DAMAGE TOLERANCE OF STIFFENED HYBRID GLARE PANELS CONTAINING LOCAL INTERNAL CARBON REINFORCEMENTS

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Keywords: fatigue, damage tolerance, tailoring, hybrid material.

Abstract

This paper provides an overview of experimental feasibility studies that have been undertaken to evaluate the damage tolerance characteristics of an aluminum/glass-epoxy Fibre Metal Laminate panel containing local carbon-epoxy reinforcements. The goal of the reinforcements is to increase overall skin panel stiffness, thus attracting load away from the fatigue sensitive backup structure, and mimic the effects of traditional bonded tear straps, improving the damage tolerance and large damage carrying capability of the skin panel. Experimental results demonstrated that the desired load redistribution was possible, and four-fold reductions in crack growth rate in the vicinity of the reinforcements were achievable.

1 Introduction

Developments in materials and structural design have both contributed to improvements in the damage tolerance of modern aircraft structures. New developments in metal alloys, composite materials, and hybrid materials such as Fibre Metal Laminates (FMLs) [1, 2] have all resulted in materials less sensitive to damage and with slower damage growth rates. The concept of damage tolerance is a key aspect in ensuring and maintaining safety of an airframe structure over its design life. Damage tolerance can be defined as the ability of a structure to sustain sufficient levels of damage, resulting from fatigue, corrosion, and incidental sources such as impact; such that the damage can be detected and repaired through regular inspection before it reaches a critical level.

Fibre Metal Laminates (FMLs) are a hybrid laminate material composed of alternating layers of thin aluminum sheet (0.3-0.5 mm) and cross-ply pre-impregnated glass fibre/epoxy resin layers (Fig. 1). The combination of traditional composites and metallic sheets has a synergistic effect whereby the composite layers act as pre-embedded bonded repair patches against metal fatigue cracking, and the ductility of the metal layers both reduces and makes it easier to detect incidental damages such as impact. This synergy has been widely studied [1-10] and led to the selection of the aluminum-glass/epoxy variant of FMLs, known as Glare, as the upper-fuselage skin material on the Airbus A380 superjumbo jet; a structural component driven mainly by fatigue and damage tolerance issues.

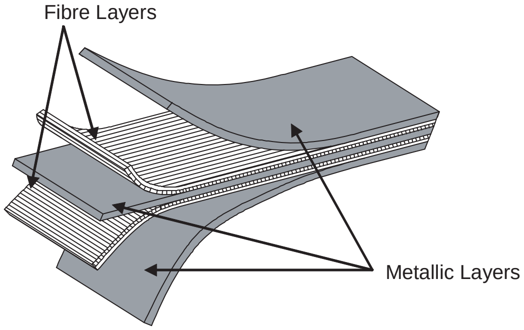

Figure 1. Illustration of a Fibre Metal Laminate (FML).

Despite the high damage tolerance of FMLs, these materials are not without their challenges when applied in aircraft structures. Cost-driven factors make it desirable to implement FML skins with monolithic metallic backup structures. This was the approach adopted on the A380 where Glare skin panels were joined to monolithic aluminum stringers and frames. The Glare skins, however, have a lower stiffness relative to the aluminum backup structure resulting from the relatively lower stiffness of the glass/epoxy layers in the Glare laminate. As a result, load is attracted away from the damage tolerant skin into the more fatigue sensitive backup structure; opposite of the desired situation. The obvious solution is to replace the glass/epoxy system with a stiffer composite system, although higher stiffness composite systems tend to have a lower strain-to-failure which sacrifices the impact resistance and ductility of the FML.

The solution adopted in the A380 to counter the stiffness imbalance between the Glare skins and aluminum backup structure was to add interlaminar doublers in the Glare skins (see Fig. 2), thereby increasing their geometric stiffness. The drawback of this solution is that it results in local variations in the skin thickness, which necessitates joggling or match-machining of the backup structure and increase production cost.

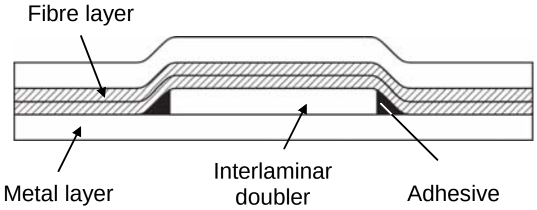

Figure 2. Schematic of an FML interlaminar doubler.

This paper investigates another possibility for overcoming the stiffness imbalance. Rather than creating a local increase in panel stiffness through the inclusion of additional material, this paper investigates the possibility of a local material substitution within the fibre layers. This approach gives rise to the possibility of producing a stiffer FML panel without introducing thickness steps and without reducing its global impact sensitivity. This concept, first proposed in [11] as an alternative concept to a bonded tear strap, was given the name ITS-Glare (for *Internal Tear Strap Glare*). For consistency, the term ITS-Glare will be used in the present context of applying the concept.

2 The ITS-Glare concept

The ITS-Glare concept, illustrated in Fig. 3, was first proposed in [11] as an alternative to bonded tear straps for improving the damage tolerance of Glare skins. The local substitution of glass-epoxy prepreg with carbon-epoxy prepreg mimics the presence of a bonded tear strap by locally varying the laminate stiffness. The higher stiffness of the carbon-epoxy prepreg region alters the damage tolerance of the Glare skin in three ways:

1. By attracting load, thereby reducing the driving force for crack growth in the unreinforced region of the panel.
2. By providing a stiffer bridging load path, thereby reducing crack growth driving force in the reinforced region of the panel.
3. By introducing a bulging effect in the case of pressurization loading, thereby introducing bulging stresses which can alter the crack path and lead to a flapping-failure where the pressure vessel leaks before bursts.

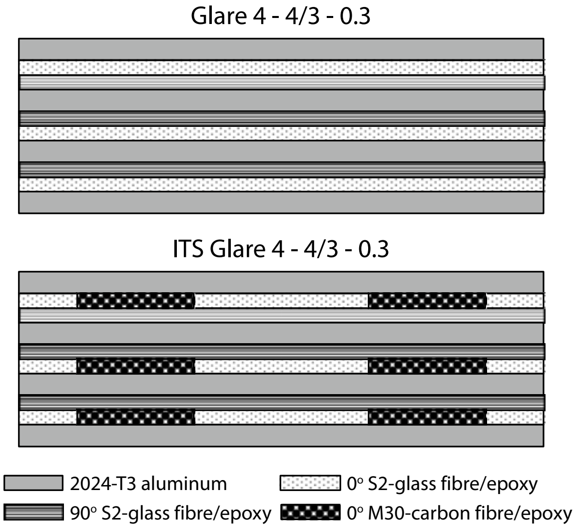

Figure 3. Illustration of the internal tear strap Glare concept.

In addition to altering the damage tolerance of the Glare skin, the presence of the carbon-epoxy prepreg region increases the overall panel damage tolerance by attracting load away from the more fatigue sensitive aluminum backup structure. The reduction in impact resistance and ductility of the FML where carbon-epoxy is introduced can be countered by limiting the application of carbon-epoxy to the interface regions between the skin and backup structure.

Finally, the higher strength of the carbon-epoxy will also contribute to an improved residual strength of the Glare skin, and overall panel configuration, including backup structure.

3 Experimental test program

Given the potential structural, cost, and manufacturing related improvements offered by the ITS-Glare concept in combination with a monolithic aluminum backup structure, an experimental investigation into its damage tolerant behaviour was carried out. Three aspects of the damage tolerant behavior were examined:

1. The crack growth performance of the ITS-Glare skin panel.
2. The load reduction within the aluminum backup structure.
3. The increase in residual strength.

The remainder of this section briefly summarizes the various tests utilized to evaluate the damage tolerance aspects.

3.1 Specimen configurations

The damage tolerance of ITS-Glare was compared to standard Glare using large centre-crack tension (CCT) specimens. Specimens were tested with and without a representative aluminum backup structure in the form of bonded J-profile stringers as illustrated in Fig. 4, for a total of four panels. The nominal layup used in the specimens was a Glare3-4/3-0.3, consisting of four 0.3 mm thick 2024-T3 aluminum sheets with 0°/90° cross plies of S2-glass-epoxy. In the ITS-Glare specimens, the 0° glass-epoxy layers were replaced with 30 mm wide strip of 0° carbon-epoxy directly beneath the stiffener regions illustrated in Fig. 3. All panels were cured at a temperature of 120°C at 6 bar pressure, while stringers were bonded in a second cure cycle at the same pressure and temperature. Further details regarding the specimen configuration and constituent material properties are given in Fig. 4 and Table 1.

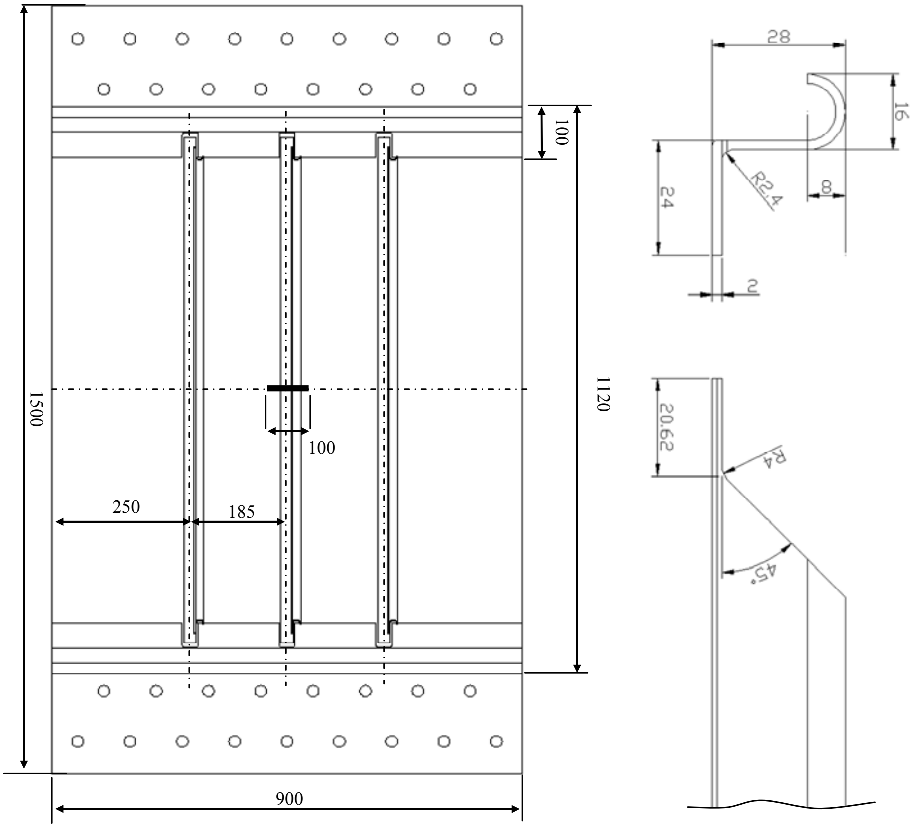

Figure 4. Centre crack tension specimen configurations.

Table 1. Properties of ITS-Glare specimen constituent materials.

Property	UD M30SC/DT120 prepreg	UD S2 glass/FM94 prepreg	2024-T3 aluminum
E_{xx} [GPa]	155	48.9	72.4
E_{yy} [GPa]	7.8	5.5	72.4
G_{xy} [GPa]	5.5	5.5	27.6
ν_{xy}	0.27	0.33	0.33
ν_{yx}	0.022	0.0371	0.33
α [1/°C]	0°: $-4.5\cdot10^{-7}$ / 90°: $2.6\cdot10^{-5}$	0°: $6.1\cdot10^{-6}$ / 90°: $2.6\cdot10^{-5}$	$2.2\cdot10^{-5}$
t [mm]	0.156	0.133	0.3/0.4

3.2 Test procedure

The four CCT test panels were test under fatigue loading to quantify the crack growth performance and subsequently tested for their residual strength. Each panel contained an initial crack, $2a_0$ = 100 mm, generated by a saw cut. In the panels containing bonded stringers, the initial saw cut also passes through the central stringer, simulating a fully broken stringer.

For panels containing stringers, a custom design anti-bending guide was fabricated to allow translation of the panel, but eliminate out of plane deformation due to load-path eccentricity introduced by the stringers. Additionally, strain gauges were installed on the stringers and skin panel to monitor the farfield strains in these elements, and to assess the influence of the carbon-epoxy strap region on stringer strains.

Fatigue loading was carried out using a constant amplitude loading spectrum with a R-ratio of 0.05, test frequency of 10 Hz, and under lab air conditions. The maximum applied stress was 120 MPa and 145 MPa for the unstiffened and stiffened panels respectively. Crack growth measurements were made using a monocular microscope for each crack tip on the front and back side of the panel. Reported crack growth measurements represent an average of the four crack tips. The residual strength of the specimens was tested when the fatigue crack length reached a nominal value of a = 250 mm (50 mm beyond the far edge of the ITS). During the residual strength test, “L-shaped” anti-buckling guides were used. Due to the small thickness to width ratio and due to the high tension loading, crack-edge buckling could have occurred as result of the compressive stress along the edge of the crack if no anti-buckling guides were used.

4 Results

The following section summarizes the results of the stiffened and unstiffened panels made of standard Glare and ITS-Glare. Only a small sample of the data is provided here. A more in-depth analysis of the data from the unstiffened panels is provided in [11].

4.1 Stringer strains

The observed stringer strains as a function of crack length for the stiffened Glare and ITS-Glare panels are plotted in Fig. 5. For the ITS-panel configuration tested, the addition of carbon as implemented results in an overall skin panel stiffness increase of 4%. From the measurements in Fig. 5, this resulted in a 5% reduction in strain in the stiffeners for small crack lengths. As the fatigue crack grew, the local stiffening effects of the carbon fibres became more apparent and the stiffener strain reduction grew above 8%. Although these strain reductions appear small, small reductions in stringer load can result in significant increases in fatigue crack initiation lives for these structural elements. Furthermore, it demonstrates the feasibility of the concept for reducing loads in monolithic backup structures. Further optimization of panel geometry and ITS placement/size could be undertaken to achieve larger and more beneficial load reductions for a given FML skin-monolithic backup structure combination.

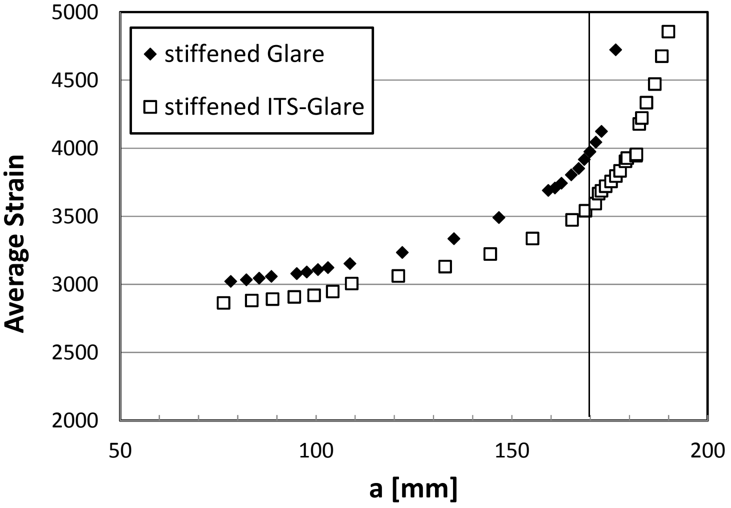

Figure 5. Observed stringer strains along the crack plane as a function of crack length.

4.2 Crack growth resistance

Crack growth results for the unstiffened Glare and ITS-Glare panels are shown in Fig. 6. Results for crack growth in the stiffened panels are not shown, as they are dominated by the bridging effect of the stringer and thus do not show any appreciable difference. The results in Fig. 6 demonstrate the tear strap like effect of the carbon-epoxy region which is highlighted in grey. This region attracts load as the crack approaches, and bridges more load as the crack grows across is, as a result of its higher stiffness, greatly reducing crack growth rates in the vicinity of the ITS.

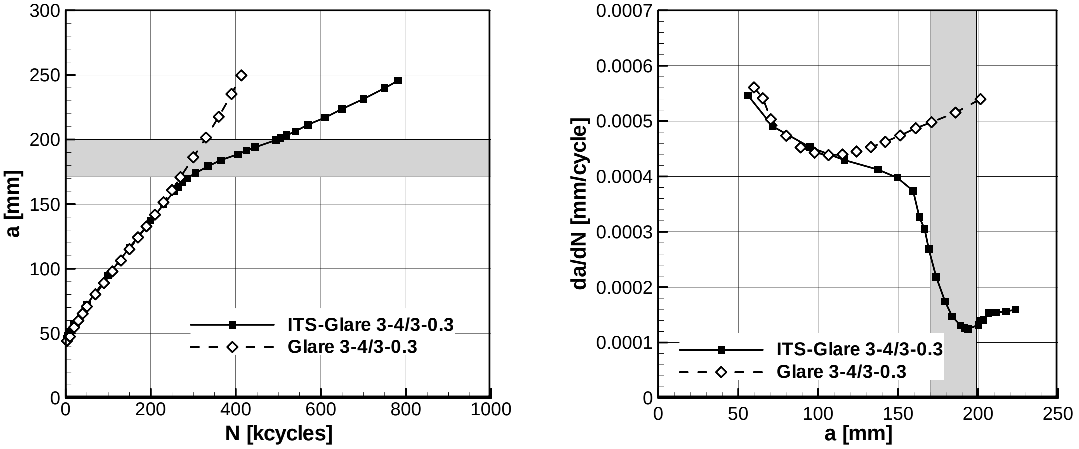

Figure 6. Crack growth in unstiffened Glare and ITS-Glare panels.

This observed tear strap behavior of the carbon-epoxy region suggests that a benefit in damage tolerance could be achieved by placing ITS regions between stringer elements in addition to beneath them. The addition of more ITS within the Glare panel would permit larger stiffness increases in the overall panel, further contributing to the reduction in load carried by a monolithic aluminum backup structure. This, however, comes at a risk. The impact resistance of the ITS is significantly lower than the standard Glare regions of the panel. For the ITS regions located beneath the stringers, the stringers reinforce the panel, making up for this reduction in impact resistance. Trade-offs in damage sensitivity and critical damage modes for a given structure would have to be taken into account in order to achieve an optimal solution.

4.3 Residual strength

Residual strength results for both the stiffened and unstiffened panel pairs are shown in Fig. 7. The results for the stiffened panels are a bit misleading, suggesting that the presence of the ITS reduced the residual strength of the panel. As for fatigue crack growth, the residual strength of the panel with a large skin crack is heavily dominated by the stringers themselves. This was observed in the stiffened panel residual test results where early failure of one of the stringers (resulting from some asymmetry in the fatigue crack grown prior to the residual strength test) resulted in a lower observed residual strength of the ITS-Glare stiffened panel. In the test results for the unstiffened panel, the higher strength of the ITS relative to the glass-epoxy it replaced becomes evident, and a greater than 20% increase in residual strength for the crack geometry tested was observed.

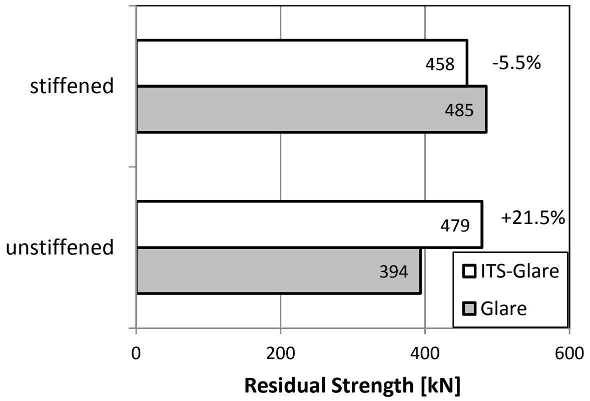

Figure 7. Residual strength comparison of stiffened and unstiffened Glare and ITS-Glare panels.

5 Conclusions

Overall, the results of this work demonstrated the feasibility of utilizing a material substitution strategy in improving the damage tolerance of a standard aluminum/glass-epoxy FML panel containing a monolithic aluminum backup structure. The following potential improvements to damage tolerance were observed by adding carbon-epoxy ITSs:

- A reduction in load carried by the more fatigue sensitive backup structure due to an overall increase in skin stiffness.
- A reduction in fatigue crack growth rate for cracks located in the skin near the ITS. This effect mimics that of a traditional bonded titanium tear strap used in some monolithic aluminum structures.
- An increase in residual strength of the FML skin panel.

In addition to the damage tolerance benefits, the ITS concept also presents a potential improvement in manufacturing cost. Although the application of local fibre substitutions will carry a manufacturing cost penalty, the potential to eliminate thickness variations necessitated by the current interlaminar doubler solution (see Fig. 2) could reduce costs associated with joggling and match machining of a mating backup structure. Further investigation into the actual cost benefits is still necessary.

Acknowledgements

The work presented in this paper was sponsored by the Netherlands Organization for Scientific Research (NWO) and Technical Science Foundation (STW) under the Innovational Research Incentives Scheme Veni grant.

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