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Static Strength of RTM Composite Joint with I-fiber Stitching Process

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Abstract

Resin transfer molding (RTM) is a mass production process that can replace autoclave processes, and composite lap joints are extensively used in composite structures. When a tensile load is applied to a single-lap joint, both shear and tensile peel stresses are generated owing to the eccentric load effect. Reinforcing the composite joint in the thickness direction can reduce the shear and peel stresses generated in the joint, which can contribute considerably to the increase in the strength of the composite joint. Several reinforcing methods have been developed to improve the directional properties along the material's thickness. Accordingly, a stitching process is typically used. However, the conventional stitching process has disadvantages because a) it requires complex equipment, and b) it cannot use highly elastic brittle fibers, such as carbon fibers. Recently, we proposed an I-fiber stitching process to minimize the bending of carbon fibers to prevent their fracture.

In this study, composite, single-lap joint specimens were fabricated with RTM using an I-fiber stitching process, and their strengths were evaluated. The strengths of composite joint specimens fabricated at different stitching intervals and with the use of different patterns were compared with those of specimens fabricated without the use of the stitching process.

Keywords

Stitching, Resin transfer molding (RTM), I-fiber, Composite Joint

1. Introduction

Resin transfer molding (RTM) process is a mass-production process that can replace the autoclave process. In recent years, RTM processes have increasingly been applied to aircraft structures that are co-cured. Thick composite structures produced by co-curing have the disadvantage that their mechanical properties are weak in the thickness direction [1]. In order to compensate for this weakness, various methods have been developed for reinforcing the mechanical properties of the composite along the thickness direction. Some of these methods, including z-pinning and stitching, are being extensively used.

The z-pinning process is a method for reinforcing the mechanical properties along the thickness direction by inserting pins made of various materials and shapes into the prepreg material. Son et al. [2] and Ko et al. [3] studied the fatigue characteristics of single-lap joint specimens reinforced with stainless steel and jagged pins exposed to various environmental conditions. Chang et al. [4] studied the tensile and fatigue characteristics of single-lap joint specimens reinforced with z-pins, and evaluated the optimization of the insertion pins. Park et al. [5] studied the tensile properties through pull-off tests of T-joint specimens reinforced with z-pins.

The conventional stitching process is a method of reinforcing the mechanical properties in the thickness direction by intersecting the upper and lower fibers of the preform. Mouritz et al. [6] performed tensile, compressive, shear bending, and fatigue tests on the stitched composite specimens, and studied the characteristics of the stitching process. Beylergil et al. [7] studied the strength of the stitched composite, single-lap joint, and proved that the stitching process decreases the peel and shear stresses along the thickness direction and increases the joint strength. Aymerich [8] conducted fatigue testing on a single-lap joint specimen using a stitching process, and evaluated the stiffening effect of stitching.

The I-fiber stitching process is a method used to improve and complement the z-pinning and the conventional stitching processes. Carbon fibers can be stitched, such that the increase of the strength along the z-direction is superior, and the stitching operation can be completed in one direction. Kim et al. [9] fabricated T-joint specimens with the application of the I-fiber stitching process to laminated prepregs, compared their strengths to those of T-joint specimens prepared with the z-pinning process, and demonstrated the superiority of the I-fiber stitching process.

In this study, single-lap joint specimens with I-fiber stitching were fabricated by RTM, the strengths of the single-lap joint specimens were evaluated for various stitching patterns, and the reinforcement effect of the I-fiber stitching process was verified.

2. Test specimen fabrication

Fig. 1 shows conventional stitching processes. As observed, the structures are such that the top and bottom fibers are knitted together and the fibers are bent by more than 180°. Carbon fibers have very high-tensile strength as well as a high-elastic modulus, and are therefore are not suitable for conventional stitching processes in which the fibers are bent by more than 180°. The I-fiber stitching process is suitable for stitching high-stiffness fibers, such as carbon fibers, because the bending of the reinforcing fibers can be minimized to 90° or less.

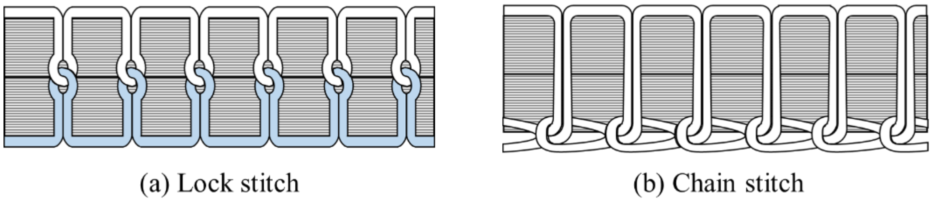


Fig. 1 Conventional stitching processes.

Fig. 2 shows the I-fiber stitching method. The hollow needle containing the carbon fiber is lowered to penetrate the preform or prepreg, and an inner pneumatic pressure is then applied to release the fiber. After the hollow needle is raised, the inserted fiber is cut. In this study, the samples were prepared using a portable I-fiber stitching machine, as shown in Fig. 3.

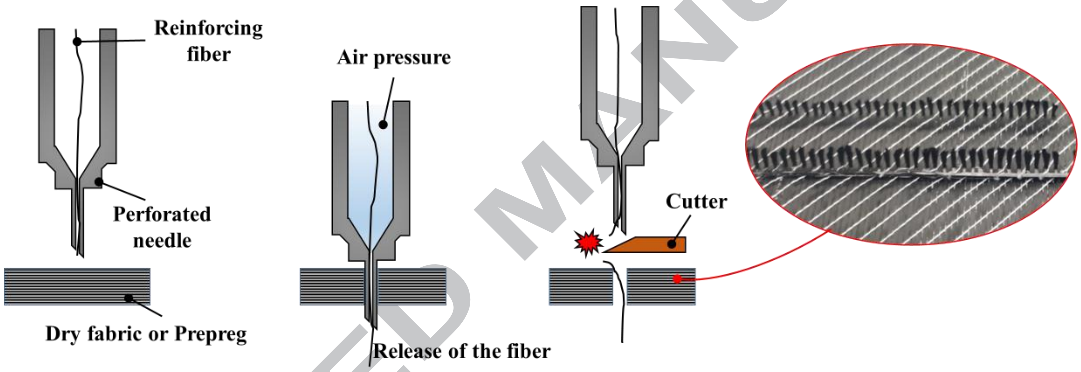


Fig. 2 I-fiber stitching process.

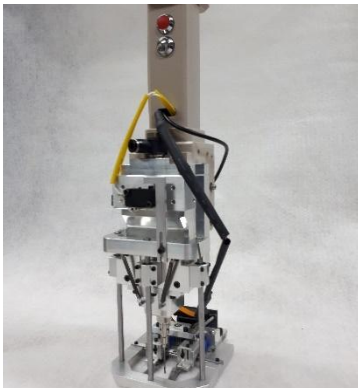


Fig. 3 Portable I-fiber stitching machine.

The shape of an RTM single-lap joint specimen with I-fiber stitching is shown in Fig. 4. It was prepared according to ASTM D1002 and ASTM D5686. Noncrimp fabric (NCF) material provided by CNF Co. was used for the single-lap joint production, and the stacking sequences of the NCF materials and the resin used are shown in Table 1.

In general, the bending moments due to the eccentric load effect produce high peel and shear stresses in the single-lap joint. Given that the maximum peel stress acts on the tip of the single-lap joint, to decrease the peel stress and maximize the reinforcement effect along the z-direction, the reinforcing fibers were arranged at both ends of the joint [7, 10]. The specimens were fabricated by changing the edge distance (*E*) from the end and the pitch distance (*P*) between the reinforcing fibers. Table 2 shows the *E* and *P* values for each specimen. In Case 6 in Table 2, the two lines of fibers were aligned at both ends of the joint, and the number of fibers was twice as high as that of Case 5.

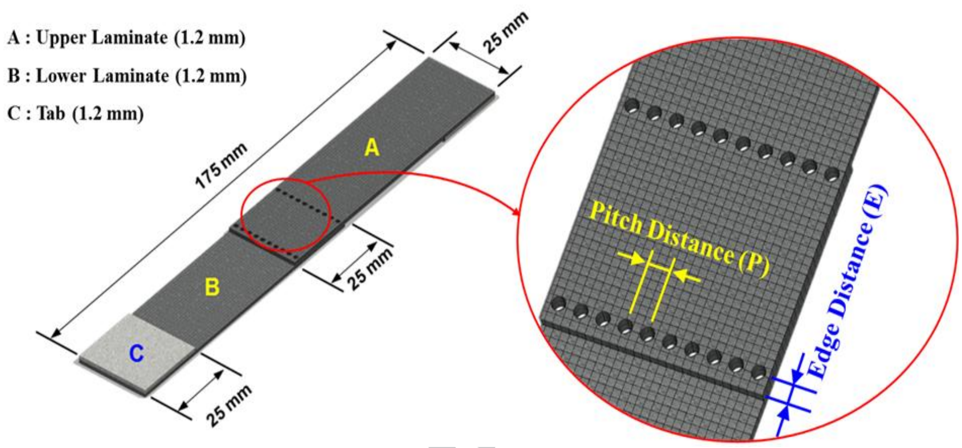


Fig. 4 Shape of the RTM single-lap joint.

Table 1 NCF material and resin.

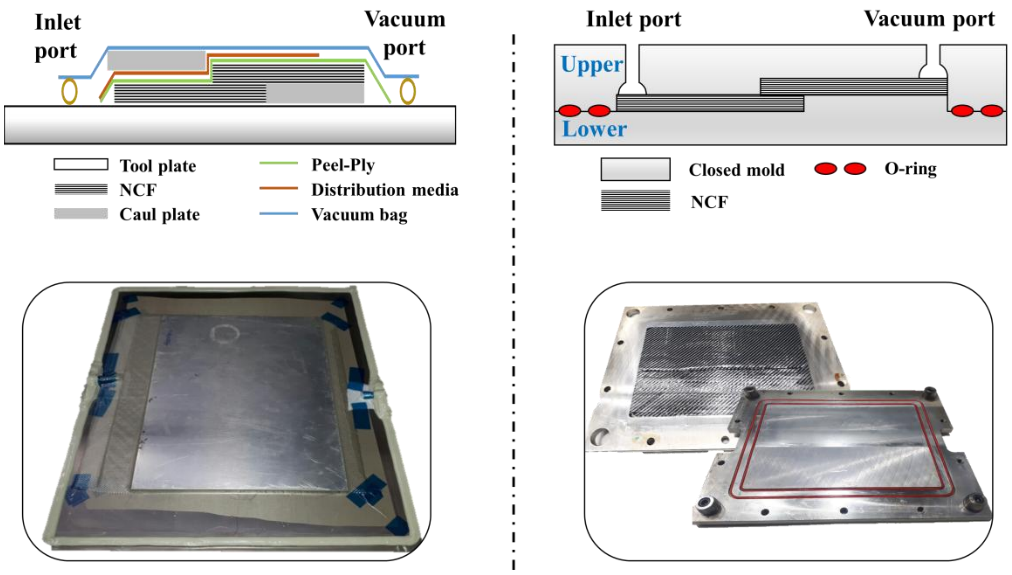
NCF [45/-45]	Manufacturer : CNF Co., Republic of Korea
	Fiber : 12 k (H3055), Hyosung Co., Republic of Korea
	Stacking Sequence (A, B, C) : $[0/90/45/-45]_s$
Adhesive	Epoxy Resin : KFR–120V, Kukdo Chemical Co., Republic of Korea
	Hardner : ETHACURE–100, Kukdo Chemical Co., Republic of Korea
Stitching Fiber	Carbon fiber 6 k (T300), Toray Co., Japan

Table 2 Edge and pitch distances of single-lap joints.

Test Specimen	Case 1 :	Reference (No Stitching)

	Case 2 : *E*: 1.5 mm, *P*: 5.0 mm, 1 Line
	Case 3 : *E*: 1.5 mm, *P*: 2.5 mm, 1 Line
	Case 4 : *E*: 2.0 mm, *P*: 5.0 mm, 1 Line
	Case 5 : *E*: 2.0 mm, *P*: 2.5 mm, 1 Line
	Case 6 : *E*: 2.0 mm, *P*: 2.5 mm, 2 Line

Two types of RTM mold were applied to fabricate the composite joint specimens. Fig. 5 (a) shows the RTM process with open molds, which have a vacuum bag on the upper side, and Fig. 5 (b) shows the RTM process with closed molds, which consist of lower and upper molds.



(a) Open mold (b) Closed mold

Fig. 5 RTM process molds.

Fig. 6 shows the RTM fabrication process for the single-lap joint specimen. The NCF material is preformed in a single-lap joint shape, and is then stitched using a portable I-fiber stitching machine. The stitched specimen is then inserted into the closed mold to inject the resin. The resin enters the inlet port and exits from the vacuum port. The resin-filled specimens were cured in an oven at 150 °C. Subsequently, the cured RTM single-lap joint specimens were cut with a diamond wheel cutter. Fig. 7 shows photographs of regions around the stitched zones of the cured, single-lap joint specimens, at increased magnification for the two types of molds (open and closed). As shown in Fig. 7, the dry spot is observed in the stitched zone of the composite joint formed by the open mold of Fig. 5 (a). However, it is not observed in the composite joint formed by the closed mold of Fig. 5 (b). Therefore, RTM composite joint specimens without the dry spot were fabricated by using the closed mold process.

Five specimens were fabricated in each case. Fig. 8 shows a photograph of a cross-section taken by cutting the stitched part of the fabricated specimen. It can be observed that the stitched fibers are inclined at approximately 45° along the thickness direction of the material.

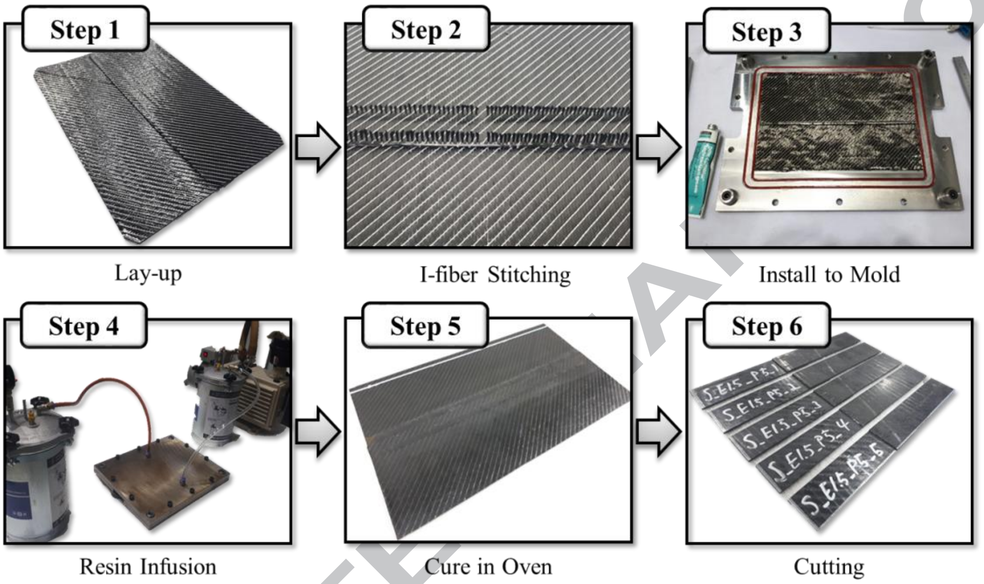
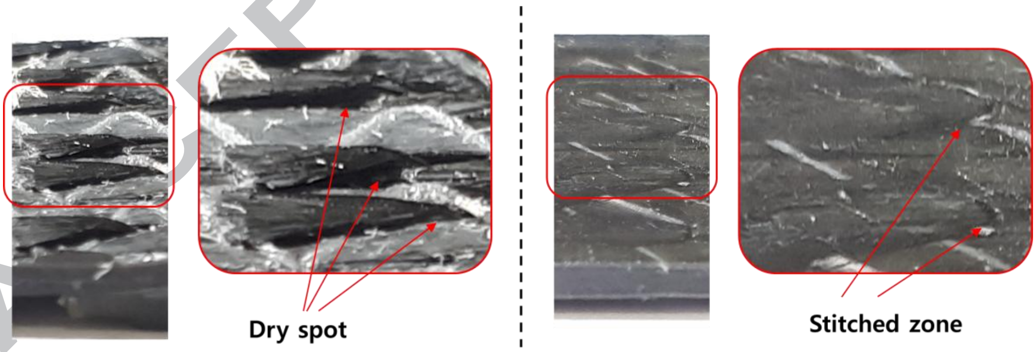


Fig. 6 Fabrication process for the single-lap joint specimen.



(a) Open mold (b) Closed mold

Fig. 7 Photographs at increased magnification around the stitched zones of the cured, single-lap joint specimens for the two types of molds studied herein (open and closed).

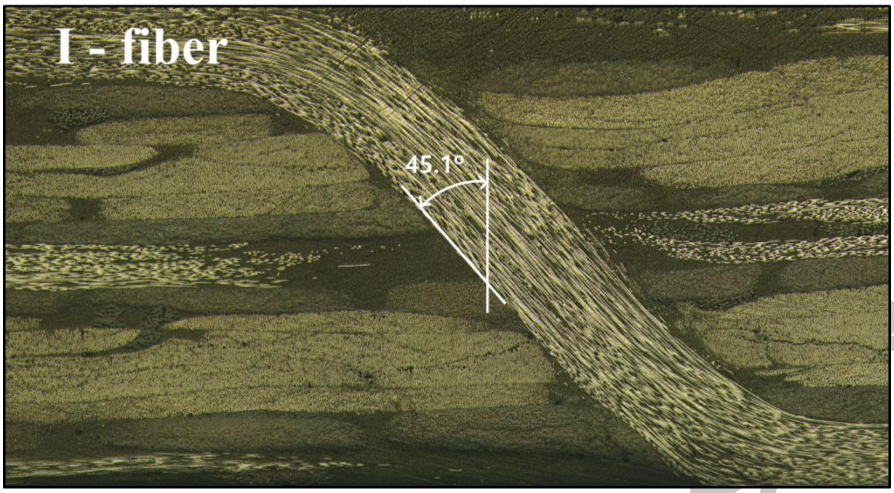


Fig. 8 Cross-section of stitched I-fiber specimen.

A tensile test was performed to evaluate the reinforcement effect of the RTM single-lap joint specimen with the I-fiber stitching method. Fig. 9 shows the tensile test of the single-lap joint specimens. The universal testing machine of Instron Co. (Model 5582) was used for the testing, with a cross-head speed of 1.27 mm/min.

Fig. 9 Tensile test of a single-lap joint specimen.

3. Test results

Fig. 10 shows the force–displacement curves of single-lap joint specimens. It can be observed that they are similar to each other, regardless of whether the specimens are stitched or patterned. The average failure loads of each case are calculated and shown in Fig. 11 to verify the reinforcement effect of the I-fiber stitching method. As it can be observed in this figure, the specimens with I-fiber stitching elicited a 34.6–68.0% increase in the failure load compared to the specimen without stitching. Case 3 (*E*: 1.5 mm, *P*: 2.5 mm) elicited a minimum strength increase of 34.6%, and Case 6 (*E*: 2 mm, *P*: 2.5 mm), which was stitched with two lines, elicited a maximum strength increase of 68.0%.

The failure modes of the single-lap joint specimens were analyzed to clarify the cause of the increased strength of the stitched specimens. The failure modes of the single-lap joint specimens could be observed in three forms: shear-out failure, I-fiber failure, and composite adherend tensile failure. Fig. 12 shows the fracture of the specimen in Case 3 and the shear-out failure of the composite adherend at the end of the joint. This can be attributed to the weakening of the composite adherend because the spacings of the I-fibers were small and the edge distances were short. Correspondingly, the specimen of Case 3 elicited the lowest failure load increase among all the stitched specimens, and was equal to 34.6%. Fig. 13 shows the fracture of the specimen in Case 4, which indicates that the fracture occurs at the center of the I-fiber. I-fiber failure occurred in Cases 2, 4, and 5. In Case 5, which had the highest density of I-fibers, the highest failure load increase was 60.0% in the absence of any composite adherend failure owing to the weakening of the composite adherend. Fig. 14 is a photograph of the fractured specimen of Case 6, which has two lines of fibers. It can be observed that the nonoverlapped composite adherend at the end of the lap joint has undergone tensile failure. Case 6 showed a failure load increase of 68.0%, which was the highest strength increase. However, given that there was no breakage in the overlapped part of the joint specimen, this load cannot be regarded as the failure load of the single-lap joint. Therefore, it was considered that a) the failure load of the single-lap joint can be evaluated by strengthening the composite adherend, and b) the failure load of the single-lap joint will increase further.

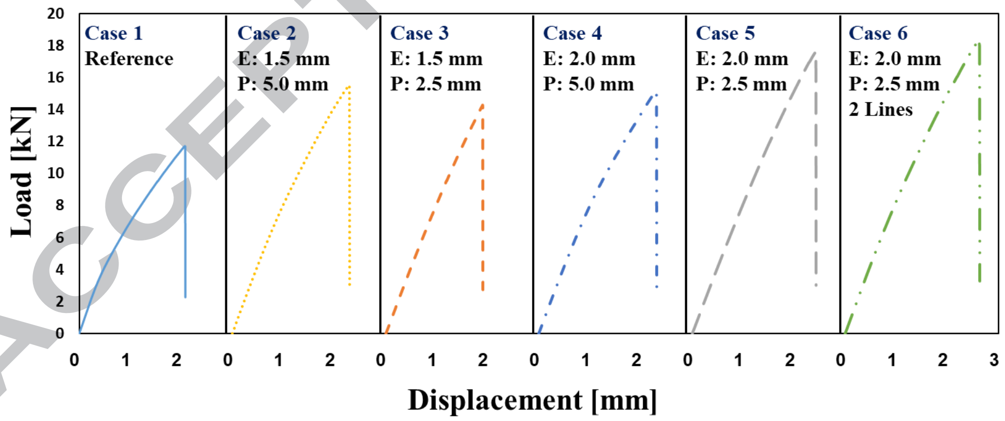


Fig. 10 Force–displacement curves of single-lap joint specimens.

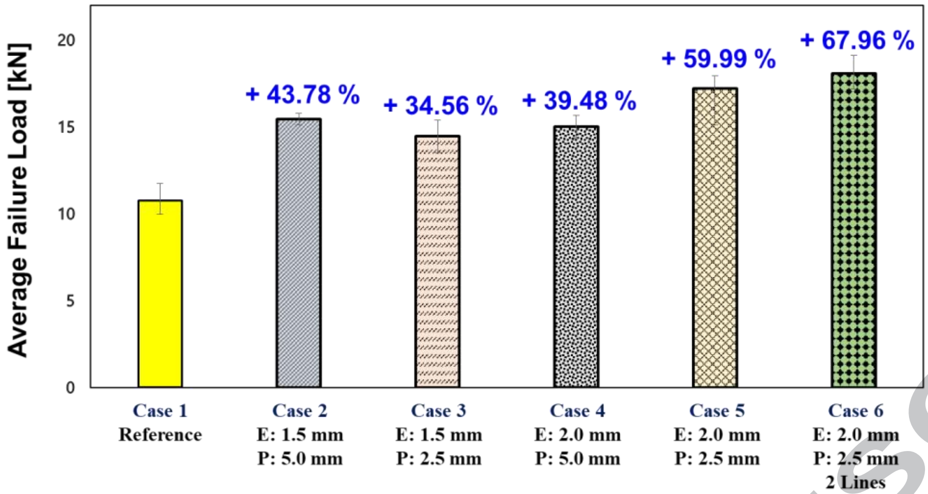


Fig. 11 Average failure loads of single-lap joints.

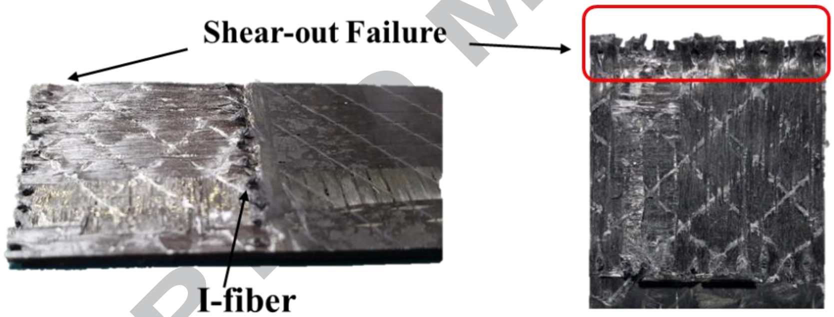


Fig. 12 Shear-out failure of the composite adherend (Case 3).

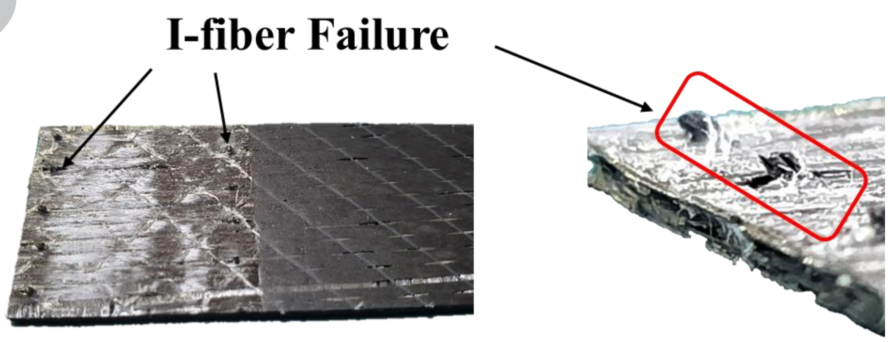


Fig. 13 I-fiber failure (Cases 2, 4, and 5).

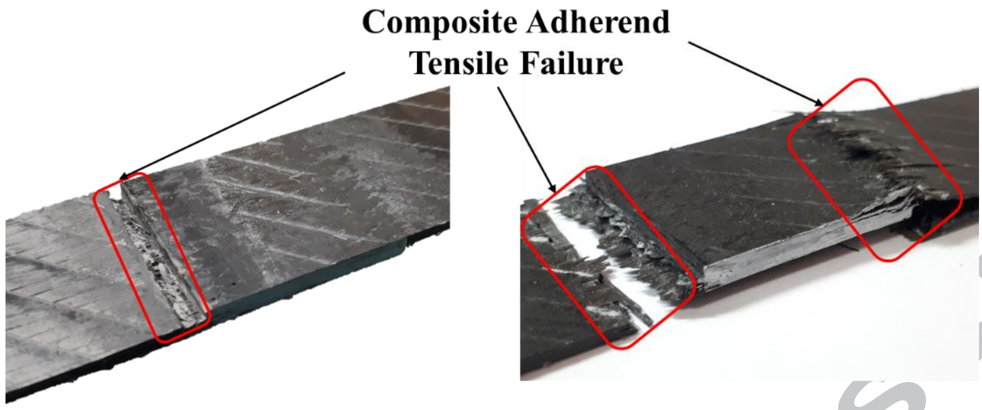


Fig.14 Composite adherend tensile failure (Case 6).

A study on the strength of the RTM single-lap joint constructed by a conventional stitching process was performed by Tong et al. [11], whereby they used the lock stitching method and Kevlar fibers. The maximum increase in the strength of the RTM single-lap joint made by the conventional stitching process was 20%, which was much lower than the strength increment of the single lap joint with the use of the I-fiber process in this study, based on similar experimental conditions. The reason for the much higher strength elicited in this study is considered to be caused by a) the use of carbon instead of Kevlar fibers, and b) the minimization of the fiber damage caused by bending during the I-fiber stitching process.

4. Conclusions

The following conclusions can be drawn regarding the failure loads of single-lap joint specimens with RTM and the use of I-fiber stitching.

1. The RTM single-lap joint specimens prepared using the I-fiber stitching process yielded an increase in the fracture load in the range of 34.6–68.0% for the studied specimens compared to the specimens without stitching
2. The failure load of the stitched single-lap joint specimen was maximized when the fracture of the I-fiber occurred, and increased by approximately 60.0% compared to the specimen without stitching for all the studied specimens
3. The failure load of the stitched single-lap joint specimen yielded its lowest value when the shear-out failure of the composite adherend occurred, and increased by approximately 34.6% compared to the specimen without stitching

Acknowledgments

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