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Effect of fiber densities on impact properties of biaxial warp-knitted textile composites

O Demircan[1,2], C Yilmaz[1], ES Kocaman[1], S Tang[3], H Hamada[3] and M Yildiz[1]

Abstract

In this study, an appropriate fabric weight content controlled by the density of the warp and weft fibers is determined for biaxial warp-knitted composites referring to mechanical test results. Six different types of composite panel with two different fabric weights (813 and 1187 gr/m^2) and with three different stacking sequences $[90_{we}/0_{wa}/90_{we}/0_{wa}]_s$, $[90_{wa}/0_{we}/90_{wa}/0_{we}]_s$, and $[90_{wa}/0_{we}/90_{we}/0_{wa}]_s$ are fabricated by using Resin Transfer Molding method. Having produced composite panels, drop weight impact tests are conducted on specimens. Microstructural characterization of impact tested materials is performed using optical microscope. The results of this study reveal that composites with biaxial warp-knitted preforms with lower weft and warp fiber densities (thin-ply) could absorb higher impact energies compared to those with higher weft and warp fiber densities (thick-ply).

Keywords

Textile composites, impact behavior, knitting

Introduction

Due to their high specific strength and stiffness, composite materials are valuable structural materials in engineering applications. Some fields benefiting from the qualities of composites include aerospace, automotive, wind energy, and civil infrastructure. The mechanical properties of composites can be tailored through using various forms of reinforcements. Knitted composites are generally considered to have inferior mechanical properties due to their highly looped structure and low fiber volume fraction.[1] In order to improve the mechanical properties, such as strength and stiffness, of warp-knitted fabric, straight yarns both in weft and warp directions can be integrated. These types of reinforcements are called biaxial warp-knitted (BWK) structures. Weft and warp yarn layers are held together by stitching yarns in BWK fabrics. Reinforcing yarns, e.g., glass or aramid fibers, can be used within all yarn systems.

Mechanical properties of knitted fabric composites were investigated by Hamada et al.[2] 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 produced using injection-compression molding were reported by Khondker et al.[3] The tensile properties of weft-knitted composites for energy absorption were studied by Xue et al.[4] They described correlations between fabric structure (e.g., loop height and width, number of wale or

[1]Faculty of Engineering and Natural Sciences, Advanced Composites and Polymer Processing Laboratory (AC2PL), Sabanci University, Istanbul, Turkey
[2]Materials Science and Engineering Department, Faculty of Engineering, Ondokuz Mayıs University, Samsun, Turkey
[3]Department of Advanced Fibro-Science, Graduate School of Science and Technology, Kyoto Institute of Technology, Kyoto, Japan

Corresponding author:
M Yildiz, Faculty of Engineering and Natural Sciences, Advanced Composites and Polymer Processing Laboratory (AC2PL), Sabanci University, Orhanli-Tuzla, Istanbul 34196, Turkey.
Email: meyildiz@sabanciuniv.edu

course per unit length, etc.), matrix damage, and material properties.

The impact properties of weft-knitted fabric reinforcement composites were investigated by several researchers.[5–8] In comparison to composites manufactured from a single layer of fabric, knitted composites with an increased number of fabric layers demonstrated improved impact damage resistance and fracture toughness.[9–11] Impact properties of three-dimensional (3-D) biaxial weft-knitted composites were studied both numerically and experimentally by Li et al.[12] They pointed out that energy absorption increased with the increase of impact velocity. Hufenbach et al.[13] studied hybrid 3-D biaxial weft-knitted reinforced composites for impact applications. They compared impact properties of composites with biaxial weft-knitted preforms consisting of different fiber combinations, such as glass-glass-glass, glass-glass-aramid, and glass-glass-polyethylene. Demircan et al. have also investigated the biaxial weft-knitted composites made of glass-glass-glass fibers and indicated that the fabric structure improves the impact properties of composites notably due to the presence of 0° and 90° fiber inside the preform. Based on the results of plate-bending impact test,[14] they showed that the total absorbed impact energy of the biaxial weft-knitted composites (46.0 J) is three times more than that of the glass weft-knitted fabric composites without biaxial fibers (13.9 J).[15] This increase can be attributed to the fact that biaxial fibers facilitate global load distribution thereby making it difficult for the impactor to penetrate through the thickness of the plane. Due to the similitude between the fabric structures of biaxial weft and warp-knitted composites, BWK fabric structure should also present improved impact performance due to the above discussed mechanism.

The stacking sequences can affect mechanical properties of composites. Khashaba et al.[16] reported failure and reliability analysis of pinned-joints composite laminates with different stacking sequence. They studied four configurations such as $[0/90]_{2s}$, $[15/-75]_{2s}$, $[30/-60]_{2s}$, and $[45/-45]_{2s}$ and reported that specimens with $[0/90]_{2s}$ stacking sequence had the maximum failure displacement and ultimate stress compared to the other stacking sequences from bearing tests. Aktas and Dirikolu[17] studied the effect of stacking sequence of carbon epoxy composite laminates on pinned-joint strength through considering two configurations, namely $[0/45/-45/90]_s$ and $[90/45/-45/0]_s$. They found that the $[90/45/-45/0]_s$ orientation had higher strength from bearing tests compared to the $[0/45/-45/90]_s$. Park[18] reported the effects of stacking sequence and clamping force on the bearing strengths of mechanically fastened joints in composite laminates through studying two orthotropic ($[90_6/0_6]_s$ and $[0_6/90_6]_s$) and three quasi-isotropic ($[90_3/\pm45_3/0_3]_s$, $[90_3/0_3/\pm45_3]_s$, and $[0_3/\pm45_3/90_3]_s$) laminate lay-up configurations. He found that the orthotropic composite laminates had almost the same bearing strengths, while $[90_6/0_6]_s$ lay-up had the delaminations bearing strength nearly two times stronger than $[0_6/90_6]_s$ stacking sequence. According to the results of delaminations bearing failure, the stacking sequence of the lay-up $[90_6/0_6]_s$ with 90° layers on the surface was more advantageous than the lay-up $[0_6/90_6]_s$ with 0° layers. He also reported that the higher ultimate bearing strengths for quasi-isotropic laminates were $[90_3/\pm45_3/0_3]_s$, $[90_3/0_3/\pm45_3]_s$, and $[0_3/\pm45_3/90_3]_s$. Mattsson et al.[19] studied damage in non-crimp-fabric (NCF) composites under tension. They found that stacking sequence with $[0/90/0/90]_s$ lay-up had much larger elastic modulus reduction than that with $[90/0/90/0]_s$ lay-up.

The fiber densities (thin and thick plies) can affect mechanical properties of composites. Tsai et al.[20] investigated thin-ply composites and found that laminate made of thin-plies showed remarkable resistance to microcracking, delaminations, and fatigue loading. Sihn et al.[21] performed experimental studies on thin-ply laminated composites and found that the thin-ply composites could suppress the microcracking and delamination damages without special resin or 3-D reinforcements. Guillamet et al.[22] reported damage occurrence at the edges of NCF thin-ply laminates under off-axis uniaxial loading. They found that the thick region of composites was the critical region for the occurrence of the damage, whereas the thin region of the composites experienced damage mechanism (delaminations), which are delayed or suppressed. Yokozeki et al.[23] experimentally investigated the strength and damage resistance properties of thin-ply carbon fiber/toughened epoxy laminates and reported that composites with thin-ply prepregs compared to standard prepregs had superior characteristics for tension, tension–tension fatigue, non-hole and open-hole compression strengths, and compression strength after impact loading tests. Amacher et al.[24,25] studied thin-ply composites and noted that the uniaxial tension, open-hole compression, and open-hole tensile fatigue tests on quasi-isotropic $[45^\circ/90^\circ/-45^\circ/0^\circ]_{ns}$ laminates show significant improvements in terms of the onset of damage, and in some cases ultimate strength upon decreasing the ply thickness. Tan et al.[26,27] studied the effect of stitch density and stitch thread thickness on compression after impact strength and the response of stitched composites. They obtained increased compression after impact strength for laminates with larger stitch thread thickness.

In literature, one may find quite many excellent contributions reporting on the mechanical properties of thin and thick plies composites, some of which have been cited above. However, to our best knowledge, there is no study dedicated to address the effect of fiber thickness and fabric stacking sequences on the mechanical properties of BWK composites concurrently. Moreover, only a few studies are there about the impact properties of knitting composites with different fiber densities and stacking sequence combinations. The aim of study is to determine appropriate fabric weight content controlled by the density of the warp and weft fibers for BWK thin and thick plied composites referring to impact test results. To this end, the effect of fiber densities and fabric stacking sequences on impact properties of BWK thin and thick plied composites is reported within this study. The results of impact tests might be used to design the new textile preforms during the development of different composite materials. For example, due to the higher impact energy absorption capacity of the BWK reinforced composites, which will be addressed in detail subsequently, BWK composites can specifically be considered for ballistic applications.

Experimental procedure

Composites constituents

The BWK fabrics with several fabric weights (813 gr/m^2 (G3) and 1187 gr/m^2 (G5)) were produced on warp knitting machine of Metyx Composites Ltd., Turkey. Figure 1 depicts the fabricated BWK reinforcement fabric. E-glass fibers were used as biaxial warp and weft fibers and stitch fiber materials. Epoxy resin system (LY 564 resin, XB 3403 hardener by Huntsman) was used as matrix material. Table 1 shows the parameters of the E-glass fiber reinforcements. The BWK composite with the fabric weights of 813 gr/m^2 and 1187 gr/m^2 is respectively referred to as thin-ply and thick-ply.

Fabrication method

Four-layer BWK composites have been produced using Resin Transfer Molding (RTM) method with three different stacking sequences, namely, $[90_{we}/0_{wa}/90_{we}/0_{wa}]_s$, $[90_{wa}/0_{we}/90_{wa}/0_{we}]_s$, and $[90_{wa}/0_{we}/90_{we}/0_{wa}]_s$. Here, 0° and 90° fiber orientation in the preforms respectively indicate directions parallel and perpendicular to the length of the composite plate which is aligned with the flow direction of the resin, while warp and weft fibers are denoted with the subscripts of "wa" and "we" correspondingly. Here, within the preforms, 0° fiber orientation indicates the warp direction, whereas the 90° denotes the weft direction. In the following, the designation G and B is used to refer to fabric type and stacking sequence, respectively. Here, the G3 and G5 are correspondingly the fabric codes for LT800 E 10 A 0/90 (thin-ply) and LT1200E 05B 0/90 (thick-ply), where 10 A and 05 B in fabric designation stands for the number of stitch per inch, which is 10 and 5 for the fabrics in question correspondingly. Because the fiber densities in warp and weft directions are not the same, we have prepared composites with three different stacking sequences using each type of fabric, where B1, B2, and B3 respectively represent the first, the second, and the third type of stacking sequences, $[90_{we}/0_{wa}/90_{we}/0_{wa}]_s$, $[90_{wa}/0_{we}/90_{wa}/0_{we}]_s$, and $[90_{wa}/0_{we}/90_{we}/0_{wa}]_s$. Figure 2 yields the schematic drawing

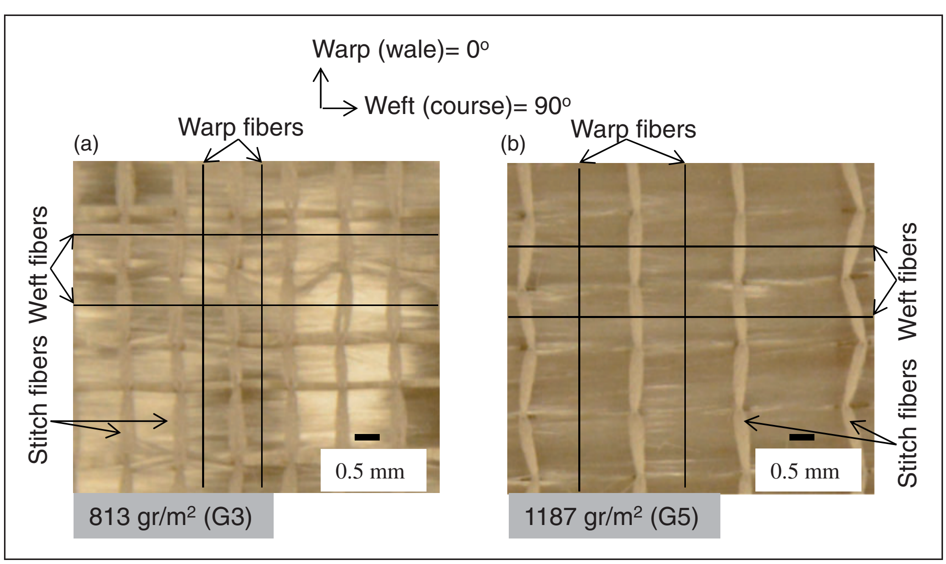

Figure 1. Biaxial warp-knitted reinforcement fabrics.

Table 1. Parameters of the biaxial warp-knitted (BWK) fabric reinforcements.

E glass samples	0° (warp) fibers, Tex	90° (weft) fibers, Tex	Area weight of 0° warp fibers (gr/m^2)	Area weight of 90° weft fibers (gr/m^2)	Area weight of stitch fibers (gr/m^2)	Fabric weight (warp, weft and stitch fibers) (gr/m^2)
LT800 E 10A 0/90 (G3)	900 + 1200 = 2100	900	413	390	10	813
LT1200E 05B 0/90 (G5)	2400	1200	566	614	7	1187

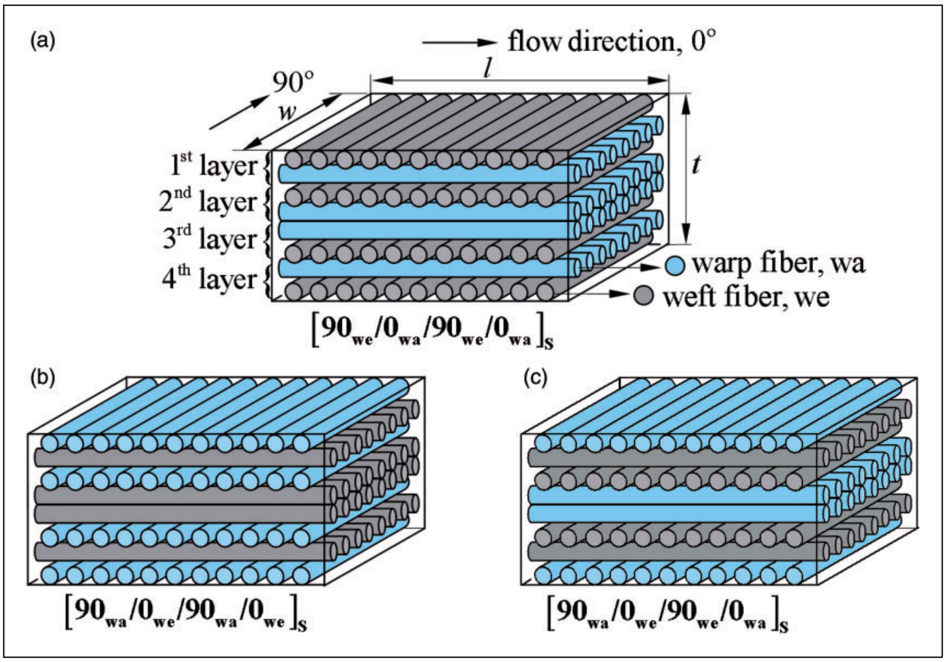

Figure 2. The schematic drawing for three different stacking sequences, namely, (a) B1, (b) B2, and (c) B3. Here, *l*, *w*, and *t* indicate the length, width, and the thickness of the manufactured composite plate.

Table 2. Fiber volume fraction and thickness of composites.

Specimens (composites)	Number of layers	Weft V_f (%)	Warp V_f (%)	Stitch V_f (%)	Total V_f (%)	Thickness (mm)
G3-B1	4	20.3	21.5	0.52	42.4	2.89
G3-B2	4	20.9	22.1	0.53	43.5	2.85
G3-B3	4	22.6	23.9	0.58	47.1	2.74
G5-B1	4	23.7	21.8	0.27	45.8	4.03
G5-B2	4	25.0	23.0	0.30	48.3	3.81
G5-B3	4	24.4	22.4	0.28	47.1	3.91

for three different stacking sequences. The total volume fractions of composite plates are about 45%. Composite volume fractions are found out by performing burn-out tests. Table 2 lists the volume fraction of manufactured composites.

The RTM method can produce high quality near net-shape parts with high fiber volume fractions, two high-quality surfaces, and requiring little post processing in a fully contained system that eliminates human operator exposure to chemicals and reduces the chance

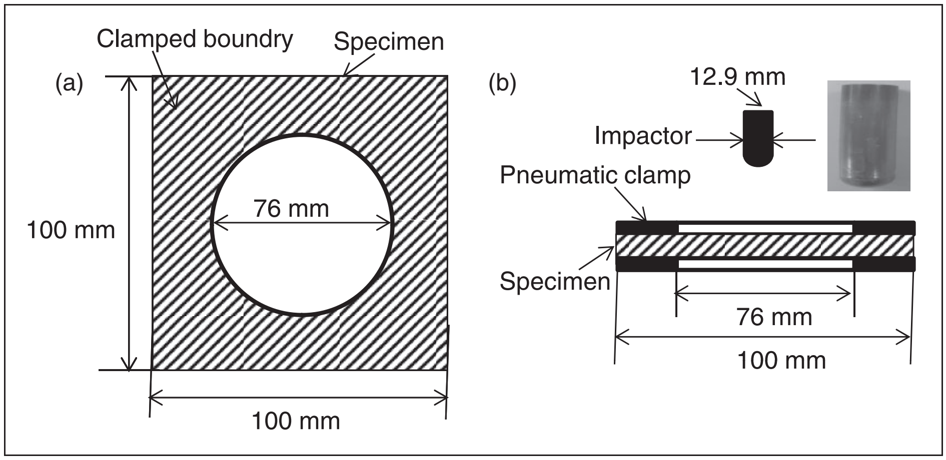

Figure 3. Schematic drawings of drop weight impact test set-up: (a) top view and (b) side view.

of human error. For these reasons, RTM has been selected to produce specimens for this study. In order to compare the specimens among each other, the fiber volume fraction of composites is kept constant by varying specimen thickness. The depth of the RTM mold cavity or equivalently the composite plate thickness is controlled through using steel plates of different thickness. The RTM apparatus is used to produce flat panels (620 mm × 320 mm) with different thickness. The manufactured panels undergo an initial cure at 65°C for 24 h with a post cure at 80°C for 24 h.

Mechanical characterization

The schematic drawings of drop weight impact test set-up are shown in Figure 3(a) to (b). The impact damages are inflicted on different specimens in a drop weight test using universal testing machine type Dynatup 9250HV, Instron. The drop weight is used as an impactor for the tests. The boundary of the impact specimens is clamped on all sides by a rectangular steel plate with 76 mm diameter circular hole. The center of the specimen was impacted by a striker with a narrow hemispherical indenter of 12.9 mm diameter. The arrangement in impact tests was intended to prevent any motion of the plate boundary, both in-plane and out-of-plane.

The weight of the impactor and incident impact energy are 6451 g and 44 J for the impact tests. The value of the utilized impact energy was chosen based on the experience gained during our previous drop weight impact test experiments on biaxial weft-knitted composites with 2.9 mm thickness.[14] If relatively low impact energy was applied to the specimens, the impactor would not be able to inflict the required damage on the specimens with the thicknesses of 3–4 mm. To be able to have a consistent experimental condition for all specimens, the single impact energy was used for all specimens regardless of their thickness. The composite coupons have a nominal dimension of 100 × 100 mm. The impact test measurements are performed at ambient conditions of 23 ± 2°C and 50 ± 5% relative humidity. Following the relevant literature,[28–31] the impact tests were conducted on a single sample for each type of composite panel.

Results and discussions

Microstructural observation of as-fabricated composites

The thickness-wise cross-sectional photographs of as-fabricated composites are shown in Figure 4(a) to (b). It can be seen that there are no voids in cross-section of the as-fabricated composites indicating the production of high-quality composites for this study. However, the voids seen in the fracture area of impact tested specimens (Figure 7) are the entrapped air bubbles created as a result of pouring the resin into the fracture area to prepare specimens for microstructural observation.

Impact properties of composites

Impact resistance is an important property for comparing the mechanical performance of composite samples. In literature, high energy absorption of the knitted composites due to the loop structure was reported. Figure 5 shows the load–displacement curves of samples with different fiber densities and stacking sequences, subjected to impact loading.

For the fabric type of G5, the highest peak load is recorded for the G5-B2 as 9008 N, the G5-B1 has slightly lower peak load as 8975 N than the G5-B2, and the lowest peak load belongs to the G5-B3 with the value of 8451 N. As for the fabric type of G3,

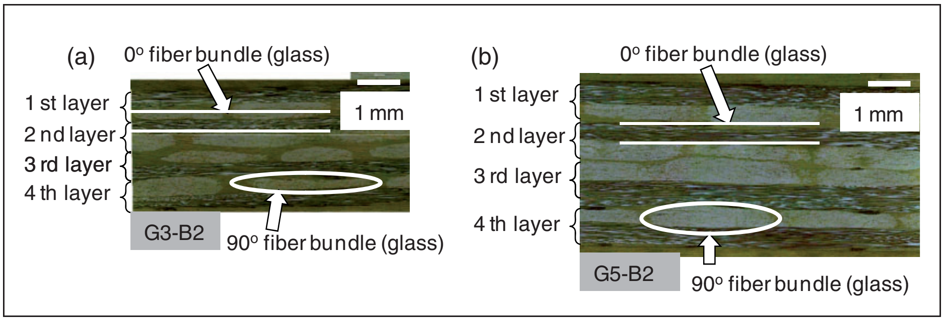

Figure 4. Cross-sectional photographs of as-fabricated composites of type (a) G3-B2 and (b) G5-B2. The cross-sections correspond to the right-hand side surface of Figure 2(b).

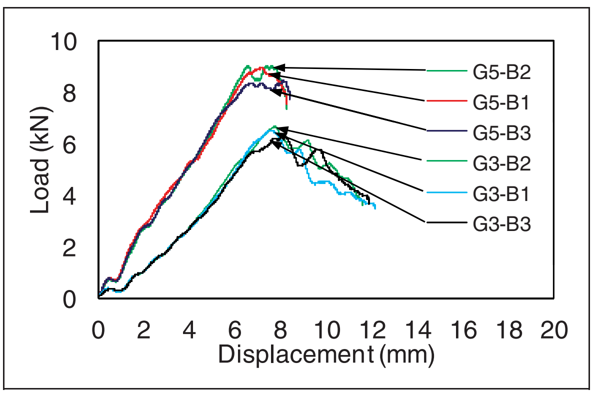

Figure 5. Load–displacement curves of impact loading for samples with different fiber densities and stacking sequences.

similarly, the G3-B2 has the highest peak load as 6668 N, while the peak load values for G3-B1 and G3-B3 are respectively 6514 N and 6319 N. Table 3 lists the impact properties for all these samples wherefrom one can see that all of the specimens have about the same total energy of around 43.3 J except G3-B3 specimens. Remembering that to compare the specimens among each other, the fiber volume fraction of composites is kept constant by varying specimen thickness. Hence, the thickness of G3-type and G5-type composites are different with G3 composites being thinner than G5 composites. To eliminate the effect of the thickness on the energy absorption, the results are also presented in terms of normalized absorbed energy thereby making the effect of the thickness on the results irrelevant. The specific or normalized total absorbed energy of a given specimen is obtained by dividing the total energy to the thickness and then provided in the same table as specific absorbed energy. It is found that the specimen labeled as G3-B2 has the highest specific absorbed energy (15.9 J/mm) of all other five composite types. Hereafter, the specific total absorbed energy will be tersely referred to as total absorbed energy. The ductile index (DI) is defined as the ratio of the propagation energy (energy after the maximum load) and initiation energy (energy up to maximum load).[32,33] The G3-B1 specimen has highest propagation energy of the other specimens, leading to DI of nearly 0.99. It can be seen from Table 3 that thin-ply laminate has higher DI than thick-ply laminate, implying better energy absorption ability of thin play laminate than the thick-ply one.

The total absorbed energy of G3-B2 and G5-B2 is respectively 15.9 J and 10.6 J, leading to a difference of roughly 33% in the total absorbed energy. This difference is caused by the lower warp and weft fiber densities (i.e., 413 and 390 g/m^2, respectively) in the G3 type of BWK fabric than those (i.e., 614 and 566 g/m^2, respectively) in G5 type of BWK fabric, which is shown in Table 1. Due to the inherent variability in composite materials mainly arising from the manufacturing process, the volume fractions of the composites were not able to be kept constant at the intended level. Naturally, these rather small variations in volume fraction may affect the results. However, the effect of volume fraction on the results is deemed to be negligible in comparison to the effect of fiber type and associated stacking sequence. That is to say, G5-type composite has higher volume fraction than G3 type, and hence, one may ideally expect that it should present better impact performance than G3 type, whereas it is just the otherwise. To this end, several reasons can be proposed for the better impact performance of thin-ply laminate than thick-ply laminate. The tow thickness of the thin-ply laminate is smaller than the thick one. Therefore, recalling the succinct literature review provided in the introduction, one should expect better load distribution in thin-ply laminate than the thick-ply one and also the thin-ply laminate can arrest microcracks better thereby showing improved resistance to micro-crack propagation and delamination.[20,21] Moreover, the tow of thin-ply laminate can be much easily and

Table 3. Impact properties of specimens subjected to drop weight impact test.

Samples	Max. load (kN)	Energy to max load (J)	Energy after max load (J)	Total energy (J)	Specific total absorbed energy/mm (J)	DI
G3-B1	6.51	21.8	21.6	43.4	15.4	0.99
G3-B2	6.67	23.0	20.5	43.5	15.9	0.89
G3-B3	6.32	24.5	15.8	40.3	14.1	0.65
G5-B1	8.98	34.0	9.30	43.3	9.90	0.27
G5-B2	9.01	35.3	8.00	43.3	10.6	0.23
G5-B3	8.45	41.0	2.20	43.2	10.5	0.05

DI = ductile index.

better impregnated by the resin, thereby enhancing the load transfer between the matrix and reinforcement. Rodini and Eisenmann[34] showed based on a probabilistic argument that a laminate having thick plies includes statistically more defects than laminates with thin plies. Hence, composites made of thicker plies are expected to fail at lower stress levels. The current results of impact tests are behaviorally in agreement with relevant other studies[20–27] which have investigated the effect of fiber densities on the tensile properties of composites and reported that thin-ply composites have higher mechanical properties than thick-ply composites. Additionally, the area weight of stitch fibers could be very important parameter on the energy absorption. G3 composites have higher area weight of stitch fibers ($10\,gr/m^2$) than G5 composites ($7\,gr/m^2$), which might further contribute to the higher impact energy absorption of G3 than G5.

The comparison of the total absorbed energies of three stacking sequences for the fabric G3 indicates that the composite with the B2 stacking sequence has the absorbed energy of (15.9 J) which is 3% and 11% higher than those for B1 and B3 stacking sequences (15.4 and 14.1 J), respectively. The total absorbed energy for G5-B2 (i.e., 10.6 J) is 6% and 1% higher than that for the G5-B1 and G5-B3 stacking sequences (i.e., 9.9 J and 10.5 J, respectively). These results indicate that the stacking sequence also affects the impact behavior of composites albeit being small in comparison to fabric type, which can be attributed to the change in the fracture behavior. Two possible reasoning for the effect of stacking sequence on the fracture performance might be considered, namely, the uniform distribution/ordering of weft fibers along the thickness direction, and that the weft fibers form the backbone of the laminate at the symmetry axis since the thickness of fibers influences the impact properties of composites recalling that the thinner the tow thickness, the higher the mechanical performance of composites.[21] In G3 and G5 fabric types, the thickness of warp fibers (2100 and 2400 tex, respectively) is much higher than the weft fibers (900 and 1200 tex). G3-B2 has better weft fiber distribution than G3-B3, thus leading to notable difference in the impact energy. Even though G3-B2 and G3-B1 have nearly similar and uniform weft fiber distribution, the backbone of the symmetry axis in G3-B2 is formed by the weft fibers leading higher impact energy than G3-B1. Similar reckoning holds true for G5 fabric type except the fact that G5-B2 and G5-B3 has nearly the same impact performance unlike G3-B2 and G3-B3. This difference might be attributed to that in G5-B3, the weft fibers having a higher area density than warp fibers form the interior structure of the laminate primarily. Referring to the rather small variability in the volume fraction, it can be concluded from the results that the variance in the volume fraction does not have a notable effect on the impact properties of composites as much as the stacking sequence does. Otherwise stated, for example, even though G3-B3 is of the largest volume fraction of the composites in the G3 family, it has the lowest impact performance. The consistency of the results with the relevant literature in terms of the fact that the thinner the tow thickness, the better the mechanical performance of composites bespeaks the reliability of the obtained results.

Knowing that the area under the load–displacement curve gives the absorbed energy during three-point bending test, the initiation energy is determined through calculating the area under load–displacement curve up to the maximum load, while the propagation energy is found out by computing the area under load–displacement curve after the maximum load. The values of the absorbed energies calculated from three-point bending test[30] are tabulated in Table 4. Considering fiber densities, composites with BWK fabric of G5 type has higher total absorbed energies than those with the G3 type of fabric in both 0° and 90° directions. G5-B1-type composite has the highest total absorbed energy (6.81 J) in the 0° direction. Among various stacking sequences in G5, composites with the B1-type stacking sequence has higher total absorbed

Table 4. Energies calculated from the results of three-point bending tests.[35]

Samples	Max. load (kN)	Energy to max load (J)	Energy after max load (J)	Total energy (J)	Specific total absorbed energy/mm (J)	DI
The length of the flexural specimen is along 0° direction						
G3-B1	1.03	2.90	0.54	3.44	1.11	0.19
G3-B2	0.95	2.59	0.97	3.56	1.19	0.38
G3-B3	1.06	3.11	0.59	3.70	1.23	0.19
G5-B1	1.35	4.64	2.18	6.81	1.58	0.47
G5-B2	1.36	4.89	1.03	5.93	1.48	0.21
G5-B3	1.33	4.71	0.85	5.56	1.36	0.19
The length of the flexural specimen is along 90° direction						
G3-B1	1.24	2.44	0.88	3.32	1.11	0.36
G3-B2	1.29	2.52	0.57	3.09	1.07	0.22
G3-B3	1.34	2.48	0.91	3.39	1.13	0.38
G5-B1	1.85	5.14	0.93	6.06	1.41	0.18
G5-B2	1.64	3.63	0.75	4.38	1.10	0.21
G5-B3	1.59	3.62	1.15	4.77	1.16	0.35

DI = ductile index.

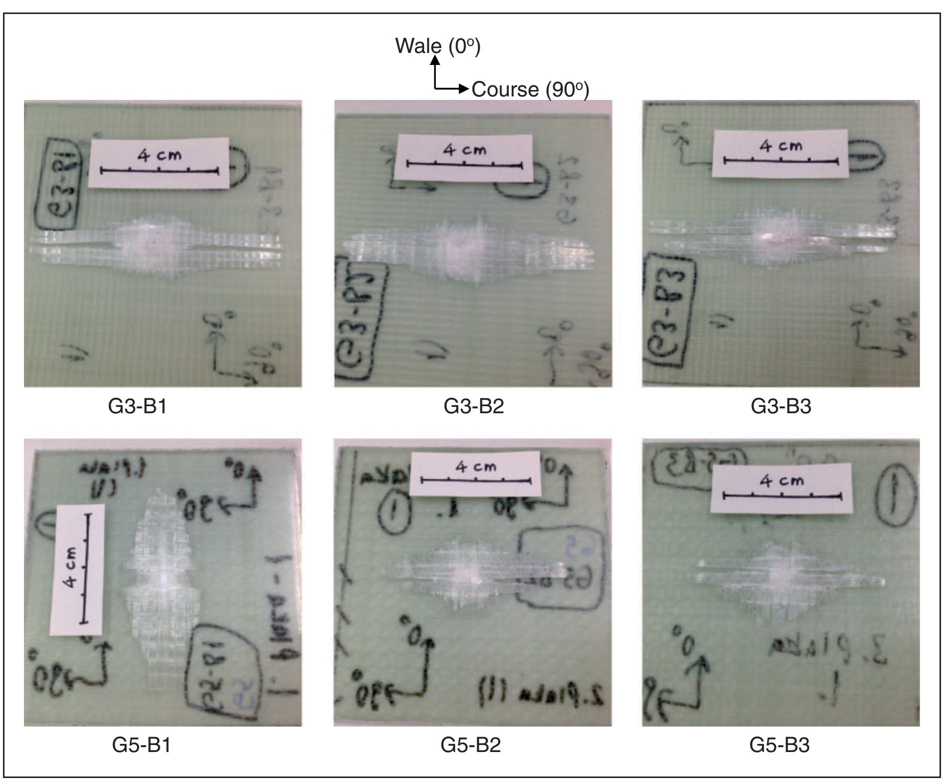

Figure 6. Fracture aspects of the reverse side of the drop weight impact tested specimens.

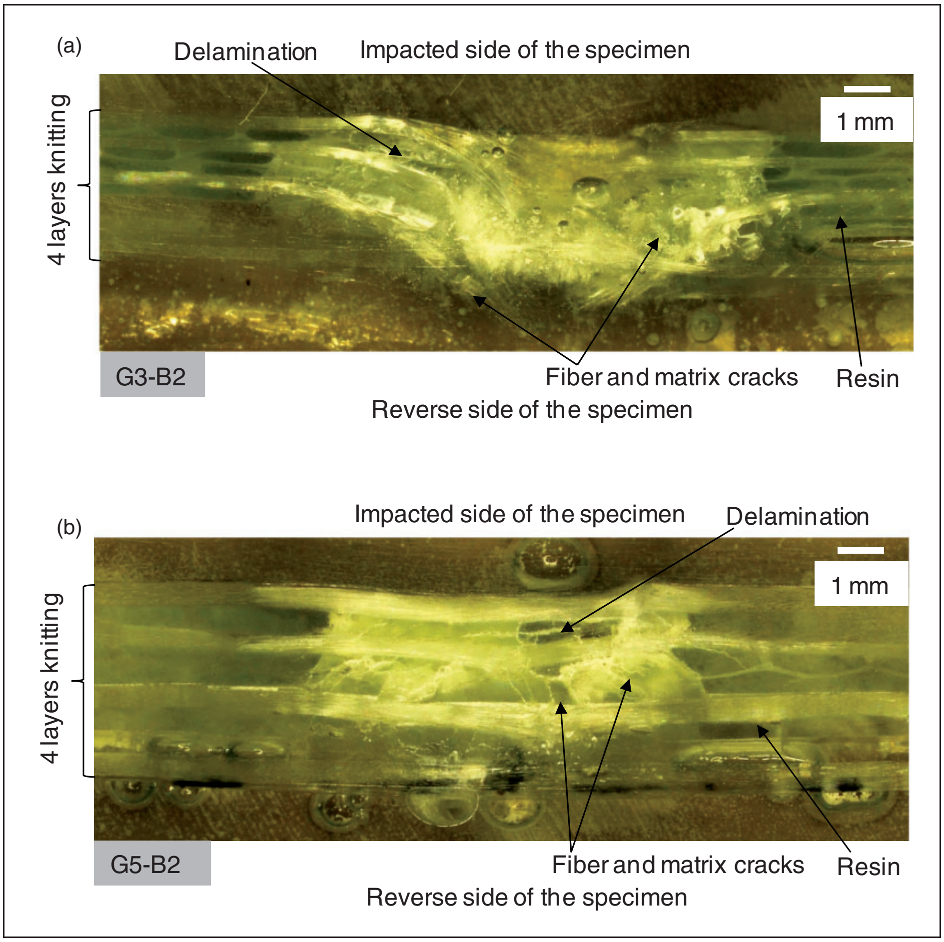

Figure 7. Cross-sectional photographs of the G3-B2 and G5-B2 specimens after drop weight impact test.

energy that those with the B2- and B3-type stacking sequences in both 0° and 90° directions. In flexural tests, composites with G5 fabric type have higher flexural strain values than those with G3 fabric type. Therefore, the computed total absorbed energies for G5-B1, G5-B2, and G5-B3 composites are bigger than those for G3-B1, G3-B2, and G3-B3 specimens in the 0° and 90° directions. The G5-B1 specimen has higher propagation energy compared to the other specimens in 0° direction, resulting in a high DI of 0.47.

Fracture images of specimens

The images of the reverse side of the drop weight impact tested specimens are presented in Figure 6. Due to enhanced impact properties in the composites with lower fiber densities, the damage area in the G3-B1, G3-B2, and G3-B3 composites is higher than the G5-B1, G5-B2, and G5-B3 composites. One may visually see that for G3-B1, G3-B2, and G3-B3 specimens, the crack propagation length is longer in the course direction since the impact energy could pervade easier in the course than the wale in view of smaller area weight for 90° weft fibers (390 g/m^2) than for 0° warp fiber (413 g/m^2). The same phenomenon can be extended for the composites with the G5 fabric type. Especially, in the G5-B1 type of composite, the crack propagation length is longer in the wale direction, which is prudently attributed to the fact that the area weight of the 0° warp fibers (566 g/m^2) is somewhat smaller than that of the 90° weft (614 g/m^2) and in turn, the impact energy could spread easier through the wale than the course.

Fracture damage characterization

The cross-sectional photographs of the G3-B2 and G5-B2 specimens after drop weight impact test are shown in Figure 7(a) to (b). Owing to the fact that composites with B2 stacking configuration show better impact performance than that with both B1 and B3 as given in Table 3, the G3-B2 and G5-B2 specimens have been selected as representative samples for the comparison of the fracture behavior of the composites.

The specimens were cut in the 90° (course) direction, and the cross-section of these composites was visualized under an optical microscope in the 0° (wale) direction. In these photographs, the impact load is applied from the upper side of the specimens. The highest intensity of the fiber breakages is observed near the impact point, entailing that the entire impact energy is spent for creating delaminations, fiber, and matrix fractures. The larger damage area is observed during the impact test of the G3-B2 specimen. This result further indicates that G3-B2 specimen with the lower fiber densities (BWK composites, thin-ply) absorbs more energy than the G5-B2 specimen (BWK composites, thick-ply).

Conclusions

This paper has experimentally studied impact behaviors of BWK composites. To this end, six different types of composites panel with two different fabric weights and with three different stacking sequences were chosen for impact tests. The impact load versus displacement curves and impact damage morphologies were used to analyze the influence of area density and stacking sequence on the impact energy absorptions. It was found that the BWK thin-ply composites with the lower weft and warp fiber densities could absorb higher impact energies compared to those with higher weft and warp fiber densities (thick-ply). Changing stacking configuration of fabric layers affects the impact properties of composites. It was shown that the effect of fiber densities on impact properties of BWK composites is more pronounced than that of fabric stacking sequences. The good agreements from the results of impact tests and fracture behavior of composites indicated the reliability and validity of the performed tests. The results obtained in this paper are deemed to contribute to future composite engineering.

Conflict of interest

None declared.

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References

1. Khondker OA, Fukui T, Nakai A, et al. Initial fracture of the welt weft-knitted textile composites. *Compos: Pt A* 2004; 35: 1185–1194.
2. Hamada H, Sukimoto K, Nakai A, et al. Mechanical properties of knitted fabric composites. *J Reinf Plast Compos* 2000; 19: 364–376.
3. Khondker OA, Yang X, Usui N, et al. Mechanical properties of textile-inserted PP/PP knitted composites using injection-compression. *Compos: Pt A* 2006; 37: 2285–2299.
4. Xue P, Yu TX and Tao XM. Tensile properties and meso-scale mechanism of weft knitted textile composites for energy absorption. *Compos: Pt A* 2002; 33: 113–123.
5. Pandita SD, Falconet D and Verpoest I. Impact properties of weft knitted fabric reinforced composites. *Compos Sci Technol* 2002; 62: 1113–1123.
6. Kocsis JK and Yuan Q. Transverse impact behaviour of knitted carbon fiber fabric reinforced thermoplastic composite sheets. *J Thermoplas Compos Mater* 1997; 10: 163–172.
7. Kocsis JK and Czigany T. Effect of the interface on the fracture and failure behaviour of knitted fabric reinforced composites produced from commingled GF/PP yarn. *Compos: Pt A* 1998; 29A: 1319–1330.
8. Khondker OA, Leong KH, Herszberg I, et al. Impact and compression-after-impact performance of weft-knitted glass textile composites. *Compos: Pt A* 2005; 32: 638–648.
9. Ramakrishna S, Hamada H, Cuong NK, et al. Mechanical properties of knitted fabric reinforced thermoplastic composites. In: *The 10th international conference on composite materials*, Whistler, BC, Canada, 1995, pp. 245–252. Sawston, Cambridge: Woodhead Publishing.
10. Ramakrishna S, Hamada H, Rydin RW, et al. Impact damage resistance of knitted glass fibre fabric reinforced polypropylene composites. *Sci Eng Compos Mater* 1995; 4: 61–72.
11. Karger-Kocsis J, Czigany T and Mayer J. Fracture behaviour and damage growth in knitted carbon fibre fabric reinforced polyethylmethacrylate. *Plas Rub Process Appl* 1996; 25: 109–114.
12. Li JJ, Sun BZ, Hu H, et al. Responses of 3D biaxial spacer weft-knitted composite circular plate under impact loading (part ii: impact tests and fem calculation). *J Text Inst* 2010; 101: 33–45.
13. Hufenbach W, Gude M and Ebert C. Hybrid 3D-textile reinforced composites with tailored property profiles for crash and impact applications. *Compos Sci Technol* 2009; 69: 1422–1426.
14. Demircan O, Kosui T, Shinsuke A, et al. Effect of stitch and biaxial yarn types on impact properties of biaxial weft knitted textile composites. *Sci Eng Compos Mater* 2013; 20: 255–264.
15. Pandita SD, Falconet D and Verpoest I. Impact properties of weft knitted fabric reinforced composites. *Compos Sci Technol* 2002; 62: 1113–1123.
16. Khashaba UA, Sebaey TA and Alnefaie KA. Failure and reliability analysis of pinned-joints composite laminates: effects of stacking sequence. *Compos: Pt B* 2013; 45: 1694–1703.
17. Aktas A and Dirikolu MH. The effect of stacking sequence of carbon epoxy composite laminates on pinned-joint strength. *Compos Struct* 2003; 62: 107–111.
18. Park HJ. Effects of stacking sequence and clamping force on the bearing strengths of mechanically fastened joints in composite laminates. *Compos Struct* 2001; 53: 213–221.

19. Mattsson D, Joffe R and Varna J. Damage in NCF composites under tension: effect of layer stacking sequence. *Eng Fract Mech* 2008; 75: 2666–2682.
20. Tsai SW, Sihn S and Kim RY. Thin-ply composites. In: *46th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics & materials conference*, Austin, Texas, 18–21 April 2005, pp. 1–5. Sawston, Cambridge: Woodhead Publishing.
21. Sihn S, Kim RY, Kawabe K, et al. Experimental studies of thin-ply laminated composites. *Compos Sci Technol* 2007; 67: 996–1008.
22. Guillamet G, Turon A, Costa J, et al. Damage occurrence at edges of non-crimp-fabric thin-ply laminates under off-axis uniaxial loading. *Compos Sci Technol* 2014; 98: 44–50.
23. Yokozeki T, Aoki Y and Ogasawara T. Experimental characterization of strength and damage resistance properties of thin-ply carbon fiber/toughened epoxy laminates. *Compos Struct* 2008; 82: 382–389.
24. Amacher R, Cugnoni J, Botsis J, et al. Thin-ply composites: experimental characterization and modeling of size-effects. *Compos Sci Technol* 2014; 101: 121–132.
25. Amacher R, Cugnoni J and Botsis J. Thin-ply composites: experimental characterization and modeling. In: *The 19th international conference on composite materials*, Montreal, Canada, 28 July–2 August 2013, pp. 1–13. Montreal, Canada: Canadian Association for Composite Structures and Materials.
26. Tan KT, Watanabe N, Iwahori Y, et al. Effect of stitch density and stitch thread thickness on compression after impact strength and response of stitched composites. *Compos Sci Technol* 2012; 72: 587–598.
27. Tan KT, Watanabe N and Ishikawa T. Effect of stitch density and stitch thread thickness on low-velocity impact damage of stitched composites. *Compos Pt: A* 2010; 41: 1857–1868.
28. Walker L, Sohn MS and Hu XZ. Improving impact resistance of carbon-fibre composites through interlaminar reinforcement. *Compos: Pt A* 2002; 33: 893–902.
29. Gao SL and Kim JK. Cooling rate influences in carbon fibre/PEEK composites. Part III: Impact damage performance. *Compos: Pt A* 2001; 32: 775–785.
30. Lee NJ and Jang J. The effect of fibre content on the mechanical properties of glass fibre mat/polypropyle composites. *Compos: Pt A* 1999; 30: 815–822.
31. Cheng KB, Lee KC, Ueng TH, et al. Electrical and impact properties of the hybrid knitted inlaid fabric reinforced polypropylene composites. *Compos: Pt A* 2002; 33: 1219–1226.
32. Yao L, Li W, Wang N, et al. Tensile, impact and dielectric properties of three dimensional orthogonal aramid/glass fiber hybrid composites. *J Mater Sci* 2007; 42: 6494–6500.
33. Kim JK and Xu TX. *Impact response and dynamic failure of composites and laminate materials Part 1: Impact damage and ballistic impact*. Switzerland: Trans Tech Publications, 1998.
34. Rodini JB and Eisenmann JR. An analytical and experimental investigation of edge delaminations in composite laminates. In: *Proceedings of the 4th conference fibrious composites*, San Diego, CA, November 1978.
35. Demircan O, Yılmaz C, Kocaman ES, et al. Tensile and bending properties of biaxial warp knitted textile composites. In: *1st joint Turkey-Japan workshop on polymeric composite materials*, Istanbul, Turkey, 12–13 May 2014, pp. 1–8.