Improvement of an 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. For example, the total percentage increase in the tensile load was 39% for five-carbon-fiber-layer CFRP. The final joining efficiency reached 59% for seven-carbon-fiber-layer CFRP. However, the tensile fracture behavior of all joints showed the same pattern of cracks, originating near the joint ends, followed by crack propagation until fracture.

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1. Introduction

Carbon fiber-reinforced plastic (CFRP) composite materials have attracted particular and increasing interest, in aviation, space, automotive, shipbuilding, and wind turbine applications [1–7] 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.

Because composite joints are crucial load-carrying elements, their stress analysis and design is a key technique for the large-scale use of composites. Thus, 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 [8].

There are generally two kinds of joining methods for composite structures [9]: (1) mechanical fastening and (2) adhesive bonding. 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 [10]. 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 [11]. Additionally, bonded joints offer structural integrity, low weight, and high strength-to-weight ratios [12,13].

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 [11,14], double-lap [15,16], and stepped [17,18] joints. Various experimental studies have been reported to improve the strength of adhesive joints. For example, Lobel et al. [4] showed enhanced tensile strength using z-pinning for CFRP double-lap joints. Another approach for adhesive joint improvement was reported by Nogeira et al. [30]. 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. [28] and Heb et al. [29] showed that this
technique enhanced the fracture 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 [19–21]. 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 [22–24].

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 [12,13]. 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.

2. Experimental method

2.1. Materials and manufacturing

The staircase joint [12] 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 [13]: constructing a vacuum package, resin filling, and curing. The vacuum package assembly used in the experimental work is shown in Fig. 1. In the first step, to prepare the vacuum package, a chemical agent was applied to the mold surface and left to dry. After that, the reinforcement layers were added, followed by adding a peel ply on the top carbon fiber layer. Both the chemical agent and peel were applied to prevent the adhesion of the final CFRP fabric to the mold and/or other components. Two pieces of infusion mesh were put on the peel ply at the start and the end of the mold. In the VARTM process, the infusion mesh is used to promote resin flow through the reinforcement, facilitating the ability of the vacuum pump to draw resin into any voids before resin curing. The inlet for infusion, composed of a rubber connector 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 connector and a segment of spiral tube. Because the inlet and vent are considered critical points in the entire process, they are tightly sealed with sealant tape. 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 gage. 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 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 gage 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. Table 1 shows the detailed constituents for the given CFRP fabric.

To fabricate the staircase joint, the VARTM process is applied twice. First, the VARTM process was used to fabricate the CFRP fabric half. Fig. 2a shows the stacking system of five-carbon-fiber layers for the joint’s first half. The carbon-fiber layers are stacked together, and the joint length (80 mm) is divided into equal stairs. Some staples were used to hold all the carbon fabric in position and prevent any relative movement during mold preparation.

Fig. 2a shows a detailed drawing of the VARTM manufacturing process used to produce this CFRP part. Following the steps explained above, the mold was prepared. Fig. 2b shows a real image of the mold used.

After resin filling, the pump was stopped and the mold was left for 24 h for resin curing, and the first CFRP half was successfully fabricated. Fig. 2c 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. After fabrication of the first half, it was necessary to remold this part again after stacking the carbon fabrics, which represents the second half. An additional step was needed before remolding this part. To obtain a better staircase joint bond, any surface resin at the contact length had to be removed from the first half. Generally, the staircase joint strength is sensitive to the existence of any resin at the contact surface of the first half before remolding. In fact, this resin layer acts as an insulator and thus a weakened joint will result. 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.

The staircase joint was recommended by Abusrea et al. [12]. Although it did not achieve the highest strength, its strength was moderate with respect to the other joints tested. However, the joints that achieved the highest strength were not applicable given the structural nature of a wind-lens [12]. The reason for this is that

![Fig. 1. A schematic diagram of the vacuum-assisted resin transfer molding (VARTM) process.](image)

**Table 1**

<table>
<thead>
<tr>
<th>Carbon fabric type (density)</th>
<th>Resin/Hardener</th>
<th>No. of carbon fiber layers</th>
<th>CFRP thickness, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitsubishi Rayon UD 1 M (317 g m⁻²)</td>
<td>XNR6815/XNH6815</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>Mitsubishi Rayon UD 1 M (317 g m⁻²)</td>
<td>XNR6815/XNH6815</td>
<td>7</td>
<td>2.0</td>
</tr>
</tbody>
</table>
these joints were developed for two dry carbon halves, meaning it was necessary to mold them together at one time.

In this work, we describe 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). Fig. 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). Fig. 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 [12]. Fig. 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/D3039 M, with a constant crosshead speed of 2 mm/min at room temperature (23 °C). Fig. 5 shows the tensile strength results for all joints and the original CFRP. First, the tensile loads for five- and seven-carbon-fiber layer CFRP were 26 and 28 kN respectively, showing that the tensile strengths in the fiber direction were 1.7 and 1.4 GPa, respectively. Both tensile loads coincided with the CFRP tensile load range of 1.2–2 GPa [4,13,15].

The tensile results showed a recorded tensile load of 9.5 kN for the original staircase joint of five-carbon-fiber layers, which represents 36.5% joining efficiency. The seven-carbon-fiber joint recorded a tensile load and joining efficiency of 14.5 kN and 52%, respectively. The reason for this higher tensile load and joining efficiency is not only the higher number of carbon fabric layers but also the higher number of stairs [12]. This is in agreement with previous studies that have suggested that joining carbon fabrics and CFRP fabrics results in low strength [12]. Abusrea et al. [12] 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 strength is still relatively high compared with conventional adhesive joints. For example, a double-lap joint achieved a tensile strength of 7.1 kN [4,13].

The second joint, the staircase joint with covers, showed an improved tensile load. For this joint, the five-carbon-fiber-layer fabric achieved a tensile load of 11.7 kN, 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, the addition of carbon fiber pieces on the joint ends is helpful for reducing the peak stresses at the joint ends [25]. A similar idea was used to improve the single-lap joint. For example, Tsai et al. [26] performed a finite element (FE) analysis to study the strain/stress distributions in laminated composite single-lap joints with and without a spew fillet [26,27].

For the third joint, the overlapped staircase joint, the tensile load recorded for five-carbon-fiber layers was 13.2 kN, which represents a 39% increase and 51% joining efficiency. Additionally, the load for seven-carbon-fiber layers was as high as 15.6 kN, representing a further 14% increase and 59% 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 [4,13]. Furthermore, the overlap length is the main factor that affects how much improvement is achieved. Lobel et al. [4] 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
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 [28,29] overlapping mated dry carbon fabrics [13], or inserting extra dry carbon fabrics [12], may improve the joint strength. Abusrea et al. [12] proposed novel joints that were improved by inserting additional carbon fabric pieces.

Fig. 6a shows the stress–strain curves for the five-carbon-fiber-layer 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. The same trend for stress—strain behavior was observed for the seven-carbon-fiber layers (Fig. 7).

Fig. 6b shows a typical fracture scenario for the second joint at the given positions in Fig. 6a. First, a crack initiated at the joint end, then it propagated in the direction of the joint length, and finally the specimen fractured [12,13]. The same fracture scenario was observed in the other joints.

To highlight the failure behavior of the current joints, failure analysis using optical microscopy was performed [31]. In optical microscopy, the fractured part is photographed, as shown in Fig. 8 (a), and the part is then scanned to identify the images that are to be analyzed further.

Fig. 8b–d shows typical optical microscopy analysis of the 7-carbon-fiber joints. As shown, the end of each CFRP joint was imaged. The analysis of the original staircase joint showed a uniform mixture of resin and fiber. There were no overlaps in this joint, and failure was due to the separation of the carbon fibers and stairs, as shown in Fig. 8b. Fig. 8e shows the images taken of the second joint. These images demonstrate fiber alignment with some pits and scratches caused by the sanding and sand blasting processes that were previously used to remove the surface resin. Consequently, the tensile load increase at this joint was caused by the representation of more joint zones. Fiber breakage was observed near to the end of the overlapped staircase joint. For this reason, the overlapped joint exhibited the greatest tensile load, as shown in Fig. 8d.

4. Conclusions

A 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 depended on the number of carbon fiber layers. For example, the total percentage increase in the tensile load recorded was 39% for the five-carbon-fiber-layer CFRP, with a further 14% increase for the seven-carbon-fiber layers. The final joining efficiencies reached 51% and 59% for five- and seven-carbon-fiber-layer CFRP fabrics. Finally, the fracture scenarios observed were consistent with previous work.

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