International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:9, No:9, 2015

Novel CFRP Adhesive Joints and Structures for Offshore Application

M. R. Abusrea, Shiyi Jiang, Dingding Chen, Kazuo Arakawa

Abstract**—**Novel wind-lens turbine designs can augment power output. Vacuum-Assisted Resin Transfer Molding (VARTM) is used to form large and complex structures from a Carbon Fiber Reinforced Polymer (CFRP) composite. Typically, wind-lens turbine structures are fabricated in segments, and then bonded to form the final structure. This paper introduces five new adhesive joints, divided into two groups: one is constructed between dry carbon and CFRP fabrics, and the other is constructed with two dry carbon fibers. All joints and CFRP fabrics were made in our laboratory using VARTM manufacturing techniques. Specimens were prepared for tensile testing to measure joint performance. The results showed that the second group of joints achieved a higher tensile strength than the first group. On the other hand, the tensile fracture behavior of the two groups showed the same pattern of crack originating near the joint ends followed by crack propagation until fracture.

Keywords**—**Adhesive joints, CFRP, VARTM, resin transfer molding.

I. Introduction

COMPOSITE materials have high stiffness-to-weight and strength-to-weight ratios, and have been used for many applications including aerospace, automotive, and wind turbine structures [1], [2]. The wind-lens, a curved ring around the turbine blades, is manufactured from six identical parts joined together to form the final structure. Consequently, its performance depends not only on material properties but also on the joining technique. As such, structural integrity depends critically on the efficiency of this technique. Composite structure connections depend on many factors such as size, design, available technology, and logistical limitations [3], [10]. Therefore, the performance and failure modes of different joint types, including composite-to-composite [4]–[6] and composite-to-other materials [7]–[9], have been extensively studied both numerically and experimentally.

Bonded joints have mechanical advantages over bolted joints because fibers are not cut, and stresses are transmitted more homogenously. However, the strength and durability of bonded joints strongly depend on various factors such as surface preparation, joint-end configuration, fiber angles, overlap length, and process parameters [10], [11]. Because the interface is usually, the weakest part of a structure, most reported methods have aimed to improve the strength of the adhesive or adhesive–composite interface. However, if the adhesive or adhesive–composite interface can be avoided altogether, the strength could be further improved.

This paper introduces various adhesive bonded joints, made of Carbon Fiber Reinforced Polymer (CFRP), for use in offshore wind-lens structures. The main objective of this work was to develop high-strength joint applicable to offshore wind-lens structures. The strengths of five joints were assessed. All joints and CFRP material tested in this study were made using a technique developed from the Vacuum-Assisted Resin Transfer Molding (VARTM) process.

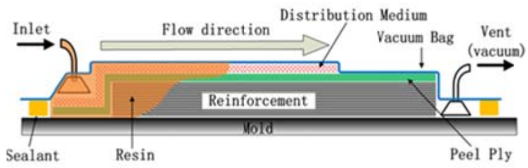
Mahmoud Ramadan Abusrea is with the Kyushu University, Japan (e-mail: mahmoud.r.abusrea.127@s.kyushu-u.ac.jp).

II. Experimental Work

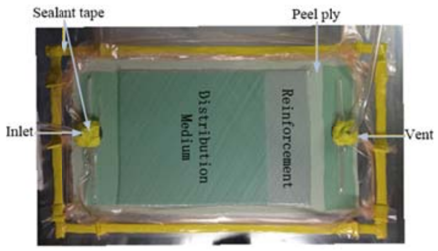
The composite material was CFRP, consisting of a carbon fabric hardened with a resin. All CFRP fabrics were produced using VARTM. The entire process comprised three steps: fabricating a vacuum package, infusing the resin and molding. The structure of the vacuum package used in the experiment is shown in Fig. 1 (a). A solid mold, covered with a piece of peel ply, was used. Four layers of stitched unidirectional carbon-fiber fabric (from Saertex GmbH & Co. KG, the carbon fiber is TENAX STS, the stitching material is PES) with 30 cm in length were laid on the peel ply and then covered by another piece of peel ply. The horizontal direction of Fig. 1 (a) was the fiber direction. A small piece of distribution medium, a kind of mesh, was placed on the peel ply to promote the flow of resin.

The inlet for infusion, which was 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 inlet and vent were composed of a rubber connecter and a segment of spiral tube. Since inlet and vent considered very critical points in the entire process, they are tightly sealed by the sealant tape. Finally, the entire package was enclosed in a vacuum bag and sealed with tape. Fig. 1 (b) shows a picture of the adopted structure. After establishing a vacuum, degassed resin was infused from the inlet. After 40 min, the inlet was closed, and the vent was left open until the resin was cured. An epoxy resin that could be cured at room temperature (XNR/H 6815, supplied by Nagase & Co., Ltd.) was used in the experiment. The initial viscosity of the resin at $25^{o}C$ was 260 MPa s. When the resin was cured completely (about 24 h later), the CFRP laminate was removed from the mold. The thickness of the plate was about 2 mm.

Joint strengths were evaluated via tensile testing using standardized test specimens [1]. Fig. 2 shows the dimensions of the specimens; the total length was 250 mm and the width was 10 mm. Pairs of GFRP tabs were used to reduce the stress when holding each specimen. All specimens are tested using SHIMADZU DSS-5000 universal testing machine. Fig. 3 shows the setup used for the current tensile test. The specimen was fixed between the machine's jaws, and the load-time data was recorded through a load cell mounted on the upper jaw. A real time camera connected to PC was mounted to record the deformation of the specimen during the loading.



(a)



(b)

Fig. 1 (a) A schematic view of the VARTM process used in this work and (b) Picture of adopted VARTM process

The strength of the original CFRP was measured, and used as a reference for the strength of subsequent joints. Five joint types were tested, divided into two groups. One was constructed using dry carbon fabrics and CFRP. In this group, the CFRP half of the joint was manufactured first, and then re-molded again with dry carbon fabric. Fig. 4 shows types 1 and 2 of the first joint group. The left half of both joints was a stepped CFRP portion that had been molded, and the right side represents a dry carbon fabric. We used these to investigate the effects of the number of steps connected to dry carbon fabrics, and therefore the major difference between the two joints is the number of CFRP steps.

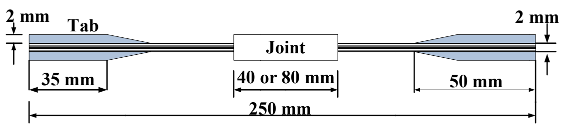


Fig. 2 The standard specimen dimensions used for tensile testing

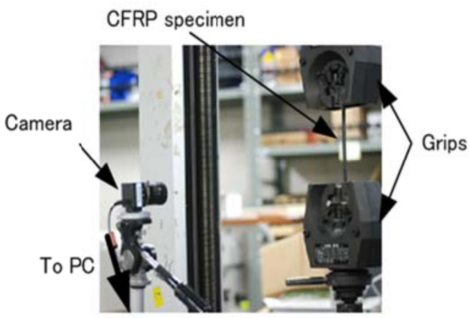


Fig. 3 Tensile test setup for the current work

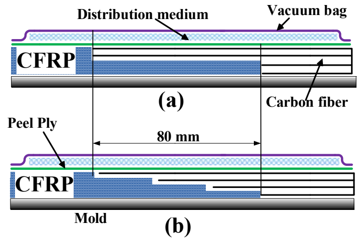


Fig. 4 Joint group 1: (a) staircase joint-1, and (b) staircase joint-2

The second group was constructed with two dry carbon fiber halves; thus, the whole joint was made in a single step. Fig. 5 shows types 3, 4, and 5 of the second joint group. These joints were named laminated joint-1, laminated joint-2, and multi-overlapped joint, respectively.

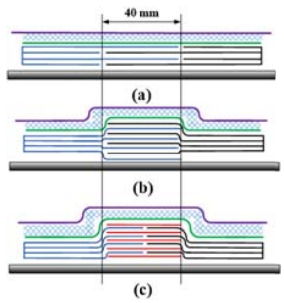


Fig. 5 Joint group 2: (a) laminated joint-1, (b) laminated joint-2, and (d) multi-overlapped joint

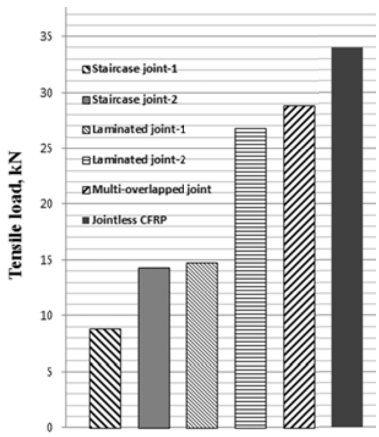


Fig. 6 Tensile strengths of the joints and the original CFRP material

III. Results and Discussions

Fig. 6 shows the tensile strengths of the five joints, and the original CFRP. A tensile load of 34 kN was recorded for the CFRP, indicating that the tensile strength along the fiber direction was 1.7 GPa.

The lowest joint tensile strength recorded was for staircase joint-1, with a measured strength of 8.8 kN (26% joining efficiency). However, the strength of the other staircase joint, staircase joint-2, was significantly higher (14.3 kN; 42% joining efficiency), and this is in agreement with previous studies that have suggested that joining carbon fabrics and CFRP fabrics results in low strength [1]. This 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 [10]. On the other hand, staircase joint-2 achieved a much higher strength than joint-1. This is attributed to the three fiber layers in that joint type that contact the CFRP part, three times more than the number of layers in joint-1. Hence, joining dry carbon fabrics together resulted in generally higher strengths. The laminated joint-1 had a tensile strength similar to that of staircase joint-2, with a measured strength of 14.7 kN. This can be attributed to the absence of overlap contact between the two halves in laminated joint-1, which reduces the strength and promotes crack propagation near the joint ends. The introduction of overlap areas not only increases the contact area, but also increases joint thickness. On the other hand, the remaining two joints were much stronger than the previous four joints. Laminated joint-2 and the multi-overlapped joint had tensile strengths of 26.8 kN (79%) and 28.8 kN (85%), respectively. These two joints performed similarly, with the major difference being the greater thickness of the multi-overlapped joint-2, which could be the reason for the higher observed strength. Löbel et al. [10] constructed CFRP joints based on stainless pins, which resulted in a high joining efficiency of 83%. However, the metal-to-carbon fiber contact caused galvanic corrosion of the carbon fabrics, weakening the structure over time [12].

Fig. 7 shows a typical tensile load-displacement diagram combined with images that show the deforming specimen of the staircase joint-1. In staircase joint-1, 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 displacement. As the load increased, the crack size also increased until the specimen ultimately fractured. As noted, the initial cracking occurred at the end of the joint. This behavior can be explained as follows. In staircase joint-1, when joining the CFRP with carbon fabric, two separation lines were formed on both surface sides (Fig. 8). These two lines were filled with resin after joining, and the crack initiated at these lines at the beginning of the tensile test. As the tensile load increases, the shear stress in the contact area increases and this causes relative motion between the CFRP portions. This leads to the enlargement of both separation lines and hence crack propagation. The failure patterns were also investigated for other joint types. Fig. 9 shows a typical tensile load-displacement diagram for multi-overlapped joint-2. Two cracks appeared near the joint ends, due to the accumulation of stress in these zones, which apparently caused a gradient change. Then the cracks propagated until specimen fracture. Fig. 10 shows a schematic drawing of the multi-overlapped joint-2. The possible zones of fracture are near the joint ends, where there is an accumulation off stress.

There are seven failure modes, including but not limited to the separation of the interface between the adhesive and composite, de-lamination within the composite, and a mixture of these two modes [13]. Micromechanical investigations have revealed different dominant failure modes under tensile and shear loads [5]. In addition, the strength of the interface between the adhesive and composite at a joint is a key factor determining the failure mode and the strength of a structure. In the present study, both staircase joints 1 and 2 showed separation of the interface, whereas joint group 2 showed a mixture of failure modes.

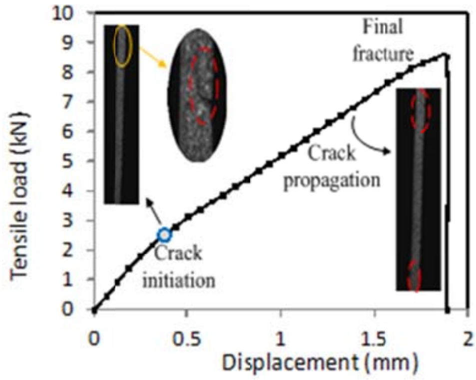


Fig. 7 A diagram of typical tensile load-displacement, with images for staircase joint-1

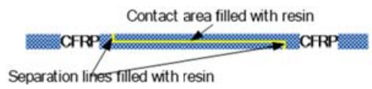


Fig. 8 Schematic drawing of a staircase joint after bonding

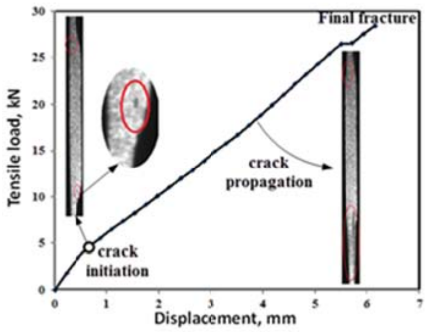


Fig. 9 Typical tensile load-displacement diagram with images for a multi-overlapped joint

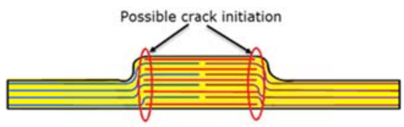


Fig. 10 Schematic drawing of a multi-overlapped joint with possible crack zones highlighted

IV. Conclusions

Five adhesive joints were designed using manufacturing process developed from the VARTM process. The tensile test results showed low strength when one-half of the joint is CFRP fabrics, which was the case for the first two developed joints. On the other hand, the last two joints, laminated joint-2 and multi-overlapped joint, showed higher tensile strength. However, joining techniques that use dry carbon fibers are still limited for simple shapes, so there are some difficulties for applying these techniques for complex curved shapes like wind blades and lens as well.

References

[1] Chen D.D., Arakawa K, Jiang S.Y. Novel Joints Developed from Partially Un-Moulded Carbon-Fibre-Reinforced Laminates. Journal of Composite Materials, 2015, Vol. 49(14) 1777–1786.
[2] Lee D. G., Jeong K. S., Kim K. S., et al. Development of the Anthropomorphic Robot with Carbon Fiber Epoxy Composite Materials. Compos. Struct. 1993; 25: 313–324.
[3] Niu M. Airframe Structural Design. 9th Printing. Hong Kong: Conmilit. Press Ltd.; 1997.
[4] Wang Z. Y., Wang L, Guo W, et al. An Investigation on Strain/Stress Distribution around the Overlap End of Laminated Composite Single-Lap Joints. Compos Struct. 2009; 89: 589–595. 3.
[5] Liu F, Zhao L, Mehmood S, et al. A Modified Failure Envelope Method for Failure Prediction of Multi-Bolt Composite Joints. Compos Sci. Technol. 2013; 83: 54–63.
[6] Quaresimin M and Ricotta M. Stress Intensity Factors and Strain Energy Release Rates in Single Lap Bonded Joints in Composite Materials. Compos Sci Technol 2006; 66: 647–656.
[7] Al-Zubaidy H, Al-Mahaidi R and Zhao X-L. Experimental Investigation of Bond Characteristics between CFRP Fabrics and Steel Plate Joints under Impact Tensile Loads. Compos Struct 2012; 94: 510-518.
[8] Fawzia S, Al-Mahaidi R and Zhao X-L. Experimental and Finite Element Analysis of a Double Strap Joint between Steel Plates and Normal Modulus CFRP. Compos Struct 2006; 75: 156–162.
[9] Fawzia S, Zhao XL, Al-Mahaidi R, et al. Bond Characteristics between CFRP and Steel Plates in Double Strap Joints. Int J Adv Steel Constr 2005; 1: 17–27.
[10] LÖbel T., Kolesnikov B, Scheffler S, et al. Enhanced Tensile Strength of Composite Joints by Using Staple-Like Pins: Working Principles and Experimental Validation. Compos. Struct. 2013; 106: 453–460.
[11] Banea M. D., Da Silva L. F. Adhesively Bonded Joints in Composite Material: an Overview. J. Mater Des Appl. 2009; 223:1–18.
[12] Wen-Xue W., Yoshiro T., Terutake M. Galvanic Corrosion-Resistant Carbon Fiber Metal Laminates. 16th Int. Conf. on Composite Materials.
[13] Katnam KB, Comer AJ, Stanley WF, et al. Characterising Pre-Preg and Non-Crimp-Fabric Composite Single Lap Bonded Joints. Int J Adhes Adhes 2011; 31: 679–686.