thin Glare fuselage shells has shown to be competitive with state of the art aluminium panel manufacturing. For the thicker lower wing panels Glare may appear to be too complex to produce with the current manufacturing principles. The lower wing panel of A320 – B737 type aircraft is for example 2.5 to 3.5 meter wide. This dimension will require spliced Glare. In this technology the metal sheets somewhat overlap, creating a metal to metal bond in these metal sheet overlap areas[1]. Double curved lower wing skins, as today's aerodynamic optimization requires, will reduce the maximum possible width of the aluminium sheets. Only for this reduced aluminium sheet width, the proper double panel curvature can be obtained using flat aluminium sheets. As a consequence 3 or 4 splice areas will be needed over the cord of the wing. The splice configuration in Glare becomes more complex with increasing material thickness. The width of the splice area increases as well. In the splice area special design rules apply. Locations for rivet positioning are limited in the splice areas and crossing stiff elements (shear cleats and stringers) must be joggled at the thickness step. For Glare wing structures the splice configuration could perhaps be changed to the more conventional “butt-splice”. However also in that case, addition of adhesive strips at the gaps in the metal sheets will be required (as for the overlap splice). For any of the potential splice geometries, the much larger thickness of the lower wing panel in comparison with the fuselage panels, creates a more complex splicing configuration which delays the design and manufacturing process.

The 20/19 Glare lay-up at the root of the wing must be reduced to roughly a 4/3 lay-up at the tip of the wing. Each ply-drop-off contains details that need careful lay-up. Proper positions of ending fiber layers and metal layers and addition of adhesive film, is needed. In view of these manufacturing details, the larger amount of layers in the Glare lower wing cover, built in a similar way as the Glare fuselage skin panels, is expected to be one step too far. The high production rates required for the future single aisle aircraft (up to two aircraft each day), seem to become impossible for thick Glare lower wing skins.

Another manufacturing aspect creating an issue for current standard Glare is countersinking. For standard Glare with its thin aluminium sheets, this has not been a significant problem, because of the relatively small diameter rivets and bolts used in the fuselage. The 0.4 mm thick outer layer of Glare is sufficiently supported by the countersunk head. For the wing structure, much thicker bolts are used, installed in the structure with significant interference and clamping forces on the laminate. Because of the larger bolt diameter, the outer layer of Glare will no longer be clamped by the countersunk head. The bolt installation and bolt clamping may create damage to the material.

A last disadvantage of Glare is related to the aluminium type that can be used. So far Glare has been qualified with two metal alloys, 2024-T3 and 7475-T761. Both alloys are in use already for a long time. Improved Glare performance might be obtained if the latest aluminium alloys could be used, instead of the above two more conventional alloys. However, the new alloys (like Al-Li) are difficult to roll to the required small thickness. If rolling is feasible, a quite extensive Glare laminate qualification program is needed in addition to qualification of the alloy itself. This causes reluctance to create laminates based on state of the art aluminium alloys and it weakens the position of Glare relative to some modern alloys.

From the above discussion is concluded that the use of Glare in lower wing skins is not the most obvious solution in order to increase the fatigue performance of such skins, especially because of the large material thickness required. It creates several issues in the area of manufacturing and assembly. Furthermore, the Glare concept with its thin metal sheets is not flexible enough to adapt to the latest developments in alloy technology. For these reasons a new hybrid material concept is needed.

3 DEVELOPMENT

A test program performed by Alcoa evaluated the suitability of Glare straps, bonded on an aluminium skin in order to improve the structure's damage tolerance. This concept has been used in several aircrafts, using aluminium or titanium straps, for example for the Lockheed Tristar (see upper right hand side image in figure 2). Alcoa's idea was to use this concept, referred to as "Selective Reinforcement", on the much thicker lower wing panels as well (see lower right image in figure 2). Very promising results were generated with this concept[2,3].

The left hand images in figure 2 show the development of laminated aluminium structures, finally resulting in ARALL and Glare. CentrAl has been developed from these laminates (left hand part in figure 2) and the concept of Selective Reinforcement (right hand side in figure 2).

A first step towards the CentrAl material concept was to integrate the reinforcing Glare straps into the material, in a symmetrical lay-up (see figure 3). The originally thick metal sheet is split in two thinner layers in order to obtain a symmetrical configuration, while the Glare reinforcement is bonded in between. In this configuration the shear load per metal/Glare interface is reduced by 50% in comparison with the single side reinforcement (two interfaces for the same load transfer from cracked thick aluminium sheets).

The fatigue crack growth properties are significantly better for the centre reinforced aluminium in comparison with the material with the single sided reinforcement. However, detailed evaluation of centre cracked specimens for both configurations showed that the thin aluminium layer of Glare adjacent to the adhesive layer and the thick aluminium sheets, cracked with the same rate as the thick outer aluminium layers (8 mm or 4 mm thick). It was observed that a large delamination occurs at the interface between the thin outer aluminium layer of Glare and the adjacent S2-glass fiber layer, not the interface between the thick aluminium layer and Glare. This large delamination reduced the stiffness of the crack bridging Glare layer, providing relatively low crack closing forces, also acting upon the thick cracked aluminium layer at a larger distance from the crack edges (thus less effective[4]). The fatigue properties of these combinations of Glare and metal layers were concluded to be limited by the delamination resistance of the S2-glass prepreg to metal interface in Glare. This interface has been defined in 1991 for Glare[5], not for the above material concepts. The load transferred from thin (0.3 to 0.4mm) cracked aluminium sheets in Glare, is an order of a magnitude smaller than the load transferred from the thick cracked aluminium layers in the here considered configurations. The S2-glass / metal interface optimized for Glare is not suitable for the here considered high load transfer from thick cracked metal sheets.

The typical delamination damage and fatigue damage is shown in figure 4 in a number of schematic images: The complete material concept is shown in the first step of this figure. It shows the large fatigue crack in the outer aluminium layer. In the adjacent second image the narrow delamination on the adhesive interface is made visible by removal of the thick outer aluminium layer.

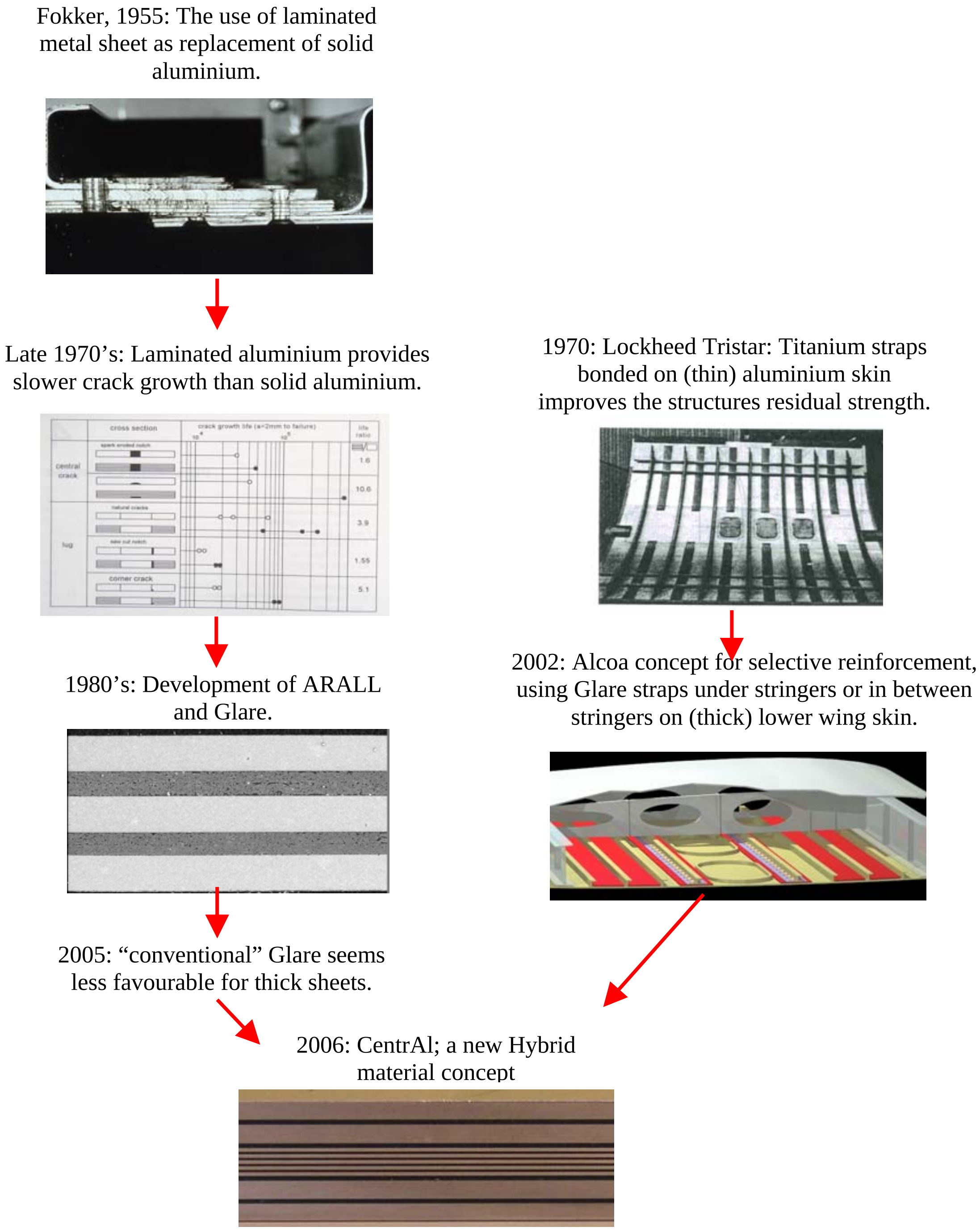

Figure 2: Development steps resulting in CentrAl material concept

The adhesive provides an almost perfect bond between thick and thin metal sheet, preventing delamination at that location. The third image shows the size of the fatigue crack in the outer thin metal sheet of Glare. It is approximately as large as the crack in the thick outer layer of the material (image number 1). Removal of the thin outer aluminium layer of Glare in image number 4 shows the delamination size on the outer S2-glass / metal interface in Glare. This is the large delamination as referred to above. Also the (kind of round) shape is unusual for Glare. In image 5 the small fatigue crack in the second aluminium layer of Glare becomes visible. Image 6 of figure 4 shows that the rest of the delaminations in the Glare laminate towards the centre line of the material have normal size and geometry. In figure 5 the actual delamination areas in the material in the images 4 and 6 of figure 4 are shown.

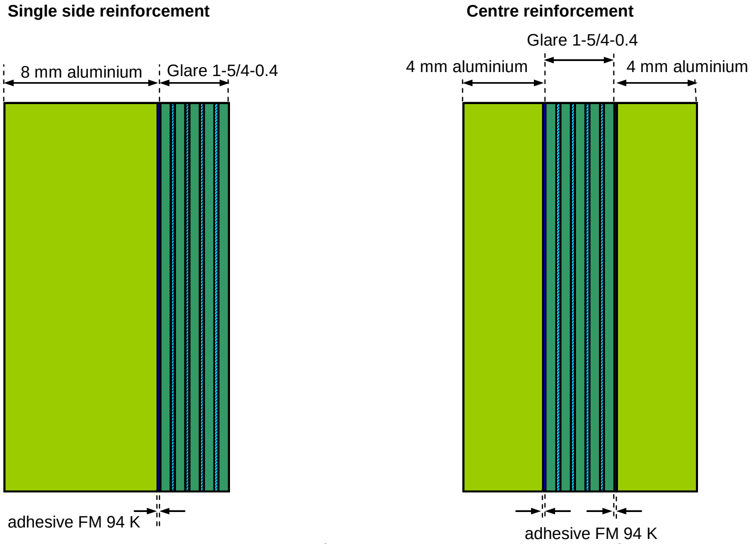

Figure 3: Cross sections of single side and centre reinforced aluminium

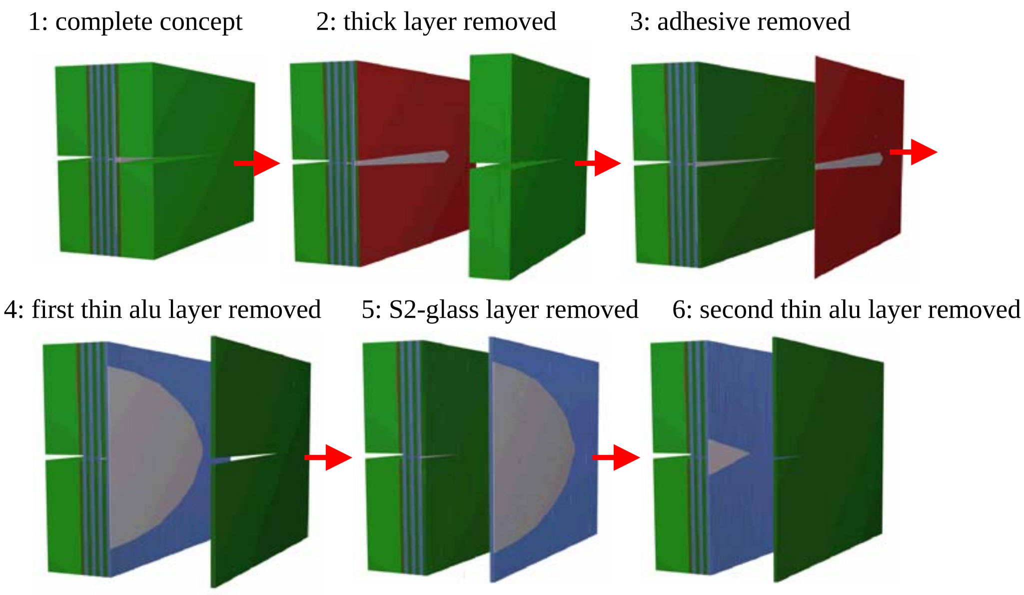

Figure 4: Fatigue cracked material concept, layers removed step by step

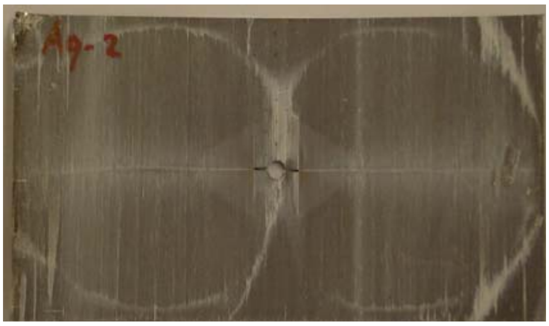

Figure 5: Large delamination on outer metal/S2-glass prepreg interface (left) and normal delamination in second metal/S2-glass prepreg interface (right).

The above results explain why the combination of standard Glare bonded on one side of a single thick aluminium sheets or bonded in between two thick aluminium sheets, gives a relatively large delamination on the outer metal / S2-glass prepreg interface of Glare. The large delamination limits the crack closing forces on the thick aluminium layer(s). A reduction of the size of this delamination would increase these crack closing forces and reduce the crack growth rates in the thick aluminium layers. This improvement is obtained with the development of bondpreg^{TM}. This product is a combination of standard adhesive bondfilm and S2-glass prepreg as used in Glare. Bondpreg^{TM} combines the crack bridging capabilities of the S2-glass prepreg used in Glare, with the resistance to delamination similar as obtained for standard adhesive layers. In other words: Bondpreg^{TM} provides an optimized balance between crack bridging and delamination resistance for thick metal sheets. This product not only has the bonding properties of standard adhesive layers, it also has the manufacturing characteristics of adhesive film. Its flow during cure is comparable to that of adhesive film. A low pressure autoclave cycle can be used for production. It fills small gaps

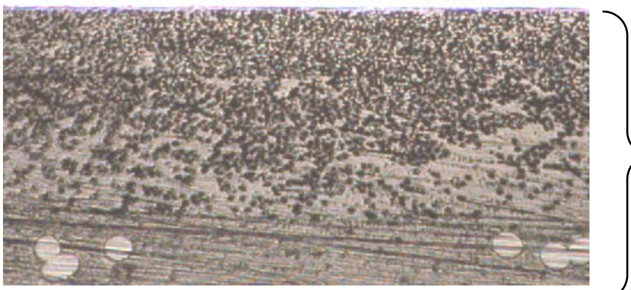

Figure 6: Bondpreg^{TM} cross section

between layers during the autoclave cycle, allowing the use of stepped Glare or aluminium layers without a precise surface match of the individual material ingredients. Figure 6 shows a cross section of bondpreg^{TM}. Two S2-glass FM94 prepreg layers and a single side FM 94 K adhesive film are combined in this product.

Bondpreg^{TM} is used as interface between Glare and thick metal sheets. A significant reduction of the delamination growth rates between the layers under fatigue loading conditions is obtained. This is shown in figure 7. It compares the typical delamination areas after fatigue, for the material using standard adhesive film between Glare and thick metal sheets (shown also in figure 5), with the material using bondpreg instead of standard adhesive film. For bondpreg^{TM} based material, the outer thin aluminium layer of Glare no longer cracks at the same rate as the thick outer layer, but at a much lower rate as for the other thin layers of the central reinforcing Glare layer. The size of the delamination area over the interface of the bondpreg^{TM} is also much smaller compared to the adhesive based material. It resembles the geometry as normally found for Glare. With its increased delamination resistance, bondpreg^{TM} significantly reduces the fatigue crack growth rate in the material as shown in figure 8.

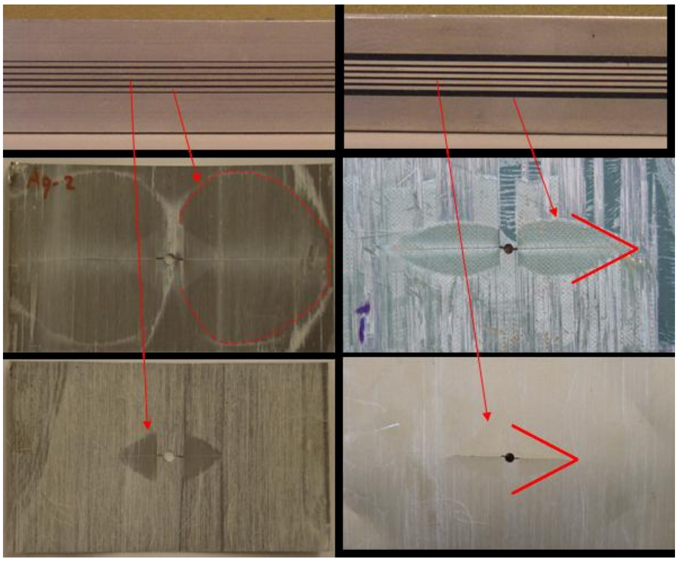

Figure 7: Comparison of delamination areas for adhesive (left) and bondpreg^{TM} based materials.

The above material based on thick outer aluminium layers bonded on each side of a Glare reinforcing laminate with bondpreg^{TM} is referred to as CentrAl (Centre reinforced Aluminium). The improved fatigue performance is evident. However, the fatigue crack growth rates in CentrAl can be further reduced.

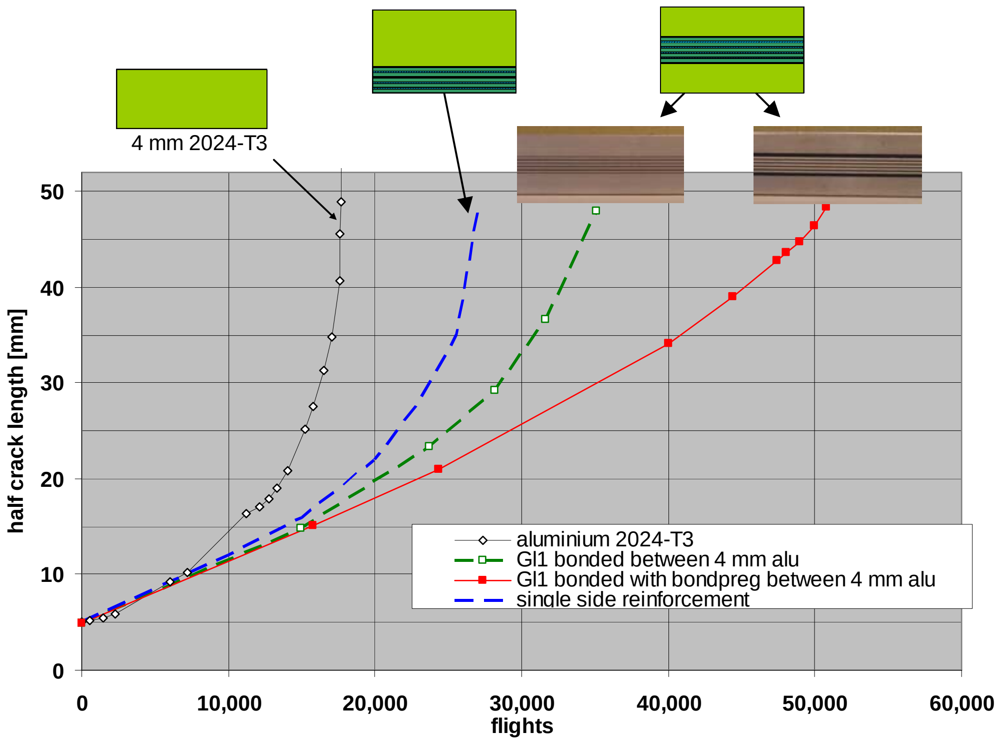

Figure 8: Fatigue crack growth behaviour for center cracked specimen under mini-TWIST fatigue loading (Smsf = 100 MPa, GTA = -0.1, trunc. = 1.15)

The first additional step to further improve the fatigue properties is to reduce the thickness of the outer aluminium sheet. This minimum thickness is the one that can be readily obtained for the rolling process of the aluminium alloys that are believed to be most suitable for CentrAl. This is approximately 1 mm. By using several of those aluminium sheets on each side of the central Glare reinforcement, all bonded together with bondpreg layers, the total required material thickness is obtained. Figure 9 shows a range of such materials, all with approximately the same total material thickness and with the same 5/4 lay-up for the central Glare reinforcement. The outer metal layer thickness in these materials is 4 mm (left image), 2 mm and 1.3 mm (right image).

Figure 9: CentrAl configurations with various outer metal sheet thicknesses

The influence of the thickness of the outer metal sheets on the fatigue crack growth behaviour is significant. For thinner layers, the crack closing forces originating from the bondpreg™ layers cause a larger reduction of the stress intensity factor (a similar effect was observed for the much thinner layers in ARALL in the 1980's[6]). The advantage of the use of 1.3 mm thick aluminium layers instead of 4 mm thick outer aluminium layers is shown in figure 10 (note that the red line for specimen H-3b corresponds to the red line in figure 8).

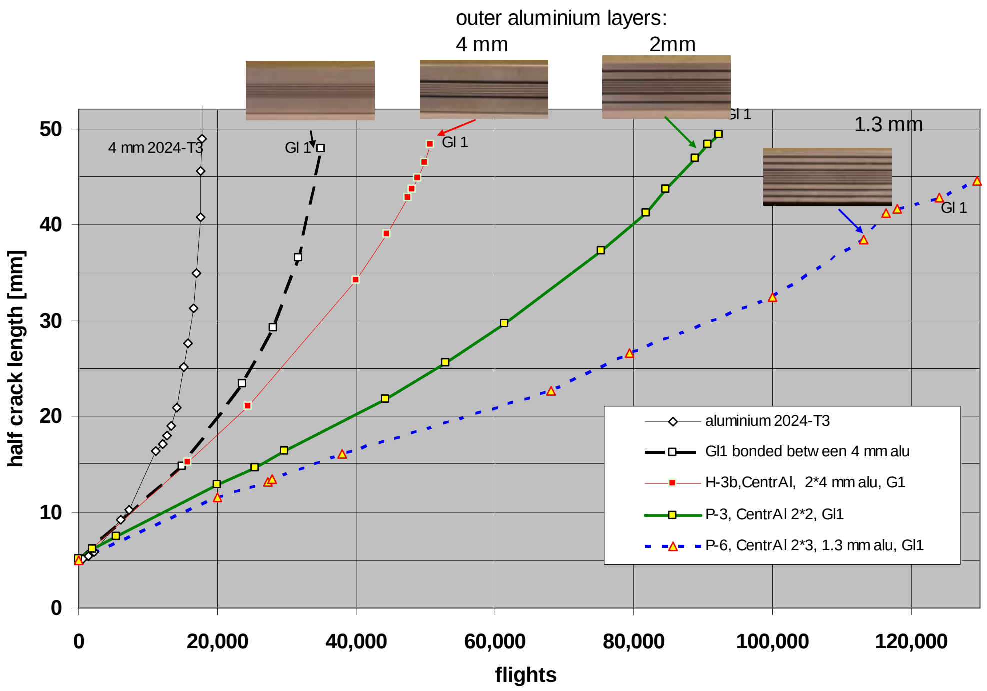

Figure 10: The effect of the thickness of the outer aluminium layers on fatigue crack growth in CentrAl (mini-TWIST loading)

The second material variable influencing the fatigue crack growth rates in CentrAl is the choice of the Glare type. Glare 1 (post-stretched material containing favourable residual compressive stress in the 0.4 mm thick 7475-T761 aluminium layers) has better fatigue properties in comparison with Glare 2[7] (as-cured material with residual tensile stress in the 0.4 mm thick 2024-T3 aluminium layers). The influence of this difference is provided in figure 11.

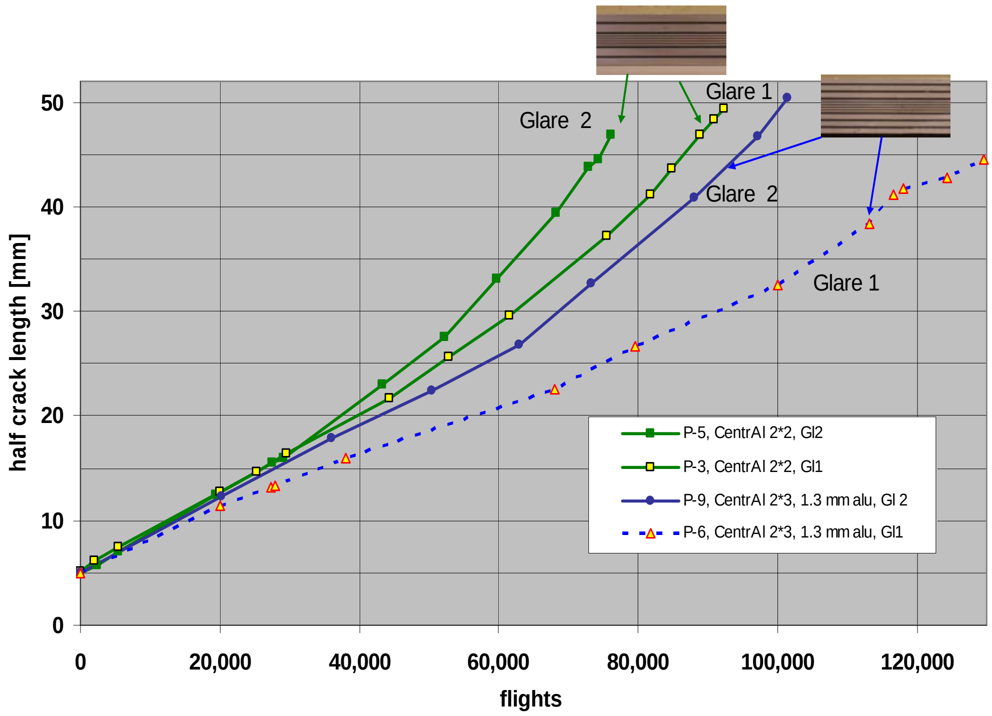

Figure 11: The influence of the Glare type used in CentrAl on fatigue crack growth under mini-TWIST fatigue loading.

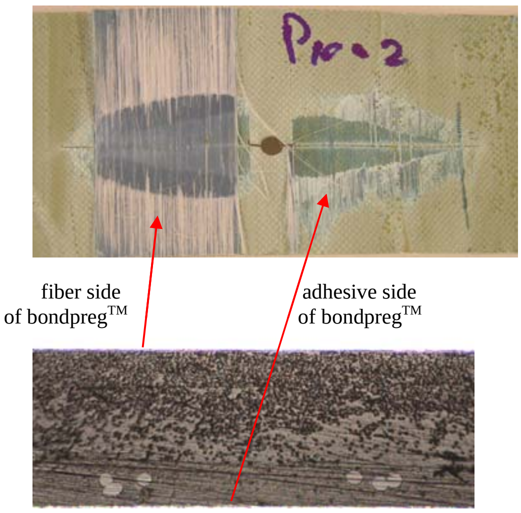

Figure 12: Unequal delamination size at both interfaces of non-symmetric bondpregTM

The third material variable influencing fatigue crack growth is the bondpreg™ composition. All results presented above are based on the bondpreg™ composition shown in figure 6. The adhesive film in this product is applied on the bondpreg™ interface towards the outside of the laminate only. The other interface of the bondpreg™ (towards the centre of the laminate) is comparable to the prepreg / metal interface of standard Glare and has more or less the same delamination resistance as found for the prepreg in Glare. This non-symmetrical composition gives unequal delamination sizes on the two interfaces of the bondpreg™ in CentrAl, as is displayed in figure 12. The stiffness of the crack bridging bondpreg™ layer is governed by the largest size delamination at one of the bondpreg interfaces. So, creating increased delamination resistance at both interfaces of the bondpreg™ rather than at one interface only, further increases the crack closing forces, reducing the crack growth rates in the material. It makes the bondpreg™ symmetrical; a significant benefit for production. The effect of this change is shown in figure 13.

Further improvements of the fatigue crack growth rates, relative to the behaviour of specimen T-1 in figure 13 have been obtained already. Clearly, the possibilities for lay-up are numerous, intelligently choosing the order, the number and the thickness of metal layers, bondpreg™ and Glare, depending on local stress conditions including bending and considering wing panel tapering from wing root to wing tip. For all above test results the thick outer aluminium sheets are 2024-T3. Improved fatigue behaviour and static strength will be obtained for CentrAl versions based on modern aluminium alloys.

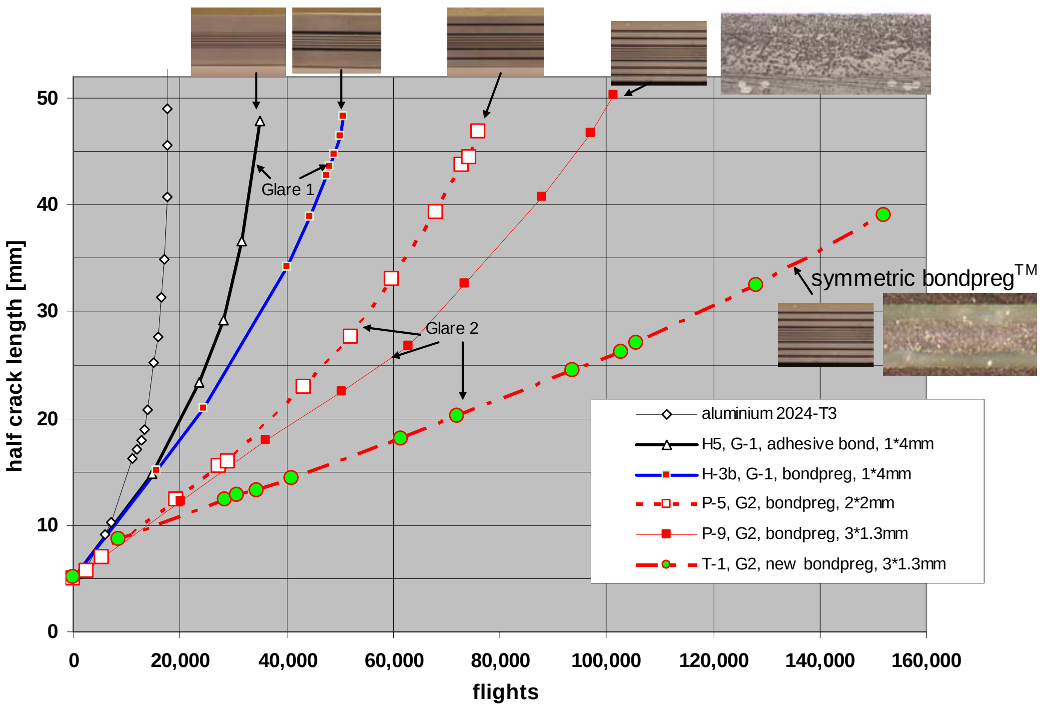

Figure 13: Reduced crack growth rates in CentrAl with symmetric bondpregTM

4 MATERIAL PROPERTIES

The above described development of CentrAl has been based on minimizing the fatigue crack growth rates in centre cracked specimens loaded with a mini-TWIST fatigue spectrum. The final result of this work is a reduction of the fatigue crack growth rates with up to two orders of magnitude for the larger fatigue crack lengths. The wide range of fatigue crack growth curves that can be obtained for CentrAl is displayed in figure 13.

The blunt notch strength is an important design parameter for Hybrid materials like Glare and CentrAl. Blunt notch tests were performed for CentrAl including the effects of fatigue cracking from open and filled holes (interference fit bolts). These specimens were fatigue loaded with a mini-TWIST spectrum using 90 and 95 MPa mean stress in flight values (GTA cycle of -0.1 and a truncation level of 1.15). After the specimens were pulled to failure, the fatigue damage was determined in the net cross section for all layers of the material. Reference fatigue tests were performed on 4mm thick aluminium 2024-T3.

The typical fatigue damage in the net section of CentrAl was different for the two specimen configurations; for open holes the fatigue crack length in the thin Glare aluminium layers was approximately 50% of the fatigue crack length in the thick outer aluminium layers, for filled holes the fatigue crack length in one thick outer layer was significantly larger than in all other layers of the laminate. Plotting all results for open and filled holes in one graph with the average fatigue crack length as horizontal axis, as is performed normally for Glare (CentrAl results in left image in figure 14), gave different strength versus crack length relations for CentrAl open hole and for filled hole specimens. Equal results were obtained for the two specimen configurations, when the maximum fatigue crack length in the net specimen cross section was used instead (right image in figure 14). The use of the maximum crack length as main strength parameter is in better agreement with the expected micro-mechanical failure behaviour of the material. The maximum stress level in the fibre layer (causing the cascade of failures resulting in specimen failure) is reached directly adjacent to the aluminium layer with the largest fatigue crack length. At that point the smaller fatigue crack length in the other aluminium layers has little contribution to specimen failure.

The results in figure 14 show a gradual los in strength for increasing maximum fatigue crack length in CentrAl blunt notch specimens. Even if the maximum fatigue crack length reaches the full net section width, the strength reduction is limited. For monolithic aluminium the strength drop due to fatigue cracking is much faster.

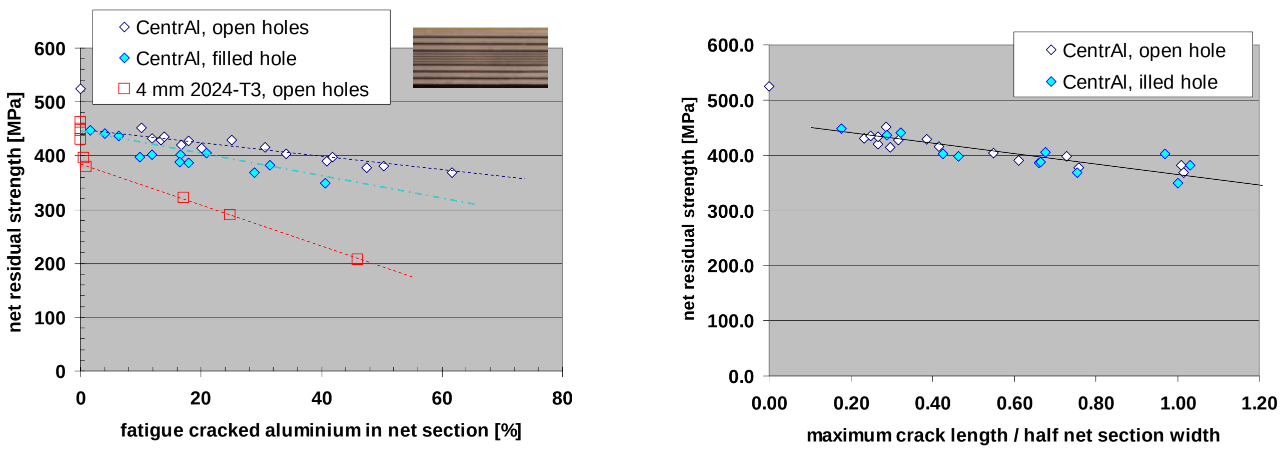

Figure 14: Residual net strength of fatigued blunt notch specimen

For all fatigue results in this investigation the maximum fatigue crack length occurred in one of the two outside layers of the material. So, the residual strength of the specimen is determined from the fatigue crack length observed from the specimen outside, as found during visual inspection of the material.

Static material properties (allowables) have been determined for Glare in an early phase by using the Metal Volume Fraction approach. It supported structural design before the formal allowables became available. The MVF approach assumes a linear relation between the properties of aluminium for MVF = 1 and the properties for the S2-glass fibre layers with MVF = 0. A schematic image for this relation is provided in figure 15. The properties of Glare (with MVF values typically between 0.5 and 0.8) are accurately determined using a linear relation between the two extremes. So, for a certain Glare material family (for instance Glare 2 with unidirectional glass fibers), the properties of all laminates within this family are determined with only 3 parameters: the property of the metal, the property of the fiber layer and the MVF value for the laminate. For CentrAl this amount of variables increases. For this material not only the composition of the reinforcing Glare material needs to be defined (3 variables as for Glare), but also the volume ratio of Glare within the total laminate, the properties of the potentially different aluminium alloy for the thick outer layers, the properties of the bondpreg layers and the volume fraction of the bondpreg layers need to be provided as input for CentrAl's MVF calculation tool as well, bringing the amount of needed variables to seven. An additional option in the developed MVF tool is the use of post-stretched Glare reinforcing layers resulting in 8 material variables for the CentrAl MVF tool.

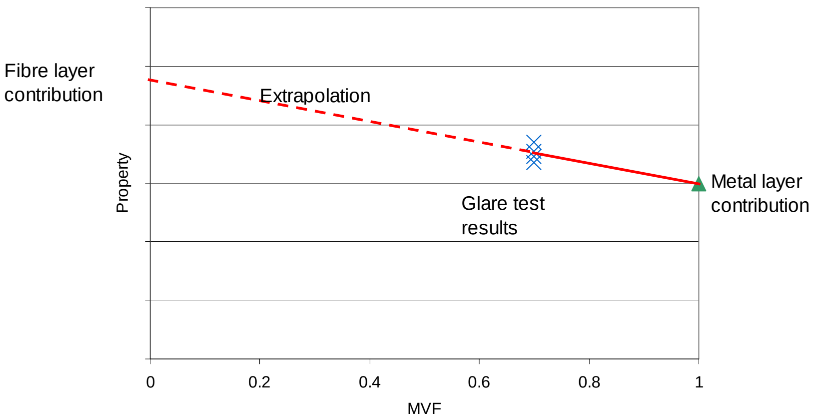

Figure 15: The Metal Volume Fraction approach

The MVF calculation tool has been verified with tests on various CentrAl materials for tension (modulus, yield and strength), blunt notch (strength) and shear (modulus and yield). The test results are generally within 4% of the calculated values with sometimes larger deviations to 8%; similar as has been found in the past for Glare.

The developed MVF tool for CentrAl allows determining material properties, well before the material is actually tested. It assists the determination of the most suitable material combination for the targeted application.

5 MANUFACTURING ASPECTS

In the first pages of this presentation, several remarks were made on the suitability of Glare for thick wing panels. The need for a new hybrid material concept, not having the disadvantages expected for thick skin Glare manufacturing, was expressed. The above definition for CentrAl now allows revisiting this item.

The number of layers in CentrAl is significantly reduced relative to Glare. The thick aluminium sheets do not only build up panel thickness fast, they are also much easier to handle during pre-treatment and lay-up eliminating the chance of denting the metal, compared to the thin aluminium layers used in Glare.

The thick metal sheets applied in CentrAl can be shaped to double curvature using autoclave forming techniques. So, the reduction of the width of the thick aluminium sheets of the material is not needed, unlike the use of thin aluminium layers used in double curved (fuselage) Glare panels. The Glare reinforcing layer in CentrAl is produced as flat sheets. These Glare sheets are cut in narrow strips (up to 800 mm, depending on wing panel curvature). For this small width the Glare panels can be formed under the autoclave pressure to obtain the double curved wing contour and bonded to the other pre-formed aluminium sheets using bondpreg™. The splice in the narrower Glare straps, running in span wise direction is much simpler as for Glare (see figure 16). The butted Glare layers in CentrAl are easy to position on the double curved bond tool. Picture frame shear tests have shown that the butt splice in the Glare layer of CentrAl does not influence the shear stiffness nor the shier yield strength.

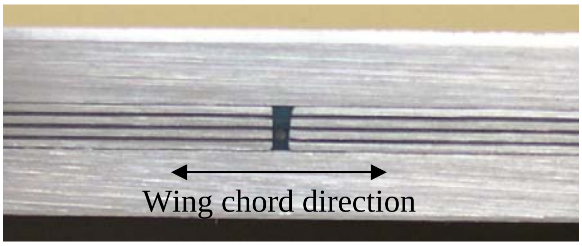

Figure 16: Butt-splice in Glare layer

Figure 17: Ply drop off in CentrAl

Countersinking for large diameter bolts is no longer an issue. Especially the aluminium layer at the loft side of the skin will be somewhat thicker compared to the other thick aluminium layers in the laminate, because of performance considerations. This further facilitates bolt countersinking. More in general can be concluded that the use of thick outer aluminium sheets in CentrAl, significantly improves the drilling and milling properties of the material relative to Glare. The material is significantly less sensitive to edge delaminations due to machining operations.

Lower wing panel tapering is relatively easy for CentrAl. Ply drop offs can be positioned on the outside of the laminate (at the inside of the wing-box) or interlaminar (see figure 17).

Both options have been tested on static and fatigue performance with excellent results. Towards the wing tip, there will be no need for the additional central Glare reinforcement. This can be accomplished by applying the Glare reinforcement over only (approximately) 50 to 70% of the wing span; an option that can not be realised for a Glare lower wing panel.

Finally, the CentrAl material concept can benefit from the latest alloy developments such as Aluminium-Lithium. These alloys do not need to be rolled to the relatively thin sheet thickness needed for Glare like materials. Generation of allowables for the CentrAl concept can be based on the allowables made available for the alloy in a thickness range between 1 and 4 mm and the available allowables for Glare 2 (today's choice for the reinforcing layer), using current calculation tools (including the MVF approach).

6 CONCLUSIONS

Fatigue crack growth in single sided Glare reinforced thick aluminium sheets, causes large delaminations on the outer metal / prepreg interface of Glare. This is solved by using bondpreg™ instead of standard adhesive film between the thick aluminium sheets and Glare. The resulting CentrAl material concept has been further improved by metal sheet thickness reduction, the use of the proper Glare reinforcement material and bondpreg™ optimization. It provides the targeted fatigue and strength properties, combined with significantly improved manufacturing for thick material over the current Glare grades that are successfully used in thin walled aircraft structures.

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