Compression Responses of Preform in Vacuum Infusion Process

Duan Yuexin*, Tan Zhaoyuan, Zhao Yan, Sun Jing

School of Materials Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100083, China

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Abstract

The final thickness of a product after the vacuum infusion process (VIP), which is equal to the fiber volume fraction, depends in part on the compression responses of the preform because one of the mold faces is flexible in VIP. This study aims at investigating the compression responses of different fabrics under dry or wet conditions. The main factors affecting the compression response under investigation include, the vacuum pressure, the loading and unloading repeatability on the preform, the layup design, the kinds of fabrics, and the resin viscosity. Besides, the effects of some internal factors such as nesting and elastic recovery of fibers, lubrication of resin, friction between fibers, and so on, are also studied. In the end, this article expatiates the meaning of the matching requirements of the permeability of the preform and that of the distribution medium.

Keywords: vacuum infusion process; compression response; fiber volume fraction

1 Introduction

Today, the composite industry is facing a lot of formidable challenges. The first one is from the ever increasing, strict environmental regulations, which limits the workers’ exposure to volatile organic compounds. This has threatened to decrease the competitiveness of many existing technologies such as the hand layup and spray-up technologies because they typically use styrene, a reactive solvent, ranging from 30% to 45%. As a result, an urgent need for new alternatives to those old methods emerges to enable the users to meet the ecofriendly legislation[1]. The second one is from the ever-enhancing costs of many existing technologies, such as autoclave processing and hot compression molding, due to higher expenses in power and mold manufacturing. To respond to these challenges, of late, the liquid composite molding (LCM) inclusive of resin transfer molding (RTM), vacuum infusion processes (VIP), resin film infusion (RFI), and so on, have come to the fore. However, popular as it is, RTM is still too expensive because it needs building complex and heavy molds, which can withstand the injection pressure for large parts. For the production of large structures in small volumes, as new major stride in injection strategy, VIP uses the vacuum pressure as the only driving force to impregnate the mold cavity of the preform. As was mentioned by Williams et al., early interest in this technology goes back to the 1940s, when the so-called Marco method was introduced[1-2]. Since then, many developments have helped the VIP to become an economical and ripe technology.

The parts produced by VIP have higher fiber content (typically 60 wt%-70 wt%) as against most open mold processes (45 wt%) and lower porosity (less than 1%), which makes the VIP-produced part stronger than the one produced by most open mold processes if they have the same thickness. Most important of all, VIP is able to manufacture large,
highly integrated products at low costs.

As for VIP, one of chief concerns in producing large structures is to predict the final thickness of the part, which should be equal to the fiber volume fraction \( V_f \), and be governed by the compression responses of the preform as well as the vacuum pressure\[3\]. If \( V_f \) does not satisfy the specified requirement, the part will be scrapped, which can not be tolerated by large composite parts such as boat hulls. Therefore, an exact estimation of the ultimate thickness must be ensured before the infusion.

To date, a lot of research work has been done on the compression responses of fibers in VIP outside China. Hammami et al. researched the compression responses of warp knitting fabrics\[1,3\]. Williams et al. studied the compression responses of plain weave fabrics\[2\]. Kellya et al. investigated the compression responses of continuous felt reinforcement in dry and wet compression tests\[4\]. Regretfully, nowhere in China is there any mention of somebody who has been working on this subject. This article carries out an experimental study on the compression responses of materials used in VIP inclusive of two kinds of fiber: glass fibers and carbon fibers containing six layup designs. The effects of the main factors, such as vacuum infusion, the loading and unloading repeatability on the preform, layup design and types of fabrics, will be examined.

2 Experimental Analysis

2.1 Experimental setup

The compression tests were performed by using the homemade testing equipment, as shown in Fig.1. As a preform, the piece of fabric was cut into 100 mm × 100 mm size and placed on a flat glass plate, covered by a flexile nylon vacuum film. The pressure applied on the film was controlled by a vacuum pump. The changes of thickness were measured by a micrometer gauge.

During the experiment, the applied maximum compression pressure did not exceed 0.10 MPa, which was close to the actual manufacturing condition thanks to the precise control by the vacuum pump.

VIP could be divided into two stages: the first was called dry test stage where the dry preform was compacted and the second was called the wet test stage, wherein the resin infuses. During the dry test stage, a cyclic pressure, increasing from 0.02 MPa to 0.10 MPa was applied, and then it was decreased back to the starting value. When the vacuum pressure became stable, the thickness of the sample was registered if it did not change for 1 min\[3-5\], for taking account of the relaxation in the fibers of the preform under a given vacuum pressure. After the dry test was completed, the resin inlet valve was opened to start the wet (saturated) test. Salad oil was infused into the mold cavity under the pressure of 0.06 MPa. During this stage, three thickness values stable for 1 min under the pressure of 0.06 MPa, 0.08 MPa, and 0.10 MPa, respectively, had to be noted with the resin inlet valve closed. An interval of 2.5 h had to be ensured between the dry test and the wet test in all the experiments.

In the wet test stage, the vacuum pressure drove the resin to enter the mold, making the resin infuse into the preform completely. In the end, the resin got cured into composites with fibers. In this study, the resin was replaced by salad oil, as its viscosity was as low as 0.036 Pa·s, and it underwent such a negligible change at room temperature that it could be neglected. Other reasons were: the salad oil did not exert negative effects on the results and was easy to clean off.

With the collected data, the \( V_f \) or the preform thickness can be plotted as a function of vacuum pressure. Here, the thickness of preform is selected to express the results for the same fabric and \( V_f \) to
2.2 Materials

In the compression tests, two kinds of fabrics were used: glass fiber fabrics and carbon fabrics. Glass fiber fabrics of four different types with volume density of 2.54 g/cm³, that is, plain weave fabric, (0, 90) fabric, (±45) fabric and unidirectional fabric, were provided by Changzhou Zhongxin Tianma Glass Fiber Products Co. Ltd., in China. Furthermore, special attention was paid to the warp knitting fabrics, that is, (0, 90) fabric, (±45) fabric, and unidirectional fabric. The carbon fabric T700, with a volume density of 1.80 g/cm³ was procured from the Toray Group in Japan. All the fabrics were cut into pieces of 100 mm×100 mm. For every test, the preform of the plain weave fabric was made by 30 stacked-up layers; the preform of (±45) fabric by 15 layers, and the preforms of other materials by ten layers.

As a very important factor during stacking the fabric pieces together, the layup design includes ply angle, ply number, and ply sequence. In practices, by using layup design, different laminates, such as [0] or anisotropic composite laminates can be fabricated, which possess demand mechanical properties similar to unidirectional reinforcement or bending resistance. As the plain weave fabric of glass fiber has nothing to do with the ply angle, all pieces of this material are just stacked up in one direction. The layup designs for the other fabrics are shown in Fig.2. Here, the oil flow way during resin infusion is named according to the 0° direction of fabrics. In fact, [(0, 90)/(90, 0)] and [(+45, −45)/ (−45, +45)] are some of the layup designs that are different from each other in the ply angles, as is the case with [(0, 90)/(0, 90)] and [(+45, −45)/(+45, −45)].
3 Results and Discussion

3.1 Influencing factors on compression responses

(1) Different compression responses of dry and wet tests

The plain weave fabric of glass fiber was selected to perform the compression experiments to differentiate between the dry and the wet tests. Fig.3 shows the thickness of the preforms in the dry and wet tests. The “dry” curve can be divided into two sections: the first one, the section of “Increasing Pressure”, where the thickness of the preform decreases when the pressure increases from 0.02 MPa to 0.10 MPa; and the second one, the section of “Decreasing Pressure”, which implies that its thickness increases when the pressure decreases from 0.10 MPa to 0.02 MPa, which corresponds to the vacuum pressure cycle. Compared to the first section, the thickness in the second section is lower, which means that a bigger \(V_f\) can be obtained in the second section. This is attributed to the permanent deformation during the vacuum pressure cycle caused by the irreversible nesting of fibers into the gaps of the preform structure\(^{[4,6-8]}\), thereby resulting in an incomplete elastic recovery of the fibers\(^{[4]}\). Practically, the importance of this process lies in instructing the operators to apply the vacuum pressure of 0.10 MPa first to check whether the film bag leaks or not and, if not, then to reduce it to the specified level. Furthermore, the same phenomenon can be found in Fig.4, which shows that when vacuum pressure cycles are repeated thrice in the dry tests, both the first section and the second section of “dry” curves show the thickness descending as the cycle increases, meaning that repeated compression can increase the \(V_f\).

From Fig.4, in the range of 0.02 MPa to 0.08 MPa, it is observed that the thickness of the first section (the section of “Increasing Pressure”) of the “2nd dry cycle” curve is higher than that of the second section (the section of “Decreasing Pressure”) of the “1st dry cycle” curve. The same phenomenon is also found between the “3rd dry cycle” and the “2nd dry cycle” curves. This can be ascribed to the elastic recovery of fibers during the restoring course of the second section.

From Fig.3, at the pressure of 0.06 MPa, it is noted that the thickness of the “dry” (before infusion) curve is higher than that of the “wet” curve. The same can be found in other experiments. In addition, the thickness values on the “wet” curve at both 0.08 MPa and 0.10 MPa are also lower than those on the “dry” curve. Some scholars are of the opinion that it is because of the infusion liquid acting as a lubricant to reduce the friction between fibers\(^{[2-3, 9]}\).

(2) Different compression responses with different layup designs

As is presented in Fig.5, the thickness with the \([0, 90)/(90, 0)]\) layup design is lower by 3%-5% than that with the \([0, 90)/(0, 90)\) layup design in the dry and wet compression tests. In the \([0, 90)/(90, 0)]\) layup design (see Fig.2(a)), a great
many fiber bundles between the two abutting layers have nested in together, which lower the thickness when compare to the [(0, 90)/(0, 90)] layup design. Furthermore, as is presented in Fig.6, the thickness with the [0] layup design is lower by 1%-4% than that with the [0/90] layup design and the [0/+45/90/–45/0] layup design in the dry and wet compression tests. Moreover, the thickness of “[0] change” curve, for example, the case without 90° bundles (see Fig.2(f)), is even lower than that of “[0]” curve. This may be due to the decreased 90° bundles and, more significantly, the fibers of the two abutting layers become much easier nested with each other than when the 90° bundles are decreased.

As shown in Fig.7, in the T700 carbon fabric, are also observed the same results as from the unidirectional fabric in the dry and wet compression tests.

(3) Different compression responses with different glass fiber fabrics
Apart from Section 3.2, where the different layup designs for the same fabric will be examined, here the compression responses of different fabrics with the same layup design are discussed. In Fig.8,
$V_f$ is used in place of the thickness, on the $Y$-axis, because four different fabrics have a different thickness per layer.

In Fig.8, the (0, 90) fabric is with the [(0, 90) / (0, 90)] layup design; the (±45) fabric is with the [(±45, −45) / (±45, −45)] design, and the unidirectional fabric is with the [0/90] design. By comparing the four curves, it is seen that $V_f$ of the unidirectional fabric is the highest which is credited to absence of yarns to hold the two layers together if omitting the effects of 90° bundles which can be understood by comparing Fig.2(d) with Fig.2(b). The plain weave fabric has the lowest $V_f$, which can be attributed to the huge number of nodes generated by the one-up-one-down characterized structure.

![Dry compression responses](image1)
(a) Dry compression responses

![Wet compression responses](image2)
(b) Wet compression responses

Fig.8 Dry and wet compression responses for different fabrics.

In practices, if the type of fabric and the layup design are fixed, on the premise of ensuring $V_f$ and the porosity, a composite with integrated property can be obtained.

(4) Different compression responses of different type of fibers

Carbon fibers have been found wide applications thanks to their high strength and modulus. Especially, associated with the VIP process, a large number of high-quality products have been turned out. Among all kinds of glass fiber that are undergoing the test, the unidirectional fabric possesses the best compression responses. Fig.9 and Table 1 compare the compression responses of T700 to

![Dry compression responses](image3)
(a) Dry compression responses

![Wet compression responses](image4)
(b) Wet compression responses

Fig.9 Dry and wet compression responses of different fibers.

<table>
<thead>
<tr>
<th>Tests</th>
<th>$p$/MPa</th>
<th>Glass fiber [0] $V_f$%</th>
<th>Glass fiber [0] absolute $V_f$%</th>
<th>Carbon fiber [0] $V_f$%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.10</td>
<td>57.208</td>
<td>59.075</td>
<td>69.629</td>
</tr>
<tr>
<td>Dry</td>
<td>0.08</td>
<td>57.155</td>
<td>58.894</td>
<td>69.536</td>
</tr>
<tr>
<td></td>
<td>0.06</td>
<td>56.969</td>
<td>58.625</td>
<td>69.353</td>
</tr>
<tr>
<td></td>
<td>0.04</td>
<td>56.496</td>
<td>58.093</td>
<td>68.898</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>54.608</td>
<td>56.526</td>
<td>67.829</td>
</tr>
<tr>
<td>Wet</td>
<td>0.06</td>
<td>57.611</td>
<td>59.015</td>
<td>71.526</td>
</tr>
<tr>
<td></td>
<td>0.08</td>
<td>59.141</td>
<td>60.123</td>
<td>73.529</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>60.098</td>
<td>61.047</td>
<td>75.323</td>
</tr>
</tbody>
</table>
those of the unidirectional fabric. Obviously, the $V_f$ of carbon fabrics is higher than that of the glass fiber fabrics, with the biggest discrepancy amounting to 15.225% at 0.10 MPa. The diameter of the carbon fiber is about 7 $\mu$m, whereas that of glass fiber 11-15 $\mu$m. The difference of their diameters enables the packing density of carbon fibers to be higher than that of glass fiber. This might contribute to the carbon fabrics’ compression response.

(5) Variation of compression responses according to resin viscosity

The preform of T700 was designed to be of [0/90/+45/–45/+45/90/0]. The dry and wet compression experiments were conducted with the resin viscosity being 0.008 Pa·s, 0.089 Pa·s, 0.247 Pa·s and 0.525 Pa·s separately.

Table 2 shows the coefficients of variation ($C_v$) of thickness in the #1, #2, #3 and #4 wet experiments.

<table>
<thead>
<tr>
<th>$p$/MPa</th>
<th>$h$/mm</th>
<th>$C_v$/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>1.368</td>
<td>1.304</td>
</tr>
<tr>
<td>0.08</td>
<td>1.320</td>
<td>1.274</td>
</tr>
<tr>
<td>0.10</td>
<td>1.290</td>
<td>1.258</td>
</tr>
</tbody>
</table>

In Table 2, the $C_v$ of thickness is less than 5% at each vacuum pressure in four experiments, which allows the effects of error to be neglected. Therefore, it can be concluded that, within a tolerable range of error, changes in resin viscosity in the VIP will not exert any influences upon the compression responses of the preform.

3.2 Permeability matching of preform and distribution medium

The features of resin flow in the VIP supported by a distribution medium which is one of the high-permeable materials are: when driven by the vacuum pressure into the vacuum bag, because the permeability of distribution medium is much bigger than that of the preform, the resin infuses quickly and uniformly into the distribution medium – an in-plain soaking in the $X$-$Y$ direction (namely the 0° and 90° direction of fabrics). After that, the resin in the distribution medium further infuses into the preform in the $Z$ direction (namely direction of preform’s thickness). This lays bare the advantages of VIP, which has a higher efficiency of resin impregnation than the RTM, in which resin makes a slow simultaneous infusion into the preform in the $X$-$Y$-$Z$ direction.

As one of the utmost important factors in the VIP, the permeability affects the filling time of resin into the preform. The $V_f$ of the preform is directly affected by the compression responses of the fabric, which varies with the vacuum pressure, and is finally affected by the permeability of the preform. Therefore, the permeability of preform bears an indirect dependence on the vacuum pressure, which renders the research on permeability matching of the preform and the distribution medium as being very significant, because it has a dramatic influence on the resin filling time and the quality of the products.

Suppose that Fig.10(a) represents the best permeability matching, in which the resin firstly makes a rapid and uniform infusion into the distribution medium, followed by a filling in the preform, in the $Z$ direction. Two situations may occur when the permeability does not match: (1) the resin may flow in the distribution medium much more rapidly than in the preform in the $Z$ direction (see Fig.10(b)) thus causing an incomplete filling of resin in the preform before the resin inlet valve closes; (2) the resin may flow in the distribution medium so slowly (see Fig.10(c)) that a large area may remain nowhere
near impregnated in the $Z$ direction, which makes the distribution medium useless.

This provides a theoretical and practical guidance for further study on the VIP, in which, by way of the systematic research into compression responses, the permeability matching of the preform and the distribution medium should be investigated.

4 Conclusions

This article aims to study the compression responses of the preform in the VIP. The compression responses of glass fiber fabrics and carbon fiber fabrics are investigated with different layup designs and different kinds of fabrics in dry and wet compression tests. It can be concluded that the loading and unloading repeatability on the preform can achieve a higher $V_f$ under dry condition, and the $V_f$ increases further as the resin impregnates the preform. If there are fiber bundles in the same direction in the interfaces of two abutting layers, the $V_f$ also increases. Different fabrics have different compression responses, the warp knitting fabric has a better compression responses when compared to the plain weave fabric. The compression responses of the carbon fiber fabric are better than the glass fiber fabric. Finally, the article gives an insight into the meaning of researching the permeability matching of the preform and the distribution medium.

References


Biography:

Duan Yuexin  Born in 1970, as a senior engineer, he engages in the research of processing polymer composites.
E-mail: duanyuexin@126.com