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Prediction methodology for fatigue crack growth behaviour in Fibre Metal Laminates subjected to tension and pin loading

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ABSTRACT

Fibre Metal Laminates (FMLs) are a hybrid metal-composite laminate technology known for their superior resistance to fatigue crack growth compared to monolithic metals. This crack growth behaviour has been the subject of many studies, resulting in numerous empirical and analytical models to describe the complex damage growth phenomenon in the material. This study builds upon the analytical Alderliesten crack growth prediction methodology for FMLs, extending it from a tension loaded plate to a case of a combined tension-pin loaded plate. This new loading case is a more representative case to utilise for predicting fatigue crack growth behaviour in mechanically fastened joints. Development of the model extension and validation through experimental testing are detailed within this paper.

1. Introduction

Fibre Metal Laminates (FMLs) are a material technology known for their superior fatigue crack growth behaviour. This favourable behaviour is a result of the fibre bridging mechanism whereby the intact fibre layers provide an alternative load path around the cracked metal layers, reducing stress in front of the crack tip (see Fig. 1).

Although the basic concept of fibre bridging is simple to understand, it proved to be a complex phenomenon to capture effectively in crack growth prediction models for FMLs. Early attempts at predicting fatigue crack growth took a phenomenological approach, treating an FML as a bulk material and developing empirical β correction factors to represent the contribution of the fibre bridging mechanism. These β corrections were then used to correct the standard stress intensity factor solutions used in the Linear Elastic Fracture Mechanics approaches for crack growth prediction in monolithic materials [1–3]. Additional phenomenological approaches based on treating FMLs as a bulk material include the compliance method of Takamatsu [4], bridging stress linearization approach of Cox [5], and the equivalent crack length approach of Guo and Wu [6]. Although these models achieved some limited success, the bridging mechanism could not be adequately captured with this bulk material approach [7].

Greater success was achieved by embracing the composite nature of FMLs and attempting to analytically describe the interplay between the metal and fibre layers. Marissen [8] investigated the influence of bridging stress on the growth of the interface delamination between cracked metal layers and intact fibre layers. The opening of the crack in the metal layers is dependent on the compliance, and thus size, of this delaminated region. Alderliesten [9,10] further built on this work by formulating an analytical fracture mechanics model that captured the load redistribution of the fibre bridging mechanism by enforcing compatibility between the crack opening displacement in the metal layers and elongation of the delaminated region of the fibre layers. With the bridging stress determined, growth of the interface delamination under the driving force of the bridging stress could be predicted, and growth of the crack through superposition of the far-field and bridging stress intensity factors in the metal could be achieved. This analytical approach, referred to in this paper as the Alderliesten model, has been the backbone of continued effort in extending crack growth prediction capabilities in FMLs with extensions to account for residual strength [11], variable amplitude loading [12–14], generalized laminate configurations [15,16], and more recently multiple site damage [17,18].

It is worth noting that mechanically fastened joints are potentially vulnerable structures in consequence of secondary bending, stress concentration at fastener holes and pin bearing effects as load transfers from one substance to another via the joint. The structural behaviour of mechanically fastened FML joints has therefore drawn particular attention. In open literature, the neutral line model developed by Schijve [19] has been extended by de Rijk for calculating the load transfer and secondary bending stresses in FML joints [20]. The progressive damage behaviour in pin loaded FMLs has been investigated by Frizzell et al. [21,22] and the bearing strength of FMLs has also been extensively

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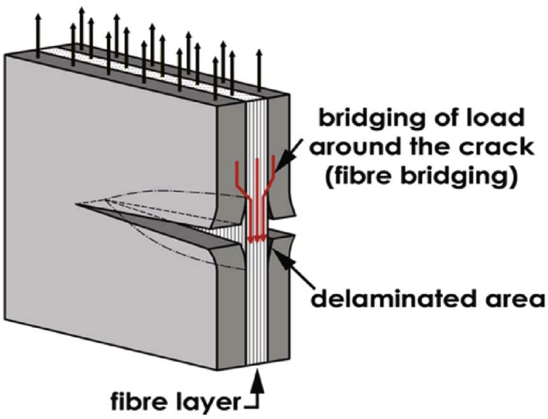

Fig. 1. Illustration of the bridging mechanism in FMLs.

studied [23–25].

Apart from the static behaviour of FML joints, another issue associated with mechanically fastened FML joints is the fatigue crack growth in the metal layers and the delamination propagation at metal-composite interfaces under fatigue loading. Even though extensive analytical models have been developed for predicting the crack growth behaviour in flat FML panels subjected to tensile loading [9,10,14,15], the influence of pin loading on the crack growth behaviour in FMLs has not been fully studied. There is a risk that multiple cracks are present simultaneously in the critical row of an FML joint, which is crucial to examine in light of the introduction of Limit of Validity (LOV) to the airworthiness regulations that defines a fatigue life free of Widespread Fatigue Damage [18,26,27]. The analysis of pin loading effects on the crack growth behaviour in FMLs becomes indispensable for the analysis of MSD crack growth behaviour in FML joints.

This paper aims to develop an analytical model capable of predicting the growth behaviour of an isolated crack in a mechanically fastened FML joint where the pin loading effects are present. This model is developed with the intention to further incorporate it into an analysis frame which can eventually analyse the MSD growth behaviour in FML joints. The development of this model is based on the findings of an experimental investigation of pin loading effects on the crack growth behaviour in FMLs [28] and the success of an analytical model by Alderliesten for analysing the damage growth in FMLs subjected to pure far-field loading. Firstly the test procedure and test results are briefly summarized in Section 2, and then the model development is detailed in Section 3. The analytical model will be validated against the test data in Section 4.

2. Remarks regarding test results

The principle of superposition is normally applied to calculate the stress intensity factor for a crack in a metallic panel subjected to tension-pin loading by splitting the loading case into simpler loading cases and summing the stress intensity factors for simpler split loading cases together [29]. The crack growth mechanism in FMLs, however, differs from that of monolithic metallic panels because of the fibre bridging. The bridging mechanism is accounted for using the principle of

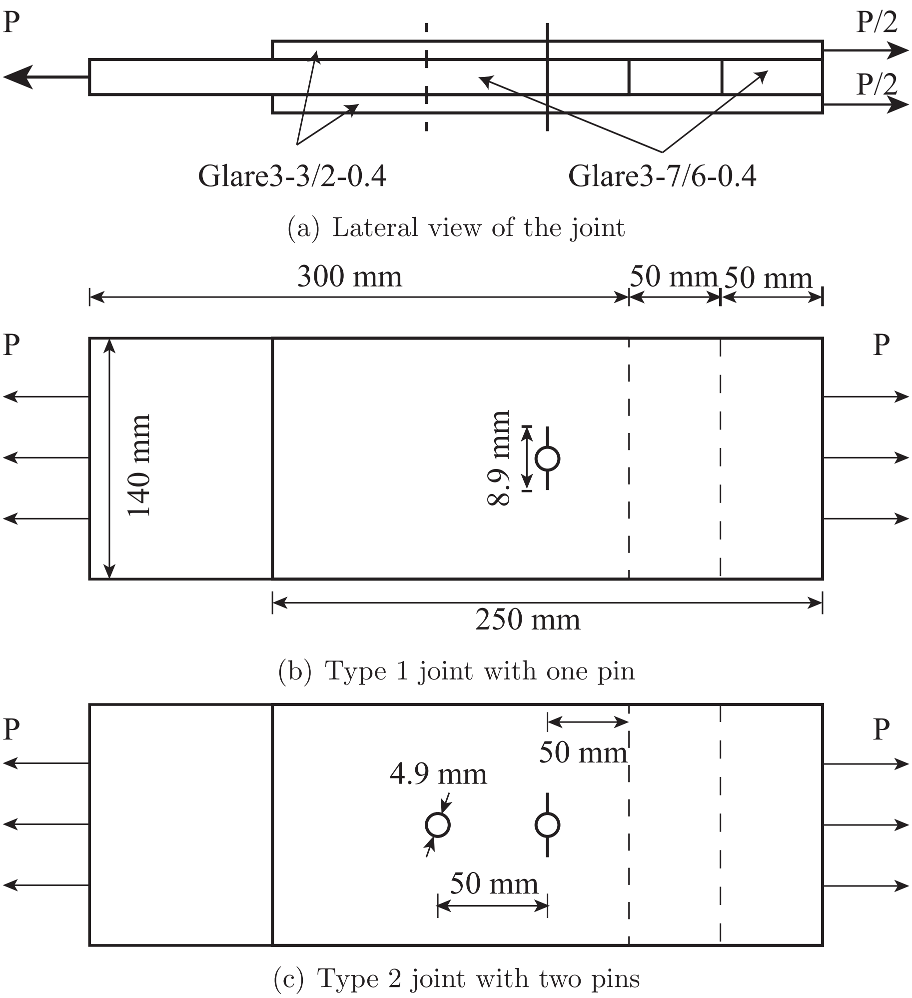

Fig. 2. Symmetric FML joint configurations.