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A Study on the Fatigue Strength of the 3D Reinforced Composite Joints

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Abstract

Composite lap joints have been extensively used due to their excellent properties and the demand for light structures. However, due to the weak mechanical properties in the thickness direction, the lap joint is easily fractured. Various reinforcement methods that delay fracture by dispersing stress concentration have been applied to overcome this problem, such as z-pinning and conventional stitching. The z-pinning is a reinforcement method by inserting metal or carbon pin in the thickness direction of prepreg, and the conventional stitching process is a method of reinforcing the mechanical properties in the thickness direction by intersecting the upper and lower fibers on the preform. I-fiber stitching method is a promising technology that combines the advantages of both z-pinning and the conventional stitching. In this paper, the static and fatigue strengths of the single-lap joints reinforced by the I-fiber stitching process were evaluated. The single-lap joints were fabricated by a co-curing method using an autoclave vacuum bag process and I-fiber reinforcing effects were evaluated according to adherend thickness and stitching angle. From the experiments, the thinner the composite joint specimen, the higher the I-fiber reinforcement effect, and I-fiber stitched single-lap joints showed a 52% improvement in failure strength and 118% improvement in fatigue strength.

Keywords

I-fiber (I-fiber stitching)
Single-lap joint
Failure strength
Fatigue strength

1. Introduction

Composites have excellent mechanical and chemical properties as well as high specific stiffness and strength compared to conventional metals, therefore they are attracting attention as a substitute for conventional metals for structures that require high efficiency. In the past, composites in the aviation industry were mainly applied to secondary structures such as control surfaces and landing gear doors, but with the development of composite design technology and the establishment of a test database, their application to main structures such as wing skins and fuselages is expanding. Laminated composites, which are commonly applied to aircraft structures, have excellent physical properties in the direction of the fibers, but they have very weak physical properties because the fibers are not arranged in the direction in which they are laminated, i.e., the thickness of the composite. Due to this feature, laminated composites are prone to fracture, which is the separation of the layers of the composite by loading in the thickness direction. Composite structures with interlaminar separation suffer from loss of properties in the in-plane direction, making it difficult to maintain structural performance. To overcome this problem, various researchers have developed three-dimensional reinforcement methods for composites, such as z-pinning, stitching, and tufting [1-7].

Recently, the I-fiber stitching process, which complements z-pinning and conventional stitching methods, has been proposed and studied [8-16]. Kim [8] confirmed the change of pull-off failure load due to the density change of I-fiber stitching process, and An [9,10] evaluated the failure load of joint specimens made by RTM (Resin Transfer Molding) process and vacuum bag molding process, and analyzed the reinforcement effect and failure mode by the spacing of reinforcement fibers. Tapullima [11-13] evaluated the reinforcement effect of double cantilever beam (DCB) and unit-cell specimens reinforced with I-fiber stitching according to mode I and II failure modes, and predicted the failure load through various analysis techniques. Song [14] and Choi [15] evaluated the tensile strength of the connection by selecting various process parameters such as the thickness of the connection and the angle of the reinforcing fiber. Kim [16] evaluated the impact properties of composite panels as a function of reinforcement density. In this paper, single-lap joint specimens reinforced with I-fiber stitching method were fabricated by autoclave vacuum bagging method, and the failure and fatigue strength characteristics were evaluated according to the thickness of the base material and the stitching angle to verify the reinforcement effect of the three-dimensional reinforced composite joint structure.

2. Specimen fabrication

In order to evaluate the strength characteristics of the three-dimensional reinforced composite joint structure, the joint specimen was fabricated as shown in **Figure 1**, referring to ASTMD5868. **Figure 2** is a schematic diagram of the I-fiber stitching process, which uses a hollow needle and pneumatic pressure to place carbon fibers discontinuously and perpendicularly to the base material [8].

The material used to make the joint specimen is SK chemicals' unidirectional carbon/epoxy prepreg USN-125B, and the reinforcing fiber for stitching is Hyosung Advanced Materials' H2550 6K carbon fiber, and the material properties are as shown in **Table 1**. An industrial hollow needle was used to insert the reinforcing fiber, and a 19G (internal diameter: 0.73 mm, external diameter: 1.06 mm) needle was used.

The lamination pattern of each base material is quasi-isotropic [0/45/90/-45]ns, and the specimens were made by laminating 8, 16, and 32 ply, and the overlap width and length of the joint were fixed at 25 mm. The stitching pattern and angle are shown in **Figure 3**. 8 reinforcing fibers are inserted at 3.125 mm intervals at both ends of the joint, and the insertion angle of the fibers is 45 degrees. The types of specimens used in the tests are summarized in **Table 2**.

Figure 4 shows the process for fabricating the joint specimen. Autoclaved vacuum bag molding was used. The curing process is a co-curing method in which the bonding is done with the bonding paper without inserting a separate adhesive film between the two materials. The curing cycle is shown in **Figure 5**.

The fabricated composite panels were cut at 25 mm intervals with a diamond wheel cutter. To evaluate the fiber insertion angle of the I-fiber stitching reinforcement, the vertical cross-section of the fabricated specimen was photographed at 50x magnification using a Nikon Eclipse LV 150L optical microscope. As shown in **Figure 6**, the insertion angle of the reinforcement fibers was measured to be 45.5 degrees, indicating that the fibers were relatively well arranged.

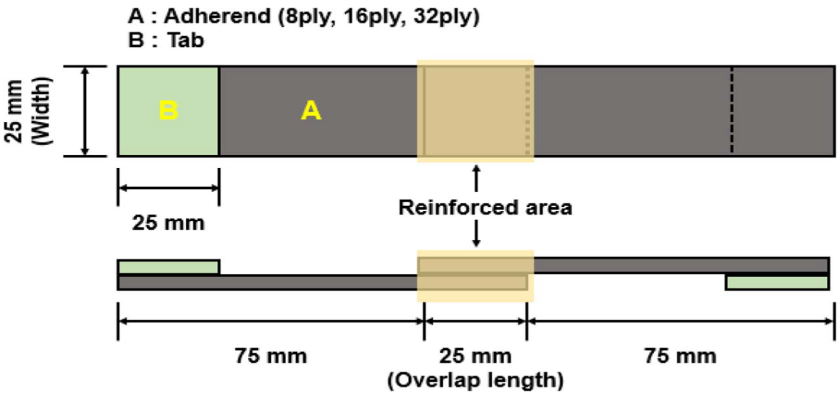

Figure 1. Single-lap joint specimen configuration

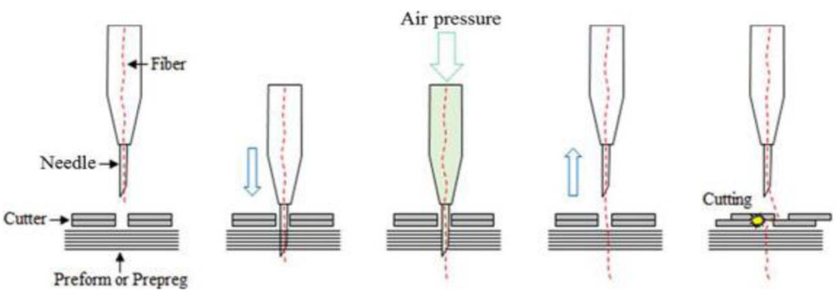

Figure 2. I-fiber stitching process

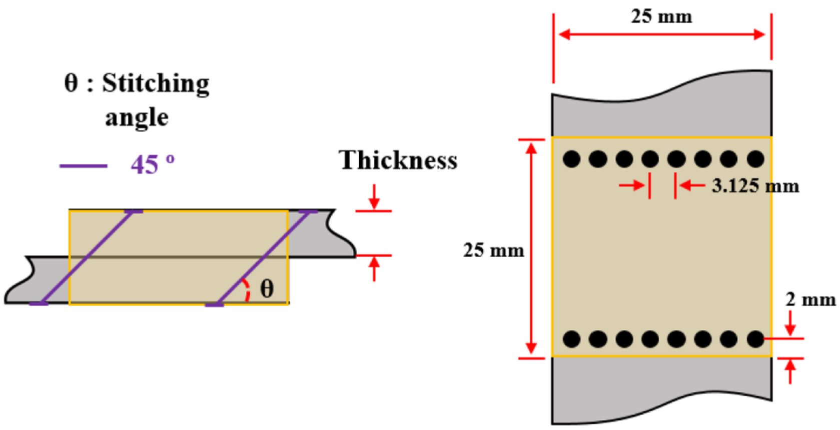

Figure 3. Schematics of stitching pattern and angle

Table 1. Material properties of TANSOME H2550

Property	Symbol	Value
Elastic modulus in fiber-direction	E_1	250 GPa
Strength in fiber-direction	X_T	5,516 MPa

Table 2. Test matrix of composite joint specimen

Specimen ID	Adherened stacking sequence	Adherend thickness (t)	Stitching angle
2_Un	$[0/45/90/-45]_S$ (8 ply)	1 mm	-
2_S			45°
4_Un	$[0/45/90/-45]_{2S}$ (16 ply)	2 mm	-
4_S			45°
8_Un	$[0/45/90/-45]_{4S}$ (32 ply)	4 mm	-
8_S			45°

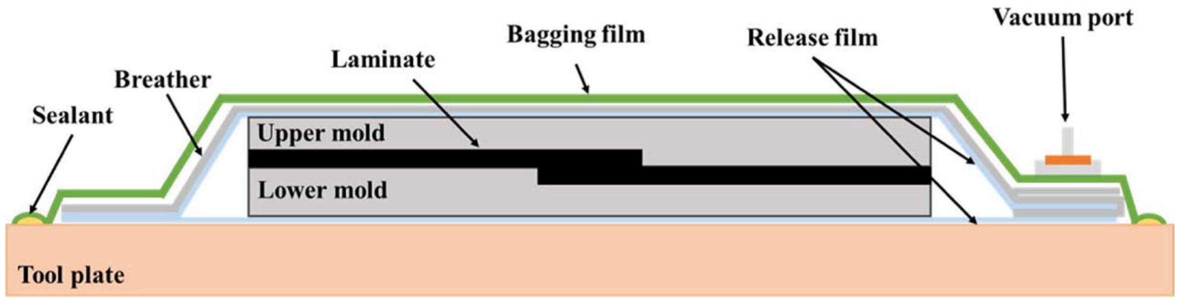

Figure 4. Autoclave vacuum bag process

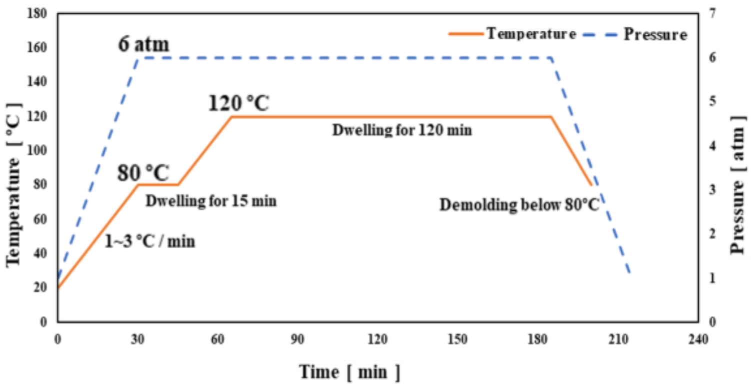

Figure 5. Cure cycle of the composite joint specimen

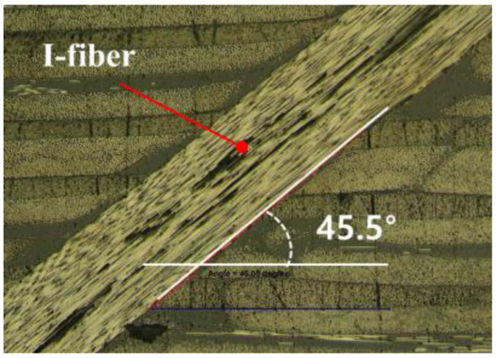

Figure 6. Cross-section of stitched I-fiber (45 degree)

3. Tensile and fatigue testing

3.1. Tensile testing

Figure 7 shows the tensile test of the joint specimen with I-fiber stitching. The test was performed on an E45 universal testing machine from material test system (MTS) with a controlled crosshead displacement of 1.27 mm per minute [10].

Figure 8 is the load-displacement graph of the fabricated composite single-lap joint specimen, and it can be seen that there is a rapid load drop after reaching the maximum load, and the stiffness values of the specimens with and without I-fiber stitching are similar.

Figure 9 shows the failure modes of the composite single-lap joint specimens after tensile testing. In all specimens without I-fiber stitching, interfacial failure occurred between the base material and the parent material as shown in **Figure 9(a)**. In the specimen with the thinnest thickness of 1 mm, where the reinforcement method was applied, the failure of the base material occurred as shown in **Figure 9(b)**, and in the specimens with the thickness of 2 mm and 4 mm, the failure of the interface between the base material and the base material, and the failure of the I-fiber fibers occurred.

Figure 10 is a graph of the average failure strength of the base material, which is defined as the failure load divided by the area of the joint (25 × 25 mm). As shown in the figure, the thickness of the base material of 1 mm, 2 mm, and 4 mm increased the strength by 39%, 52%, and 47%, respectively, compared to the unreinforced specimen. For the 1 mm thick specimen, it was not possible to accurately evaluate the reinforcement effect due to the breakage of the specimen as analyzed in the breakage mode, and it is believed that the reinforcement effect would be higher if the specimen did not break.

3.2. Fatigue test

The fatigue test of the I-fiber stitched joint specimen was performed to analyze the fatigue strength and failure mode. The fatigue test was conducted using the

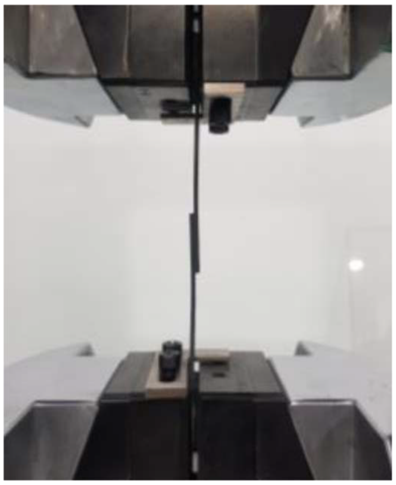

Figure 7. Tensile test of joint specimen

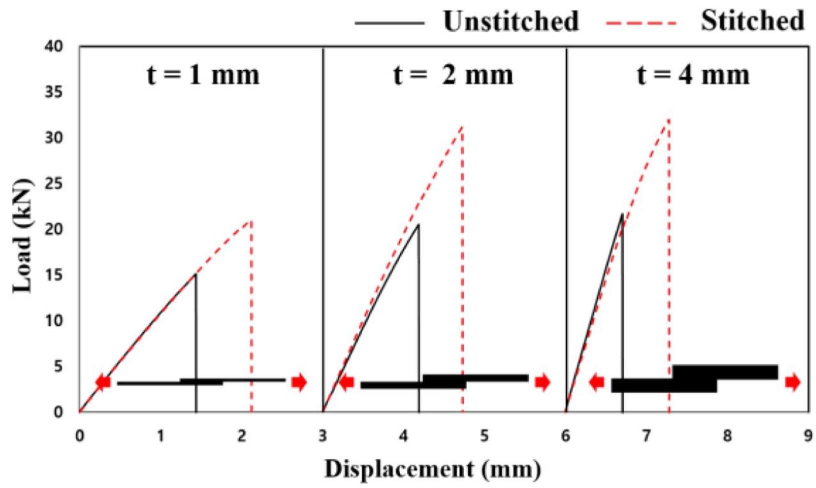

Figure 8. Typical load-displacement curves

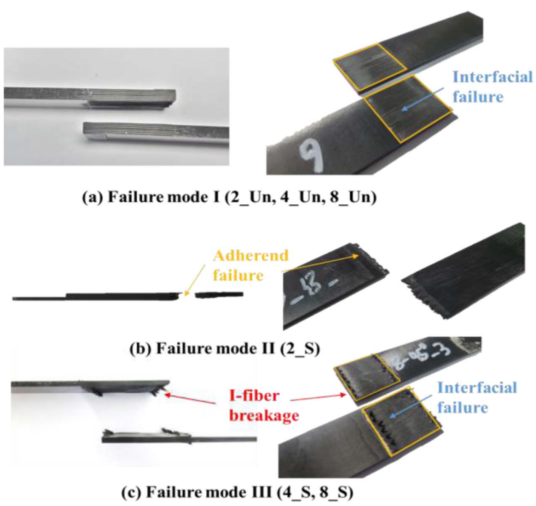

Figure 9. Failure modes of tensile tests

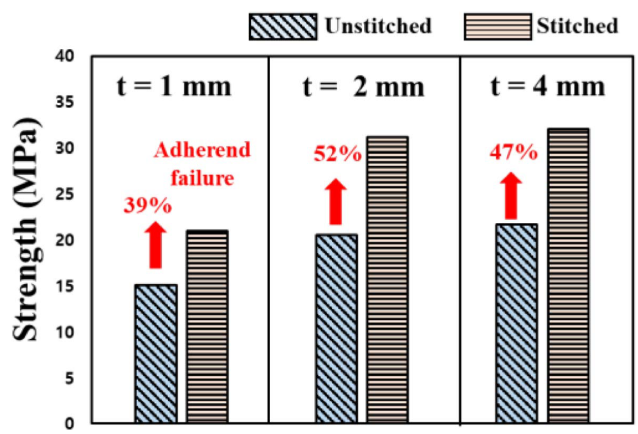

Figure 10. Strengths of composite single-lap joints

INSTRON 8801 fatigue tester of Instron, with a stress ratio of 0.1 and a frequency of 5 Hz.

Figures 11, **12**, and **13** are graphs showing the S-N curves of the specimens with 1 mm, 2 mm, and 4 mm base metal thickness after fatigue testing. It can be seen that the fatigue strength of the stitched specimens is higher in all test conditions, and the fatigue strength for 1 million cycles was determined from the trend line using a logarithmic function after performing the test at each load step.

For a specimen with a thickness of 1 mm, the fatigue strength of the unreinforced specimen was 4.95 MPa, while the fatigue strength of the I-fiber reinforced specimen was 10.78 MPa, showing an increase in fatigue strength of about 118%.

For a specimen with a thickness of 2 mm, the fatigue strength of the unreinforced specimen was 6.56 MPa and the fatigue strength of the I-fiber reinforced specimen was 13.41 MPa, showing an increase in fatigue strength of about 104%.

For a 4 mm-thick specimen, the fatigue strength of the unreinforced specimen was evaluated to be 9.18 MPa, and the fatigue strength of the I-fiber reinforced specimen was evaluated to be 10.58 MPa, indicating an increase in fatigue strength of about 15%.

Figure 14 shows the fatigue failure mode of the joint specimen reinforced with the I-fiber stitching method. **Figure 15(a)** is the failure mode of the specimen

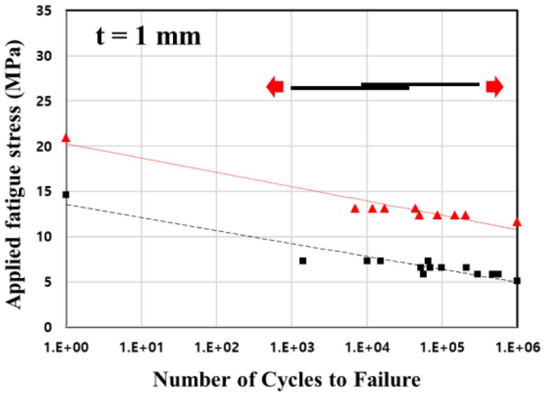

Figure 11. S-N curves of single-lap joint (t = 1 mm)

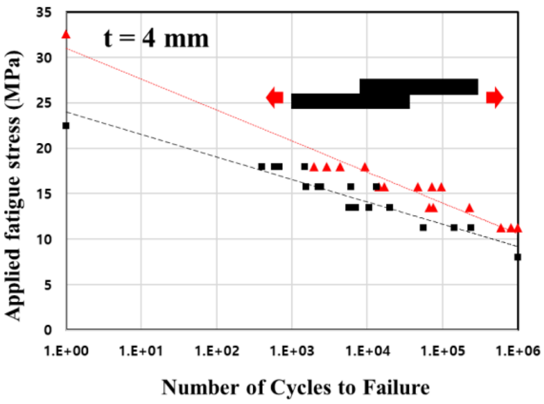

Figure 13. S-N curves of single-lap joint (t = 4 mm)

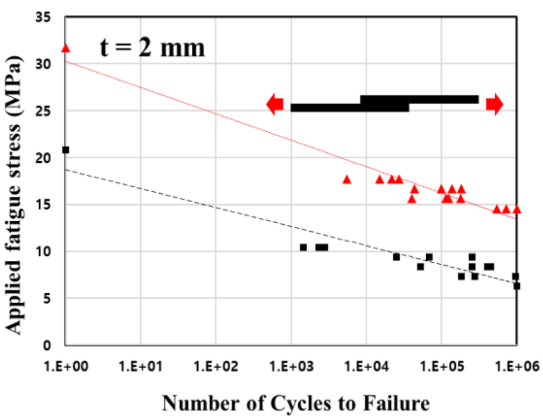

Figure 12. S-N curves of single-lap joint (t = 2 mm)

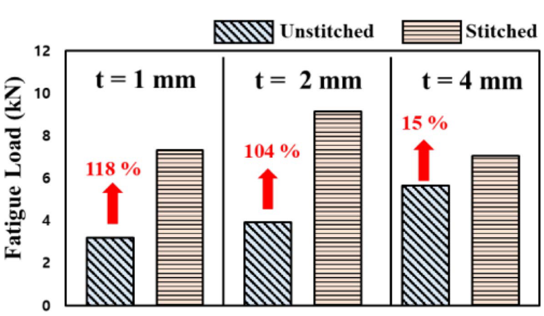

Figure 14. Fatigue strength of joint specimen (106 cycles)

without I-fiber stitching, which is the same as the failure mode of the joint failure test in **Figure 9(a)**, and the interface failure between the base material and the base material occurred. **Figure 15(b)** is the failure mode of the specimen with a thickness of 1 mm and 2 mm, and it can be seen that the same failure mode of the base material as in **Figure 9(b)** did not occur, and interfacial failure occurred between the base material and the base material, and between the I-fiber and the base material. It is assumed that the fatigue strength of the composite base material itself is very high, more than 80% of the failure strength [17], thus no fatigue failure of the base material occurred. **Figure 15(c)** shows the failure of a specimen with a thickness of 4 mm of the base material, and interfacial failure and fiber failure of the I-fiber occurred between the base material and the base material. This can be seen as the same failure mode in **Figure 9(c)**, which is the failure mode of the joint failure test, and when the composite base material is thicker, the interfacial area between the I-fiber and the base material is large, hence it is estimated that the interfacial failure does not occur and the fiber failure of the I-fiber occurs.

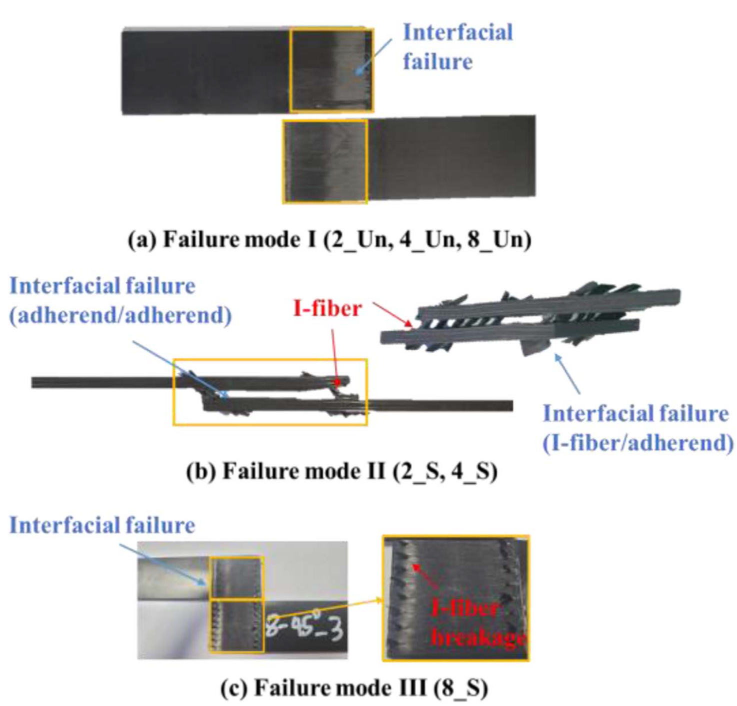

Figure 15. Failure modes of fatigue tests

4. Conclusion

In this paper, single-lap joint specimens using I-fiber stitching method were fabricated and evaluated for failure strength and fatigue strength characteristics with and without reinforcement, and the following conclusions were made.

(1) The failure strength of the joint specimen reinforced with I-fiber stitching method was improved by about 52% compared to the specimen without reinforcement.

(2) The thinner the thickness of the composite joint, the higher the effect of I-fiber reinforcement, and the fatigue strength of the joint specimen reinforced with I-fiber was improved by about 118% in a specimen with a thickness of 1 mm of the base material.

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Disclosure statement

The authors declare no conflict of interest.

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