



IMPACT LOCATION EFFECTS ON BALLISTIC PERFORMANCE OF CHECKERBOARD-FORMATION CERAMIC SPHERE ARMOR

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ABSTRACT

This study explores the influence of localized impact positions on the ballistic performance of modular ceramic armor systems. Utilizing a previously validated finite element model based on experimental data, simulations were conducted on an armor panel composed of alumina ceramic spheres arranged in a checkerboard configuration. The selected sphere diameter and layout had been previously identified as optimal for energy dissipation in high-velocity projectile impacts. In this extended analysis, the effect of varying projectile impact locations across the ceramic surface was evaluated. Rather than assuming central impacts, the study considered more realistic scenarios where projectiles may strike the edges of ceramic elements, vertical and horizontal locations between them, or the interstitial voids that naturally occur in such configurations. The findings indicate that the location of impact significantly alters the armor's ability to absorb and dissipate kinetic energy. Certain locations were found to enhance resistance, while others allowed more efficient projectile penetration. These results underscore the importance of incorporating spatial variability into the design of advanced ceramic-based protective structures and highlight the need for optimizing geometric configurations not only by material and layout, but also by accounting for the probabilistic nature of real-world ballistic interactions.

Keywords: metal-ceramic composites; ballistic impact; finite element method

INTRODUCTION

Ceramic materials have emerged as a pivotal component in advanced armor systems due to their unique combination of high hardness, low density, and excellent energy absorption capacity. Their ability to disrupt and erode incoming projectiles through localized brittle failure makes them particularly effective in applications requiring lightweight yet resilient ballistic protection.

Over the past two decades, numerous studies have investigated the performance of ceramic plates, tiles, and particulate forms against high-velocity ballistic threats. Among these, the use of spherical ceramic elements has gained attention for enabling non-monolithic, modular, and potentially reconfigurable armor architectures that offer improved multi-hit capability and manufacturability. Recent works have continued to validate these modular concepts; for instance, Tsirogiannis et al. reported that ceramic-metal composite panels, particularly those

using alumina strike faces, showed excellent multi-impact durability with controlled back face deformation, even under high-speed projectile impacts [1].

Furthermore, recent investigations such as that by Pan et al. [2] demonstrated the significance of geometric configurations in ceramic-metal hybrid armor using FEM-SPH models, highlighting the importance of spatial continuity in stress wave distribution. Complementing this, Wang et al. [3] focused explicitly on the ballistic behavior of spherical ceramic components within composite structures, confirming their effectiveness in dissipating impact energy and enhancing localized resistance. These studies collectively reinforce the role of geometry—not only in arrangement but also in individual ceramic unit shape—in determining ballistic efficiency under high-velocity threats.

A prominent example of such an approach is seen in the experimental investigation conducted by Gamache [4], wherein alumina ceramic spheres were bonded onto a hardened steel substrate in a hexagonal packing pattern. This study evaluated ballistic performance using ceramic spheres of 12.7 mm and 15.9 mm diameters and quantified the residual velocities of projectiles to assess energy dissipation efficiency. The experimental findings confirmed that ceramic sphere-based armor panels could significantly reduce projectile energy upon impact, with performance varying based on sphere diameter and arrangement.

Building upon this experimental groundwork, a subsequent finite element modeling (FEM) study [5] employed the ANSYS Autodyn platform to simulate the same impact scenarios using the material and geometric parameters validated in the previous physical tests. The computational models closely mirrored the experimental setups, and results demonstrated strong agreement with empirical data, thus verifying the reliability of the simulation framework. This modeling framework was then extended to simulate alternate sphere arrangements -most notably the checkerboard layout- and various sphere diameters. The outcomes revealed that a checkerboard pattern with 20 mm diameter alumina spheres outperformed both the original hexagonal arrangement and smaller diameter configurations in terms of energy dissipation and reduction of projectile residual velocity.

While these studies provided critical insight into material and geometric factors affecting ceramic armor performance, an important aspect remained underexplored: the localized interaction between the projectile and its point of impact on the armor surface. In real-world engagements, the impact location is inherently stochastic and cannot be assumed to always coincide with the center of a ceramic element. Similar observations were made by Ma et al. [6], who numerically investigated how impact positioning relative to hexagonal ceramic tile geometry influenced penetration depth and energy absorption in composite armor configurations; however, similar spatial impact effect studies have not been comprehensively conducted on spherical ceramic elements. The effectiveness of energy absorption may thus vary significantly depending on whether the projectile hits the central region of a ceramic sphere, its periphery, or the interstitial voids between multiple spheres.

The present study addresses this gap by simulating various projectile impact locations on an armor panel composed of 20 mm diameter alumina spheres arranged in a checkerboard pattern—the configuration previously shown to yield optimal ballistic performance. Using a previously validated finite element model [5], five distinct impact scenarios were simulated, ranging from direct central impact on a ceramic sphere to hits in void regions between spheres. Residual velocities of the projectiles were extracted and compared across cases to determine how impact location influences ballistic resistance. By examining these micro-spatial interactions, the study aims to provide novel insights into the vulnerability patterns of

ceramic-based armor systems and to inform the design of next-generation modular protection concepts.

METHOD

The simulations performed in this study utilized a comprehensive 3D finite element model developed in ANSYS Autodyn, built upon validated experimental data and modeling protocols described in [5]. The projectile was defined as a standard NATO 7.62 × 51 mm armor-piercing round with a muzzle velocity of 2280 m/s. The projectile material behavior was described using the Johnson-Cook constitutive model, suitable for high strain-rate applications, while the alumina ceramic spheres were modeled using the Johnson-Holmquist II ceramic model to accurately represent brittle failure and fragmentation under impact.

The target panel consisted of 20 mm diameter alumina spheres embedded in a checkerboard arrangement over a 5.13 mm thick HHS steel plate. The checkerboard layout provided an alternating symmetry not only in surface coverage but also in stress wave dispersion, which has been shown to impact multi-hit ballistic resistance.

To isolate the influence of impact location, five distinct impact scenarios were defined. Figure 1 shows each impact location on simulation model.

- Centered on Sphere Impact (C1): The projectile impacts directly at the geometric center of a ceramic sphere.
- Upper-right Region Impact (C2): A hit at the upper-right quadrant of the sphere, offset from the central axis.
- Vertical Contact Zone Impact (C3): The projectile is directed between two vertically aligned adjacent spheres.
- Horizontal Contact Zone Impact (C4): Impact occurs between two horizontally aligned adjacent spheres.
- Interstitial Void Impact (C5): The projectile strikes the open space located equidistantly between four surrounding spheres.

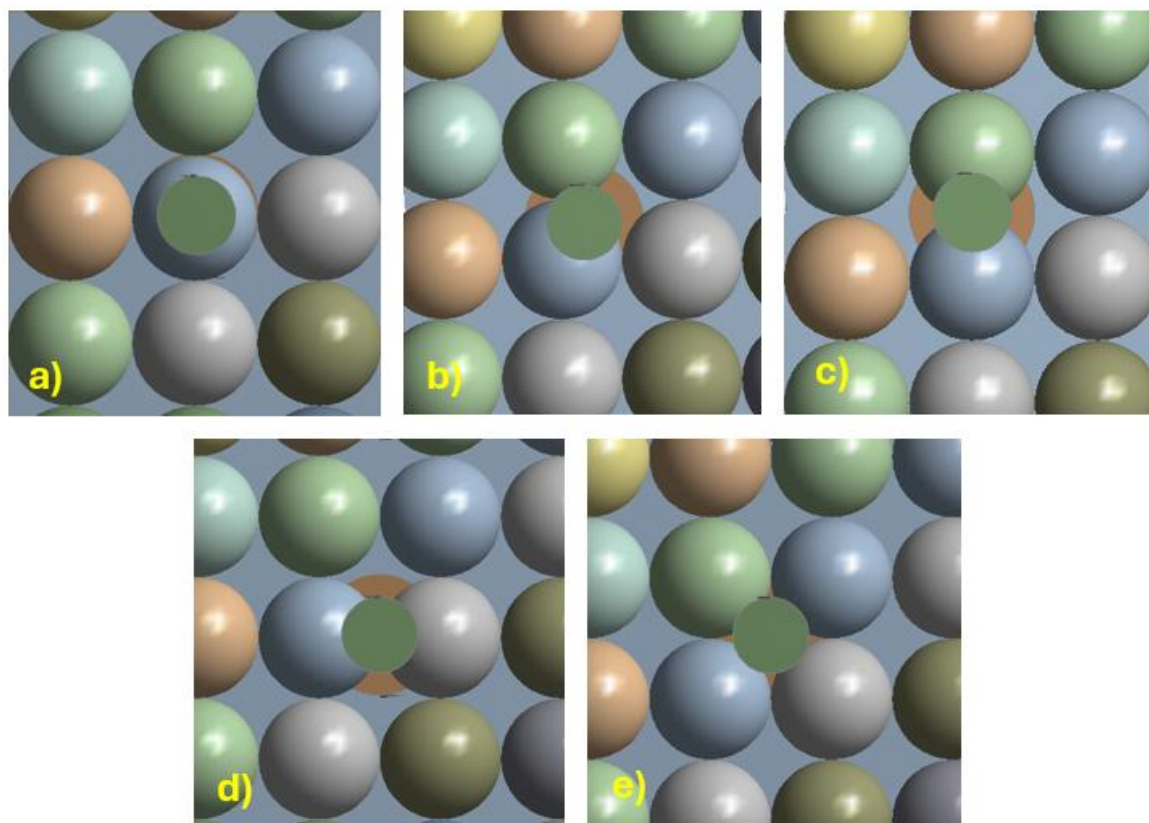


Figure 1. Impact locations of each scenario: a) centered on sphere, b) upper-right region, c) vertical contact zone, d) horizontal contact zone, e) interstitial void

For all scenarios, boundary conditions were defined as symmetric along the lateral edges, and the backing steel plate was fully constrained to mimic experimental clamping. Contact algorithms accounted for erosion, allowing the projectile to penetrate and interact dynamically with fractured ceramic fragments.

The projectile’s residual velocity was recorded for each case, with kinetic energy loss calculated using initial and residual velocities. Table 1 below summarizes the numerical outcomes. The relation of bullet velocity with elapsed time is illustrated in Figure 2 for each impact scenario. The fluctuations indicating increase in the residual velocity values along the graph lines are caused by instantaneous deviations that may occur during the analysis solution process and do not have an error effect on the average velocity values.

Table 1. Residual velocity results of different impact zone scenarios

Impact location	Centered on sphere (C1)	Upper-right region (C2)	Vertical contact zone (C3)	Horizontal contact zone (C4)	Interstitial void (C5)
Residual velocity (m/s)	277.7	630.2	613.9	784.6	1075.7
Energy loss (%)	98.5	92.3	92.8	88.2	77.74

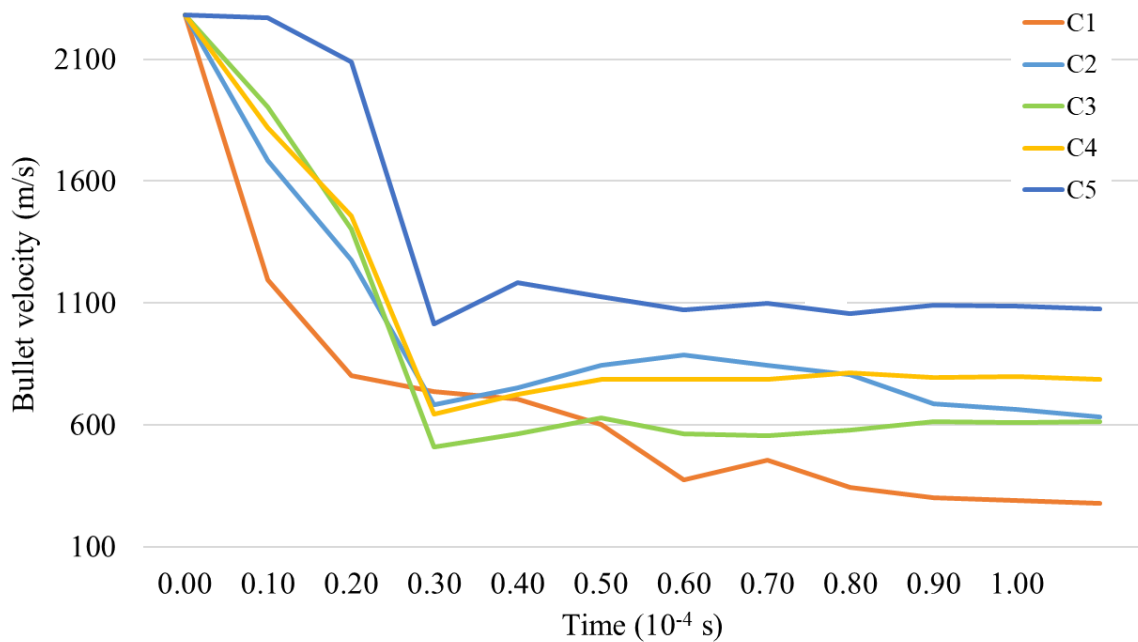


Figure 2. Analysis results of bullet velocity and elapsed time relation for each impact scenario. Finite element analysis results showed that stress and pressure contours further supported these observations. Central impacts generated the highest compressive stress within the ceramic and initiated radial cracking early in the impact timeline. In contrast, void and inter-sphere impacts allowed partial projectile bypass, resulting in lower resistance and higher residual velocities. These findings underline the significance of localized impact effects on overall armor performance.

CONCLUSIONS

The results of this simulation-based investigation offer valuable insights into the micro-scale influence of impact positioning in ceramic-based armor configurations. While material composition, sphere diameter, and layout have been previously optimized in literature, the spatial positioning of impact remains an often-overlooked parameter with measurable consequences.

Among the five simulated scenarios, a projectile striking the center of a ceramic sphere resulted in the greatest reduction in residual velocity, highlighting the ability of the ceramic material to absorb and redistribute kinetic energy effectively when fully engaged. Hits near the periphery of spheres or between two adjacent spheres exhibited intermediate energy dissipation, whereas impacts in the void region allowed significant projectile progression with minimal energy loss.

These observations suggest that enhancing interstitial connectivity or minimizing void areas between ceramic elements may further improve energy absorption, especially in multi-hit contexts. Moreover, integrating hybrid sphere arrangements or implementing secondary energy-absorbing layers beneath void regions could mitigate this vulnerability.

Overall, this study extends existing understanding of ceramic armor design by addressing the nuanced yet critical role of impact localization. The findings provide a foundation for future design strategies that consider not just material selection and geometric configuration, but also spatial susceptibility to optimize protective performance in real-world applications.

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