Bulletin of Environment, Pharmacology and Life Sciences
Bull. Env.Pharmacol. Life Sci., Vol 4 [Spl issue 1] 2015: 348-356

Online ISSN 2277-1808
Journal's URL:http://www.bepls.com
CODEN: BEPLAD
Global Impact Factor 0.533
Universal Impact Factor 0.9804

FULL LENGTH ARTICLE **OPEN ACCESS**

Simulation and Analysis of Steel Projectiles Impact with RB SIC-based composite ceramic plates

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ABSTRACT
Ceramics are brittle materials with a linear stress-strain curve and significantly higher compression strength comparing to their tensile strength. Ceramics are extremely abrasion-, and wear-resistant in low temperatures and also have a high hardness. Silicon carbide, among them,is characterized by high thermal conductance meeting the requirements of thermal applications and meanwhile, low thermal expansion and high hardness suitable for armor applications. This study aims at investigating the ballistic behavior of compound armors-that have beenmade ofreaction bonded silicon carbide-based ceramic as front layer and Dyneema/epoxy polymeric composite in three different thicknesses as supporting layer- through simulation using finite element softwares i.e. Ls-Dyna and HyperMesh, then the results of each experiment will be analyzed individually. In the next phase the obtained results from the simulations will be compared and their accuracy will be evaluated, and finally, the optimum design of armors based on the examined thicknesses will be investigated.
***Key Terms**: ceramic, Reaction Bonded Silicon Carbide (RB SIC), armor, Dyneema/Epoxy polymeric composite, Ballistic Range.*

INTRODUCTION

Development of armors dates back to 3000 BC when linen and later leather was used as protective covering. During 8th and 9th centuries Romans used steel armors which have advanced and strengthened in the course of time. Considering the use of ceramic, a relevant study conducted in 1918 showed that one-sixteenth inch glaze can enhance resistance to penetration of a steel plate. Ceramic was also used for protection of ammunition warehouses during World War I. But, it was not until World War II when the advantages of using ceramics for making armors were known[1]. The word "ceramic" originates from a Greek word: "keramos" which means pottery or a baked object. Before development of metals, early man used clay for making his needed tools. All inorganic materials excluding metals and their alloys in the range of polycrystals and glasses are categorized as ceramics. Ceramics are brittle materials with a linear stress-strain curve and significantly higher compression strength comparing to their tensile strength. Ceramics are extremely abrasion-, and wear-resistant in low temperatures and also have a high hardness. Ceramics rupture like as a brittle material. Silicon carbide, reaction bonded silicon carbide, titanium di-borid, and aluminum nitride are among widely-used ceramics in military applications[2].
Reaction bonded silicon carbide can meet a wide range of potential applications including thermal applications due to its high thermal conductance, low thermal expansion, and high specific strength; armor applications because of its outstanding hardness, high Young's modulus, and low density; moreover, abrasion-related applications in high temperatures thanks to its high hardness and resistance in high temperatures. Reaction bonded silicon carbide is a composite made of silicon carbide and silicon[3]. Apart from its main usage in metallurgy of abrasive and refractory materials, silicon carbide is used in the structural applications which require higher and thermal strength relative to weight. Considering the recent raising demand for effective energy in engines and need for replacing critical metals, and on the other hand, development of ceramic materials particularly for gas turbines, we will realize that the introduction of reaction bonded silicon carbide finds its roots in this necessity[4].

The properties of silicon carbide elements depend on material type. In the case of a fully dense silicon carbide composite, the material shows a good flexural strength in room temperature (400 mega-Pascal) and when decreases to 250 mega-Pascal keeps silicon melting point at a constant level (1410 ^{0}C). Young's modulus usually ranges from 350 to 400 giga-Pascal. The features like resistance to corrosion and wearing, high tolerance to a wide range of acids and bases, resistance to oxidation and abrasion, good resistance to thermal stresses due to lower thermal expansion coefficient, resistance to high temperatures, and a favorable dimension control, make this material an attractive choice in many applications[5].
It should be noted that the used projectile in the present study is J3 rifle bullet which is categorized into the group of small-mass, small-geometry, and high-speed projectiles. On the other hand, the properties of Dyneema polymer fibers are relatively better in comparison with Aramid (Kevlar) fibers which are specific to military applications. For this reason, a limited experimental and numerical data is available in the pertinent literature.
In order to verify the accuracy of the simulation results, the results of ballistic tests were used to compare and assess their compliance. It can be seen that the simulation results have acceptable consistency with the results. Furthermore, the indicated armor with more favorable ballistic performance and more appropriate weight comparing to other armors with different thicknesses of the ceramic layers is chosen as the optimum armor. The thickness optimization results are also compared with the findings of an analytical model which has a good consistency. Numerical simulation results are compatible with the existing tests and analytical model and it indicates the validity and accuracy of the assumptions made in simulation including materials selection, type of their behavior, geometrical model, meshing, contact surfaces, controls, etc. The percentage of logical error between the existing results and simulation often associates with simplifications and assumed hypotheses or lack of access to some experimental variables and parameters required for simulation inputs.

PROPERTIES OF DYNEEMA FIBERS

DSM Company used ultra high molecular weight poly ethylene for producing particular fibers with Dyneema trademark and exploited them in supplying its textiles. Dyneema has been widely used in various fields including military, aerospace, and shipbuilding industries. Dyneema fibers have significantly low density (about 0.97 gr/cm^3), while very high strength and favorable mechanical properties. Dyneema, at a certain weight, is 15 times stronger than steel and 40% stronger than aramid fibers (Kevlar). They show excellent stability and resistance to harsh working conditions. Due to lower specific density than water, they can float on the surface of water and this characteristic has made them an ideal option for armor and ballistic applications on the water or out of it.

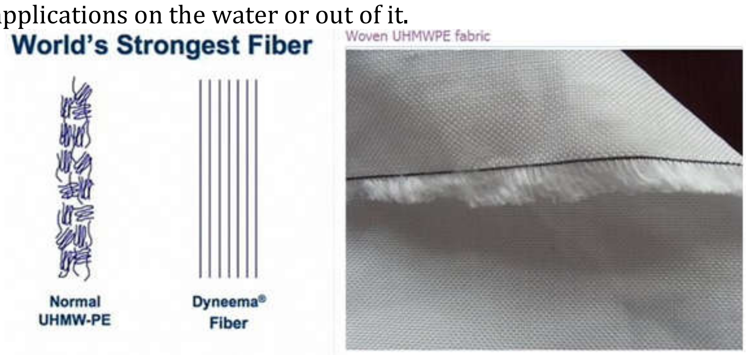

Figure 1: (a) Dyneema woven Fibers (b) comparing Dyneema fibers with conventional fibers

Dyneema fibers are supplied in various types and for wide different applications. HB type is used in constructing armored sections of combat aircrafts, ships, and troop carriers. These fibers are extremely resistant to heat and have very low flammability limit. Moreover, their textures are such that prevent shrapnel, debris, and particles from be scattered around after the projectiles shot from military arms hit the surface[6]. Dyneema of HB25 type has been used in the present study. Besides, composite panels consisting fibers and resin are highly important, therefore a wide range of studies have been done on this field. When the number of textiles (lamina) is low, better strength will be achieved in dry mode, but when thickness increases density will increase accordingly. When resin is incorporated in the panels, flexural strength will increase and it leads to higher efficiency. Addition of resin can improve the strength through four mechanisms[7,8]:

1. Addition of resin to composite reinforces panel resistance to bending (however, if resin is not added and just dry fibers are used instead, only tensile strength will be achieved), thus the ballistic range of speed will be increased.

2. Increase in flexural strength which is obtained by adding resin to composite, leads to increase in transverse wave velocity and decrease in strain, and eventually an increase in ballistic range.
3. Reinforcement of panel strength provides a situation that the cross section of bullet raises after collision, hence ballistic range will increase.
4. Higher resin content will lessen deformations in the fibers, thus the fibers will fracture under shear stress rather than tensile stress and so ballistic range will be increased[9].

RESEARCH CONDITIONS

In the present study the examined armor has been selected with three different ceramic thicknesses, then the obtained results from simulation will be compared with existing data results. Ceramic/composite compound armor made up of reaction bonded silicon carbide incorporating HB25 type polymeric composite Dyneema as a supporting layer consists of 64 woven layers. In the case of epoxy resin (20% by volume) the layers have been annealed and compressed at high temperature and pressure and have been transformed into composite laminates. However, 18% of resin was collected from pressing die end because of the high pressure applied on it. Thus, resin only acts like an adhesive to bind the laminate components together and integrating them, so has a very little role in composite final mechanical properties. Therefore it won't be modeled in simulation. Once the Dyneema laminate (white) of 5 mm thickness has been prepared, a layer of Kevlar (yellow) is applied on its both sides. Kevlar also has anti-UV and anti-fire properties. Kevlar is the trademark of aramid which has approximately the same mechanical characteristics as Dyneema but it is denser. As the final step the mixture of ceramic and composite is pushed into a plastic injection mould, thena black Poly Urethane (PU) substance is injected into the surrounding free space. This substance only forms an integrated panel and prevent the particles and shrapnel of the armor from be scattered around after ballistic test. It never plays the role of a secondary support for the armor.

Small ceramic tiles are mounted onto the composite support by 0.3 mm double-sided tapes and also an adhesive is injected into the seam between the tiles to form an integrated structure. The adhesive is also neglected in modeling and 2% fault is considered for it since there is no appropriate model for identifying its behavior, thus its modeling may cause additional fault[8]. Furthermore, according to Shokrieh [10] the kinetic energy which is converted into thermal energy because of the projectile impact on composite/ceramic layer influences the results by 3%, so it is also ignored since there are limitations on the modeling of composite/ceramic. The simulation was carried out at constant hitting speed with similar projectiles. Figure 2 illustrates the dimensions of the used projectile. Thickness of the supporting layer remains constant (5 mm) in all tests. The dimensions of the examined armored are given in Figure 3 and Table 1. The thicknesses of the tested armors are indicated by 1, 2, and 3 in Table 1.

The collision occurs in normal mode during simulation stages. Since the outer layer of the bullet has a negligible influence on the penetration mechanism and disappears by the first hit, only the steel core of the bullet has been simulated. However, since the outer layer has an influence on the impact energy at the moment of collision, the mass of the projectile is taken into account based on the interpolation method between density and volume percentage of the bullet penetrating coating. The increase in the mass may be met through raising density or penetrator length during modeling but the increase in density is not recommended because projectile material changes. Table 2 represents the interpolated masses of three military bullets types used in ballistic tests.

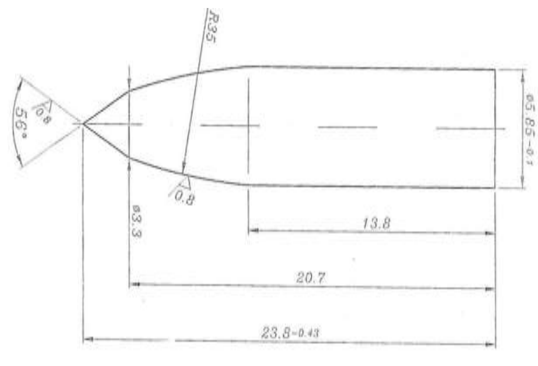

Figure 2: Geometrical dimensions of the bullet steel core used in the tests

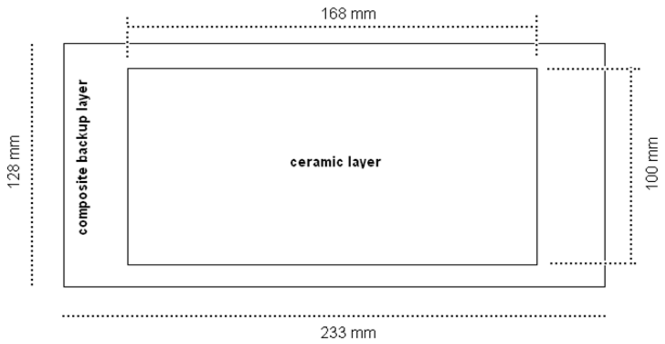

Figure 3: Geometrical dimensions of composite/ceramic compound armor used in the tests

Table 1: Designation of compound armors according to ceramic layer thickness

Sample Designation	Ceramic layer thickness (mm)	Composite supporting layer thickness (mm)
RB SIC1	5.5	5
RB SIC2	6	5
RB SIC3	6.5	5

Table 2: Interpolated length calculated based on the bullet type for simulation

Bullet type (with steel core)	Interpolated mass (gr)	Interpolated length (mm)
Kelashnikov bullet core (AK47)	4.02	23.8
Kelashnikov bullet (AK47)	5.03	29.75
J3 bullet	5.46	32.31
Grinov bullet (PKM)	5.82	34.46

The examined projectile for the purposes of this study is J3 rifle bullet of AP type with caliber of 7.62 x 51 which is used for penetrating into hard targets. 7.62indicates inside diameter of the rifle tube and equals to the bullet diameter; and 51 indicates the length of the bullet main body. The bullet core (penetrator) is made up of steel with a hardness of 55-56 HRC, a copper or lead layer, and a decorative coating of manganese or tin[11]. Composite/ceramic panel is fixed by a clamping fixture and shot by a J3 rifle from a certain distance. The velocity of the projectile is measured by two optical windows. This test is applicable on ceramic panels of 5.5-6.5 mm thicknesses for reaction bonded silicon carbide provided that the thickness of supporting layer is 5 mm and the bullet velocity is 855±10 m/s. Figure 4 shows the positions of the fixture and optical windows for an armor sample.

Figure 4: The configuration of fixture and armor sample

Once the bullet hit the armor and stopped, a plate-like bulge will protrude from the composite stack. However, because of the existing elasticity the cluster of fibers which have not been fractured yet return a little back but since they have combined with resin this return will not take place completely. But in any case the amount of composite initial protuberance (before returning back) will be reflected on the sand and this concavity is critical for concerns in designing protective armors. Therefore, displacement of composite stack is calculated based on this quantity.

4. Analyzing the simulation results

In the present study the projectile penetration into the examined armor with a certain total thickness and different thicknesses of ceramic and composite is evaluated and the thickness ratio in which the highest ballistic performance can be achieved is obtained through simulation. The obtained results from optimization are compared with the results of analytical methods available in authentic references.

At the first stage, RB SIC1 armor with the ceramic layer of 5.5 mm thickness is examined. As can be seen from Figure 5, at the time of 23 microseconds after collision the projectile tip takes gradually the shape of a mushroom. This happens because the speed of the projectile end is higher than its tip. In this figure the stress distribution in ceramic layer can be seen by a shape like a cone. The base of this cone is transmitted to composite stack and makes the force distribute to a larger area of the composite layers. Therefore, more energy is required for deformation of composite layers and this leads to an increase in armor ballistic efficiency. The fracture mechanism of the composite fibers is clearly seen in the simulation. Since the velocity of the projectile at the moment of leaving the ceramic layer is 530 m/s, the first layers of the composite are fractured prior to experience elastic-plastic deformation and meet fracture-strain criteria. Moreover, the fibers fracture criteria has been satisfied and the projectile energy is spent to break the fibers (a little energy is spent to break the matrix as well).

Figure 5: Fracture of composite first layers inside the RBSIC1 armor prior to deformation and meeting fracture strain at the moment of 48µs

The velocity of the projectile reduces to 320 m/s as it reaches to final layers. At this speed, the most part of the projectile energy is spent to elastic-plastic deformation of the layers (until reaching the maximum level of fibers fracture strain), lamination, and to overcome the friction between layers, and finally, dishing phenomenon occurs at the end part of the composite. However, the composite is unable to absorb the whole energy at this speed, thus a complete penetration takes place.

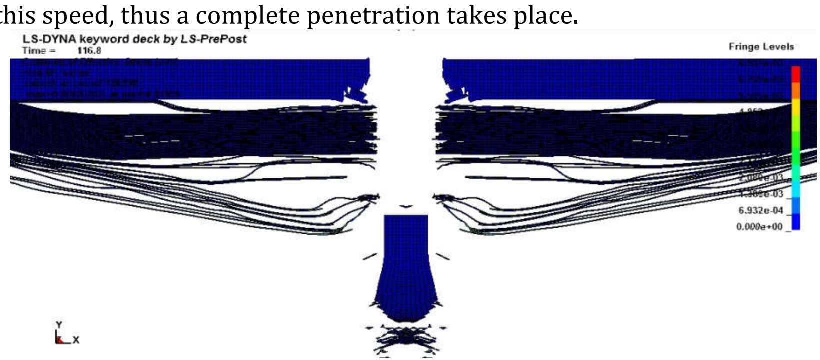

Figure 6: Composite destruction and thorough penetration into RB SIC1 armor at the moment of 117µs

Figure 7 depicts the diagram of the projectile velocity changes vs. time (velocity and time are expressed by mm/s and µs respectively). The projectile speed at the moment of leaving the armor is 175 m/s.

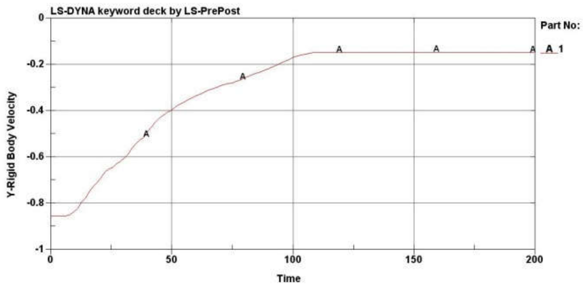

Figure 7: Diagram of the projectile velocity changes vs. time in hitting RB SIC1 armor

A slight jump in the projectile velocity (decrease and then increase in the diagram slope) occurs at the moment of 35µs. The reason is that the projectile passes through and the ceramic layer and touches composite laminate. The projectile loses approximately 325 m/s of its velocity as passing through the ceramic layer. Then loses another 355 m/s of its velocity at the time of hitting the composite laminate and finally passes through the armor by a speed of 175 m/s. We can use Equation (1) to calculate the resultant ballistic range from simulation considering the velocity diagram data (see Figure 7), when V_s represents collision velocity and V_r represents residue velocity after exiting the armor.

(1) $V_s^2 - V_r^2 = V^2_{50}$

$855^2 - 175^2 = V_{50}^2 V_{50}^2 = 837$ m/s

The whole process of the armor destruction takes 109 microseconds from which 35 microseconds is spent to break the ceramic and the other 74 microseconds to destruct the composite laminate. Figure 8 shows the fracture of reaction bonded silicon carbide ceramic after accomplished ballistic tests.

Figure 8: Reaction bonded silicon carbide ceramic fracture after ballistic test

As the ceramic thickness increases the projectile is more likely to be halted behind the composite stack. As already mentioned about the RB SIC armor, as the thickness of ceramic increases the performance of the ballistic armor will be reinforced accordingly. In the case of RB SIC1 samples obtained from simulation the projectile passes through the armor. The available data from ballistic tests also support the fact. However, in the case of RB SIC2 and RB SIC3 armors the thorough penetration does not occur. Comparison criterion among these three armors associates with the amount of displacement that occurs at the composite laminate stack. The obtained results are compared in Table 3.

Table 3: Comparing experimental and simulation resultsin terms of composite laminate displacement

Armor Type	Composite Stack Thickness (mm)	Ceramic Layer Thickness (mm)	Experimental Displacement (mm)	Simulation Displacement (mm)	Percentage of Discordance in the Results
RB SIC1	5	5.5	Complete penetration	Complete penetration	-
RB SIC2	5	6	36	31	13.88%
RB SIC3	5	6.5	34	29	14.7%

It can be stated that by raising ceramic layer thickness the formed ceramic cone will be larger and by extension of the cone base the area of the affected material which takes the form of a plate will be greater, thus greater energy is required to form the protrusion and piercing the aft layer, so it finally results in increasing the ballistic range provided that the projectile and its properties remain constant. For this reason the amount of displacement in the RB SIC3 armor is lesser than that of RB SIC2 type.

5. Optimum Design of Compound Composite-Ceramic Armor in terms of Thickness

Evaluating the phenomenon of penetration into compound ceramic targets accounts for a critical issue for armor designers and particularly designing light armors. Therefore, in this section by the way of simulation using LS-Dyna Software ceramic thickness ratio to composite support is determined in order to identify an optimum thickness for achieving the highest ballistic range with a constant target thickness and minimum density. In other words, the main purpose of the study is to find an optimum armor thickness through which the penetration of the projectile with a constant collision speed is hindered as much as possible, while the armor weight remains justifiable. For this purpose the assumptions of the present study are taken into consideration. In other words, bullet type, collision speed, armor material, fixtures type, etc. are all the same as the items used in this research. Total thickness of the armor is considered 11 mm. Then, four different configurations with various ratios of ceramic thicknesses to composite thicknesses are chosen such that the condition of $h_{ceram} + h_{comp} = 11$mm is true for all of them. Table 4 shows the different configurations considered for the tests.

Table 4: Different configurations considered for ceramic and composite thicknesses

Configuration	Ceramic Thickness (mm)	Composite Thickness (mm)
1	6.5	4.5
2	6	5
3	5.5	5.5
4	5	6

Considering the criteria for residue velocity of the projectile in the case of penetration and the amount of displacement in the case of stoppage, ballistic behaviors of the mentioned configurations are compared. The obtained results from numerical simulation for each configuration are represented by Table 5 and Figure 9.

Table 5: The obtained results from numerical simulation for each configuration (refer to Table 4)

Configuration	Ceramic Thickness (mm)	Composite Thickness (mm)	Residue Velocity (m/s)	Composite Displacement (mm)
1	6.5	4.5	Stop	30
2	6	5	Stop	31
3	5.5	5.5	Stop	34
4	5	6	195	Penetration

As can be seen, configuration 1 shows the best performance in confrontation with the shot projectile. Then configuration 2 is rated in the next position in terms of ballistic range. Generally, the more thickness of the ceramic layer, the more wear will occur in the projectile which is partially or completely worn by the ceramic tile before the complete penetration of the projectile into the target and it equals to a reduction in mass and leads to a decrease in the projectile kinetic energy and consequently less penetration of the projectile (less stack displacement). However, on the other hand, as the thickness extends the volume of the ceramic tile is increased, thus surface density and total weight of the armor will increase accordingly which is an unfavorable factor for armor designers. In fact, it is desirable that surface density and weight (particularly in armors used as bulletproof vests) be kept as low as possible, while having appropriate ballistic performance. Considering the bar graph shown in Figure 9, the issue is observable in the case of configuration 2.

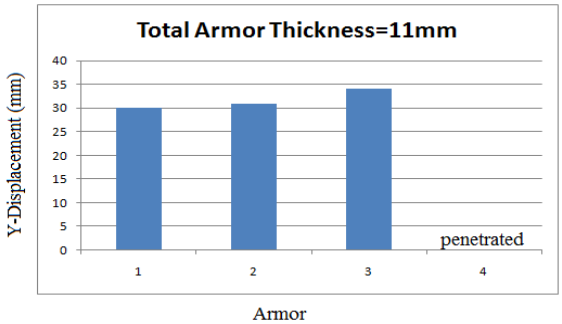

Figure 9: Bar Chart of Composite Stack Displacement in Different Armor Configurations

An analytical investigation on achieving an optimum thickness for compound targets to have the highest ballistic performance was conducted by Heterington in 1992[12]. After numerous studies using Florence analytical model he found that the optimum thickness ratio for a fixed total thickness can be estimated by the following equation.

$$\frac{h_{Cer}}{h_{Comp}} = 4\frac{\rho_{Comp}}{\rho_{Cer}} \quad (2)$$

However, as already noted this equation has been obtained through simplifications and is an approximate. Now using the above equation and available data from the present study, the ratio of optimum thickness based on the Heterington model is calculated as follows.

$$\frac{h_{Cer}}{h_{Comp}} = 4 \times \frac{1}{3.1} = 1.2 \rightarrow h_{Comp} = 5\text{mm}\,, h_{Cer} = 6\text{mm}$$

As can be seen, the obtained results from simulation in relation to optimum configuration regarding thickness and weigh is configuration 2 in which h_{ceram} = 6 mm and h_{comp} = 5 mm and it is completely

consistent with as predicted by Heterington analytical model, so the most efficient ballistic performance is observed in this configuration.
More interestingly, configuration 3 shown in Table 5 is very close to configuration 2 regarding ballistic performance. Therefore, we can conclude that RB SIC2 armor is more optimum choice compared to other armors, and meanwhile has high ballistic performance and appropriate weight.

6. Conclusion

The issue of projectiles penetration into ceramic targets incorporating one ceramic layer and one supporting laminate layer has been dealt with in this study. The present research focused on evaluating ceramic and composite as protective armor with high ballistic performance, and for the purpose of this study a numerical model using LS-DYNA Software was proposed. The conducted simulation using LS-DYNA was aimed at presenting a numerical model and also clarifying concepts like collision, erosion, and penetration. The obtained results from this numerical analysis indicates that numerical codes are cost-effective and time-effective tools in dealing with collision problems and can pave the way for experiments. Analytical models are typically developed for simple and normal collisions using physical laws and various simplifications. However, in the case of more complicated problems in terms of structure, geometry, and constituents these approaches cannot result in favorable results. Therefore, applying numerical Softwares particularly in the field of collision along with or instead of other methods will be rewarding. In order to validate the reliability of the presented simulation the results obtained from it were compared with ballistic tests and a relative conformity was observed. The reason for the unconformity usually associates with considered simplifications and assumptions and also unavailability of some variables and parameters required for simulation inputs. In the next phase the optimization of armor design in terms of thickness and desirable weight was taken into account. Here, the purpose was determining the best ceramic thickness ratio to supporting composite laminate for achieving a favorable design with the highest ballistic range and minimum surface density with a constant target thickness. Considering different numerical models presented here, the results met the expectations. However, more detailed investigation regarding optimization of armor against any projectile requires more comprehensive experiments. Some of the obtained results can be summarized as follow:

1. Due to unique properties including lower density compared to metals, high compressive strength, and high shear and bulk modulus, ceramics can be applied in protective and ballistic systems.
2. Since ceramics are brittle materials, a composite-metal support backs them. The supporting layer helps to absorb the projectile remaining energy and provide ceramic stability.
3. Due to high strength and resistance-to-weight ratio, composites have widely used in recent armor technologies.
4. Design of composite armors is a very complicated task in comparison with conventional single-layer armors because of their weak transverse shear strength and inconsistency of mechanical properties throughout the laminate thickness.
5. Numerical simulations provide a clear and cost-effective understanding of the penetration process into ceramic and also can be used in dealing with complicated ballistic problems for example in the cases of inclined collisions.
6. Optimum thickness ratio for target was obtained from numerical simulation, then was compared with the Heterington analytical model and showed a good consistency.
7. The utilized ceramic and composite support in this study are of new types which have better properties particularly for protective armors compared to conventional composites. This is why their fracture and destruction mechanisms are slightly unknown and using analytical approaches to evaluate their ballistic behavior is almost impossible. Therefore, in the present study finite element Ls-Dyna Software was used to investigate ballistic behavior of the compound armors.

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