ARRESTING CRACK IN COMPOSITE BONDED JOINT USING FIBER-REINFORCEMENT-BASED DESIGN FEATURE

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Abstract
Development of new design features that stop cracks from growing above a critical size is one of the keys to realization of boltless structures. The author recently proposed a fiber-reinforcement-based concept that introduces continuous fibers in the adhesive layer and suppresses crack propagation using massive fiber bridging. This study evaluates its arresting performance under a mode-II loading condition. In addition, a new manufacturing method is proposed to enhance the crack-entrapment performance.

1. Introduction

Bonded joints potentially possess clear advantages over traditional bolted joints. It significantly reduces the manufacturing cost related to drilling, fastening, and lightning protection. Furthermore, it allows more efficient load path with reduced component thickness and eliminates stress concentration around bolt holes. In spite of these advantages in terms of cost, weight, and performance, composite primary structures in aircraft are currently assembled with several tens of thousands of bolts. This is because existing bonding technologies and related non-destructive inspection techniques are unreliable (e.g., weak-bond detection is practically impossible) and cannot satisfy airworthiness requirements. Currently, mechanical fastening is required even in bonded areas so that the joints can maintain the limit load capability under the condition of global bondline failure. It is recognized that development of new design features that stop cracks from growing above a critical size is one of the keys to realization of boltless structures [1].

A previous study from the authors' research group proposed a new crack arrester concept based on fiber-reinforcement [2]. The basic idea is that continuous high-strength fibers are introduced in the adhesive layer and their massive bridging suppresses crack propagation [3]. One example is depicted in Fig. 1. This x-type crack arrester consists of 0° and 90° composite layers cured during the bonding process. The 90° layer is inserted between the 0° layers that are interlocked during the layup process. When a crack including the one propagating in the adherend approaches the arrester, the crack is robustly entrapped in the arrester by employing the surface feature of the adherends. When the crack passes through the crossing part, one 0° layer bridges the crack and suppresses the crack opening (Fig. 1 A). Furthermore, the 90° layer, which is constrained by the other side 0° layer, prevents the bridging layer from peeling off (Fig. 1 B). So when the crack further propagates, fibers break in the 0° or 90° layers and significant energy is absorbed.

Following the previous study evaluating the arrester performance under a mode I loading condition (Fig. 2, [2]), this study conducts end notched flexure (ENF) tests to assess the performance under a

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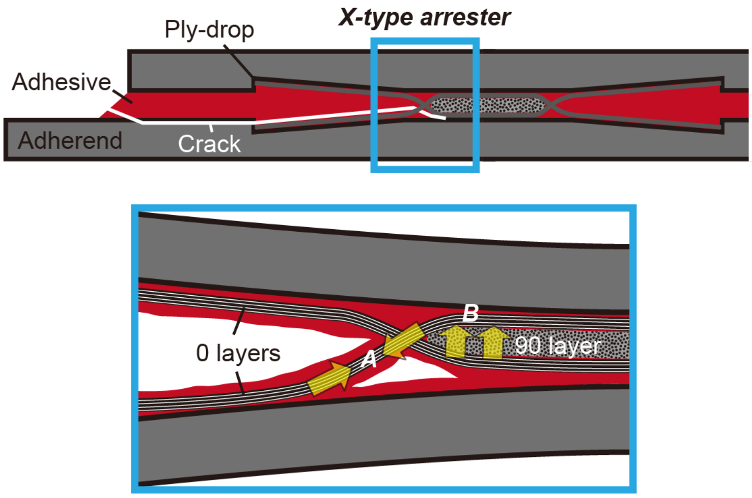

Figure 1. X-type crack arrester employing interlocked continuous fibers [2].

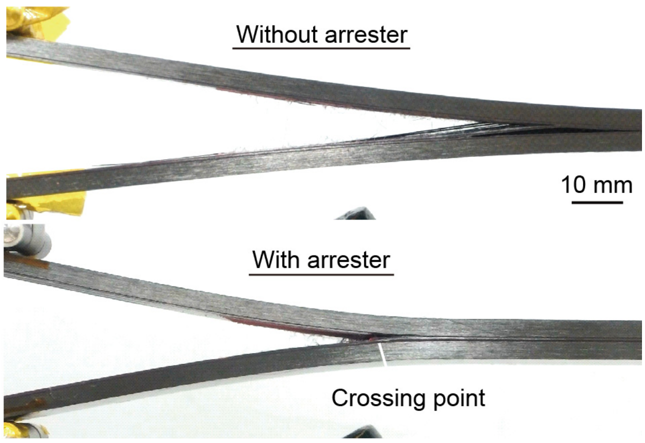

Figure 2. Deformation of specimens without and with crack arrester under the same crack opening displacement [2].

mode II loading condition. In addition, robust crack entrapment is demonstrated using a new manufacturing procedure.

2. ENF tests

Figure 3 depicts a schematic of the ENF specimen. Adherends were pre-cured unidirectional carbon/epoxy laminates (T700SC/2592 prepreg, Toray Industries, Inc., 2 mm thickness, 25 mm width). Two plies of Kevlar/epoxy prepreg (KF9355-381IUP, Mitsubishi Rayon Co., Ltd.) were used for the 90° layer of the arrester. In contrast, combination of 3plies of Kevlar/epoxy prepreg (KF9355-381IUP) and carbon/epoxy prepreg (T700SC/2592) was applied to the two 0° layers of the arrester. When the arrester stops a crack, 0-a and 0-b in Fig. 3 are under compression and tension respectively. So three specimens with different material combination were prepared to clarify the effect of the material selection on the performance; Specimen A with Kevlar 0-a and Kevlar 0-b, Specimen B with Kevlar 0-a and carbon 0-b, and Specimen C with carbon 0-a and Kevlar 0-b. First, the 0° layers of the arrester were slit at intervals of 5 mm and interlocked as depicted in Fig. 4 (a). The non-crossing parts were removed. The 90° layer was then inserted between the 0° layers, Fig. 4 (b). Finally, the stacked prepregs and epoxy adhesive films (FM300, Cytec Industries Inc.) were sandwiched between the sanded adherends and cured in an autoclave. Additionally a specimen without arrester was fabricated

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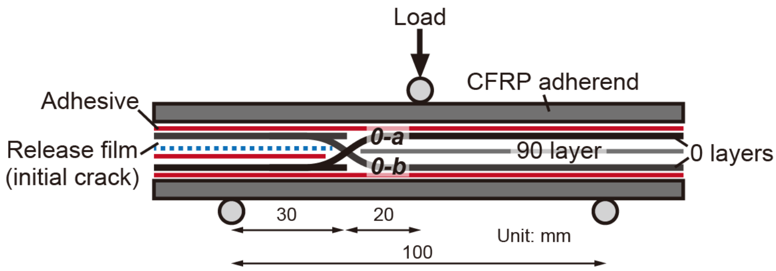
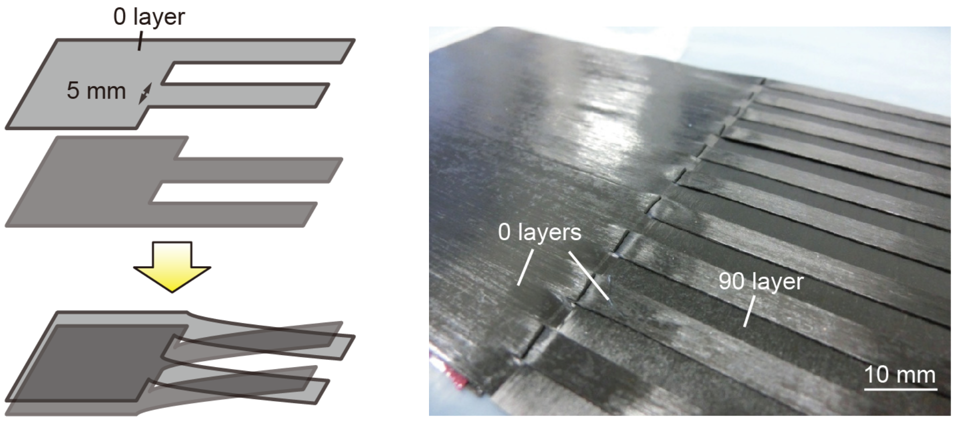


Figure 3. ENF specimen.



(a) Interlocking process of 0° layers. (b) Stacked arrester.

Figure 4. Preparation of arrester [2].

for comparison. ENF tests were conducted using a material testing system (AG-50kN, Shimadzu Co.). Loading speed was set to 1 mm/min. A crack was propagated from the crossing point of the arrester by implanting a release film in the adhesive layer during fabrication.

Figure 5 presents the load-displacement curves obtained. Without arrester, unstable crack propagation occurred at 2000N after the elastic deformation and the crack tip reached the loading position. In Specimen A with Kevlar 0° layers, however, the crack gradually propagated and passed though the crossing point of the arrester. 0-a under compression failed during the crack propagation but the load kept increasing. Finally 0-b under tension started to intermittently break at 2800N and the load decreased. Fracture toughness calculated from the maximum load was 8.7kJ/m^2 and tripled compared to the value of the specimen without arrester 3.3kJ/m^2, successfully confirming the effectiveness of the proposed arrester concept under a mode II loading condition. Furthermore, when carbon/epoxy having higher strength was used in the tension side (Specimen B), the strength further increased. With carbon/epoxy in the compression side (Specimen C), however, the arrester could not stop the crack. This difference may be attributed to the material behavior after initial failure. When Kevlar 0-a failed under compression, the fibrillar structure in the Kevlar fibers microbuckled due to the weak inter-fibrillar force. However, the microbuckled fibers did not break and maintained a certain amount of the load bearing capacity especially under tension [4], so the failed 0-a functioned to stop the crack. In contrast, when carbon 0-a failed under compression, brittle carbon fibers completely broke and the arrester lost the crack-stopping function. This result implies the importance to select optimal materials by considering both strength and material behavior after initial failure.

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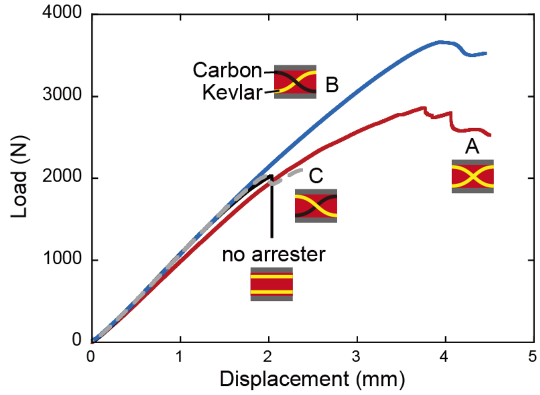

Figure 5. Load-displacement curves depending on material combination.

3. Demonstration of robust crack entrapment

The arrester concept in this study relies on robust entrapment of a crack into the arrester (Fig. 1). So weakbond between the arrester and the adherend is a critical issue because a crack may propagate between the arrester and the adherend and the arrester cannot stop the crack. In order to avoid this situation and to improve the robustness of the crack entrapment, a new manufacturing method is introduced. Specifically, each 0° layer of the arrester is first co-cured with an adherend and the two adherends are then coupled and bonded after inserting a 90° layer between the co-cured 0° layers.

A single lap joint specimen was made to demonstrate this idea. First, carbon/epoxy adherends were cured with Kevlar 0° layers (Fig. 6 (a)). Carbon/epoxy prepregs were partially removed, and slit Kevlar/epoxy prepregs were embedded into the space formed. Across-the-width hollows were introduced in the 0° layers by using release sheets to insert a 90° layer after coupling the two adherends. It is important to note that the surface ply of the carbon/epoxy adherend covered the edge of the 0° layer (Fig. 6 (b)), with which a crack propagating within the adherend can be robustly guided into the arrester. The two adherends with adhesive films were then coupled after sanding (Fig. 6 (c)) and two plies of carbon/epoxy prepreg (i.e., 90° layer) were inserted into the hollow between the 0° layers (Fig. 6(d)). Finally, the specimen was heated in an autoclave to cure the adhesive and the 90° layer (Fig. 6(e)). Figure 7 shows the fracture surface after tensile failure. The crack propagated within the surface layer of the carbon/epoxy adherend, so the fracture surface was black. The surface ply of the carbon/epoxy adherend covering the edge of the 0° layers successfully guided the crack into the arrester, validating the robust crack entrapment. Meanwhile, the arrester could not stop the crack and the joint failed unstably. Currently, optimal material selection and arrester geometries are under investigation. Future work will address crack stopping under practical loading conditions using the improved arrester configuration.

4. Conclusions

This study evaluated the performance of the fiber-reinforcement-based crack arrester under a mode-II loading condition. The fracture toughness tripled compared to the specimen without arrester and the test result implied the importance of material behavior after initial failure. In addition, a new manufacturing method was successfully demonstrated to enhance the crack-entrapment performance.

Acknowledgments

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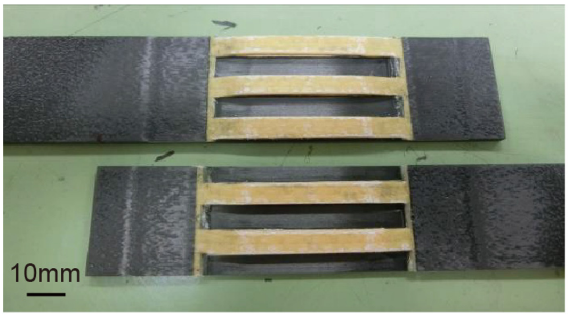
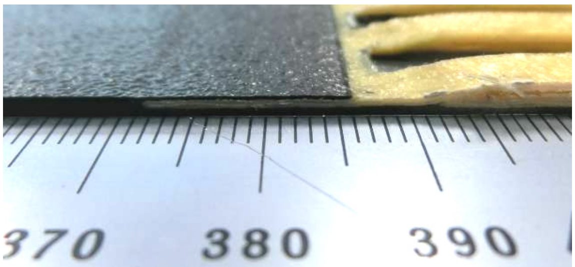
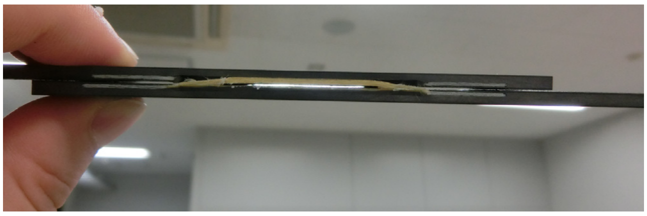


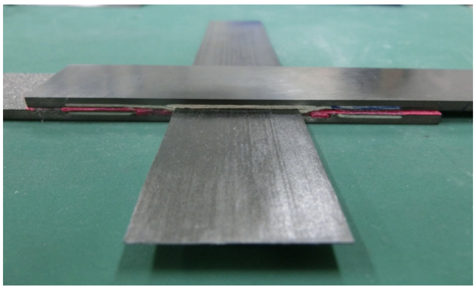
(a) Adherends with co-cured 0° layers.



(b) Edge of 0° layer covered with surface layer.



(c) Coupled adherends with hollow for 90° layer.



(d) 90° layer inserted into hollow.

(e) Cross-section of single lap-joint specimen.

Figure 6. New manufacturing method to enhance crack-entrapment performance.

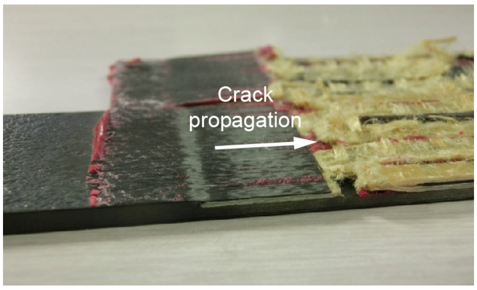


Figure 7. Fracture surface of joint specimen. Crack in adherend was robustly entrapped in arrester.

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