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# On the interplay behavior of fatigue crack growth and delamination of Ti/Cf/PMR polyimide hybrid laminates under overloading

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ABSTRACT

The effect of overload on the fatigue crack growth and delamination of the Ti/Cf/PMR (Polymerization of Monomeric Reactants) polyimide hybrid laminates and the interplay behavior between crack growth and delamination were studied by applying single-peak, multi-peak, and block overloads. The retardation effect was discovered under variable overloads. The mechanism of crack growth and delamination was also analyzed. It was found that the crack grew perpendicular to the fiber direction and the initiation site of delamination always located around the micro-cracks of metal layers. The delamination growth was affected by the maximum stress level and the stress sequence. The interplay between crack growth and delamination on fatigue failure of Ti/Cf/PMR polyimide hybrid laminates could accelerate the crack growth and delamination extension.

## 1. Introduction

Fiber metal laminates (FMLs) as light weight hybrid materials have become more and more popular in aerospace, automobile and shipping industries [1,2]. As shown in Fig. 1, thin metal sheets and fiber reinforced composites stack up alternately and bond together to form a FMLs [3,4]. The Ti/Cf/PMR polyimide hybrid laminates (Fig. 1) are heat resistant type FMLs [5–8], which has an excellent thermal stability after suffering thermal shock from 0 °C to 300 °C [9,10] and can suffer over 1000 times thermal shock without delamination [11].

During actual service process, the Ti/Cf/PMR polyimide hybrid laminates bear various loads, including constant amplitude (CA) load and variable amplitude (VA) load. Therefore, analysis of the fatigue crack propagation behavior under variable loads is the key of fatigue resistance performance. Since the effect of fibre-reinforced layers, the fatigue resistance of FMLs is excellent. Under fatigue loading, there are two damage modes: crack propagation in the metal layers and delamination between metal and fibre layers. During the fatigue test, cracks initiate and grow only in the metal layers. The fibre layers are still intact and restrains the crack growth by bridging effect, which transfers the load to the fibre layer to reduce the stress intensity factor at the crack tip.

Studies on the FMLs fatigue behavior have been investigated for decades. Fatigue experiments with various specimens, observation analyses and theoretical models have been developed extensively [12–14]. It has been well known that FMLs have a very slow and almost constant crack growth under CA loading due to the intact fibre bridging effect. Delamination also expands in a constant rate along with crack growth. The stress intensity factor at the crack tip of *Glass-re*inforced aluminum laminate (Glare) could be calculated by a phenomenological method presented by Toi [15] or by a flexibility method put forward by Takamatsu et al. [16]. Considering the stress intensity factor and the bridging stress along the crack, the crack growth rate and delamination area under CA loading could be evaluated through using the Paris empirical equations presented by Alderliesten et al. [17,18]. Delamination was the main damage mode and became more obvious if using thick fibre layers (Cortes and Cantwell [19,20]). The fatigue crack of the carbon fibre reinforced titatium laminate (TiGr) initiated from the free edges and the area of stress concentration [21]. The interfacial strength was the main impact factor on delamination shape and crack propagation rate based on the Yamaguchi et al. [22] study. The crack growth was predicted by the Virtual Crack Closure Technique (VCCT) [23,24].

Compared to CA loading, most of the airplane structures are submitted to VA loading. A few researches has paid close attention to the issue through investigating the crack growth characteristic or delamination behavior [12,25,26]. However, the interplay behavior between fatigue crack growth and delamination under VA loading, especially

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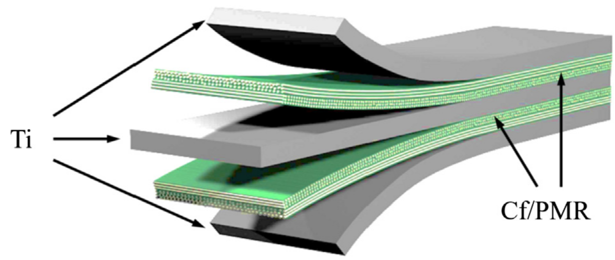


**Fig. 1.** Schematic diagram of the Ti/Cf/PMR polyimide hybrid laminates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with overload, has not been studied systematically. Plokker et al. [27] observed the fatigue crack growth behavior of Glare under different kinds of variable amplitude loading. They found that there was a retardation phenomenon like metal material. The phenomenon was not such obvious as metal material because of the bridging effect. Moreover, compared to the single overload, block overload could affect more retardation. Alderliesten and Woerden [28] measured the delamination shapes with and without overloads, but did not give the relationship between crack growth and delamination. Afterwards, Khan et al. [26] proved that applied load sequences and load transition had no influence on the delamination growth rate in Glare. Most of researches [29–31] have kept watchful eyes on the Glare fatigue properties under amplitude loading. However, for other FMLs like TiGr (*Gr*aphite fiber reinforced *Ti* tanium alloy laminates), there is no clear answer on whether the delamination growth is still independent of the applied load sequences and whether the fatigue crack growth can affect the delamination behavior under amplitude loading with overload.

Since PMR polyimide prepregs could be easily prepared following the process of epoxy prepregs, it has been widely used to heat-resisting composites. Based on this characteristic, Ti/Cf/PMR polyimide hybrid laminates has been developed to improve the heat resistance of TiGr. In this study, this new TiGr was adopted to find out the answer of major questions above. Crack growth and delamination behaviors of the TiGr under overload were investigated and the interplay behavior between crack growth and delamination was found out by using single-peak overload, multi-peak overload, and block overload (high-low overload and low-high overload).

## 2. Fatigue crack growth test

For the specimens of Ti/Cf/PMR polyimide hybrid laminates, the prepregs with 0.25 mm were made in our lab by using PMR (Polymerization of Monomer Reactants) polyimide KH-308, which was obtained from the Institute of Chemistry Chinese Academy of Science, and TR50S 6L Carbon fibre, which was provided by Mitsubishi Rayon Co., Ltd. The volume fraction of the carbon fibres in the prepreg was 45%. Each titanium layer with 0.3 mm thickness was constructed by TA2 from BAOJI Titanium Industry Co., Ltd. Unidirectional Ti/Cf/PMR polyimide hybrid laminates with 3/2 structure were prepared by stacking layers of titanium prepreg as [Ti/0°/0°/0°/0°/Ti/0°/0°/0°/0°/Ti] and by using hot press method. The forming curve presented by Hu et al. [11] was used in this study. The temperature stepped up to 300 °C under 2 MPa within 600 min.

**Table 1**
The overload tests for fatigue crack growth.

| Mode | $S_{max}$/MPa | R | $a_{ol}$/mm | $R_{ol}$ |
|---|---|---|---|---|
| Single-peak overload | 160 | 0.1 | 5.5 | 1.4 |
| | | | | 1.6 |
| | | | | 1.8 |
| Multi-peak overload | 160 | 0.1 | 5.5 | 1.6 |
| Block overload (high-low cycle) | High: 140 Low: 100 | 0.1 | 6.0 | / |
| Block overload (low-high cycle) | Low: 100 High: 140 | 0.1 | 6.0 | / |

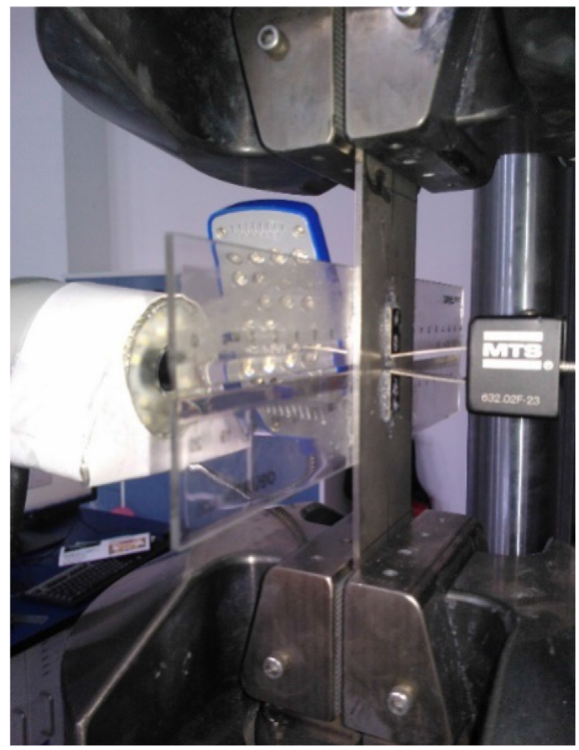


**Fig. 3.** The test process of the fatigue crack growth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

According to the standard of ASTM E647-15 [32], the Middle-Tension (MT) specimens were prepared as shown in Fig. 2. The fatigue testes were carried out with f = 10 Hz wave loading in the fatigue testing machine (MTS 810-5T) at the room temperature. The test conditions are listed in Table 1. The overload ratios $R_{ol}$, which are the ratios of maximum overload stress $S_{ol}$ and maximum stress of initial load $S_{max}$, were set as 1.4, 1.6 and 1.8 respectively. The fatigue crack growing process was observed and recorded in real time by a digital

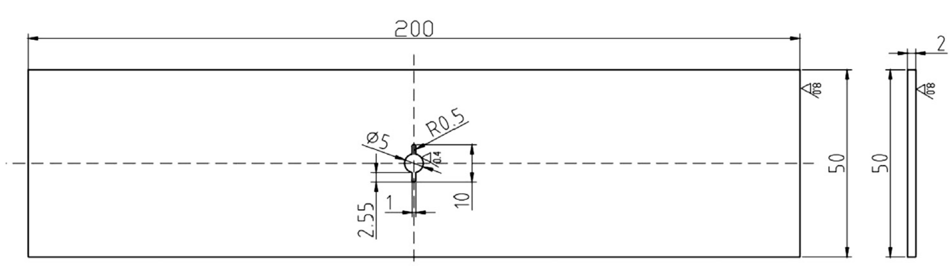


**Fig. 2.** The Middle-Tension specimen for the fatigue test.