Fatigue Behaviour of Glare Panels Containing Internal Carbon Tear Straps

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ABSTRACT: This paper presents a novel hybrid structural concept for improving the damage tolerance of a thin panels subjected to fatigue, such as the skin of an aircraft fuselage. The concept is based on the hybrid fibre metal laminate (FML) technology utilized as a fuselage skin material in the Airbus A380. By tailoring the stiffness of an FML locally by variation of the reinforcing fibre, a damage tolerant feature analogous to the bonded titanium tear strap in monolithic metallic fuselage skins can be introduced internally within the laminate, without variations in laminate thickness. The overall merits of this concept are discussed, including a preliminary experimental investigation into its improvements to damage tolerance of standard FMLs. Overall, the concept was shown to result in nearly a two-fold reduction in crack growth and up to a 25% increase in residual strength for fatigue cracks located near the damage tolerant feature.

KEYWORDS: Fatigue; damage tolerance; crack growth; FML; tear strap.

NOMENCLATURE:
1 Introduction

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. In aircraft structures, this critical level is typically associated with the ability of the structure to carry limit loads. From a design standpoint, implementing the damage tolerance concept requires an understanding of the growth and evolution of damages such that a structure can be designed to
maximize the growth period for damages (time available for inspection) or arrest the growth of potentially critical damages.

Developments in materials and structural design have both contributed to improvements in the damage tolerance of modern airframe structures. New developments in metal alloys, composite materials, and hybrid materials such as the fibre metal laminate concept [1-8] have all resulted in materials less sensitive to damage and with slower damage growth rates. Similarly, design features which arrest damage propagation, such as tear straps and shear clips in metal airframes [9-13], or introduce redundant load paths have also provided designers with methods for improving the damage tolerance of a structure.

![Illustration of a fibre metal laminate](image)

**Figure 1: Illustration of a fibre metal laminate**

Fibre metal laminates (FMLs) are laminates comprising of alternating layers of thin metallic sheets and pre-impregnated composite layers (Figure 1). Recent developments in FML technology have highlighted the trend in shifting the treatment of FMLs as standardized grades with given layups and properties to fully tailorable structural solutions [13]. The application of FMLs to the upper fuselage skin of the Airbus A380 commercial jet aircraft has embraced this shift by integrating reinforcing material (doublers) into the layup of the FML skin: the so-called interlaminar doubler (Figure 2) [12]. The interlaminar doubler provides a local increase in stiffness which can be exploited for a number of design purposes, including local retardation and/or turning of fatigue cracks as is typically achieved through bonded tear straps.
Similar to bonded tear straps, the interlaminar doubler solution produces local variations in the thickness of a skin panel. These thickness variations can complicate the design, manufacturing tolerances, and manufacturing processes for the supporting backup structure for the skin panel. Features such as joggled stringers and frames with matching thickness steps machined into their mating surfaces would need to be incorporated in order to accommodate the thickness variations. For high production run aircraft, such as narrow-body regional jets, the cost of these manufacturing complexities combined with the cost of laminating and curing an FML reduce the competitiveness of the technology compared to monolithic metallic solutions.

This paper investigates another possibility for integrating a tear strap into an FML panel. 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 skin panel having the performance of a panel with tear straps but without local variations in the panel thickness, thus simplifying the needed backup structure and improving the cost competitiveness of FMLs compared to monolithic metal alloys for narrow-body aircraft skin applications.

2 Background and the Internal Tear Strap Glare Concept

The addition of a bonded tear strap to a monolithic metallic panel improves the damage tolerance of the panel in three ways:

1. The added stiffness of the tear strap attracts load away from the centre of the panel. This reduces the driving force for crack growth in the unreinforced region of the panel, particularly as the crack approaches the tear strap.
2. The bonded interface between the tear strap and panel provides a barrier to the propagation of a fatigue crack from the panel into the tear strap. This allows the tear strap to remain intact and bridge load over the fatigue crack as it grows under the tear strap.

3. The local increase of panel stiffness around the tear strap region can result in bulging (out-of-plane deformation) in the case of loading due to pressurization. The added stress components due to bulging can alter the crack path and result in the formation of a flapping failure whereby the pressure cylinder depressurizes before unstable fracture occurs.

In this context, FMLs can be looked at as a monolithic metallic panels with continuous composite tear straps adhered along their entire width. As the composite layers are continuous across the whole panel width in an FML, there is no local variation in panel stiffness. Thus, mechanisms 1 and 3 as stated above are not present and mechanism 2 is responsible for the increased damage tolerance of FMLs over monolithic metallic panels. Indeed, the description of the bridging load in terms of fibre and metal layer stiffness, and metallic crack and interface delamination damage states has been key to predicting the damage tolerance behaviour of FMLs [4, 14-19].

Damage tolerance is not only related to crack growth performance. Impact behaviour, notch sensitivity, and residual strength behaviour are also key aspects of damage tolerance for aircraft structures. This is evident when looking at the fibre selection for the most prevalent variant of FMLs known as Glare (glass reinforced aluminum). The stiffness of the glass-epoxy layer is lower than that of aluminum, and thus bridging of the fibre layer is less effective. The use of a stiff fibre layer, as in the carbon-epoxy/aluminum FML variant known as Carall, will result in a superior crack bridging effect and crack growth resistance [20, 21]. The low strain-to-failure of carbon-epoxy, however, results in a significantly lower impact resistance and more brittle residual strength behaviour of Carall compared to Glare [3]. Thus, Glare represents a compromise in potential crack growth performance for overall damage tolerance behaviour.

In order to increase the crack growth resistance of Glare without adversely affecting its global impact and residual strength behaviour, a new FML concept has been developed. Starting with a basic Glare panel configuration, regions of reinforcing glass-epoxy prepreg were substituted with carbon-epoxy prepreg during layup as illustrated in Figure 3. In the region of material substitution, the bridging
capability of the fibre layer will be improved due to the added stiffness, improving crack growth resistance. In the regions adjacent to the material substitution, crack growth resistance will be improved due to the load attracting behaviour of the stiffer region and the potential for bulging under pressurization loading as described for a bonded tear strap in mechanisms 1 and 3 above. Indeed, the local carbon-epoxy region acts analogous to a bonded tear strap. To distinguish this new concept from standard Glare, it will be referred to as internal tear strap Glare, or ITS-Glare, throughout this paper.

**Figure 3: Illustration of the internal tear strap Glare concept**

The application of carbon fibre material in conjunction with aluminum in the ITS-Glare concept raises the possible concern of galvanic corrosion. The application of the carbon fibre material internal to the laminate offers several isolation options and limits the potential for exposure to electrolytic moisture necessary for the galvanic corrosion process. Furthermore, the local application of the carbon fibre material permits fastener holes, cut-out, and other structural details which may provide access for moisture within the laminate to be planned to avoid the carbon containing regions. Alternatively, the ITS-Glare concept can in principle be achieved using an alternative stiff reinforcing fibre material, avoiding this concern entirely. Carbon-epoxy has been chosen for this study mainly due to its availability, relatively high stiffness, and experience with carbon-epoxy in Carall laminates.

The ITS-Glare concept offers several advantages over a conventional bonded tear strap configuration or the interlaminar doubler FML concept illustrated in Figure 2. Considering a bonded tear strap configuration (bonded strap on base FML skin), curing of the structure would typically involve two
cure cycles. The first cure cycle would consolidate the constituent layers of the base FML skin while the second cycle would be used to bond the tear straps to the base skin. This two-step cycle approach is often adopted to minimize relative motion of the layers and tear straps, and to facilitate non-destructive inspection of the base FML skin after the first cure cycle [22, 23]. Conversely, the ITS-Glare concept requires only one cure cycle as the tear strap is an integral constituent of the FML skin. It should be noted that the additional cutting and placing of different fibre types in the ITS-Glare concept adds some complexity to the layup process, however, the impact of this complexity can be minimized by modern automatic fibre placement technologies. Relative to an interlaminar doubler configuration, the ITS-Glare concept eliminates potential problems of wrinkling or draping of the metal layers over the thickness variation caused by the interlaminar doubler. Strict guidelines in maximum thickness step and distance between thickness steps are currently enforced for interlaminar doublers in FMLs to avoid this, which are unnecessary in ITS-Glare due to the uniform thickness. Finally, the uniform structural thickness in ITS-Glare provides advantages in structural assembly, especially in the attachment of stringers and frames. The lack of thickness variations eliminates the need for match-machining of frames and joggling of stringers to conform to the internal surface of the reinforced skin.

3 TEST PROGRAM

Given the potential structural, cost, and manufacturing related improvements offered by the ITS-Glare concept, an experimental investigation into its damage tolerant behaviour was carried out. This investigation consisted primarily of fatigue tests to characterize the influence of the ITS in Glare on crack initiation and crack growth performance. Residual strength tests were also carried out for various crack lengths. This section summarizes the various tests and test specimen configurations used in this study, while the remainder of this paper will draw upon the study results in order to assess the potential of the ITS-Glare concept.

3.1 Specimen Configurations

Two panel configurations were used to investigate the damage tolerance behaviour of the ITS-Glare concept. A small panel, which will be referred to as the narrow-panel configuration, was used to conduct a preliminary assessment of the ITS-Glare concept. A second study was performed with a larger specimen, referred to as the wide-panel configuration, which contained a more representative spacing for the internal tear straps and a larger width to minimize finite width effects on the results. In
addition to different panel sizes, the two configurations had different laminate layups. The narrow panel consisted of a 3/2 layup (3 metal layers and 2 cross-ply fibre layers) while the wide panel had a 4/3 layup. Each configuration also had different aluminum layer thicknesses, with the narrow panel containing 0.4 mm thick aluminum sheets and the wide panel containing 0.3 mm thick aluminum sheets. Additional details about the panel geometries and layups are summarized in Figure 4. The material properties for each of the layer material types are given in Table 1. All panels were cured at a temperature of 120°C at 6 bar pressure.

Table 1: Properties of ITS-Glare specimen constituent materials

<table>
<thead>
<tr>
<th>Property</th>
<th>UD M30SC/DT120 prepreg</th>
<th>UD S2 glass/FM94 prepreg</th>
<th>2024-T3 aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{xx}$ [GPa]</td>
<td>155</td>
<td>48.9</td>
<td>72.4</td>
</tr>
<tr>
<td>$E_{yy}$ [GPa]</td>
<td>7.8</td>
<td>5.5</td>
<td>72.4</td>
</tr>
<tr>
<td>$G_{xy}$ [GPa]</td>
<td>5.5</td>
<td>5.5</td>
<td>27.6</td>
</tr>
<tr>
<td>$v_{xy}$</td>
<td>0.27</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>$v_{yx}$</td>
<td>0.022</td>
<td>0.0371</td>
<td>0.33</td>
</tr>
<tr>
<td>$\alpha$ [1/°C]</td>
<td>0°: -4.5·10^{-7} / 90°; 2.6·10^{-5}</td>
<td>0°: 6.1·10^{-6} / 90°; 2.6·10^{-5}</td>
<td>2.2·10^{-5}</td>
</tr>
<tr>
<td>$t$ [mm]</td>
<td>0.156</td>
<td>0.133</td>
<td>0.3/0.4</td>
</tr>
</tbody>
</table>

3.2 Crack Initiation Tests

The crack initiation performance of the carbon ITS and Glare regions of the ITS-Glare concept were evaluated using an open-hole tension fatigue test. A single narrow-panel specimen was fatigue tested with a pattern of six holes, each with a diameter of 5.7 mm. The holes were arranged in two rows, spaced 50 mm above and below the mid-plane of the panel (see Figure 4). Each row contained a single
hole along the centre line of the panel (in the Glare region) and a hole located along the centre line of each of the two carbon straps (ITS region). For each hole, four crack initiation measurements were possible; left and right side of the hole in each of the two outer metallic layers. This arrangement permitted eight crack initiation measurements in the Glare region and sixteen measurements in the ITS region.

The open-hole tension specimen was loaded in fatigue under a constant amplitude loading spectrum with a maximum applied stress of 120 MPa, R-ratio of 0.05, test frequency of 10 Hz, and under lab air conditions. The specimen was instrumented to detect crack initiation using the potential drop method. This method has been successfully applied for measuring crack initiation, defined as the fatigue life required to generate a 1.0 mm fatigue crack, in previous studies of FML crack initiation [24]. Once detected, individual cracks were measured with an optical microscope to ensure the detected crack was close to the 1.0 mm length defined as the transition from crack initiation to crack growth.

3.3 Crack Growth Tests

The crack growth performance of the ITS-Glare concept was evaluated using centre-cracked tension (CCT) fatigue specimens. Crack growth measurements were performed on wide- and narrow-panel configurations of the ITS-Glare concept and standard Glare. The narrow-panel configurations contained a starter saw-cut of length $2a_0 = 25$ mm, while the wide-panel configuration contained a starter saw-cut of $2a_0 = 75$ mm. The length of the saw cut in an FML panel is of significance as the fibres are cut along the saw-cut length, and thus do not contribute to fibre bridging.

Fatigue loading of the CCT specimens was carried out using the same constant amplitude fatigue spectrum as used in the crack initiation tests, with a maximum applied stress of 120 MPa, R-ratio of 0.05, test frequency of 10 Hz, and under lab air conditions. 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.

3.4 Residual Strength Tests

The influence of the internal carbon tear strap on the residual strength of a standard FML panel was evaluated using CCT specimens containing fatigue cracks of various lengths. Residual strength tests were performed on narrow-panel ITS-Glare and standard Glare specimens (initial saw cut $2a_0 = 25$ mm).
with two nominal fatigue crack lengths; \( a = 40 \text{ mm} \) (10 mm before the near edge of the ITS) and \( a = 85 \text{ mm} \) (10 mm after the far edge of the ITS). Additionally, residual strength tests were performed on the two wide-panel fatigue test specimens with a nominal final crack length of \( a = 250 \text{ mm} \) (50 mm beyond the far edge of the ITS). Growth of the fatigue crack to the nominal value for residual strength testing was performed using the same constant amplitude fatigue spectrum used for the crack initiation and crack growth tests.

4 RESULTS AND DISCUSSION

4.1 Crack Initiation

Results from the crack initiation life test are summarized in Figure 5, with the error bars indicating one standard deviation in the observed initiation life. The initiation life for the ITS region of the panel is based on 16 crack measurements (4 for each notch) while the Glare region is based on 8 crack measurements. The average and standard deviation for crack length at detection where 1.1 mm (0.2 mm) and 1.2 mm (0.1 mm) for the ITS and Glare regions respectively. Overall, similar crack initiation lives were observed for the Glare and ITS regions of the test panel.

![Figure 5: Comparison of crack initiation life of the ITS and Glare regions of an ITS-Glare panel](image)

The similarity in crack initiation lives between the Glare and ITS regions of the test panel is expected. Despite the fact that locally the ITS region of the panel can be viewed as a Carall laminate and the Glare region as a Glare laminate, these regions interact and influence each other in terms of applied loads and residual stresses. Compatibility between the glass and carbon layers is enforced through their connection to each other and through the metal layers they are bonded to. This compatibility can be modelled as a simple spring system, where each layer of the laminate is represented by a spring and the 0° hybrid fibre layer is represented by two parallel springs (one for each fibre type), as illustrated in Figure 6. Based upon this representation, the laminate spring stiffnesses are given by:
Where $E$ is the layer Young’s modulus, $t$ is the layer thickness, $n$ is the number of layers of a given type in the laminate, and geometry parameters $L$, $W$, and $W_s$ are defined in Figure 4. Subscripts $A_l$, $C0^\circ$, $G0^\circ$, and $G90^\circ$ refer to aluminum, 0° carbon, 0° Glass, and 90° glass layers respectively. Based upon compatibility of the spring displacements, the stress in each layer due to the applied load can be defined as:

$$\sigma_{\text{layer}} = \frac{P \cdot E_{\text{layer}}}{L(k_{A_l} + k_{G0^\circ} + k_{C0^\circ})}$$

(1.2)

The stress in the metal layers is thus constant due to the strain compatibility with the adjacent layers. The effect of the added stiffness of the carbon ITS is to increase $k_{0^\circ}$, and thus lower the stress in the aluminum layers compared to its standard Glare equivalent. Similarly, the residual stress due to curing can also be computed using the spring-system analogy in terms of $\Delta T = T_{\text{cure}} - T_{\text{operating}}$:

$$\left(\sigma_{\text{res}}\right)_{\text{Al}} = \Delta T \cdot \frac{k_{C0^\circ}(\alpha_{\text{Al}} - \alpha_{C0^\circ}) + k_{G0^\circ}(\alpha_{\text{Al}} - \alpha_{G0^\circ}) + k_{G90^\circ}(\alpha_{\text{Al}} - \alpha_{G90^\circ})}{k_{A_l} + k_{G0^\circ} + k_{C0^\circ}} \cdot E_{\text{Al}}$$

(1.3)
Based on equations 1.1-1.3, the cyclic stress cycle experienced by the aluminum layers can be calculated based upon the cyclic stresses carried by the aluminum layers ($\sigma_{Al}$ from eqn. 1.2) and the aluminum layer residual stress ($\sigma_{res,Al}$ from eqn. 1.3). The results of this calculation for the ITS-Glare crack initiation panel are summarized in Table 2. It should be noted that the results of this calculation for ITS-Glare depend on the width ratio of the ITS and overall panel, and thus the values calculated for the crack initiation panel are not the same as for the wide-panel configuration used in the crack growth tests. For comparison purposes, Table 2 includes details about the aluminum layer stress cyclic stress cycle for the Glare and Carall laminates with the same lay-up and metal layer thicknesses.

Table 2: Comparison of applied vs. metal layer fatigue stress cycles in various FMLs

<table>
<thead>
<tr>
<th>Laminate</th>
<th>$\sigma_{applied}$ [MPa]</th>
<th>$R_{applied}$ [-]</th>
<th>$\sigma_{res,Al}$ [MPa]</th>
<th>$\sigma_{max,Al} = \sigma_{Al} + \sigma_{res,Al}$ [MPa]</th>
<th>$R_{Al}$ [-]</th>
<th>Predicted $N_{in}$ [cycles]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carall 3-3/2-0.4</td>
<td>120</td>
<td>0.05</td>
<td>51.0</td>
<td>165.8</td>
<td>0.342</td>
<td>1,100,000</td>
</tr>
<tr>
<td>Glare 3-3/2-0.4</td>
<td>120</td>
<td>0.05</td>
<td>14.3</td>
<td>174.3</td>
<td>0.116</td>
<td>62,000</td>
</tr>
<tr>
<td>ITS-Glare 3 panel</td>
<td>120</td>
<td>0.05</td>
<td>13.3</td>
<td>178.3</td>
<td>0.176</td>
<td>76,000</td>
</tr>
</tbody>
</table>

According to Homan [24], crack initiation in FMLs is a metallic phenomenon and can be predicted based upon the crack initiation behaviour of the metallic material and the actual cyclic stress cycle experienced by the metal layer in an FML. This was confirmed by Homan by plotting the crack initiation behaviour of Glare laminates on an S-N diagram for the crack initiation behaviour of 2024-T3 aluminum. To confirm that this trend still holds for ITS-Glare, the observed crack initiation results have been plotted on the 2024-T3 S-N curve from [24] in Figure 7. In order to fairly compare to the crack initiation results for ITS-Glare, the original S-N data from Homan ($R = 0.05$) was transformed to the same R-ratio experienced by the aluminum layers of the ITS-Glare specimen ($R = 0.176$) using the Gerber parabola [25] and an ultimate stress of 400 MPa for 2024-T3. Results from Figure 7 indeed show that the crack initiation life of ITS-Glare is accurately predicted by the S-N behaviour of 2024-T3 when looking at the actual stress cycle in the aluminum layers.
Homan’s methodology for predicting crack initiation in FMLs based on the S-N behaviour of the metal layer provides a simple way for comparing the relative crack initiation behaviour of different FMLs. Using this method, the predicted crack initiation life for the ITS-Glare crack initiation specimen and its Glare and Carall equivalents were calculated and are given in Table 2. The ITS-Glare concept resulted in a 20% improvement in crack initiation life over standard Glare for the crack initiation test specimen, however in a real application of the concept the spacing of the ITS would be much greater, reducing the overall stiffening ratio and resulting benefit in crack initiation life. In general, however, the ITS-Glare concept should result in similar or slightly improved crack initiation behaviour compared to standard Glare.

4.2 Crack Growth

Crack growth results from the centre-crack tension fatigue tests are summarized in Figure 8 for the narrow-panel configuration and in Figure 9 for the wide panel configuration. Both panels show similar trends and similar influence of the carbon ITS; however, it is clear that there is a significant finite-width influence on crack growth in the narrow panel. The presence of the carbon ITS resulted in approximately a 60-80% reduction in crack growth rate with the ITS region relative to standard Glare panels.
The relative fatigue crack growth performance of stiffened vs. unstiffened panels is typically expressed in terms of a Beta correction factor such that:

\[
\beta = \frac{K_{\text{stiffened}}}{K_{\text{unstiffened}}}
\]

Where \( K_{\text{stiffened}} \) and \( K_{\text{unstiffened}} \) are the crack tip stress intensity factors of the stiffened and unstiffened panels respectively. This is a relatively straight forward calculation for a monolithic metallic panel as \( K \) for such materials is a function of panel geometry (which is fixed), applied load and crack length (which can vary). The Beta factor is thus defined at the same crack length and applied load for the stiffened and unstiffened panel in order to result in a factor dependant on only the panel geometry.
The same approach is not as straightforward for FMLs. In addition to panel geometry, applied load, and crack length, the stress intensity factor in an FML panel is also dependent on the shape and size of the interface delamination between the cracked metal layers and bridging fibre layers. The shape and size of the delamination are directly linked to the amount of fibre bridging provided by the intact fibre layer. To account for this influence, Alderliesten [15, 16] developed a crack growth model in which the stress intensity factor in the cracked metal layers is reduced to superposition of the stress intensity factor solutions for the cracked sheet subjected to the far-field metal layer stresses \( K_{ff} \) and the bridging stress distribution along the perimeter of the delamination front \( K_{br} \). The influence of delamination shape and size is accounted for in \( K_{br} \), which is a path dependant term. Different loading scenarios can lead to different delamination shape/sizes for the same crack length in an FML, resulting in different crack tip stress intensity factors and resultant crack growth rates in similar FMLs with the same crack length. This behaviour is clearly illustrated by the crack growth behaviour of FMLs at different temperatures [26] and under variable amplitude fatigue loading [5, 6, 18].

The additional effect of the stiffening element can be viewed using the same superposition approach of Alderliesten. The total crack tip stress intensity factor in the cracked metal layers can be subdivided into \( K_{ff}, K_{br}, \) and \( K_{stiffener} \) as illustrated in Figure 10. Using this definition, the Beta factor for the ITS-Glare panel can be defined as:

\[
\beta_{ITS-Glare} = \frac{\left( K_{ff} - K_{br} - K_{stiffener} \right)_{ITS-Glare}}{\left( K_{ff} - K_{br} \right)_{Glare}}
\]  

(1.5)

Although calculation of each of the individual \( K \) components is not straightforward, defining Beta in this way for ITS-Glare helps illustrate the different competing mechanisms at play. \( K_{ff} \) is dependent on the far field metal layer stresses which can vary between the stiffened and unstiffened FML panels based on the stiffness ratios of the metal to fibre layers and base laminate to stiffened laminate regions. \( K_{br} \) is dependent on the shape and size of the interface delamination which is load history dependent and can vary between the stiffened and unstiffened panels. Finally, \( K_{stiffener} \) is related to the stiffness ratio of the stiffened and unstiffened region, and the proximity of the stiffened region to the crack tip. Thus Beta for ITS-Glare is dependent on all of these factors and its definition is not as straightforward as it is for a monolithic panel.
Despite the complexity in the definition of Beta for a stiffened FML, the ability to relate crack growth in an FML to the crack growth behaviour of the metal material [15, 16] provides a means to experimentally determine Beta. Using the Paris Law to describe the fatigue crack growth behaviour of the metal layers, Beta can be experimentally determined by:

\[
\beta_{\text{ITS-Glare}} = \frac{\frac{1}{n} \log \left( \frac{(\Delta u/N)_{\text{ITS-Glare}}}{c} \right)}{10^{ \frac{1}{n} \log \left( \frac{(\Delta u/N)_{\text{metal}}}{c} \right)}}
\]

(1.6)

Where \(C\) and \(n\) are the Paris law coefficients for 2024-T3. Using the coefficients \(C = 2.17 \cdot 10^{-12}\) and \(n = 2.94\) [15], the Beta factor for ITS-Glare was calculated using the above equation and plotted for both panel configurations in Figure 11. Also plotted for comparison is predictions of Beta for a monolithic panel with the same stiffening ratio as the ITS-Glare panel based on the approach detailed in [27]. It should be noted that this prediction does not include the effect of bridging stress on Beta.
From the results for Beta in Figure 11, it is clear that the majority of the improvement in crack growth performance of the ITS-Glare panel occurs once the crack grows into the ITS region. Before reaching this region, the carbon ITS strap primarily influences crack growth through $K_{\text{stiffener}}$ illustrated in Figure 10. This is the same effect illustrated by the predictions in Figure 11. Once the crack grows into the carbon ITS region, the stiffer carbon fibres provided improved fibre bridging capability, resulting in a more favourable $K_{\text{br}}$. The stiffer fibres behind the crack tip provide a greater resistance to crack opening, lowering the overall crack tip stress intensity factor in the metal layer. Due to the lower fatigue sensitivity of the fibre layer relative to metallic materials commonly used for bonded tear straps, such as titanium, the beneficial load bridging capability of the carbon ITS is also maintained for a greater period of time.

### 4.3 Residual Strength

The final area of damage tolerance examined in this assessment of the ITS-Glare concept is residual strength. Results from the three residual strength tests are summarized in Figure 12. In all cases, the ITS-Glare concept exhibited a higher residual strength relative to a standard Glare laminate with the same crack length (increase expressed as a percentage in Figure 12). The higher stiffness and strength of the carbon ITS produces this increase in residual strength by diverting load away from the crack tip. When the ITS is ahead of the crack tip, the amount of load carried by the ITS is governed by displacement compatibility with the surrounding laminate ahead of the crack tip. Conversely, when the ITS is behind the crack tip, the crack opening displacement of the metal layer over the ITS governs the load carried by the ITS. The latter case results in a higher load carried by the ITS, and thus a greater improvement in residual stress relative to the standard Glare laminate. Overall, the residual strength of
the ITS-Glare panel still drops with increasing crack length; however, the rate of this drop is less severe than observed/expected in a standard Glare laminate.

![Diagram showing comparison of ITS-Glare and standard Glare gross residual strengths](image)

**Figure 12: Comparison of ITS-Glare and standard Glare gross residual strengths**

## 5 CONCLUSIONS

A novel tear strap concept for FMLs, utilizing the composite nature of the material and the ability to tailor locally the fibre type and stiffness, has been presented. The potential of this novel concept, termed ITS-Glare, was evaluated for its potential improvements to the damage tolerance of the commercial FML Glare. The ITS-Glare concept was shown to result in a small improvement in crack initiation performance, up to an 80% reduction in crack growth rate (in the region of the ITS), and an increase in residual strength ranging from 15-25% (dependant on the location of the crack relative to the ITS) relative to an equivalent Glare laminate. These improvements represent a significant improvement in damage tolerance over standard Glare.

The ITS-Glare concept has been presented as an alternative to bonded titanium tear straps (commonly applied on metallic aircraft structures) and interlaminar doubler straps (currently applied on the Airbus A380). The major benefit of the ITS-Glare concept is that it results in improvements in damage tolerance, by means analogous to the other two alternatives, without resulting in local thickness variations in the finished structure. The lack of thickness variations eliminates the need to joggle stringers and match-machine frames to which the skin panel would be joined. This represents a potentially significant improvement in manufacturing and assembly costs for stiffened aircraft.
structures and could help offset the higher material cost of FMLs relative to monolithic metals for narrow body aircraft applications.

Finally, although this initial assessment of the ITS-Glare concept demonstrated a significant increase in damage tolerance relative to standard Glare, the influence of bulging due to local stiffness variation has not been evaluated. The presence of bulging in pressure vessels, such as an aircraft fuselage, represents a significant contribution of tear straps to damage tolerance through introducing a crack turning driving force. This aspect of the ITS-Glare concept has not yet been evaluated.

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References


