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"Advances in Ballistic Protection: A Review of Ramor Steels and Hybrid Composite Laminates."

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Abstract

Ballistic protection materials play a decisive role in modern defense systems, armored vehicles, and personal protection equipment, where the dual requirement of high impact resistance and reduced structural weight presents a persistent engineering challenge. This review presents a comprehensive and critical assessment of high-hardness armor steels, with particular emphasis on Ramor steel grades, alongside hybrid composite laminate systems used for ballistic protection. Peer-reviewed experimental investigations, standardized ballistic testing methodologies, and validated numerical simulations reported in the literature are systematically reviewed and compared. Special focus is placed on material behavior under high strain-rate loading, dominant failure mechanisms, and finite element modeling approaches implemented using ABAQUS/Explicit, including Johnson–Cook constitutive and damage models for steels and progressive damage formulations for composites. The review highlights the comparative performance, advantages, and limitations of monolithic steel, composite, and hybrid armor systems. Finally, current research gaps and future directions are identified to guide the development of lightweight, high-performance ballistic protection materials.

Keywords

Ballistic protection; Ramor steel; high-hardness armor steel; hybrid composite laminates; finite element modeling; ABAQUS

1. Introduction

Ballistic protection systems are engineered to withstand high-velocity projectile impacts while maintaining structural integrity and minimizing weight. Historically, rolled homogeneous armor and conventional steel plates have been extensively used due to their predictable mechanical behavior and ease of fabrication [1], [2]. However, increasing threat levels and mobility requirements in modern defense platforms have exposed the limitations of traditional armor solutions, particularly their high density and associated mass penalties.

Figure 1. General Classification of ballistic armor material (monolithic steel, composite, hybrid armor concept).

High-hardness armor steels, such as Ramor grades, have emerged as an effective solution by offering enhanced penetration resistance through optimized microstructures and heat treatment routes [3]–[6]. At the same time, fiber-reinforced composite laminates have gained prominence due to their superior specific energy absorption and lightweight characteristics [7], [8]. Despite extensive individual studies on metallic and composite armor systems, a clear and integrated understanding of their comparative ballistic performance remains limited. This review aims to bridge that gap by synthesizing experimental, analytical, and numerical findings reported in the literature.

2. Literature Review

2.1 Ballistic Performance of Armor Steels

The ballistic behavior of armor steels has been widely investigated to understand penetration mechanics and failure modes under high-velocity impact. Børvik et al. demonstrated that armor steels subjected to normal projectile impact typically fail through localized shear deformation, resulting in plugging or adiabatic shear band formation [9]. Subsequent studies confirmed that increasing steel hardness generally improves ballistic resistance, although it may reduce ductility and fracture toughness [10], [11].

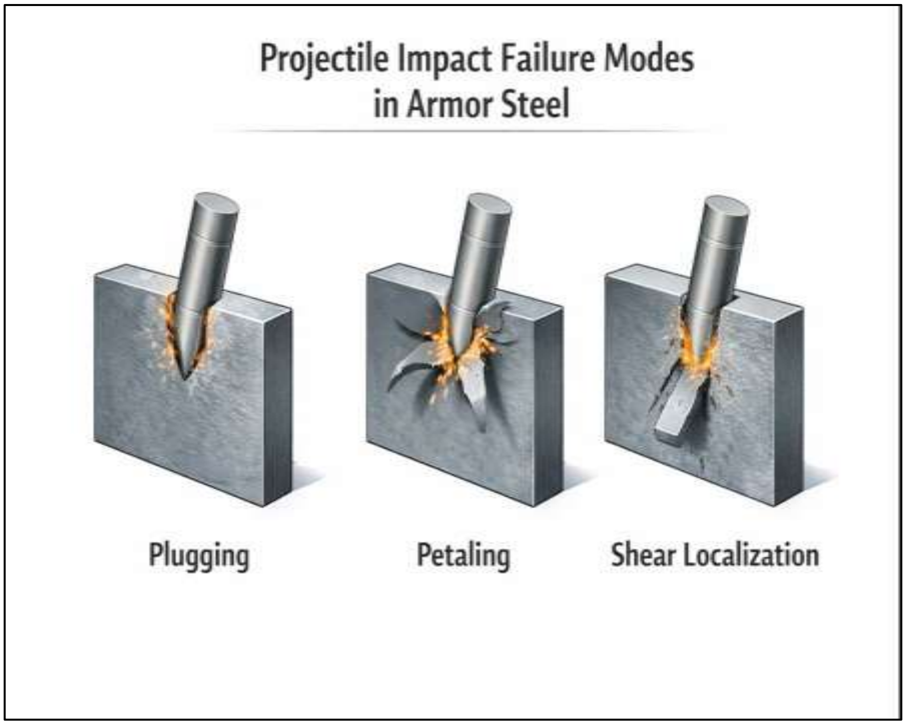

Figure 2. Projectile impact failure modes in armor steel (plugging, petaling, shear localization)

Specific investigations on Ramor 400, 500, and 550 steels indicate that their performance is strongly influenced by microstructural characteristics such as martensite morphology and carbide distribution [12], [13]. Ballistic testing using standard projectiles, including 7.62 mm armor-piercing rounds, has shown that Ramor steels provide consistent ballistic limits when appropriately heat treated [14]. Microstructural analyses further reveal that tempered martensitic structures contribute to the balance between hardness and impact resistance [15].

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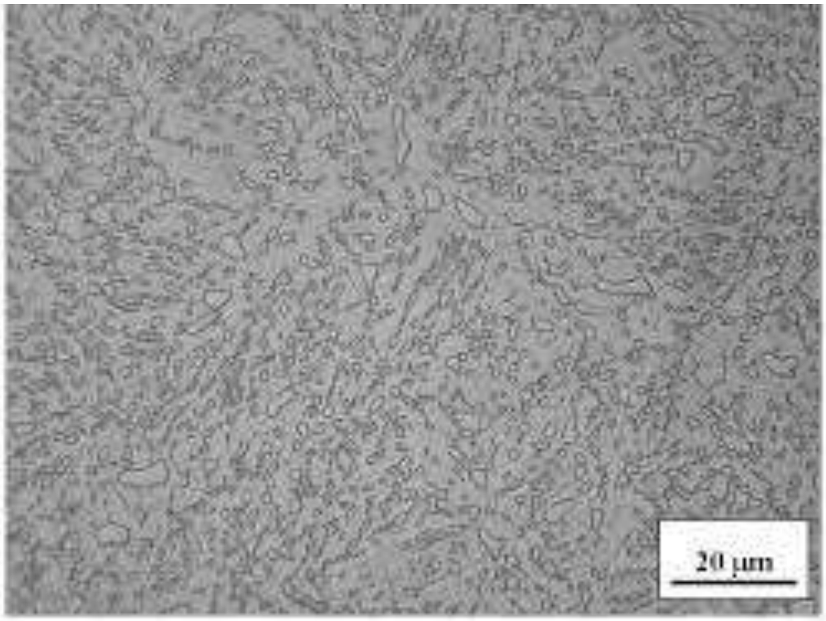


Figure 3. Microstructure of high-hardness armor steel (tempered martensite morphology)

Table 1. Properties of Ramor Steels

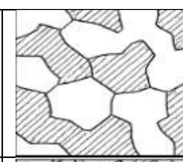
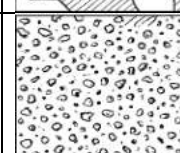
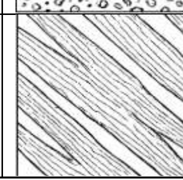
Grade	Hardness (HB)	Density g/cm^3	Ballistic Limit (V50, 7.62 mm AP)	Key Microstructure	
Ramor 400	~400	7.78	Moderate	Tempered Martensite	
Ramor 500	~500	7.78	High	Fine martensite + carbides	
Ramor 550	~ 550	7.78	Very high	Refined Martensite	

Table 1 compares Ramor steel grades, showing that increased hardness from Ramor 400 to 550 enhances ballistic resistance while density remains constant. The microstructural evolution—from tempered to refined martensite with carbides—highlights the role of heat treatment in optimizing penetration resistance.

2.2 Composite and Hybrid Composite Laminates

Composite armor systems rely on different energy dissipation mechanisms compared to metallic armor. Instead of plastic deformation, composites absorb energy through fiber stretching, rupture, matrix cracking, and interlaminar delamination [16]. Abrate and López-Puente et al. demonstrated that laminate architecture, fiber orientation, and stacking sequence play a critical role in determining ballistic resistance [17], [18].

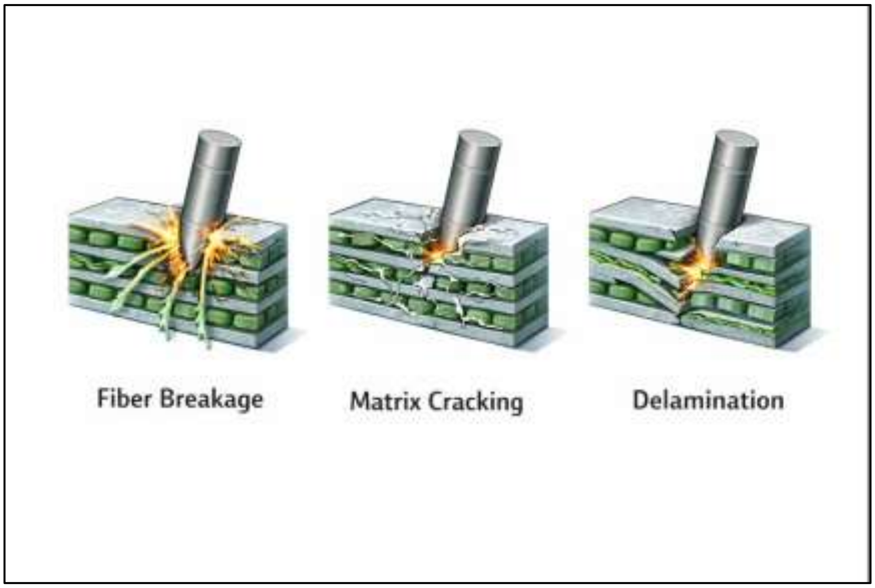


Figure 4. Schematic showing fiber breakage, matrix cracking, delamination

Aramid and UHMWPE fiber composites are particularly attractive for ballistic applications due to their high tensile strength and low density [19], [20]. Hybrid composite laminates, which combine different fiber types or matrix systems, have been proposed to improve overall performance by balancing stiffness, toughness, and cost [21]. Recent reviews emphasize that delamination is often the dominant energy absorption mechanism in laminated composite armor systems [22].

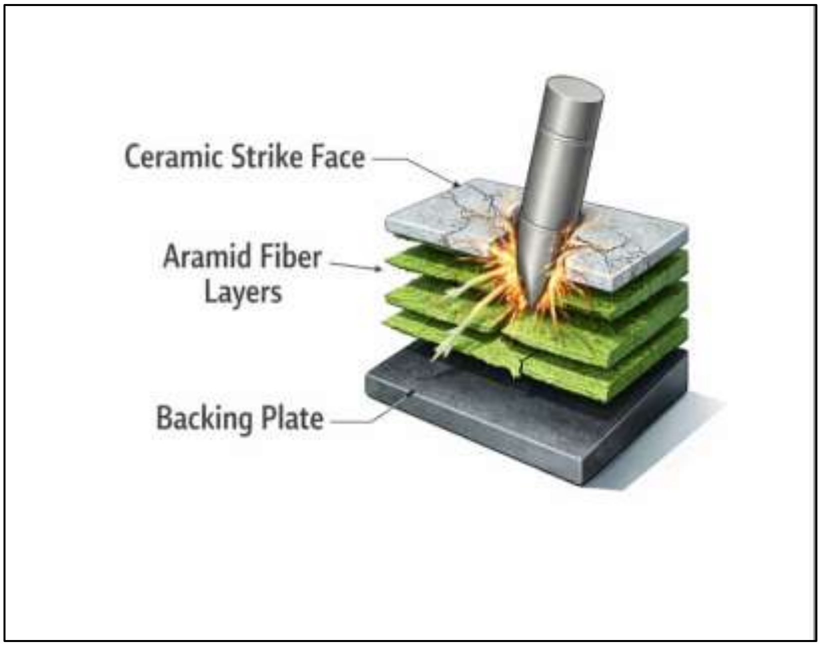


Figure 5. Composite laminate stacking sequence under ballistic impact

2.3 Steel–Composite Hybrid Armor Systems

Hybrid armor systems integrate a metallic strike face with a composite backing layer to exploit the advantages of both material classes [23]. Experimental studies show that the steel layer blunts, fractures, or erodes the projectile, while the composite layer absorbs the remaining kinetic energy and limits back-face deformation [24], [25]. Such configurations often achieve superior ballistic performance compared to monolithic steel plates of equivalent areal density.

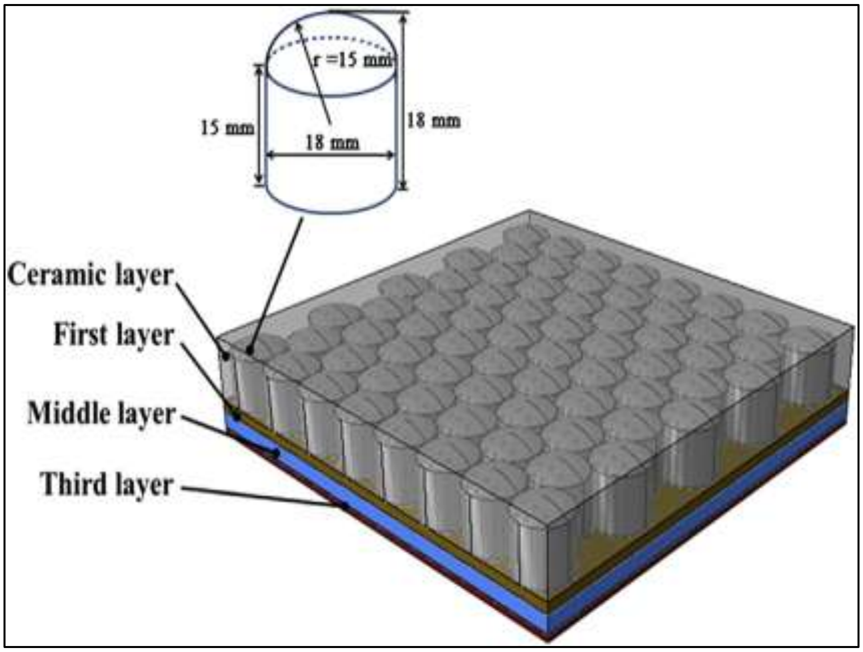


Figure 6. Steel strike face + composite backing schematic

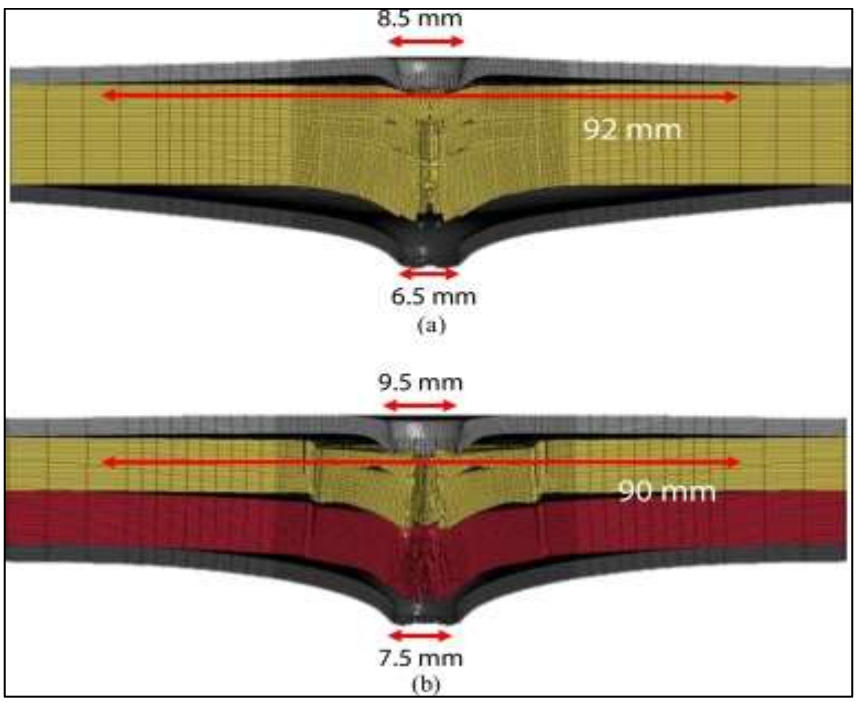


Figure 7. Post-impact comparison of steel plate vs hybrid armor

3. Ballistic Testing Standards

To ensure reproducibility and comparability of ballistic performance, standardized testing protocols are widely employed. Standards such as NIJ 0101.07, EN 1522, and NATO STANAG 4569 define threat levels, projectile types, impact velocities, and acceptance criteria [26]–[28]. These standards provide a common framework for evaluating armor materials across experimental studies and industrial applications.

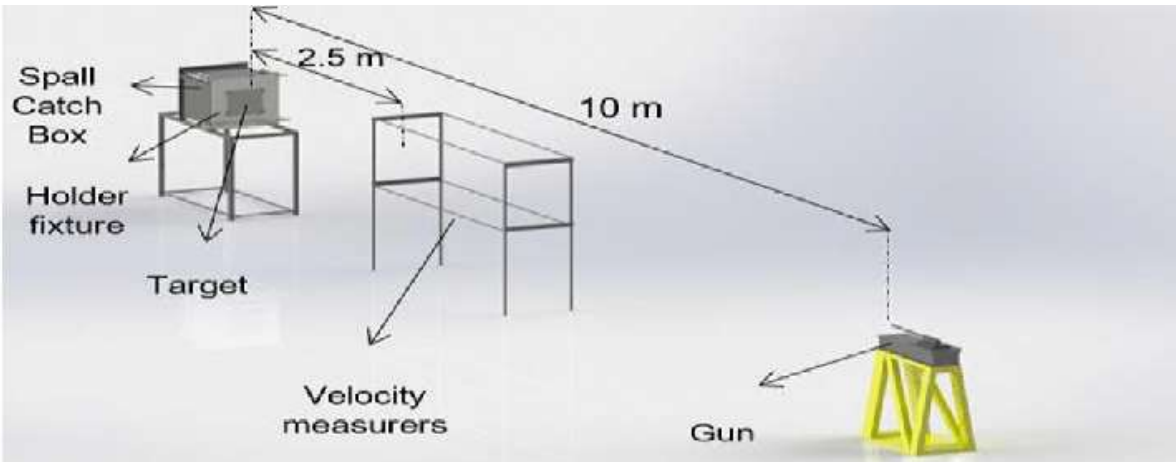


Figure 8. Standard ballistic test setup schematic

4. Finite Element Modeling and ABAQUS Simulations

Numerical simulation has become an indispensable tool in ballistic research due to the high cost and logistical complexity of experimental testing [29]. ABAQUS/Explicit is widely adopted for simulating high-velocity impact events because of its robust handling of large deformations, contact interactions, and high strain-rate effects [30].

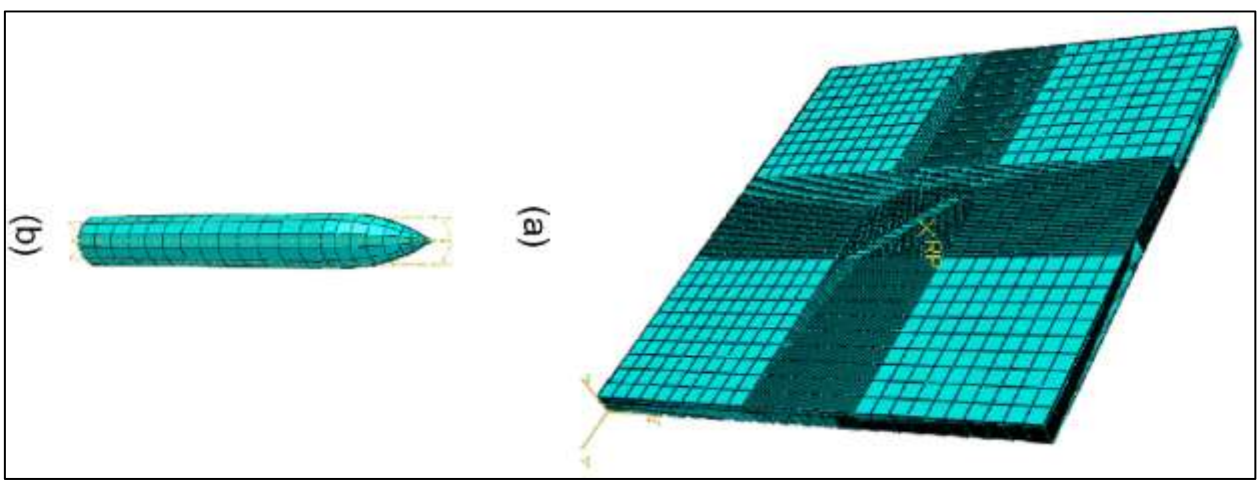


Figure 9. FE model geometry of projectile–target interaction

The Johnson–Cook constitutive and damage models are commonly applied to describe the behavior of armor steels under dynamic loading [31], [32]. For composite laminates, continuum damage mechanics models and cohesive zone formulations are used to simulate fiber failure and interlaminar delamination [33]–[35]. Several validation studies report good agreement between simulated and experimental ballistic limits when material parameters are carefully calibrated [36].

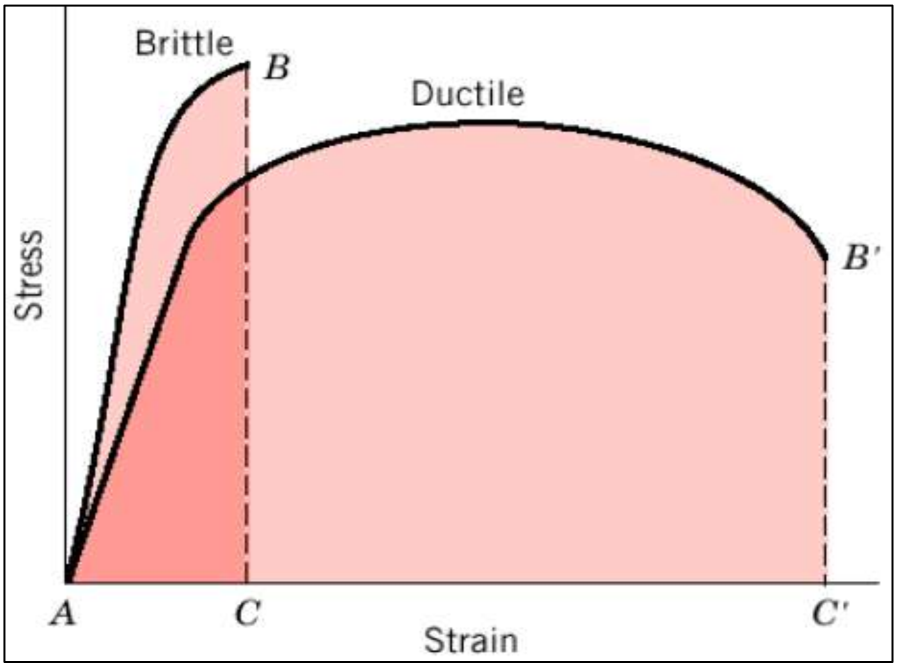


Figure 10. Johnson–Cook stress–strain and damage model curves

5. Comparative Performance and Critical Analysis

High-hardness armor steels such as Ramor provide excellent resistance to penetration and are well suited for severe threat levels [37]. However, their relatively high density limits their use in weight-sensitive applications. Composite laminates offer high specific energy absorption and reduced mass but may exhibit reduced durability and sensitivity to environmental conditions [38]. Hybrid armor systems represent a promising compromise, although challenges remain in optimizing layer thickness, interface bonding, and multi-hit performance [39], [40].

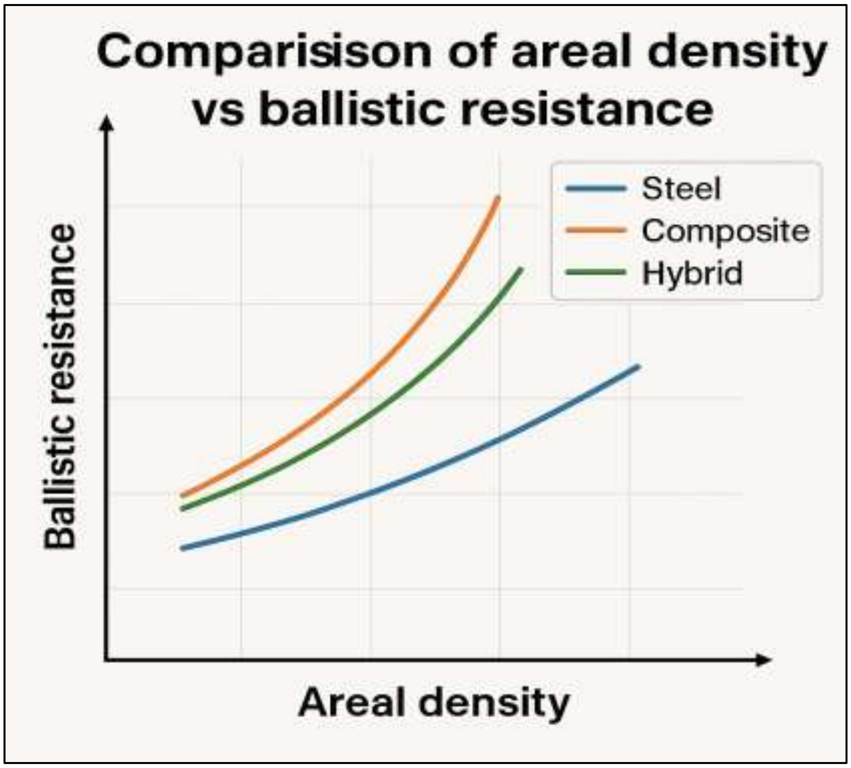


Figure 11. Comparison of areal density vs ballistic resistance (steel vs composite vs hybrid)

The graph demonstrates that composites achieve higher ballistic efficiency at lower areal density, while steels provide superior resistance at the cost of weight. Hybrid systems balance both, offering intermediate density with enhanced resistance.

Table 2. Comparative performance

System	Areal Density	Energy Absorption Mechanism	Strengths	Weaknesses
Monolithic Steel	High	Plastic deformation, shear plugging	High penetration resistance	Heavy, limited mobility
Composite	Low	Fiber rupture, delamination	Lightweight, high specific absorption	Sensitive to environment
Hybrid	Medium	Steel blunts projectile, composite absorbs residual energy	Balanced performance	Interface bonding, cost

This comparison emphasizes the trade-offs among armor systems: steels deliver maximum penetration resistance but are heavy; composites are lightweight yet environmentally sensitive, and hybrids combine the strengths of both with interface challenges.

6. Future Research Directions

Future research should prioritize systematic investigation of multi-hit ballistic performance in hybrid systems [41], the effects of environmental exposure on composite armor durability [42], and the development of advanced constitutive models incorporating strain-rate and temperature dependence [43]. Improved experimental validation under realistic combat conditions is also essential [44].

7. Conclusions

This review provides a comprehensive synthesis of published research on Ramor steels and hybrid composite laminates for ballistic protection. The findings indicate that hybrid armor systems offer the most promising pathway toward achieving lightweight, high-performance ballistic protection. Continued integration of experimental testing and validated numerical modeling is essential for advancing armor material design and application.

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References

[1] M. M. Moure, I. Rubio, J. Aranda-Ruiz, J. A. Loya, and M. Rodríguez-Millán, "Analysis of impact energy absorption by lightweight aramid structures," *Composite Structures*, vol. 203, pp. 917–926, Jun. 2018, doi: 10.1016/j.compstruct.2018.06.092.

[2] F. Siddique, F. Li, M. Z. Hussain, Q. Zhao, and Q. Li, "Design and performance of layered heterostructure composite material system for protective armors," *Materials*, vol. 16, no. 14, Art. no. 5169, Jul. 2023, doi: 10.3390/ma16145169.

[3] M. Walicki, J. Janiszewski, and K. Cieplak, "Estimation of ballistic performance of armor steels based on the split Hopkinson shear bar data," *J. Theor. Appl. Mech.*, vol. 60, no. 1, pp. 129–140, 2022, doi: 10.15632/jtam-pl/144793.

[4] D. Goldbaum *et al.*, "The effect of deposition conditions on adhesion strength of Ti and Ti–6Al–4V cold spray splats," *J. Therm. Spray Technol.*, vol. 21, no. 2, pp. 288–303, 2012, doi: 10.1007/s11666-011-9720-3.

[5] A. Rusinek and J. A. Rodríguez-Martínez, "Thermo-viscoplastic constitutive relation for aluminium alloys," *Mater. Des.*, vol. 30, no. 10, pp. 4377–4390, 2009, doi: 10.1016/j.matdes.2009.04.011.

[6] SSAB AB, *Ramor Armor Steel Technical Handbook*. Oxelösund, Sweden: SSAB AB, 2020.

[7] V. Arora *et al.*, "Ballistic performance of composite laminates," *Composite Structures*, vol. 94, no. 9, pp. 2738–2745, 2011.

[8] P. Abrate, "Impact on composite structures," *Appl. Mech. Rev.*, vol. 51, no. 2, pp. 69–90, 1998.

[9] T. Børvik *et al.*, "Perforation of steel plates by projectiles," *Int. J. Impact Eng.*, vol. 27, no. 1, pp. 19–35, 2001.

[10] S. Dey *et al.*, "Failure mechanisms of high-strength armor steel," *Int. J. Impact Eng.*, vol. 30, no. 8–9, pp. 1107–1123, 2004.

[11] R. Zaera and J. Sánchez-Gálvez, "Analytical modeling of projectile impact," *Int. J. Impact Eng.*, vol. 21, no. 5, pp. 383–401, 1998.

[12] M. L. Bekci *et al.*, "Microstructural effects on ballistic performance of armor steels," *Eng. Sci. Technol.*, vol. 24, no. 3, pp. 738–746, 2021.

[13] H. Y. Ban *et al.*, "Mechanical and ballistic behavior of Ramor steel," *Materials*, vol. 12, no. 22, Art. no. 3684, 2019.

[14] J. Nilsson *et al.*, "Ballistic performance of high-hardness steels," *Defence Technology*, vol. 14, no. 3, pp. 256–264, 2018.

[15] G. Krauss, *Steels: Processing, Structure, and Performance*, 2nd ed. Materials Park, OH, USA: ASM International, 2015.

[16] N. M. Nurazzi *et al.*, "Energy absorption mechanisms in composite armor," *Polymers*, vol. 13, no. 3, Art. no. 447, 2021.

[17] P. Abrate, "Modeling of impacts on composite structures," *Composite Structures*, vol. 51, no. 2, pp. 129–138, 2001.

[18] J. López-Puente *et al.*, "Ballistic impact on composite laminates," *Int. J. Impact Eng.*, vol. 29, no. 1–10, pp. 497–508, 2003.

[19] S. L. Phoenix and P. Porwal, "A new model for ballistic impact," *Int. J. Solids Struct.*, vol. 40, no. 24, pp. 6723–6760, 2003.

[20] A. C. Orifici *et al.*, "Failure mechanisms in composite structures," *Composite Structures*, vol. 94, no. 2, pp. 471–482, 2012.

[21] M. Yahaya *et al.*, "Hybrid composite laminates for armor applications," *Compos. Part B*, vol. 88, pp. 344–353, 2016.

[22] S. Bandaru *et al.*, "Delamination mechanisms in laminated composites," *Composite Structures*, vol. 129, pp. 1–14, 2015.

[23] M. Grujicic *et al.*, "Ballistic performance of hybrid armor systems," *Mater. Des.*, vol. 30, no. 3, pp. 879–890, 2009.

[24] S. B. Choi *et al.*, "Impact response of steel–composite armor," *Composite Structures*, vol. 92, no. 2, pp. 315–322, 2010.

[25] R. Heimbs, "Computational methods for impact on composites," *Int. J. Impact Eng.*, vol. 38, no. 2–3, pp. 81–93, 2011.

[26] National Institute of Justice, *Ballistic Resistance of Body Armor*, NIJ Standard 0101.07, 2023.

[27] European Committee for Standardization, *Windows, Doors and Shutters—Burglar Resistance*, EN 1522, 1998.

[28] NATO, *Protection Levels for Occupants of Logistic and Light Armoured Vehicles*, STANAG 4569, 2018.

[29] A. Rusinek *et al.*, "Numerical modeling of ballistic impact," *Int. J. Impact Eng.*, vol. 35, no. 6, pp. 466–475, 2008.

[30] Dassault Systèmes, *ABAQUS Documentation*, Providence, RI, USA.

[31] G. R. Johnson and W. H. Cook, "A constitutive model and data for metals subjected to large strains," in *Proc. 7th Int. Symp. Ballistics*, The Hague, The Netherlands, 1983, pp. 541–547.

[32] T. Børvik *et al.*, "Failure modes of steel under impact," *Eur. J. Mech. A*, vol. 20, no. 5, pp. 685–712, 2001.

[33] C. Soutis, "Fibre reinforced composites in aerospace," *Prog. Aerosp. Sci.*, vol. 41, no. 2, pp. 143–151, 2005.

[34] P. P. Camanho *et al.*, "Modelling of delamination in composites," *Compos. Sci. Technol.*, vol. 63, no. 7, pp. 987–999, 2003.

[35] E. G. González *et al.*, "Numerical simulation of composite impact," *Compos. Part A*, vol. 95, pp. 1–14, 2017.

[36] M. Xiao *et al.*, "Validation of numerical models for ballistic impact," *Int. J. Impact Eng.*, vol. 68, pp. 12–25, 2014.

[37] J. O. Hallquist, *LS-DYNA Theory Manual*. Livermore, CA, USA: Livermore Software Technology Corp., 2006.

[38] A. P. Mouritz *et al.*, "Environmental effects on composite armor," *Composite Structures*, vol. 53, no. 1, pp. 21–42, 2001.

[39] M. Alves *et al.*, "Experimental study of hybrid armor," *Int. J. Impact Eng.*, vol. 31, no. 5, pp. 623–640, 2004.

[40] R. Zaera *et al.*, "Ballistic performance of layered armor," *Int. J. Impact Eng.*, vol. 67, pp. 34–50, 2014.

[41] H. Xue *et al.*, "Multi-hit performance of armor systems," *Defence Technology*, vol. 16, no. 2, pp. 421–430, 2020.

[42] M. Hosur *et al.*, "Durability of composite armor under environment," *Composite Structures*, vol. 80, no. 3, pp. 381–391, 2007.

[43] S. Nemat-Nasser, "Constitutive modeling at high strain rates," *Mech. Mater.*, vol. 36, no. 7, pp. 617–628, 2004.

[44] D. Case *et al.*, "Experimental validation of ballistic models," *Int. J. Impact Eng.*, vol. 95, pp. 27–38, 2016.