Forming of sheet textile reinforcements

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Abstract: This paper reviews the sheet forming processes (in which the diaphragm forming process is discussed particularly in detail), analyzes all the possible anomalous events (such as gaps, overlaps, buckling, wrinkles, ply thickness variation, interlaminar slip as well as excessive intraply shearing) that may occur during forming. And it presents the mapping modeling methodology and illustrates the substantial importance of dart inserting in 2D textile reinforcement design. In addition, some practical means for assessing the conformability of sheet textile reinforcements are put forward. The analysis suggests that the property of shearing of a sheet cloth plays most important role when conforming to a 3D surface. Furthermore, the anomalous events or in other words, the defects are just due to the excessive shearing deformation.

Keywords: forming, sheet textile reinforcements, mapping and shearing property

1 Introduction

Composites, especially the textile—reinforced materials, have received increasing interest and attention over the past two decades. In place of aluminum and duralumin, advanced composite materials have been increasingly used in the field of aircraft and other vehicle industries[1]. Although there are so many 3D textile preforms[1,3] (such as 3D braiding, 3D weaving, orthogononal nonwovens, winding, hand lay up, etc.), their production costs are usually too high and shapes as well as sizes of these kinds of preforms are also limited to machines and manufacturing technology. On the contrary, the 3D preforms produced by sheet forming process present a great potential in vast applications due to low production cost, easy handling, large range of optional sheet forms as well as uniform mechanical properties.

The dominant sheet forming processes for thermoplastic composite materials can be classified as rubber pad forming, matched-metal die forming, hydroforming, vacuum forming and diaphragm forming[13,16], of which the diaphragm forming is shown to be one of the more promising fabrication routes for complex—curvature structures, as shown in Fig. 1. Fig. 2 is an example of diaphragm—formed product.
Fig. 1 Diaphragm forming process[3]

It can be seen from Fig. 1 that complex deformations may occur during sheet forming. The primary deformation mechanisms[4] are illustrated in Fig. 3. Theoretical approaches to model the sheet forming process must take these factors into account.

As far as the conforming or fitting of 2D cloth to 3D curved surface is concerned, many authors[5-8,11-12,14-15,17-19] have been carrying out much research work, all of which are limited to plain-weave fabrics. Except Mack and Taylor, who gave an analytical solution in modeling of fitting process, numerical mapping method is particularly esteemed.

2 Anomalous events that may occur during sheet forming

During sheet forming process, the sheet reinforcement will transform from its original plane state to a 3D curved state. Many deformations (especially shearing deformation) must take place in this process, otherwise an acceptable fitting is impossible to be obtained. But on the other hand, many anomalous events may also occur during this process. The possible unfavorable events are listed below:

Fig. 2 Diaphragm formed 8-ply quasi-isotropic

\[
\begin{bmatrix}
0^\circ/45^\circ/0^\circ/90^\circ
\end{bmatrix}, \text{ trailor shape}^{4}
\]

Longitudinal fiber flow; Transverse fiber flow; Excessive intraply shearing; Interlaminar slip; Resin percolation; Interlaminar debonding or rotation; Fiber waviness changes; Buckling (Fig. 4); Wrinkles (Fig. 5); Ply thickness variation (Fig. 6).

Fig. 3 Laminate deformation mechanisms

The laminate is \(\begin{bmatrix} 0^\circ/90^\circ \end{bmatrix}^4\) and the central section is a shallow segment of a sphere. The wrinkles form at 45° to the fiber direction.

Fig. 5 Diaphragm—formed part with laminate wrinkles

(The laminate is \(\begin{bmatrix} 0^\circ/90^\circ \end{bmatrix}^4\) and the central section is a shallow segment of a sphere. The wrinkles form at 45° to the fiber direction.)
During the forming process, the intraply shear deformation will result in a surface area reduction of the ply, as shown in Fig. 6. Under the assumption of unchanged fiber volume fraction in the deformed ply, the ply thickness $t$ of each deformed layer can then be obtained:

$$t = \frac{t_0}{\sin \theta}$$

![Fig. 6 Area reduction and ply thickness increase due to shear deformation](image)

3 Modeling—A mapping method

At present, there are two popular schemes to model the sheet forming process: one is mapping, the other is continuum mechanical model. The former views forming as a process of geometric transformation: the initially flat sheet of composite is mapped onto the curved, three-dimensional surface of the tool, and the intermediate stages during forming are not considered. In contrast, the mechanical approach views forming as a process of gradual shape change; which considers all of the intermediate stages as the composite laminate deforms from its initial shape to the final one. This means that mechanical approach is much richer in detail than mapping calculations, and also more complicated. In addition, the mapping approach gives a clean, well-defined mathematical problem that can be solved accurately by analytical or numerical solutions. Therefore, researchers particularly esteem the mapping scheme.

Here, the concrete mapping process is demonstrated which is based on the research of Masaki Aono and his co-workers. There are three basic assumptions concerning the mapping model, as listed below:

1. The cloth consists of vertical and horizontal inextensible threads;
2. There is no slippage at a crossing of a vertical thread (warp) and a horizontal thread (weft) when the cloth is deformed;
3. A thread segment between adjacent crossings is straight.

According to these three assumptions, the plain weave cloth can be regarded as a pin-jointed net system, as shown in Fig. 7.

![Fig. 7 Illustration of a pin-jointed system](image)

Then, the cloth can be represented by a two-dimensional rectangular array of fixed links, the warp and the weft, which are connected at pin points that represent the crossover points in the weave. The location of each point on the surface of the part can be calculated point by point using three conditions.

- The distance between the point calculated and the previous point in the weft direction of the fabric is equal to the given yarn spacing.
- The distance between the point calculated and the previous point in the warp direction of the fabric is equal to the given yarn spacing.
- The point coordinates must satisfy the surface equation.

From Fig. 7(c), pin-joint 3 can be generated by pin-joints 1 and 2, and $a$ and $b$ are the yarn spacing in the warp and weft directions of the fabric. Accordingly, coordinates of point 3 can be obtained by solving the following equations, where $x_i$, $y_i$ and $z_i$ are the points' coordinates and $F$ is the surface equation.

$$\begin{align*}
(x_3-x_1)^2+(y_3-y_1)^2+(z_3-z_1)^2 &= a^2 \\
(x_3-x_2)^2+(y_3-y_2)^2+(z_3-z_2)^2 &= b^2 \\
F(x_3, y_3, z_3) &= 0
\end{align*}$$

In Fig. 8, an example of simulation result using the above mapping model is given.

4 Removal of anomalous events—dart insertion method

As mentioned in Part 2 of this paper, there are so many anomalous events in other words—defects, that may be produced during sheet forming process. Some of them, not very serious, may be acceptable as far as the final composite part is concerned. Others (such as visi-
ble buckling or wrinkles), however, must be removed or avoided either in the 2D cloth design stage or in forming process. It can be noted that the shearing deformation plays the most important role as far as both of the conformability of the flat reinforcement and defects that may occur are concerned. Most of the serious defects are related to excessive shearing deformation, especially for wrinkles and buckling. Since it is basically impossible to make the flat fabric "shear free" (This means that the fabric can be sheared to any degree as needed. As far as a plain weave cloth is concerned, this implies that the angle between the central lines of warps and wefts can freely vary from 0° to 180°), anomalous events must occur when the flat cloth undergoes an excessive shearing deformation. That is to say, to a great degree, the anomalous events are unavoidable. Then how to remove the defects produced in sheet forming will bear great practical significance.

![Mold geometry used for experimental verification](image1)

![Simulation results](image2)

**Fig. 8** An example of simulation using pin-jointed system model [10]

Masaki Aono and his co-workers made a great contribution [9] in this respect. They developed a software that incorporates the dart insertion approach in it to tackle the anomalous events caused by excessive shearing deformation.

The inserted darts are classified into two types—stitched darts and trimmed darts, as shown in Fig. 9. With stitched darts, excessive materials are removed and the edges are stitched to produce a darting edge. With trimmed darts, excessive materials are simply removed without stitching. There are two types of trimmed darts—linear cut and polygonal cut.

Dart insertion process is illustrated in Fig. 10. First, the mapping process is made according to the model demonstrated above. Then find out the anomalous regions where darts may be inserted. Last, follow the steps listed in Fig. 10 to insert darts.

![Illustration of types of darts](image3)

**Fig. 9** Illustration of types of darts [9]

(a) Stitched darts (before and after insertions)

(b) Trimmed darts (before and after insertions)

In Fig. 11, two examples of dart insertion are given.

**5 Assessment of the conformability of sheet textile reinforcements**

Since the sheet forming is one of the most impor-
tant composite forming processes, it is necessary to develop a set of parameters as well as experimental methods to assess the conformability of sheet textile reinforcements, in which the composite designers should take great interests. Currently, these kind of parameters and experimental methods are still unavailable or have not formally come into being.

Mack and Tayler published a paper\[5\] about "fitting" in 1956, which should be the earliest literature concerning the conformability of plain weave fabric. As shown in Fig. 12, their experimental results are illustrated. It can be seen that remarkable shearing deformation occurs between the two yarn systems.

Actually, the following three aspects, at least, can be employed when considering the conformability of a sheet textile reinforcement:

1) Study the shearing properties of a flat fabric. Fabric is quite different from paper, which can form curved surfaces with double curvatures; on the contrary, paper can not. This kind of deformability of fabrics mainly concerns the shearing deformation. Therefore, the shearing properties can be used to assess the conformability of a fabric. For example, the initial shearing modulus, energy of shearing deformation as well as the shear recovery rate can be obtained from the shearing hysteresis curve of a fabric, and these parameters can be taken as assessing criteria. Fig. 13 shows an example of shearing hysteresis curve of a woven fabric which is obtained by Kawabata’s Evaluation System.

2) Study the drape properties of flat fabrics. Drape properties can be used to describe the conformability of a fabric from a more comprehensive sense. Actually, draping and forming are very much alike from each other, and draping process itself is just as same as forming process by nature, in which only the gravity of the fabric is involved, but without external forces (such as air pressure in diaphragm forming, as shown in Fig. 1). Generally, the better of the drape of a flat fabric, the better of its conformability.

3) Apply the experiment of semi-sphere pressing. This method, developed by the authors of this paper, turned out to be workable(Fig. 14). And Fig. 15 shows the outline of the deformed fabric (a multiaxial warp knitted fabric with 4 glass inserting yarn systems).

This experiment is much close to the real forming process. Not only the anomalous events (buckling or wrinkles, as shown in Fig. 15) can be observed directly, but also a pressing curve can be obtained from the computer that is attached to Instron 4466. As shown in Fig. 16, an example of pressing curve is illustrated.
as modeling of sheet forming is concerned, there are two popular approaches, one is mapping, the other is continuum mechanical method. They are not completely competitive but complementary\[2\]. The present paper prefers the mapping method due to its unique advantages as mentioned in Part 3. All anomalous events that may occur during sheet forming process are also presented. Dart insertion in 2D cloth is a feasible method to tackle some of the anomalous events (especially for wrinkles and overlaps), even though this may be at the cost of some mechanical properties of the final composite part.

With the spreading of application fields of textile composites, study of the forming of sheet textile reinforcements will deserve more and more attention as well as more and more practical significance. Currently, the research work is still in its preliminary stage, and the methodology and theory have not been well developed. Besides, the experimental approaches, to a great degree, are also not available. Common sense about the assessment of the conformability of a flat fabric has not been reached. In the near future, all the issues mentioned above should be solved. The mapping method will deserve more attention due to its cleanliness, simplicity as well as directness. The three assessing aspects as mentioned in part 5 will lay a foundation for the subsequent research work.

References:


6 Summary

This paper presents an outline of the forming of sheet textile reinforcements in which the diaphragm forming process is particularly described in detail. As far

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