Composites Part B 97 (2016) 368–373

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Improvement of an adhesive joint constructed from carbon fiber-reinforced plastic and dry carbon fiber laminates

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ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form
16 March 2016
Accepted 1 May 2016
Available online 9 May 2016

Keywords:
A. Polymer-matrix composites (PMCs)
D. Mechanical testing
E. Resin transfer molding
E. Joints

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.

1. Introduction

Carbon fiber-reinforced plastic (CFRP) composite materials have attracted particular and increasing and 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

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http://dx.doi.org/10.1016/j.compositesb.2016.05.005
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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 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. 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 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 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.

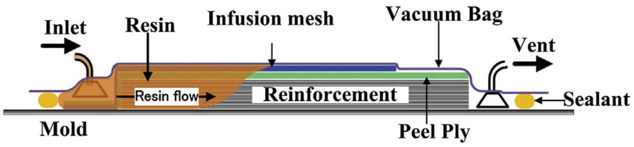

Fig. 1. A schematic diagram of the vacuum-assisted resin transfer molding (VARTM) process.

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

Table 1
CFRP composite material constituents.

Carbon fabric type (density)	Resin/Hardener	No. of carbon fiber layers	CFRP thickness, mm
Mitsubishi Rayon UD 1 M (317 g m^{-2})	XNR6815/XNH6815	5	1.5
Mitsubishi Rayon UD 1 M (317 g m^{-2})	XNR6815/XNH6815	7	2.0