International Journal of Architecture, Energy and Urbanism
Volume 4, Issue 1, June 2026
https://ijaeu.globalpublisher.org/
https://globalpublisher.org/journals-1004/

Optimization of vehicle body ballistic protection using ceramic–composite layers

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ABSTRACT
The increasing demand for lightweight armored vehicles with high protection levels has directed researchers' attention toward the application of multilayer systems composed of advanced materials. In this study, the ballistic performance of armored vehicle body panels reinforced with a hybrid structure consisting of boron carbide ceramic (B_4C) and carbon fiber reinforced polymer composite (CFRP) was numerically investigated and optimized .Numerical modeling was performed using explicit dynamic analysis in ABAQUS software. A multilayer structure consisting of a supporting steel plate, a B_4C ceramic layer as the primary impact-resistant layer, and a CFRP layer for impact energy absorption was considered. To simulate the material behavior, the Johnson–Cook model for steel, the Johnson–Holmquist (JH-2) model for boron carbide ceramic, and a progressive damage model for CFRP composite were employed. The effects of varying the B_4C layer thickness in the range of 18–20 mm and the CFRP layer thickness in the range of 2–3 mm on stress distribution, impact force, energy absorption, and total structural displacement under ballistic impact with an initial velocity of 120 m/s were systematically investigated. The numerical results indicate that increasing the thickness of the boron carbide layer significantly reduces stress transfer and plastic deformation in the supporting steel plate, creating an optimal thickness range between 19 and 20 mm. Moreover, increasing the CFRP layer thickness from 2 to 3 mm decreases the maximum impact force and provides a more uniform stress distribution within the multilayer structure. The optimal configuration, consisting of a 20 mm thick B_4C layer and a 3 mm thick CFRP layer, demonstrated the best ballistic performance, achieving approximately a 17% reduction in total displacement and a 15% reduction in peak impact force compared with thinner configurations. The findings of this study highlight the critical role of ceramic–composite hybrid structures in achieving both high ballistic resistance and weight reduction. This approach can serve as a practical design guideline for the development of lightweight armor panels in military and security vehicle applications.

Keywords: Numerical Analysis, Reinforcement, Armored Vehicle Body, Ballistic Impact, Finite Element Method, Boron Carbide, CFRP Composite

1- INTRODUCTION

In recent decades, the increasing security threats, expansion of urban armed conflicts, and growth of shooting incidents have significantly increased the need for the development of lightweight protective systems with high ballistic resistance. Among these systems, armored vehicles used in military, security, and even civilian applications are considered as one of the most important protective equipment. These vehicles require body structures that can provide an appropriate level of safety for occupants while preventing excessive weight increase and deterioration of dynamic performance. This challenge has encouraged designers to move toward the application of advanced materials and high-performance multilayer structures.

Traditionally, improving the ballistic resistance of vehicle bodies has mainly been achieved through increasing steel thickness or using heavy alloys. However, this approach results in a significant increase in structural weight, reduced fuel efficiency, decreased acceleration capability, and operational limitations. Therefore, in recent years, research efforts have focused on the development of multilayer armor systems composed of ceramic and composite materials, which can dissipate projectile impact energy more effectively with lower weight.

Among advanced materials used in protective systems, hard ceramics such as boron carbide (B_4C) play a critical role as the primary impact layer due to their high hardness, low density, and effective capability in projectile tip erosion. However, the brittle nature of these ceramics may limit the overall protective performance of the system due to brittle fracture and crack propagation if not properly designed. On the other hand, carbon fiber reinforced polymer composites (CFRP) have attracted significant attention as intermediate or backing layers in multilayer structures due to their high strength-to-weight ratio, excellent energy absorption capability, and effective stress distribution characteristics. The purposeful combination of these two materials can lead to the development of hybrid structures with optimized ballistic performance.

Experimental investigation of the ballistic behavior of such structures is often associated with considerable challenges due to high costs, safety limitations, and the requirement for specialized equipment. In this regard, the finite element method and explicit dynamic analysis have emerged as powerful tools for simulating ballistic impacts, enabling accurate evaluation of stress distribution, energy absorption, and failure mechanisms. In particular, the use of advanced constitutive models, such as the Johnson–Cook model for metals and the Johnson–Holmquist model for ceramics, significantly improves the accuracy of predicting material responses under high strain-rate loading conditions.

A review of previous studies indicates that numerous experimental and numerical investigations have been conducted on the ballistic performance of ceramic–composite systems. These studies have mainly focused on evaluating the effects of material type, layer arrangement, and mechanical properties. However, determining the optimal thickness range of ceramic layers and understanding the role of composite layers in reducing transmitted impact forces and achieving more uniform stress distribution still require further investigation.

More comprehensive investigations are required, particularly for automotive applications where weight limitations and installation space constraints are of critical importance. Providing quantitative design guidelines for selecting the appropriate thickness and arrangement of layers remains a significant research gap.
Accordingly, the primary objective of this study is to numerically analyze and optimize the ballistic performance of armored vehicle body panels reinforced with a hybrid structure consisting of boron carbide and CFRP composite. In this research, the effects of varying the thickness of B_4C and CFRP layers on stress distribution, impact force, energy absorption, and total structural displacement under ballistic impact are investigated. Furthermore, an optimal thickness range is proposed to achieve maximum protective efficiency with minimum weight increase.

The results of this study can serve as a design guideline for the development and optimization of next-generation lightweight armor panels for military and security vehicles.

2- Numerical Analysis Method

The numerical modeling of the multilayer system was performed using the Abaqus/Explicit software environment. Each structural layer was discretized using three-dimensional reduced-integration elements of type C3D8R, and the interaction between layers was defined through a Tied contact constraint. Therefore, stress and displacement transfer between the layers was ensured without any relative sliding.
To accurately simulate the ballistic impact process and the transient behavior of materials under high strain-rate loading conditions, an explicit dynamic solver was employed. This approach enables accurate tracking of stress wave propagation, damage initiation and evolution, and failure mechanisms within the extremely short time interval of the impact event.
The mechanical behavior of the boron carbide ceramic (B_4C) was modeled using the Johnson–Holmquist II (JH-2) constitutive model. This model is capable of considering the effects of hydrostatic pressure, high strain rates, damage-induced softening, and progressive failure. In addition, advanced damage and failure models for composite materials were employed for the CFRP layers to realistically capture anisotropic behavior, fiber breakage, matrix crushing, and energy absorption mechanisms.
To reduce computational costs and improve numerical efficiency, geometric and loading symmetry conditions were utilized, and only one-quarter of the complete system geometry was considered for analysis. Appropriate symmetric boundary conditions were applied on the corresponding planes to reproduce the mechanical behavior of the entire structure without loss of accuracy.
This strategy significantly reduces the analysis time and computational resource requirements while enabling the application of a finer mesh in critical regions, particularly near the impact zone. Consequently, the accuracy of predicting the dynamic response of the structure under ballistic impact is substantially improved.

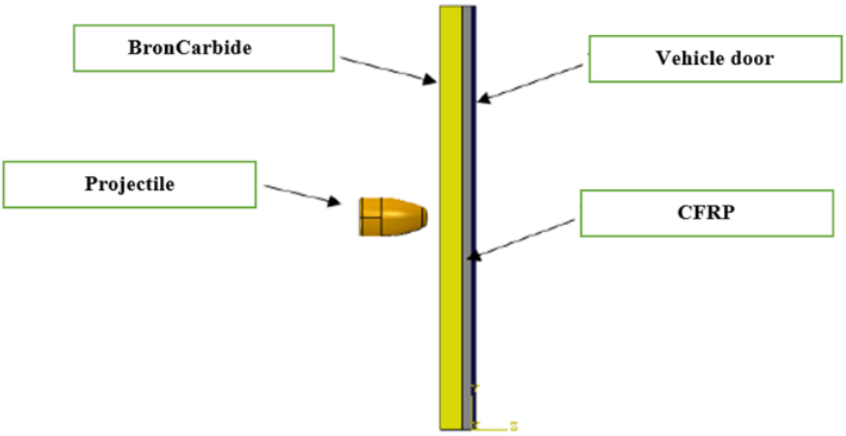

Figure 1 - Numerical Modeling and Analysis Model

Boundary Conditions, Loading, and Mesh Strategy

To realistically reproduce the dynamic response of the structure under ballistic impact, boundary conditions and loading conditions were defined with high accuracy. Initially, appropriate support constraints were applied to the selected surfaces of the plate to eliminate rigid-body motions and unrealistic displacements, thereby ensuring the numerical stability of the model. These boundary conditions were configured to prevent computational instability while minimizing artificial disturbances in the stress and strain fields.

The impact loading was modeled by applying an initial velocity to the projectile. For this purpose, a reference point was defined on the projectile, and an initial velocity of 120 m/s was assigned along the y-axis, allowing the projectile to be released at the beginning of the analysis and move toward the target. This velocity does not remain constant during the impact process and is automatically updated by the explicit solver due to the nonlinear interaction with the target structure. This loading approach enables accurate tracking of momentum exchange, stress wave propagation, and energy absorption mechanisms.

The mesh strategy was selected to achieve an optimal balance between numerical accuracy and computational cost. The geometry was discretized using a structured mesh with a uniform distribution of elements throughout the computational domain. In critical regions, particularly near the contact area and the projectile penetration path, local mesh refinement was applied to represent severe gradients of stress, strain, and damage with higher resolution.

The employed elements were selected as C3D8R elements (eight-node three-dimensional solid elements with reduced integration), which are suitable for nonlinear dynamic analyses under high strain-rate loading conditions and provide efficient numerical performance. This element selection prevents volumetric locking, reduces computational cost, and enables accurate prediction of stress distributions, deformations, and failure mechanisms during the ballistic impact process.

Figure 2 - Model Meshing

3- MATERIAL PROPERTIES

The mechanical and physical parameters of the constituent materials of the multilayer protective system used in the ballistic analysis of the armored vehicle body are presented in Table.(1)

In this study, three main material categories, including structural steel, boron carbide ceramic (B_4C), and carbon fiber reinforced polymer composite (CFRP), were employed to evaluate the ballistic performance of the vehicle body protection system. This material combination was selected to achieve an optimal balance between hardness, energy absorption capability, and low weight in the design of bullet-resistant structures.

Table 1 - Material Properties Used in the Analysis[2]

Other Properties	**Constitutive Model**	**Density (kg/m³)**	**Young's Modulus (GPa)**	**Poisson's Ratio (-)**	**Shear Strength (MPa)**	**Compressive Strength (MPa)**	**Tensile Strength (MPa)**	**Shear Modulus (GPa)**	**Young's Modulus (GPa)**	**Density (kg/m³)**	**Material**
Strain Hardening, Strain Rate Dependent	Johnson–Cook (J-C)	**7800**	**210**	0.34	350	250	550	80	210	**7800**	Steel (Vehicle Body)
Extremely Hard and Brittle Ceramic Material	Johnson–Holmquist Model (JH-2)	**3163**	**450**	0.17	2500	4100	4000	183	450	**3163**	**Boron Carbide (B_4C)**
High Strength-to-Weight Ratio	Composite Damage Model	**1600**	**70**	0.3	150	850	800	5	70	**1600**	**CFRP Composite**

Steel, as the base material of the vehicle body, plays the primary role in load-bearing and stress distribution due to its high tensile strength, suitable ductility, and stable elastic–plastic behavior. To accurately model the behavior of steel under impact loading and high strain-rate conditions, the Johnson–Cook constitutive model was employed. This model is simultaneously capable of describing strain hardening, strain-rate dependency, and thermal softening effects, and it is widely used in the simulation of ballistic and explosive impact events.

Boron carbide ceramic was utilized as a hard and lightweight reinforcing layer in the multilayer structure. Due to its extremely high hardness, low density, and excellent compressive strength, this material plays a critical role in projectile nose fragmentation and reduction of its kinetic energy. To simulate the brittle behavior and progressive failure of this ceramic under high-velocity impacts, the Johnson–Holmquist II (JH-2) constitutive model was applied. This model, specifically developed for brittle materials, is capable of considering hydrostatic pressure effects, cumulative damage, softening behavior, and ceramic fragmentation under severe dynamic loading conditions.

CFRP composite, as a lightweight and anisotropic material with a very high strength-to-weight ratio, was employed in the rear layers of the structure to ensure energy absorption, damage propagation control, and prevention of secondary penetration. Due to its high Young's modulus, appropriate thermal stability, and energy dissipation capability through fiber and matrix failure mechanisms, CFRP is considered an efficient option for modern protective systems. In this study, the behavior of CFRP was simulated using advanced composite damage models, which enable prediction of fiber failure, matrix cracking, interlaminar delamination, and effective stiffness degradation.

This material modeling framework enables accurate analysis of the nonlinear interactions between layers and provides a realistic evaluation of energy absorption mechanisms, damage evolution, and projectile penetration behavior within the multilayer vehicle body structure.

4- NUMERICAL RESULTS EVALUATION

4-1- Effect of Increasing Boron Carbide Reinforcement Thickness on Stress Analysis

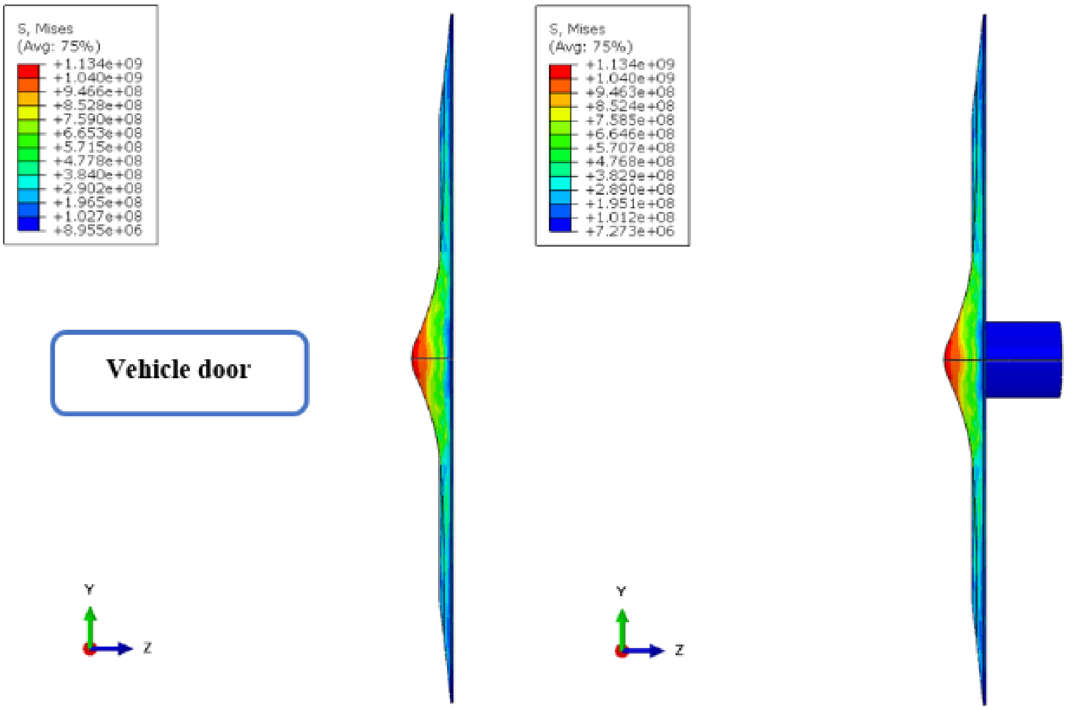

Figure 3 - Vehicle Plate Without Reinforcement

In this configuration, the vehicle body plate without the application of reinforcing layers of boron carbide (B_4C) and CFRP composite was numerically analyzed under direct projectile impact. The stress field results indicate that the kinetic energy of the projectile is almost entirely absorbed by the metal plate, leading to severe stress concentration in the impact region.

The maximum von Mises stress is observed at the center of impact, and its value exceeds the yield strength of the steel, indicating that the material enters a state of extensive plastic deformation. This condition makes the structure susceptible to severe damage mechanisms, including localized thinning, tearing, and even complete projectile penetration. In the absence of energy-absorbing reinforcement layers, gradual distribution of the impact load through the thickness of the structure cannot be achieved; consequently, stress transfer to the surrounding regions increases.

This concentrated loading causes the expansion of plastic strain over a wide area of the plate and leads to a significant reduction in the effective energy absorption capacity of the structure. In other words, the absence of a multilayer protective system forces the steel plate alone to undertake the primary role in dissipating the impact energy. Consequently, the structure remains vulnerable to high-velocity ballistic impacts and exhibits limited resistance against projectile penetration.

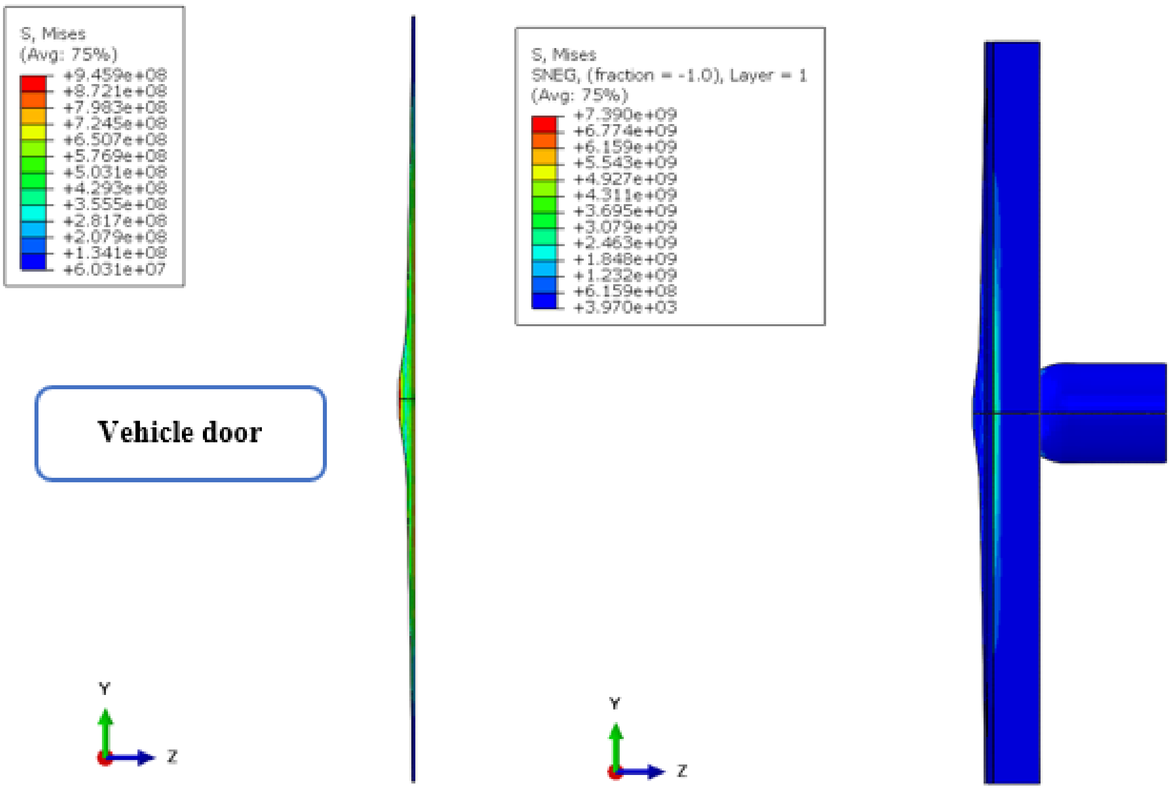

Figure 4 - Vehicle Plate Reinforced with 18 mm Boron Carbide (B_4C) and 2 mm CFRP Composite

In this configuration, an 18 mm thick B_4C ceramic layer and a 2 mm thick CFRP composite layer were added to the protective system. The numerical results indicate that the presence of the ceramic layer plays an effective role in dissipating a significant portion of the projectile's kinetic energy, thereby considerably reducing the intensity of stress concentrations in the vehicle body steel plate.

However, due to the relatively limited thickness of the B_4C layer, the induced stresses within this layer remain significant, and a portion of the impact energy is transferred to the underlying layers after localized ceramic fragmentation. In this regard, the CFRP layer acts as an energy-absorbing interface and plays an important role in attenuating the remaining stresses. By restricting crack propagation and redistributing the stress field, this layer prevents severe damage concentration in the rear section of the structure.

These results demonstrate that the addition of B_4C and CFRP layers effectively reduces the plastic deformation of the steel plate. However, to achieve a higher level of ballistic protection and complete penetration resistance, increasing the thickness of the ceramic layer appears to be a critical design parameter.

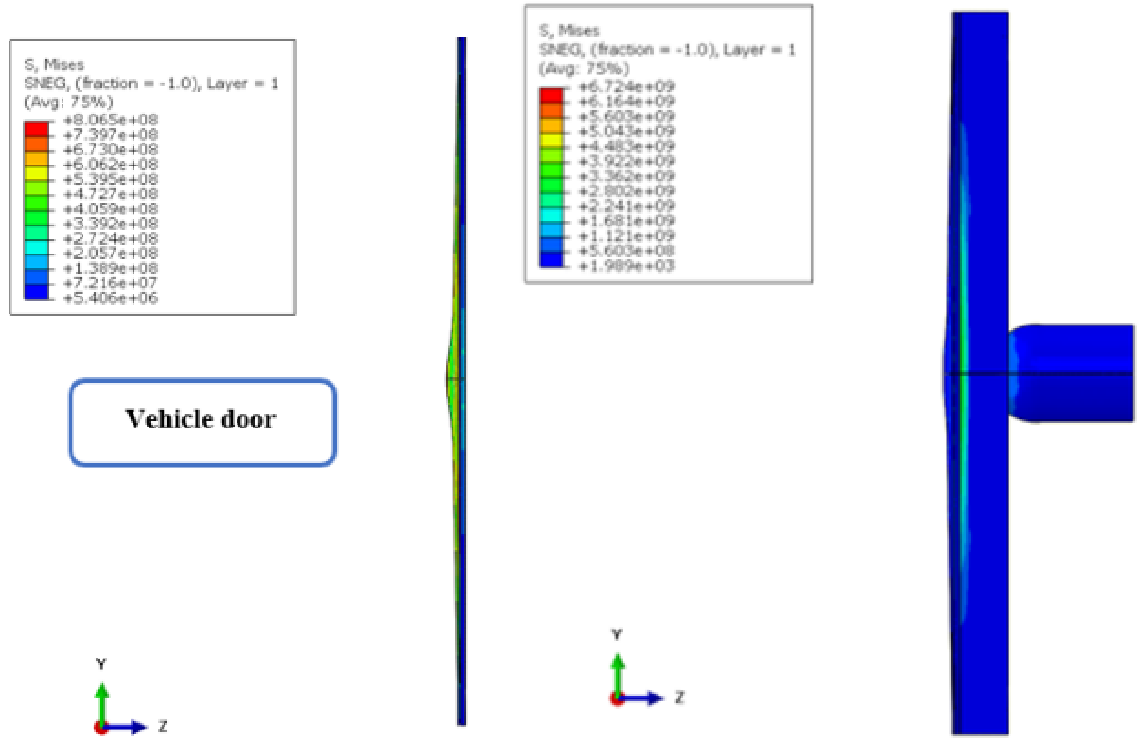

Figure 5 - Vehicle Plate Reinforced with 19 mm Boron Carbide (B_4C) and 2 mm CFRP Composite

In this configuration, by increasing the thickness of the B_4C ceramic layer to 19 mm, the stress field demonstrates a more significant reduction in von Mises stress within the underlying structural layers. The ceramic layer contributes more effectively to the dissipation of the projectile's kinetic energy and significantly prevents the transmission of impact forces to the vehicle body steel plate.

The maximum stress in this case is mainly concentrated within the B_4C layer, indicating the dominant role of this reinforcement as a hardening and primary energy-absorbing layer. Compared with the configuration containing an 18 mm thick ceramic layer, the damaged region in the steel plate becomes noticeably smaller, and the probability of the steel entering the extensive plastic deformation regime is considerably reduced.

Meanwhile, the CFRP layer continues to act as an interface for absorbing residual stresses and redistributing the applied loads. However, due to the increased overall stiffness of the system resulting from the thicker ceramic layer, the relative contribution of CFRP to energy dissipation is lower compared with the B_4C layer. These results highlight the critical role of ceramic thickness as a key design parameter in optimizing the ballistic performance of the structure.

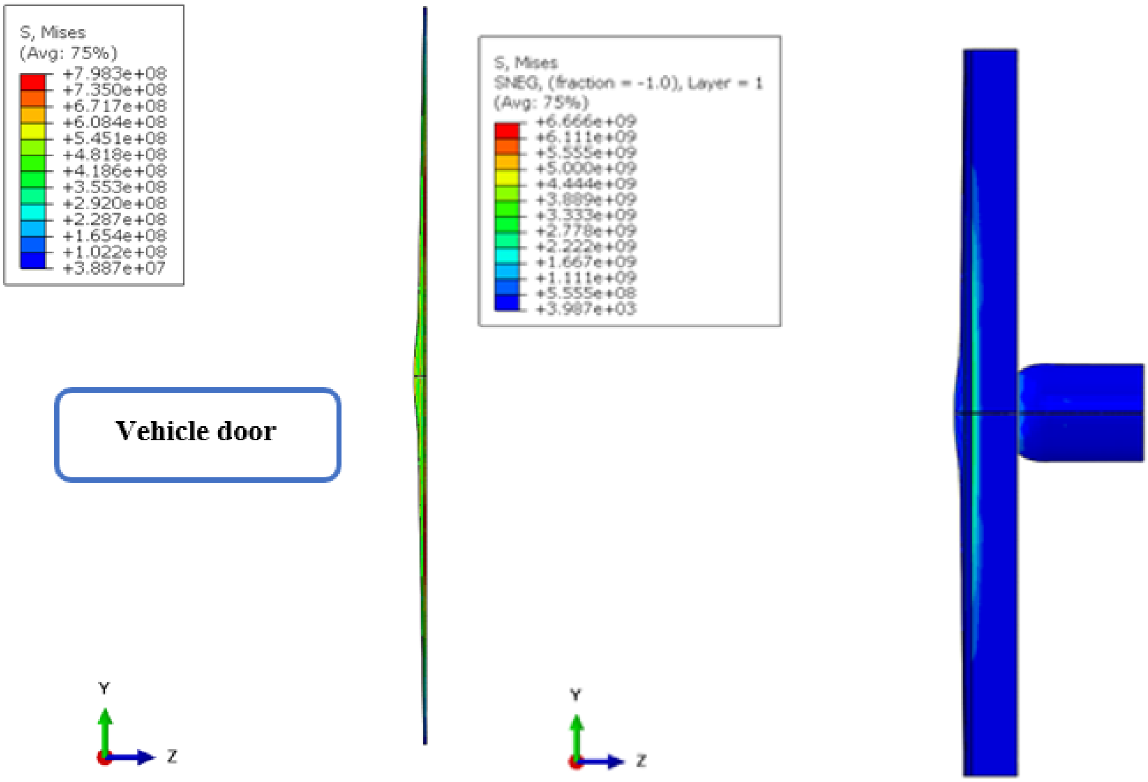

Figure 6 - Vehicle Plate Reinforced with 20 mm Boron Carbide (B_4C) and 2 mm CFRP Composite

In this configuration, the highest contribution to impact energy absorption is observed within the ceramic layer. The resulting stress field indicates that the von Mises stress in the vehicle body steel plate reaches its minimum value, such that almost the entire kinetic energy of the projectile is dissipated within the B_4C layer before reaching the steel substrate.

This increase in thickness effectively reduces the plastic deformation of the steel plate and limits the damaged region. However, the high stress concentration within the ceramic layer itself may activate brittle failure mechanisms and localized fragmentation in B_4C. Therefore, a detailed analysis of the damage field and failure criteria in this configuration is essential to determine whether increasing ceramic thickness leads to a stable improvement in ballistic performance or increases the possibility of sudden and unstable failure.

Overall, the results of this numerical model demonstrate that a 20 mm thickness of the B_4C layer provides the highest efficiency in reducing the transmitted stresses to the steel plate and can be introduced as a superior option from the perspective of ballistic protection, provided that ceramic fracture stability is appropriately considered in the design process.

4-2- Effect of Increasing CFRP Thickness on Stress Analysis

In this configuration, the thickness of the CFRP layer was considered 2 mm, while the thickness of the B_4C layer was maintained at 19 mm. The simulation results indicate that the von Mises stress distribution in the vehicle body steel plate is significantly reduced, as the B_4C ceramic layer absorbs the majority of the impact energy and the CFRP layer acts as an intermediate interface that prevents direct transmission of stresses to the underlying layers.

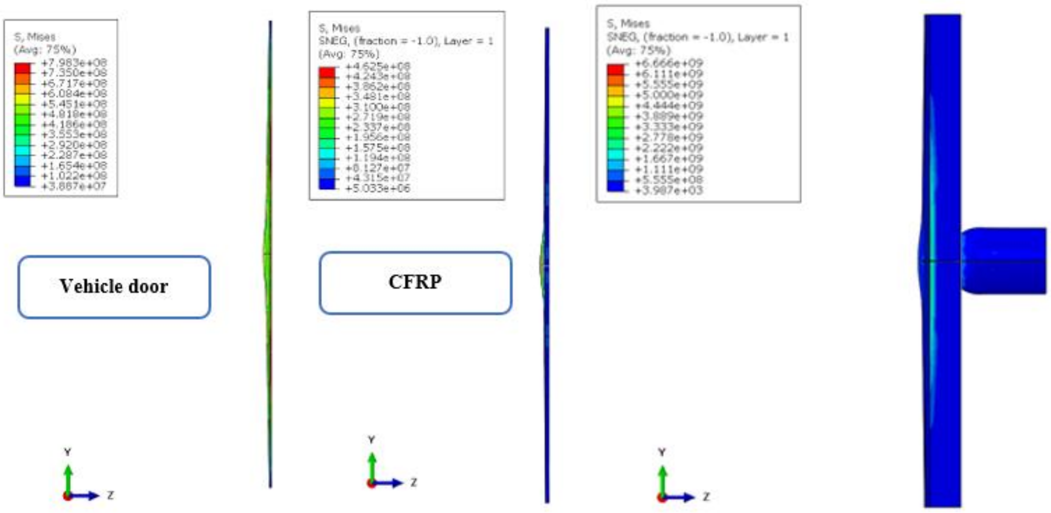

Figure 7 - Vehicle Plate Reinforced with 19 mm Boron Carbide (B_4C) and 2 mm CFRP Composite

However, due to the relatively limited thickness of the CFRP layer, its contribution to reducing localized stress concentrations remains restricted, and a portion of the residual impact energy is still transferred to the steel plate. This configuration demonstrates a significant improvement in reducing the plastic deformation of the plate compared with the unreinforced models; however, the capability of CFRP to achieve uniform stress distribution remains limited.

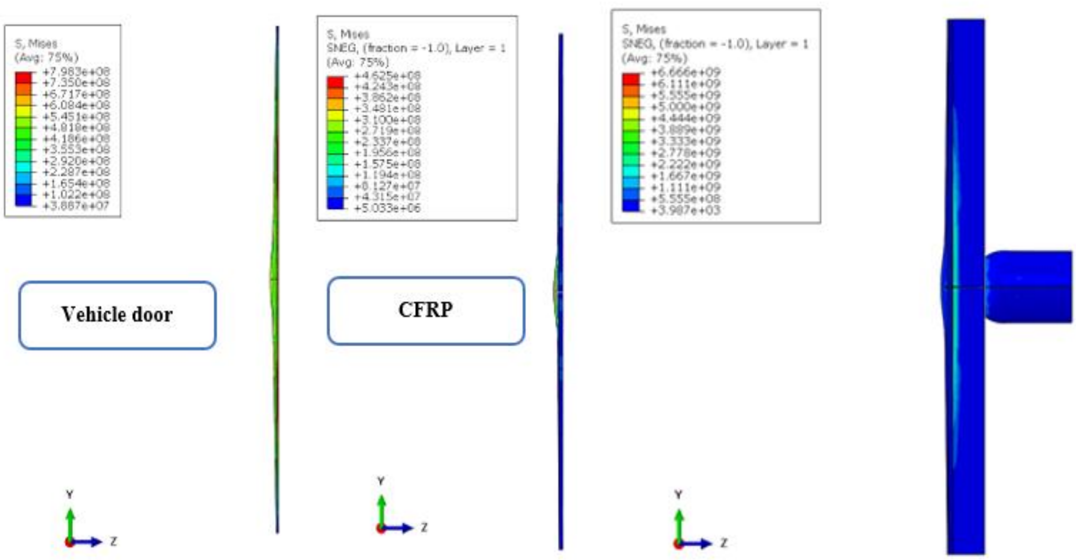

Figure 8 - Vehicle Plate Reinforced with 19 mm Boron Carbide (B_4C) and 2 mm CFRP Composite

In this configuration, the thickness of the CFRP layer was increased to 3 mm, while the thickness of the B_4C ceramic layer was maintained at 19 mm. Increasing the CFRP thickness enhances the contribution of this layer to impact energy absorption and significantly reduces stress concentration at the interface between the B_4C layer and the vehicle body steel plate.

The simulation results indicate that the regions with high stress values are more confined compared with the previous model, and the transmission of impact loads to the steel plate is minimized. The increased thickness of CFRP improves stress distribution within the multilayer structure by providing a more effective energy-dissipation mechanism and reducing the residual stresses transferred from the ceramic layer.

This configuration demonstrates that CFRP thickness plays an important role in controlling damage propagation and improving the overall stability of the protective system. Therefore, increasing the thickness of the composite layer, in combination with an optimized ceramic thickness, can provide an effective strategy for enhancing ballistic performance while maintaining structural efficiency.

However, increasing the CFRP thickness may affect the shear modulus variations and bending behavior of the underlying layers. Under certain conditions, it may also activate interlaminar failure mechanisms at the CFRP/B_4C interface. Therefore, the optimal performance of this configuration is not only dependent on the thickness of the composite layers but also requires a detailed investigation of the interaction between layers and the quality of adhesion between B_4C and CFRP.

These results indicate that increasing CFRP thickness can effectively improve stress distribution and enhance the ballistic resistance of the protective system, provided that the bonding mechanisms and interlaminar behavior are accurately modeled and properly controlled.

4-3- Investigation of Boron Carbide Damage Due to Projectile Impact

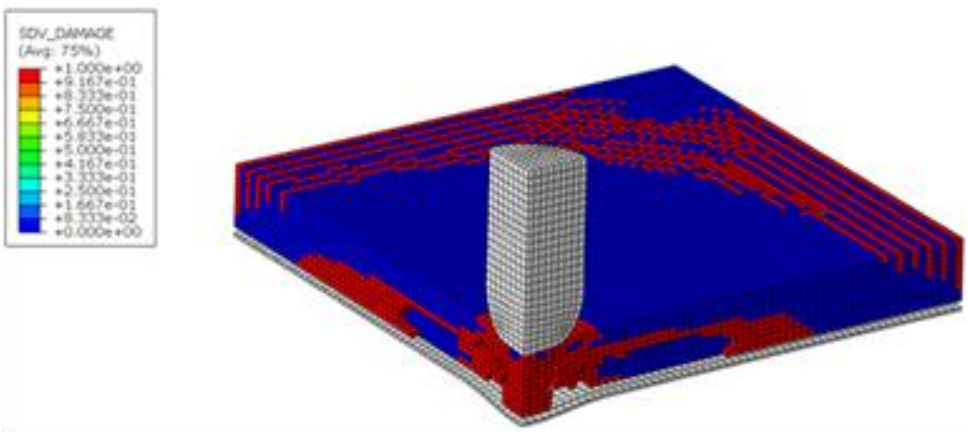

Figure 9 - Boron Carbide Damage Due to Projectile Impact with a Thickness of 18 mm

In this configuration, the B_4C ceramic layer with a thickness of 18 mm was investigated under projectile impact loading. The simulation results indicate that the damage at this thickness mainly occurs in the form of localized brittle fracture in the central impact region. The relatively high level of cracking and fragmentation on the B_4C surface demonstrates the limited capability of this thickness in completely dissipating the impact energy.

In this model, the possibility of partial projectile penetration into the ceramic layer and the transmission of residual stresses to the underlying layers are increased, which may result in plastic deformation of the steel plate. These findings indicate that an 18 mm ceramic thickness is insufficient for resisting high-velocity ballistic impacts, and increasing the ceramic thickness or employing additional energy-absorbing layers is necessary to enhance the ballistic resistance of the protective system.

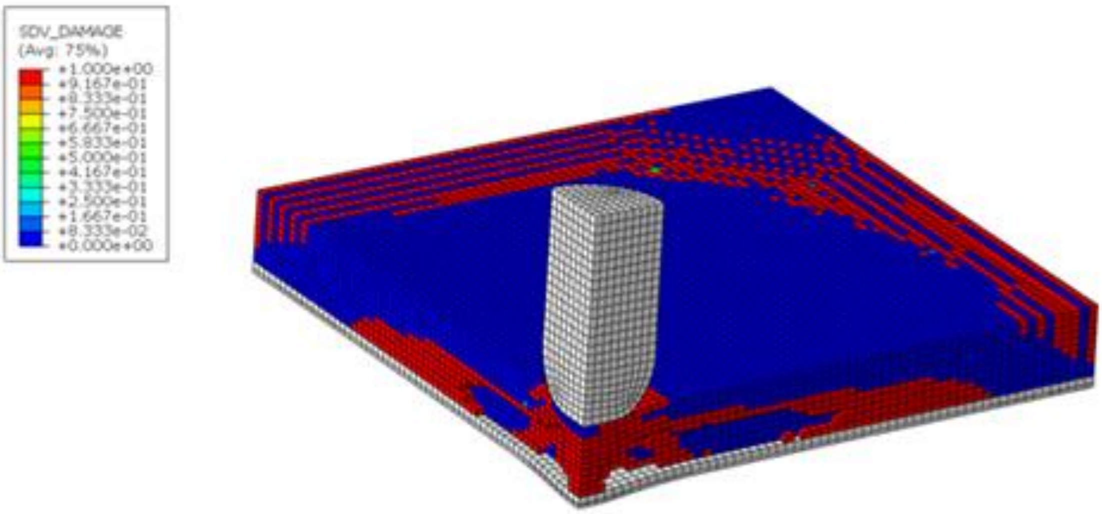

Figure 10 - Boron Carbide Damage Due to Projectile Impact with a Thickness of 18 mm

Increasing the thickness of the B_4C ceramic layer to 19 mm leads to a significant improvement in the protective performance of the system. In this configuration, the intensity of fracture in the central impact region is reduced, and the cracks developed on the ceramic surface become shorter and more localized, indicating a higher capability of this thickness in dissipating impact energy.

However, signs of radial crack propagation at the edges of the impact region are still observed, which may initiate progressive failure mechanisms. Compared with the 18 mm thickness configuration, energy transfer to the underlying layers is reduced; nevertheless, a portion of the residual impact energy is still transmitted to the steel plate, indicating that complete protection cannot be achieved at this thickness without employing complementary energy-absorbing layers such as CFRP.

This analysis confirms that increasing ceramic thickness provides a substantial improvement in local resistance; however, achieving optimal stress distribution and complete impact energy mitigation requires an appropriate combination with energy-absorbing layers.

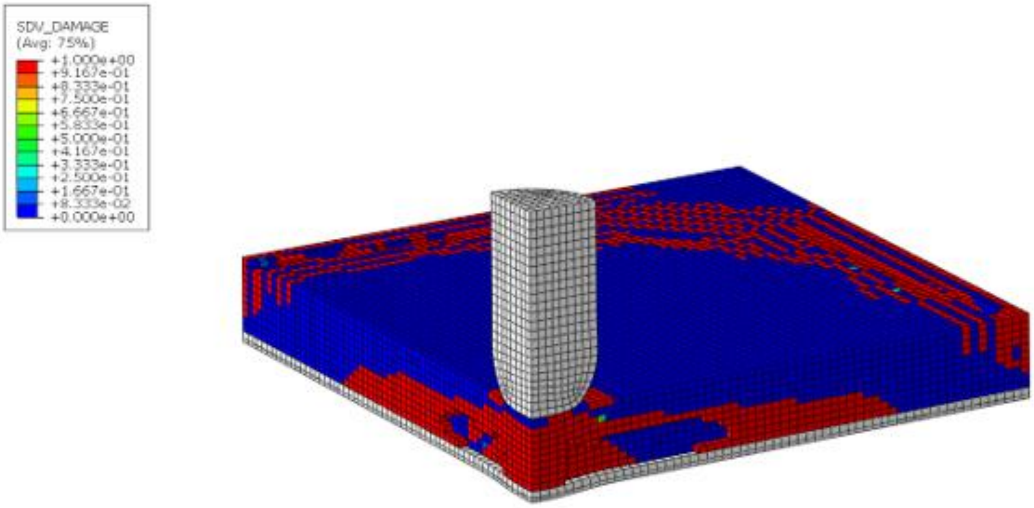

Figure 11 - Boron Carbide Damage Due to Projectile Impact with a Thickness of 18 mm

In this configuration, the thickness of the B_4C ceramic layer was increased to 20 mm, resulting in a significant reduction in localized damage at the impact region. Comparison with models having lower ceramic thicknesses indicates that surface fracture of the ceramic is more limited, and radial crack propagation around the damaged area is minimized. This behavior demonstrates a considerable increase in the energy absorption capacity of the ceramic layer and a reduction in damage intensity.

Despite the improvement in protective performance, internal stress concentrations in certain regions may activate sudden brittle failure mechanisms, highlighting the necessity of a detailed investigation of interlayer interactions and bonding mechanisms. Therefore, although a 20 mm ceramic thickness provides a higher capability for reducing energy transmission to the steel plate and controlling plastic deformation, damage analysis and stress concentration management are essential to ensure the stability of the protective system.

Overall, increasing the B_4C thickness to 20 mm optimizes the ballistic performance of the system and enhances resistance against projectile penetration. However, proper design of the interlayer bonding and accurate prediction of brittle fracture in the ceramic layer are necessary conditions for the reliable application of this configuration.

4-4- Distribution of Total Displacement of the Vehicle Door Plate

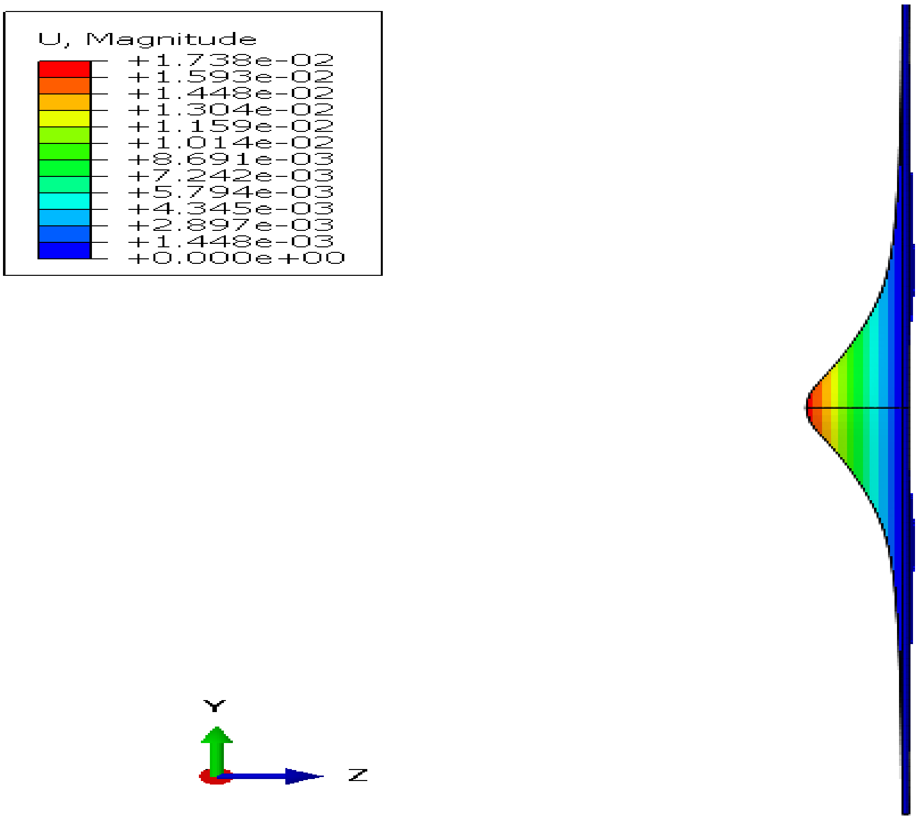

Figure 12 - Total Displacement Distribution of the Vehicle Door Plate without Reinforcement

In this configuration, the vehicle body plate without any reinforcing layers was analyzed under projectile impact loading. The total displacement distribution (U Magnitude) indicates that the maximum displacement is concentrated at the center of the impact zone and gradually decreases with increasing distance from the impact point. Due to the absence of energy-absorbing layers, the magnitude of total displacement is significantly higher than that observed in the reinforced configurations, and the steel plate experiences extensive plastic deformation.

This behavior indicates that a major portion of the impact energy is converted into permanent deformation and plastic energy dissipation, thereby increasing the likelihood of localized failure in the plate. Furthermore, lower displacement values are observed near the plate boundaries, highlighting the role of boundary conditions in restricting structural movement and influencing the distribution of stress and strain throughout the plate.

Overall, the absence of reinforcing layers results in the concentration of impact energy within the central region and a substantial increase in the plastic deformation of the plate. These findings clearly demonstrate the importance of incorporating energy-absorbing layers to control displacement and enhance the ballistic resistance of the structure.

International Journal of Architecture, Energy and Urbanism
Volume 4, Issue 1, June 2026
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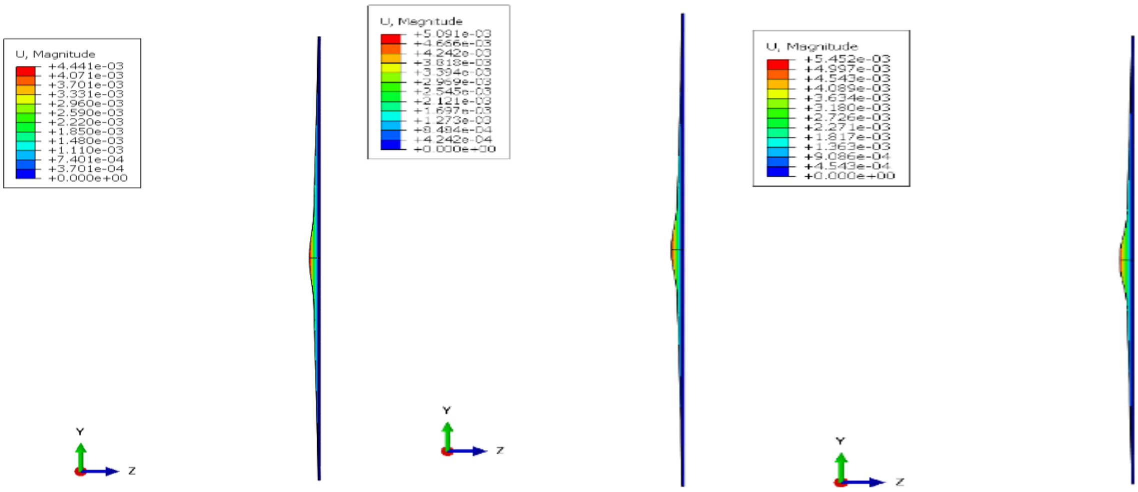

Figure 13 - Total Displacement Distribution in the Vehicle Door Plate Reinforced with B_4C Thicknesses of 18, 19, and 20 mm

In these configurations, the effect of increasing the B_4C thickness on the total displacement distribution was investigated. As the ceramic thickness increased from 18 mm to 20 mm, the displacement at the center of the plate decreased and the displacement distribution became more uniform. This improvement is attributed to the increased energy absorption capacity of the B_4C layer and the reduction of impact energy transmitted to the steel plate.

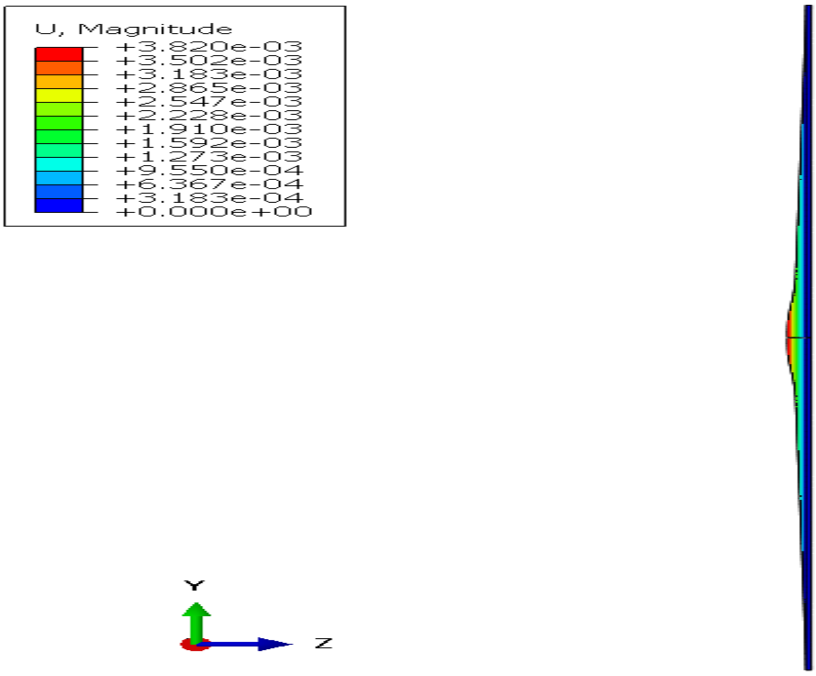

Figure 14 - Total Displacement Distribution in the Vehicle Door Plate Reinforced with 19 mm B_4C and 3 mm CFRP

In this configuration, the thickness of the B_4C ceramic layer is 19 mm, while the thickness of the CFRP composite layer is 3 mm. The total displacement analysis indicates that increasing the CFRP thickness effectively reduces the deformation of the steel plate. Comparison with the model containing a 2 mm CFRP layer shows that the displacement at the center of the impact zone decreases and the displacement distribution around the damaged region becomes more uniform.

The observed improvement is attributed to the enhanced energy absorption capacity of the CFRP layer, which helps reduce the residual stresses transmitted to both the B_4C layer and the steel plate, thereby improving the control of plastic deformation. However, increasing the CFRP thickness may influence the quality of interfacial bonding between the layers and increase the likelihood of interlaminar failure (delamination) at the CFRP–B_4C interface.

These findings indicate that increasing CFRP thickness can improve the distribution of impact energy and reduce the displacement of the steel plate. Nevertheless, the success of the protective design requires a detailed evaluation of bonding mechanisms and interlaminar behavior to prevent sudden structural failure.

4-5- Pressure Analysis in the B_4C Damage Model

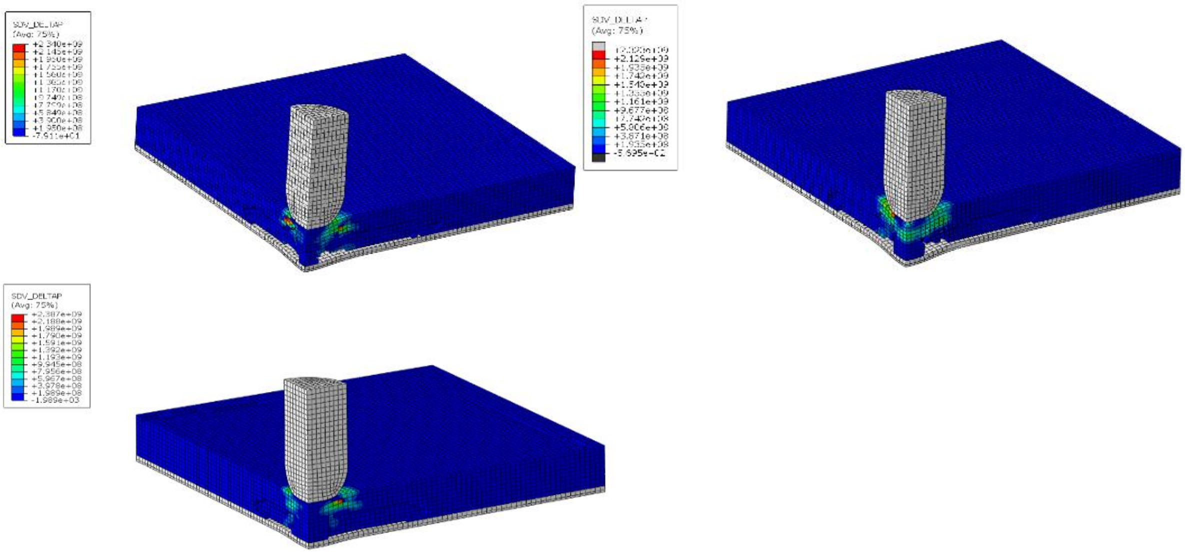

Figure 15 - Boron Carbide (B_4C) Damage under Projectile Impact for Thicknesses of 18, 19, and 20 mm

This figure comparatively illustrates the ceramic damage at three different thicknesses, showing a clear reduction in damage severity with increasing thickness.

4-6- Force Analysis at Different Thicknesses

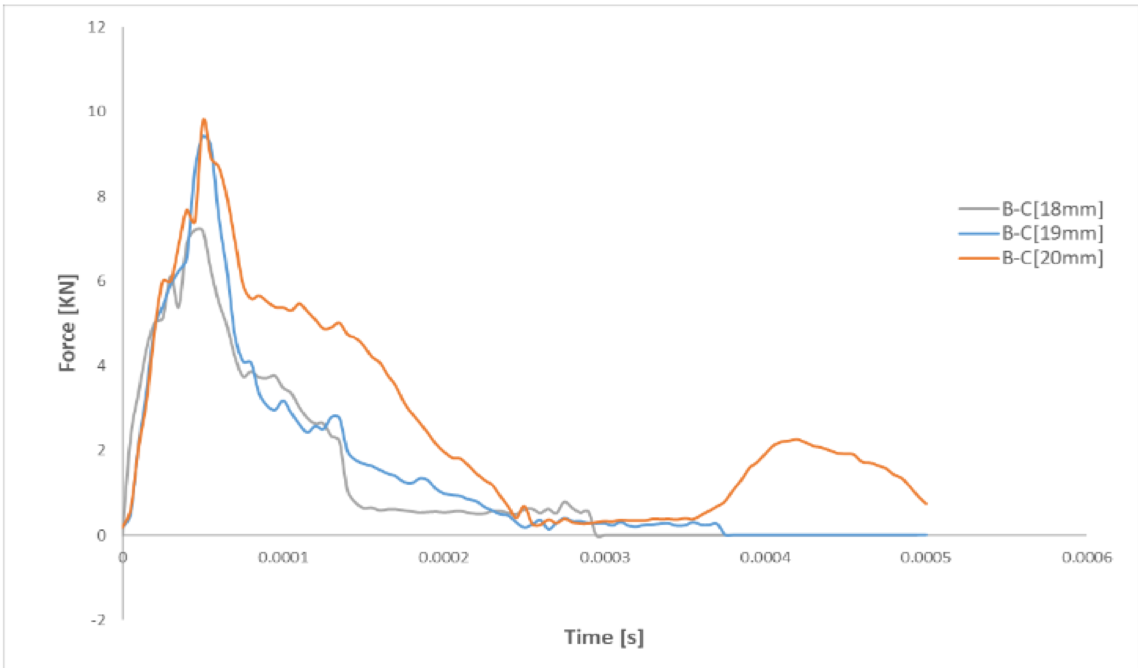

Figure 16 - Force at Different B_4C Thicknesses

Figure 16 illustrates the variations in the force applied to the B_4C ceramic layer at different thicknesses. The analysis of this graph indicates that increasing the ceramic thickness from 18 to 20 mm leads to a reduction in the maximum force and results in a more uniform force distribution across the ceramic surface. At a thickness of 18 mm, the maximum force is higher because this thickness has a limited capacity for absorbing impact energy, and the impact loading is primarily concentrated in the contact region. This load concentration causes an increase in localized stresses and enhances the probability of brittle failure in the ceramic.

As the thickness increases to 19 and 20 mm, the maximum force decreases, and its distribution becomes more widespread across the ceramic surface, indicating more effective impact energy dissipation and reduced transmission of severe stresses to the underlying layers. At a thickness of 20 mm, a smoother force reduction gradient and a more uniform load distribution over the ceramic surface are observed, demonstrating improved structural optimization in force distribution.

However, increasing the ceramic thickness may also lead to internal stress concentration in certain regions and increase the risk of sudden failure. Therefore, selecting an optimal ceramic thickness between 19 and 20 mm, depending on operational conditions and the required balance between energy absorption and stress concentration control, can be considered an effective approach for improving the ballistic resistance of the structure.

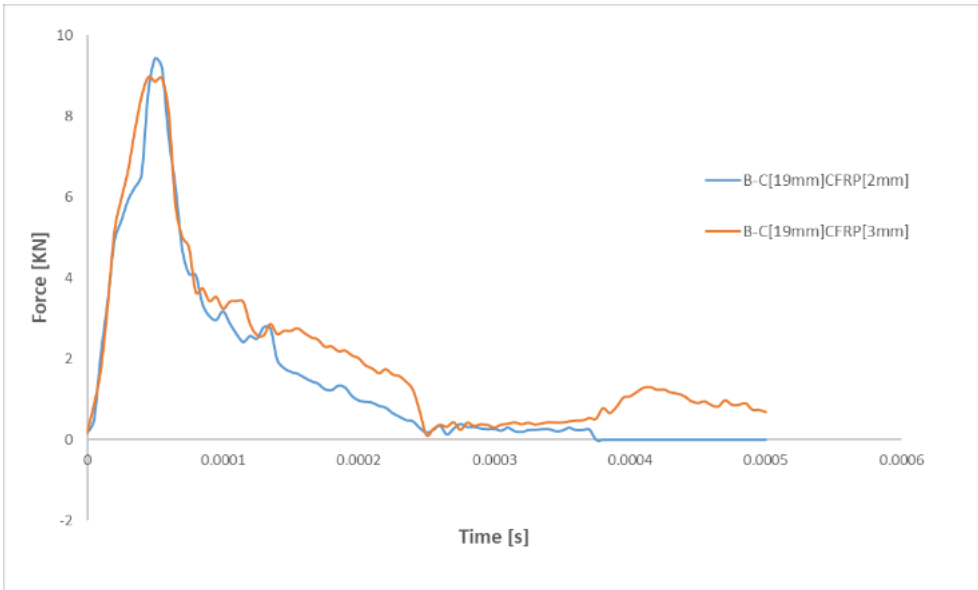

Figure 17 - Force at Different CFRP Thicknesses

The analysis of the force diagram at different CFRP layer thicknesses shows that increasing the thickness of this layer from 2 to 3 mm reduces the maximum force and results in a more uniform force distribution throughout the layer. At a thickness of 2 mm, the energy absorption capacity of the CFRP layer is limited; therefore, the applied force is higher and is concentrated primarily in the projectile impact region. This force concentration can lead to severe interlaminar stresses, matrix cracking, and localized failure of the composite fibers.

With increasing the CFRP thickness to 3 mm, the maximum force decreases and the load is distributed over a wider area, indicating an improvement in the energy absorption and dissipation capacity of the composite layer. Consequently, the force transferred to the underlying layers, including the metallic plate, is significantly reduced. Furthermore, at a thickness of 3 mm, the force reduction gradient becomes smoother, and the stress concentration at the CFRP/B_4C interface is decreased, which plays an important role in preventing localized damage and achieving a more effective stress distribution.
However, increasing the CFRP thickness can potentially increase the overall stiffness of the layer and induce interlaminar stress concentrations at the CFRP/B_4C interface, thereby increasing the possibility of interlaminar failure (delamination). Therefore, determining the optimal CFRP thickness should be performed by simultaneously considering the reduction of maximum force, improvement of stress distribution, and preservation of the interfacial bonding strength between the layers.

5- CONCLUSION

a) Reduction of Total Displacement (U Magnitude)

Increasing the thickness of the B_4C ceramic layer from 18 to 20 mm reduced the average total displacement of the vehicle body sheet by approximately 17.3%. This reduction indicates an improvement in the impact energy absorption capacity of the ceramic layer and a decrease in the direct transmission of impact force to the metallic plate. This effect plays an important role in controlling plastic deformation and enhancing the structural safety of the system.

b) Reduction of Force Concentration in B_4C

The force analysis results show that at a thickness of 18 mm, the applied force on the ceramic layer is concentrated in the impact region, leading to increased localized stresses and a higher probability of brittle failure. By increasing the thickness to 19 and 20 mm, the maximum force decreases and its distribution becomes more uniform over the ceramic surface. In the 20 mm thickness model, the average force applied to the ceramic layer is approximately 15% lower than that of the 18 mm model, indicating improved performance in impact energy dissipation and reduced stress transfer to the underlying layers.

c) Effect of Increasing CFRP Thickness

Increasing the thickness of the CFRP layer from 2 to 3 mm has a significant effect on reducing the transmitted forces to the metallic plate. The average reduction in the force applied to the metallic plate is approximately 12%, and the force distribution across the CFRP layer becomes more uniform. This finding indicates that the CFRP layer not only contributes to the absorption of the remaining impact energy but also plays a critical role in improving load distribution and reducing interlaminar stress concentrations.

d) Optimal Combined Performance

The best protective performance is achieved by combining a 20 mm thick B_4C layer with a 3 mm thick CFRP layer. This configuration provides the greatest reduction in displacement, pressure, and force applied to the metallic plate, while ensuring a more uniform force distribution throughout the structure. The average performance of this combination shows an improvement of approximately 15–17% compared with other models and minimizes the possibility of damage caused by force transmission to the metallic plate.

e) Reduction of Plastic Damage Probability

Models with higher B_4C and CFRP thicknesses are capable of dissipating a significant portion of the impact energy and preventing stress concentration in the vehicle body sheet. Consequently, plastic deformation and the associated damage mechanisms are significantly reduced, leading to improved ballistic resistance of the structure.

f) Consideration of Ceramic Brittle Failure Risk

Although increasing the thickness of B_4C improves the protective performance, it may also lead to internal stress concentration and increase the possibility of sudden brittle failure. Therefore, to ensure stable performance, a detailed investigation of the interfacial bonding mechanisms between layers and an evaluation of failure behavior in thicker models are essential.

Summary:

The results of this study demonstrate that the selection of optimal B_4C and CFRP thicknesses plays a decisive role in enhancing ballistic resistance, controlling displacement, and improving force distribution. The proper combination of these layers enables maximum impact energy absorption, reduction of stress concentration, and improved load uniformity, providing a fundamental basis for the advanced design of armored vehicle body structures.

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