LIMITATIONS OF FIBRE PLACEMENT TECHNIQUES FOR VARIABLE ANGLE TOW COMPOSITES AND THEIR PROCESS-INDUCED DEFECTS

B.C. Kim[1], K. Hazra[1], P. Weaver[1], K. Potter[1]*
[1] ACCIS (Advanced Composite Centre for Innovation and Science), University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, UK
* Corresponding author (K.Potter@bristol.ac.uk)

1 Introduction

The structural efficiency of composite panels with tailored fibre paths has attracted great attention in recent decades. It was proved analytically that tailoring of the in-plane stiffness of composite laminates can improve the buckling and post-buckling characteristics by redistributing the applied loads **[1-3]**. Experimental research demonstrated its superior stiffness and buckling characteristic as well **[4-5]**. Currently, there is significant interest in developing methodologies to design optimal fibre orientations for maximizing the structural efficiency **[6-8]**.

The fibre placement technique is the core technology underpinning variable stiffness composites. Typical analytical research does not model its underlying manufacturing limitations sufficiently. Some researchers have tried to apply the process-induced defects such as the tow overlap and tow drop to the finite element analysis **[9-11]**. However, significant defects, to be considered in the analysis, still remain.

In this paper, realistic limitations of the current fibre placement techniques and their process-induced defects are investigated.

2 Limitations of conventional techniques

The automated fibre placement techniques can be distinguished by the status of fibre. Pre-impregnated fibre bundles, i.e. towpreg or slittape, have widely been used previously **[1]**. Recently some researchers have attempted to use the dry fibre bundle to overcome the disadvantages of the tape placement and increase the design flexibility of the variable stiffness composite **[5]**.

2.1 Tow deformation characteristics

Both techniques use in-plane bending deformation of the tow element to achieve a curved tow path, as shown in Table 1. Even if the tow element is a perfect rectangle, the inner edge of the curved path is necessarily buckled. When the imperfections of the tow element such as the difference of the edge lengths and the width variation are introduced additionally, the distortion of the tow element becomes worse. In principle, the defects induced by the in-plane bending deformation such as local buckling and thickness change are unavoidable. It has, therefore, been recommended to keep a minimum curvature of the tow path to reduce these local defects.

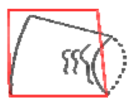
Case	Deformed shape	Defects
Perfect condition		Local buckling Thickening Thinning
Width variation		Local buckling Thickening Thinning
Tension variation		Local bending Thinning
Feed length variation		Local buckling Thickening Thinning

Table 1. Tow deformation characteristics

2.2 Tow path definition and its limitation

In defining tow paths, the parallel and shifted methods have been used **[10, 11]**, as shown in Fig. 1. The former is the most obvious method mathematically, which implies no gaps between each paths and leads to a constant ply thickness. However, it has not been widely used because it is not easy to manufacture the tow-steered plate with a large stiffness by using it.

The shifted method is a more efficient way to make the variable-stiffness plate. However, the width of a tow is dependent on the applicator head that has a finite width. Rotation of the head leads to a realignment of fibres within a tow parallel to the centerline of the tow path, which creates overlapped regions and gaps between two adjacent tows **[10, 11]**. Though several methods such as staggering, tow overlap and tow drop techniques have been developed to solve this problem **[10, 11]**, there still remain some tow path configurations where the resin rich areas are not covered.

In terms of the fibre trajectory, the conventional shifting method is a sort of mixed method because paths of each single fibre within a tow are always parallel due to the head rotation, which inevitably requires tow gap or overlap region to fill the space between two tow paths, as shown in Fig. 2. As the curvature of the tow path increases, the area of tow gap or overlap increases. If the fibre orientation needs to be straight in some area as shown in Fig. 1 (a), every tow in that area should be overlapped to cover the tow gap around the curved path. Otherwise, localized large tow gap area can be created. This is the worst case which can happen when the conventional shifting method is used with the conventional machine using a rotational head motion.

3 Process-induced defects

In addition to the local fibre buckling induced by in-plane bending deformation, defects caused by the process characteristics of each tow placement method also exist.

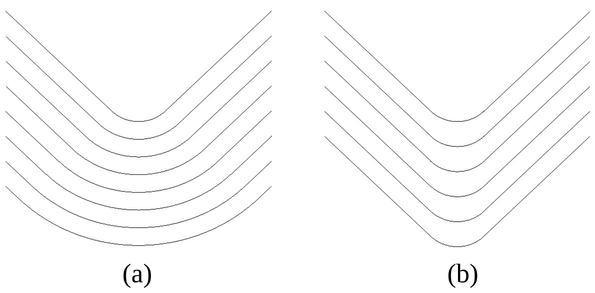


Fig. 1. Definition of tow paths: (a) parallel method, (b) shifting method.

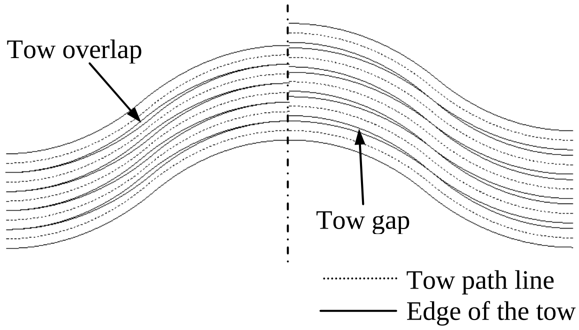


Fig. 2. Comparison between fibre and tow paths following the shifting method.

3.1 Tape placement

Generally the automatic fibre placement (AFP) machine uses the pre-impregnated tow tape which is called towpreg or slittape. In the case of the tow placement process using tapes, since the width of the pre-impregnated tow bundle cannot be easily changed, tow drop and overlap techniques should be applied to prevent a significant thickness change and cover the resin rich area. Tow drop introduces many fibre discontinuities which may affect the mechanical performance. In addition, when the cut tape laid by the compaction roller loses tension, unwanted geodesic tow paths can be produced **[13]**.

In many cases, the AFP machine lays multiple tows simultaneously to improve the productivity **[9, 13]**. As illustrated in Fig. 3, the main disadvantage of this method is that the mismatch between designed and real fibre paths increases as the width of a single tow and the number of tows laid at the same time increase. This always requires the sacrifice of uniformity of the fibre orientation, some defects such as tow gap and overlap and irregularity of the thickness distribution, which consequently causes another mismatch with the analytical solution. Because of this non-uniformity of the fibre orientation and thickness distribution, a complex program creating finite elements which can take all imperfection into account is required for accurate structural analysis **[9-11]**. All these problems are caused by the mixed method which has been called a 'shifting method' previously.

The negative effects of these defects were already proved through experiments. It was reported that the structural strength of the variable stiffness panel with tow drop was considerably lower than that with tow overlap although the specific structural stiffnesses of them were similar **[4]**. It was also revealed that the in-plane shear strength decreased significantly when the tow overlap exists along the perpendicular direction to the loading direction **[14]**.

3.2 Dry tow placement

Some researchers have attempted to overcome the disadvantages of the tape placement technique by using dry tow because it is much easier to bend or sheared **[5, 15]**. The advantage of this method is that the finished preform can be kept at room temperature with unlimited shelf life. Also, dry tows and resin purchased individually are significantly cheaper than the towpreg or slittape produced. Although the dry tow placement method can also introduce a mismatch between designed and real fibre paths as illustrated in Fig. 2, it can be diluted by the rearrangement of fibres within the dry tow. However, the improved design flexibility causes other types of process-induced defects which are quite different from those of the tape placement techniques besides local defects induced by the in-plane bending deformation previously mentioned.
Because dry tow does not have tackiness, it can't be laid without a proper fixing method. The most widely used method is an embroidery technique in which the numerically controlled stitching head stitches tows with any type of thread to hold the preform shape together onto a backup fabric **[5, 15]**. Additional backup felt is generally used to reinforce the backup fabric. And, resin film infusion (RFI) is used to impregnate the preform.

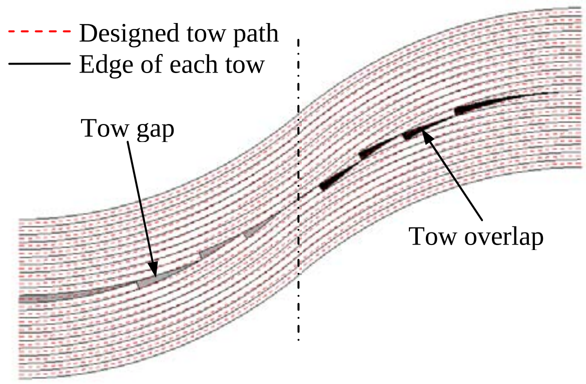


Fig. 3. Multiple tow laying using the conventional AFP machine: Tow drop (left), Tow overlap (right).

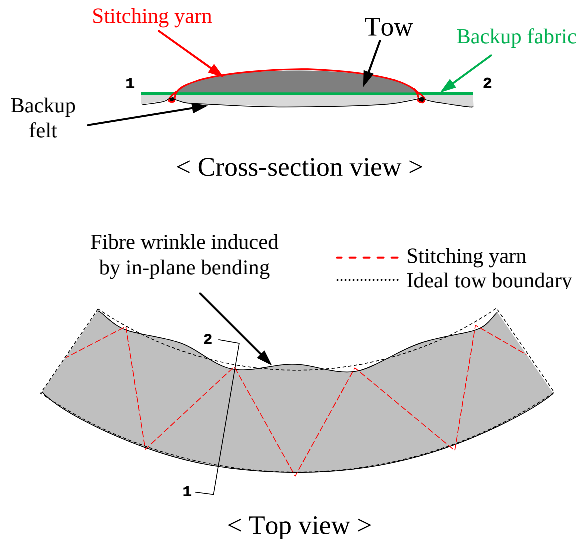


Fig. 4. Ideal tow deformation during the embroidery process.

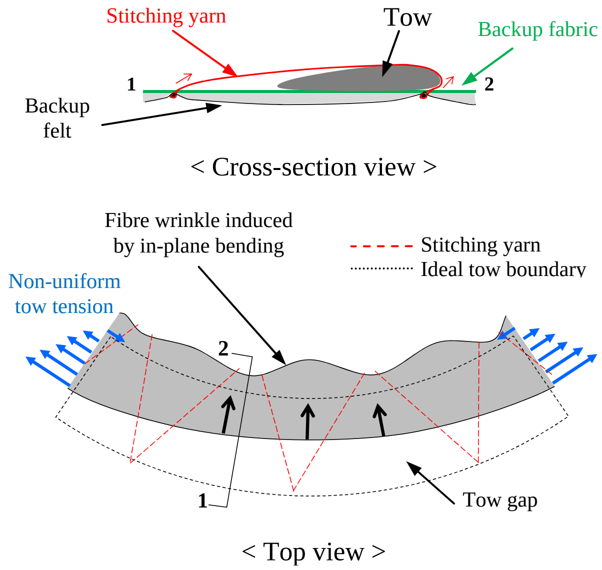


Fig. 5. Real tow deformation during the embroidery process.

Fig. 4 shows the ideal tow deformation when assuming the tow fixing is perfect. Even for this case, local buckling of the fibres inside the curved tow path is induced by the in-plane bending deformation. However, the real deformation of the tow introduces more complex types of process-induced defects, as shown in Fig. 5. Because the fabric may be wrinkled if the tension of the stitching yarn is too high and the softness of the backup felt allows the stitching yarn

to move upward, the laid tows cannot be fixed firmly on the substrate. Furthermore, the machine head without a tow feeding mechanism needs to pull the tow by applying some tension. This tension force makes the laid tow move toward the origin of the curvature under the influence of the looseness of the stitching yarn, which increases the buckling intensity of the fibres inside the tow path and significantly enlarges tow gap area outside the tow path respectively. Fig. 6 shows the preform with shifted tow paths shown in Fig. 1 (b) which was made by the embroidery machine. The indicated tow gap is a combined effect of a mixed tow laying method explained in the previous section and the tow deformation during the embroidery process.
In Fig. 6, additional factors causing the process-induced defects can be observed easily. The marks show the stitching points along the outer tow boundary of the curved path. Although the head position is controlled numerically, the stitching points are irregular. The inherent characteristic of the embroidery machine is that the rotation angle and in-plane position of the laid tow are separately controlled by the head unit located at the upper part of the machine and the table moving in zigzag pattern. As the process speed increases, the stitching accuracy decreases due to the inertia and vibration of the table, which causes irregular stitching.
Although AFP machines laying dry tows with thermoset or thermoplastic binding material have being developed recently, few of these cutting edge machines have been revealed **[16]**. However, they cannot remove the process-induced defects as long as they use the same tow laying method with the conventional AFP machines.

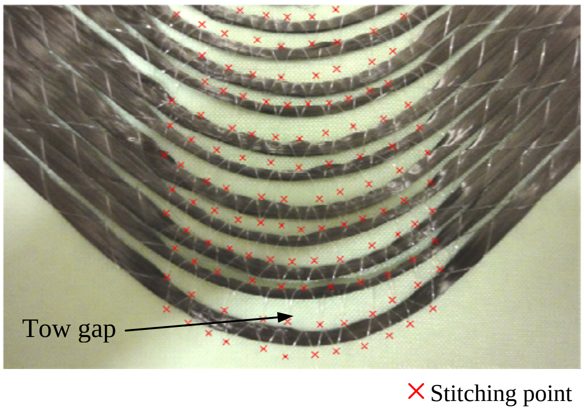


Fig. 6. Preform made by embroidery machine.

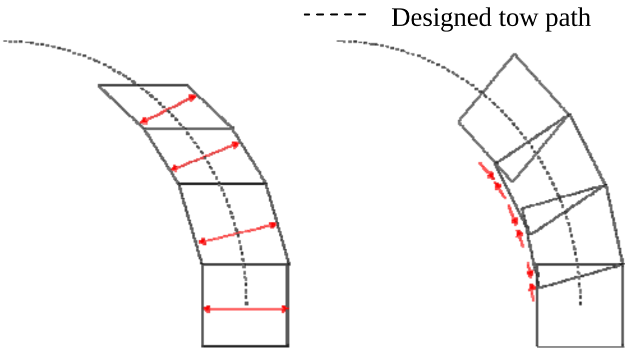
4 Future of the automatic fibre placement

As discussed in the previous sections, the conventional method cannot realize both the perfect shifting and parallel methods in terms of the real fibre orientation because it is a type of mixed method. In this section, a method which can make fibre orientations shifted perfectly will be discussed. In the conventional techniques, defects were mainly caused by in-plane bending deformation of the tow. If the idea that the tow should be bent can discarded, a novel way can be derived, which is the method using the in-plane shear deformation of the tow.
Fig. 7 shows the comparison between the new and conventional tow laying method. As shown in Fig. 7 (a), the local fibre buckling can be prevented by shearing the tow continuously. Also, since all fibres are shifted along one shifting direction and exactly follow the designed tow path, the process-induced defects such as tow gap and overlap can also be avoided. By changing the most fundamental principle, most process-induced defects of the conventional techniques can be removed. Another great advantage of this method is that there is no limitation of the curvature of the tow path. This can improve design flexibility enormously.
The only concern is the thickness change. Since each fibre cannot be sheared and the width of the tow along the parallel direction to the fibre cross-section needs to be smaller, the fibres in a tow should be rearranged according to the shear angle. If the pre-impregnated tape is used for this method, it may be buckled with defects because of the matrix with high viscosity. In contrast, the fibres in a dry tow can be easily rearranged because each fibre is weakly bonded together with a small amount of sizing material such as B-staged epoxy and polyurethane. Fig. 8 (a) shows the sheared dry tow. Some fibres tend to protrude out of the tow surface since the tow width along the parallel direction of the fibre cross-section should be decreased and there is no constraint on the outer surface. However, it was found that fibres can be rearranged well after applying some compressive load on the tow surface, as shown in Fig. 8 (b). Although the whole thickness of the tow is increased, all other defects can be prevented. Even the thickness uniformity of this method is much superior to that of the conventional methods which require tow drop, tow overlap and

staggering to dilute the irregularity of the thickness distribution.

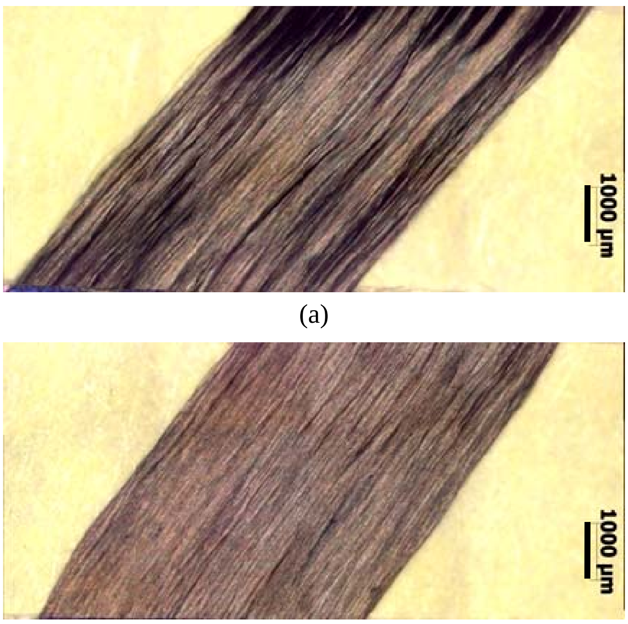
5 Conclusions

In this paper, various limitations of the current fibre placement techniques were broadly investigated as well as their process-induced defects. In light of these defects, potential future development of the fibre placement techniques was discussed.



(a) (b)

Fig. 7. Tow laying method using: (a) shear deformation, (b) in-plane bending deformation.



(a)

(b)

Fig. 8. Fibre rearrangement: (a) before compaction, (b) after compaction.

Through the technical review on the conventional wet and dry tow placement techniques, it was found that the key factor causing all process-induced defects was the in-plane bending deformation of the tow. Especially in the shifting method, all defects such as tow gap, tow overlap, fibre misalignment and irregular thickness distribution were come from this fundamental principle of the conventional method. Also, it significantly decreased design flexibility by limiting the minimum radius of curvature of each tow path.

As a novel way of solving these problems, a method using the in-plane shear deformation of the tow can be used with dry tows. For the shifting method which has been mainly used for a variable stiffness composite panel, this method can make every fibre trajectory follow the designed tow path without causing all the defects mentioned above. Although the thickness change according to the shear deformation is inevitable, the thickness uniformity can be much superior to that of the conventional method using tow drop, tow overlap and staggering to dilute the irregularity of the thickness distribution. Consequently, this continuous shearing method using a dry tow will be a main stream of the future composite manufacturing technology.

References

[1] Z. Gürdal and R. Olmedo "Composite laminates with spatially varying fiber orientations: variable stiffness panel concept". *Proceedings of the AIAA/ASME/ ASCE/AHS/ASC 33rd structures, structural dynamics and materials conference*, Dallas, TX, Vol. 2, AIAA 92-2472, pp 798-808, 1992.

[2] Z. Gürdal and R. Olmedo "In-plane response of laminates with spatially varying fiber orientations: variable stiffness concept". *AIAA Journal*, Vol. 31, No. 4, pp 751-8, 1993.

[3] R. Olmedo and Z. Gürdal "Buckling response of laminates with spatially varying fiber orientations". *Proceedings of the AIAA/ASME/ASCE/AHS/ASC 34th structures, structural dynamics and materials conference*, La Jola, CA, Vol. 1, AIAA 93-1567, pp 2261-9, 1993.

[4] K. C. Wu, Z. Gürdal and J. H. Starnes "Structural response of compression-loaded tow–placed, variable stiffness panels". *Proceedings of the AIAA/ASME/ ASCE/AHS/ASC 43rd structures, structural dynamics and materials conference*, Denver, CO, AIAA 2002-1512, 2002.

[5] P. Weaver, K. Potter, K. Hazra, M. Saverymuthapulle and M. Hawthorne “Buckling of variable angle tow plates: from concept to experiment”. *Proceedings of the AIAA/ASME/ ASCE/AHS/ASC 17th structures, structural dynamics and materials conference*, Palm Springs, CA, AIAA 2009-2509, 2009.

[6] G. Duvaut, G. Terrel, F. Léné and V. E. Verijenko “Optimization of fiber reinforced composites”. *Composite Structures*, Vol. 48, pp 83-9, 2000.

[7] S. Setoodeh, M. Abdalla and Z. Gürdal “Design of variable-stiffness laminates using lamination parameters”. *Composites Part B: Engineering*, Vol. 37, pp 301-9, 2006.

[8] S. Setoodeh, M. Abdalla, I. Samuel and Z. Gürdal “Design of variable-stiffness composite panels for maximum buckling load”. *Composite Structures*, Vol. 87, pp 109-17, 2009.

[9] A. Blom, C. Lopes, P. Kromwijk, Z. Gürdal and P. Camanho “A theoretical model to study the influence of tow-drop areas on the stiffness and strength of variable-stiffness laminates”. *Journal of Composite Materials*, Vol. 43, No. 5, pp 403-25, 2009.

[10] B. Tatting and Z. Gürdal “Automated finite element analysis of elastically-tailored plates”. *NASA Scientfic and Technical Information*, NASA/CR-2003-212679, 2003.

[11] P. Langley “Finite element modeling of tow-placed variable-stiffness composite laminates”. *Master’s thesis of Virginia Polytechnic Institute and State University*, 1999.

[12] Z. Gürdal, B. Tatting and K. Wu “Tow-placement technology and fabrication issues for laminated composite structures”. *Proceedings of the AIAA/ ASME/ASCE/AHS/ASC 46th structures, structural dynamics and materials conference*, Austin, TX, AIAA 2005-2017, 2005.

[13] A. Blom, P. Stickler and Z. Gürdal “Design and manufacture of a variable-stiffness cylindrical shell”. *Proceedings of the SAMPE Europe 30th international conference*, Paris, 1-8, 2009.

[14] K. Croft, L. Lessard, D. Pasini, M. Hojjati, J. Chen and A. Yousefpour “Experimental study of the effect of automated fiber placement induced defects on performance of composite laminates”. *Composite: Part A*, Vol. 42, pp 484-91, 2011.

[15] D. Feltin and K. Gliesche “Preforms for composite parts made by tailored fibre placement”. *Proceedings of ICCM-11*, Gold Coast, Australia, V-17-26, 1997.

[16] “Dry fiber placement – process for the future”. *CTC Newsletter*, Composite Technology Center Strade, 2011. (http://ctc-gmbh.com/das-ctc/newletter/)