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Effect of stitch and biaxial yarn types on tensile, bending, and impact properties of biaxial weft-knitted composites

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Within the scope of experiments, the effect of stitch yarn type (aramid, glass and nylon), and biaxial, warp and weft, and yarn type (aramid and glass) was investigated in the biaxial weft-knitted (BWK) composites. Five different types of composite panel, which include fiber contents, such as glass-glass-glass, glass-glass nylon, glass glass aramid, aramid glass aramid and aramid aramid aramid were fabricated by hand lay-up method. After production of composite panels, tensile, three-point bending and three-point, bending impact tests were conducted on specimens. Microstructural characterization of tested materials was performed using a scanning electron microscope. This study showed that composites with BWK preforms consisting of fiber combinations, such as aramid-aramid-aramid, had higher tensile strength (in course direction), of aramid-glass-aramid had higher bending strength (in course direction), and of glass glass aramid had higher three-point bending impact properties (in course and wale directions) than other types of tested composite structures.

Keywords: biaxial weft knitting; composite materials; mechanical properties; mechanical testing; SEM

1. Introduction

Knitting with advanced fibers, such as glass and aramid, to produce near-netshape preforms has in recent years received increasing an interest.[1] At a constant fibre volume fraction, the introduction of in-lay yarns can significantly improve the properties of knitting composite as was reported by Ramakrishna and Hull.[2]

Knitted fabrics are constructed by easily extendible loops, which generate a higher degree of deformability in comparison with other types of reinforcement. Knitted fabrics are basically categorized into two types, namely warp-knitted fabrics and weft-knitted fabrics. Warp-knitted fabrics are produced by knitting in the lengthwise direction (wale direction) of the fabrics. Weft-knitted fabrics are produced by knitting in the horizontal direction (course direction) of the fabrics.[3] Biaxial weft-knitted (BWK) fabrics include weft and warp yarn layers, which are held together by a stitching yarn system. Reinforcing yarns, such as glass or aramid fibers, can be used within all yarn systems. The strength and stiffness of the composite can be improved by reinforcing yarns.[4] BWK composite is the subject of the current work.

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The effect of architecture on the mechanical properties of knitted composites was reported by Anwar et al. [5] They investigated tensile and compression properties of three milano ribs and one rib weft-knit glass fabric reinforcement. Micromechanical modeling approaches for the stiffness and strength of knitted fabric composites were pointed out by Huang et al. [6] They also compared the tensile modulus and strength of various textile composites such as knitted, braided, woven, unidirectional and short fiber composites. Rios et al. [7] studied damage development and tensile properties of weft-knitted composites. They tested one-layer milano weft-knitted glass-fabric-reinforced composites at various angles to loading direction. Mechanical properties of knitted fabric composites were investigated by Hamada et al. [8] They conducted tensile, three-point bending, and plate-bending tests on knitted composites. Mechanical properties, such as tensile, three-point bending, and impact, of textile-inserted PP/PP knitted composites using injection–compression molding were reported by Khondker et al. [9] The tensile properties of weft-knitted composites for energy absorption were studied by Xue et al. [10] They described correlation between fabric structure (e.g. loop height and width, number of wale or course per unit length, etc.), matrix damage, and materials properties. Fabrication and mechanical properties of aramid/nylon plain knitted composites were reported by Khondker et al. [11] They investigated mechanical properties of aramid/nylon and aramid/epoxy composites and their relationships to the fiber/matrix interfacial adhesion. Moreover, only a few numbers of contributions were made about mechanical properties of BWK composite.[12–14] Demircan et al. [15] reported tensile properties of one-layer BWK composites and found that aramid aramid aramid type of composites showed the highest tensile properties in course direction. The impact properties of BWK composites were reported by Demircan et al. [16]

In literature, contributions about the mechanical properties of knitted composites were reported, which were explained above. However, we found that very few studies were done about mechanical properties of BWK composites. Because the fabrication method of BWK fabrics is comparatively very new comparinf to traditional knitting fabrics, it is very necessary to characterize the mechanical properties of composites with BWK fabric. The present study investigates tensile, bending, and impact properties of one-layer and six layer BWK composites and analyzes the fracture aspects by using a scanning electron microscopy (SEM). The obtained results of tests will be used to modify the conventional weft-knitting machine and to improve the mechanical properties of BWK composites.

2. Experimental procedure

2.1. Composites constituents

Five types of BWK fabric were produced on a flat-bed knitting machine (Shima Seiki Mfg., Ltd., Japan) (Figure 1). Schematic drawing of BWK fabric is shown in Figure 2 (a)–(c). Figure 2(a) depicts warp and weft yarns. The knitted fabric with stitch yarn is shown in Figure 2(b). And Figure 2(c) shows BWK fabric with warp, weft, and stitch yarns. 575 tex E-glass yarn (Nippon Electric Glass Co. Ltd., Japan) and 330 tex aramid yarn (Kevlar-29, Dupont-Toray Co. Ltd., Japan) were used as biaxial materials (warp and weft yarns). 68 tex E-Glass (ECG 75 1/0 1 OZ, Hokuriku Fiber-Glass Co. Ltd., Japan), 44 tex aramid (Kevlar-29, Dupont-Toray Co. Ltd., Japan), and 29 tex nylon were used as stitch yarns. Vinyl ester resin (Ripoxy R-806, Showa High Polymer Co. Ltd., Japan) was used as matrix. Table 1 shows the parameters of the BWK fabric. In order to achieve more reliable comparison of the specimens, the warp and weft yarn

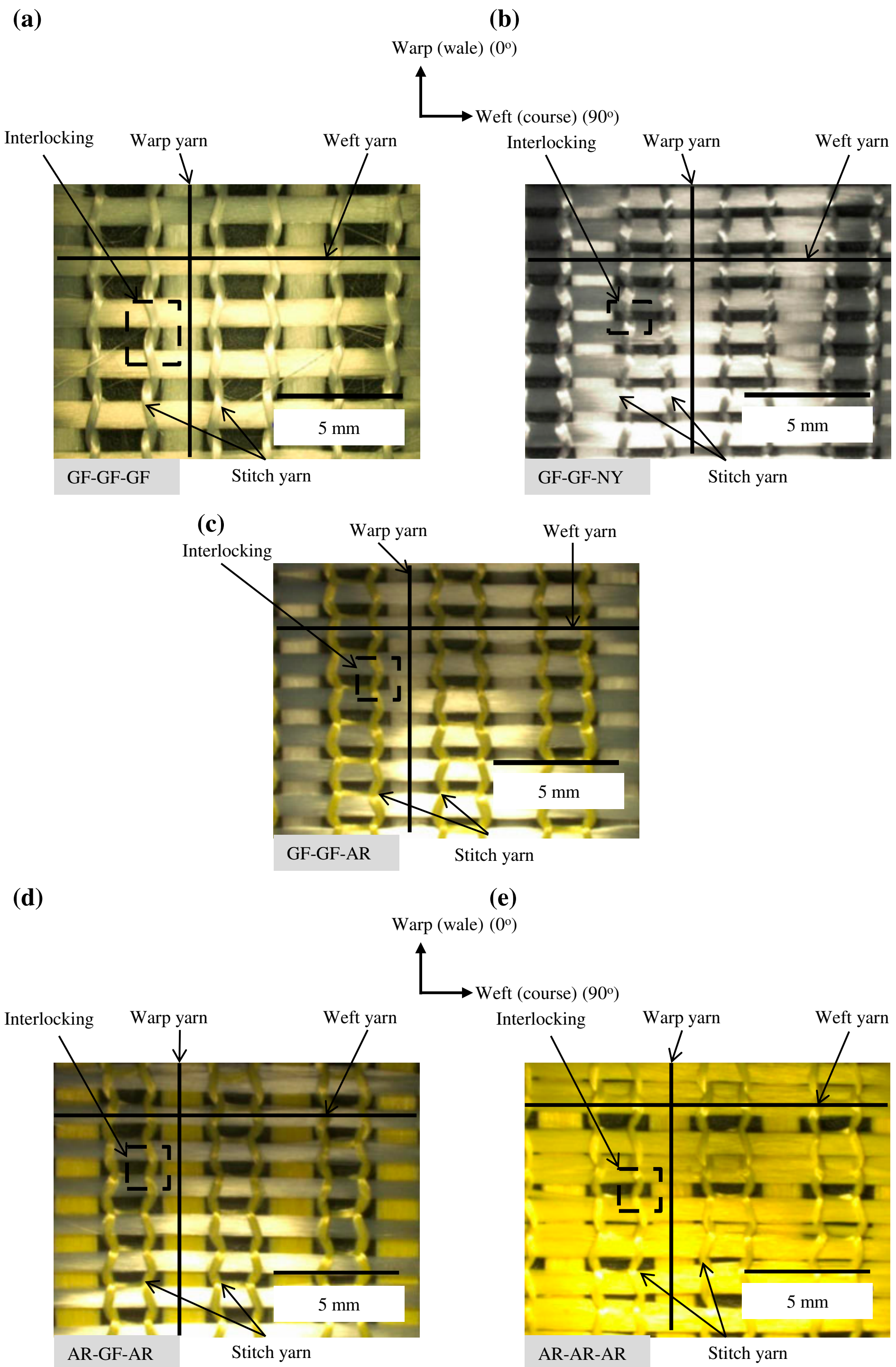


Figure 1. Photographs of the BWK fabric; (a) GF-GF-GF, (b) GF-GF-NY, (c) GF-GF-AR, (d) AR-GF-AR, (e) AR-AR-AR.

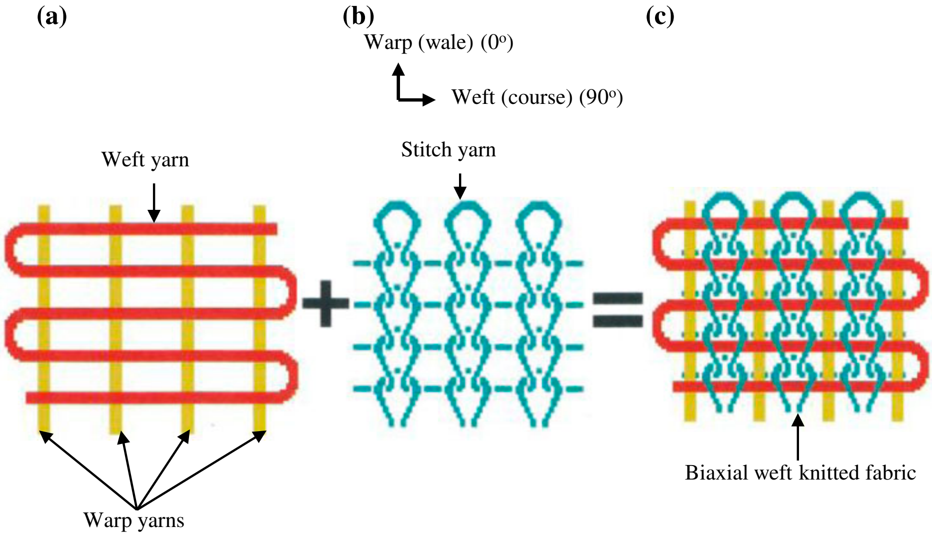


Figure 2. Schematic drawing of BWK fabric.

Table 1. Parameters of the BWK fabric.

Sample name	Biaxial yarn: Warp yarn	Biaxial yarn: Weft yarn	Stitch yarn	Density of warp yarn in fabric (end/cm)	Density of weft yarn in fabric (end/cm)
1) GF-GF-GF	Glass 575 tex	Glass 575 tex	Glass 68 tex	2.0	5.4
2) GF-GF-NY	Glass 575 tex	Glass 575 tex	Nylon 29 tex	2.2	5.5
3) GF-GF-AR	Glass 575 tex	Glass 575 tex	Aramid 44 tex	2.0	5.8
4) AR-GF-AR	Aramid 330 tex	Glass 575 tex	Aramid 44 tex	2.1	6.0
5) AR-AR-AR	Aramid 330 tex	Aramid 330 tex	Aramid 44 tex	2.1	6.0

densities of each type of specimen were adjusted as near as possible, which is shown in Table 1.

2.2. Fabrication method

Before fabrication of composites, the BWK preforms were stayed in a vacuum heater at 100 °C for six hours. Due to vacuum-heating process, good interaction between fiber and resin was provided. After the vacuum-heating process, composite panels with one ply and six plies were fabricated directly by the hand lay-up method. The stacking sequence of six layers was written in a symmetric laminate code such as [0/90/0/0/90/0]. 0° means the direction of warp yarns or the wale direction and 90° means the direction of weft yarns or the course direction. Volume fractions of the five types of specimen were kept constant to compare the specimens. Spacers were used to control the required specimen thickness. The composite panels were cured at room temperature for 24 h, followed by a 2 h post-cure at 100°C. The overall fiber volume fraction was about 40% for one layer of BWK composite structure; this was about 41.5% for six layers of BWK composite structure. The overall composite thickness was 0.5 mm for one layer of BWK composite; that was 2.9 mm for six layers of BWK composite. A notation system was used to differentiate the name of five specimens. The notation 'GF-GF-AR' means that in the order warp yarn is GF (glass fiber), weft yarn is GF (glass fiber), and stitch yarn is AR (aramid fiber). The density of glass fiber (ρ_f) was 2.68 gr/cm^3. The volume fraction (V_f) of GF-GF-GF composite plates was calculated using the following equation [7]:

$$V_f = \frac{\frac{B}{\rho_f}}{A \times h} \tag{1}$$

where B is the weight of one-layer glass reinforcement; ρ_f is the density of glass fiber; A is the area of the laminate, and h is the thickness of the laminate.

2.3. *Mechanical characterization*

Tensile and three-point flexural tests were conducted on the specimens according to ASTM-D303 and ASTM-D790 standard. The measurements for both tests were performed using a universal testing machine (type 55R4206), Instron, under a displacement control with speed 1 mm/min. Figure 3(a) and (b) shows the geometry of the specimen from tensile and three-point bending test. In this figure, lamina and aluminium thickness is respectively shown with t_c and t_{Al}. The thickness of aluminium tabs was 0.5 mm. The composite coupons have a nominal dimension of: (i) 200 mm × 20 mm × 0.5 mm for the tensile test and (ii) 90 mm × 16 mm × 2.9 mm for bending test. the test span length was 60 mm in the three-point bending test.

Figure 3(c) shows the test setup and geometry of the specimen from three-point bending impact test. Three-point bending impact tests were carried out on specimens according to JIS-K7084 standard. The three-point bending impact damages were inflicted on different specimens in a drop weight test using a universal testing machine (type Dynatup 9250HV), Instron. The drop weight was used as an impactor for the tests, respectively. The weight of the impactor and the incident impact energy was 6490 g and 20 J for the three-point bending impact test. The composite coupons had a nominal dimensionof 80 × 10 × 2.9 mm for the three-point bending impact test.

Composite coupons were cut from produced panels parallel to the wale and course directions. For tensile tests, three specimens from each type of one-layer composite panel were tested in wale and course directions. Strain gages with 10 mm gage length were used to measure the tensile strain. Three specimens from each type of six-layer composite panels were tested in the wale and course directions in the three-point bending and three-point bending impact tests.

The fractured surfaces of the specimen from tensile test were observed by a SEM. JSM-5200 (Jeol) type of SEM was used. In order to prevent the charging effect, the specimens were coated with thin gold in JFC-1100 (Jeol) type of fine coating machine.

3. Results and discussions

3.1. *Tensile properties of composites*

The tensile properties of composites were investigated according to the effect of the stitch and biaxial yarns. Composites with the stitch yarns such as, aramid, nylon, and

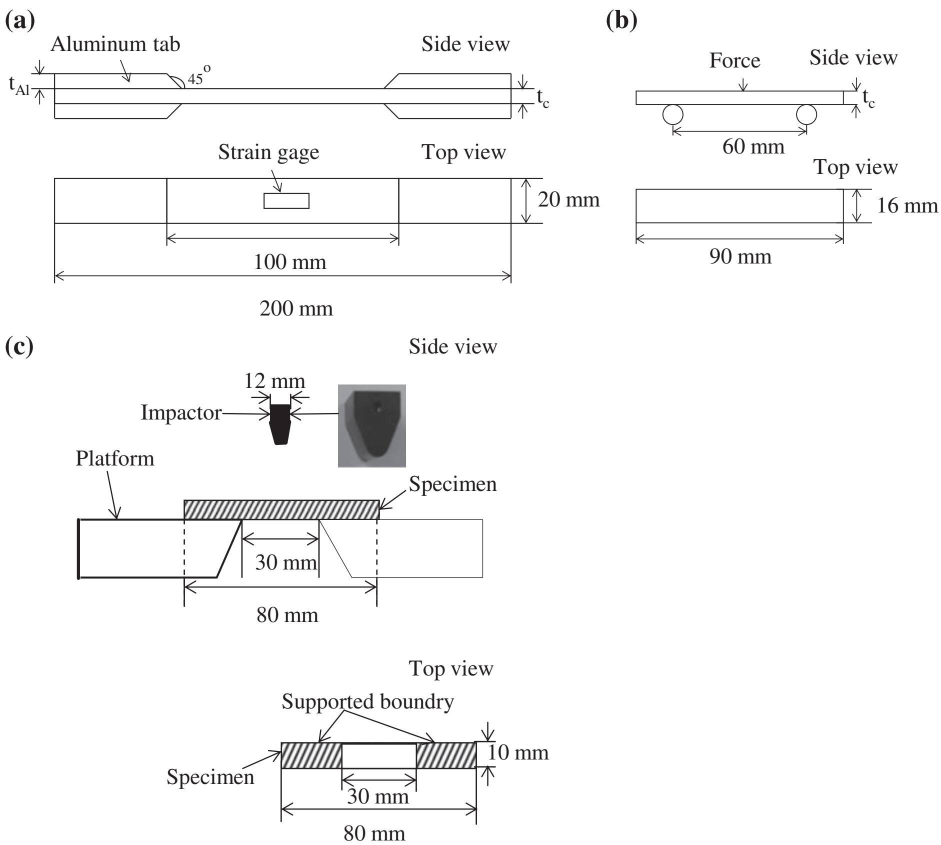


Figure 3. Geometry of the specimen; (a) tensile test, (b) three-point bending test and (c) three-point bending impact test.

glass, and the biaxial yarns, such as aramid and glass, were compared according to the tensile test.

3.1.1. Effect of stitch yarn

The tensile properties of the one-layer BWK composites with different stitch yarns (glass, nylon, and aramid) under tensile loading were presented in Figure 4(a) and (b). From these curves, it can be seen that the tensile stress increases linearly with an increase of the strain until arriving the knee point. This was followed by a sudden drop in a stress value corresponding to the ultimate failure of the composite. Among the various stitch yarns, such as glass, nylon, and aramid, the highest tensile modulus and strength of the composites were found with the aramid stitch yarn (19.3 GPa and 372.3 MPa) in the course direction and with the glass stitch yarn (15.8 GPa and 183.9 MPa) in the wale direction. Due to the high ductility behavior of the aramid stitch fibers, the GF-GF-AR composites showed the highest strain in both directions. The tensile strength of composites with the AR stitch fiber was 14% higher than that was with the GF stitch fibers in the course direction. One of the reason of this would be that the density of BWK fabric with the GF stitch fiber (5.4 end/cm) was about 7%

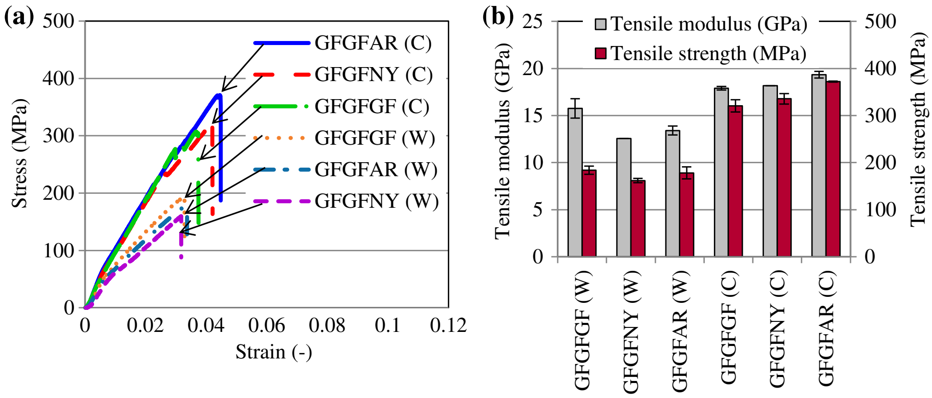


Figure 4. Tensile properties of one layer composites; (a, b) effect of stitch yarn in course (C) and wale (W) directions.

less than that was with the AR stitch fiber (5.8 end/cm). During knitting of the BWK preforms, the GF stitch fibers should be bended to give the loop form. Because of the brittlebess of the GF fibers, bending caused breaking of the GF stitch fibers, which was more dominant in the course direction than in the wale direction (Figure 5). The broken GF fibers make the straight part of the loops in the course direction weaker. This would be another reason for the lower tensile strength of the BWK composites with GF stitch fibers than that was with the AR stitch fibers in the course direction.

The tensile strength of composites with the GF stitch fiber was about 3 and 12% higher than that was with AR and NY stitch fibers in the wale direction, respectively. It was observed from the preforms that the broken GF fibers usually oriented in the course direction. Therefore, effect of the broken GF fibers could be ignored in the wale direction. In the photographs, we observed the longest length of interlocking part of the loops in the composites with the GF stitch yarn (Figure 1(a)). Also, the sizes of the loops in the GF-GF-GF were the bigger than those were in the GF-GF-AR and GF-GF-NY. Therefore, the volume fraction of the GF stitch fibers would be higherin the wale direction. That would be the reason for the highest tensile properties with the GF stitch fibers compared to the AR and NY fibers in the wale direction.

3.1.2. Effect of the biaxial yarn

The tensile properties of the BWK composites with different biaxial yarns (the glass glass biaxial yarns, the aramid glass biaxial yarns, and the aramid-aramid biaxial yarns) under tensile loading are presented in Figure 6(a) and (b). Due to a higher difference weft yarn density than in warp yarn density (2.5–2.9 times), the tensile strength results were almost two times higher in the course direction than in the wale direction. Among these three kinds of composite, such as the GF-GF-AR (the glass glass biaxial yarns), the AR-GF-AR (the aramid glass biaxial yarns), and the AR-AR-AR (the aramid-aramid biaxial yarns), the highest tensile strength was found by the aramid aramid biaxial yarns (428 MPa) in the course direction and by the aramid-glass biaxial yarns (226.7 MPa) in the wale direction. The second highest tensile strength was 372 MPa with the glass-glass biaxial yarn which was 13% lower than the aramid-aramid in the course direction. The tensile strength with the aramid-aramid biaxial yarns was the

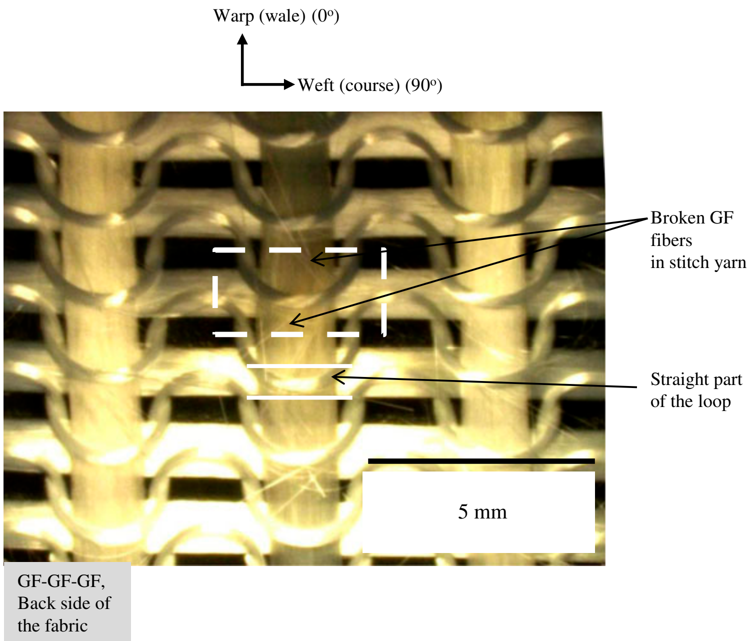


Figure 5. Photograph of the back side of the GF-GF-GF fabric.

second highest in the wale direction (216.2 MPa). In addition, the tensile strength of the GF-GF-GF BWK composite (315.3 MPa) in the course direction was also around four times higher than that was with the glass weft-knitted fabric composites (75.8 MPa),[17] which were fabricated by RTM.

3.1.3. *Comparing tensile properties of one-and six-layer composites*

Tensile test results of the BWK composites with one- and six-layer preforms in the course direction were shown in Figure 7(a) and (b). The similar tendency of the graphs

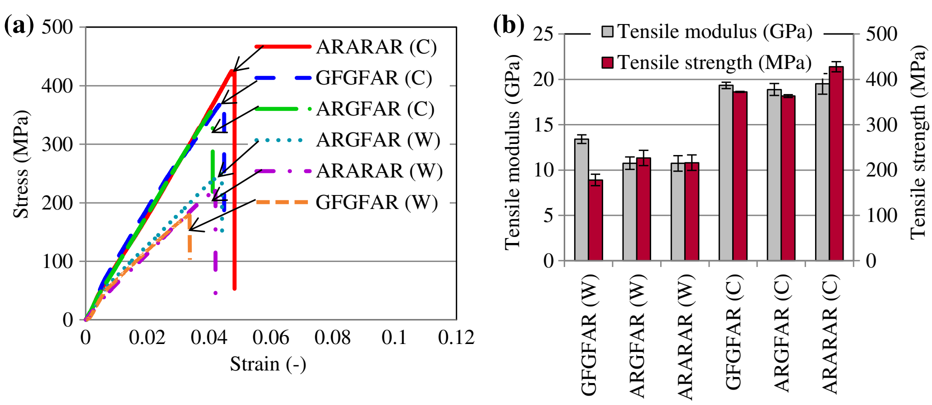


Figure 6. Tensile properties of one layer composites; (a, b) effect of biaxial yarn in course (C) and wale (W) directions.

of the tensile strength and modulus of one and six layers composites validated the test results.

3.1.4. Fracture damage characterization of tensile tested specimens

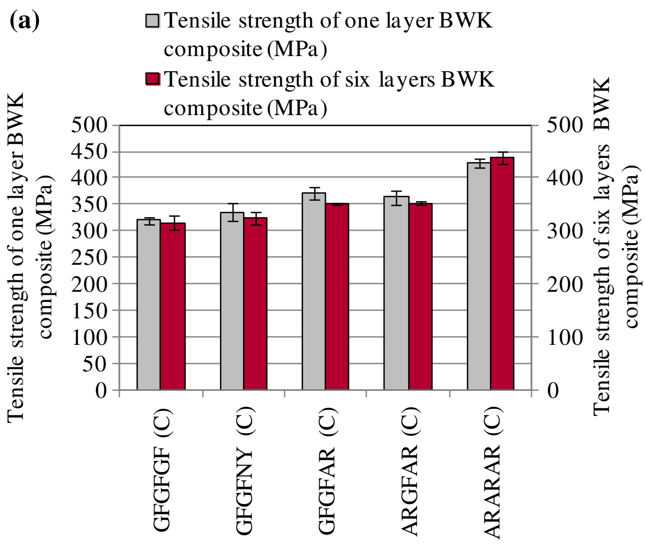
Figure 8 shows representative SEM micrographs of the fracture aspects of one–layer-tensile-tested specimens in the course direction. Schematic drawings of the fracture aspects were shown in Figure 9. The tensile strengths of the BWK composite specimens were about two times higher in the course direction those into the wale. Therefore, the specimens in the course direction were selected to study the fracture behaviors of samples. The unbound and separated NY stitch fiber bundles indicated the poor bonding adhesion in the GF-GF-NY. The long and separated GF stitch fiber bundles were also observed in the SEM micrographs of the GF-GF-GF composites. However, the compact and short AR stitch fiber length of the GF-GF-AR composites was the evidence of the highest tensile test results of one-layer BWK composites (effect of stitch yarn). In the AR-GF-AR, the longer length of GF weft fiber bundles was seen on the surface. However, the shorter length of AR weft fiber bundles in the AR-AR-AR compared to the longer length of GF weft fiber bundles in the AR-GF-AR was the evidence of the highest tensile test results of one-layer BWK composites (effect of biaxial yarn).

3.1.5. Laminate theory

The laminate theory was utilized as another modeling method for the calculation of the tensile modulus of the one-layer BWK composite. The biaxial reinforcement inside the knitted structure was assumed as 0°/90° laminate of the two uniaxial composite layers. Although the stitch yarns effect the tensile properties of BWK composites (Figure 4(a) and (b)), the effect of the biaxial yarns on the tensile performance was more dominant than that of the stitch yarns. The straight fibers (biaxial fibers) carry out most of the loads in the BWK composites. The tensile strength of the GF-GF-GF BWK composite was about four times higher than that of the glass weft-knitted composite [17] without the biaxial yarn. Therefore, effect of the stitch yarns was ignored to calculate the tensile modulus of the BWK composites. The modulus results from the laminate theory and experiments are shown in Table 2.

In the wale direction, the modulus results from the laminate theory with the AR stitch fiber deliver less deviation from the experimental results (+4.9%) than those were with the NY stitch fiber (+14.9%). The experimentally results in the wale direction with the AR stitch fiber (13.4 GPa) were much higher than those were with NY stitch fiber (12.5 GPa). Because of that, there was much higher deviation of the results with NY stitch fiber in the wale direction than that was with the AR stitch fiber.

The results of the laminate theory with the AR-AR biaxial yarns delivers less deviation from the experimental results than those were with the GF-GF biaxial yarns in the course direction. Due to have the lower young modulus of the AR-AR biaxial yarns have lower young moduls (62 GPa) than the GF-GF biaxial yarns (72 GPa), the modulus results from the laminate theory with the GF-GF biaxial yarns (24.8 GPa) were higher than those were with the AR-AR biaxial yarns (19.9 GPa) in the course direction. Also, the experimental results in the course direction with the AR-AR biaxial yarns (19.5 GPa) were much higher than those were with the GF-GF biaxial yarns



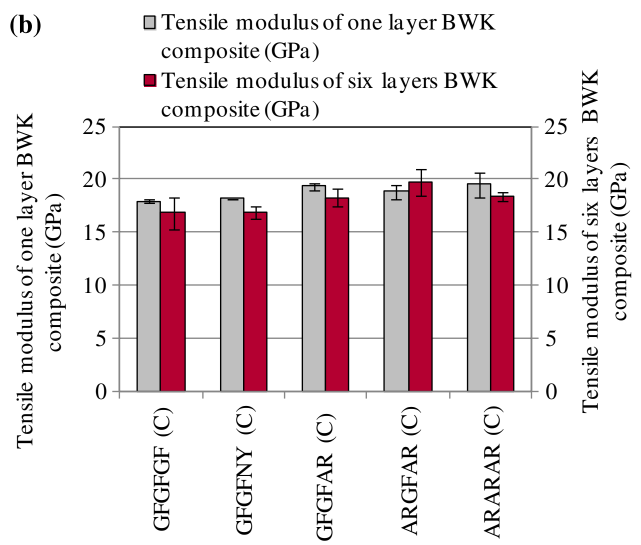


Figure 7. Comparing tensile properties of one and six layers composites.

(17.9 GPa). Based on this, the difference between E_{Lam} and E_{Exp} with the GF-GF biaxial yarns (+27.8%) was much higher than that with the AR-AR biaxial yarns (+2%) in the course direction.

3.2. Bending properties of composites

The bending properties of composites were investigated according to the effect of the stitch and biaxial yarns. Composites with the stitch yarns, such as aramid, nylon, and glass, and the biaxial yarns, such as aramid and glass, were compared according to the three-point bending test.

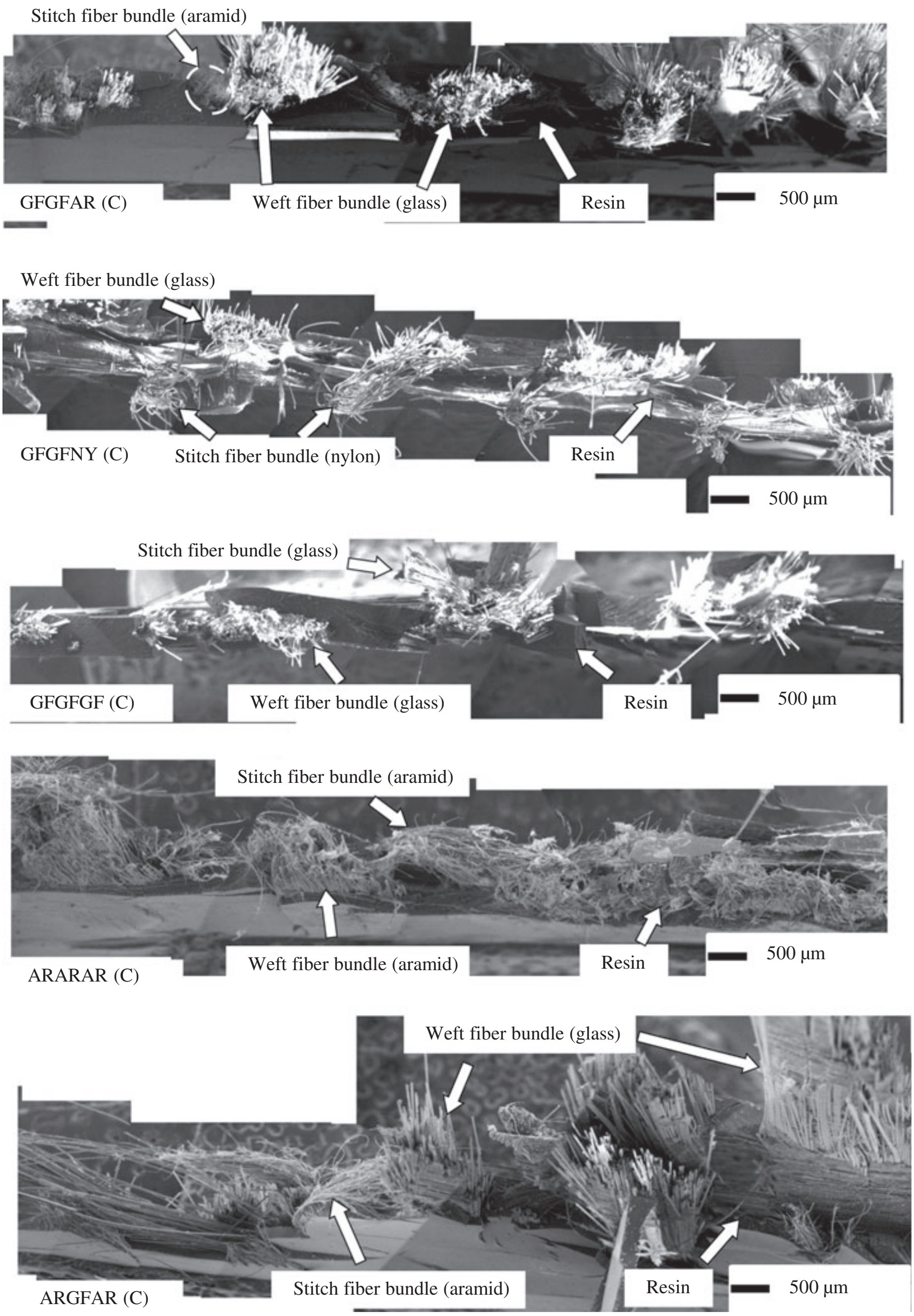


Figure 8. SEM photomicrographs of fractured surface of BWK composites specimens after tensile test in course direction.

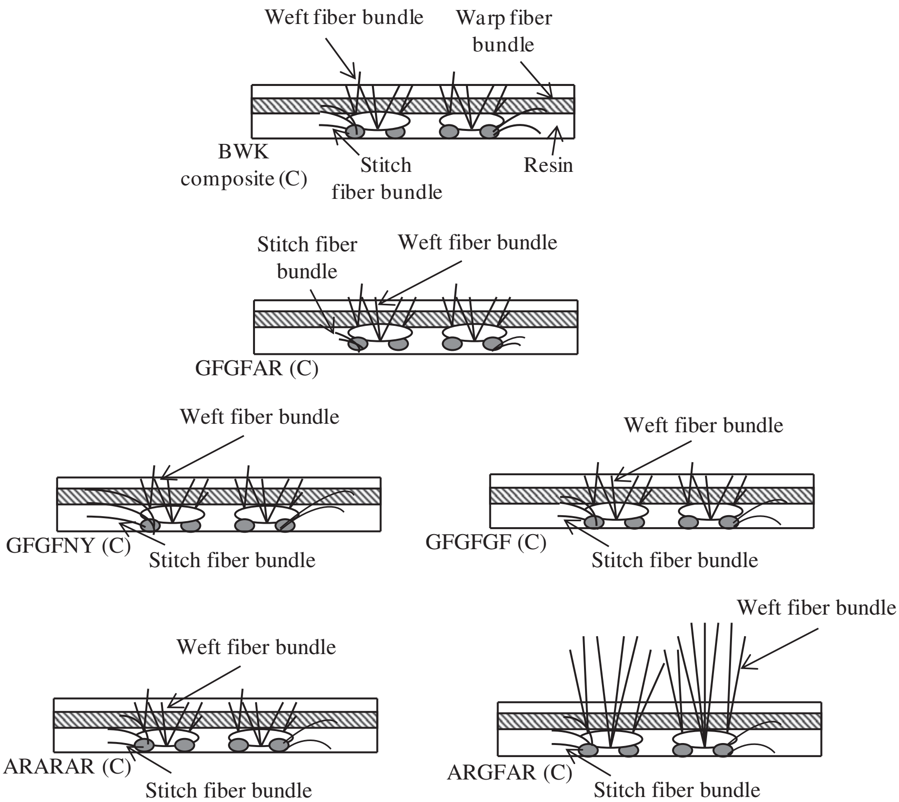


Figure 9. Schematic drawings of the fracture aspects of BWK composites specimens after tensile test in course direction.

3.2.1. Effect of stitch yarn

Figure 10(a) and (b) shows the results of the three-point bending test with different stitch yarns. The flexural strength yielded different trend compared to the tensile test results in the effect of stitch yarn in the wale direction. The tensile strength of composites in the course direction was clearly higher compared to the wale direction (Figure 4(a) and (b)). Whereas, the flexural strength of composites in the course direction was slightly different than that was in the wale direction (Figure 10(a) and (b)). And also the tensile modulus of composites (Figure 4(b)) was higher than the flexural modulus of composites (Figure 10(b)) in the course direction. Different failure mechanism could be responsible for this different trend. A measure of the resistance to deformation of the composite in bending is called flexural modulus. Flexural strength and stiffness are mainly controlled by the strength of reinforcement fibers. The GF-GF-NY composites with the NY stitch yarn exhibited superior flexural modulus and strength (10.2 GPa and 419.7 MPa) compared to other tested specimens. Composites with the NY stitch yarns exhibited 16.4% higher flexural strength than those were with the AR stitch fiber (351 MPa) in the course direction.

Table 2. The modulus results from tensile test and from laminate theory in course (C) and wale (W) directions.

Sample	Modules from experiment E_{Exp} [GPa]	Modules from laminate theory E_{Lam} [GPa]	Difference between E_{Lam} and E_{Exp} [%]
GF-GF-GF (C)	17.9 ± 0.19	24.8	+27.8
GF-GF-NY (C)	18.2 ± 0	24.5	+25.7
GF-GF-AR (C)	19.3 ± 0.36	25.1	+23.1
AR-GF-AR (C)	18.8 ± 0.66	19.9	+5.52
AR-AR-AR (C)	19.5 ± 1.14	19.9	+2.0
GF-GF-GF (W)	15.7 ± 1.04	14.4	−8.28
GF-GF-NY (W)	12.5 ± 0	14.7	+14.9
GF-GF-AR (W)	13.4 ± 0.48	14.1	+4.96
AR-GF-AR (W)	10.7 ± 0.68	6.5	−39.2
AR-AR-AR (W)	10.7 ± 0.86	7.0	−34.6

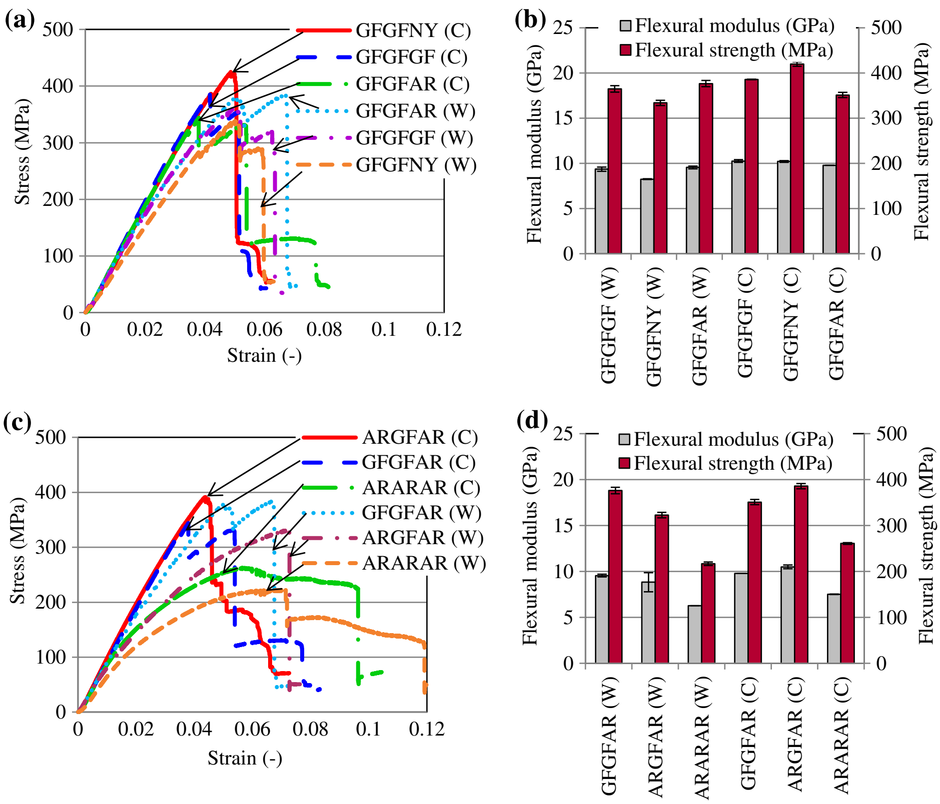


Figure 10. Bending properties of six layers composite in course (C) and wale (W) directions, (a, b) effect of stitch yarn and (c, d) effect of biaxial yarn.

3.2.2. *Effect of biaxial yarn*

The results of the three-point bending test with different biaxial yarns were shown in Figure 10(c) and (d). Composites with AR-GF biaxial yarns exhibited the highest

Table 3. Energy results from three-point bending test of BWK composites in course (C) and wale (W) direction.

Samples	Maximum load (N)	Initiation energy (J)	Propagation energy (J)	Total energy (J)	DI
GF-GF-AR (C)	617 ± 10.8	2.50 ± 0.22	1.67 ± 0.73	4.17 ± 0.59	0.69 ± 0.35
GF-GF-NY (C)	620 ± 24.1	3.33 ± 0.30	0.62 ± 0.09	3.95 ± 0.21	0.18 ± 0.05
GF-GF-GF (C)	502 ± 12.8	2.57 ± 0.20	0.88 ± 0.28	3.44 ± 0.09	0.34 ± 0.13
GF-GF-AR (W)	668 ± 33.8	4.20 ± 1.08	1.20 ± 0.81	5.40 ± 0.53	0.34 ± 0.24
GF-GF-NY (W)	463 ± 18.9	3.23 ± 0.68	0.84 ± 0.40	4.07 ± 0.43	0.29 ± 0.17
GF-GF-GF (W)	501 ± 12.8	3.16 ± 0.10	0.91 ± 0.18	4.07 ± 0.10	0.29 ± 0.07
AR-AR-AR (C)	473 ± 1.58	3.28 ± 0.10	2.73 ± 0.39	6.01 ± 0.48	0.83 ± 0.10
AR-GF-AR (C)	628 ± 30.8	3.05 ± 0.13	1.42 ± 0.13	4.48 ± 0.26	0.47 ± 0.03
AR-AR-AR (W)	381 ± 11.3	3.46 ± 0.34	2.51 ± 0.09	5.97 ± 0.30	0.72 ± 0.09
AR-GF-AR (W)	525 ± 22.4	4.89 ± 0.22	0.16 ± 0.08	5.05 ± 0.14	0.03 ± 0.02

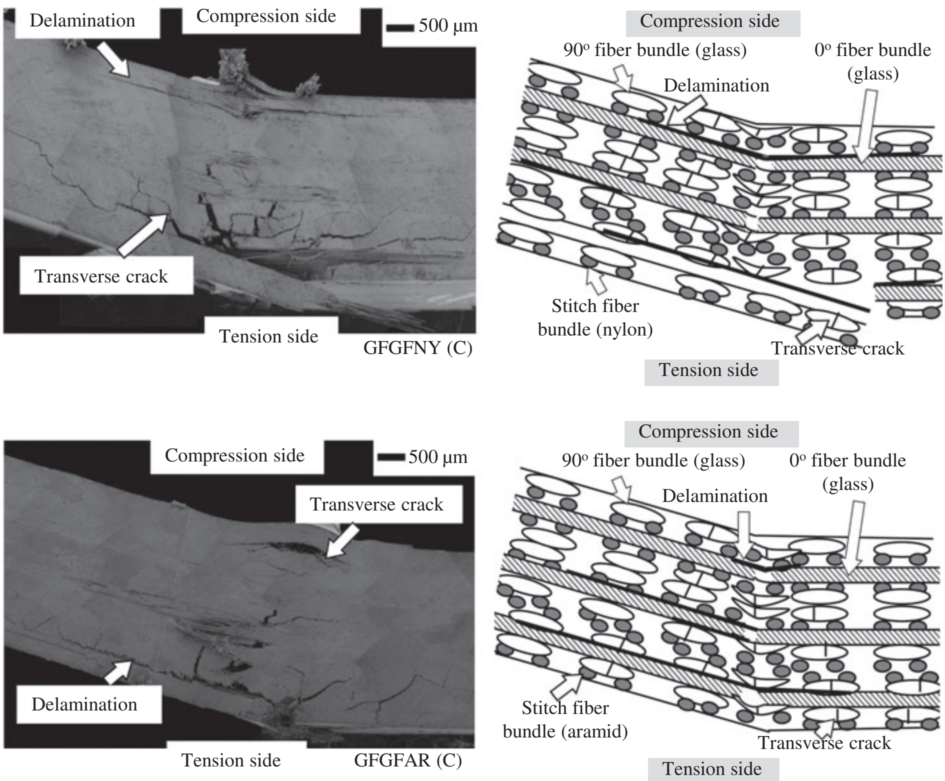


Figure 11. SEM photomicrographs (left) and schematic drawings (right) of fractured surface of BWK composites specimens after three-point bending test in course and wale directions.

flexural properties (10.5 GPa and 385.8 MPa) than other specimens in the course direction. The AR-AR-AR composites have the lowest flexural properties (7.5 GPa and 260.9 MPa) in the course direction. Using the glass weft yarn instead of the aramid weft yarn, the AR-AR-AR composites were hybridized and became AR-GF-AR composites. By hybridizing with the glass fiber, the flexural strength of composites with the AR-GF biaxial yarns was improved by 32.4% compared to that with the AR-AR biaxial yarns. Contrary to the course direction specimens, the wale direction specimens were able to maintain their robustness over a relatively large strain interval before ultimate failure occurred. Especially, the AR-AR-AR composites have the highest strain interval before the ultimate failure happened in both directions.

Energy results from three-point bending test are exhibited in Table 3. The area under load displacements curves gives the absorbed energy during three-point bending test. Initiation energy was found out to calculate the area under load displacement curve until maximum load and that was for propagation energy after maximum load. Because, composites with the AR stitch fibers had higher strain than other stitch fibers, the total absorbed energy with the aramid stitch fibers (4.17 J) was higher than that was with the nylon (3.95 J) and with the glass stitch fibers (3.44 J) in the course direction. In the wale direction, the same trend was also observed like course direction. Because of the highest strain with the aramid aramid biaxial fibers, the total absorbed energy with

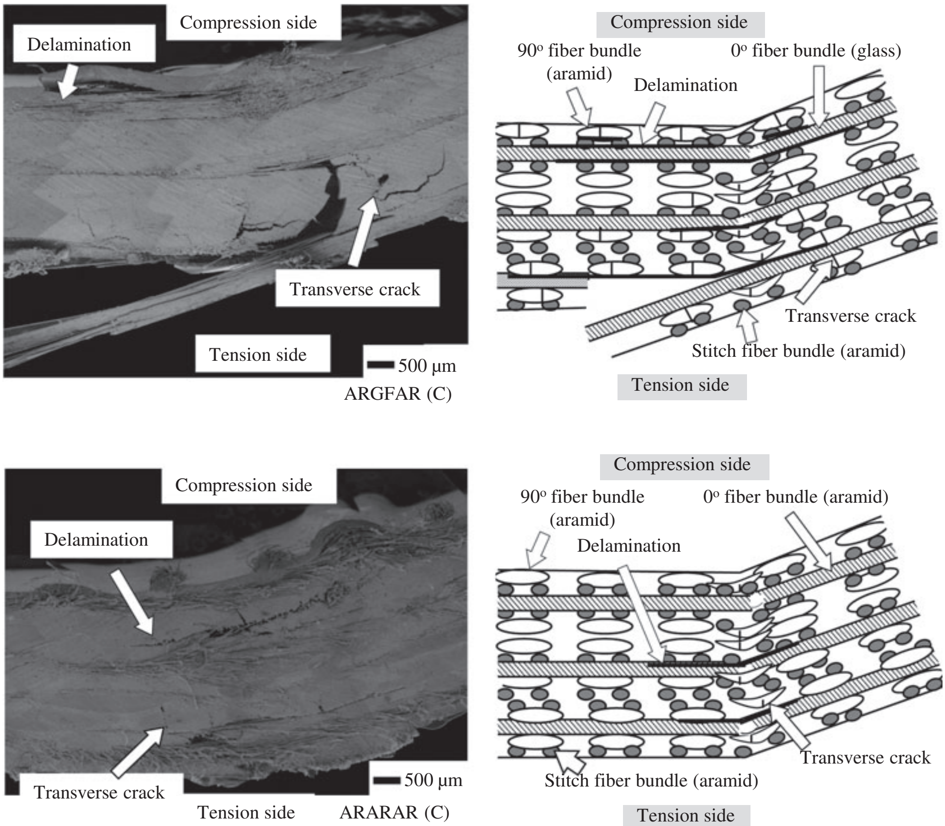


Figure 11. (*Continued*)

these fibers (6.01 J (C) and 5.97 J (W)) was also the highest compared to the other tested biaxial fibers (glass-glass and aramid-glass) in the course and wale directions. The ductile index (DI) is defined as the ratio of the propagation energy and initiation energy.[18,19] The AR-AR-AR specimens had higher propagation energy compared to the other specimens in both test directions, resulting in a high DI of 0.83 and 0.72.

3.2.3. *Fracture damage characterization of bending tested specimens*

Representative fracture damage aspects of bending tested specimens with schematic drawings are shown in Figure 11. The dominant failure mechanisms were delaminations, transverse cracks, bucklings and fiber breaks in tension, and compression sides of the specimens. A higher bending stress for the sample with the NY stitch yarn in the weft direction (GF-GF-NY (C)) and with the AR stitch yarn in the warp direction (GF-GF-AR (W)) was indicative of the larger area of the tensile fracture (effect of the stitch yarn). The higher number of transverse cracks, fiber breaks, and longer delaminations was observed with the aramid glass biaxial yarn in the weft direction (AR-GF-AR (C)) and the glass glass biaxial yarns in the warp direction (GF-GF-AR (W)), which was the indicative of the higher bending stress of the mentioned specimens

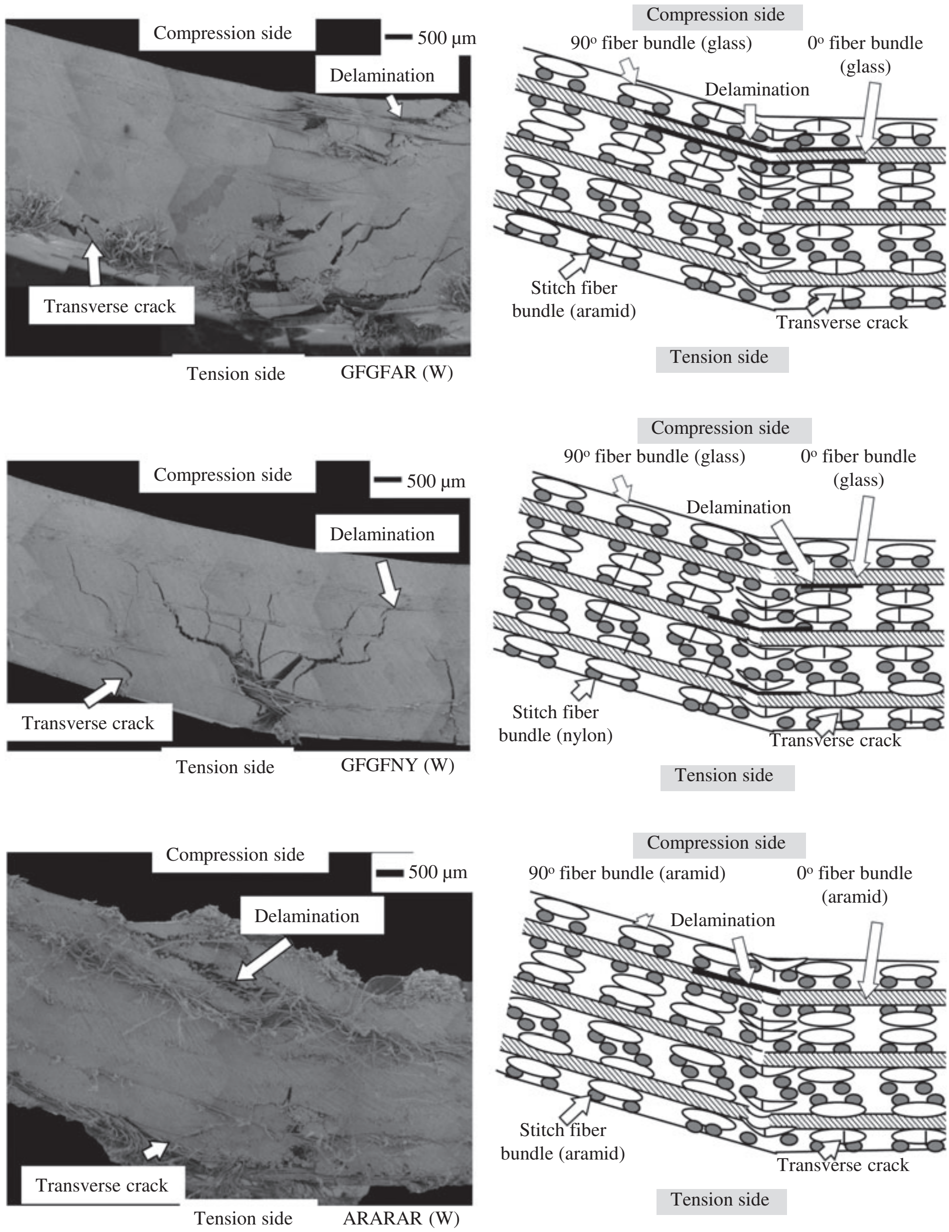


Figure 11. (*Continued*).

(effect of biaxial yarns). The lower transverse cracks and shorter delaminations were observed in the AR-AR-AR (C) and AR-AR-AR (W) composites with aramid-aramid biaxial fibers compared to other biaxial yarns both in the course and wale directions. Having high ductility properties of aramid fibers compared to glass fibers would be the reason for the lower transverse cracks and shorter delaminations length.

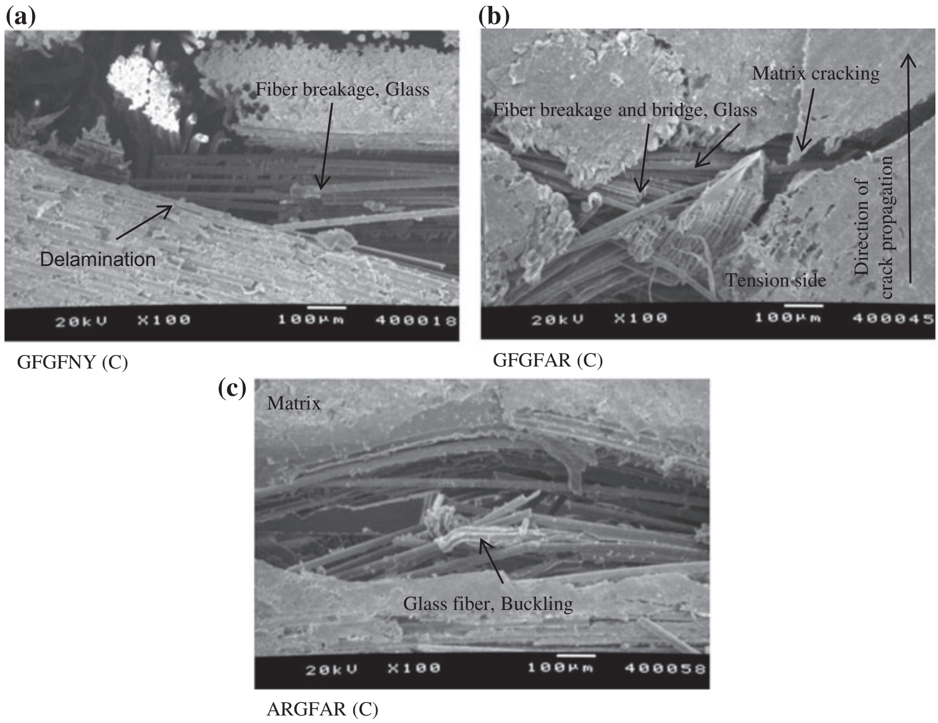


Figure 12. Enlarged SEM photomicrographs of fractured surface of BWK composites specimens after three-point bending test in course direction; (a) GFGFNY, (b) GFGFAR and (c) ARGFAR.

Figure 12 demonstrates the enlarged view of fracture damage aspects of bending tested specimens. Delamination and glass fiber breaks in the GF-GF-NY, fiber breaks and bridge mechanisms and matrix cracks in the GF-GF-AR, and glass fiber buckling in the AR-GF-AR can be seen from these figures. In all specimens, the failure initiates with the development of cracks on the tension side and propagates through the thickness till the failure occurs.

3.3. Impact properties of composites based on three-point bending impact test

The impact properties of composites based on the three-point bending impact test were investigated according to the effect of stitch and biaxial yarns. Composites with the stitch yarns, such as aramid, nylon, and glass, and the biaxial yarns, such as aramid and glass, were compared according to the three-point bending impact test.

3.3.1. Effect of stitch yarn

The impact properties of the BWK composite specimens during the three-point bending impact test in the course and wale directions with different stitch yarns are exhibited in Figure 13(a) and (b) and Table 4. The GF-GF-AR composites had average peak load 1153 N in the course direction and 1051 N in the wale direction, which was higher than other specimens. The GF-GF-AR specimens with the aramid stitch yarn had the

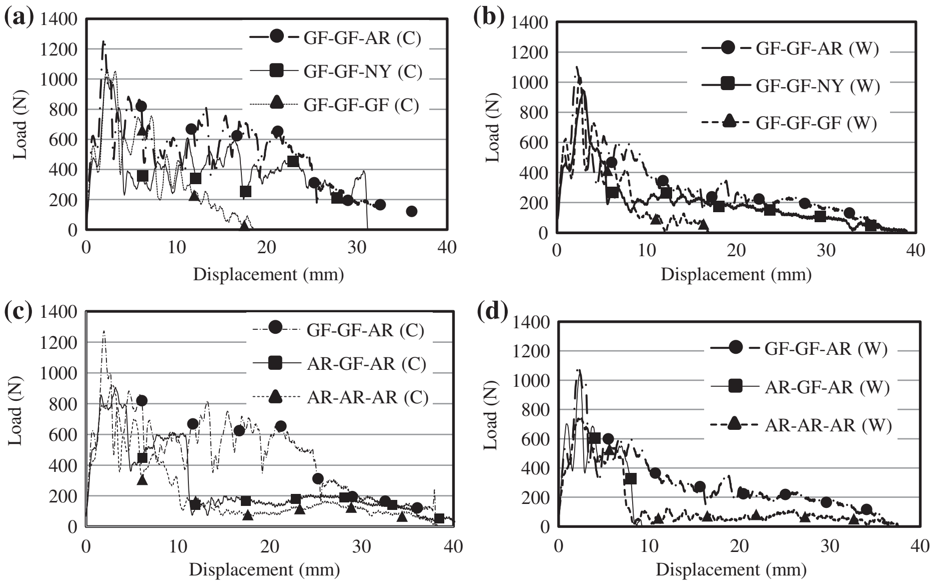


Figure 13. Load–displacement curves of BWK composites during three-point bending impact test; effect of stitch yarn; (a) course (C) direction, (b) wale (W) direction and effect of biaxial yarn; (c) course (C) direction, (d) wale (W) direction.

highest total absorbed energy in the course and wale directions, 12.8 and 7.35 J respectively. The GF-GF-AR specimens had higher propagation energy compared to the other specimens in both test directions, resulting in a high DI of 10.4 and 3.94. The total absorbed impact energy of the BWK composites (GF-GF-GF = 46.0 J) based on the plate-bending impact test [16] was also more than three times higher than that was with the glass weft-knitted fabric composites (13.9 J),[20] which are fabricated by autoclave method.

3.3.2. *Effect of biaxial yarn*

The three-point bending impact test results in the course and wale directions with different biaxial yarns are shown in Figure 13(c) and (d) and Table 4. Generally, the specimens showed 1.2–2.3 times higher total energy results in the course direction than the wale direction. This was caused by the higher weft yarn density than the warp yarn density (2.5–2.9 times) in the BWK, which is shown in Table 1. The GF-GF-AR composites with the glass glass biaxial yarns had higher peak load and total absorbed energy than the other specimens in both testing directions. The AR-AR-AR specimens with the aramid aramid biaxial yarns showed the lowest total absorbed energy in the course direction with 6.52 J. The GF-GF-AR specimens showed: (a) 88% higher total absorbed energy than the AR-AR-AR in the course direction, and (b) 85% higher total absorbed energy than the AR-GF-AR specimens in the wale direction.

The relationship of the total absorbed energy from three-point bending test and from three-point bending impact test [16] in course direction is shown in Figure 14. This graphic showed that there was a good relationship between both tests.

Table 4. Energy results from three-point bending impact test of BWK composites in course (C) and wale (W) direction.

Samples	Maximum load (N)	Initiation energy (J)	Propagation energy (J)	Total energy (J)	DI
GF-GF-AR (C)	1153 ± 105	1.13 ± 0.20	11.6 ± 3.36	12.8 ± 3.51	10.4 ± 1.99
GF-GF-NY (C)	1005 ± 9.76	1.23 ± 0.02	9.50 ± 2.02	10.7 ± 2.03	7.69 ± 1.54
GF-GF-GF (C)	1149 ± 58.2	1.20 ± 0.50	5.69 ± 1.91	7.69 ± 1.85	3.13 ± 1.34
GF-GF-AR (W)	1051 ± 46.7	1.64 ± 0.27	5.70 ± 3.03	7.35 ± 2.76	3.94 ± 2.82
GF-GF-NY (W)	937 ± 7.97	2.04 ± 0.33	4.06 ± 2.62	6.10 ± 2.37	2.23 ± 1.60
GF-GF-GF (W)	1032 ± 8.98	1.40 ± 0.05	3.04 ± 0.45	4.90 ± 0.96	2.16 ± 0.27
AR-AR-AR (C)	946 ± 21.5	1.81 ± 0.12	4.71 ± 1.92	6.52 ± 1.81	2.68 ± 1.20
AR-GF-AR (C)	1017 ± 73.4	1.41 ± 0.40	8.35 ± 1.22	9.76 ± 1.40	6.22 ± 1.38
AR-AR-AR (W)	739 ± 10.6	1.35 ± 0.11	3.88 ± 0.36	5.23 ± 0.31	2.90 ± 0.47
AR-GF-AR (W)	989 ± 38.4	1.24 ± 0.09	2.99 ± 0.07	4.23 ± 0.13	2.43 ± 0.17

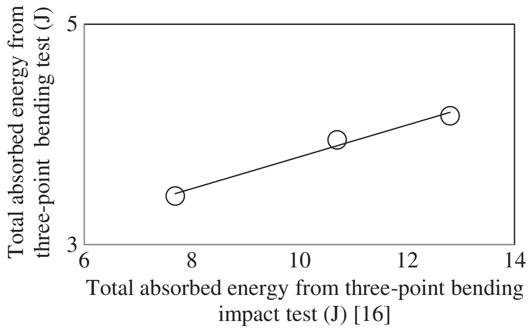


Figure 14. Total absorbed energy from three-point bending test and from three-point bending impact test.[16]

4. Conclusions

This study showed that the composites with the aramid stitch fiber had the higher tensile properties in the course direction than composites with the glass and nylon stitch fibers. And also, composites with the aramid aramid biaxial yarns had the higher tensile properties in the course direction than composites with the glass-glass and aramid glass biaxial yarns. Whereas, composites with the nylon stitch yarn and aramid glass biaxial yarns had the higher bending properties than other tested composites in the course direction. Composites with the aramid stitch yarn and with the glass glass biaxial yarns had the highest three-point bending impact properties than the other tested composites specimens in both course and wale directions. The microstructural characterizations of the tensile tested materials were investigated using a SEM in the course direction. SEM photographs showed that the GF-GF-AR composites had good fiber/resin interaction and the compact AR stitch fibers. However, the GF-GF-NY composites had unbound and separated NY stitch fibers. The SEM results were validated the experimental results in course direction. The laminate theory was utilized as another modeling method for the calculation of tensile modulus with an acceptable agreement. SEM photographs of bending tested specimens showed that the dominant failure mechanisms were delaminations, transverse cracks, bucklings, and fiber breaks. Future work will be the analysis of the tensile properties of aramid thermoplastic BWK composites produced by compression molding.

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