Vacuum infusion method for woven carbon/Kevlar reinforced hybrid composite

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Abstract. The vacuum assisted resin transfer moulding (VaRTM) or Vacuum Infusion (VI) is one of the fabrication methods used for composite materials. Compared to other methods, this process costs lower than using prepregs because it does not need to use the autoclave to cure. Moreover, composites fabricated using this VI method exhibit superior mechanical properties than those made through hand layup process. In this study, the VI method is used in fabricating woven carbon/Kevlar fibre cloth with epoxy matrix. This paper reports the detailed methods on fabricating the hybrid composite using VI process and several precautions that need to be taken to avoid any damage to the properties of the composite material. The result highlights that the successfully fabricated composite has approximately 60% of fibres weight fraction. Since the composites produced by the VI process have a higher fibre percentage, this process should be considered for composites used in applications that are susceptible to the conditions where the fibres need to be the dominant element such as in tension loading.

1. Introduction

Composite material, which has been used domestically since 1960s, is one of the superior materials that can replace metals and wood in various application fields. Due to its lighter weight, anti-corrosion and also good capability in sustaining high loads, composite material is often preferred as alternative for steel, aluminium and wood in some applications like bridge structures, wind turbine blades, aircraft structures and automobile parts. Since composite material consists of two different constituents (fibre and matrix), they can be chosen accordingly to design various composite materials with characteristics based on the required application. Polymer matrix composite material is one of composite materials that have been used widely in the manufacturing industries. This material generally consists of fibres and polymer matrix, and also called as Fibre Reinforced Polymer (FRP) composite. The fibres used in these materials commonly have higher strength and modulus than the matrix, hence making it the main component to sustain the load [1].

There are different processes invented for fabricating the FRP composites, which are hand lay-up, prepregs and Vacuum-assisted Resin Transfer Moulding (VaRTM). Hand lay-up method is one of the easiest methods but it can be rather inconvenient as the resin has to be distributed evenly by hand. Air bubbles that appear during the process are also difficult to be removed using human power, especially in a large scale fabrication. Using prepregs is one of the expensive processes that use the autoclave to
cure. This method is widely used for fabricating the primary aircraft structures [2–4]. VaRTM or also known as Vacuum Infusion (VI) process is invented to reduce the manufacturing cost of the composite using prepregs [5]. This process has been developed such that composite materials can be fabricated and cured without using the autoclave. It has also been proven that the composites fabricated using the VI process are not only low in cost [4] but also of high quality that makes them adequate to be used in primary structures of an aircraft [3–4]. Previous works have compared the performance of composites made by hand lay-up and VI processes, and it is found that the composites made from the VI process have better performance in mechanical properties [6–8].

Although VI process has been proven to be able producing high quality composite materials that are suitable to be used in aircraft structures, this fabricating process has always been overlooked since using prepregs is much more popular in recent days. Most of previous studies have investigated on the flow rate, permeability and compaction pressure effect on the composite laminates’ properties [9–11]. However, a detailed discussion on the preparation technique and its effects on the properties of the composite materials are rarely found. To address this gap, this work discusses the steps followed and the precautions taken during fabrication of woven carbon/Kevlar reinforced epoxy hybrid composite laminates. The results are presented by weight fraction of fibres obtained from the finishing products and several steps that affect the properties of the final product are also discussed.

2. Methodology

The fabrication process of hybrid composite laminate starts with the preparation of the materials and tools. Moreover, the right dimension of the composite and required thickness are very important to be determined first to ensure that it is consistent with the requirements for mechanical testing. The fibres used in this work are the 3K carbon fibres and Kevlar-29. These two fibres are weaved together in one cloth, where carbon fibres as the warp and Kevlar fibres as the weft. The area of one cell of the carbon fibre is approximately 3mm$^2$ and 3.75mm$^2$ for the Kevlar fibre (Figure 1). The thickness of the woven cloth is approximately 0.26mm. The matrix of the composite was made of EpoxAmite 100 base epoxy resin, which can be cured in room temperature. To avoid the resin starts hardening too early during the process, 103 slow hardener is used with mix ratio by weight 100:24 (resin:hardener). The specification of the resin can be found in Table 1 as provided by the products' manufacturer.

The schematic diagram of the vacuum infusion method is shown in Figure 2. Ten plies of woven fibre cloths are stacked together on a glass laminate that has been coated with mould release wax. Two spiral tubes are placed at both ends of the fibre cloths. One of them is connected to outlet tube while the other is connected to inlet tube. The outlet tube is connected to the vacuum pump and this is where the vacuum pressure is applied during the fabrication process.

![Figure 1: Woven carbon/Kevlar cloth (Black fibre: carbon, Golden yellow fibre: Kevlar 29)](image-url)
Table 1: Specification of EpoxAmite 100 epoxy base resin with 103 slow hardener

| Handling properties           | Physical Properties             |
|-------------------------------|---------------------------------|
| Specific gravity              | Ultimate tensile strength       |
| 1.108 g/cm³                  | 54.54 Mpa                       |
| Mixed viscosity               | Tensile modulus                 |
| 650                           | 3.12 Gpa                        |
| Specific volume               | Flexural strength               |
| 9.1 x 10⁻⁴ m³/kg             | 84.81 Mpa                       |
|                               | Flexural modulus                |
|                               | 2.96 Gpa                        |
|                               | Compressive strength            |
|                               | 72.39 Mpa                       |
|                               | Heat deflection                 |
|                               | 53 °C                           |

Figure 2: Schematic diagram of vacuum infusion process

A peel ply that works as a barrier between the fibre cloth and the vacuum bag is laid up first on the fibre cloth. It is very important to make sure that the peel ply used is big enough to cover the fibre cloths and spiral tubes. A mesh sheet, which works to accelerate the resin distribution inside the fibre cloths, is then placed on the peel ply. Finally, the fibre cloth is covered and sealed tightly with the vacuum bag. The arrangement diagram is shown in Figure 3. After the vacuum bag is tightly sealed, it is turned on to check for any occurrence of leak before the resin is infused. The leak is checked using the leak detector. The resin infusion process is started by setting the pump with low pressure, around -30kPa for several minutes. This step is done to observe any leaks around the vacuum bag and it is also claimed that this can minimize the air trap between the fibre layers and ensure that they are compacted steadily before the resin infusion [12]. The pressure is then increased to -60kPa and the resin started to be infused from the inlet tube. When the resin has already been distributed into half of the area of the fibre cloths, the pressure is once again increased to -80kPa and the resin is let to flow until it reaches the spiral tube at the other end of the fibre cloths. During this time, the flow rate of the resin starts to decrease and the pressure increases to -100kPa. When all resin has been completely infused into the fibre cloths, both inlet and outlet tubes of the laminates are closed tightly and they are set to cure in room temperature for 24 hours in vacuumed condition.

Figure 3: Arrangement of fibre cloths and fabrication tools for fabrication process
It is very important to identify several precautions during the process to avoid any damage to the composite laminate. Minor leaks sometimes can occur during resin infusion process, which is caused by tiny tear at the vacuum bag and leaks between the vacuum bag and the sealant tape. These leaks usually can be detected by observing any substantial air bubbles inside the laminate. When air bubbles appear during the resin infusion process, leak spots have to be closed immediately before closing the outlet tube. Air bubbles also can be removed by adding extra resin, in which the resin flow will take all air bubbles to the outlet tube. Failure in removing the air bubbles will possibly cause the occurrence of voids and the composite laminate cures in non-vacuum condition, which happens when the vacuum pressure stopped. The air trapped inside the laminate is eventually accumulated on the surface of the laminate and causes the vacuum bag to be lifted. An example of failed fabrication caused by leaks and air trap can be seen in Figure 4.

To measure the weight fraction and volume fraction of fibre and matrix in the fabricated composite laminates, density of the material have to be determined first. Density test is carried out following the ASTM D792 procedures. The composite laminates are cut into small pieces and tied with a string and immersed in distilled water (Figure 5). The amount of distilled water has to be enough for the material to be fully immersed and the material must not touch the bottom of the water container. Assuming that the weight of the string is negligible, density of the composite material can be obtained. Meanwhile, after the laminates are completely cured, its final weights are measured to determine the fibre weight fraction $W_f$ and fibre volume fraction $V_f$. Weight fraction of fibres calculation is done using Equation 1, where $w_f$ and $w_c$ are the mass of fibres used and the mass of the composite laminate, respectively.

$$ W_f = \frac{w_f}{w_c} \quad (1) $$

The weight fraction of fibres obtained is then used to calculate the volume fraction of fibres, $V_f$ by using Equation 2 and Equation 3. $V_m$ is the volume fraction of the matrix in the composite laminates.

$$ V_m = (1 - W_f) \frac{\rho_c}{\rho_m} \quad (2) $$

$$ V_f = 1 - V_m \quad (3) $$

3. Results and Discussions

Eight laminates are fabricated using the VI process in this work. Three laminates have the dimension of 300mm x 500mm while the rest are fabricated with the dimension of 350mm x 500mm. The results from the density test are tabulated in Table 2. From the laminates’ weight obtained, the weight fraction of fibre, $W_f$ and fibre volume fraction, $V_f$ are calculated and compiled in Table 3. In addition, several random samples have been cut into smaller rectangular shape (i.e. 250mm x 25mm) from laminate B. They are scanned under ultrasonic damage detector machine and the results are indicated in Figure 6. The yellow coloured area indicates that the area is not fully covered with resin. The thickness of these samples is also measured and the average value is shown in Table 4.
Table 2: Density of composite material obtained from the density test

| Sample | Weight in air (g) | Weight immersed in water (g) | Composite material’s density (g/cm²) |
|--------|-------------------|-----------------------------|-----------------------------------|
| 1      | 2.286             | 1.793                       | 1.275                             |
| 2      | 2.132             | 1.701                       | 1.253                             |
| 3      | 2.147             | 1.677                       | 1.280                             |

Average and standard deviation: 1.269 ± 0.01

Table 3: Composites’ weight fraction and volume fraction of each composite laminate

| Laminate | Size (mm x mm) | Fibre’s mass (g) | Composites’ mass (g) | Fibre weight fraction, W_f | Fibre volume fraction, V_f |
|----------|----------------|------------------|----------------------|---------------------------|---------------------------|
| A*       | 500 x 300      | 280.61           | 537.82               | 0.522                     | 0.447                     |
| B        | 500 x 300      | 282.26           | 448.89               | 0.629                     | 0.571                     |
| C*       | 500 x 300      | 286.30           | 528.0                | 0.542                     | 0.470                     |
| D        | 500 x 350      | 327.56           | 514.66               | 0.637                     | 0.565                     |
| E        | 500 x 350      | 326.90           | 527.01               | 0.621                     | 0.561                     |
| F        | 500 x 350      | 331.58           | 530.8                | 0.625                     | 0.566                     |
| G        | 500 x 350      | 328.59           | 541.09               | 0.607                     | 0.546                     |
| H        | 500 x 350      | 329.80           | 517.84               | 0.637                     | 0.580                     |

*Air bubbles occurred during fabrication and extra resin was infused to remove it. However, the leaks still occurred and the vacuum bag lifted up after the vacuum process finished.

Table 4: Thickness of composite laminates

| Laminate          | Thickness average (mm) |
|-------------------|------------------------|
| 500mm x 300mm     | 2.2 ± 0.06             |
| 500mm x 350mm     | 2.39 ± 0.06            |

Out of the eight laminates of hybrid composite fabricated, six of them have been successfully cured without any major voids. From the calculation, it is found that the weight fraction of each laminate is ranging from 60% to 64% of the total composites’ mass while the volume fraction of fibres obtained ranges from 55% to 58%. These results show that the complete fabricated composites are dominated by fibres in weight and volume composition, which also similar to the results obtained in [7, 8, 13]. However, for the failed composite laminates (i.e. laminate A and laminate C), adding the extra resin as a method of removing the air bubbles might be ineffective as it is found that it has many voids and lower fibre weight fraction compared to the other laminates. During the fabrication process, it is very crucial to ensure that the vacuum bag is sealed tightly to prevent any leaks that can bring damage to the composite laminate. Failure of removing the air bubbles can cause the appearance of voids.

From the ultrasonic scan results, resin can be seen to be distributed evenly at the centre area of the composite laminates. The resin is lacking at both ends of the specimen where the inlet and outlet tube are located. The uneven distribution of the resin is caused by the high pressure used during infusion process. It has been reported in a previous study that higher speed and pressure applied during vacuum infusion process for woven reinforcements will draw the resin out of the laminates faster and at the same time, the remaining resin in the inlet spiral tube would have partly cured and resulted in reduced flow [11]. This phenomenon will eventually cause insufficient wetting at the laminate area close to the inlet. Furthermore, lubrication effect can cause the fibre cloth’s thickness to decrease once its wetted with resin [12, 14]. Lubrication effect is where the resin causes the fibre to rearrange and nested more
closely, and decreases the thickness of the wetted area. Thus, the changes of fibre thickness are also causing the flow of resin towards the outlet tube becomes more difficult, resulting in insufficient and uneven resin distribution in the outlet area. Based on the results shown, if the sample cut from the laminate needs to have even distribution of resin, it is recommended to consider fabricating a bigger size of laminate with 10% excess area from the required sample size at both ends as shown in Figure 7.

![Figure 7: Recommended extra area needed during the vacuum infusion process](image)

The results shown in previous Table 3 highlight that, even when each laminate has almost the same volume fraction of matrix, thickness of smaller samples cut from the laminates is slightly different. As the bigger plate has longer distance for the resin to flow, less resin can flow successfully to the outer area of the laminate. The findings indicate that different flow rates are achieved during the infusion process. Thus, different pressure level is needed to be applied according to the size of the fibre cloth.

### 4. Conclusion

All in all, woven carbon/Kevlar hybrid composite laminates are successfully fabricated using vacuum infusion method in this work. However, as the results show, even a small leak can damage the whole composite laminates. This process should be improved to minimize the occurrence of leaks by giving extra cautions during the leak checking process. The results also show that the amount of resin infuse, infusing pressure and fibre cloth size have significant influence to the thickness and resin distribution of composite laminate. The composite laminates made from the VI process have higher weight ratio of fibres and might be the most suitable to be applied on structures that are prone to tension loading.

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