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IMPROVEMENT OF COMPOSITE DRAPE FORMING QUALITY BY ENHANCING INTERPLY SLIP

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Abstract

Diaphragm forming such as hot drape forming (HDF) is a cost effective method that has been used to manufacture large composite aircraft structures with relatively low geometrical complexity. This technique improves production rate by laying multiple prepregs to create an uncured laminate preform first and then forming it into a desired shape, instead of the time consuming manual ply-by-ply lay-up process. However, the disadvantage of this method is that out-of-plane wrinkles occur during forming, which makes this method challenging. This undesirable defect is generated by high interfacial friction between the plies due to the tacky surface resin preventing ply slippage. Therefore, the process usually needs to be carried out at an elevated temperature to enhance the ply slippage by reducing the resin viscosity, however the cost of heating energy and processing time can be significant in manufacture of large aircraft components, such as wing spars. In this research, a new method using interleaving materials to reduce the interply friction was developed, which could effectively minimise the wrinkles during forming. Additionally, the effect of interleaving material on the interlaminar fracture toughness was investigated experimentally.

1. Introduction

Diaphragm forming (Fig. 1) is one of the composite sheet forming techniques that were originally developed for manufacturing thermoplastic composites in the late 80s [1]. In this technique, a stack of thermoplastic prepregs is placed under a diaphragm (or between two diaphragms) and softened by heat. An external air pressure is then applied to make it conform to the tool surface. The diaphragm forming process for thermosetting composites [2] such as hot drape forming (HDF) is similar to the aforementioned process, but generally the heat is applied to reduce the surface tackiness by decreasing resin viscosity. The forming process is followed by consolidation and autoclave curing. This technique can significantly reduce the time for the manual ply-by-ply lay-up onto three-dimensional tools as a

Figure 1. Illustration of composite vacuum forming process.

single step forming process. However, this method is sensitive to the complexity of component geometry, high forming quality is difficult to achieve as out-of-ply wrinkle or fibre buckling occurs around the geometric features during forming even though the material may be softened by heat (Fig. 2a).

Generally, the defect is caused by the high interply friction between two contacted prepregs [3]. During draping, the prepregs are forced to conform tool geometry, which requires slippage between prepregs. However, the highly viscous resin on prepreg surface prevents ply slippage during forming, which causes high interply shear stress. When this out-of-plane shear stress cannot be relieved during the deformation, compressive stress is developed in the prepreg, which causes ply wrinkling or fibre buckling (Fig. 2b) due to the low buckling resistance. Dodwell. et al. [4] demonstrated that the wrinkle generation is associated with the length of the deformation area (Fig. 2c), and the wrinkle could be generated if this length is too long to allow ply slippage. In other words, the HDF process may not be suitable for manufacturing large and thick components as a large area has to be sheared through the thickness. The interply friction can also be influenced by manufacturing conditions such as the forming temperature, forming speed and debulking process [5]–[7], because of the viscoelastic resin properties and increased ply to ply bonding. Conventional methods minimise the wrinkling by increasing the forming temperature to reduce the tackiness and resin viscosity. However, the low resin viscosity might lead to in-plane fibre distortion as the resin matrix also plays an important role of binding fibres before cure. Furthermore, the heating process requires a considerable amount of energy especially when the composite component is large: e.g. an aircraft wing spar.

The aim of this project was to study a new method that can improve the composite HDF quality and energy efficiency. Instead of reducing the resin viscosity by increasing the forming temperature, dry lubrication layers were interleaved at the ply interfaces to reduce interply friction. The interleaving layers were formed using powders and thin veils that have been reported as materials increasing interlaminar fracture toughness [8], [9]. This approach could minimise the forming defects and improve the energy efficiency of the process, as well as increasing the structural performance of the cured component. The work focused on the following parts. Firstly, a quantitative study on prepreg interply friction when interleaving materials were included at ply interfaces, and how forming conditions influence the ease of ply/ply slip. Secondly, the quality improvement was experimentally evaluated by simulating the HDF process of C-section carbon fibre composite specimens with slip enhancement materials. Finally, how the interleaving layers influence the interlaminar fracture toughness after curing was experimentally investigated.

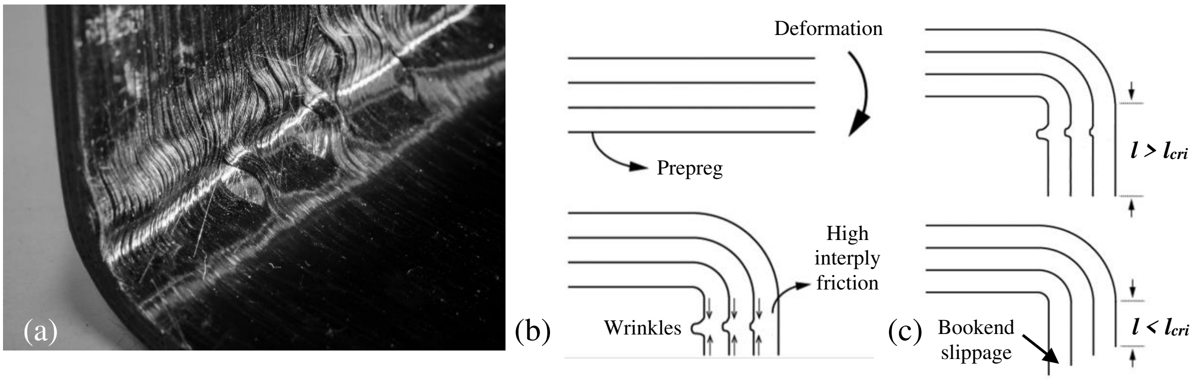

Figure 2. Ply wrinkling and fibre buckling: (a) defects at inner radius of a composite part from drape forming, (b) schematic diagram of wrinkling mechanism during forming, and (c), defect associates with the critical length (l_{cri}) of deformation region.

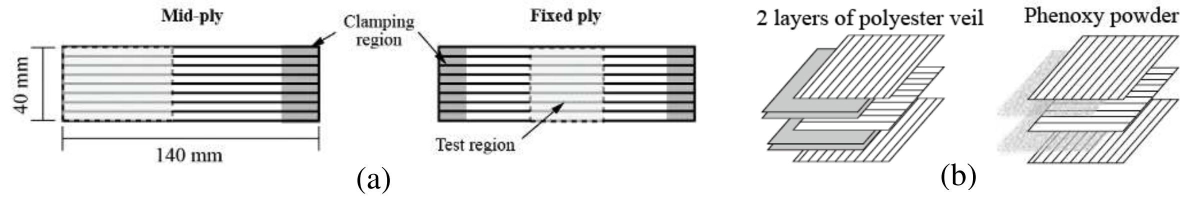

Figure 3. Schematic diagram of (a) interply friction test specimens, (b) HDF test specimens.

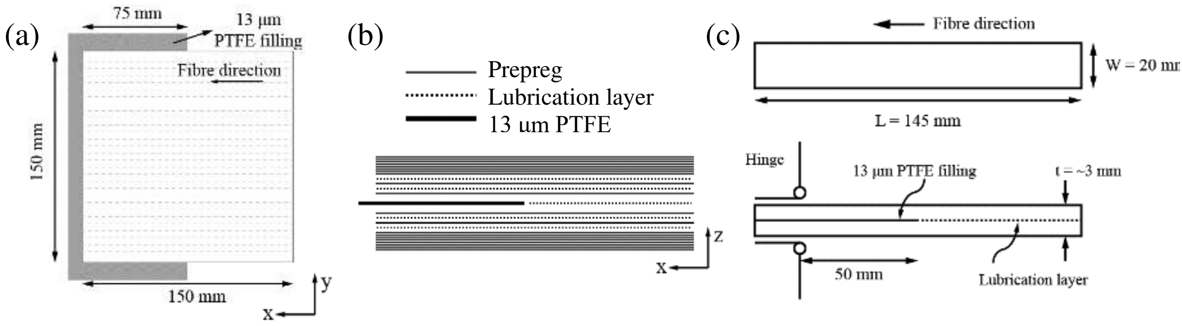

Figure 4. Schematic of DCB specimens and their fabrication method: (a) specimen top view before cutting, (b) cross-section, (c) DCB specimen dimensions after cutting.

2. Experimental

2.1 Materials

Unidirectional carbon fibre epoxy prepregs (IM7/8552, Hexcel, US) were used for the preform material. The interleaving materials were Polyester non-woven veil (Optiveil®, Technical Fibre Products Ltd, UK) and Phenoxy powder (PKHP-200, InChem, US). The areal density of the polyester veil was 4 g/m^2, its thickness was approximate 20 μm; For the phenoxy powder, the particle size was in a range from 40 to 200 μm approximately, average molecular weight (M_w) was 52,000 Daltons. Phenoxy is known as a polymer with low melting temperature (110-120°C) that can be dissolved within epoxy resins [10]. The silicone rubber diaphragm (SuperClear, Silex Ltd, UK) used in HDF simulation was 1.6 mm thick.

2.2 Specimen Preparation

Three types of specimens were prepared for interply friction tests, drape forming tests and fracture toughness tests. For the interply friction test, the specimen comprised three pieces of prepreg with dimensions of 140 mm × 40 mm. It was fabricated in such a way that the mid-ply was sandwiched between the two outer plies forming a contact area with dimensions of 40 mm × 40 mm. Before they were overlapped, the lubrication materials were applied only on the contact area (test region), and their areal weight were 8 g/m^2 and 2 - 3 g/m^2 for the veil and powder layers, respectively, shown in Fig. 3a. The drape forming test was carried out using preforms with a quasi-isotropic (QI) $[90/45/0/-45]_{2s}$ stacking sequence with dimensions of 70 mm × 150 mm. 15 minutes debulking at room temperature was carried out every four plies when the preforms were fabricated. For the slip enhanced cases, polyester veils or phenoxy powders applied over the prepreg surfaces (Fig. 3b). For the fracture toughness test, the specimens were prepared following ASTM D5528 [11]. The specimens were made of 24 plies of all 0° prepreg with 150 mm × 150 mm in dimension (Fig. 4a). Lubrication materials were applied at the mid-plane as well as the four adjacent ply interfaces over and under the mid-plane of the laminate during layup. A 13 μm thick PTFE film was placed at the mid-plane to create a sharp crack front (Fig. 4b). Specimens were consolidated at 80°C for two hours in an autoclave. The cured composite panels were cut and bonded with hinges for the test (Fig. 4c).

2.3 Interply Friction Test

Table 1 shows test conditions for interply friction measurement. The measurement was carried out by a pull-out test (Fig. 5a) with a test rig (Fig. 5b) developed in this work. As shown in Fig. 5a, the two outer plies were fixed on to the chamfered aluminium blocks, a mid-ply was clamped with the two outer plies by applying external pressure using a pneumatic cylinder. This method measured the average interply friction at two contact surfaces on both sides of the mid-ply. The aluminium blocks have built-in cartridge heaters to control test temperature, and the applied clamping force on the contact surface was controlled by high-precision pneumatic regulator to simulate variable forming pressures. The test rig was designed to be used with a tensile testing machine to measure the pull-out force.

The effect of the debulking process was also investigated by testing non-debulked (Case 1 and 2) and debulked (Case 3 and 4) specimens. The way of determining the appropriate pulling test speed is shown in Fig. 6a and Eq. 1. Assuming that the round corner is a quarter circle, the length difference between outer ply (*L*) and inner ply (*l*) is:

Table 1. Pull-out interply friction test conditions.

Case	Debulking condition			Testing condition	
	T (°C)	P (MPa)	t (min)	T (°C)	P (MPa)
1	No debulking			RT	0.043
2	No debulking			40	0.043
3	RT	0.1	15	RT	0.043
4	RT	0.1	15	40	0.043

*RT = Room temperature.

$$L - l = \frac{2\pi\,(R-r)}{4} = \frac{\pi}{2} \times (R-r) = \frac{t\pi}{2} \qquad (1)$$

where the *R* and *r* are the outer and inner radii, *t* is the ply thickness. The *t* was assumed to be 0.125 mm, and the total forming time was around 10 seconds, so the theoretical ply slippage speed is 1.18 mm/min. Therefore, the pull-out speed was set constant at 1 mm/min in the test.

2.4 Hot Drape Forming Test

In order to investigate the out-of-plane wrinkle generation during the composite forming process, an in-house hot drape forming test rig was manufactured. A flat prepreg laminate was positioned on top of an aluminium tool and covered by release films and a breather (Fig. 6b and c). The whole tool was bagged with a silicone rubber sheet and air-tightened with sealant tapes. The forming condition was 15 minutes debulking at room temperature, followed by drape forming at 40°C (Case 4) shown in Table 1. When the forming process was completed, only the laminate and C-section aluminium tool were left in the oven for consolidation. In order to freeze the forming defects, curing process was carried out at 80°C for 17 hours without any external pressure.

2.5 Mode-I Fracture toughness test

Since the interleaving material could significantly affect the interlaminar property of the cured composites, interlaminar fracture toughness was evaluated using double cantilever beam (DCB) test following the ASTM D5528. The test was carried out with a material test machine (Shimadzu, Japan)

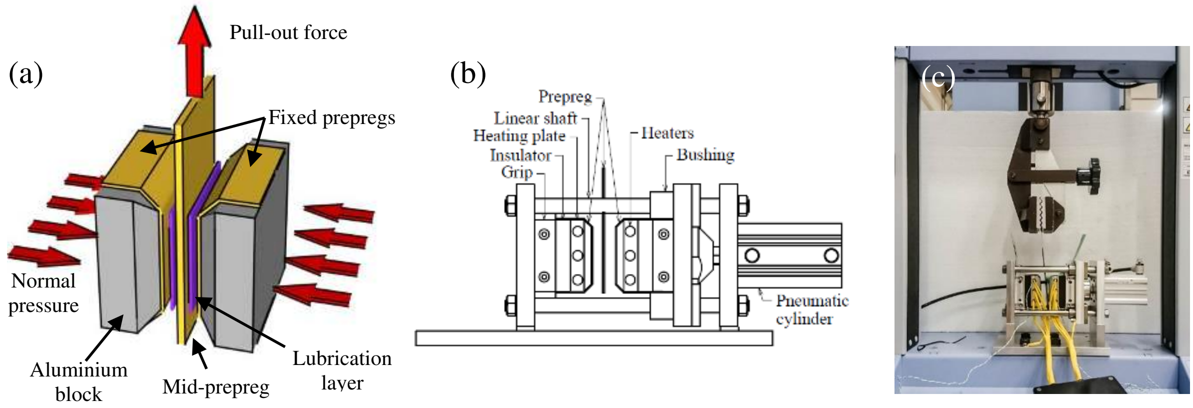

Figure 5. Interply frictional test rig: (a) schematic diagram of friction test, (b) side view of the test rig, (c) test setup of the friction test rig on a tensile test machine.

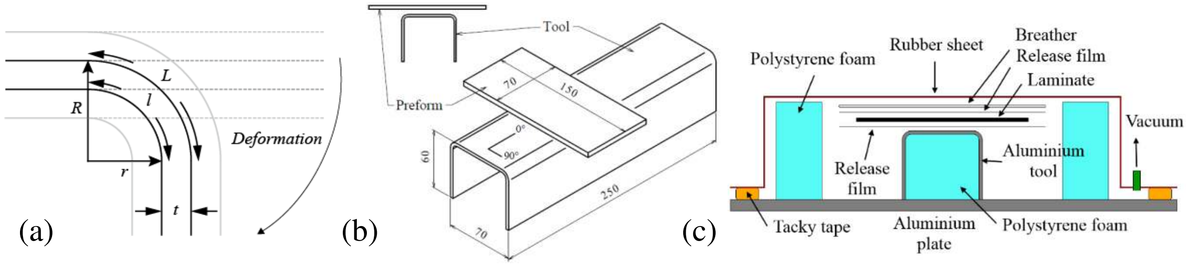

Figure 6. Drape forming test: (a) the length difference between each layer around the corner (b) the flat preform on the C-section aluminium tool (dimension in mm), (c) schematic of the draping test set up.

with 1 kN load cell. Testing speed was 1 mm/min, onset crack propagation was recorded by a high-resolution camera. The Mode-I energy release rates, G_I, were calculated using a modified beam theory (MBT) method as Eq. 2:

$$G_I = \frac{3P\delta}{2b(a + |\Delta|)} \tag{2}$$

where P is the measured load, δ is the displacement of opening crack, a is the crack length, b is the width of specimen and Δ is determined experimentally by generating a least square plot of the cube root of compliance, $C^{1/3}$.

3. Results and discussion

3.1 Interply friction and draping quality

Fig. 7 shows the characteristic load-displacement curve recorded in the interply friction test. At room temperature, in both non-debulked (Fig. 7a) and debulked (Fig. 7b) cases, the friction load was reduced when slip enhancement materials were applied at ply interfaces (black lines in Fig.7). The maximum friction load in the non-debulked test dropped from 340 N to 127 N (powder interleaving) and 58 N (veil interleaving) room temperature. When the specimens were debulked, the interleaving materials reduced the interply friction load significantly, from 950 N (force reached the load cell limit) in the non-interleaved inter-leaved case to 249 N (powder interleaving) and 49 N (veil interleaving), which means

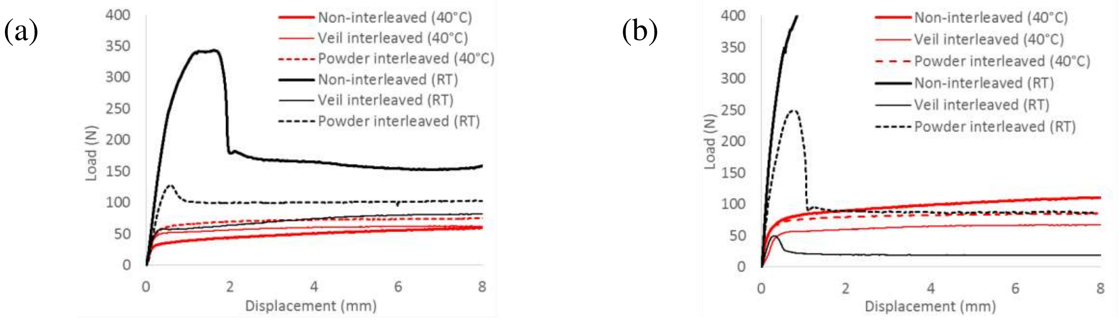

Figure 7. Frictional resistance force of different interleaving materials at different process conditions: (a) non-debulked (Case 1 and Case 2), (b) debulked (Case 3 and Case 4).

Figure 8 Internal corners of C-section preform produced by HDF process: (a) veil interleaved, (b) powder interleaved (c) non-interleaved.

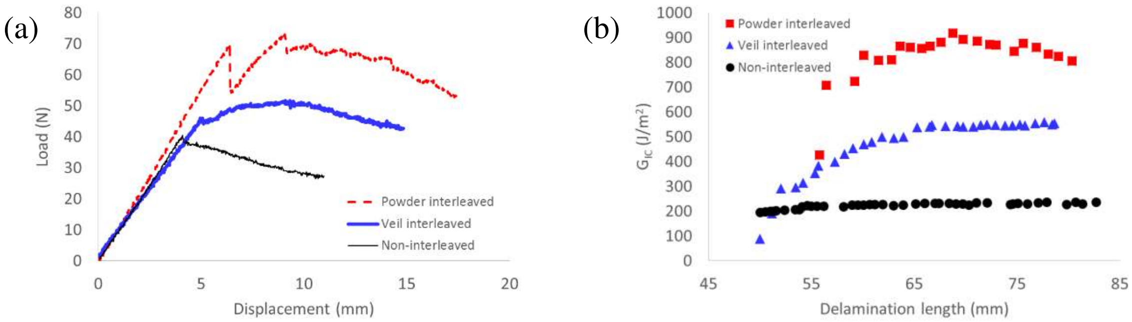

Figure 9 Mode-I fracture toughness test results of specimens with and without interleaving lubrication materials: (a) load-displacement curve, (b) R-curve.

the interleaving materials were able to promote ply slippage even when the debulking process was applied, and reduced the friction load to the value similar to the non-debulked case (veil interleaving). Comparing with the test results at 40°C, the friction loads were decreased to a range of 40-90 N. This experimental result indicated that using slip enhancement materials could effectively reduce the interply friction even without applying heat during forming. In the draping test, forming quality was also improved when polyester veils and phenoxy powders were interleaved in the laminates (Fig. 8a and b), while a large amount of buckled fibres at the inner corner was found in the non-interleaved sample.

3.2 Interlaminar fracture toughness test

The experimental test results show that the slip enhancement materials were also effective in increasing the interlaminar fracture toughness of cured composite. Fig. 9a shows the load-displacement curve of Mode-I DCB test. Interleaving polyester veils and phenoxy powder increased the amximum load by approximately 10 N and 30 N, respectively. In the delamination resistance curve (R-curve) of each type of sample (Fig. 9b), the G_I value of non-interleaved sample was around 200 J/m^2. However, the G_I value of the specimen with interleaving materials was increased, and especially phenoxy powders increased around three to four times G_I value of the non-interleaved case at room temperature .

4. Conclusions

The ply lubrication effect of different interleaving materials was investigated for different forming conditions using the interply friction test rig. The test results showed that the interply friction was reduced by interleaving polyester veils and phenoxy powders between plies, and its impact on forming quality improvement was demonstrated by manufacturing composite C-sections using HDF simulation tests. Both materials were also effective in increasing the interlaminar fracture toughness of cured composites. Therefore, the proposed method was proven to be an effective way to use two mechanisms simultaneously to improve the quality of composite end products: reducing the fibre wrinkling and increasing the interlaminar matrix property. The method has a potential to achieve high forming quality at lower forming temperature, as well as high energy efficiency when manufacturing large composite components using HDF in aerospace industry.

Acknowledgement

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