A COMPARISON OF BULLET-PROOF BEHAVIORS BETWEEN THREE-DIMENSIONAL ANGLE-INTERLOCK WOVEN FABRIC AND ITS REINFORCED COMPOSITE

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1 Introduction

Due to the advantages of lighter weight and higher strength which compared with the conventional impact resistance materials, textile structural fabrics and their reinforced composites have been widely used in the field of bullet-proof [1-6]. Among them, three-dimensional angle interlock woven fabric (3DAWF) and its reinforced composite (3DAWC) have gained growing interest because of the high interlayer strength owing to the weft yarns are interlaced through the different layers of the warp yarns in the fabric architecture. The structure stability of 3DAWF is pretty good, and such structure may induce the impact energy propagates to the large area of the materials with high stress wave propagation speed. Therefore, the 3DAWF and 3DAWC have great potential in the body armors design.

For the mechanical properties of the 3DAWF and 3DAWC, Chen and Huang et al [7-8] studied the 3D angle-interlock woven structures and found that the fabric structure had a strong effect on the tensile strength and the dimensional stability of the composites. Whitney and Chang et al [9-10] developed different methods to study the elastic properties of 3DAWC. Tsai et al [11] investigated the tensile fatigue behavior of the 3DAWC. Sun et al [12] employed a split Hopkinson pressure bar (SHPB) apparatus to analyze the frequency of stress waves in testing 3DAWC at high strain rates. However, few researches were reported on the ballistic impact resistance behaviors of the 3DAWF and 3DAWC so far.

In this paper, a comparison of the bullet-proof behaviors between the 3DAWF and 3DAWC under different ballistic impact velocities are presented. The residual velocities of the projectiles after ballistic impact tests and the impact energy absorbed by both kinds of targets are given to compare the bullet-proof performances of the 3DAWF and 3DAWC. The ultimate ballistic impact damage morphologies of both types of targets are also presented to illustrate the impact energy absorption mechanisms.

2 Experimental

2.1 3DAWF and 3DAWC

Fig.1 shows sketch diagram of the 3DAWF architecture. Two adjacent layers of weft yarns are joined together by the weaving of the warp yarns. This structural feature imparts both the higher stiffness and strength to the thickness direction and in-plane direction. Table.1 lists the specifications of the fabric. Twaron® (a kind of aramid fiber) filament tows manufactured by Akzo Nobel were used for weaving. The linear density of warp yarn is 3360dtex and weft yarn is 6720dtex (tex is a basic textile unit of linear density --- the weight in grams of a fiber one kilometer in length. Units = g/km = (g/cm) × 10^{-5}, 10 dtex=1tex). The photographs of surface and cross-section of the 3DAWF are shown in Fig.2.

Unsaturated polyester resin was injected into the 3DAWF with vacuum assisted resin transfer molding (VARTM) technique to manufacture the 3DAWC. The fiber volume fraction of the composite is about 50%. The thickness of the composite panel is 8.64mm. Fig.3 shows the surface and cross-section of the 3DAWC.

2.2 Ballistic impact tests

Ballistic impact tests were conducted at No.53 Institute of China Ammunition Co. Ltd. As shown in Fig.4, the projectile of Type 56 (China Military Standard) was used for testing. The strike velocity of the projectile was adjusted by changing the weight of gunpowder. Four sides of the fabric or composite target plate were fixed in the testing. The impact point was located at the center of the target surface. The strike velocity and the residual velocity of the projectile were measured respectively with two laser-diode pairs.

For the 3DAWF, the strike velocities of the projectiles were 550m/s, 400m/s, 268m/s and 248m/s, respectively. And for the 3DAWC, the strike velocities of the projectiles were 550m/s, 395m/s, 276m/s, 238m/s and 210 m/s, respectively. The fabric and composite targets were perforated by the projectiles in the tests. Especially, the projectiles were captured by the targets under the ballistic impact velocity of 248m/s for the 3DAWF and the ballistic impact velocity of 210m/s for the 3DAWC.

3 Results and discussions

3.1 Comparisons of the residual velocities and impact energy absorption

The residual velocities of the projectiles after the ballistic impact tests for the 3DAWF and 3DAWC targets are shown in Fig. 5.

It is found that the residual velocities of the projectiles in the ballistic tests for the 3DAWC are less than those for the 3DAWF at the high ballistic impact velocities of approximately 400 m/s and 550 m/s, while it is converse at the low velocities of approximately 240 m/s and 270 m/s. This means the 3DAWC has a greater ballistic resistance performance than the 3DAWF at the high ballistic impact velocities. As well as a worse ballistic resistance performance at the relative lower velocities. This is characterized by the different deformation and damage magnitudes of two types of targets under different ballistic impact velocities. For the high ballistic impact velocities, the impact energy propagates to a large area of the 3DAWC at a high stress wave velocity during a very short period of time. This induces a large amount of impact energy absorbed by the composite target and therefore a large damage area. As for the 3DAWF, consider its structure which is different from the 3DAWC, the impact energy can't propagate to the large area during the relative short period of ballistic impact time. The absorption of the impact energy by the 3DAWF is less than that of the 3DAWC. As for the low ballistic impact velocities, it provides enough time for the deformation of the targets, especially for the 3DAWF. Its deformation magnitude is greater than that of the 3DAWC. This factor results in the absorption of a large amount of impact energy by the 3DAWF. In addition, it is found that the projectiles were captured by the targets at the ballistic velocities of 210 m/s and 248 m/s for the 3DAWC and 3DAWF respectively.

As shown in Fig. 6, the observations mentioned above can be further confirmed by investigating the absorbed impact energy of both targets. It indicates that impact energy absorbed by the 3DAWC is more than that absorbed by the 3DAWF at the high ballistic impact velocities of approximately 400 m/s and 550 m/s, and it is converse at others. It is also interesting to find the energy absorbed by the 3DAWF increases as the decrease of the ballistic impact velocity, which is also mainly due to the deformation and damage magnitudes of the targets.

3.2 Ballistic impact damage morphologies and mechanism of energy absorption

Fig. 7 presents the comparisons of ultimate ballistic impact damage morphologies between the 3DAWF and 3DAWC, which at the ballistic impact velocities of 550 m/s and 248 m/s for the 3DAWC, and 550 m/s and 210 m/s for the 3DAWF.

It indicates that deformation of the targets, yarns breakage and pulling out of the target surfaces，and matrix cracking (for 3DAWC only) are the main damage pattern of the 3DAWF and 3DAWC under ballistic impact.

Consider the residual velocity of the projectile is mainly determined by the deformation and damage magnitudes of the target. And due to the different impact damage mechanisms between the 3D fabric and composite. For the in-depth reasons for the 3DAWC has absorbed more energy than the 3DAWF under the relative higher ballistic velocities. It may due to the strain rate effect of the materials caused by the high velocity impact [13], which induces the impact energy propagates to the large

area of the target at a very high stress wave velocity during a relative short period of time, this leads to the absorption of a large amount of energy. And for the 3DAWC has absorbed less energy than the 3DAWF under the relative lower ballistic velocities. The strain rate effect is no longer donating the energy absorption, while the deformation of the target plays an important role. Therefore, the 3DAWF has absorbed more energy due to its larger area of deformation.

4 Conclusions

The comparisons of ballistic impact properties between the 3DAWF and 3DAWC were studied. The ballistic tests were conducted to measure the residual velocities of the projectiles and obtain the impact damage morphologies of both kinds of targets. The different energy absorption mechanisms between them were also presented. It was found that the 3DAWC has absorbed more energy than the 3DAWF under the relative higher ballistic velocities which may mainly due to the strain rate effect of the materials. And for the opposite phenomena under the relative lower ballistic velocities, the important role of the magnitudes of deformation and damage of the target should be taken into consideration.

Table1 Specifications of the 3DAWF

Yarns	Weaving density (ends/cm)	Length (mm)	Linear density (dtex)	Layers
Warp	8	192	1680×2plies	11
Weft	4	214	1680×4plies	12

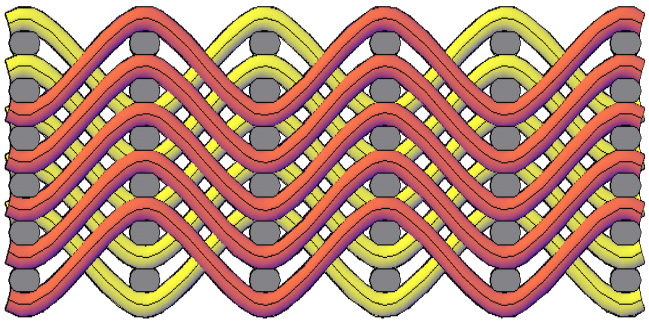
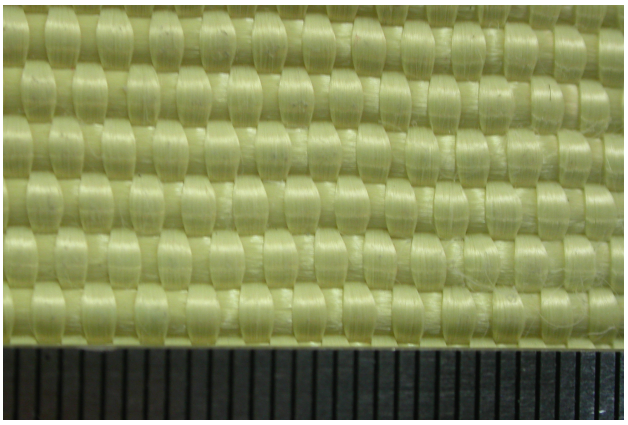
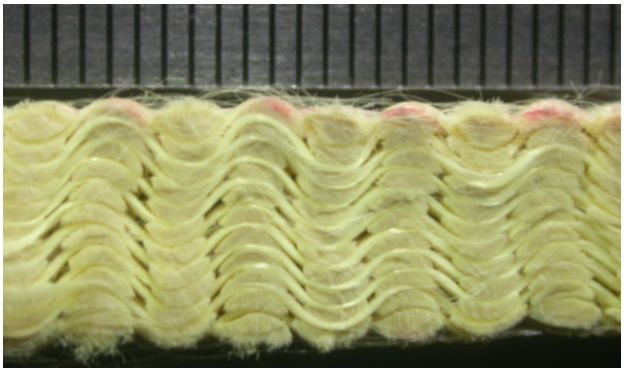


Fig.1 Sketch of the 3DAWF construction

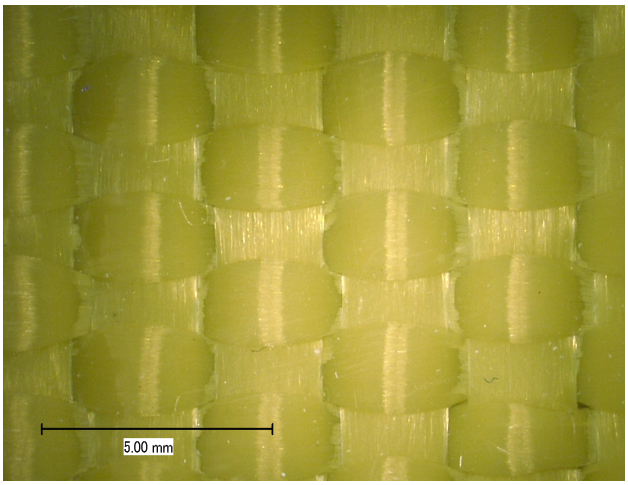


(a) Surface

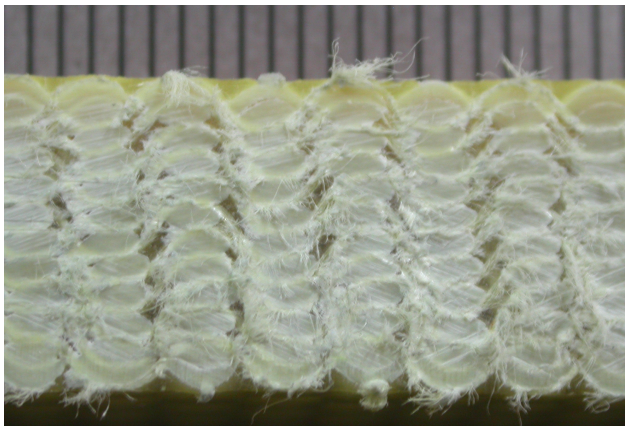


(b) Cross-section

Fig.2 Photographs of the 3DAWF



(a) Surface



(b) Cross-section

Fig.3 Photograph of the 3DAWC

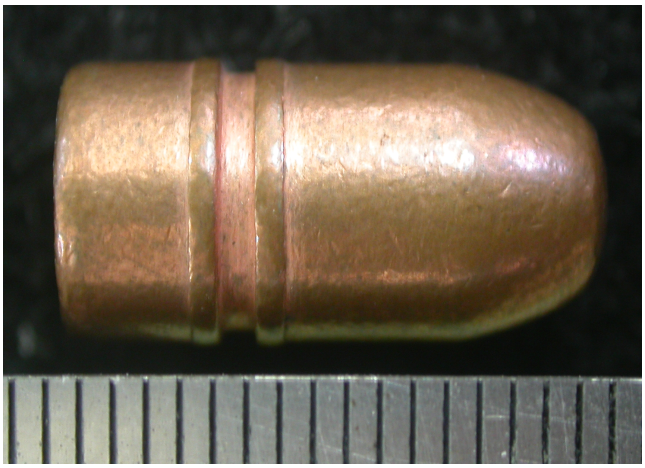


Fig.4 Projectile

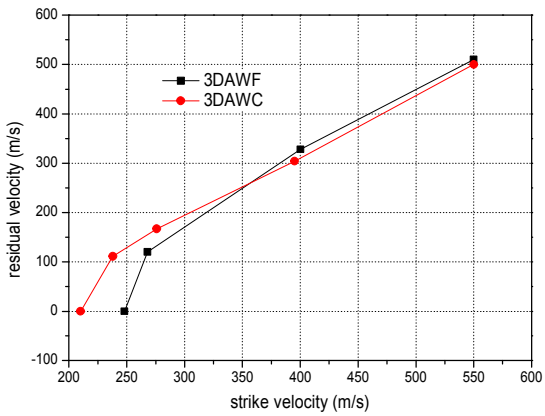


Fig.5 Comparison of strike velocity vs. residual velocity curves

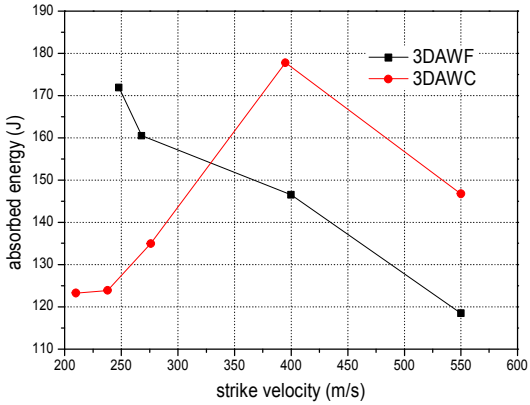
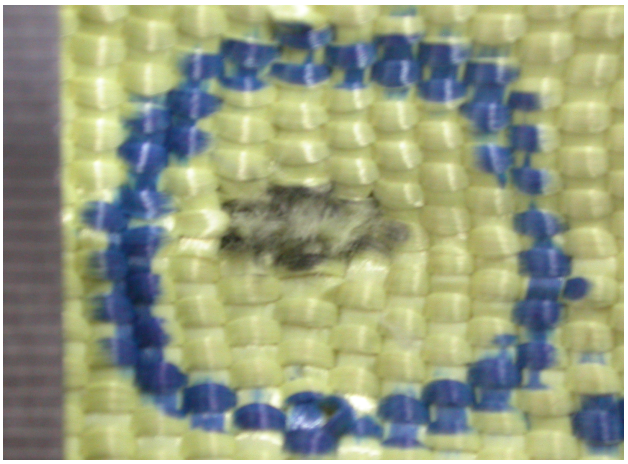
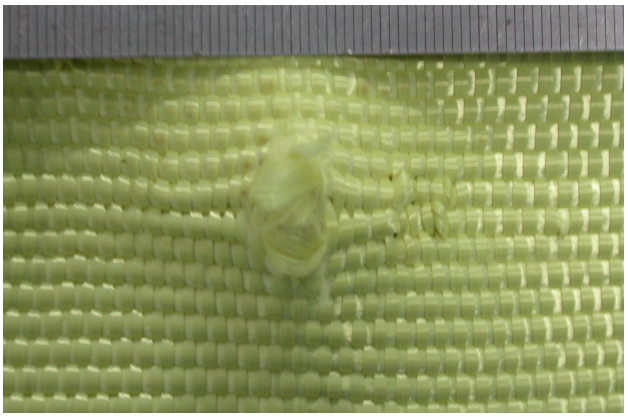


Fig.6 Comparison of absorbed energy vs. strike velocity curves

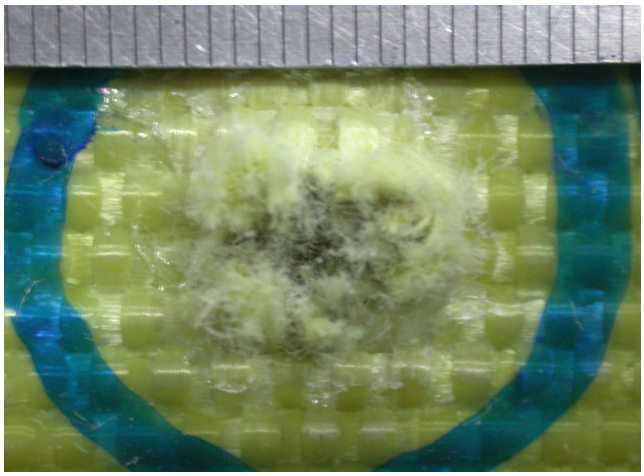


Striking side



Distal side

(a) 3DAWF (Vs=550 m/s)



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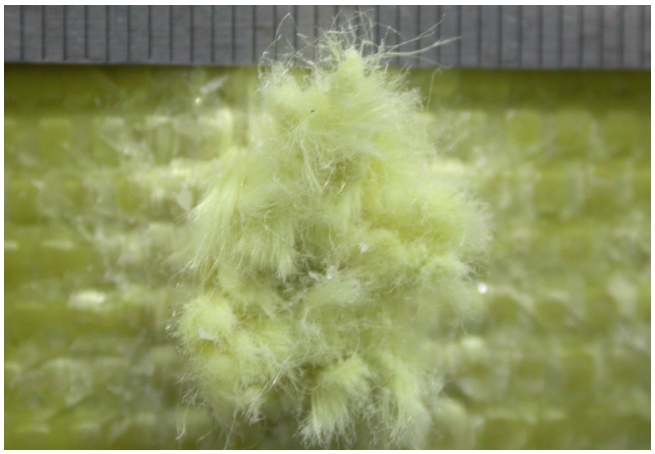
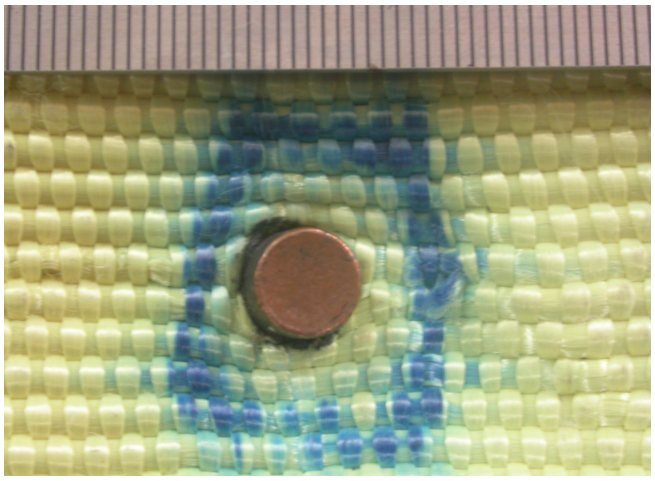


Distal side

（b）3DAWC (Vs=550 m/s)



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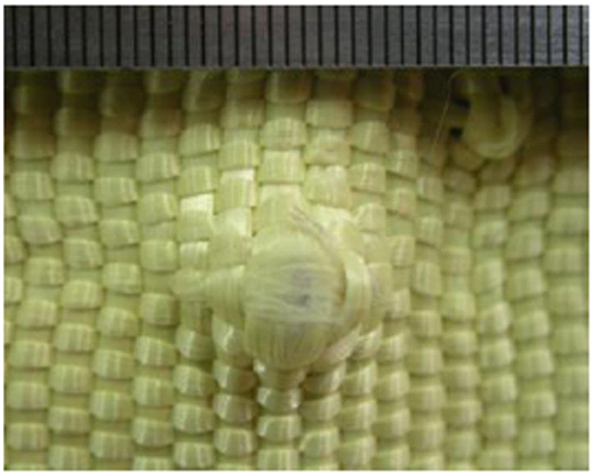
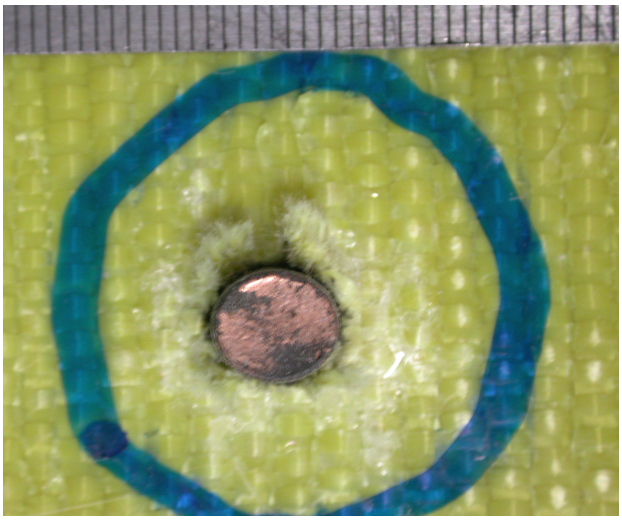
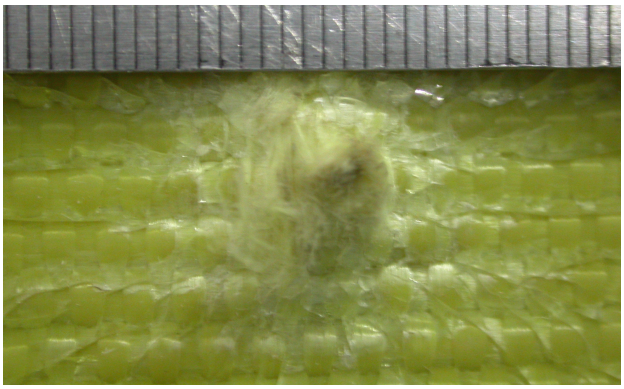


Distal side

(c) 3DAWF (Vs=248 m/s)



Striking side



Distal side

(d) 3DAWC (Vs=210 m/s)

Fig.7 Ballistic impact damage morphologies

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