IMPROVEMENTS OF CFRP COMPOSITE LAMINATED JOINT FABRICATED FROM TWO DRY CARBON HALVES USING VACUUM ASSISTED RESIN TRANSFER MOULDING VARTM

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ABSTRACT

Vacuum-assisted resin transfer moulding (VARTM) process was used to fabricate CFRP joints and fabrics used as adhesive composite joints. This study focuses on carbon fibre reinforced plastic CFRP adhesive joint sdedicated to offshore wind turbine structures. The main objective of this study is to improve the mechanical performance of an adhesive joint called a “laminated joint”. The joint is developed by stacking two dry carbon fibre fabric halves together and moulding them using the VARTM process. The improved design of this joint includes overlapping the two half fabrics and adding extra carbon fibre fabric pieces. Four joints are considered in this work: conventional laminated joint, two overlapped joints, and multiple-covers laminated joint. Specimens are prepared for static flexural and Charpy impact testing. In addition, post-fracture analysis is performed using optical microscopy to identify the dependence of modes of damage and its propagation on the type of joint.

1 INTRODUCTION

The structural applications of composite materials in the offshore wind turbine structures are increasing due to their excellent mechanical properties, specifically high stiffness-to-weight and strength-to-weight ratios [1, 2]. These applications generally involve large-scale manufacturing, so the parts are produced from smaller components and are joined together. Adhesive bonding is one of the best means to join structural composite components due to its advantages compared to mechanically fastened joints, such as lower stress concentrations, more uniform load distribution, less weight penalty and better fatigue behaviour. Consequently, adhesive composite joints are widely used in many composite structures in aerospace, turbine, and ship designs. These structures are subjected to combinations of mechanical loadings, including static, fatigue and impact loadings and thus the mechanical performance of these structures is highly dependent on the joining efficiency.

Because composite joints work as structure-critical load-carrying elements, the design and analysis of composite joints have attracted attention in a series of light-weight, low-cost, and efficient composite integration projects [3]. ‘Traditional’ mechanical fasteners such as bolts, pins, and rivets, have been extensively used to join CFRP structures [4-6]. This composite joining technique is simple and its joints can be disassembled [7]. However, drilling holes in composite parts before fastening may cause problems due to stress concentration and weight increases. In contrast, adhesively bonded joints have mechanical advantages over bolted joints because the fibres are not cut, and stresses are transferred more homogeneously [8]. In addition, they offer better structural integrity, lower weight, and higher strength-to-weight ratios [9, 10]. Due to their advantages, CFRP composite adhesive joints are increasingly used in structures [11].

CFRP composite adhesive joints include ‘traditional’ adhesive joints, such as single-lap [9, 12], double-lap [13, 14], stepped [15, 16], and scarf-lap [17-20] types. In addition to the existing adhesive joints, making novel composite joints to enhance the mechanical performance is an ongoing research. For example, using z-pinning for CFRP double-lap joints to enhance tensile strength [21], placing spiked metal sheets placed within the bondline to gain mechanical load transfer [22] and using stitching technique for reinforcing the laminate [23, 24] to enhance the fracture toughness of composites are few out of many to mention.

In this study, a novel CFRP adhesive joint, called a “laminated joint,” is introduced. This joint was constructed of two mated dry carbon fibre halves. Two modifications were made to the joint. The first was done by overlapping the two halves with overlap lengths of 20 mm and 40 mm. The second was made by the addition of carbon fibre pieces (i.e., a multiple-covers laminated joint, MCL). All CFRP joints and fabrics were made using vacuum-assisted resin transfer moulding (VARTM) and compared to one another in terms of flexural and impact properties.

2 EXPERIMENTAL DETAILS

2.1 Materials

The CFRP composites and their joints consist of carbon fabric and a resin (Denatite XNR6815/XNH6815) [25]. Three different carbon fibre types are used: Type 1 (Mitsubishi Rayon UD 1M; 317 g/m^2), type 2 (Mitsubishi Rayon UD 1M; 212 g/m^2) and type 3 (Mitsubishi Rayon, plain, 60 g/m^2) as presented in Table 1. The basic carbon fibre used in this work is type 1, while type 2 and 3 are used as extra carbon fibre pieces for the multiple-covers laminated joint, as shown in Fig. 1.

Type	Carbon fibre designation	Style	Weight (g/m^2)	Density (g/cm^3)	Thickness (mm)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation (%)
1	TRK976PQRW	UD	317	1.82	0.33	4900	253	1.9
2	TRK979PQRW	UD	212	1.82	0.25	4900	253	1.9
3	TR30S3L	Plain	60	1.79	0.09	4410	234	1.9

Table 1: Characteristics of the carbon fibre types used in this work.

2.2 Fabrication of Adhesive joints

Four different types of joints namely, laminated joint, laminated joint with 20 mm overlap, laminated joint with 40 mm overlap and multiple-covers laminated joint, were fabricated, as shown in Fig. 1, and compared with jointless CFRP composites in terms of their properties. The laminated joint proposed in this work is a composite adhesive joint constructed of two 6-layer-dry-carbon half fabrics that are stacked together in a mating formation. The first improvement to this joint is done by overlapping the two halves. To emphasize the effect of overlap length, two different overlap lengths are used: 20 and 40 mm. The second improvement is made by adding extra carbon fibre pieces of 40 mm in length. These carbon fibre fabric pieces were put between the carbon fibre layers in order to cover contact between the two joint halves. In this joint, the carbon fibre piece at the bottom is made from type 2 carbon fibre (see Table 1) and the remaining carbon fibre pieces are made from type 3 carbon fibre.

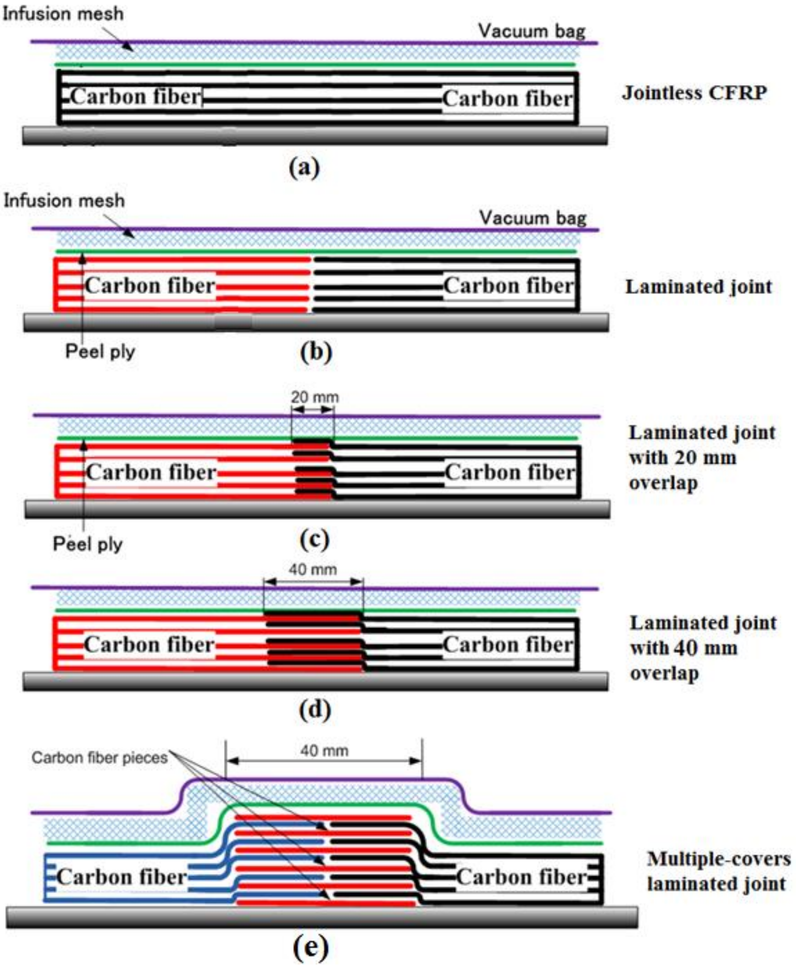

Figure 1: (a) Jointless CFRP, (b) Laminated joint, (c) Laminated joint with 20 mm overlap, (d) Laminated joint with 40 mm overlap, (e) Multiple-covers laminated joint

All the joints were made using VARTM process. In the VARTM process, the reinforcement (carbon fibres) were placed on the surface of the mould that is coated with release agent. Then, one layer of peel ply is added on the top of the carbon fibres to prevent sticking of the final fabric to the mould. Two pieces of infusion mesh were put on the peel ply at the start and the end of the mould to promote resin flow. The entire package was enclosed in a vacuum bag and sealed with gum tape. Two external hoses were connected to the inlet of the resin source and vent to the vacuum pump. Prior to resin infusion, the inlet was closed and the vacuum pump was turned on to draw the air trapped inside the mould. After establishing the vacuum, degassed resin was infused from the inlet. The excess resin was removed from the vent, then the inlet was closed and the vent was left open for 24 h until the resin was cured.

2.3 Test specimens

In both static flexural and impact, specimens are cut in the same size of 80×12.7×*t* mm (*t* is the thickness) according to the ASTM D790, as shown in Fig. 2. The specimens are divided into two groups based on the type of testing, i.e., static flexural and impact. Each test group consists of five test series which represent the joint types. Five samples are assigned for each test series.

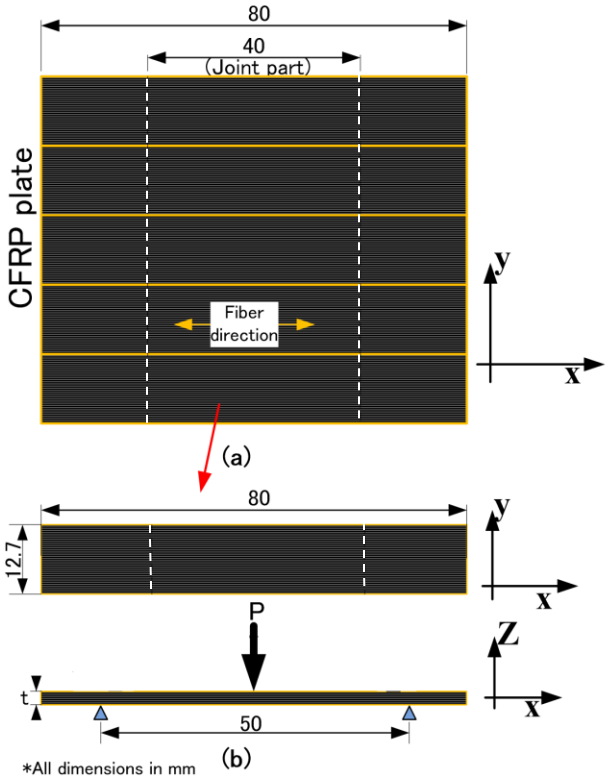

Figure 2: Specimen preparation procedure: (a) The location of specimens taken from CFRP plate and (b) an illustration of the specimen for the three-point bending test

2.3 Characterization techniques

2.3.1 *Microscopy*.

A Leica DM2500 polarized light optical microscope was used to study the modes of damage and crack propagations with respect to the type of joint in post-test impact samples.

2.3.2 *Specific density and void content*

Water displacement method was used to measure the specific density and void content of the composites. Water displacement method was performed according to ASTM D-792. The void content for composites was calculated according to ASTM D2734-16 using the following equation,

$$V_{void} = 100 \times (\rho_{theoretical} - \rho_{\exp})/\rho_{theoretical} \qquad (1)$$

where ρ_{exp} is the measured density using ASTM D-792 and $\rho_{theoretical}$ is the density determined by the rule of mixtures, as given in Eq. (2).

$$\rho_{theoretical} = \frac{1}{(w_f/\rho_f)+(w_m/\rho_m)} \qquad (2)$$

where w_f and w_m are mass fraction, and ρ_f and ρ_m are density of the fibre and resin respectively. For each joint type, five samples were tested.

2.3.3 *Mechanical testing*

The flexural properties of the adhesive joints were determined using three-point bending tests according to ASTM D790-02 using an Instron 33R 4466 equipped with 10 kN load cell with a displacement rate of 1 mm/min. Each flexural data point is an average of five tests. The modulus was calculated between the axial strain values of 0.05% and 0.2%.

The impact energy was measured using Charpy on non-notched samples (described in section 2.3) with a support span of 43 mm using an Instron SI series pendulum impact tester with a maximum impact head of 406.7 J (300 ft-lbf) according to ISO179. Each impact data point is an average of five tests.

3 RESULTS AND DISCUSSION

3.1 Specific density and void content

The measured density and void content for different types of joints are shown in Table 2. The void contents are calculated based on eq. (1). The average measured density of all composite joints are similar. The void content in different types of adhesive joints ranges in 3-5%.

Adhesive joint	Measured density (g/cm^3)	Theoretical density (g/cm^3)	Void content using Eq. (1) (%)
Jointless	1.58±0.1	1.63	3
Laminated joint	1.57±0.1	1.63	4
Laminated joint with 20 mm overlap	1.56±0.1	1.63	4
Laminated joint with 40 mm overlap	1.55±0.1	1.63	5
Multiple-covers laminated joint	1.55±0.1	1.63	5

Table 2: Measured density and void content

3.3 Mechanical properties

The effect of joint type on flexural and impact properties is presented in Fig. 3 and Fig. 4 respectively. The strength and modulus results are normalized with respect to the thickest cross section area and the impact results are normalized to the weight of the joint. Laminated joint with 40 mm overlap show the highest strength and modulus compared to those of the other types of adhesive joints as plotted in Fig. 3. Interestingly, the modulus of the laminated joint with 40 mm overlap is even higher than that of jointless composites. The strength and modulus laminated joint with 20 mm overlap and multiple-covers laminated joints are both lower than those of laminated joints.

The impact strength of both laminated joints with 20 and 40 mm overlap is higher than that of the other types of joints and even jointless composite, as shown in Fig. 4. Development of other types of damage modes such as delamination and transverse cracking absorbs energy during impact leading to higher strength compared to jointless composites. Multiple covers laminated joints exhibited the lowest impact strength mainly due to weak bonds between the mating dents of the joint as seen in Fig. 5(h).

Overall, laminated joints with 20 and 40 mm overlap exhibited the highest mechanical properties and multiple covers laminated joints resulted in the lowest mechanical properties among various types of adhesive joints.

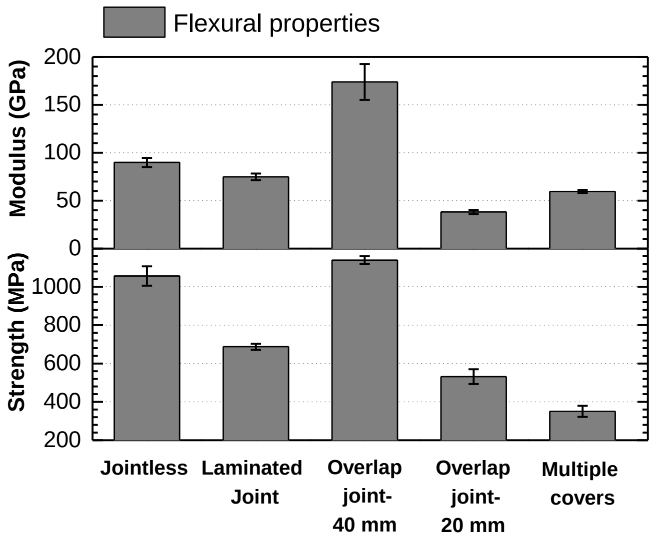

Figure 3: Flexural properties of the adhesive joints (properties are measured at the thickest part)

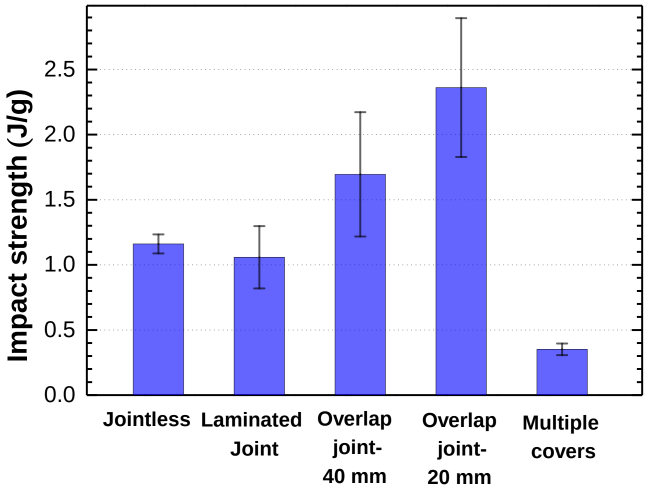

Figure 4: Impact properties of the adhesive joints

3.2 Damage modes

The main damage modes in the post-test impact samples are transverse cracking, delamination between the plies, and fibre breakage as shown in Fig. 5. Transverse cracking due in-plane stresses usually occur at early stages of loading and continue until final stages close to catastrophic failure. Delamination due to out-of-planes stresses usually develop in the final stages of loading prior to catastrophic failure [26]. In contrast to the jointless laminates in which fibre breakage is the leading damage mode to failure, other modes of damage such as delamination and transverse cracking also develop in addition to fibre breakage in adhesive joint composites, especially the laminated joint with overlap, leading to higher resistance to impact. It is noted that separation of the fabricated staircase joint is dominant to other damage modes in multiple-covers laminated joints (Fig. 5(h)).

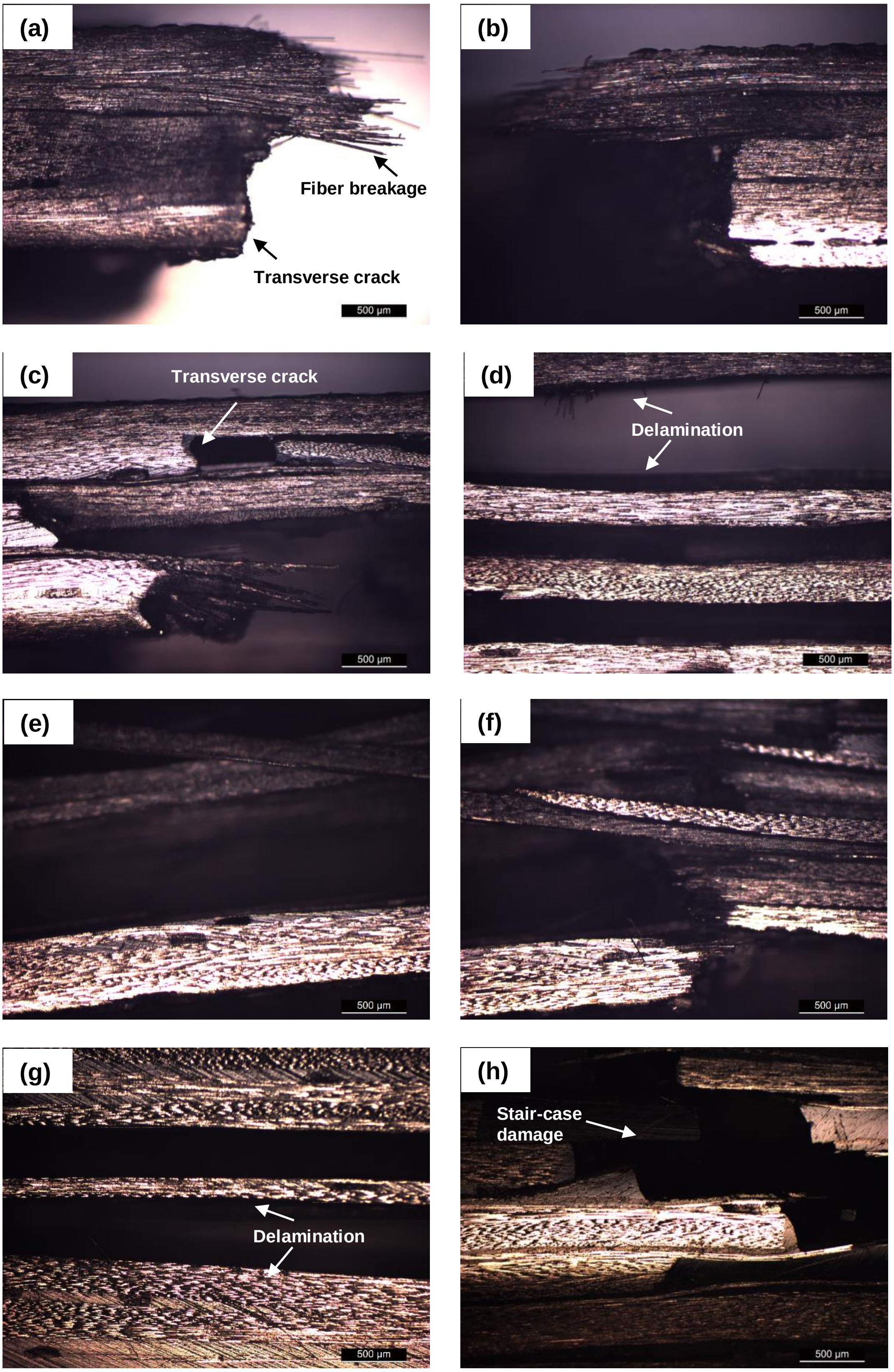

Figure 5: damage modes in different types of adhesive joints; (a) and (b) Jointless; (c) and (d) Laminated joint; (e) and (f) Laminated joint with 20 mm overlap; (g) Laminated joint with 40 mm overlap; (h) Multiple-covers laminated joint

4 CONCLUSIONS

Different types of joints namely, laminated joint, laminated joint with 20 mm overlap, laminated joint with 40 mm overlap and multiple-covers laminated joint, were fabricated using VARTM process; they were compared to one another in terms of flexural properties and impact strength. The results showed enhanced flexural and impact properties for laminated joints with overlap especially the joints with 40 mm overlap. In addition, optical microscopy of post-test impact samples revealed that the extent of other types of damages modes such as delamination and transverse cracking increased in adhesive joints compared to jointless laminates resulting to increased flexural and impact strength.

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