A novel approach for estimation of crack paths in Fibre Metal Laminates

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ABSTRACT. *This paper discusses experimental results of fatigue tests under off-axis loading with respect to the principal direction of fibres in Fibre Metal Laminates. The cracks in the metal layers of the FMLs does not propagate perpendicular to loading but at an angle to this orthogonal direction. Previous attempts to explain the crack path direction with established theories for predicting crack paths in monolithic metals are unable to explain the results in FMLs. This paper explains the crack path is primarily a consequence of fibre bridging in the two directions: the direction of loading, and the direction perpendicular to loading.*

Keywords – FMLs, mixed-mode fibre bridging

INTRODUCTION

Crack propagating under an angle with respect to the horizontal direction - the direction perpendicular to the tensile loading direction - has been a subject of investigation since decades. Oblique cracks were first studied by Erdogan and Sih [1] who developed the Maximum Tangential Stress (MTS) theory describing the crack propagation angle using the first singular terms in the Williams series for stress field [2]. Subsequently, other research studies showed the influence of the higher order terms – T-stress [3] – of the William's stress field [2] on the crack path. Williams and Ewing [4] concluded their study on angled cracks with the stresses at a distance r_c [5] from the crack tip to the directionality of crack paths.

Further studies have shown the influence of the T-stress on the fracture toughness, size and shape of the plastic zone [6], and on the crack path stability in isotropic materials [7]. Later, studies showed the crack paths to remain stable and straight only under homogeneous remote stress fields [8]. However, the condition of homogeneity is not obeyed with applied mixed mode-loading, geometrical disturbances and anisotropy of the materials.

Smith, Ayatollahi and Pavier [6] suggested that the influence of the mixed-mode parameter – i.e. related to the ratio of Mode I loading to Mode II loading – combined with the T-stress describes the crack path. However, limited work has been performed to understand the problem of loss of directional stability of cracks in anisotropic materials.

This paper discusses crack paths observed in Fibre Metal Laminates (FMLs) – anisotropic materials with layers of fibres between layers of metal – under static and fatigue off-axis loading. The observed damage modes and failure mechanisms are introduced, followed by a description of the fatigue experiments performed by Gonesh [9, 10]. These experimental results are discussed in this paper to propose an alternative theory to describe crack paths in FMLs.

Theoretical Background on Damage Mechanisms in FMLs

FMLs are hybrid materials containing both metal and fibre constituents developed for primary aeronautical applications. The use of fibres in FMLs makes them intrinsically anisotropic in nature. Glare (GLAss REinforced aluminium) is an FML currently being used as fuselage skin material in the Airbus A380. Since several grades of Glare with a large amount of lay-ups are possible, a coding system as follows is used to identify the Glare grade and lay-up.

The cross-ply laminate Glare 3-3/2-0.3 refers to respectively Glare grade, the lay-up (no. of metal layers and fibres) and, the aluminium layer thickness. The lay-up for this case is defined as [11]

$$[2024\text{-T3}/0^0\ \text{glass}/90^0\ \text{glass}/2024\text{-T3}/90^0\ \text{glass}/0^0\ \text{glass}/2024\text{-T3}]$$

Intensive research has been undertaken in the previous years, to understand the phenomena of various damage mechanisms in FMLs. Marissen [12] introduced the concept of fibre bridging to explain the reduced crack growth rates of the Mode I cracks propagating in metal layers of ARALL. Alderliesten [11] developed a closed form analytical solution to predict crack propagation and delamination growth in the wake of the propagating cracks by reducing the damage problem to a crack in the metallic layer and the fibre bridging contribution to that particular layer. Alderliesten's model [11] has been recently further developed towards arbitrary FML configuration and different load cases by Wilson. [13, 14].

Despite, the advances in studying damage mechanisms in FMLs, little knowledge is available on the behaviour of FMLs under off-axis loading [9, 10, 15]. Kawaii *et al.* [16-18] studied the behaviour of Glare-2 and Glare-3 under off-axis loading for both static and fatigue tests. They reported the fatigue strength to reduce significantly as the direction of off-axis angle increases.

Thibault-Liboiron *et al.* [19] presented the results of fatigue test for edge notched specimens. They observed in cross-ply laminates the fatigue crack growth rates to increase with the off-axis angle up to 45^0 where the laminate stiffness is minimal. However, in Glare laminates where the fibre layer adjacent to the metal layer is perpendicular to the loading direction, the ability of the fibres to bridge the crack opening in the loading direction reduces.

Zaal [15] presented a model to predict crack paths in FMLs based on the anisotropic T-stress criterion. The model considered the laminate entirely as one homogeneous material, and using different values for r_c [5] to predict the fracture angle. However, the experiments by Gonesh [10] and Thibault-Liboiron [19] seem to indicate different angles than what this theory predicts.

At the present state of the art, the mechanisms controlling the path taken by a propagating crack in FMLs are not yet completely understood. However, crack turning has already been recognized as a potentially important crack arrest mechanism in aircraft fuselages [20]. For this reason and to extend the application of Glare further to lower wing structures, where unidirectional laminates are considered rather than cross-ply laminates, it becomes necessary to develop understanding of the crack turning behaviour in an FML under off-axis loading.

OFF-AXIS FATIGUE EXPERIMENTS

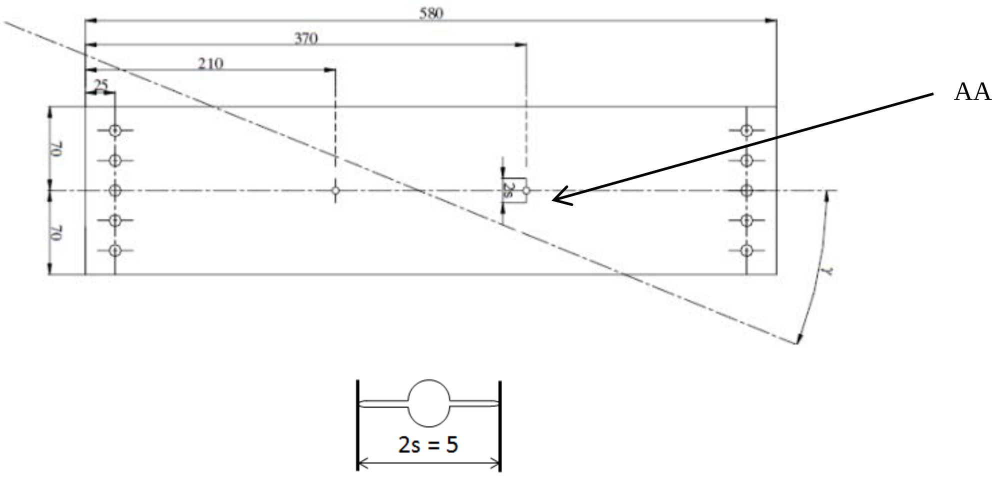
Gonesh [9, 10] reported results of fatigue tests on different grades of Glare (Glare-2B, Glare- 3, Glare-4B, Glare-5)[11] under off-axis loading. To limit the discussion, this paper will focus on the results of Glare 3 and Glare 4B only.

The test matrix listing the relevant experiments is presented in Table 1. The orientation of the fibres is defined with 0^o in the rolling direction of aluminium (L-direction). The Glare specimens were cut with the L-direction under an angle γ with the primary axis of the specimen as shown in Figure 1. The angle γ becomes thus the off-axis. The specimens were tested until 200k cycles under maximum stress 100MPa and stress ratio 0.05.

Table 1. Test Matrix [10]

Specimen no.	Material	Fibre lay-up (^{0})	Off-axis angle (γ) (^{0})
OA2	Glare-3 – 4/3 – 0.4	0/90	22.5
OA1	Glare-3 – 4/3 – 0.4	0/90	45
OA11[1]	Glare-3 – 3/2 – 0.4	0/90	67.5
OA6	Glare-4B – 4/3 – 0.4	90/0/90	22.5
OA9	Glare-4B – 4/3 – 0.4	90/0/90	45
0A7	Glare-4B – 4/3 – 0.4	90/0/90	67.5

[1] Tested by the current authors under the same fatigue tests conditions as [9]



Detail AA

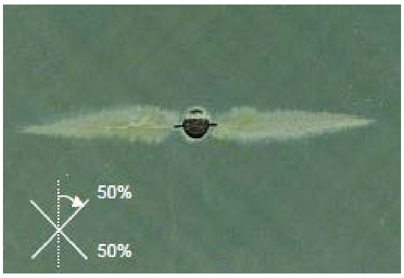
All dimensions are in mm

Figure 1. Specimen configuration

DISCUSSIONS

Figure 2 shows the results of delaminated shapes and related crack paths in 2 Glare types at 45^0 off-axis loading. These images are taken after the aluminium layer has been etched from the surface of the specimen by chemical milling.

The crack path angles [9] observed for the various off-axis angles for the specimen listed in Table 1, have been compared to the available crack turning theories, as illustrated in Figure 3. It should be noted that these theories were primarily developed for static loading, while the data represents fatigue crack growth.



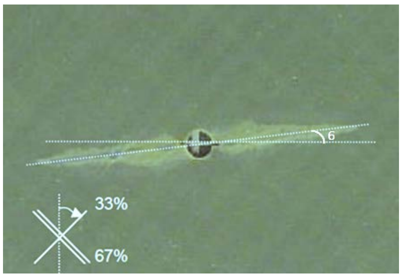


Figure 2. Delamination shape and crack paths in Glare-3 (left) and Glare-4B (right) at S_{max}=100MPa and R=0.05 under 45^0 off-axis loading [9, 10]. Crack grows at 6^0 in Glare-4B (right)

The crack angle in Figure 3 is the angle between the crack and the principal axis of the material (90^0 – off-axis angle Figure 1) as defined by [8]. The fracture angle is the crack propagation angle in Figure 3. The solid curve in the figure represents the maximum tangential theory from Erdogan and Sih [1]. The region above this curve represents positive T-stresses - implying unstable crack paths (or cracks moving away from the horizontal axis in Figure 2), - and the region below represents negative T-stresses [6].

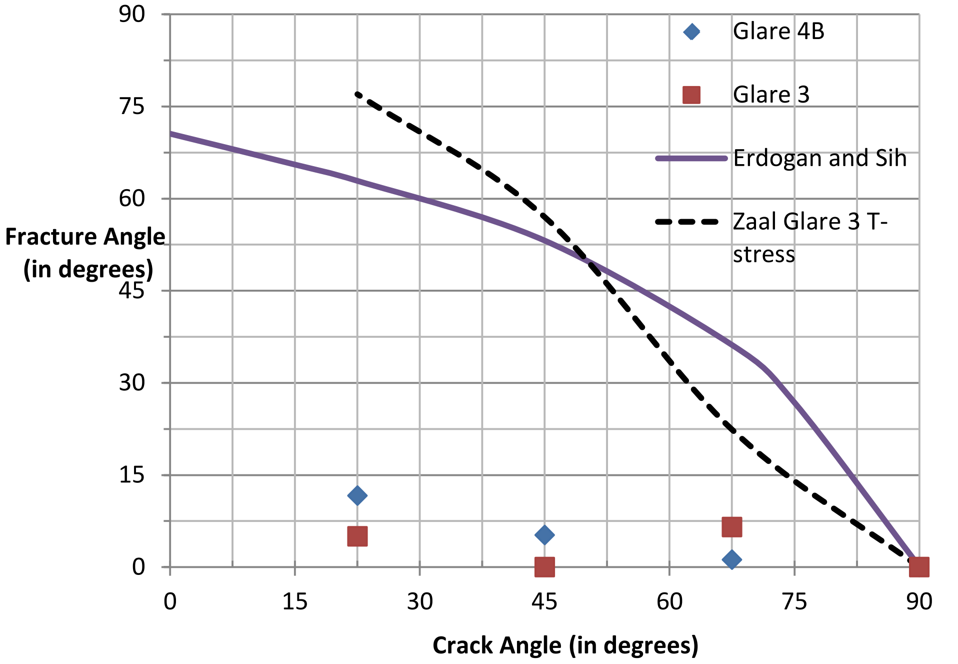


Figure 3. Comparison of prediction models with experimental results of Glare-3 and Glare-4B

As the curve extends towards the left side of the figure, the fracture angle (crack initiation angle) with respect to the horizontal axis of the specimen increases as Mode II becomes more dominant. The anisotropic T-stress model developed by Zaal [15] (dashed line in Figure 3) illustrates in a similar manner the increasing mode II contribution as it considers T-stress for Glare-3.

These theories only consider crack angle in predicting the fracture angle in monolithic metals to incorporate the mixed-mode loading at the crack tip. Thus, the crack angle in Glare was considered to be the determining factor to predict the fracture angle. However, the theories do not predict the angles measured in the tests. The lack of correlation between predicted and measured crack paths in FMLs is attributed to the mechanism of fibre bridging – a distinguishing characteristic of FMLs illustrated in Figure 4.

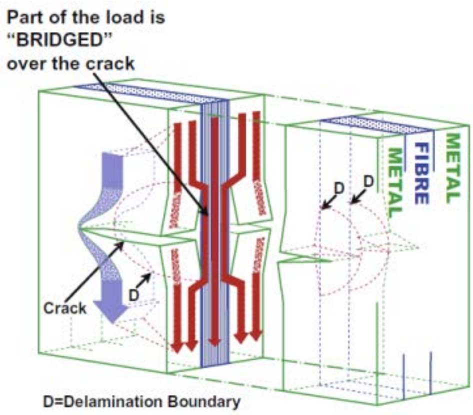


Figure 4. Illustration of unidirectional fibre bridging mechanism in FMLs [21]

The cross-ply grades of Glare-3 and Glare-4B have fibre layers in 2 orthogonal directions. The orthogonal directions make the fibres to bear loads in the two directions. Thus, the fibres are able to carry the load in the horizontal direction also which reduces the horizontal component of load in the metal. Consequently, the loads in the metals are reduced and hence, the fracture angles in FMLs are of lesser magnitude for the same crack angle compared to the crack angles in metals alone.

Under off-axis loading, the fibre layers have different load bearing capacity depending on their angle, and carry some load depending on this angle. However, the decrease in crack angles as defined by Broberg [8] (equivalent to increase in off-axis angles) increases the horizontal load in the fibres. This reduces the horizontal load in the metals which decreases the influence of Mode II on the crack in metals, increasing the mixed-mode loading and making the crack path more stable.

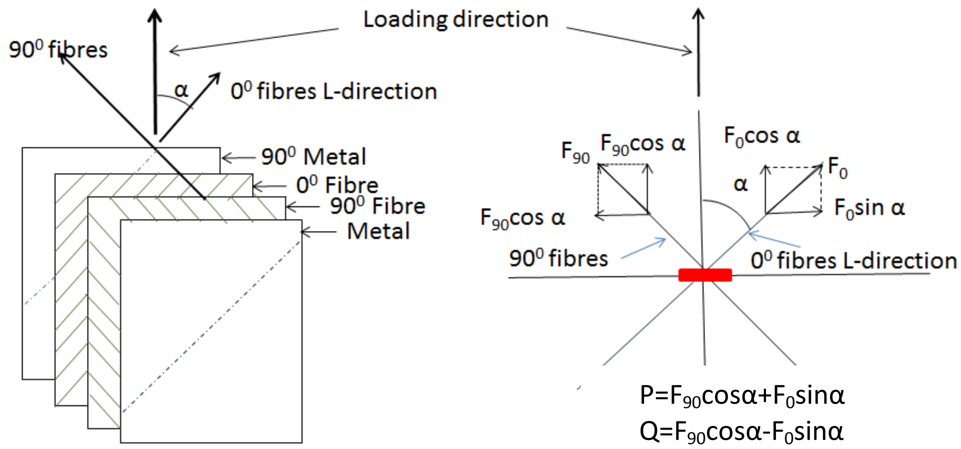


Figure 5. Glare-3-2/1(left) and effect of off-axis fibres on crack path in Glare-3 (right)

Figure 5 illustrates the cross section of Glare-3 at off-axis angle of loading α. In Glare-3 at 22.5^0 off-axis angle, there is a layer of fibre at 22.5^0 angle with respect to loading, and another layer perpendicular to this. These layers bear a certain portion of the vertical load and bridge the crack in the vertical direction. The deformation of the fibres along the off-axis angle introduces a horizontal component of loading at the crack tip in the metals and these horizontal components are not balanced at 22.5^0 as shown in Figure 5. This induces a Mode II component at the crack tip, and thus the crack begins to incline depending on the mixed-mode loading at the crack tip. Thus, FMLs follow a different trend depending on the number of fibre layers fibres and their direction compared to the metals alone.

At 45^0 off-axis angle in Figure 5, the 2 cross-ply grades of Glare-3 at 45^0 has the crack propagation angle of 0^0 that implies there is only Mode I component acting on the crack. Fibre bridging over the crack is balanced in Glare-3 at 45^0 off-axis angle because of the equal number of prepreg layers in the 2 directions, resulting in no Mode II acting on the crack faces.

The fracture angles are of the same magnitude in Glare-3 at 22.5^0 67.5^0 because the magnitude of the fibre bridging forces in the 2 directions at the crack tip are equal.

Figure 6 illustrates the cross section of Glare-4B at off-axis angle of loading α. In Glare-4B at 22.5^0 off-axis angle, there is a layer of fibre at 22.5^0 angle with respect to loading, and 2 layers perpendicular to this. This increases the load bearing capacity of the fibres in the horizontal direction with respect to the vertical direction. Thus, the metal has lesser horizontal load to carry compared to Glare-3 at 22.5^0 off-axis angle. Consequently, the mixed-mode loading is higher, and the crack path is stable compared to Glare-3.

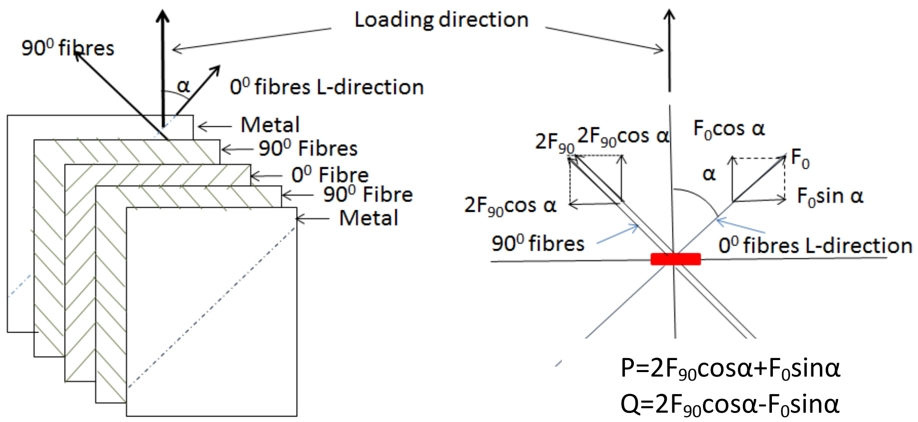


Figure 6. Glare-4B-2/1 (right) and effect of off-axis fibres on crack path in Glare-4B (right)

At 45^0 off-axis angle, in Glare-4B, the cracks propagate at an angle. Due to unequal number of fibre layers in the 2 directions, the fibre bridging over the crack is unbalanced in the horizontal direction. This is caused due to the presence of the 1 excess fibre layer in 1 of the mutually orthogonal directions of fibres. Consequently, a Mode II component at the crack tip in the metal exists resulting in mixed-mode loading at crack tip. Hence, the crack propagates at a slight angle to the horizontal direction compared to Glare3 where the crack propagates at 0^0. At 67.5^0 off-axis angle, there is only 1 layer of fibre to carry the load in the horizontal direction. This increases the horizontal load in the metals. Consequently, the dominance of Mode II is evident in the measured crack paths with the increasing fracture angle.

Therefore, it becomes imperative to develop the existing bridging model of Alderliesten [11] further to include the Mode II bridging component to predict the crack paths in FMLs. The SIFs due to fibre bridging loads in the crack tip vicinity can be calculated as following from Tada *et al.* [22].

$$\boldsymbol{K_{II\_br}} = \frac{\mathbf{1}}{\sqrt{\boldsymbol{\pi a}}}(\boldsymbol{Q})\left[\mathbf{1} + \boldsymbol{\beta y_o}\frac{\boldsymbol{\partial}}{\boldsymbol{\partial y_o}}\right]\left\{\frac{\boldsymbol{a}}{\sqrt{\boldsymbol{a^2 - z_o^2}}} - \frac{\boldsymbol{a}}{\sqrt{\propto^2 - \boldsymbol{z'^2_o}}}\right\} \quad (1)$$

Q is the horizontal fibre load in Figure 5 and Figure 6 for Glare-3 and Glare-4B respectively

z_0 and $\overline{z_0}$ are delamination boundaries,

$$\beta = \begin{Bmatrix} \frac{1}{2}(1+\vartheta) \text{ for plane stress} \\ \frac{1}{2}\left(\frac{1}{1-\vartheta}\right) \text{ for plane strain} \end{Bmatrix},$$

The bridging components can then be added to the farfield loads in the horizontal direction to calculate the effective SIF according to Eq. (2) where $K_{farfield\_II}$ is the SIF in mode II due to the farfield loads, and K_{II_br} is the bridging load Mode II direction defined by Eq. (1).

$$\boldsymbol{K_{eff\_II}} = \boldsymbol{K_{farfield\_II}} + \boldsymbol{K_{II\_br}} \quad (2)$$

CONCLUSIONS AND COMMENTS

This paper reviewed the application of some already established theories of crack path propagation to directionality of damage growth in FML under off-axis fatigue loading. An analysis of the previous experimental results with these theories can be concluded as follows:

1. The inability of the existing theories to explain the experimental results is considered to be due to their lack of consideration of fibre bridging as shown in Figure 4 – a distinguishing characteristic of FMLs compared to metals.

2. Although the metal is under external tensile loading, the fibre bridging due to off-axis produces a component of shear at the crack tip in the metal. These 2 loads combine together to produce the effect of crack turning because of mixed-mode loading. The use of the mixed-mode parameter with the incorporation of the fibre-bridging could provide us with a better understanding and estimation of the crack paths in FMLs.
3. The paper also provides the background to calculate effective Mode II SIF in FML.

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