COMPARATIVE ANALYSIS OF PHYSICAL PROPERTIES OF LAMINATED COMPOSITES AND 3-D WOVEN REINFORCED COMPOSITES UNDER ELASTIC IMPACT

by

Li WEI[a*], Jumei ZHAO[a], Weiqing JIANG[a], Chunqin MA[b], Qihu BU[b], Ni QI[c], Yuankun LIU[d], and Leigen LIU[e*]

[a]Textile and Clothing College, Yancheng Polytechnic College, Yancheng, China
[b]Jiangsu Yueda Textile Group Co., Ltd, Yancheng, China
[c]National Engineering Laboratory for Modern Silk, College of Textile and Clothing Engineering, Soochow University, Suzhou, China
[d]Beijing Aerospace Leite Electro-Mechanical Engineering Co., Ltd., Beijing, China
[e]Changshu Institute of Technology, Suzhou, China

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Glass fiber was used as warp and weft yarn of 3-D woven fabric, aramid fiber was used as Z-yarn to prepare 3-D orthogonal woven fabric, basalt fiber was used as warp and weft yarn of laminated fabric, and these two fabrics were used as reinforcing bodies, and vinyl resin was used as matrix to prepare reinforced composites. The ballistic impact tests of the two composite materials were carried out in the range of 310~790 m/s bullet initial velocity, and their anti-elastic energy was compared. The results show that the energy absorption value of the 3-D orthogonal woven composite is much larger than that of the basalt laminated composite, the residual velocity of the bullet after impacting the composite target is linear with the initial velocity.

Key words: *3-D woven fabric, laminated fabric, composite materials, impact*

Introduction

At present, there are many protective fabrics, such as bulletproof vest, bulletproof helmet, bulletproof insert plate, bulletproof shield, and armoured equipment, and extreme research has been carried out to achieve high protective performance. Nanomaterials such as carbon nanotubes [1-3] and nanofiber yarns [4] have been used to improve the protective performance. The nanofiber yarns are much cheaper than carbon nanotube yarns because they can be produced by bubble electrospinning [5-8].

In this paper, 3-D orthogonal woven composites and basalt fiber laminated composites were respectively prepared for ballistic impact experiment with the impact velocity between 310 m/s and 790 m/s. The experimental results were compared and analyzed to provide a theoretical basis for the development of new bulletproof materials and the design of reasonable bulletproof structures.

* Corresponding authors, e-mail: wlxzyc@126.com, liuleiyin@aliyun.com

Experimental

With unsaturated resin (vinyl resin) as the matrix, 3-D orthogonal woven fabric, and basalt fiber woven fabric as the reinforcing body, the reinforced composite material was prepared by vacuum-assisted resin transfer moulding [9]. The moulded 3-D woven reinforced composite was cut to 30 cm × 20 cm × 1.5 cm, and the basalt laminated composite was cut to 30 cm × 20 cm × 0.5 cm.

The ballistic impact tests of the two samples were conducted in the laboratory of Beijing Institute of Aerospace Test Technology. The front velocity measurement point was 3.3 m away from the composite target, and the projectile body and composite target were fired vertically. The projectile body selected was a Type 56 7.62 mm steel-core armour-piercing incense bomb with a mass of approximately 7.68 g and a diameter of approximately 7.60 mm. The design velocity of the projectile is adjusted by the amount of charge.

The 3-D orthogonal woven composite and the basalt laminated composite were subjected to five live-fire steel-core projectile impact tests, with the bullet velocity varying from 350 m/s to 800 m/s. When the bullet penetrated the composite target plate, there was no deformation and the bullet deformation and heat loss could be ignored. Then, the energy absorbed by the composite target plate is the kinetic energy loss of the projectile body, and the calculation formula is:

$$E_\mathrm{k} = \frac{m_p (V_s^2 - V_\mathrm{r}^2)}{2} \tag{1}$$

where m_p is the mass of the bullet, V_s – the incident velocity of the bullet, and V_r – the residual velocity of the bullet after it breaks through the composite target.

The impact energy of the composite material is evaluated by the V50 ballistic limit velocity, which is the arithmetic mean of all projectile velocities when 50% of the target plate is penetrated by the projectile body. Six shots are required, three shots are the highest velocity of the target plate but not penetrated, the other three shots are the lowest velocity of the penetration, and the difference between the highest and lowest velocity is not more than 50 m/s. The deformation of the projectiles is ignored during the test and the calculation formula is:

$$\frac{m_p V_\mathrm{r}^2}{2} = \frac{m_p (V_s^2 - V_{50}^2)}{2} \tag{2}$$

$$V_{50} = \sqrt{V_s^2 - V_\mathrm{r}^2} \tag{3}$$

The total energy absorption, E_a, is:

$$E_\mathrm{a} = \frac{m_p (V_s^2 - V_\mathrm{r}^2)}{2} \tag{4}$$

The energy absorption value BPI per unit surface density can also be used to evaluate the anti-elastic energy of composites. The BPI is the ratio of the absorbed energy of the composite target to the surface density of the target. The higher the BPI, the better the anti-elastic energy of the composite.

$$BPI = \frac{E_\mathrm{a}}{AD} \tag{5}$$

where AD is the surface density of the target plate.

Assuming that the energy absorbed by the projectile is absorbed by the target plate, and the energy absorbed by the target plate is absorbed by the material in the thickness direction, the corresponding theoretical calculation value is obtained, and calculated:

$$E_h = \frac{E_\mathrm{a}}{h} \tag{6}$$

where h is the thickness of the target plate.

Results and discussion

A composite material with a good bulletproof effect requires that the matrix and the fiber or filament reinforced composite material should have almost the same tensile strength and elongation, so that the textile structure reinforced composite material can absorb the highest bullet impact energy as much as possible. In addition, it also requires a good flame retardant, because the impact process generates high temperature due to high friction, so the composite material will heat up quickly. The composite material with higher requirements for high speed impact resistance is to optimize the matrix and the process, so that the energy absorbed can be maximized.

It is generally believed that the impact resistance is mainly because the reinforcement body (fabric structure) absorbs the impact energy of the bullet. After the bullet hits the target plate of the composite material, a stress wave is immediately generated at a certain position in the longitudinal direction of the fiber, and it will propagate along the longitudinal axis of the fiber. There is a functional relationship between the energy absorption rate of the composite target plate and the propagation velocity of the stress wave. When the bullet impacts the yarn in the normal direction, the longitudinal wave velocity can be calculated according to the formula of J. C. Smith's single yarn normal ballistic impact theory:

$$c = \sqrt{\frac{E}{\rho}} \tag{7}$$

where E is the elastic modulus of the fiber at high strain rate and ρ – the bulk density of the filament yarn.

From eq. (7) we can see that the wave velocity is directly proportional to the modulus of the fiber, but the higher the modulus, the higher the brittleness of the fiber. Once brittle fracture occurs, the absorption of strain energy is compromised. Therefore, the composite material with good elasticity must not only have a suitable modulus, but also have a certain fracture toughness, elongation at break and specific strength. If the direction of impact of the bullet is perpendicular to the longitudinal axis of the fiber in the composite target plate, the stress wave generated by the impact of the fiber will instantly propagate along the longitudinal axis of the fiber, reach the head and tail ends of the reinforced fiber, and then instantly turn into a strain wave reflected back along the original path near the point of impact of the bullet, driving the fiber or matrix in the same direction. Therefore, the tensile strain borne by the fiber is closely related to the impact velocity of the bullet. The stress wave formed after multiple reflections increases the tensile strain of the reinforced fiber, and finally makes the absorption value of the reinforced fiber to the bullet impact energy become larger and larger. At the same time, during the impact of the bullet on the composite material, the stress wave generated on the reinforced fiber will also propagate along the direction of the impact of the bullet, which can be called transverse seeding. If the stress generated on the fiber exceeds the yield point of the fiber, it will be destroyed and the fiber will fibrillate. This phenomenon will consume a certain amount of the bullet energy. Impact failure continues, the composite target plate will be penetrated by the bullet body if it is thin.

The ballistic test results of the 3-D orthogonal composite are shown in tab. 1 and the ballistic test results of the basalt laminated composite are shown in tab. 2. It can be clearly seen from tabs. 1 and 2 that the energy absorption value of 3-D orthogonal woven composites is much larger than that of basalt laminated composites, and the different spatial structure of the woven fabric between them is a factor that cannot be ignored, as shown in fig. 1. The main characteristics of 3-D orthogonal woven fabrics are that the warp and weft yarns are vertically arranged in the same plane, and the Z-yarn (bonding yarn) gives the stability of the 3-D orthogonal woven fabric structure in the thickness direction, so that the interlayer shear strength of the composite is significantly improved, the delamination phenomenon is reduced, and the impact resistance and bending fatigue of the 3-D orthogonal composite are improved. The basalt laminated composite limits the lateral movement of the filament fiber bundle due to its woven structure. Under high-speed impact, the elasticity resistance of the laminated composite is not as good as that of the 3-D orthogonal structure. The main reason is that the bending rigidity is too low, and there is no connecting fiber in the thickness direction, so it is easy to cause bending deformation and damage.

Table 1. Ballistic impact of 3-D woven fabric reinforced composites

No.	Projectile velocity before impact [ms^{-1}]	Projectile velocity after impact [ms^{-1}]	Projectile energy loss [J]	Composite material damage
L1	738	641	577.212	Penetration
L2	661	565	437.327	Penetration
L3	612	497	462.272	Penetration
L4	491	371	386.437	Penetration
L5	403	245	366.086	Penetration

Table 2. Ballistic impact of basalt fiber laminates

No.	Projectile velocity before impact [ms^{-1}]	Projectile velocity after impact [ms^{-1}]	Projectile energy loss [J]	Composite material damage
H1	744	699	249.675	Penetration
H2	676	610	326.348	Penetration
H3	602	535	292.908	Penetration
H4	476	437	136.909	Penetration
H5	357	317	103.661	Penetration

Although laminated to a certain extent, the composite material has a certain thickness, but this thickness is different from the thickness of the 3-D structure, because the 3-D is a whole in thickness, and the laminated composite material is formed by lamination. When the projectile body is affected by high-speed impact, the bound structure is not conducive to the stress wave propagation back and forth. As a result, its anti-elastic energy is reduced.

The bullet incident velocity-residual velocity curve is shown in fig. 1 and the composite incident velocity-absorbed energy curve is shown in fig. 2. Figure 1 shows that regardless of the material, the residual velocity after the bullet impacts the composite target plate is essentially linear with the initial velocity before the bullet impacts the composite target plate. The residual kinetic energy after the bullet impacts the composite target plate and the initial kinetic energy before the bullet impacts the composite target plate are also the same, which is consistent with the research conclusions of some scholars previously, and the penetration energy of the laminated plate is usually considered constant. Whether the elastic resistance of 3-D orthogonal woven composites is a fixed value remains to be investigated further. The relationship between the ultimate ballistic velocity V50 and the initial incident velocity is shown in fig. 3, and the trend of the curve variation is basically similar to the fitting curve of the incident velocity energy absorption curve.

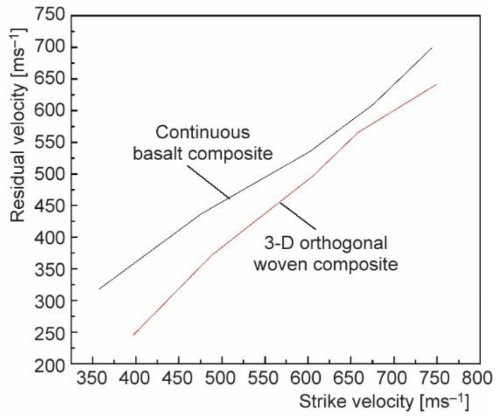

Figure 1. Velocity-residual velocity curve

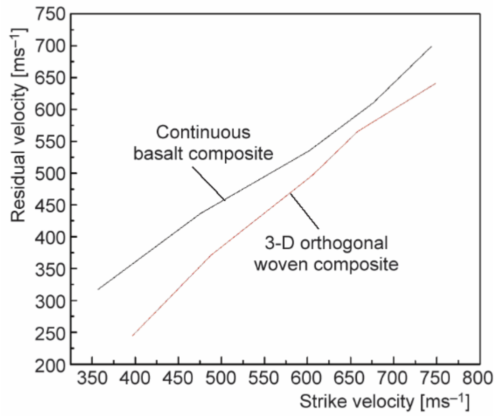

Figure 2. Strike velocity-absorption energy curve

Figure 3 shows that the energy absorbed by the 3-D woven reinforced composite is obviously higher than that of the basalt laminated composite during the bullet impact. Therefore, the 3-D woven reinforced composite has a better elastic resistance and is not easily hit by bullets. The main reason is that the bullet impact energy absorbed by the 3-D woven reinforced composite in the thickness is higher than that of the basalt laminated composite. It is sufficient to prove that the impact resistance of the basalt laminated composite is not sufficient due to the lack of binding yarn in the thickness direction. Therefore, it can be said that the thickness and the yarn in the thickness direction of the textile structure reinforced composite are not negligible factors for the impact resistance [10].

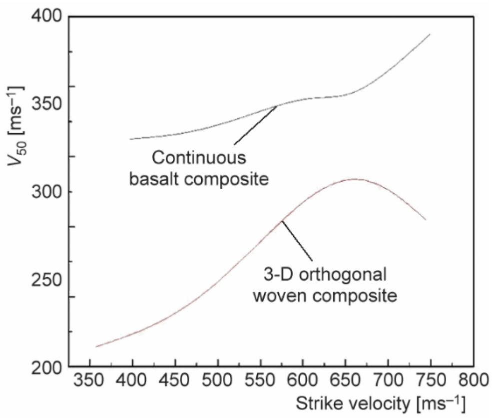

Figure 3. Ballistic limit velocity V_{50}-nitial strike velocity

Conclusions

During the impact of the bullet on the composite material, the stress wave generated on the reinforcement fiber will propagate along both the longitudinal and transverse directions of the reinforcement fiber, and the impact energy of the bullet will be consumed in this process.

The energy absorption value of 3-D orthogonal woven fabric composite is much higher than that of basalt laminated composite, the main reason being that there is a big difference in the mechanism of the reinforcing body. The thickness of the textile structure reinforced composite and the yarn in the thickness direction are not negligible factors in the impact resistance.

The residual velocity of the projectile after impacting the composite target plate is linearly related to the initial velocity of the projectile before impacting the composite, and the relationship between the final ballistic velocity V50 and the initial impact velocity is basically similar to the fitting curve of the impact velocity and energy absorption curve. The experimental results can be explained by the fractal theory, as those discussed in [11-13].

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References

[1] Zhang, M., *et al.*, Multifunctional Carbon Nanotube Yarns by Downsizing An Ancient Technology, *Science*, *306* (2004), Nov., pp. 1358-1361
[2] Miaudet, P., *et al.*, Hot-drAwing of Single and Multiwall Carbon Nanotube Fibers for High Toughness and Alignment, *Nano Letters*, *5* (2005), 11, pp. 2212-2215
[3] Zachariah, S. A., *et al.*, Experimental Analysis of the Effect of the Woven Aramid Fabric on the Strain to Failure Behavior of Plain Weaved Carbon/Aradmid Hydbrid Laminates, *Facta Universitatis, Series: Mechanical Engineering, 22* (2024), 1, pp. 13-24
[4] Dou, H., *et al.*, A Mathematical Model for the Blown Bubble-Spinning and Stab-Proof of Nanofibrous Yarn, *Thermal Science, 20* (2016), 3, pp. 813-817
[5] He, J.-H., *et al.* The Maximal Wrinkle Angle During the Bubble Collapse and Its Application to the Bubble Electrospinning, *Frontiers in Materials*, *8* (2022), 800567
[6] Qian, M. Y., He, J.-H., Collection of Polymer Bubble as a Nanoscale Membrane, *Surfaces and Interface*, *28* (2022), 101665
[7] Ali, M., *et al.*, Double Bubble Electrospinning: Patents and Nanoscale Interface, *Recent Patents on Nanotechnology, 18*, On-line first, https://doi.org/10.2174/0118722105259729231004040238, 2024
[8] Liu, G. L., *et al.*, Last Patents on Bubble Electrospinning, *Recent Patents on Nanotechnology, 14* (2020), 1, pp. 5-9
[9] Prabhakar, M. N., *et al.*, Surface Flame Retardancy of Clay Mineral Powder Infused Onto the Top of the Layer of Vinyl Ester/Bamboo Composites Through a Modified VARTM Process, *Polymer Testing, 132* (2024), 108367
[10] Flanagan, M. P., *et al.* An Experimental Investigation of High Velocity Impact and Penetration Failure Modes in Textile Composites, *Journal of Composite Materials, 33* (1999), 12, pp. 1080-1103

[11] Ji, F. Y., *et al.*, A Fractal Boussinesq Equation for Non-linear Transverse Vibration of a Nanofiber-Reinforced Concrete Pillar, *Applied Mathematical Modelling, 82* (2020), Jun., pp. 437-448
[12] He, C. H., Liu, C., Fractal Dimensions of a Porous Concrete and Its Effect on the Concrete's Strength, *Facta Universitatis Series: Mechanical Engineering, 21* (2023), 1, pp. 137-150;
[13] He, C. H., *et al.*, A Novel Bond Stress-Slip Model for 3-D Printed Concretes, *Discrete and Continuous Dynamical Systems-Series S, 15* (2022), 7, pp. 1669-1683

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