Composites Research
Vol. 28, No. 3, 136-141 (2015)
DOI: http://dx.doi.org/10.7234/composres.2015.28.3.136
ISSN 2288-2103(Print), ISSN 2288-2111(Online)

Paper

Stitching Effect on Flexural and Interlaminar Properties of MWK Textile Composites

Joon-Hyung Byun*†, Yi-Qi Wang*, Moon-Kwang Um*, Sang-Kwan Lee*, Jung-Il Song, Byung-Sun Kim***

ABSTRACT: The stitching process has been widely utilized for the improvement of through-thickness property of the conventional laminated composites. This paper reports the effects of stitching on the flexural and interlaminar shear properties of multi-axial warp knitted (MWK) composites in order to identify the mechanical property improvements. In order to minimize the geometric uncertainties associated with the stacking pattern of fabrics, the regular lay-up was considered in the examination of the stitching effect. The key parameters are as follows: the stitch spacings, the stitching types, the stitching location, and the location of compression fixture nose. These parameters have little effect on the flexural and interlaminar shear properties, except for the case of stitching location. However, the geometry variations caused by the stitching resulted in minor changes to the mechanical properties consistently. Stitching on the 0^o fibers showed the lowest flexural strength and modulus (12% reduction for both properties). The stitch spacing of 5 mm resulted in 8% reduction for the case of interlaminar strength compared with that of 10 mm spacing.

Key Words: Stitching, MWK (Multi-axial Warp Knit), Flexure, Interlaminar, Stitching parameter, Regular stacking

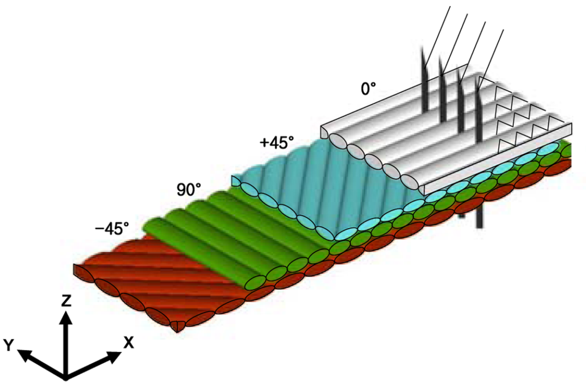
1. INTRODUCTION

MWK (Multi-axial Warp Knit) reinforcements consist of multi-directional fiber bundles held together by stitches in the thickness direction of the fabric as shown in Fig. 1(a). The major advantages of this textile are the straightness of fiber bundles, the possible incorporation of nonwoven fabrics, and elimination of ply-by-ply lamination. Because this type of textile doesn't involve a yarn crimp which can be seen in woven textile, MWK is also called non-crimp fabric (NCF) [1]. Especially, those MWK composites are rapidly and widely applied in the automobiles, aircraft, wind turbine blades and some other complex structural components [2-4]. Although the whole layers of MWK are bound together by knitting yarns, the reinforcement in the thickness direction doesn't effective when they are used in composites. This is due to that polyester or polyethylene fibers are usually utilized for knitting yarns. Owing to the development of processing technology and introduction of new type of reinforcements, composites have been applied to larger structures such as boats and bridges. Structural design in these areas requires thicker sections and higher performance such as strength and damage tolerances. Since laminated composites have inherent weakness of delamination, it is crucial to develop three-dimensional preforms by providing additional reinforcements in the thickness direction [5]. One of the most effective ways of delamination suppression is the stitching of several layers of fabrics.

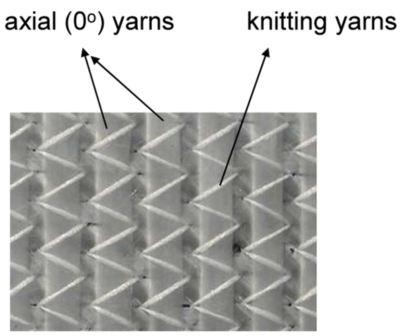
Many efforts have been carried out on stitched textile composites. Due to the large number of factors, including the preform types (prepregs, various types of fabrics), the stitching parameters (stitching density, stitching type, yarns and needle diameters, yarn tension, etc), and the fabrication methods for composites (autoclave, RTM, RFI, etc), many contrasting results have been reported regarding the effect of stitching on the mechanical properties and damage propagations [6-12]. Beier *et al.* [6,7] have comparatively evaluated the influence of innovative thermoplastic stitching yarns in NCF composites. They found that polyamide or phenoxy clearly lead to an

Received 18 June 2015, received in revised form 25 June 2015, accepted 29 June 2015

*Composites Research Division, Korea Institute of Materials Science
*†Composites Research Division, Korea Institute of Materials Science, Corresponding author (E-mail: bjh1673@kims.re.kr)
**Department of Mechanical Engineering, Changwon National University



(a)



(b)

Fig. 1. Multi-axial warp knit: (a) fabrication schematic; (b) fabric surface

improved mechanical composite performance as compared to those achieved with a standard polyester yarn. And yarn parameters such as linear density as well as the base thermoplastic material both influence the microstructure of the composite and the resulting overall properties.

Tan *et al.* [8,9] further experimentally studied the effects of stitch density and stitch thread thickness on low velocity impact damage and compression after impact strength of stitched composites. It has been found out that both stitch density and stitch thread thickness have considerable effect on the damage response, mechanisms and behavior of stitched composites due to out-of-plane impact loading. They also investigated the damage progression and failure characteristics of stitched composites under out-of-plane loading. The damage initiation occurs at a lower load at the resin-rich regions which act as crack initiation sites. During the damage propagation, stitching becomes highly effective in suppressing delamination growth, and the rate of delamination growth being inversely related to stitch density. The final failure load increases with increasing stitch fiber volume fraction [10]. Finite element analysis has been applied for understanding influences of the stitching on the mechanical behavior of carbon NCF composites [11,12].

Moreover, depending upon the fabric architecture such as the size of unit cell, the gap between yarns or tows, and the penetration location of needles, the stitched composites may give a wide variation of mechanical properties. Stitching considerably increases the capability of plastic deformation during crack propagation and extra energy absorption is gained through crack bridging mechanism of sewing thread breakage and pullout [13]. Asp *et al.* [14] found the strength and stiffness is insensitive to the stitch pattern for tensile and compressive loading, respectively, by considering stitch style, gauge and length. In the case of MWK fabrics, the gaps between 0^o yarns may produce resin rich area as shown in Fig. 1(b). Depending upon the relative location of 0^o yarns in the lay up process, stacking pattern can be in-phase (regular) or random arrangement. In the analytic study of fiber tow phase angles of adjacent layers on the longitudinal modulus of plain woven composites, a minimum value occurred when the adjacent fiber tows were in-phase (anti-symmetric lay-ups), while it becomes a maximum when the fiber tows are in out-of-phase (symmetric lay-ups) [15]. The maximum percentage difference of the moduli was reported as 39%. Experimental results of plain woven AS4/vinylester composites indicated that the longitudinal modulus of out-of-phase lay-up is 19% higher than that of in-phase lay-ups [16]. Among various parameters, the most uncertain one is the stacking pattern of the fabric layers. Thus, it will be meaningless to examine the improvement of mechanical properties without consideration of the fabric stacking pattern. In this study, various stitching parameters have been examined to identify their effectiveness on the flexural and interlaminar properties of MWK composites. More emphasis has been placed in the minimization of the geometric uncertainties associated with stacking pattern of MWK fabrics. By varying stitching parameters with fixed stacking pattern, the stitching effects on the mechanical properties will be examined precisely.

2. EXPERIMENTAL

2.1 Multi-axial Warp Knits

For the reinforcements, E-glass MWK textiles with layer sequence of [0/-45/90/45] have been used. Another layer sequence of [0/45/90/-45] has also been used together for symmetry construction of laminates. In order to differentiate the unit layer with the whole layer of MWK textiles, unit layer is termed as a 'layer', and the set of layers as a 'blanket' [1]. In this type of fiber arrangement, the width of 45^o yarn is smaller than that of 0^o yarn for the purpose of knitting. However, the content of yarns for 0^o, ±45^o, and 90^o directions are similar for providing quasi-isotropic property. The areal weight of MWK textiles in this study is 847 g/m^2 approximately, and areal weight of individual layer of 0^o, ±45^o, and 90^o are 212 g/m^2, 212 g/m^2, and 203 g/m^2, respectively. The areal weight of stitch yarns is 8 g/m^2. It is also noted that there exists a gap between planar yarns due to the penetration of knitting yarn, and this may cause resin pocket area when composites are fabricated.

2.2 Sample Preparation and Test Methods

In order to examine the property variation of stitched composites, the stacking regularity of MWK and the stitching parameters were considered. All sample panels were fabricated by stacking five blankets of [0/-45/90/45] and [0/45/90/-45], symmetrically. Thus, the stacking sequence of the sample was $[0/-45/90/45]_{5s}$. Fig. 2(a) and (b) show the stitch threads on the cross-section of plain lock stitched composites. It can be seen that two threads supplied from a needle and a bobbin meet in the middle of the perform thickness. Due to the excessive tension in the thread, the larger area of resin pocket exists on the sample surface. Fig. 2(b) shows the surface of the stitched sample. There exists resin area around the stitch threads caused by the penetration of needles. The separation of yarns can be enlarged if larger diameter of needle is used.

Depending upon the relative location of 0° fiber bundles from layer to layer, the regular stack and the random stack can be defined as shown in Fig. 3. In Figs. 3-5, only four blankets of symmetric arrangement were shown for clarity. The patterns of yarn section indicate the different orientations of yarns in each layer. Three parameters for stitching process have been considered: stitch spacing, types, and location. The stitching pitch was fixed as 5 mm, and the width between the stitch lines was varied as 5 mm and 10 mm. The twisted Kevlar 29 fiber was used for the stitching thread. The stitching direction was fixed in the 0° fiber direction. The stitching type can be classified as the plain lock stitch, where loops are in the middle of thickness, and the modified lock stitch, where the loop locates on the surface as shown in Figs. 4(a) and (b). Another variation of the stitch can be whether it locates on the 0° fiber bundles or on between them, as shown in Fig. 5. Table 1 summarizes the cases of stitching parameters considered in

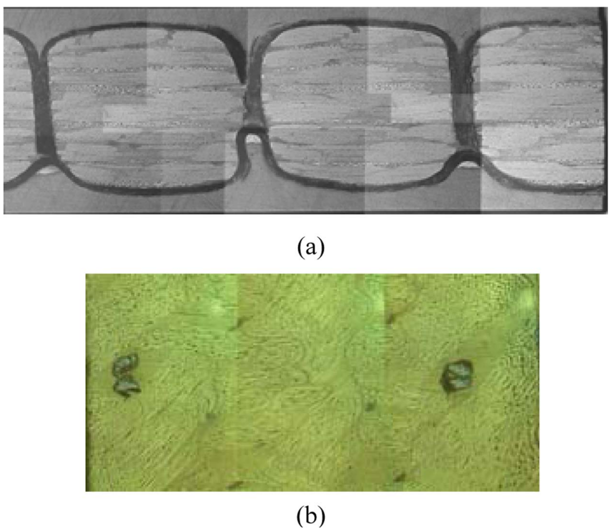


Fig. 2. Microstructures of stitched composites: (a) section along the 0° fiber direction with stitching threads passing in z-x plane; (b) sample surface with stitching threads penetrating in the thickness direction

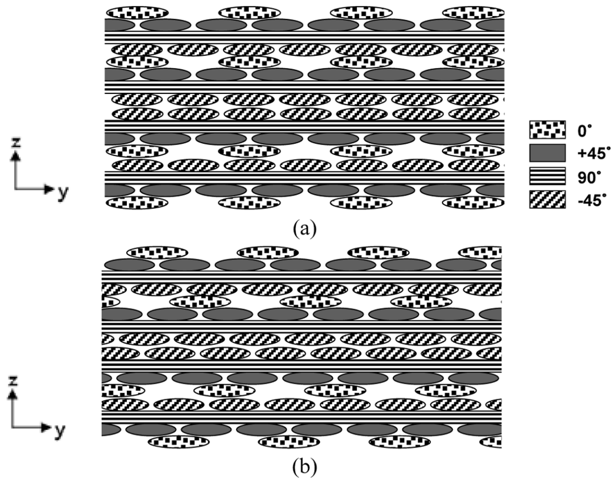


Fig. 3. Stacking types shown in y-z plane: (a) regular stack; (b) random stack

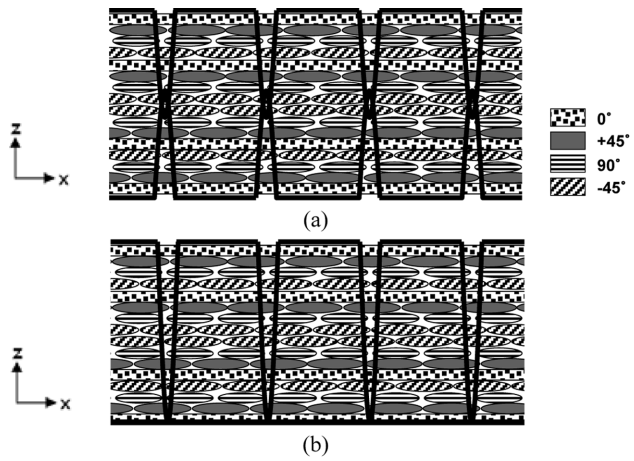


Fig. 4. Stitching types shown in z-x plane: (a) plain lock stitching; (b) modified lock stitching

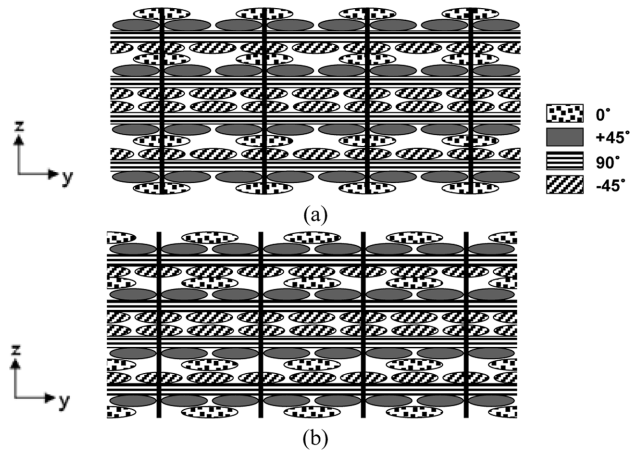


Fig. 5. Stitching locations in y-z plane: (a) on 0° fiber bundles; (b) between 0° fiber bundles

Table 1. Cases of stitching parameters

Case	RE05	RE10	RE10-M	RE10-A	RE10-H
Stitch spacing, mm (axial, lateral)	5, 10	10, 10			
Stitch type	Plain lock		Modified lock	Plain lock	
Stitch location	Between axial (0°) yarns			Axial yarns	Between axial yarns
Loading point	Between stitch holes				On stitch holes

this study. After carrying out the stitching according to various parameters, composite panels were fabricated by RTM process. As a baseline material, un-stitched samples were also prepared. The resin was epoxy for all composite panels.

To identify the effects of stitching on composites properties, flexural and interlaminar shear tests were conducted based on the specifications of ASTM D790 and ASTM D2344. The cross head speeds for each test were 2.6 mm/min and 1 mm/min, respectively.

3. RESULTS

Table 2 is the summary of flexural and interlaminar test results, respectively. Numbers in the parentheses are the standard deviations. The coefficients of variation (COV) of all data except for the case of modified lock stitching (RE10-M) were less than 5%, indicating the data deviation is very small. The modified lock stitching involves proper adjustment of tension of threads that are supplied form bobbin and needle. Carrying out modified lock stitching in this study, however, tension adjustment was not always consistent, and this might result in the difficulty in obtaining modified lock stitches on the whole area of the sample.

Fig. 6(a) and (b) show load-displacement curves of stitched (RE-10) and un-stitched (RE) specimens. All curves show non-linearity. Both curves of stitched and un-stitched specimen for each loading condition follow the similar trend with discrepancies in maximum load and displacement. Stitched sample showed higher flexural strength and modulus due to the reinforcing effect of stitching yarns. It is noted that direction of stitching yarn is along the specimen length. In the case of interlaminar test, shear stresses were dispersed due to the existence of stitching yarns, and sample endured to higher load.

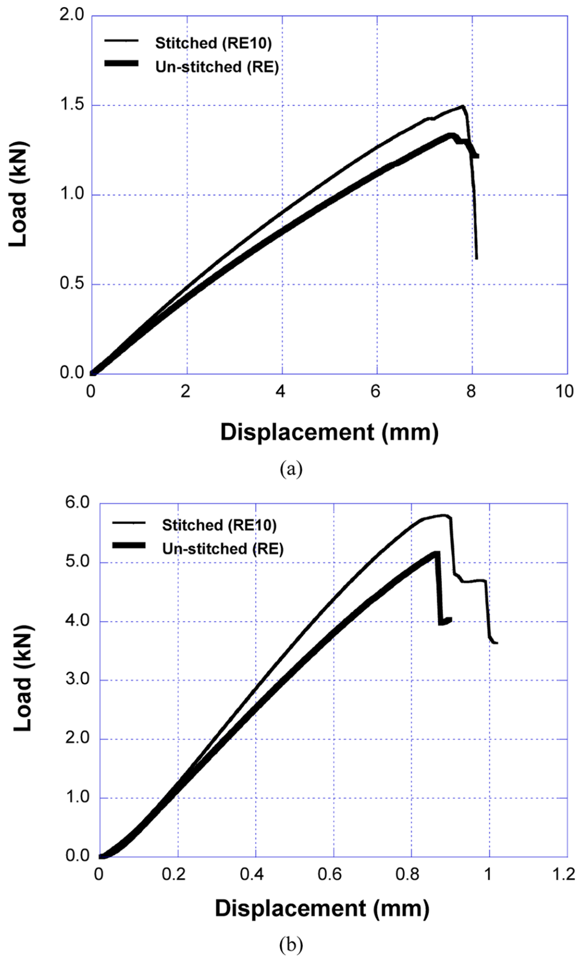


Fig. 6. Load-displacement curves: (a) flexural test; (b) interlaminar test

Table 2. Flexural and interlaminar shear test results of un-stitched and stitched samples

Case		Flexural Modulus (GPa)	Flexural Strength (MPa)	Interlarminar shear strength (MPa)
Un-stitched	RA	18.65 (±0.19)	527 (±13.2)	57.8 (±2.29)
	RE	18.23 (±0.21)	518 (±11.9)	55.6 (±1.41)
Stitched	RE05	18.70 (±0.68)	524 (±22.8)	52.9 (±4.01)
	RE10	18.70 (±0.28)	525 (±19.7)	57.4 (±1.13)
	RE10-M	17.30 (±1.08)	510 (±42.2)	56.5 (±1.10)
	RE10-A	16.50 (±0.42)	461 (±7.63)	55.8 (±2.64)
	RE10-H	18.00 (±0.43)	530 (±13.9)	55.0 (±3.57)

3.1 Effect of Stacking Type

Both the regular stacking (RE) and the random stacking (RA) of un-stitched specimen showed similar results within the standard deviation. However, flexural and interlaminar properties were consistently higher for the case of random stacking as shown in Figs. 6(a) and (b). This is due to the fact that the random stack has more uniform stress distribution in the width direction. As shown in Fig. 3, the normal stress in x-direction, and the shear stress in the z-x plane due to the bending have higher variation in y-direction for the case of regular stack compared with that of random stack.

3.2 Effect of Stitching Density

Comparing between stitched (RE05 and RE10) and un-stitched (RE) specimens for the regular stacks, the former cases showed higher flexural strength and modulus. This is mainly due to the additional reinforcements by the stitch yarns located on specimen surfaces where the maximum stress locates. It is also noted that the direction of stitch yarn is the same as that of normal stress due to the bending. The difference of flexural property between RE05 and RE10 is negligible. This is because length of stitch thread on the surfaces of RE05 and RE10 are the same, and thus there is no difference for the reinforcement effect caused by the stitch thread. However, interlaminar strength of stitch spacing of 10mm was 10% higher than that of 5 mm spacing. It can be stated that as the number of stitches increases the possibility of resin rich area around them becomes higher, resulting in the reduced strength. Comparing RE, RE5, and RE10, stitching with 5 mm spacing gave the lowest interlaminar strength. But, when the stitch spacing increases from 5 mm to 10 mm, load sharing by stitch yarns compensates the negative effect due to the resin pocket. Therefore, increasing the number of stitches doesn't always result in the improvement of interlaminar strength.

3.3 Effect of Stitching Type

Referring to the stitch type, it is generally accepted that modified lock stitching is recommended in composites in order to avoid stress concentration at loops (Fig. 4(a)). Another reason may be due to that the plain lock stitch causes tension on the perform surface, resulting in the separation of fiber bundles and potential of resin pocket. The resin rich area on the composites surface is more serious when it is under the flexural loading condition. But, results in this study showed lower strength and modulus in the modified lock stitch. This is due to the loops formed on specimen surfaces that may cause stress concentration under the flexural and interlaminar shear loading conditions. However, due to the larger standard deviation for the case of modified lock stitch (Table 2), the general tendency can't be stated based upon these results.

3.4 Effect of Stitch Location

The most evident effect of stitching on the mechanical property was the stitch location where needles penetrate as shown in Fig. 5(a). In specimens of RE10, stitch threads are located between 0^o yarn bundles. For RE10-A specimens, however, stitch threads penetrate right on 0^o yarn bundles, which may cause fiber misalignment due to the bundle separation and thus resin rich area is formed around the penetration point (Fig. 2(b)). The fiber breakage during the stitching process is also associated with strength reduction. The fiber damage in 0^o fiber bundles makes it worse under the bending mode. The flexural strength and modulus of the specimen with stitch location on 0^o fiber bundles were reduced by 12% compared to that of stitching between 0^o fiber bundles. The resin richness and the fiber breakage of RE10-A are believed to be the reason for the lower interlaminar strength.

3.5 Effect of Loading Point

Due to the introduction of stitching threads, the unit cell of composites is larger than that of un-stitched samples. Thus, the nose point of the loading jig in the test machine may affect the flexural and interlaminar properties. Comparing the results of loading point between the stitching holes (RE10) and those of loading point on the stitching hole (RE10-H) showed that the latter case gave higher flexural strength and modulus. The reason for this can be due to that stress was absorbed by stitching threads when the compressive load was applied. Thus, specimens of RE10-H can take higher load, and flexural strength increased.

4. CONCLUSIONS

Effects of stacking type and stitching parameters on the flexural and interlaminar properties of MWK textile composites have been identified. E-glass MWK textiles with layer sequence of [0/-45/90/45] have been used. The stacking sequence was $[0/-45/90/45]_{5s}$. For the stacking type, the regular stack and the random stack were considered. Three parameters for stitching process have been considered: stitching spacing, types, and location. The location of loading nose of the test jig was also examined. Most of results were close with each other within the range of standard deviation. Among other parameters, stitching on 0^o fiber bundles showed the lowest flexural strength and modulus, and the reduction was 12%, respectively, compared with those of stitching between 0^o fiber bundles. This is due to the fact that stitching threads penetrating right on 0^o yarn bundles may separate fiber bundles and cause fiber misalignment and resin rich area around the needle penetration point. For the case of interlaminar strength, stitching density showed the greatest effect. Stitching with 10 mm spacing gave the highest interlaminar strength, and the increment was 9% compared with that of 5 mm spacing. The reason for this may be the less possibility of resin rich area for the case of longer spacing of stitching.

ACKNOWLEDGEMENT

We would like to acknowledge the financial support from the R&D Convergence Program of MSIP (Ministry of Science, ICT and Future Planning) and NST (National Research Council of Science & Technology) of Republic of Korea (Grant: CMIP-13-4-KIMS).

REFERENCES

1. Ga, B.B., Hogg, P.J., and Kemp, M., "Mechanical Characterization of Glass- and Carbon-Fibre-Reinforced Composites made with Non-Crimp Fabrics," *Composites Science and Technology*, Vol. 57, No. 9-10, 1997, pp. 1221-1241.
2. Kamiya, R., Cheeseman, B.A., Popper, P., and Chou, T.W., "Some Recent Advances in the Fabrication and Design of Three-dimensional Textile Preforms: A Review," *Composites Science and Technology*, Vol. 60, No. 1, 2000, pp. 33-47.
3. Leong, K.H., Ramakrishna, S., Huang, Z.M., and Ga, B.B., "The Potential of Knitting for Engineering Composites-a Review," *Composites: Part A*, Vol. 31, No. 3, 2000, pp. 197-220.
4. Hufenbach, W., Böhm, R., Thieme, M., Winkler, A., Mäder, E., and Rausch, J., "Polypropylene/glass Fibre 3D-textile Reinforced Composites for Automotive Applications," *Materials and Design*, Vol. 32, No. 3, 2011, pp. 1468-1476.
5. Byun, J.H. and Chou, T.W., *Comprehensive Composite Material*, Elsevier Science Publishers, Netherlands, 2000.
6. Beier, U., Fischer, F., Sandler, J.K.W., Altstädt, V., Weimer, C., Spanner, H., and Buchs, W., "Evaluation of Preforms Stitched with a Low Melting-temperature Thermoplastic Yarn in Carbon Fibre-reinforced Composites," *Composites Part A*, Vol. 39, Issue 5, 2008, pp. 705-711.
7. Beier, U., Wolff-Fabris, F., Fischer, F., Sandler, J.K.W., Altstädt, V., Hülder, G., Schmachtenberg, E., Spanner, H., Weimer, C., Roser, T., and Buchs, W., "Mechanical Performance of Carbon Fibre-reinforced Composites Based on Preforms Stitched with Innovative Low-melting Temperature and Matrix Soluble Thermoplastic Yarns," *Composites Part A*, Vol. 39, No. 9, 2008, pp. 1572-1581.
8. Tan, K.T., Watanabe, N., and Iwahori, Y., "Effect of Stitch Density and Stitch Thread Thickness on Low-velocity Impact Damage of Stitched Composites," *Composites Part A*, Vol. 41, No. 12, 2010, pp. 1857-1868.
9. Tan, K.T., Watanabe, N., Iwahori, Y., and Ishikawa, T., "Effect of Stitch Density and Stitch Thread Thickness on Compression after Impact Strength and Response of Stitched Composites," *Composites Science and Technology*, Vol. 72, No. 5, 2012, pp. 587–598.
10. Tan, K.T., Watanabe, N., Iwahori, Y., and Ishikawa, T., "Effect of Stitch Density and Stitch Thread Thickness on Damage Progression and Failure Characteristics of Stitched Composites under Out-of-plane Loading," *Composites Science and Technology*, Vol. 74, 2013, pp. 194-204.
11. Margossian, A., Bel, S., Balvers, J.M., Leutz, D., Freitas, R., and Hinterhoelzl, R., "Finite Element Forming Simulation of Locally Stitched Non-crimp Fabrics," *Composites: Part A*, Vol. 61, 2014, pp. 152-162.
12. Li, L., Zhao, Y., Vuong, H., Chen, Y., Yang, J., and Duan, Y.X., "In-plane Shear Investigation of Biaxial Carbon Non-crimp Fabrics with Experimental Tests and Finite Element Modeling," *Materials and Design*, Vol. 63, 2014, pp. 757-765.
13. Zhao, N.P., Rodel, H., Herzberg, C., Gao, S.L., and Krzywinski, S., "Stitched Glass/PP Composite Part I: Tensile and Impact Properties," *Composites: Part A*, Vol. 40, 2009, pp. 635-643.
14. Asp, L.E., Edgren, F., and Sjögren, A., "Effects of Stitch Pattern on the Mechanical Properties of Non-crimp Fabric Composites," Proceeding of the 11th ECCM, Rhodes, Greece, May 2004, pp. 31-05.
15. Woo, K. and Whitcomb, J.D., "Effects of Fiber Tow Misalignment on the Engineering Properties of Plain Weave Textile Composite," *Composite Structures*, 37, 1997, pp. 343-355.
16. Ito, M., and Chou, T.W., "An Analytical and Experimental study of Strength and Failure Behavior of Plain Woven Composites," *Journal of Composite Materials*, 32, 1998, pp. 2-30.