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An experimental investigation into pin loading effects on fatigue crack growth in Fibre Metal Laminates

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Abstract

This paper provides an experimental investigation into the pin loading effects on the crack growth behaviour in Fibre Metal Laminates. The pin loading effects and bypass loading effects are incorporated in two different tested joints. The analysis of the test results shows that pin loading dominates the crack growth only in the vicinity of the pin hole and the superposition method for analysing stress intensity factor in FMLs with pin loading effects can be applied.

Keywords: Fibre Metal Laminates; Pin loading effects; Fatigue crack growth; Superposition method

1. Introduction

Fibre metal laminates (FMLs) are a family of hybrid materials which are comprised of metal layers and composite layers designed for light-weight aircraft structural applications. Extensive investigative work has been performed on the fatigue crack growth behaviour of the Glare, which is one of successively developed FMLs, containing glass fibres. Glare has become known for its excellent fatigue and damage tolerance behaviour, due to the

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bridging mechanism which restrains the crack opening in the metal layers and leads to stable and slow crack growth under fatigue loading. Because of its superior mechanical properties especially in terms of fatigue and damage tolerance, compared with monolithic aluminum alloys, Glare has been applied as fuselage skin of Airbus A380 jet airliner, where weight reduction and improved damage tolerance ability are critical.

The load for fuselage panels is mainly introduced by the Ground-Air-Ground (GAG) pressurization cycles which create roughly constant amplitude fatigue loading, and the load is transferred from one panel to another via the fasteners in the fastened joints. The bypass loading, secondary bending and pin loading due to the load transfer in mechanically fastened joints exacerbate the stress concentration at fastener holes, making the joints susceptible to Multiple-site Damage during the service life of an aircraft.

MSD in metallic airframe has been extensively investigated since Aloha airline accident in 1988 (Galatolo and Lazzeri (2016), Hendricks (1991), Chang and Kotousov (2012), Pártl and Schijve (1993), Silva et al. (2000)). However, it has not been fully studied for FML joints where much longer crack growth life should be allowed compared to metallic structures due to the fact that the crack growth life in FMLs accounts for a significant portion of the total fatigue life. It has to be highlighted that the bypass loading, secondary bending and pin loading play different roles during the course of fatigue crack growth initiating from the fastener holes. Therefore addressing MSD issue in FML joints without understanding the effects of pin loading on the crack growth behaviour is impossible.

This paper presents an experimental investigation into the cyclic pin loading effects on the crack growth behaviour in FML joints. The objective of this paper is to show the fatigue damage mechanisms in FMLs due to pin loading and the effects of pin loading on the growth behaviour of a crack in the vicinity of a pin loaded hole and relatively away from the pin hole. Therefore, FML specimens subjected to only pin loading and subjected to pin and bypass loading were conducted and their test results are compared in this paper.

This paper describes the FML materials used and the experimental procedure of the fatigue tests. The fatigue crack growth results and the evolution of delamination shapes obtained using Digital Image Correlation and etching after tests are present and analysed in this paper. This experimental investigation will serve as a basis and validation data for developing an analytical model that predicts the crack growth behaviour in FMLs with pin loading effects.

Nomenclature

a	Half crack length
c	Paris equation constant
L_s	Saw-cut length
da/dN	Crack growth rate
f	Test frequency
F_{bypass}	Bypass load
F_{pin}	Pin load
n	Paris equation constant
R	Stress ratio
K	Stress intensity factor
K_{total}	Total stress intensity factor as result of far field stress and bridging stress

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2. Test procedure

2.1. Test specimens and test matrix

Symmetric double lap joints (see Fig. 1(a)) were employed to investigate the pin loading effects on fatigue crack growth behaviour in FMLs in order to eliminate the secondary bending effects. The outer sheets were standard Glare3-3/2-0.4 FML panels and the inner sheets and the filling sheets were Glare3-7/6-0.4 laminates. The used laminates were consisted of 2024-T3 aluminium layers of 0.4 mm thickness and the S2 glass fibre reinforced FM 94

prepreg layers. The lay-up of Glare3-3/2-0.4 is [Al/0/90/Al/90/0/Al] and the lay-up of Glare3-7/6-0.4 is [Al/0/90/AL/90/0/Al/0/90/Al/90/0/Al/0/90/Al/90/0/Al] with 0 denoting that the fibres are in the rolling direction of Al sheets and 90 being perpendicular to the rolling direction.

The outer sheets were the specimens where damage evolution could be observed with cameras. The inner sheet and filling panel were used to introduce load to the specimens. Two types of joints were tested, which are illustrated in Fig. 1(b) and Fig. 1(c) respectively. Titanium high-lock fasteners were used to join the specimens and middle plate. Detailed dimensions (mm) of the assembled joints are shown in Fig. 1. The diameter of the pin hole and fastener shaft is 4.9 mm. Saw cuts were applied to stimulate crack growth under fatigue loading with pin loading effects. The length of the starter saw-cut (L_s) is 2 mm on each side of the hole.
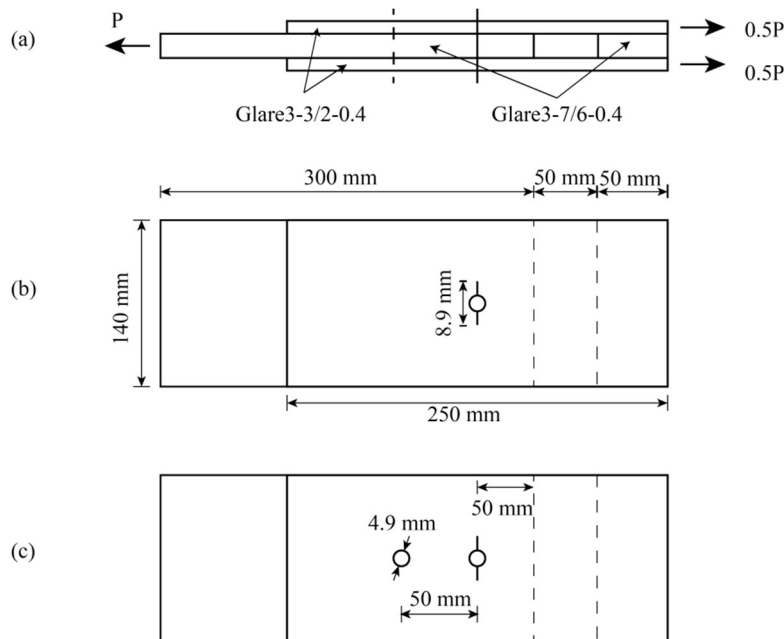

Fig. 1. (a) symmetric lap joint configuration; (b) type 1 joint with one pin; (c) type 2 joint with two pins

These two types of joints comprise the test matrix which is summarized in Table 1. Test type 1 had only one pin, the crack was loaded by pin loading at the hole edge and tensile applied loading at the far-field. Test type 2 had two pins in the joint, in addition to the load cases for the specimen in test type 1, the added fastener introduced bypass loading to the crack in the specimen as a result of load transfer in the type 2 joint. The loading parameters are summarized in Table 1.

Table 1. Test matrix

Test type	Test name	Maximum load P (kN)	Stress ratio R	Number of test
1	Single pin loading test	10	0.05	2
2	Pin and bypass loading test	20	0.05	2

2.2. Test set up

The fatigue tests were conducted on a computer controlled 60kN servo-hydraulic testing machine. The fatigue test set up is given in Fig. 2. Constant amplitude fatigue load was applied with the frequency of 10 Hz. The maximum applied loads for two different joints are given in Table 1 respectively.

The Digital Image Correlation (DIC) technique was used to detect the delamination evolution at the interface between outer Al layer and fibre layer. DIC technique is wildly used to detect the strain distribution of the surface of a specimen (Rodi et al. (2010)). The delaminated Al layer around the crack in the metal layer carries negligible stress compared to bonded Al, the contrast of the strain distribution between disbanded and still bonded part could be used to detect the delamination shape in FMLs (Rodi et al. (2009)).

Arbitrary black particles were painted on a white base coat on the surface of the specimen facing DIC cameras before testing. The DIC cameras took a picture of the area of interest (surface around the pin hole) when the specimen was unloaded. Then fatigue loading was applied on the specimen, after a number of cycles, the test was suspended and maximum load was applied. The DIC cameras took a picture of this deformed specimen. Meanwhile, the high resolution camera on the opposite side of the specimen took a picture of another surface with a millimeter paper pasted along the crack propagation direction. Then the fatigue test was resumed. The same procedure repeated until the test finished. Then chemical etching was used to remove the outer aluminum layer to reveal the delamination shape at the metal/fibre interface.

The DIC pictures were post-processed to obtain the delamination evolution and the crack lengths were read from the pictures taken by the high resolution camera. The crack length was measured from one crack tip to another. The half crack length, a, is used to get the crack growth rate. The crack growth rate was obtained with crack lengths and corresponding life cycles using the seven point polynomial method.
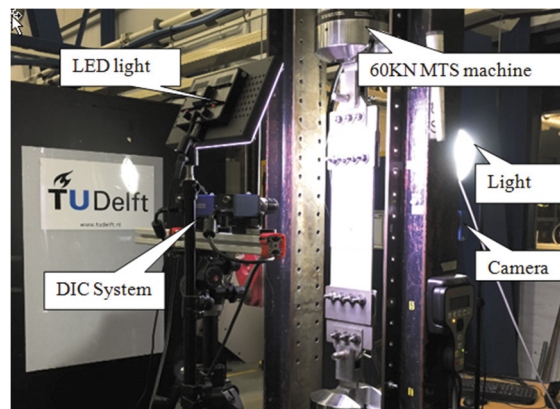

Fig. 2. Test set up

3. Experimental results and analysis

Previous studies have found that fatigue damage in FMLs can be divided into two main mechanisms: crack growth in metal layers and delamination extension at the metal-fibre interface. Fatigue crack growth and delamination growth are coupled phenomena, and they achieve a balance during the fatigue growth (Alderliesten (2007)). The test results of crack growth rates and the results of delamination extension are presented and analysed separately as below.

3.1. Crack growth rate

The obtained crack growth rate curves from test type 1 (pin loading) and test type 2 (pin and bypass loading) are given in Fig. 3. For the crack growth of type 1 joint without bypass loading effects, the crack growth rate decreases as crack length increases. The crack stopped growing when the length reached 10 mm. For type 2 joint, the crack growth was affected both by the pin loading and the bypass loading introduced by the added fastener. The crack growth rates have the same trend until the crack length reaches 10 mm, then the crack growth rates become stable onwards.

Based on the comparison of the crack growth rates in Fig. 3, the pin loading effects dominate the crack growth in the vicinity of the pin hole. As crack grows, the driving force from the pin loading for the crack growth becomes

weaker. After the crack reached 10 mm length for the tested configuration, the bypass loading starts dominating the crack growth.
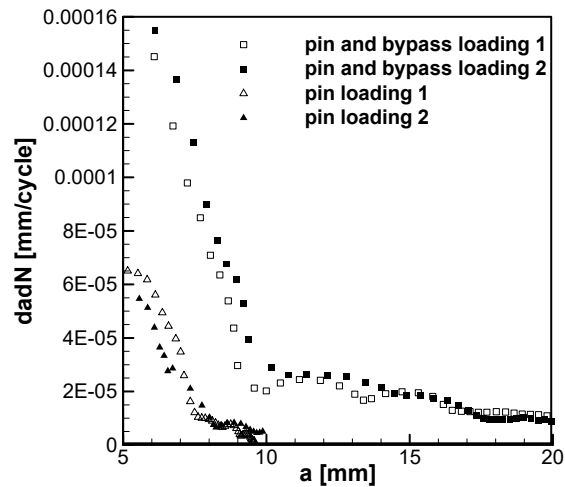

Fig. 3. Crack growth rate comparison between test type1 and test type 2.

3.2. Characteristics of delamination extension

In Fig. 4(a), an example of strain measurement around the pin head obtained with the DIC technique is given. The boundary of the red areas is approximately the delamination frontier. The displacement in the delaminated zone contains the crack opening, which resulted in the largest strain distribution that is denoted as red color in the DIC measurement even though the delaminated Al carries negligible stress compared to the surrounding intact Al. This difference in the strain distribution outlines the delamination shape.

An image of a specimen from test type 1 after etching is given in Fig. 4(b). Since the pin loading and far-field tension are not symmetric loading for the crack in the tested specimen, the asymmetric delamination shape and the crack path not perpendicular to the loading direction can be observed in the etched specimen. In contrast, the symmetric Mode I fatigue loading resulted in the crack path perpendicular to the loading direction and the delamination shapes are symmetric with respect to the crack path in FMLs (Alderliesten (2007)).
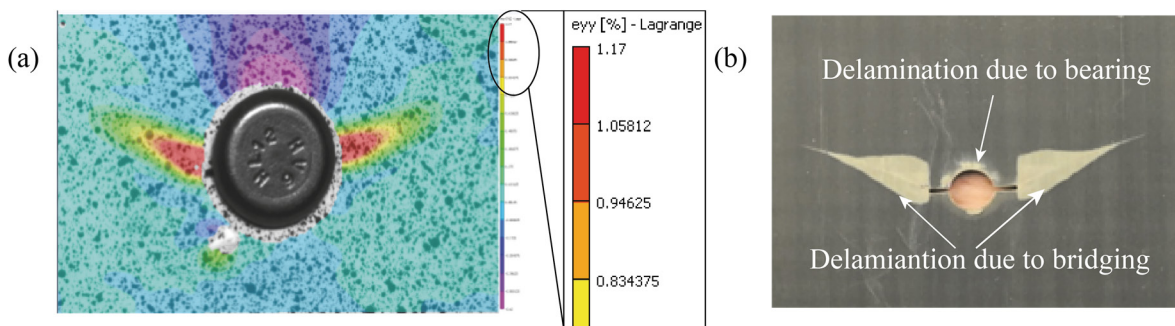

Fig. 4. (a) strain distribution; (b) chemical etching result

As can be seen from Fig. 4(b), delamination also occurred at the upper hole perimeter, this is attributed to the plastic deformation due to bearing. The tested joints were disassembled after fatigue test, very small degree of plastic deformation due to bearing could be observed at the hole edges.

The DIC measurements for test type 1 in Fig. 5. The coordinate origin in Fig. 5 denotes the pin hole centre. The etching measurement is compared with the last DIC measurement. Good correlation can be observed. The delamination shapes measured with DIC method confirm that the delamination evolution and crack propagation are not symmetric due to the non-symmetric pin loading case.
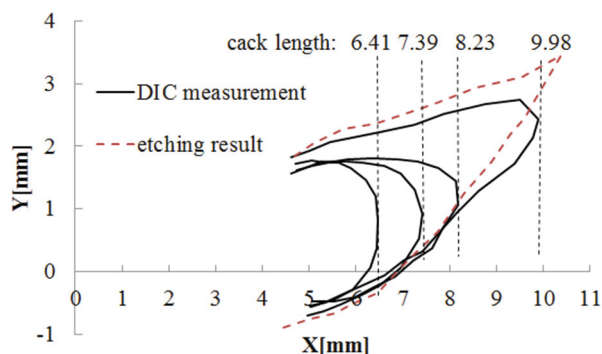

Fig. 5. Delamination shape evolution

4. Discussion

For metal panels, the superposition method in the context of linear elastic fracture mechanics is normally applied to calculate the stress intensity factor experienced at the crack tip. The principle of superposition has been illustrated below in Fig. 6. After decomposition, the stress intensity factor for each loading case can be easily derived.
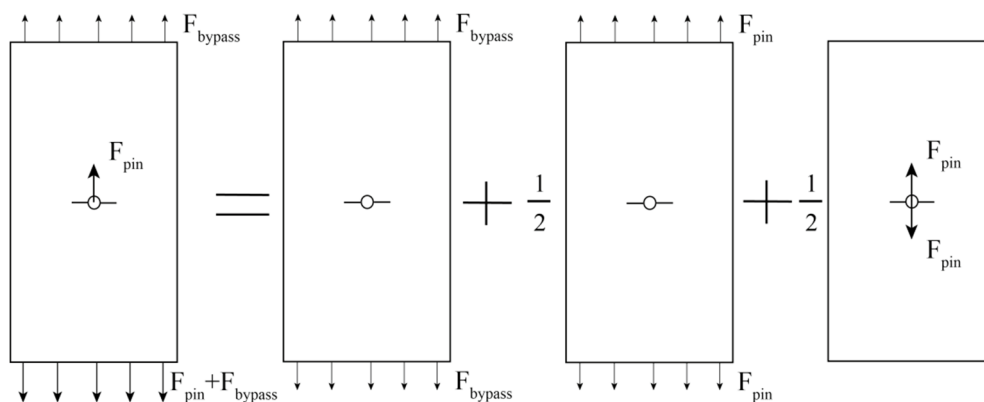

Fig. 6. illustration of superposition scheme for a metal panel

The test data is used to prove that the same superposition method can be used for analysing the crack growth in a FML with pin loading effects involved.

In the type 2 joint, both fasteners transfer loads. Due to the fact that the middle plate has a little bit higher stiffness than the total stiffness of two outer specimens and the fact that small degree of plastic deformation occurred due to bearing during the fatigue test, the fasteners in type 2 joint transfer 10 kN respectively (Müller (1995)). Comparing the loading for the specimens in both joints, it can be easily found that the loading for the crack in the specimen from type 2 joint can be decomposed into the loading case for the specimen from type 1 joint and bypass loading (see Fig. 7). This bypass loading is introduced by the added fastener in type 2 joint compared to one fastener in type 1 joint. Both pin load and bypass load are equal to 10 kN in Fig. 7.

Due to the bridging mechanism, the total stress intensity factor for the crack tip in a FML is decomposed into two parts:

$$K_{total} = K_{ff} - K_{br} \tag{1}$$

where K_{ff} is the stress intensity factor due to the far-field stress and the pin loading and K_{br} is the stress intensity factor due to the bridging mechanism.
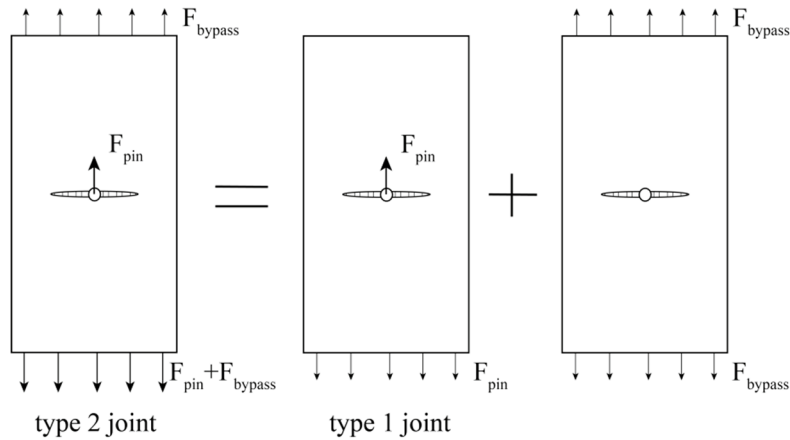

Fig. 7. Illustration of loading for the crack in the specimens in two joints
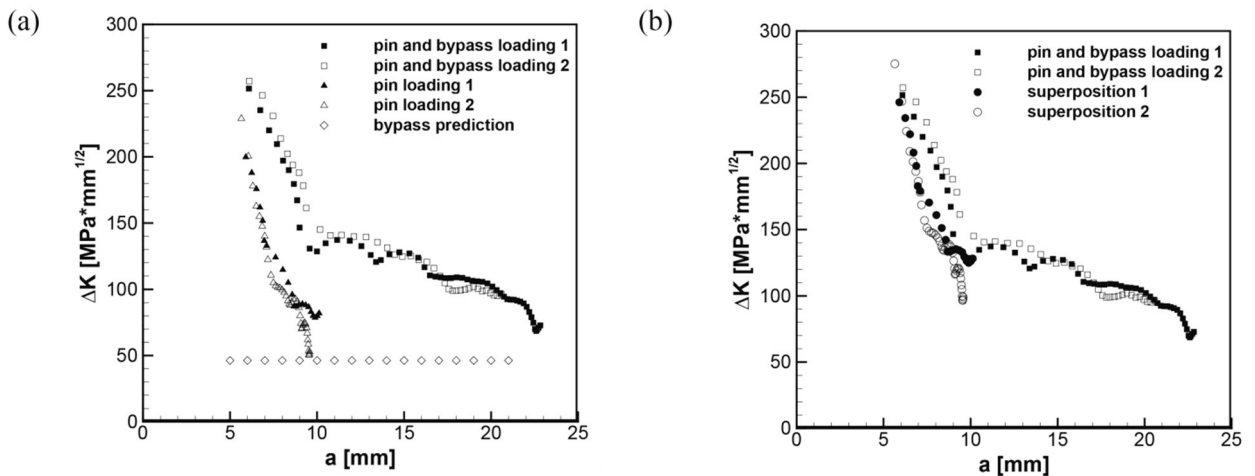

Fig. 8. (a) calculated stress intensity factors; (b) comparison between superposition and results of test type 2

The crack growth rate in a FML can be predicted with a Paris relation:

$$da / dN = c(\Delta K_{total})^n \tag{2}$$

The equation can be rearranged for total stress intensity factor range:

$$\Delta K_{total} = 10^{\frac{\log(\frac{da}{dN}) - \log(c)}{n}} \tag{3}$$

where c=2.17x10^{-12}，n=2.94.

With the measured crack growth rates, the stress intensity factor ranges for two test types can be obtained using Eqn. 3. The calculated values are plotted in Fig. 8(a). The Alderliesten model was used to calculate the stress intensity factor range under the prescribed bypass loading in Fig. 7 (Alderliesten (2007)]. The Alderliesten model only provides the stress intensity factor for a small amount of crack growth. Due to the stable crack growth behaviour in FMLs, the stress intensity factor range is extrapolated for larger crack length.

In Fig. 8(b), the superposed results of the stress intensity factor range due to bypass loading and the stress intensity factor range for the specimen in type 1 joint correlate well with the results for test type 2. This correlation proves that the superposition method can also be applied to FMLs. The total stress intensity factor resulted from complex loading cases can be decomposed into simpler loading cases whose total stress intensity factor can be derived.

5. Conclusion

Two kinds of test for evaluating the pin loading effect in Glare joints have been accomplished. The crack growth phenomena in FMLs with pin loading effects and in company with bypass loading have been observed. Based on this experimental investigation and the analysis of the test results, it can be concluded that:

- The effects of pin loading accelerate the crack growth rate in the vicinity of a pin hole and the effects will be weaker as the crack length grows longer.
- Loading is not symmetric, so the crack opening should not be symmetric either, leading to non-symmetric delamination shapes. DIC test results and etching results validate this phenomenon.
- Total stress intensity factor range of pin and bypass loading specimen is superposed by that of the single pin loading and equivalent far-field loading. The effects of bypass loading and pin loading can be calculated separately in FML joints.

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