ENHANCED TENSILE STRENGTH CFRP ADHESIVE JOINT CONSTRUCTED FROM CARBON FIBER-REINFORCED PLASTIC AND DRY CARBON FIBER LAMINATES

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Abstract

The staircase joint is an adhesive joint constructed using stepped carbon fiber-reinforced plastic (CFRP) fabric, half molded with dry carbon fibers. In this adhesive joint, the CFRP part is fabricated first, then remolded with dry carbon fiber laminates. Some improvements are provided to enhance performance in terms of tensile strength. These improvements include the addition of extra carbon fiber covers and overlapping the carbon fiber half over the CFRP. This paper introduces three adhesive joints: the first is the original staircase joint and the other two are improved staircase joints. All joints and CFRP fabrics were made in our laboratory using vacuum-assisted resin transfer molding (VARTM) manufacturing techniques. Specimens were prepared for tensile testing to measure joint performance. The results showed an improved tensile load for the modified staircase joints. The percentage increase in the tensile load recorded was 39%. The final joining efficiencies reached 51%. Finally, The tensile fracture behavior of all joints showed the same pattern of cracks, originating near the joint ends, followed by crack propagation until fracture.

1. Introduction

Carbon fiber-reinforced polymer (CFRP) composite materials have attracted particular and increasing and interest, in aviation, space, automotive, shipbuilding, and wind turbine applications due to their comparatively high strength-to-weight and stiffness-to-weight ratios [1]. They have served as important components in these applications, changing from secondary to primary structures, and are edging out conventional metal materials in some applications. The design of composite joints, as a difficult and important problem, has attracted substantial attention in a series of light, low-cost, and efficient composite integration projects [2]. Mechanical fastening, achieved for example with bolted, pinned, or riveted joints, is often preferred due to its simplicity and the fact that such joints can be disassembled [3-4]. However, holes have to be machined in the composite parts and these may cause problems due to stress concentration and weight increases. Adhesive bonding has mechanical advantages over bolted joints because the fibers are not cut, and stresses are transmitted more homogeneously [5]. Additionally, bonded joints offer structural integrity, low weight, and high strength-to-weight ratios [6].

Adhesive composite joints today play an important role in aerospace, turbine, and ship designs [2]. Usually, these joints are constructed from at least 50% CFRP fabric and include conventional joints such as single-lap [5], double-lap [7], and stepped [8] joints. Various experimental studies have been reported to improve the strength of adhesive joints. For example, Lobel et al. [9] showed enhanced tensile strength using z-pinning for CFRP double-lap joints. Another approach for adhesive joint improvement was reported by Mouritz et al. [10]. They used spiked metal sheets placed within the bondline to gain mechanical load transfer. Furthermore, stitching is another technique for reinforcing the laminate. Dransfield et al. [11] and Heb et al. [12] showed that this technique enhanced the fracture

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toughness of composites. However, these techniques were applied only to dry carbon fabrics joints. Unfortunately, they are not valid for joining CFRP fabrics, because CFRP can be damaged by notches that are produced when applying pins or needles or even small- diameter elements.
In our laboratory, we developed a manufacturing technique from resin transfer molding (RTM), which is called ‘vacuum-assisted resin transfer molding’ (VARTM). The technique has been applied to the manufacturing of offshore wind-lens turbine structures [13]. In this application, in addition to having high strength, the structure should be as light as possible. Carbon fiber-reinforced plastic (CFRP) is a suitable material, with high strength and low weight; however, forming large and complex structures using CFRP is challenging [14]. CFRP structures are typically fabricated as small parts and then joined together to form the final structure. Consequently, the performance of these structures depends not only on the material, but also on the joints. For this reason, we developed an adhesive joint called the “staircase joint.” This joint is constructed by remolding a stepped CFRP fabric half with another dry carbon fabric half [6].

In this paper, we introduce three staircase joints. The first is the original and the other two are proposed improvements. The main objective of this work was to achieve improved tensile strength in the joint. All joints and CFRP materials tested in this study were made using the VARTM manufacturing process.before submission.

2. Experimental Method

The staircase joint [6] is an adhesive joint constructed using stepped CFRP fabric, half molded with dry carbon fibers. This joint is made using a manufacturing process developed from the VARTM manufacturing process. The VARTM process comprises three steps: constructing a vacuum package, resin filling, and curing. The vacuum package assembly used in the experimental work is shown in Figure 1. In the first step, the reinforcement layers were added, followed by adding a peel ply on the top carbon fiber layer. The peel ply was applied to prevent the adhesion of the final CFRP fabric to the mold and/or other components. Two pieces of infusion mesh were put, to promote resin flow, on the peel ply at the start and the end of the mold . The inlet for infusion, composed of a rubber connecter and a segment of spiral tube, was positioned on the distribution medium. The vent for air and excess resin elimination was positioned on the other side of the inlet. Both the inlet and vent were composed of a rubber connecter and a segment of spiral tube. The entire package was enclosed in a vacuum bag and sealed with gum tape. Finally, two external hoses were connected to the inlet and vent. The first hose connected the inlet to the resin source, and the second hose connected the vent to the vacuum pump through a catch pot with a pressure gauge. Because the sealing, using sealant tape, is very sensitive and any small leakage will lead to failure of the entire process, a sealing test was made before resin filling. In this test, the inlet was closed and the vacuum pump was turned on to draw the air trapped inside the mold; then, the vent line was closed and the vacuum pump switched off, and the mold was left for 1 h. Then, the line was opened and any movement of the pressure gauge indicator indicates leakage, and thus the need for an additional check-up to seal the leak. After establishing the vacuum, degassed resin was infused from the inlet. After filling the mold and excess resin had exited the vent, the inlet was closed, and the vent was left open for 24 h until the resin was cured.
For all experiments, the composite material was CFRP. The CFRP composites consisted of carbon fabric (Mitsubishi Rayon UD 1M; 317 g m^{-2}) hardened using a resin (XNR6815/XNH6815). Five unidirectional carbon fabric sheets were stacked and molded together to form 1.5-mm-thick plates

To fabricate the staircase joint, the VARTM process is applied twice. First, the VARTM process was used to fabricate the CFRP fabric half. Figure 2a shows the stacking system and detailed drawing of the VARTM manufacturing process for the joint’s first half. The carbon-fiber layers are stacked together, and the joint length (80 mm) is divided into equal stairs. Figure 2b shows the first half of the staircase joint. This CFRP part was then used for the fabrication of the staircase joints.
The VARTM manufacturing process was used again to accomplish the fabrication of the staircase joints. An additional step was needed before remolding the first part. To obtain a better staircase joint bond, any surface resin at the contact length had to be removed from the first half. To remove the resin

layer, a sand-blasting process was applied using a Hozan shot blast SG-106 (Hozan Tool Ind. Co., Ltd, Osaka, Japan). Before applying sand blasting, the surface was treated with some sand paper.

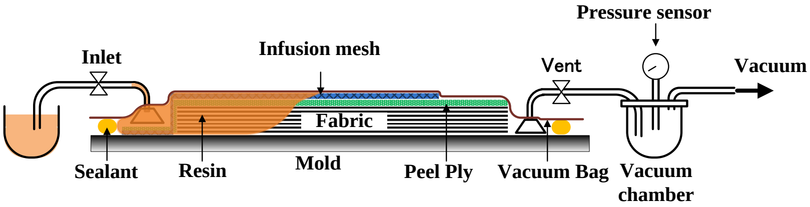
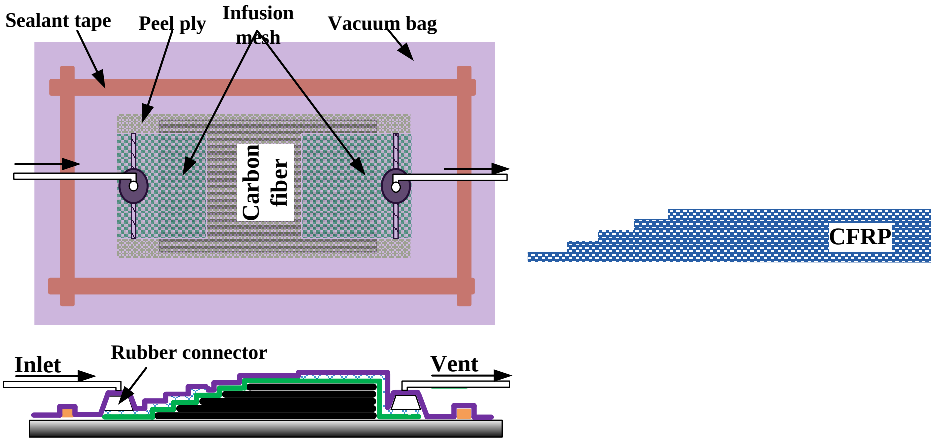


Figure 1: A schematic diagram of VARTM process



(a) (b)

Figure 2: (a) Schematic view of the manufacturing of the carbon fiber-reinforced plastic (CFRP) part. (b) Schematic drawing of the resulting CFRP fabric part.

In this work, we described three staircase joints: the first is the original staircase joint and the others are proposed improvements. These joints were made in one mold (Fig. 3a). Figure 3b shows the original staircase joint. In this joint, the first CFRP half is remolded with another identically stacked carbon fiber half. For the second joint, the staircase joint with covers, two additional carbon fiber pieces, 40 mm in length, were put on the joint ends. These carbon pieces were added intentionally to cover the joint ends (Fig. 3c). Figure 3d shows the third joint, which is called an “overlapped staircase joint.” In this joint, the contact lines were covered using a mating carbon fiber layer.
Joint strengths were evaluated via tensile testing using standardized test specimens [6]. Figure 4 shows the dimensions of the specimens; the total length was 250 mm and the width was 10 mm. Pairs of CFRP tabs were used to reduce the stress when holding each specimen. All specimens were tested using a Shimadzu DSS-5000 universal testing machine (Shimadzu Corp., Kyoto, Japan).

3. Results and discussions

All tensile tests were carried out according to the ASTM standard D3039/D3039M, with a constant crosshead speed of 2 mm/min at room temperature (23°C). Figure 5 shows the tensile strength results for all joints and the original CFRP. First, the tensile load original jointless CFRP was 26 kN, showing that the tensile strengths in the fiber direction were 1.7 GPa. It coincideds with the CFRP tensile load range of 1.2–2 GPa [6-7].
The tensile results showed a recorded tensile load of 9.5 kN for the original staircase joint, which represents 36.5% joining efficiency. This is in agreement with previous studies that have suggested that joining carbon fabrics and CFRP fabrics results in low strength [15]. Abusrea et al. [15] has explained the reasons for this limited strength. The behavior can be attributed to two factors. First, resin residue on the CFRP surface before joining can act as an insulator. Second, the absence of overlap contact in these joints reduces the contact area, resulting in a weaker joint. However, this

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strength is still relatively high compared with conventional adhesive joints. For example, a double-lap joint achieved a tensile strength of 7.1 kN [6,9].

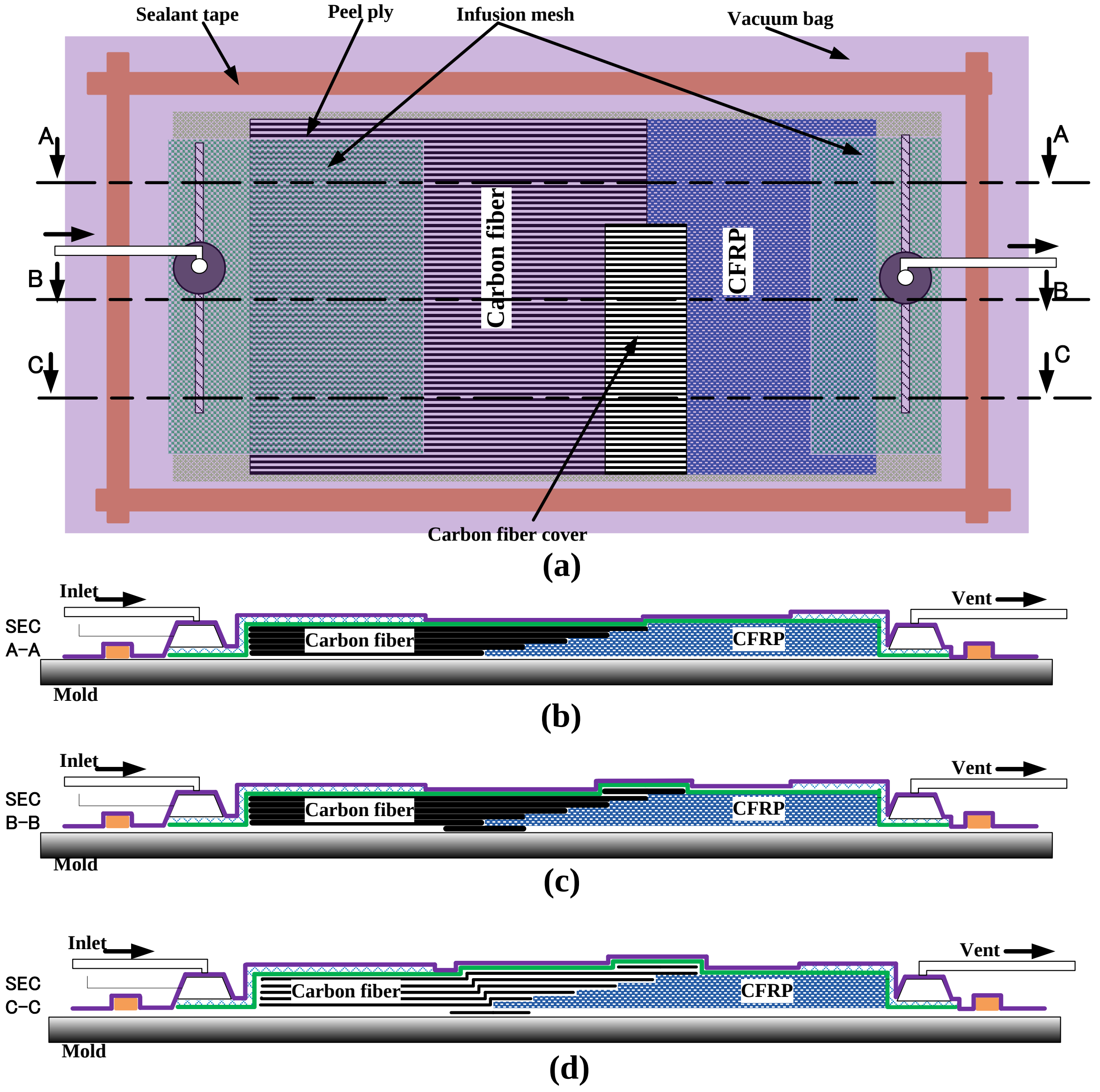

Figure 3: (a) Schematic view of the joints. (b) Sectional side view of the original staircase joint. (c) Sectional side view of the staircase joint with covers. (d) Sectional side view of the overlapped staircase joint

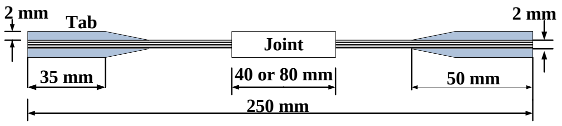

Figure 4: Standard specimen dimensions used for tensile testing.

The second joint, the staircase joint with covers, showed an improved tensile load. For this joint, a tensile load of 11.7 kN was achieved, which represents a 23% increase versus the original staircase joint. In addition, this value represents a joining efficiency of 45%. This improved strength may be due to the addition of the extra carbon fiber pieces, which helped in resisting crack initiation. Furthermore,

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the addition of carbon fiber pieces on the joint ends is helpful for reducing the peak stresses at the joint ends. A similar idea was used to improve the single-lap joint. For example, Tsai et al. [16] performed a finite element (FE) analysis to study the strain/stress distributions in laminated composite single-lap joints with and without a spew fillet.

For the third joint, the overlapped staircase joint, the tensile load recorded was 13.2 kN, which represents a 39% increase and 51% joining efficiency. In this joint, beyond the covering of the joint ends, the overlapping helped in covering all contact lines between the stairs of the CFRP and the mated carbon fabric layers. In fact, overlapping is one of the most important techniques used to improve the performance of adhesive joints [6,9]. Furthermore, the overlap length is the main factor that affects how much improvement is achieved. Lobel et al. [9] studied the effect of overlap length for the double-lap joint and reported two findings. First, the strength of the double-lap joint was increased by 20% when the overlap length increased from 40 to 80 mm. Second, no observed improvement was achieved for an overlap length that was more than 80 mm. In our overlapped staircase joint, the overlap length was determined by the stair length, which was equal to 40 mm (double stair length). Consequently, this overlap length is sufficient to achieve a reasonable improvement in the staircase joint. Thickening the joint using dry carbon fabrics, by stitching [11-12] overlapping mated dry carbon fabrics [6], or inserting extra dry carbon fabrics [15], may improve the joint strength. Abusrea et al. [15] proposed novel joints that were improved by inserting additional carbon fabric pieces.

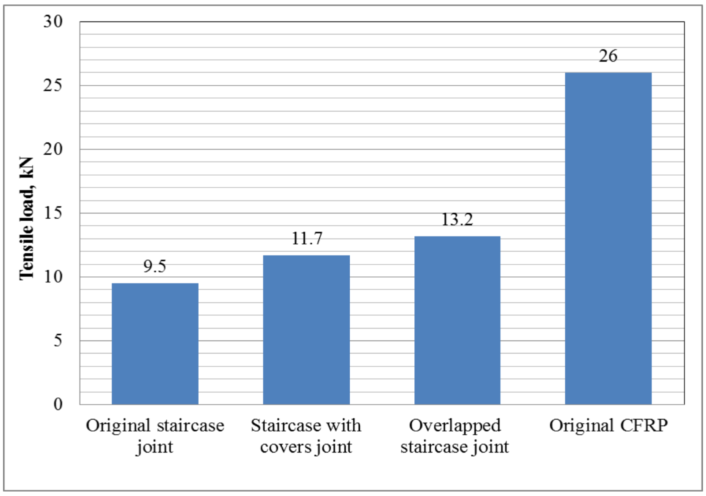
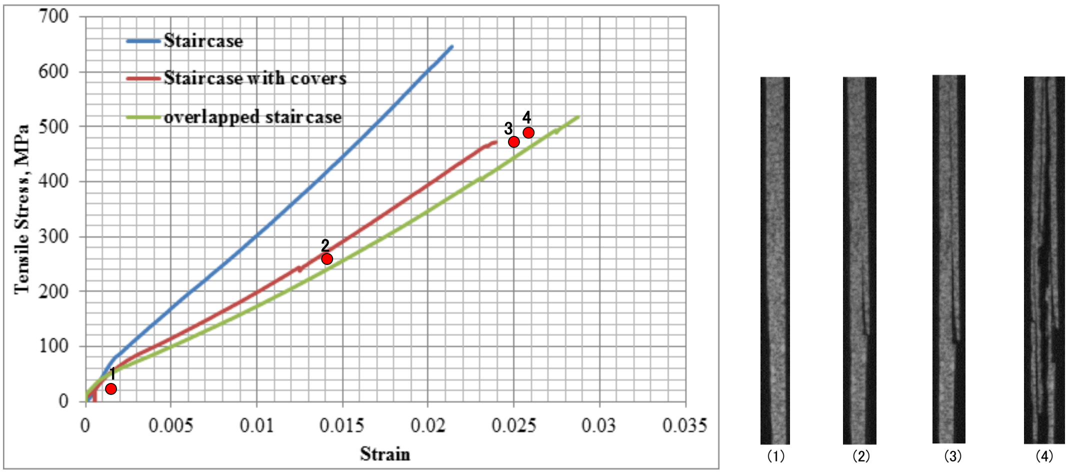


Figure 5: Tensile loads of all joints compared with the original CFRP.



(a) (b)

Figure 6: (a) Stress-strain curves for all staircase joints. (b) A typical fracture scenario for the second joint at the given positions.

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Figure 6a shows the stress-strain curves for all staircase joints. Unlike the tensile load readings, the stress-strain curves indicate different behaviors of joints. It can be seen that the stress level is lower for the improved joints. For example, the stress level for the original staircase joint was the highest among the three joints. The reason for this behavior can be further explored. First, the stress calculations are based on the maximum thickness within the specimen. As explained in the previous section, one of the main reasons for getting a higher tensile load for the adjusted joints is the increase in thickness. Furthermore, the increase in the tensile load did not recover the thickness increase.

Figure 6b shows a typical fracture scenario for the second joint at the given positions in Figure 6a. First, a crack initiated at the joint end, then it propagated in the direction of the joint length, and finally the specimen fractured [6, 15]. The same fracture scenario was observed in the other joints.

4. Conclusions

Stepped CFRP half for all staircase joints was made using a manufacturing process developed from VARTM. This CFRP part was remolded with another carbon fiber half to make the staircase joints. Three staircase joints were molded via the VARTM process. The first was the original staircase and the other two were improved staircase joints. The results showed an enhanced tensile load for the modified staircase joints. The percentage increase in the tensile load recorded was 39%. The final joining efficiencies reached 51%. Finally, the fracture scenarios observed were consistent with previous work.

Acknowledgments

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