THE EFFECT OF WEFT BINDER PATH LENGTH ON THE ARCHITECTURE OF MULTI-LAYER WOVEN CARBON PREFORMS

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SUMMARY: Multilayer woven preforms were manufactured from 12K carbon tows and 1K binder yarns with orthogonal weft binder. The effects of weft binder path before and after liquid moulding compaction were examined. A theoretical study analysed the effect of weft binder path length on the geometry of multi-layer woven carbon preforms. A differential warp yarn tension model was established to indicate the required warp yarn tension during weaving in order to produce a uniform weave architecture. It was found that the creation of a defined binder path length would ensure a uniform preform structure with minimum resin rich areas, and weaving with the optimal binder path length would ensure the production of a multilayer preform of acceptable quality.

KEYWORDS: weft binder, nominal binder length, minimal binder length, binder locking length, differential warp tension

INTRODUCTION

The use of fibre reinforced composite structures has been limited by their high cost of production and their poor resistance to damage. Using well developed textile technologies, such as multilayer weaving, structural preforms with three-dimensional fibre architectures may be produced [1,2]. Liquid moulding techniques may then be used to impregnate the preform with resin. These highly automated processes have the potential to produce low-cost, reliable composite structural components of complex shapes [3]. Due to the three-dimensional nature of the fibre architecture such structures are less prone to delamination and their impact resistance is significantly increased [4].

Glass and carbon fibre yarns are highly rigid and inextensible. Unlike textile fibres, these high-performance fibre yarns have to be controlled individually over their warp yarn tension during weaving. Due to the complex nature of warp and weft interaction over their interlacing points, it is difficult, but important to predict the fibre architecture in the preform.
and the composite, which will determine the mechanical behaviours of the composite. The influence of the weaving parameters upon the fibre orientation is significant, and must be quantified in order to design and manufacture successful composite structures [2].

The idealised fibre arrangements in a preform structure would provide full straightness of tows and therefore would enhance the in-plane mechanical properties of the composite. One of the commonly used three-dimensional woven architectures has a lattice of non-crimped warp and weft yarns held in place by a relatively thin binder yarn which provides through-thickness interlacing and which forms the basis of the through-thickness strength. Traditionally, these binder yarns have been warp binders. More versatility in the design of the architecture may be achieved by using weft binders. However, early preforms produced using weft binders had non-uniform architectures and resin rich zones, and this was probably due to the irregular binder path length placement across the width of the fabrics.[2]

This paper describes a preliminary study on the effect of weft binder path length on the preform architecture for an 11 layer (6 warp, 5 weft) multilayer woven preform with orthogonal weft binders. The preforms were woven from 12K carbon tows and 1K binder yarns. A theoretical analysis is presented to study the relationship between binder path length and resin rich area. A differential warp yarn tension model is also presented.

**SPECIMEN PRODUCTION**

Multilayer preforms were produced with different binder path lengths on a 16 shafts table loom. They were constructed from carbon yarn of 12k tows with six layers of warp and five layers of weft in an orthogonal woven structure. Weft binders (1k tows) were used to interlace the lattice of warps and wefts in a through-thickness and alternatively offset fashion. A schematic diagram of the generic architecture is shown on Fig. 9.

After preform manufacture, samples of the fabric were cut out and moulded into composite panels by using RTM process and RTM 6 resin. Composite thickness upon RTM was 3.2mm and Fibre Volume Fraction was 60%. Specimens were sectioned along both the binder and warp directions, and the sections were examined through an optical microscope. To examine the fibre architecture directly after weaving, the preform was wet out with epoxy resin by hand and then cured at room temperature for 24 hours without applying consolidation pressure.

**RESULTS AND DISCUSSION**

Figs. 1 and 2 are microphotographs of warp and weft sections respectively, of a composite produced with a short weft binder length.
As shown on Fig. 1, the weft binder followed a wavy path and impeded warp yarns from spreading evenly, causing resin rich zones outside the binder loop. The cross-sectional shape of a warp column became elliptical. From Fig. 2, it may be observed that weft yarns were pushed away from the binder and warp yarns were forced to crimp. The resulting weft was uneven and of low density allowing extensive resin rich regions.

Figs. 3, 4 and 5 are microphotographs of composites made from preforms with optimal weft binder length. Figs. 3 and 4 depict warp and weft sections, respectively, of the composite consolidated without compaction pressure and hence gives an indication of the preform architecture. Fig. 5 depicts a warp section of the composite consolidated under a compaction pressure of 276 kPa. Fig. 3 shows that a near ‘square shape’ binder path may be achieved which allows a uniform distribution of warp yarns and minimises the extent of resin-rich areas. As may be seen from Fig. 4 the wefts are uniform and tightly packed. Fig. 5 shows that when consolidated under compaction pressure a uniform structure with straight wefts and vertical binder yarns may be achieved.
Compressed and consolidated composite structures were shown on Fig. 5 and Fig. 6. The composite architecture in Fig. 5 was achieved with a near ‘square shape’ binder path. It demonstrated that the resin rich areas were kept to a minimum. The binder path length of this structure has an optimal length, leading to straight tows of a composite architecture with minimal resin rich areas.

Fig. 6 shows a composite structure with a slightly longer than the nominal binder path length. The sign of binder buckling occurred within the layers after consolidation, due to the extra binder path length. Fig. 7 demonstrates the longer than the nominal binder path structure without applying consolidating pressure.
The above examples indicate that there is an optimal binder path length, which is sufficient to reduce warp yarn crimping and pinching to an acceptable level and yet, is not so long as to cause instability in the preform during compaction.

**THEORETICAL APPROACHES**

The design and manufacturing objective for a multi-layer preform is to achieve a lattice of non-crimp warp and weft yarns in the preform architecture with minimum resin rich area. It has been shown that one of the keys to ensure a successful composite structure is to provide the exact binder length required to interlace with the warp and weft. It is difficult to achieve an architecture which requires a long path length for a weft binder because of the locking effect, due to yarn friction, during shed closure.

**Nominal Architecture**

The nominal architecture is described in Fig. 8. this architecture will not be achieved in practice because of yarn bunching and crimping due to the interactions among the warp, weft and binder yarns. The object of the analysis is to determine the process parameters which will lead to an architecture as close as possible to the nominal (see Fig. 5).

It consists of a multi-layer structure (six layers of warp and five layers of weft) with a rectangular shaped weft binder passing over and under two columns of warp alternatively. This geometric structure is defined as a nominal orthogonal weave structure, and the unit binder path length of the rectangular shape is defined as the nominal binder length.
As shown on Fig. 8, the nominal binder path length can be expressed as

\[ L_n = 4A + 2T \]  

where \( A \) is the width of warp yarn; \( T \) is the preform thickness; B.C.R. is binder crimping rate.

The thickness of the preform is

\[ T = 6B + 5C \]  

where \( B \) is the thickness of warp yarn; \( C \) is the thickness of weft yarn.

The Fibre Volume Fraction is

\[ F.V.F. = \frac{V_f}{V_T} \]  

where \( \rho \) is the fibre density; \( W_f \) is the unit weight of fibre yarn.

**Warp Yarn Pinching and Minimal Binder Path Length**

When a binder path length was shorter than the nominal binder length, the binder path could no longer be kept rectangular. As shown on Fig. 1 and Fig. 9, the binder would force the warp yarn to change its cross-sectional shape. It was assumed that 1) the two neighbouring columns of warp yarns were on the same horizontal axis plane; 2) the warp ends were not crimped under the tension of weft binders. With the cross-sectional area of warp and weft yarn being constant, the binder path would decrease to a minimal length in order to maintain its structural stability. A minimal binder path is defined as the binder path length which is shorter than the nominal length, but not short enough to cause warp yarn to crimp.
The wavy minimal binder path (see Fig. 1) may be modelled as a series of ellipses and the path length may be expressed as:

$$L_{\text{min}} = 2\pi \sqrt{\frac{A^2 + (T'/2)^2}{2}}$$  \hspace{1cm} (4)

where $T'$ is the fabric thickness when the binder is in an elliptical path.

The cross sectional area of the confined warp column is constant:

$$S_a = \frac{1}{4} \pi A T'/2 = T/2 * A$$

This leads to an expression for the preform thickness:

$$T/T' = \pi/4$$  \hspace{1cm} (5)

If $A = 2.5$ mm, $T = 3.2$ mm; then, $T' = 4.1$ mm; $L_n = 16.4$ mm and; $L_{\text{min}} = 14.3$ mm.

This indicates that a shorter binder length will lead to a thicker fabrics.

As shown earlier, the warp tows would be forced to bunch-up when the binder path length is shorter than the nominal length. For a minimal length binder, the warp yarns would be forced into an elliptical shape. If the binder length is further reduced, crimping of the warp yarns will occur and neighbouring warp columns may move vertically with respect to one-an-other.

**Resin Rich Area**

As shown on Fig. 9, the short binder path forced the warp tows to bunch-up and generated a v-shaped gap between tow warp columns. After resin infusion, this area formed a resin rich channel, which may become a microcrack initiation site [2]. The cross-sectional area of this resin rich channel is given by:

$$\text{Resin rich area} = A T' - 2S_a$$  \hspace{1cm} (6)

Using the data given by the above example, the resin rich area would be 2.2 mm$^2$. 
Warp Yarn Crimping

When the binder is further shortened beyond the minimal length, the top and bottom layers of warp would be forced to crimp in order to accommodate the reduced binder length. The resulting decrease of the crimp rate of the binder would be at the expense of the crimp generated in the warps.

Following Lord 1980 [5]; assuming the warp yarn being forced into a sinusoidal path and ignoring yarn stiffness and the frictional effect between the binder and the warps, the relationship between the tensions in the warps, binders and their crimp amplitude may be described as

\[
\frac{A_b}{A_w} \approx \left( \frac{\lambda_b}{\lambda_w} \right) \times \left( \frac{t_w}{t_b} \right)
\]

where \(A_b\) is the crimp amplitude of the binder; \(A_w\) is the crimp amplitude of the warps; \(\lambda_b\) is the pitch of the binder; \(\lambda_w\) is the pitch of the warp yarns; \(t_b\) is the tension in the binder and \(t_w\) is the tension in the warps.

From Eqn. (7) it may be seen that the crimp amplitude in the warp is dictated by the tension and spacing of the yarns. If the binder is kept at low tension (i.e. longer path length) whilst the tension in the warp direction is high, then there will be very little crimp in the warp and considerable crimp in the binder. Although the warp has bending stiffness which is much higher than that of the binder, and will consequently resist crimping, this effect may be neglected because the friction between the binder and warp yarns induces high binder tension during shed closure.

Weft Density

Once warp crimping occurs there is a severe restriction on the extent to which the weft yarns may be beat into the fabric. The resulting weft density is consequently lower and the distribution of warp tows is uneven leading to resin rich regions. An extreme example of this may be seen in Fig. 2.

Fibre Volume Fraction

From Eqn (3), F.V.F can be further expressed as:

\[
F.V.F. = \frac{V_I}{V_T} = \left[ \left( D_w * N_w + D_t * N_t \right) * Y_y / \rho \right] / T
\]

where \(D_w\) is warp density; \(N_w\) is the number of warp layers; \(D_t\) is weft density; \(N_t\) is the number of weft layers; \(Y_y\) is the warp/weft yarn linear density and \(Y_b\) is the binder yarn linear density.

Binder Buckling

Longer binder path length would generate binder buckling during preform compaction as may be seen in Fig. 6. This will reduce the effectiveness of the binders in providing delamination resistance.
DIFFERENTIAL WARP TENSION SET-UP APPROACH

In a weaving machine, a proper tension control over warp yarn may produce the required binder path. As shown on Fig. 10, the shed closure of warp yarns forces the weft binder to increase its path length (crimp). However, the friction between the binder and warp yarns would impede such an increment. The frictional force on the weft binder is of the greatest in the central region and gradually decreases toward the edges according to Amonton’s law of friction: $T_2 = T_1 e^{\mu \theta}$ assuming the binder being perfectly flexible. This indicates that a differential warp tension set-up on the loom is crucial to achieve an uniform architecture across the width of the fabric. The higher the tension in the warps, the longer the binder path length may be achieved. However, due to the practical restriction of the shedding height, the width of the fabric and also the adverse effect of higher tension on the quality of warp yarns (i.e. fibre damage), there exist a maximum achievable unit binder length. This specific binder length may be defined as a “locking length”. If the locking length is longer than the minimal binder length, then warp yarn crimp may not occur, and vice versa.

![Fig.10: A schematic diagram of binder/warp yarn interaction](image)

CONCLUSION

Multilayer woven carbon preforms have been produced. The fibre architecture examination and theoretical analysis indicated that the creation of a defined binder path length will ensure an uniform preform structure with minimum resin rich areas and full straightness of warp yarns. The high tension induced in the binder due to the shed closure and the friction between the binder and warp yarns may cause bunching of the warp yarns within the binder loops which would lead to undesirable resin-rich channels in the resulting composite. The binder might further cause the warp yarns to crimp and so reduce the mechanical properties in the composite.

An optimal binder path length can be used in the production of an acceptable quality of multilayer preforms. It was around the nominal binder path length, and not less than the minimal length, which was sufficiently long to reduce crimping and pinching to an acceptable level and yet, was not too long so as to cause instability in the preform during compaction. Differential warp yarn tension set-up across the width of the fabric would ensure the realisation of such an uniform path length. Due to the practical limitation on warp tension, there is a restriction on the control of binder path length, the binder “locking length” defines the basic ability of a loom to produce a multilayer preform with acceptable quality.
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REFERENCES


