Design and bulletproof performance investigation on the ceramic/metal laminated composite

Bianhong Li¹,², Hongbin Deng¹, Xiangsheng Gao³ and Hanjun Gao²

Abstract
In the current study, seven types of laminated composites are designed to replace the existing 616 steel plate with 5 mm thickness for the bulletproof. An explicit dynamic finite element model is developed to simulate the bullet penetration process using ANSYS Workbench software. And a specific bulletproof coefficient, which considers the ultimate bulletproof speed and area density of the target plate, is proposed and calculated, and the overall bulletproof performances of the composites and 616 steel plate are compared. The specific bulletproof coefficients of seven composites are increased by 12.53%, 14.77%, 13.28%, 12.20%, 19.59%, 23.81%, and 20.67%, respectively. The type F is the optimal type among all the structures. Eventually, the optimal composites are validated under different bullet hit positions and double-bullet situations. Results show that all the seven composites and 616 steel with 5 mm thickness can effectively defend 5.62 mm bullets, and no damage or failure is observed. Although the impact stiffness and ultimate bulletproof speed are both decreased, the area density and density are also significantly decreased.

Keywords
ceramic/metal laminated composite, bulletproof performance, specific bulletproof coefficient, explicit dynamic simulation, FE method

Introduction
The use of military vehicle armor enhances the defensive ability of military vehicle and effectively improves the survival ability of military vehicle in the battlefield. From the beginning of the 20th century to the present, there are many forms of military vehicle armor in structure and material. The existing bulletproof materials mainly include metal bulletproof materials, ceramic plate bulletproof materials, high performance fiber composite bulletproof materials, and composite bulletproof materials. Ceramic–metal composite armor combines the brittle materials with high hardness and the ductile materials with high strength, which makes the materials structured and lightweight, and has good bulletproof effect. So far, many scholars have studied and discussed it.

The components of composite bulletproof materials learn from each other’s strengths and weaknesses in performance and produce synergistic effect, which can greatly improve their comprehensive performance compared with a single homogeneous material. The ceramic plate material can be used as the impact resistance front plate of high performance fiber composite bulletproof materials instead of heavy alloy materials in bulletproof armor.¹

¹School of Mechatronical Engineering, Beijing Institute of Technology, Beijing, People’s Republic of China
²State Key Laboratory of Virtual Reality Technology and Systems, School of Mechanical Engineering and Automation, Beihang University, Beijing, People’s Republic of China
³Beijing Key Laboratory of Advanced Manufacturing Technology, Beijing University of Technology, Beijing, People’s Republic of China

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Corresponding author:
Xiangsheng Gao, Beijing Key Laboratory of Advanced Manufacturing Technology, Beijing University of Technology, Beijing 100124, People’s Republic of China.
Email: gaoxsh@bjut.edu.cn

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At present, the research of composite bulletproof materials mainly focuses on the selection of material layer, the combination design of structure and the improvement of interlayer adhesion. Tekalur et al.\textsuperscript{3} combined polyurea (PU) with E-glass fiber-vinyl ester (EVE) composite materials, which are made into laminated or sandwich plate materials in different sequence. The damage form, damage degree, and real-time bending deformation of the plate after impact test are studied by three means of naked eye observation, microscope observation, and real-time observation. The results show that when the layer faces the impact tube, PU with the same thickness has better impact resistance than that of the single EVE material.

Guo and Zhao\textsuperscript{3} found that the composite armor having thickness ratio of 2.22 between ceramic and Fiber-reinforced polymer (FRP) layers is an excellent one with highest ballistic limit velocity in all laminated composite armors and its mass is 33\% lighter than that of 4340 steel target. Furthermore, it is found that the V 50 of composite armor with square honeycomb filled with ceramic ball and epoxy cores is 13\% higher than that without epoxy filled. Tepeduzu and Karakuzu\textsuperscript{4} studied ballistic performance of ceramic composite structures. The simulation results showed that the alumina/S2 glass/epoxy composites exhibit the highest ballistic performance among the studied composites.

Yao et al.\textsuperscript{5} found that a bonded ceramic/metal target exhibited better anti-penetration performance than an unbonded target, while the interfacial bonding conditions have little influence on the anti-penetration performance of a metal/metal composite target. López-Puente et al.\textsuperscript{6} demonstrated that there is an optimum adhesive layer thickness of alumina/aluminum armors for the best ballistic performance of the lightweight protection. Vila-Ortega et al.\textsuperscript{7} implemented the multi-scale optimization of hybrid metal/nonwoven shields for ballistic protection.

Abdullah and Cantwell investigated the high-velocity impact response of polypropylene-based fiber–metal laminates\textsuperscript{8} including glass fiber-reinforced polypropylene; they also analyzed the high-velocity impact response of composite and fiber-metal laminate (FML)-reinforced sandwich structures. Results showed that the novel systems offer excellent energy absorbing characteristics under high-velocity impact loading conditions.\textsuperscript{10} Bürger et al.\textsuperscript{11} presented a ballistic impact simulation of an armor-piercing projectile on hybrid ceramic/fiber-reinforced composite armor and implemented three different constitutive models into finite element (FE) analysis. And the simulation model was validated by experimental results. Hu et al.\textsuperscript{12} found that the ballistic performance of mosaic SiC/Ultra-High Molecular Weight Polyethylene (UHMWP) composite armors is significantly influenced by the geometry of mosaic SiC ceramics (cylindrical, hexagonal, and square mosaic) and the impact zone of front layer.

Some researchers studied the bulletproof performances through FE method. Hou et al.\textsuperscript{13} proposed a theoretical model of ballistic impact on light ceramic/metal armors; Alonso et al.\textsuperscript{14} developed an analytical model for the perforation of thick and thin thickness woven-laminates subjected to high-velocity impact. Fawaz et al.\textsuperscript{15} concluded that the distributions of global kinetic, internal, and total energy versus time are similar for normal and oblique impact, but the projectile erosion of oblique impact is slightly larger than that of normal impact.

Gregori et al.\textsuperscript{16} developed a simulation model to study the multilayer alumina/aramid fiber composite ballistic performance using a full-Lagrangian FE analysis with the software LS-DYNA (LS-DYNA SMP R11), and the impact tests were in good agreement with analytical and numerical modeling. Abtew et al.\textsuperscript{17} gave a review about ballistic impact mechanisms of textiles and fiber-reinforced composites impact responses, and summarized the main factors affecting the ballistic impact performances.

Plenty of tests and characterization method are needed to accurately assess the bulletproof properties of bulletproof composites, which has high cost and randomness. The numerical simulation method is simple in operation, adjustable in parameters, time-saving and labor-saving, and is not limited by objective conditions. It can evaluate the performance of sheet metal within a certain range. In this article, the bulletproof performance of a series of composite armors with different structures is analyzed and calculated by using “ANSYS Workbench 19.0 software, Explicit Dynamics Module”, and the structure with the best protective performance under the premise of the minimum weight and thickness is determined. It has certain engineering application value.

In this article, seven types of laminated composites are designed to replace the existing 616 steel plate with 5 mm thickness for the bulletproof. An explicit dynamic FE model is developed to simulate the bullet penetration process using ANSYS Workbench software. The bulletproof performances of the composites are investigated according to the simulation results. And a specific bulletproof coefficient, which considers the ultimate bulletproof speed and area density of the target plate, is proposed and calculated, and the overall bulletproof performances of the composites and 616 steel plate are compared. Then, the optimal composite structure is obtained. Eventually, the optimal composites are validated under different bullet hit positions and double-bullet situations.

**Modeling**

**Constitutive**

**Johnson–Holquist 2 model.** For the numerical simulation of high-speed impact experiments (impact velocity is more than 500 m/s) such as projectile penetration, armor piercing, and plane impact, Johnson–Holquist 2 (JH-2) model can well predict particle free surface velocity, shock wave profile, penetration depth, and residual velocity of projectile.
The JH-2 model can be used for brittle materials. The strength is usually an expression of the intact strength, fracture strength, strain rate, and damage.\textsuperscript{11,18}

The strength model is

\[
\sigma^* = \frac{\sigma_i}{C_3} = \frac{\sigma_i}{C_0} \left( \frac{\sigma_i}{C_3} \right) \left( 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right)
\]

where \(D\) is the strain rate and damage factor. When the material is undamaged \((D = 0)\), the equivalent stress is

\[
\sigma_i = A \left( \rho^* + \sigma_{m} \right)^N \left( 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right)
\]

When the material is completely broken \((D = 1)\), the equivalent stress is

\[
\sigma_i = B \left( \rho^* \right)^M \left( 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right)
\]

At the same time, the equivalent crushing strength is smaller than the maximum crushing strength. The material constant introduced in the strength model is \(A, B, C, M, N, \sigma_{m}, \sigma_{m}^{\max}\).

\(\rho^*\) is hydrostatic pressure, \(\rho^* = \rho/\rho_{\text{HEL}}\), \(\sigma_{m} = \sigma_{m}/\rho_{\text{HEL}}\), where \(\rho_{\text{HEL}}\) is the pressure component when the material is in Hugoniot elastic limit and \(\sigma_{m}\) is the maximum hydrostatic tensile stress.

The damage model in JH-2 constitutive model is the same as Johnson–Cook’s (JC), and the damage variable \(D\) can be expressed as

\[
D = \sum \left( \frac{\Delta \varepsilon_{\rho}}{\varepsilon_f} \right)
\]

where \(\Delta \varepsilon_{\rho}\) is the integral of the effective plastic strain within the word cycle and \(\varepsilon_f\) is the crushing plastic strain of the material under a certain pressure

\[
\varepsilon_f = D_1 \left( \rho^* + \sigma_{m} \right) / D_2
\]

Therefore, the material damage functions \(D_1\) and \(D_2\) are introduced into JH-2 damage model. Because the ceramic material will break when the strain is small, it is difficult to get the values of \(D_1\) and \(D_2\) through experiments, which can be obtained by numerical simulation.

\(JC\) model. JC model consists of two parts, the first part only deals with stress, which is given by the following formula\textsuperscript{19}

\[
\sigma_{eq} = (A + B\varepsilon_{eq}^n) \cdot \left( 1 + C \ln \left( \dot{\varepsilon}_{eq} \right) \right) \cdot (1 - T^m)
\]

\[
T^* = (T - T_r)/(T_m - T_r)
\]

where \(A, B, n, C, m\) is a model parameter, \(\sigma_{eq}\) is the equivalent stress, \(\varepsilon_{eq}\) is the equivalent plastic strain, \(\dot{\varepsilon}_{eq}\) is equivalent plastic strain rate, \(\dot{\varepsilon}_{eq} = \dot{\varepsilon}_{eq}/\dot{\varepsilon}_0\), \(\dot{\varepsilon}_0\) is the reference strain rate, \(\dot{\varepsilon}_{eq}\) is the strain rate, \(T_r\) is the reference temperature, here is 293 K, \(T_m\) is the melting point temperature of the material, and \(T\) is the test temperature.

The three terms on the right of the equation, respectively, represent the effect of equivalent plastic strain, strain rate, and temperature on flow stress. The second part is about the strain of fracture. The fracture strain is given by the following formula
\[ \varepsilon_f = [D_1 + D_2 \exp(D_3 \sigma^*)][1 + D_4 \ln \varepsilon_{eq}^*][1 + D_5 T^*] \]  

(8)

where \( \varepsilon_f \) is the effective fracture strain, \( D_i, i = 1, ..., 5 \) is the constant, \( \sigma^* = \sigma / \sigma_{eq} \) is the stress triaxiality, \( \sigma_{eq} \) is the average stress.

The damage parameters are given by the following formula

\[ D = \sum \frac{\Delta \varepsilon_{eq}}{\varepsilon_f} \]  

(9)

where \( \Delta \varepsilon_{eq} \) is the equivalent plastic strain increment of an integral cycle, \( \varepsilon_f \) is the effective fracture strain at the current time step, and damage parameter \( D \) is an accumulation. When \( D \) reaches 1, damage occurs and material element is deleted.

**Multilinear isotropic strengthening model.** The plastic deformation corresponds to the dislocation movement on the micro level. New dislocations are produced in the process of plastic deformation, and the interaction of dislocations increases the resistance of dislocation movement. This shows the strengthening of the material on the macro level and the change of the yield surface in the plastic mechanics.

The law of reinforcement is very complex, which is generally represented by a simplified model. At present, the widely used reinforcement models are isotropic reinforcement model and follow-up reinforcement model.

Therefore, the yield criterion can be written as following

\[ F = \left[ \frac{3}{2} \{s\}^T [M] \{s\} \right]^2 - \sigma_k = 0 \]  

(10)

where \( \{s\} \) is deviation stress and \( \sigma_k \) is the current yield stress.

**Modeling**

Composite bulletproof armor materials include 616 (22SiMn2TiB) bulletproof steel, Al\(_2\)O\(_3\) ceramics, foam plastic materials, glass fiber, 7075 aluminum alloy, and so on. The FE calculation modeling process is defined as follows:

(1) It defines the material parameters and selects the appropriate constitutive model of the material, in which the 616 bulletproof steel plate adopts the JC strength model and the state equation for simulation analysis, and the material parameters are shown in Table 1. The 99.5\% Al\(_2\)O\(_3\) bulletproof steel plate adopts the JH-2 strength model and the state equation for simulation analysis, and the material parameters are shown in Table 2. The polyureth plates are simulated by the multilinear enhancement model and the maximum strength failure model. The density of polyureth is 1265 kg/m\(^3\), and the tensile strength is 34.5 MPa. 7075 aluminium alloy mechanical properties is shown in Table 3.
(2) Mesh. In the direction of bulletproof armor thickness, the grid size is 0.0005 m, the grid size of bullet and ceramic block is 0.001 m, and the overall grid size is 0.0025 m. In order to improve the calculation efficiency, only set ceramic blocks in the penetration part, simplifying the ceramic blocks in other parts.

(3) Solution settings. Because bullet penetration only occurs in a short time, the end time of solution is set to 0.0003 s.

The main parameters of NATO standard rifle bullet are 5.56 mm / 45 SS109 (M855), lead core, exit velocity of bullet is 900 m/s, shooting distance is 30 m, because in the actual penetration experiment, only the bullet’s warhead is involved in the penetration, so only the bullet’s warhead is taken for simulation analysis. The penetration analysis is carried out by using explicit dynamics module in Workbench software. The unit size is set as 1 mm. Finally, 21,290 units are divided.

**Design of ceramic/metal composites.** According to the ceramic panel with high hardness in ceramic/composite/metal composite armor, the projectile is deformed and worn, and the ceramic cone is formed at the contact surface of projectile and target. The projectile and ceramic cone act on the composite/metal back plate together, which increases the penetration resistance of the projectile. The composite materials such as high toughness glass fiber can block and consume the kinetic energy. The alloy back plate with high strength plays a supporting role, and further consumes the rudimentary energy of the absorbing projectile and ceramic cone. Seven different combinations of ceramic/metal composites armor (A–G) are designed to simulate the bulletproof performance. The armor structure is shown in Figure 1, and the size is shown in Table 4.

**Different hit positions and double-bullet validation.** In order to study the bulletproof performance under different bullet hit positions, corresponding simulation is conducted by building three FE models. The selected structure of composite plate is shown in Figure 2. The impact points are shown in Figure 3.

According to literature,20 the evaluation of the effectiveness and invalidity of the target plate’s impact on the projectile is as follows: the distance between the two craters on the front of the target plate is less than 2.5 times of the bullet diameter, the target plate appears unqualified damage, and the second bullet is invalid; the distance between the crater edge on the front and edge of the target plate is less than 2.5 times of the bullet diameter, the unqualified damage is ineffective, and the qualified damage is effective; the second bullet that intersects or overlaps the two craters on the front of the target plate is not available.

According to literature,21 it is required that the hit number of 5 mm 616 steel target plate with the size of 500 × 600 mm² is 5. Our target plate is 190 × 190 mm²; therefore, two bullets are used to simulate the validation of the bulletproof performance under double-bullet impact.

Based on the above regulations, we set that the distance between the bullet point and the edge of the target plate is more than 20 mm, and the distance between the two bullets is also more than 20 mm. The double-bullet impact point positions are shown in Figure 4 below.

**Results and discussions**

The deformation contours of composites and 616 steel are shown in Figure 5. The bullet velocity changes with time.
are shown in Figure 6. Bulletproof performance comparison of seven composites and 616 steel is shown in Table 5. It shows that all the seven composites and 616 steel with 5 mm thickness can effectively defend 5.62 mm bullets, and no damage or failure is observed according to the simulation results. The maximum deformations of the target plate of type A to G are 16.19, 17.86, 17.86, 14.76, 15.35, 15.34, and 21.51 mm, respectively, and that of 616 steel with 5 mm thickness is 5.89 mm. The crater depths which is equal to the maximum deformation are correspondingly obtained.

Due to the same impact force, the impact stiffness is in inverse proportion to the maximum deformation. Thus, it can be calculated that compared with the 616 steel, the...
impact stiffness of type A to G are reduced by $-63.62\%$, $-67.02\%$, $-67.02\%$, $-60.09\%$, $-61.63\%$, $-61.60\%$, and $-72.62\%$, respectively.

Figure 6 shows that the bullet velocity rapidly decreases to 0 from 900 m/s and reverse, which generates the huge impact on the target plate. The contact time of type A, B, E, and F is 0.00024, 0.00028, 0.00027, and 0.00021 s, respectively.

The ultimate bulletproof speed is the maximum speed of the bullet that the target plate can defend. The ultimate bulletproof speed of the seven composites and 616 steel are 1002, 1056, 992, 1002, 1048, 1002, 1048, and 1080 m/s, respectively. The ultimate bulletproof speed of seven composites are reduced by $-7.22\%$, $-2.22\%$, $-8.15\%$, $-2.96\%$, $-7.22\%$, $-2.96\%$, and $-8.61\%$, respectively, comparing with the 616 steel.

Although the impact stiffness and ultimate bulletproof speed are both decreased, the area density and density (volume density) are also significantly decreased. The area density is reduced by $-23.51\%$, $-16.70\%$, $-25.52\%$, $-16.08\%$, $-28.03\%$, $-23.95\%$, and $-30.79\%$, and the density is reduced by $-65.46\%$, $-41.11\%$, $-65.52\%$, $-40.18\%$, $-37.95\%$, $-37.37\%$, and $-65.63\%$, respectively. The weight of the bulletproof plate evidently affects the maneuverability and carrying capacity of the armored vehicles. The designed composites can significantly reduce the weight of the bulletproof plate with the similar defending performance. A parameter, which is called specific bulletproof coefficient in this article, is used to comprehensively assess the overall performance of the bulletproof plate.

The specific bulletproof coefficient $s$ is expressed in equation (11)

$$s = \frac{\rho_v}{\rho_a} \frac{V_u^2}{A_1}$$

where $V_u$ is the ultimate bulletproof speed, $A_1$ is the unit area, and $\rho_v$ is the area density.

As is shown in Figure 7, the specific bulletproof coefficients of seven composites are increased by 12.53\%, 14.77\%, 13.28\%, 12.20\%, 19.59\%, 23.81\%, and 20.67\%, respectively. The type F is the optimal type among all the structures.

Therefore, the bulletproof mechanism of the composites can be summarized according to the simulation results. The laminates of Al$_2$O$_3$ ceramics, 7075 aluminum alloy, and 616 steel can effectively defend the NATO 5.56 mm diameter bullet, at the same time, the area density and density are significantly reduced, comparing with 616 steel plate with 5 mm thickness. The bulletproof mechanism of 616 steel is its high yield stress and fracture strength. With the certain thickness, the NATO 5.56 mm diameter bullet cannot damage the plate. While the laminates have the different mechanism. When the laminate is hit, the impact energy first damage the ceramics. A lot of energy is absorbed at this stage. The bullet with the rest kinetic energy continues to impact the metal layer behind the ceramics. Due to the smaller thickness and stiffness, the metal layer significantly deforms until the speed decreases to zero. The fracture of ceramics and the deformation of the metal layer absorb most of the impact energy. Therefore, the maximum displacement of the composite target plate is much larger than that of 616 steel plate.
Moreover, the specific bulletproof coefficient of type F and G is higher than that of type A and B, which indicates that putting the 7075 aluminium alloy behind the ceramics is more effective than putting it ahead of the ceramics. According to the comparison of type E and F, in the certain range, the specific bulletproof coefficient increases with the ceramics thickness.

Figure 8 shows the stresses of the composite with different hit positions. It indicates that the composite plate is effective when the bullet hits the different positions. The maximum stresses of three position are 1712, 1851, and 1873 MPa, respectively. The stresses all locate on the bottom 616 steel layer, which exceed the yield limit of the material. Therefore, plastic deformation occurs to the steel layer after the impact. Besides, position II has the highest impact stiffness among the three positions, and position III has the lowest one.

Figure 9 shows that when two bullets hit the target plate at the same time, the bullets do not penetrate the plate and the bottom layer is still damaged.

**Conclusions**

Seven types of laminated composites are designed to replace the existing 616 steel plate with 5 mm thickness for the bulletproof. An explicit dynamic FE model is developed to simulate the bullet penetration process using ANSYS Workbench software. The bulletproof
performances of the composites are investigated according to the simulation results. And a specific bulletproof coefficient, which considers the ultimate bulletproof speed and area density of the target plate, is proposed and calculated, and the overall bulletproof performances of the composites and 616 steel plate are compared. Then, the optimal composite structure is obtained. Eventually, the optimal composites are validated under different bullet hit positions and double-bullet situations. Several conclusions are drawn as follows:

1. It shows that all the seven composites and 616 steel with 5 mm thickness can effectively defend 5.62 mm bullets, and no damage or failure is observed according to the simulation results.

2. Although the impact stiffness and ultimate bulletproof speed are both decreased, the area density and density (volume density) are also significantly decreased. The area density is reduced by $-23.51\%$, $-16.70\%$, $-25.52\%$, $-16.08\%$, $-28.03\%$, $-23.95\%$, and $-30.79\%$, and the density is reduced by $-65.46\%$, $-41.11\%$, $-65.52\%$, $-40.18\%$, $-37.95\%$, $-37.37\%$, and $-65.63\%$, respectively.

3. The specific bulletproof coefficients of seven composites are increased by $12.53\%$, $14.77\%$, $13.28\%$, $12.20\%$, $19.59\%$, $23.81\%$, and $20.67\%$, respectively. The type F is the optimal type among all the structures.

4. The optimal composite plate is still effective when the bullet hits the different positions and two bullets hit the target plate at the same time.

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ORCID iD
Xiangsheng Gao https://orcid.org/0000-0001-5947-5826
Hanjun Gao https://orcid.org/0000-0002-7861-5932

References
1. Grujicic M, Arakere G, He T, et al. A ballistic material model for cross-plied unidirectional ultra-high molecular-weight polyethylene fiber-reinforced armor-grade composites. Mat Sci Eng A Struct 2008; 498(1–2): 231–241.
2. Tekalur SA, Shukla A and Shivakumar K. Blast resistance of polyurea based layered composite materials. Compos Struct 2008; 84: 271–281.
3. Guo C and Zhao G. Numerical simulation of ballistic impact on composite armours. Chin J Appl Mech 2013; 30: 96–100.
4. Tepeduzu B and Karakuzu R. Ballistic performance of ceramic/composite structures. Ceram Int 2019; 45(2): 1651–1660.
5. Yao R, Su F and Mao R. Influence of interfacial bonding conditions on the anti-penetration performance of ceramic/metal composite targets. Int J Mech Mater Des 2019; 15: 833–844.
6. López-Puente J, Arias A, Zaera R, et al. The effect of the thickness of the adhesive layer on the ballistic limit of ceramic/metal armours. An experimental and numerical study. Int J Impact Eng 2005; 32(1–4): 321–336.
7. Vila-Ortega J, Ridruejo A and Martinez-Hergueta F. Multi-scale numerical optimisation of hybrid metal/nonwoven shields for ballistic protection. Int J Impact Eng 2020; 138: 103478.
8. Abdullah MR and Cantwell WJ. The impact resistance of polypropylene-based fibre–metal laminates. Compos Sci Technol 2006; 66(11–12): 1682–1693.
9. Abdullah MR and Cantwell WJ. The impact resistance of fibre–metal laminates based on glass fiber reinforced polypropylene. Polym Compos 2006; 27(6): 700–708.
10. Reyes VG and Cantwell WJ. The high velocity impact response of composite and FML-reinforced sandwich structures. Compos Sci Technol 2004; 64(1): 35–54.
11. Bürger D, de Faria AR, de Almeida SFM, et al. Ballistic impact simulation of an armour-piercing projectile on hybrid structures.
ceramic/fiber reinforced composite armours. *Int J Impact Eng* 2012; 43: 63–77.

12. Hu D, Zhang Y, Shen Z, et al. Investigation on the ballistic behavior of mosaic SiC/UHMWPE composite armor systems. *Ceram Int* 2017; 43(13): 10368–10376.

13. Hou HL, Zhong Q and Zhu X. Investigation on analytical model of ballistic impact on light ceramic/metal lightweight armours. *J Ship Mech* 2015; 19(6): 723–736.

14. Alonso L, Navarro C and Garcia-Castillo SK. Analytical models for the perforation of thick and thin thickness woven-laminates subjected to high-velocity impact. *Compos B Eng* 2018; 143B: 292–300.

15. Fawaz Z, Zheng W and Behdinan K. Numerical simulation of normal and oblique ballistic impact on ceramic composite armours. *Compos Struct* 2004; 63(3–4): 387–395.

16. Gregori D, Scazzosi R, Nunes SG, et al. Analytical and numerical modelling of high-velocity impact on multilayer alumina/aramid fiber composite ballistic shields: improvement in modelling approaches. *Compos B Eng* 2020; 187: 107830.

17. Abtew MA, Boussu F, Bruniaux P, et al. Ballistic impact mechanisms—a review on textiles and fibre-reinforced composites impact responses. *Compos Struct* 2019; 223: 110966.

18. Johnson GR and Holmquist TJ. An improved computational constitutive model for brittle materials. *AIP Conf Proc* 1994; 309: 981–984.

19. Johnson GR and Cook WH. A constitutive model and data for metals subjected to large strains, high strain rate and high temperature. *Eng Fract Mech* 1983; 21: 541–548.

20. GJB 59.18:1988. Armored Vehicle Test Standard Anti Bullet Performance Test of Armor Plate.

21. GJB 1946a:2000. The Regulations of the Steel Plate Specification for 28Cr2Mo, 26simnmo and 22simn2tib (616) Used in Armor.