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Protective performance of shear stiffening gelmodified foam against ballistic impact: Experimental and numerical study

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Abstract

As one of the most widely used personal protective equipment (PPE), body armors play an important role in protecting the human body from the high-velocity impact of bullets or projectiles. The body torso and critical organs of the wear may suffer severe behind-armor blunt trauma (BABT) even though the impactor is stopped by the body armor. A type of novel composite material through incorporating shear stiffening gel (STG) into ethylene-vinyl acetate (EVA) foam is developed and used as buffer layers to reduce BABT. In this paper, the protective performance of body armors composed of fabric bulletproof layers and a buffer layer made of foam material is investigated both experimentally and numerically. The effectiveness of STG-modified EVA in damage relief is verified by ballistic tests. In parallel with the experimental study, numerical simulations are conducted by LS-DYNA® to investigate the dynamic response of each component and capture the key mechanical parameters, which are hardly obtained from field tests. To fully describe the material behavior under the transient impact, the selected constitutive models take the failure and strain rate effect into consideration. A good agreement between the experimental observations and numerical results is achieved to prove the validity of the modelling method. The tests and simulations show that the impact-induced deformation on the human body is significantly reduced by using STG-modified EVA as the buffering material. The improvement of protective performance is attributed to better dynamic properties and more outstanding energy absorption capability of the composite foam.

Keywords

Ballistic behavior; Composite foam; Shear stiffening gel; Finite element analysis; Protective mechanism.

1. Introduction

To meet the challenge of increasingly powerful weapons and more frequent conflicts, the development of novel personal protective equipment (PPE) with more outstanding performance is imperative [1-5]. As the most common manner, wearable body armor is effective in protecting human torsos from fatal wound caused by ballistic and projectile impacts. With interdisciplinary studies conducted in recent years, traditional

criteria for PPE are not of practicability and feasibility. One major reason is that the wearer could suffer severe behind-armor blunt trauma (BABT) even though the penetration of bullets is prevented by body armor [6-8]. Since the kinetic energy is not fully absorbed by bullet-proof components, residual deformation at the rear of armor is not avertible. Erosion, skin wounds, rib fractures and organic injuries will occur if the human body is highly compressed [9]. Therefore, improving the resistance to excessive deformation and lowering the risk of blunt trauma are of great significance for the development of advanced PPE.

In the design of body armor, buffer layers are normally equipped to relieve the contact pressure on body skin. The buffer material needs to possess excellent energy absorption capacity as well as lightness property, which satisfy the mobility and protective requirements of contemporary equipment. Soft materials with the above characteristics such as foam, rubber and fabric are widely manufactured as backing pads for blunt trauma reduction [10]. However, existing standards put forward higher protection requirements hardly achieved by conventional materials. Developing new buffer products with better performance tends to be the most effective way [11, 12]. Shear thickening material (STM) is a general designation of the materials owning unique phase-change characteristics with the external circumstance. In comparison with other polymers, the physical state of such materials is not steady and highly affected by the rate of loading [13-16]. As a kind of novel STM synthesized in recent years, shear thickening gel (STG) attracts the researchers' attention of academics and industries. STG is a jellylike agglomerate and exhibits viscous and plastic properties. Relative low modulus leads to the flowability and deformability of STG under normal conditions. However, instantly applied force will result in the phase transitions from the gel state to the rubbery state and then to the glassy state accompanied by the sharp rise of stiffness and the absorption of energy [17-19]. The in-depth studies discover that the fundamental mechanism of shear thickening behavior is the competitive relationship between the connectivity of molecular chains and the rate of external loading. As a large number of unstable boron-oxygen (B-O) chemical bonds formed in STG, molecular chains are easier to break under slow loads. If dynamic effects such as vibrations, impacts and shocks are applied, the deformation speed may exceed the rate of B-O cross-links breakage as well as denser networks due to molecular entanglement contribute to shaping the solid phase [20]. Furthermore, STG will recover to the gelatinous state after unloading.

Attributed to the excellent stress distribution ability of STM, making full use of the shear thickening property is regarded as a feasible method to improve the anti-impact performance [21]. International researchers have attempted diverse approaches to take full advantage of such material characteristic to resist impact effects. The studies at the initial stage focused on the enhancement of bulletproof performance. Impregnating shear thickening fluid (STF) into fabrics to improve the anti-impact capacity is the most commonly method reported in the literature [22-27]. Further modification through incorporating STG and STF into fabrics simultaneously was conducted by He et al. [28]. The effectiveness of such a combination in resisting highvelocity bullets has been proven in corresponding works. As introduced hereinbefore, the wearer will suffer severe blunt trauma even though the bullet is prevented by the body armor. To provide better protection for the human body, the emphasis of current research is shifted to buffer components. For instance, Tang et al. [29] used the encapsulated STG as an alternative of the foam buffer layer to protect the key organs. In comparison with traditional body armor, both the pressure and the deformation at the region shielded by STG were significantly reduced in the modified armor. However, the direct application of STG would result in substantial increase in selfweight, which undermined the mobility of wearers. To achieve an optimized balance between the performance and the weight, researchers adopted appropriate technique to synthesis novel soft materials by compounding STG with foam. Liu et al. [30] and Fan et al. [31] applied different fabrication methods to successfully introduce STG into polyurethane (PU) foam. The material properties at the aspects of impact resistance, electrical conductivity and hydrophobicity were improved by the modifying agent. In the previous study, the authors developed a new type of composite foam by blending STG with ethylene-vinyl acetate (EVA), which possessed outstanding mechanical properties and energy absorption [32]. Meanwhile, STG/EVA composite foam retained the basic morphological characteristics of the base material including softness, lightness and resilience. The enhancement of anti-impact resistance without extra weight promoted the potential application of the novel material in contemporary body armor. On the basis of existing works, STG/EVA

composite foam with two different STG contents (3% and 5%) was manufactured into buffering pads. The protective performance of body armor equipped with conventional and novel buffer layers was investigated by ballistic impact. Meanwhile, numerical studies were conducted to simulate the material behavior and dynamic response of the tested body armor under the impact of high-velocity bullet. In combination with experimental and numerical approaches, key parameters related to failure, damage and energy were systematically analyzed to deeply understand the impact-strengthening characteristic of STG/EVA composite foam.

2. Experimental work

2.1. Materials and specimens

Before testing, STG/EVA composite foam needs to be prepared and manufactured to plate specimens. The synthetic STG and all the other chemicals are supplied by CAS Mechanical Confidence Science and Technology Co., Ltd. (Beijing, China). The details have been provided in the previous study [32]. A brief introduction to the preparation process is presented as follows:

Step 1: Mix STG with raw materials of EVA at 100-120 °C for 10 min.

Step 2: Refine the stirred mixture in a milling machine.

Step 3: Foam the rolled mixture in a vulcanizing machine.

Step 4: Slice the foam block to buffer pads in 5 mm thick.

During the preparation of STG/EVA composite foam, two weight ratios of STG (3% and 5%) are included in this study to investigate the influence of additive amounts on material properties, especially dynamic and anti-impact characteristics. In addition, buffer pads made of conventional EVA are tested as benchmarks. The density of plain EVA, STG/EVA-3% and STG/EVA-5% foams is 0.065, 0.067 and 0.068 g/cm³, respectively. As schematically presented in Fig. 1, EVA foam possesses a cellular microstructure consisting of cellular units and voids. With STG incorporated into the EVA matrix, the basic morphology of STG/EVA composite foam on a micro-scale is not significantly changed except the size and the distribution of cells are more uniform. Furthermore, STG fills a portion of voids and combines with cellular structures in different forms, such as films, particles and filaments, which were



characterized through microscopic observations [32].

Fig. 1. Schematic diagram of EVA and STG/EVA foam

Fig. 2 presents the typic structure of contemporary armor, which consists of bulletproof layers, buffer layers and cloth for wrapping. The ballistic protection is mainly provided by the former two components. Attributed to the excellent strength-to-weight ratio and relatively low cost, ultra-high molecular weight polyethylene (UHMWPE) is widely selected as the bullet-resistant material in PPE. In this study, 43 orthotropic unidirectional UHMWPE layers with 0.148 mm layer thickness are prepared as bulletproof layers.



Fig. 2. Typic structure of a contemporary body armor

In consideration of the neglectable contribution of wrapping cloth to resist impact, the body armor for the ballistic test is composed of UHMWPE layers and a foam layer. The fabric layers are stapled peripherally and no interlayered adhesive is used for further bonding. The bulletproof layers and the buffer layer are stacked without extra adhesion. In total, three types of buffer pads made of plain EVA foam, and STG/EVA composite foam with 3% and 5% additive amounts are prepared for testing.

2.2. Experimental setup

The details of ballistic test are sketched in Fig. 3. The setup is in accordance with the Chinese GA-2 protection standard, which is the current standard for assessing the performance of PPE and is equivalent to US NIJ- IIIA. The Chinese Type 51 bullets (7.62 mm diameter, 5.60 g) are launched by a real gun and the prescribed striking velocity is 445 ± 10 m/s. The actual flying velocity of bullets is measured by a velometer based on the traveling time between two optical sensors. Moreover, a baffle is placed at the exit of the launcher to avoid the offset of trajectory. The tested body armor is fastened on the block of ballistic clay with fixing bands. The dimension of the protected area by the body armor is about 0.4 m \times 0.3 m (height \times width). Due to the similar mechanical properties, such kind of special clay is an applicable alternative of the human body in ballistic tests. It is widely accepted that the backface signature (BFS) is an effective indicator to quantify the severity of BABT caused by weapon effects [33]. Hence, the measurement of crater depth on the clay is indispensable after each shoot. In addition, the dynamic response of body armor at the impact point is filmed by a high-speed camera and the recording speed in the ballistic test is 100000 frame/s at a resolution of 768 pixel \times 576 pixel.



Fig. 3. Setup of the ballistic test.

3. Numerical simulation

In consideration of the instantaneity and complexity of the impact process, specified critical characteristics of the bullet and the body armor are hardly captured during the ballistic test, which would impede the in-depth analysis of dynamic responses. Hence, physical-based FEM is a powerful technique to simulate the mechanical behavior of materials in various loading conditions, especially under impact, shock and blast effects [34-36]. LS-DYNA[®] is a professional finite element software to solve nonlinear and dynamic problems in multiple fields. In this study, all investigated components including the bullet, the bulletproof layers, the buffer layer and the ballistic clay are preliminarily meshed in HyperMesh and then imported into LS-DYNA for subsequent calculations. Since great deformation and significant damage are involved during the impact process, the "Lagrange" solver with element erosion algorithm is applied in the whole model.

The "Eroding Surface to Surface Contact" is assigned as the contact mechanism between the steel jacket and the lead core as well as the bullet and the bulletproof layers. Such a algorithm is effective to model the element failure due to excessive stress, which allows the representation of the compressed metals and the damaged fabrics during the impact process. Working as an available algorithm for unglued joints, "Automatic Single Surface Contact" is selected to calculate the interfacial contact of bulletproof fabric-bulletproof fabric, bulletproof fabric-buffer foam and buffer foam-ballistic clay. Attributed to the symmetry of the dynamic response around the impacted region, only a quarter of the model is established to save computational resources and time. The modelling details of each component including geometric characteristics, material properties and mesh sizes are elaborated in the following sections.

3.1. Modelling of projectiles

To be consistent with the actual tests, the Chinese Type 51 bullet in the standard size is modelled. The core of the bullet is made of lead and covered by a layer of steel jacket. The bullet is divided into 29,200 solid elements with characteristic lengths around 0.25 mm.

Johnson-Cook model is the most widely used material to describe the strain-sensitive plasticity of metals in company with the strength gain with the strain rate [37]. The applicable range of Johnson-Cook model is from the quasi-static domain to the dynamic loading condition, which is capable of describing high-rate deformation of metallic material. Hence, such a material model is selected to represent the mechanical behavior of the lead core and the steel jacket. The mathematical expression of the Johnson-Cook model is shown in Eq.1.

$$\sigma_{y} = \left(A + B\overline{\varepsilon}^{p^{n}}\right) \left(1 + c \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{0}}\right) \left(1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)^{m}\right)$$
(1)

Where A, B, c, n and m are material parameters obtained from laboratory tests. The first and the second portion of the formula represent the elastic and plastic behavior under quasi-static and dynamic loading, respectively. While the last term reflects the influence of temperature on mechanical properties. Regarding the reference strain rate $\dot{\varepsilon}_0$ as a baseline, the increment of strength under dynamic effects can be quantified through the ratio of the loaded strain rate $\dot{\varepsilon}$ and the benchmarked strain rate $\dot{\varepsilon}_0$. Moreover, the temperature differences among the current temperature T, the room temperature T_{room} and the melt temperature T_{melt} play an important role in the mechanical performance.

The modified Johnson-Cook model is obtained by incorporating damage related parameters and it is implemented to calculate failure behavior of materials. The fracture criterion is based on the effective plastic strain that is accumulated during each integration cycle. Fracture will occur once the integrated damage index reaches 1. The calculation of failure strain is given in Eq. 2.

$$\varepsilon_{f} = \left(D_{1} + D_{2} \exp(D_{3}\sigma^{*})\right) \left(1 + D_{4} \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{0}}\right) \left(1 + D_{5} \left(\frac{T - T_{room}}{T_{melt} - T_{room}}\right)\right)$$
(2)

where D_1 to D_5 are damage constants from material tests, $\sigma^* = \overline{\sigma} / \sigma_{es}$ is the stress triaxiality ratio where $\overline{\sigma}$ is the hydrostatic stress.

However, under shock effects produced by hypervelocity impact or close-in explosions, conventional constitutive relationships based on elastic and plastic are out of practicability due to the transition of material state from solid to fluid-like [38]. Thus, equation of state (EOS) is required to calculate the material properties under transient shock waves. In consideration of the contact pressure on the bullet up to several GPa, the Gruneisen EOS is imposed on both the steel jacket and the lead core. and it is mathematically expressed as Eq. 3.

$$p = \frac{\rho_0 C^2 \mu \left[1 + \left(1 - \frac{\gamma_0}{2} \right) \mu - \frac{a}{2} \mu^2 \right]}{\left[1 - \left(S_1 - 1 \right) \mu - S_2 \frac{\mu^2}{\mu - 1} - S_3 \frac{\mu^3}{\left(\mu + 1 \right)^2} \right]^2} = (\gamma_0 + a\mu) E$$
(3)

Where *a*, *C*, *S*₁, *S*₂ and *S*₃ are experimental parameters; γ_0 is the unitless Gruneisen gamma; μ is the change of density under compression. All the required constants for modelling the dynamic response of the lead core and the steel jacket are reported in the published reference [39], as tabulated in Table 1.

Material	Johnson-cook parameters						
	A (MPa)	B (MPa)	С	n	m	$T_{\rm r}({\rm K})$	$T_{k}\left(\mathbf{K}\right)$
Steel jacket	792	510	0.014	0.26	1.03	294	1793
Lead core	11.34	10.4	0.0033	0.21	1.03	297	756
Material	Damage constants						
	D_1	D_2	D_3	D_4	D_5		
Steel jacket	0.05	3.44	-2.12	0.002	0.61		
Lead core	0.25	0	0	0	0		
Material	EOS parameters						
	С	S_1	S_2	S_3	${\gamma_0}$	а	
Steel jacket	0.4569	1.49	0	0	2.17	0.46	
Lead core	0.2006	1.429	0	0	2.74	0.47	

Table 1. Constitutive constants for the steel jacket and the lead core of the bullet [39].

3.2. Modelling of bulletproof layers

In the body armor used for field tests, 43 layers of UHWMPE fabric with 0.148 mm thickness are equipped for ballistic protection. To reproduce the interaction between two adjacent laminates, the whole ballistic protection part is divided to 48 sub-laminates without joints. An individual layer is composed of 19,500 hexahedron elements and the solid algorithm is assigned. Even though the average calculating time of solid elements is longer than that of shell elements, the simulation accuracy in the thickness direction can be improved. The meshes are refined and densified at the impact region to improve the calculation accuracy.

As a type of typical composite material, the behavior of UHWMPE material is orthotropic, where the in-plane and out-of-plane strength are of great difference. The strength and failure in each orientation is linear and uncoupled. A continuum constitutive model (MAT_COMPOSITE_DAMAGE) based on the linear elastic theory with brittle fracture is employed [40, 41]. The relationship between stress and strain is given in Eq. 4.

Where *E*, *G* and *v* are the young's modulus, shear modulus and Poisson ration, respectively. The subscript *a*, *b* and *c* represent the material axis directions, where *a* and *b* indicate the direction along and normal to the fiber in the plane of laminates, respectively, and *c* denotes the out-of-plane direction. The erosion algorithm is implemented to delete the elements whose effective strain reaches the critical value. By the deletion of failed elements, the damage evolution of UHMWPE can be simulated. In this study, the failure limit is set as 0.8 after several trail-and-error

processes. The material constants of UHWMPE shown in Table 2 are used to model the bulletproof layers, which come from the reference [42].

ρ	0.97 g/cm ³	-
E_{a}	46.6 GPa	_
$E_{b}=E_{c}$	2.6 GPa	_
$G_{ m ab}$	1.75 GPa	_
$G_{bc}=G_{ca}$	1.6 GPa	_
Vab	0.008	-
$v_{bc} \equiv v_{ca}$	0.044	

Table 2. Material parameters of UHMWPE bulletproof layers [42].

3.3. Modelling of buffer layers

In total, three types of buffer pads made of EVA, STG/EVA with 3% and 5% STG content are prepared and tested. The thickness of the foam layer is 5 mm and a unified meshing strategy is used to guarantee the consistency of elements. The buffer layer is divided into 390,000 solid elements with a progressive method to refine the model at the impact region.

The incorporation of STG into EVA matrix material leads to a significant sensitivity to the loading rate. Regular constitutive models aiming at the deformation and recovery behavior under quasi-static conditions can not describe the dynamic properties of the composite foam material. To effectively include the strain rate effect of composite foam, the "Fu-Chang Foam" material model is selected. The "Fu-Chang Foam" model applies to low and medium-density foam whose properties are rate dependent [37]. Attributed to the zero Poisson's ratio assumption, the computation follows one-dimensional material law and the uniaxial compression test results can be imported directly. Compared with other methods involving complex loading paths, the required data of the applied model is relatively accessible. The validity and applicability of the "Fu-Chang Foam" to simulate the dynamic behavior of foam materials have been well verified by various researchers and the key findings were reported in corresponding references [43-47]. The consistence between experimental

and numerical results presented in these published works proves that the "Fu-Chang Foam" model is an effective and proper model for strain-rate dependent foam materials. Due to the absence of material constants, the authors adopt experimental approaches to obtain the compressive properties of plain and modified foam under different strain rates, which are shown in Fig. 4. Two strain-rate levels are produced by a universal testing machine and a split Hopkinson pressure bar, respectively. The obtained stress-strain curves demonstrate that all types of foam are sensitive to the loading rate. It worth noting that the addition of STG contributes to the gain of strength. As shown in these two charts, the compressive property of STG/EVA-5% is best followed by STG/EVA-3% and the strength of plain EVA is lowest. The gap of strength between the plain and modified foam grows wider with the increasement of loading rate. Besides, no unloading data is required as the minimum strain rate loading curve is used as the alternative. Therefore, the test results presented in Fig. 4 without extra processing are imported into LS-DYNA® as the input data. The mathematical description of the "Fu-Chang Foam" model including the strain-rate effect is given in Eq. 5.





Fig. 4. Stress-train curves of foam under (a) low strain-rate and (b) high strain-rate uniaxial compression.

$$\dot{E}_{t}^{N} = \frac{\sigma}{\|\sigma\|} D_{0} \exp\left(-c_{0} \left[\frac{tr(\sigma S)}{\left(\|\sigma\|\right)^{2}}\right]^{2n_{0}}\right)$$
(5)

Where *E* is the strain tensor; σ is the stress tensor; *S* is the state variable; *N* represents the nonlinearity; D_0 , c_0 and n_0 are material constants.

3.4. Modelling of ballistic clay

Ballistic clay is a specialized material used as an alternative to the human body. The clay block is divided into 960,000 hexahedron elements with a size of around 0.6 mm. The "power-law-plasticity" constitutive model is capable of describing the strain-rate hardening property in the form of a power law function, which is consistent with the characteristics of the clay material. The applied model is verified to produce permanent deformation approximately equal to the experimental measurement [39]. Thus, the plastic deformation is the dominant index to represent the blunt trauma on the body. The stress-strain relationship is mathematically expressed as Eq. 6. All the required material parameters can be found in the reference [48] and are presented in Table 3.

$$\sigma_{v} = k(\varepsilon_{vp} + \overline{\varepsilon}^{p})^{n} \tag{6}$$

where ε_{yp} is the elastic strain; $\overline{\varepsilon}^{p}$ is the effective plastic strain; k is the strength coefficient; n is the hardening exponent.

ρ	1.539 g/cm ³	-
Ε	5.347 MPa	-
$\sigma_{ m y}$	0.01 MPa	-
v	0.49	_
k	0.3609 MPa	- (
n	0.1649	

Table 3. Material parameters of ballistic clay [48].

4. Results and discussion

4.1. Penetration of bulletproof layers

The ballistic protection is majorly provided by the bulletproof layers. The life safety of the wearer will suffer a fatal threat if the anti-impact fabrics are fully perforated. Hence, the penetration of the bullet into the body armor is a key indicator of protective performance. As shown in Fig. 5, the tested body armor is penetrated at the impact point by the bullet. The number of damaged layers is counted after each shoot and the results are summarized in Table 4. The first column in the table is the specimen number, which consists of three parts, viz., the type of ballistic fabric, the type of foam materials for buffering and the number of tests, respectively. For example, UHMWPE-STG/EVA-5% (01) denotes the first impact test on the body armor composed of UHMWPE bulletproof layers and a buffer pad made of STG/EVA-5% foam. The impact velocity in all tests meets the requirement of the Chinese GA-2 protection standard within the range of 445 \pm 10 m/s. It is observed that 10 layers of UHMWPE fabric are penetrated in all tests except UHMWPE-STG/EVA-3% (01). Hence, the stability of the test platform and the repeatability of test results can be well proven by the minor differences.



Fig. 5. Image of the post-test specimen.

Table 4. Number of UHMWPE layers penetrated by the bullet

Specimen no.	Impact velocity (m/s)	Number of penetrated layers
UHMWPE-EVA (01)	453.5	10
UHMWPE-EVA (02)	450.3	10
UHMWPE-STG/EVA-3% (01)	452.3	12
UHMWPE-STG/EVA-3% (02)	452.4	10
UHMWPE-STG/EVA-5% (01)	450.3	10
UHMWPE-STG/EVA-5% (02)	451.4	10

Experimental approach is the most straightforward method to investigate the protective performance of novel materials and equipment by applying actual weapon effects. However, the details of the transient response are hardly captured during the tests. With the help of computational software, the whole process of the ballistic test can be simulated by a well-built numerical model to provide various dynamic parameters. As the relation presented in Fig. 7, actual test results are indispensable to the verification of modelling methods while verified models are can be used for parametric analysis reversely. The numerical model shown in Fig. 6 is established to replicate the whole process of ballistic test. Ascribed to the symmetry of the problem, only a quarter of the model is involved in calculations for time saving. The size of the model is large enough to include the localized behavior and eliminate the boundary

effect. Moreover, the meshes in the central region are densified to improve accuracy. The initial velocity of the bullet is set as 450 m/s, which follows the test requirement. After the computations of all three types of body armor are completed, the verification of the modelling approach is conducted by comparing numerical results with test measurements. The comparative study on the post-impact bulletproof layers is conducted firstly. The diameter of bullet hole on UHMWPE fabrics from both the experimental measurement and the numerical simulations is equal to 7.6 mm, approximate to the diameter of bullets (7.62 mm). Fig. 8 is the damage pattern of bulletproof layers in different body armor simulated by the models. In all these figures, the bullet is stopped by the ballistic fabric and stuck in the 10th layer, which is consistent with the test observations. Furthermore, as shown in Fig. 9, the appearance of post-impact bullets is similar that is highly compressed to be thin plates. The consistent results with the actual tests are convincing proofs for the practicability of the applied modelling approach in this study. Concluded from the above experimental and numerical results, the change of buffer materials seems to have little influence on preventing the penetration behavior of the bullet. The ballistic protection is mainly provided by the UHMWPE laminates.



Fig. 6. Numerical model of the ballistic test.



Fig. 7. Comparison of bullet hole on UHMWPE between the test and the simulation.



Fig. 8. Cross-section of the damage for bulletproof layers of (a) UHMWPE-EVA, (b) UHMWPE-STG/EVA-3% and (c) UHMWPE-STG/EVA-5%.



Fig. 9. Comparison of the post-impact bullet between the test and the simulation.

4.2. Backface signature

Backface signature (BFS) is the most significant index to assess the protective performance of equipment, which represents the depth of deformation on the human body and reflects the severity of blunt trauma caused by bullet impact. The evaluation criterion for body armor adopted in international standards is commonly based on BFS obtained in ballistic tests. As shown in Fig. 10, the measurement of BFS that is the crater depth on the clay is taken by using a caliper after each test. The results of BFS obtained from actual tests are presented in Fig. 11. In comparison with plain EVA, the improvement in protective capacity using STG-reinforced foam is significant. The crater depth on the ballistic clay is averagely reduced by 39% and 42% for the buffer layer made of ST-EVA-3% and STG-EVA-5%, respectively. In addition, increasing the STG content from 3% to 5% leads to further enhancement of anti-impact performance, which demonstrates that STG indeed collaborates with EVA matrix material to resist external loading and make a contribution to consume impact energy. However, the optimized additive amount to achieve the best property is not discovered in this study, which will be investigated in future work.



Fig. 10. Measurement of BFS after the ballistic test.



Fig. 11. Results of BFS in ballistic tests.

In the numerical models, BFS is equal to the maximum deformation at the center of clay within the allotted calculation time. The BFS-time curves plotted in Fig. 12 demonstrate the process of crater formation during the bullet impact. Meanwhile, the errors between the experimental and numerical results are obtained based on Eq. 7. It clearly shows that the differences between BFS from actual tests and FEM simulations are acceptable, where the maximum deviation is around 30%. A possible reason for underestimating the crater depth of UHMWPE-EVA is that adopting the "Fu-Chang Foam" model to describe the material behavior of plain EVA might overly enhance the dynamic properties especially under high strain rate conditions. Whereas, due to the inherent sensitivity to strain rates, the response of STG/EVA composite foam is well modelled by using this constitutive equation. For novel foam materials possessing remarkable strain rate-related characteristics, the "Fu-Chang Foam" model is a potential option to simulate the dynamic behavior under impact effects. Based on the comparative study between experimental and numerical approaches, STG/EVA composite foam possess better ani-impact performance than that of plain EVA and thus is capable to provide more effective protection for the wearer.



Fig. 12. Results of BFS in numerical simulations.

Table 5.	Tested	and	simulated	BFS	results.
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Specimen no.	BFS in tests (mm)	BFS in simulations (mm)	Error	
UHMWPE-EVA (01)	12.4	8 32	30.0%	
UHMWPE-EVA (02)	11.4	0.52	50.070	
UHMWPE-STG/EVA-3% (01)	8.2	8 19	13.0%	
UHMWPE-STG/EVA-3% (02)	6.3	0.17		
UHMWPE-STG/EVA-5% (01)	8.1	7 31	6.7%	
UHMWPE-STG/EVA-5% (02)	5.6	,	0.770	

$$\eta = \frac{\left|X_{s} - \bar{X}_{t}\right|}{\bar{X}_{t}} \times 100\% \tag{7}$$

where η is the error; X_s is the simulation result; \overline{X}_t is the average value of the test results.

4.3. Energy absorption

Since the setup and initial condition of all tests are identical, the reduction of impactinduced crater depth on the ballistic clay indicates that better protection is provided by the novel body armor. From the experimental observations, the damage mode of UHMWPE layers among three types of body armor is quite similar, where the size of penetration holes is close to the diameter of the bullet and the number of perforated

layers keeps unchanged. Hence, the total energy consumed by the fabric material is considered approximately equal. The assumption is further confirmed by the numerical results. It is found that the total energy (the sum of kinetic energy and internal energy) of ballistic protection layers in three simulated cases is in the range of 22.1 to 23.2 J. The minor differences demonstrate that the majority of energy is consumed and transferred to the fabric composite through fracture, deformation and movement of fiber near the impact region [49, 50].

The damage pattern of different buffer pads is remarkably distinct, as the post-test images shown in Fig. 13. It is clear that the plain EVA pad suffers the most severe damage while the unrecoverable deformation on STG/EVA foam is comparatively smaller, which is ascribed to the differences in dynamic property. Moreover, it is worth noting that the affected area on each specimen tends to be different. The equivalent diameter of the damaged region D is a representative parameter to quantify the concentration of deformation. As the measurements presented in Fig. 13, the deformed area of UHMWPE-EVA specimens is the smallest followed by the armor equipped with STG/EVA-3%. The influenced area on STG/EVA-5% foam is the largest. Hence, the introduction of STG leads to the improvement of mechanical performance and thus enlarges the areal extent for loading bearing. For polymer composites, the variation of material properties is commonly induced by the change of microscopic characteristics. In this study, scanning electron microscope (SEM) is used to observe the microstructure of EVA and STG/EVA. As the first SEM image presented in Fig. 14, EVA is a typic cellular material composed of plenty of cellular units with cell edges and cell walls. Incorporation of STG into the matrix material does not transform the basic structural skeleton but change several micromorphological features. For instance, thicker cell structs and rougher cell walls are observed from the STG/EVA foam. These newly formed characteristics contribute to the enhancement of macroscopical mechanical properties. Besides, the connection between STG and EVA is the other potential factor to improve the integrity and continuity of the material. Due to the existence of these channels, the transmission of loading from the localized region to the surrounding area becomes more efficient. With a wider range of materials involved to bear external loading, STG/EVA composite foam exhibits better impact resistance.



Fig. 13. Images of post-test buffer layers.



Fig. 14. Microscopic structure of (a) EVA and (b) STG/EVA.

The change of deformation mode on the buffer pad affects the dynamic response of ballistic clay shielded by the armor. From the numerical models, the geometric configuration of craters formed on clay can be obtained. In addition to the depth at the impact point, the deformation along the radial direction is extracted for the three-dimensional reconstruction of the craters. Fig. 15 presents the 3D contours of impact-

induced craters in the simulations. The morphological characteristics are consistent with the experimental observations on the buffer layers, where the most concentrated deformation occurs on UHMWPE-EVA body armor while a boxy-shaped crater is formed at the rear of STG/EVA-5% buffer pad. Hence, under the same impact loading, the composite foam is more effective in damage reduction (relief of trauma) by lowering the maximum deformation (severe blunt trauma) and increasing the surficial area (slight wound).



Fig. 15. 3D configuration of craters on ballistic clay.

With the help of the numerical approach, quantitative analysis of energy-related parameters can be implemented, which is hardly captured in actual tests. Since the bullet and the striking velocity stay in same, the total energy imported into the whole system is identical. The proportion of energy absorbed by each component is a practical index to assess the protective performance of body armor and the corresponding simulated results are shown in Fig. 16. For the conventional body armor, the proportion of energy absorption by the ballistic layers, the buffer layer and the ballistic clay is 21%, 70% and 9%, respectively. If the STG/EVA-3% foam is applied as the buffer material, the buffer layer contributes a greater amount to the consumption and dissipation of impact loading, where the percentage is up to 96%. Further improvement of energy absorption capability is achieved by using STG/EVA-5% and the corresponding proportion is 98%. Such variation indicates that the impact effect directly acting on the protected target is remarkably reduced and the risk of severe blunt trauma is consequently lowered. It has to be noted that the above numerical findings are based on the simulation model established in this study. The change of material models and/or modelling method may produce the different results.



Fig. 16. Proportion of energy absorbed by different components of the body armor.

5. Conclusions

In this study, to verify the effectiveness of STG-modified EVA foam material in protecting the human body from the impact of bullets, ballistic tests following the existing standard are conducted on the body armor composed of UHMWPE composite fabric and buffer foam. Two types of composite foam by adding different amounts (3% and 5%) of STG as well as plain EVA are prepared and processed into buffer pads. A numerical approach based on the FEM technique is adopted to simulate the whole process of bullet impact on body armor. The modeling method is validated by the actual test results and a good agreement is achieved. The protective performance of the conventional and novel foam is investigated experimentally. To quantitatively analyze the dynamic behavior and damage characteristics, mechanical parameters related to deformation and energy are obtained from numerical models. The most significant findings from experimental observations and simulation results are summarized as follows:

(1) In comparison to plain EVA, STG-EVA composite foam possess better mechanical properties especially under high strain rate effects. Moreover, the increment of STG amount from 3% to 5% can further improve the compressibility of the material.

(2) BFS, the index to represent the severity of blunt trauma, is significantly reduced by replacing EVA with the composite foam and the average decreasing amplitude in STG/EVA-3% and STG/EVA-5% test group is up to 39% and 42%, respectively.

(3) Observed from the post-test specimens, the number of bulletproof layers penetrated by the bullet is almost the same even though the buffer material is changed. This phenomenon is also replicated by the numerical models. Hence, the buffer pads made of foam materials has a minor effect on preventing the penetration behavior of the bullet.

(4) The damage pattern of conventional and modified foam is of great difference, where the deformation on plain EVA is concentrated while the affected area on STG/EVA is larger. Based on the microscopic observations, it is found that the incorporation of STG changes the micro morphological characteristics and improves the integrity and continuity of the microstructure.

(5) Ascribed to different dynamic mechanical properties between plain and composite foam, the configuration of craters formed on the ballistic clay is varied. The maximum deformation is effectively reduced and the surficial area is extended. The change in geometric size represents that the severity of blunt trauma can be lower by STG/EVA composite foam.

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Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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Declaration of interests

 \boxtimes The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

□The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: