Evaluation of the Strength of CFRP Adhesive Joints Manufactured using VARTM

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Abstract: Vacuum-assisted resin transfer molding (VARTM) is commonly used to form large and complex structures from carbon-fiber-reinforced plastic (CFRP) composites. These structures are manufactured from several parts, which are joined to form the final structure. Therefore, the mechanical performance of the adhesive joints is critical. In this paper, we describe the use of a stitching technique with two different adhesive joints. The first joint is constructed with two dry carbon fiber parts, and the second from dry carbon fiber fabric and CFRP. All samples were fabricated in our laboratory using VARTM manufacturing techniques. Specimens were prepared for tensile tests to characterize the performance of the joints. The results show that the joint constructed using two dry carbon fiber parts was stronger than that using dry carbon fiber fabric and CFRP. Furthermore, the stitching technique increased the strength of the former, whereas the strength of the latter decreased when stitching was applied.

Keywords: Adhesive Joints, Composite Joints, CFRP, VARTM

1. Introduction
Carbon fiber composite materials have a very high strength-to-mass ratio, which makes them attractive for applications in aircraft, automobiles and wind turbines [1, 2]. These applications commonly involve large-scale manufacturing, and so the parts are produced from smaller components, and are joined together. Consequently, the mechanical performance of these structures depends strongly on the properties of the joints.

Numerous approaches exist for joining composite materials. Conventional mechanical joints, such as bolted, pinned or riveted joints, are often preferred due to their simplicity and the fact that they can be disassembled [3, 4]. However, when a mechanical joint is loaded, localized damage may result at the fastener holes due to stress concentration [5]. Bonded joints have mechanical advantages over bolted joints because the fibers are not cut, and stresses are transmitted more homogeneously [6]. In addition, bonded joints offer structural integrity, low weight, and high strength-to-weight ratios.

However, there remains significant scope for improvement in the strength and durability of bonded joints [7]. Stitching is considered to be an effective method of forming strong bonded composite joints [7], and Hes et al. [8] and Dransfield et al. [9] showed that this technique could enhance the fracture toughness of composites under peel load conditions.

The development and application of renewable and clean energy resources has become a globally important issue due to the limited supply of fossil fuels and the environmental problems caused by their use. Wind energy is a particularly promising renewable energy resource. In Kyushu University, a wind turbine containing a wind lens was recently designed to augment the wind power for a given turbine diameter and wind speed. This wind turbine was designed to operate on the ocean surface mounted on a floating structure. Consequently, in addition to high strength, the structure should be as light as possible. Carbon-fiber-reinforced plastic (CFRPs) are suitable material with high strength and low weight; however, forming large and complex structures using CFRPs are challenging. We propose the use of vacuum assisted resin transfer molding (VARTM) to form CFRP structures. VARTM does not require an autoclave, high temperatures, high pressure or prepreg, which makes it possible to produce large and complex parts. CFRP structures are typically fabricated as small parts and then joined together to form the final structure. For this reason, the mechanical performance of these structures depends not only on the material, but also on the joints. Here we introduce the application of stitching for two different joints. The first was constructed using two dry carbon fiber halves, and the second using dry carbon fabrics and CFRP. The main objective of this work was to study the effects of stitching on the strength of the joints. All joints and CFRP materials tested in this study were formed using VARTM, as shown in Fig. 1.

2. Experimental Methods
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. All CFRPs’ parts were formed using VARTM, which is a variation of the resin transfer molding (RTM) technique, in which a solid mold with a flexible tape-sealed vacuum bag is used instead of a closed mold. In the VARTM process, reinforcements are stacked on a solid mold, which is treated with a mold-releasing agent and covered with a peel-ply and a distribution medium. These are enclosed in a vacuum bag, which has an inlet and a vent, and which is sealed using gum tape, as shown in Fig. 1.

The strength of the joints was evaluated via tensile testing using standardized test specimens [2]. Figure 2a 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,
as shown in Fig. 2b.

![Fig. 2](image-url)

**Fig. 2** (a) Standard specimen dimensions used for tensile testing and (b) an image of a specimen used in a tensile test

Two different types of joint were used with the stitching technique. One joint was constructed using two dry carbon fiber halves. With this joint, two five-layer carbon fiber sheets were stacked. This joint is termed multi-overlapped joint. Figure 3a shows a schematic top view of the VARTM mold for all multi-overlapped joints. The original form for this joint is shown in Fig. 3b. In this joint, the separation between the two mated carbon layers was covered using two 40-mm-wide carbon fiber pieces. The second form for multi-overlapped joint is shown in Fig. 3c. With this joint, we used stitching with carbon bundles of the same carbon fiber type, which were applied perpendicular to the plane of the laminate [8,9]. All joints were formed using a single VARTM process.

The other joint type was constructed using dry carbon fiber fabric and CFRP. A stepped CFRP fabric was manufactured first, which was then re-molded with dry carbon fiber fabric. This joint is called staircase joint. Figure 4a shows a schematic top view of the VARTM mold for all staircase joints. Figure 4b shows the original staircase joint. Two additional modifications were made to this joint. The first adjustment was made by adding two pieces of carbon fiber as covers at the ends of the joint, as shown in Fig. 4c. Afterward, stitching was applied to form a modified staircase joint. Figure 4d shows the stitched modified staircase joint. Similarly, all staircase joints were formed using a single VARTM infusion.

![Fig. 4](image-url)

**Fig. 4** (a) Schematic top view of all staircase joints (b) original staircase, (c) staircase with covers and (d) stitched staircase joints
3. Results and Discussions

All tests were carried out according to the ASTM standard D3039/D3039M, with a constant crosshead speed of 2 mm/min at a room temperature (i.e., 23°C). The tensile tests were performed at least three times and the average value of the three measurement values was used as representative. The results showed a maximum error of 15%. Figure 5 shows the tensile load of the multi-overlapped joint in both original and stitched forms. The tensile load of the original CFRP without joint is also indicated in the figure as the maximum value that logically all joints cannot exceed. The load of the unstitched multi-overlapped joint was 17.2 kN, and that of the stitched multi-overlapped joint was 20.8 kN (i.e., 21% stronger). This can be attributed to two factors. First, the use of additional carbon bundles results in an increase in the average thickness of the joint. Second, the stitching direction was perpendicular to the laminate, so that it functions as an additional carbon lamina, forming a bidirectional composite.

Figure 6 shows the tensile load of all staircase joints combined with vertical error bars. The strength of the staircase joint was only 9.5 kN. This is consistent with previous studies showing that joining carbon fabrics and CFRP fabrics results in low-strength joints [10]. This can be attributed to two factors. First, resin residue on the CFRP surface prior to joining can act as an insulator. Second, the absence of overlap in these joints reduced the contact area, resulting in a weaker joint [7]. The modified staircase joint (i.e., a staircase joint with covers), achieved a 48% increase in tensile load compared with the original staircase joint. The covers were added over the gaps at the ends of the joint to delay crack initiation and propagation.

Figure 7 shows a typical tensile load–displacement curve combined with images that show the modified staircase joint at various stages of the test. An initial crack occurred near the end of the joint, which reduced the gradient of the load–displacement curve. This resulted in a linear relationship between the tensile load and the displacement. As the load increased, the crack grew, until the specimen fractured. The initial crack occurred at the end of the joint. This can be explained as follows. When joining the CFRP with the carbon fabric, two separation lines were formed on the two surfaces of the part. These two lines were filled with resin after joining, and the crack initiated at these lines. As the tensile load increased, the shear stress in the contact area increased, which caused relative motion between the two CFRP portions, and led to enlargement of both separation lines, and hence crack propagation.

In contrast to the multi-overlapped joint, stitching weakened the staircase joint. The tensile load of the stitched staircase joint was 26% lower than that of the modified staircase joint. This can be attributed to two factors. First, the stitches over the CFRP fabric result in gaps between the mold and the CFRP part, as shown in Fig. 8a. These gaps were filled with resin during molding. In addition, due to the position of these gaps, it was difficult to remove voids in the resin that filled the gaps (see Fig. 8b). Second, stitching produced notches in the CFRP part, which weakened the structure after molding. Löbel et al. [7] showed that the existence of holes in CFRP fabrics results in peaking the stress around these holes, and hence a weaker CFRP structure. Figure 9 shows a typical tensile load–displacement curve, combined with images that show the deformed stitched staircase joint at various stages of the test. The crack initiated and propagated at the end of the joint, yet the specimen failed at the location of the notches caused by stitching.
4. Conclusion

We have described five adhesive joints formed using VARTM. Tensile testing revealed improved strength when stitching was applied to the multi-overlapped joint. We found lower strength for the staircase joint with stitching; however, this could be improved by adding carbon fiber covers at the ends of the joint.

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