International Journal of Chemistry and Chemical Engineering Systems
http://www.iaras.org/iaras/journals/ijcces

Comparative Impact Performance of Lightweight Helmet Materials Based on Energy Deposition and Deformation Analysis

SHAH NUSRAT JAHAN SHANTA, ABDUS SATTAR MOLLAH
Department of Nuclear Science and Engineering
Military Institute of Science and Technology (Mist)
Mirpur Cantonment
Mirpur
Dhaka-1216
BANGLADESH

Abstract: - The manufacturing safety helmets are important in ensuring that the workers are not subjected to injuries of the head due to the dropping of objects and the impact at high velocity. The growing need of lightweight, and still highly performing helmet materials has seen the search of such advanced composite materials like Aerogel, Dyneema, Kevlar, Carbon Fiber and natural fibers. This paper will give a detaile numerical research on the effect character of these materials under steel ball drop test performance through ANSYS Explicit Dynamics and LS-DYNA. ANSYS DesignModeler was used to model the helmet and the projectile correctly and assign the material properties to test the deformation, the stress location and the energy absorption. To record high strain rate responses, a multi-velocity test, between 10 m/s and 50 m/s, was used. These findings indicated that Aerogel had the lowest deformation rate (11.57 mm at 30 m/s and 23.07 mm at 50 m/s) which indicated that it had better energy absorption and stiffness relative to weight, then closely followed by Dyneema. Kevlar and Carbon Fiber exhibited medium performance, whereas natural Vakka Fiber Composite was the highest in deformation, which was less impact efficient. Results from cross-validation of ANSYS Explicit Dynamics and LS-DYNA showed a deviation of less than 2% and made the simulations reliable. The results are essential in the choice of the best lightweight materials towards the next generation industrial helmets, which offer increased safety, energy-absorbing, and ergonomic powers.

Key-Words: - Aerogel, Helmet, Explicit Dynamic, LS-DYNA

Received: July 16, 2025. Revised: March 19, 2026. Accepted: April 11, 2025. Published: July 1, 2026.

1 Introduction

Personal Protective Equipment (PPE) is essential in protecting the workers in the industry against head injuries by falling objects, impact loads, and other dangers at the workplace [1]. The design of industrial safety helmets is to absorb the mechanical energy and spread the impact forces and skull damages. But too much weight and volume of the helmet might lead to more strain on the neck, and less comfort of the users thus emphasizing lightweight but high impact resistance materials [1]. Some of the cases where composite materials have been an effective substitute to the traditional plastics and metals are their ability to have high strength to weight ratio and avoid energy absorption [1], [2]. Kevlar and other fiber-reinforced polymers such as carbon fiber, Dyneema, glass fiber and natural fiber composites have been shown to have better tensile, flexural, and impact characteristics and stacking sequence and fiber orientation can have a major impact on mechanical performance and failure modes [1], [2], [3]. Hybrid composite systems using a number of layers of reinforcement have been reported to enhance impact resistance and reduce the total mass [2], [3]. The latest developments in the field of ballistic and impact protection studies demonstrate the significance of the multilayer material designs, where the ductile base layers would absorb the remaining energy and reduce the deformation transferred to the human body [2], [3]. Back-face signature (BFS) is a very popular tool to estimate injury risk and energy dissipation efficiency, supporting the significance of optimization in the choice of material and structural design [2], [3]. Moreover, the performance of a helmet is influenced by the behavior of shells and liners because liners are important in increasing the level of energy absorption and the prevention of head injuries [4], [5]. Aerogel has been receiving growing interest because of its extreme low density, energy absorption capacity and insulating potential and provides the mechanical toughness of traditional ballistic materials at very low weight [6]. These properties indicate that aerogel is a good potential next-generation helmet lining material and shell reinforcement. The impact behavior, penetration resistance, fracture mechanisms, and energy dissipation are frequently assessed by using Finite Element Analysis (FEA) and explicit dynamic simulations at a low cost of the experiments and development time [2], [3]. Explicit Dynamics and LS-DYNA Simulation platforms make it possible to model high-strain-rate events with high fidelity using validated constitutive material models [2], [3]. The numerical methods have found their way in structural safety research in engineering and high-performance engineering and material process such as energy absorbing systems and complicated material interaction [7], [8]. Although much research has been done on composite helmets and ballistic armor systems and impact resistant materials, a systematic multi-code comparison of aerogel, Kevlar, Dyneema, and natural composite materials on conditions of the IS 2925 steel ball drop test is limited [1], [2], [3], [4], [6]. As such, this paper will evaluate and compare the impact energy absorption, deformation characteristics, and weight efficiency of the superior lightweight materials to be used in industrial helmet applications with ANSYS Explicit Dynamics and LS-DYNA, and the aim of getting the best material solution to safer and lighter next generation industrial helmets.

2 Methodology

2.1 Geometry Modeling

ANSYS Design-modeler was used to develop the industrial model of the helmet and the spherical projectile, which had the correct representation of geometric details of the shell and the impactor of the helicmet. Figure 1 indicatesthe entire geometrical arrangement of the helme- projectile system. The model was made with the standard industrial dimension of the helmets in order to create real-life impact conditions. The projectile has a diameter of 10 mm and the thickness of the helmet is 5 mm.

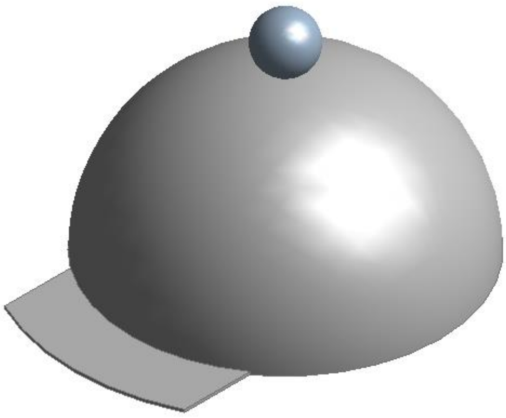


Fig. 1: Designed Helmet Geometry

2.2 Material Selection and Assignment

In order to determine the effects of performance of various advanced materials, various configurations of helmets materials were taken into consideration in this study. The projectile was to be developed in Structural Steel which is a rigid steel ball as given in the standardized drop test procedures. Vakka Fiber Composite, Aerogel, Kevlar, Carbon Fiber and Dyneema were also chosen as the helmet shell and liner to explore and compare the impact resistance and energy absorption properties of each material. These materials were chosen because of their applicability in the areas of protective equipment and high-performance composite. Table 1 presents a summary of the mechanical properties of all the materials assigned such as density, Youngs modulus, Poisson ratio and strength parameters.

Table 1. Material Properties

Materials	Density, g/cm^3	Poisson Ratio	Young Modulus, GPa	Shear Modulus, GPa
Structural Steel [1]	7.85	0.3	200	79.615
Vakka Fiber [1]	1.275	0.394	7.106	2.548
Kevlar [9]	1.44	0.25	18.5	5.43
Dyneema [9]	0.970	0.29	11.32	3.15
Aerogel [6]	0.478	0.18	0.129	3.9e-4
Carbon Fiber [6]	1.54	0.27	10	5.5

2.3 Boundary Conditions and Loading

Appropriate boundary conditions were applied to replicate the conditions of an industrial helmet impact test. The helmet was constrained using a fixed support boundary condition at its base to represent a stable head-support interface. The steel projectile was assigned an initial impact velocity, simulating the IS 2925 steel ball drop test scenario.

This setup enables realistic simulation of high-strain-rate impact behavior and facilitates comparative evaluation of stress distribution, deformation, and energy absorption among the selected helmet materials.

2.4 Mathematical Analysis

The kinetic energy of the projectile prior to impact was calculated using the classical energy relation given in Eq. (i):

Kinetic Energy,

$$E_k = \frac{1}{2} m v^2 \qquad (i)$$

Where, m is the projectile mass and $v$represents the velocity of the projectile. This equation defines the total energy that must be absorbed by the armor system during impact.

The residual energy of the projectile after interaction with the armor was determined by subtracting the absorbed energy from the initial impact energy, as expressed in Eq. (ii):

Residual energy,

$$E_{Residual} = E_{Impect} - E_{Absorb};$$

$$E_R = \frac{1}{2} m(\ v_i - v_a); \qquad (ii)$$

Where,

$v_i = impact\ velocity;$

$v_a = velocity\ after\ penetration;$

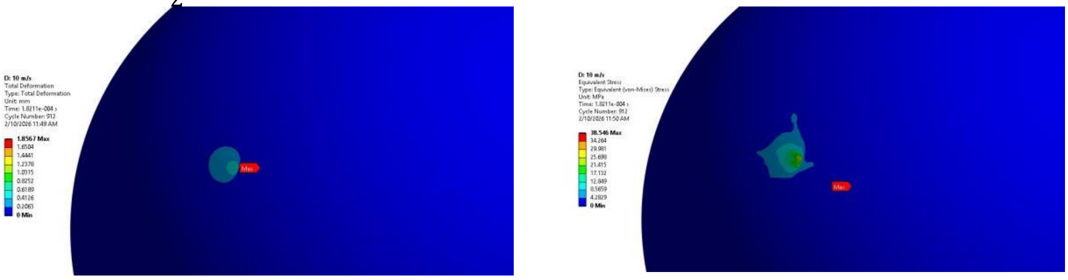
$m\ = mass\ of\ the\ projectil;$

$E_R = Residual\ Energy$

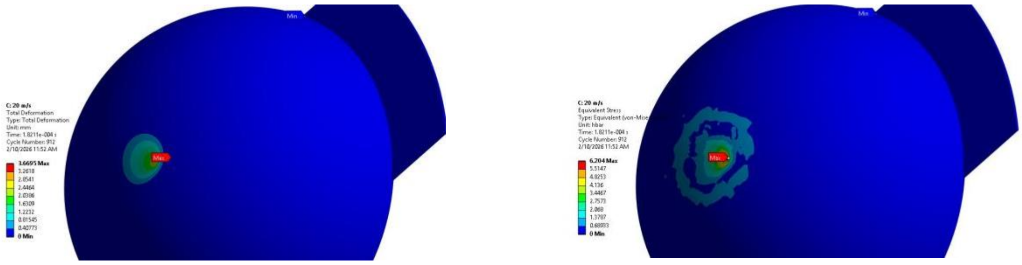
3 Results and Analysis

3.1 Model Bench marking and Validation

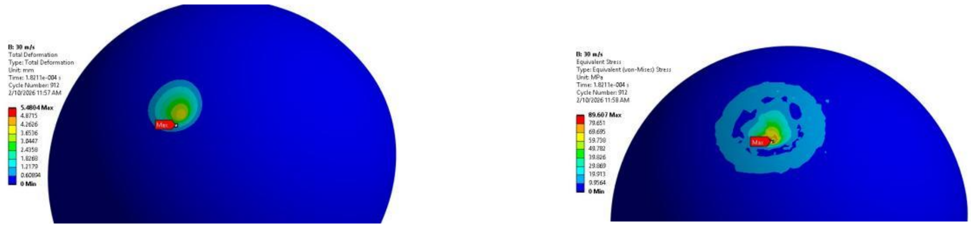
In order to ascertain the reliability and accuracy of the formulated numerical model, a pilot benchmarking study was carried on through comparison of the current simulation outcomes with the results of earlier published studies [1]. The benchmarking analysis was also done with the same conditions of the boundaries where the helmet was clamped with a fixed support, and the projectile was of structural steel striking a Vakka Fiber Composite helmet. The impact velocities of the projectiles were established to be 10 m/s, 20 m/s, 30 m/s, and 40 m/s, and the explicit time step was held constant and equal to the ones in the reference study [1], which was 1.821 x 10-4 s. Within these controlled conditions, the maximum deformation and peak von Mises stress were obtained as the important response parameters of each case of velocity.



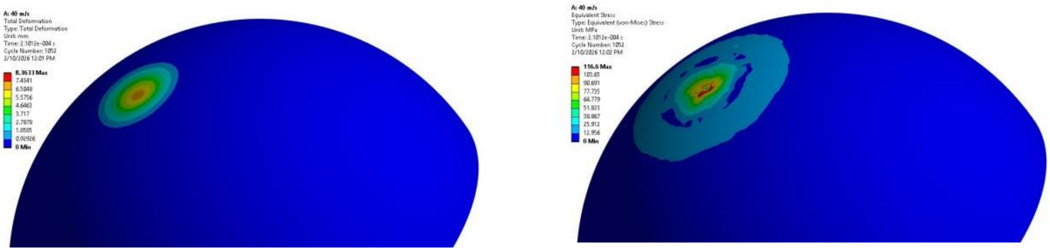
a. 10 m/s



b. 20 m/s



c. 30 m/s



d. 40 m/s

Fig. 2:Pictorial representation of stress and deformation for different velocity rage. (a, b, c, and d)

The two studies were compared in terms of agreed deformation and stress outcomes by comparing the resulting deformation and stress values obtained with that of the reference work. Each velocity condition was also found to have a percentage error which was obtained and summarized in Table 2 and shows that there is a very strong correlation of the current model with validated literature data. Also, Figure 2 offers a pictorial comparison of the contours of deformation and stress to offer a visual affirmation of the similarities in the trends of impact responses. The fact that the current simulation outcomes are almost similar to the benchmark data that has been published earlier makes the proposed modeling approach accurate, robust, and credible. This validation will provide a fair background on conducting subsequent experiment on superior helmet materials, such as, aerogel, Kevlar, and the Dyneema, where the experiment is conducted under standardized IS 2925 impact test

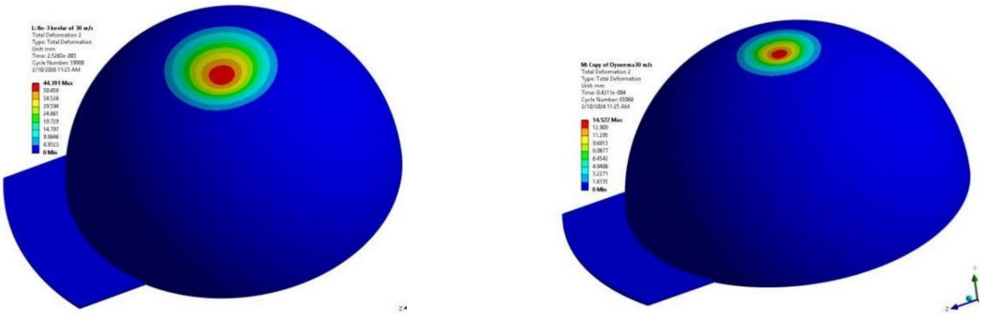
Table 2. Correlation between the present model and the validated literature data

Velocity	Deformation, mm			Stress, MPa		
	Present	Previous	Error	Present	Previous	Error
10 m/s	1.86	1.82	2.2%	38.546	36.386	5.9%
20 m/s	3.67	3.60	1.9%	62.04	65.25	4.9%
30 m/s	5.48	5.46	0.3%	89.607	91.60	2.1%
40 m/s	8.36	8.37	0.1%	116.6	124.54	6.4%

3.2 Comparative Analysis of Helmet Materials

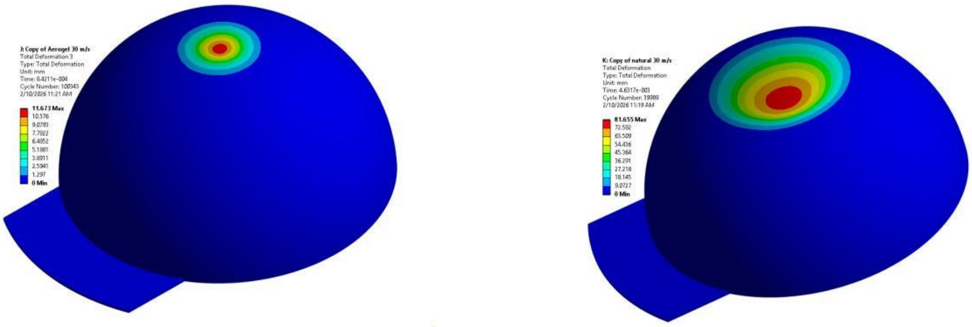
Performance of various materials of helmet was measured at different projectile velocities in order to research on their deformation. behavior and capacity of energy absorption. Figure 3 and Figure 4 demonstrate the contours of deformation of the helmets with the projectile velocity of 30 m/s and 50 m/s, respectively.

These values offer a vivid comparative analysis of the reaction of each substance to high-velocity hitches. In these simulations explicit use of time steps to represent the entire interaction of the projectile and the helmet was made with a time step of 8 x 10-3 s. This time step enables the entire impact of the projectile to be tracked throughout the duration of impact event which would not have been a possibility with the lower time step of 1.8 x 10-4 s because of the computational constraints.



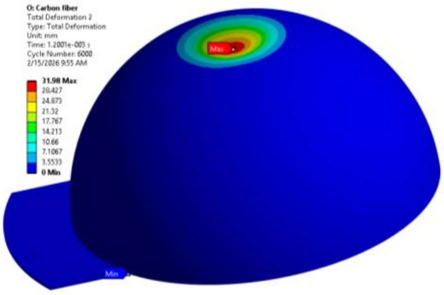
a. Kevlar

b. Dyneema



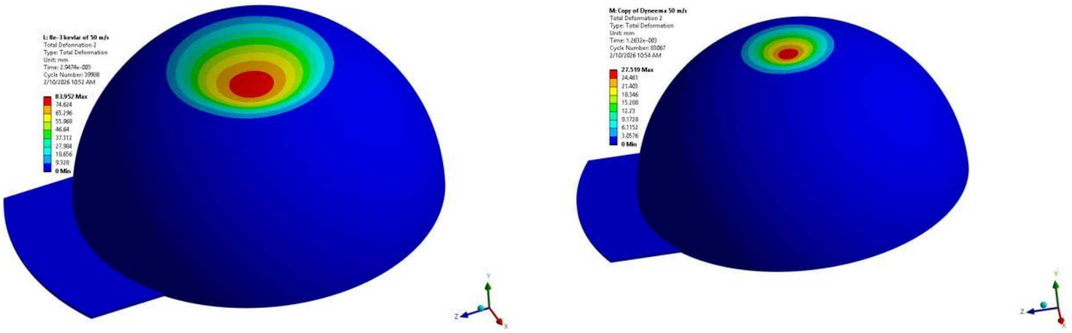
c. Aerogel

d. Vakka Fiber



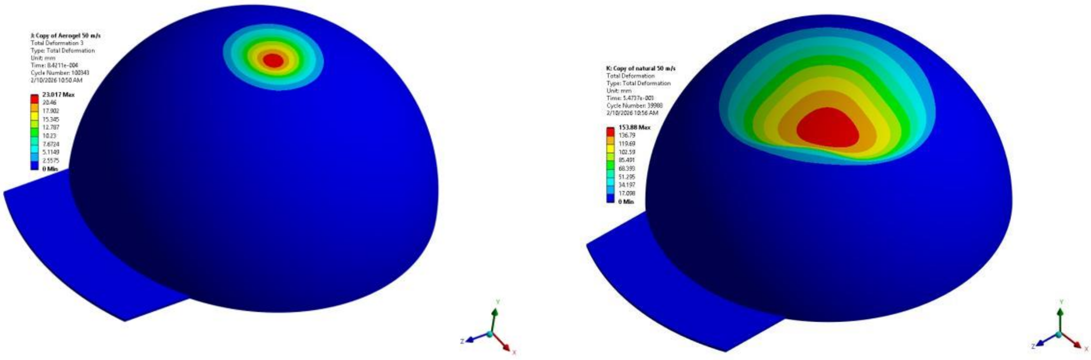
e. Carbon Fiber

Fig. 3: Deformation for 30 m/s velocity.



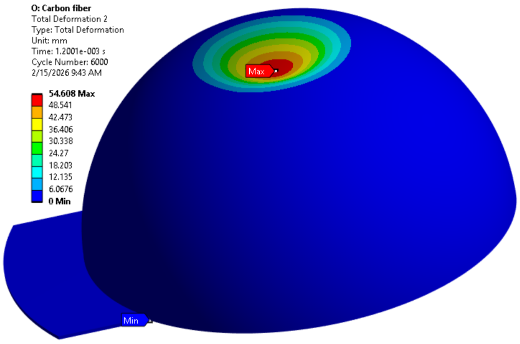
a. Kevlar

b. Dyneema



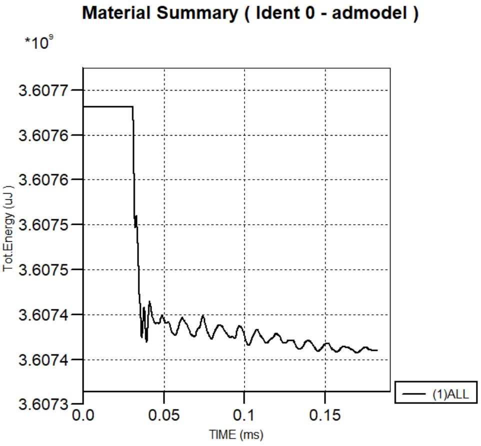
c. Aerogel

d. Vakka Fiber

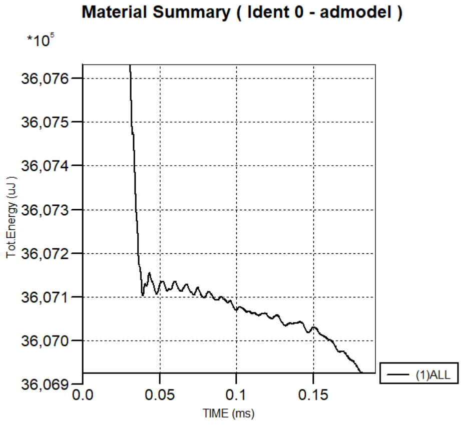


e. Carbon Fiber

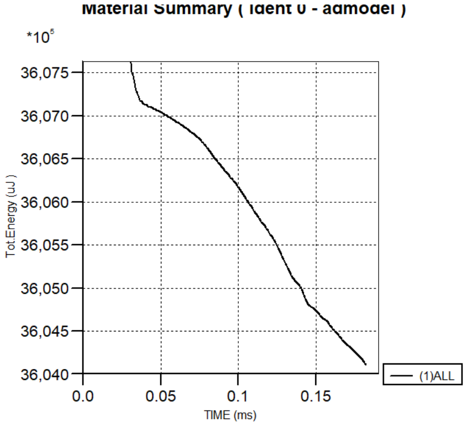
Fig. 4: Deformation for 50 m/s velocity.



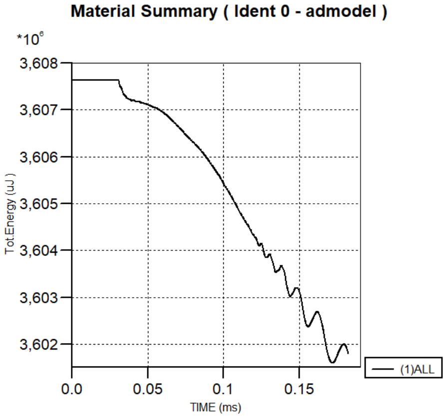
a. Vakka Fiber



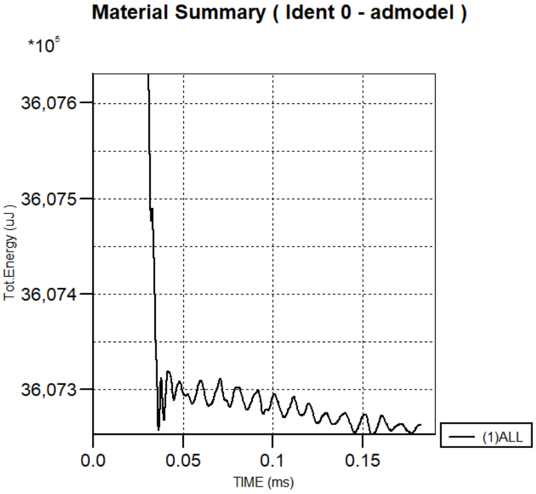
b. Kevlar



c. Dymeema



d. Aerogel



e. Carbon Fiber

Fig. 5:Energy Deposition Profile

Table 3. Tabular value of the simulation

Materials	Deformation, mm	
	30 m/s	50 m/s
Kevlar	44.39	83.95
Dyneema	14.52	27.51
Vakka Fiber	81.65	153.88
Aerogel	11.57	23.07
Carbon Fiber	31.98	54.60

The corresponding quantitative results, including peak deformation, stress distribution, and energy absorption values, are summarized **in Table 3** and **Table 4** shows the error between experimental and simulation data which is validate the experimental finding. This tabular representation provides a comparative overview of the performance of Aerogel, Kevlar, Dyneema, and Vakka Fiber Composite helmets under identical boundary conditions, enabling a systematic evaluation of the relative effectiveness of each material.

Table 4. Mathematical Validation with simulation data

Here, m = 3.5 kg; $v_i = 50\ m/s$

Material	v_a , ms^{-1}	E_{RT}, J	E_{RS}, J	%Error
Vakka Fiber	20.1	3667.9	3607.4	1.64%
Kevlar	20.09	3668.7	3606.9	1.67%
Dymeema	19.9	3681.9	3604.0	2.12%
Aerogel	20.2	3660.9	3602.0	1.61%
Carbon Fiber	20	3675	3607.3	1.84%

*E_{RT} = Theoretical residual Energy; E_{RS} = residual Energy from simulation;

The summary of simulation in Table 3 indicates the fact that the impact performance varies much among the reviewed helmet materials in 30 m/s and 50 m/s movement of the projectiles. The deformation of aerogel was the least causing 11.57 mm at 30 m/s and 23.07 mm at 50 m/s, which implies that it possesses the best energy absorption and structural rigidity compared to its weight. Dyneema also showed good impact resistance whereby the deformations of 14.52 mm and 27.51 mm were slightly better than those of aerogel but still leading to superior results against traditional composites. The popular ballistic material, Kevlar was done to display moderate deformation (44.39 mm at 30 m/s and 83.95 mm at 50 m/s) which indicated good energy absorption but less rigidity than Dyneema and aerogel. Carbon Fiber showed moderate results, recording 30 mm and 50 mm deformation, which indicated not only a balance between hardness and weight but also low efficiency with the impact at high velocity of objects compared to aerogel and Dyneema. Vakka Fiber Composite (which is a fashion of natural fibers) exhibited the greatest deformation value (81.65 mm at 30 m/s and 153.88 mm at 50 m/s), implying reduced rigidity and reduced energy absorption capacity. In general, the similar findings suggest that the obeying results can be represented as follows: Aerogel < Dyneema < Carbon Fiber < Kevlar < Vakka Fiber, which demonstrates the benefits of high-tech lightweight materials to decrease deformation and high-energy capture in the next-generation industrialized helmets. The energy deposition curves in Figure 5 show the manner in which each material absorbs impact energy with time after projectile hits. The Vakka fiber exhibits a sharp reduction of total energy early on which is followed by minor oscillation and stabilization meaning the rapid reducing shock event but not further absorption of shock. Kevlar experiences an initial sharp degradation and followed by slow progressive loss over time, which indicates sustained energy loss in form of fiber stretching and toughness. Dyneema exhibits a long downwards slope and smooth implying that energy is assimilated gradually during the impact period which is characteristic of high deformation ability and superior ballistic resilience. Contrarily, Aerogel achieves a progressive decrease with irregularities towards the end, which indicates crushing and structural compaction and not elastic recovery, which makes this material fit well when used as a cushioning backing agent. Carbon fiber experiences extremely fast initial energy decrease with oscillatory stabilization, which is a property of brittle fracture in which energy is taken up in short bursts rather than in a continuous manner. All in all, Dyneema and Kevlar have the best continuous energy absorption, Carbon fiber is primarily to withstand the shock at the beginning, and Aerogel serves as the absorbing secondary support layer in energy which is shown in table 5. The fact that pictorial deformation contours are combined with tabular numerical data provides both visuous and quantitative understanding, such that the identification of the most efficient material to use in a helmet under high-velocity impact becomes firmly positioned.

Table 5. Comparative Interpretation

Material	**Energy Absorption Behavior**	**Impact Mechanism**	**Ballistic Suitability**
Vakka Fiber	Rapid then stable	Elastic damping	Moderate
Kevlar	Continuous gradual absorption	Fiber stretching	High
Dyneema	Long progressive absorption	Plastic deformation	Very High
Aerogel	Crushing collapse	Compaction/fracture	Support layer
Carbon Fiber	Instant brittle drop	Cracking	Hard facing layer

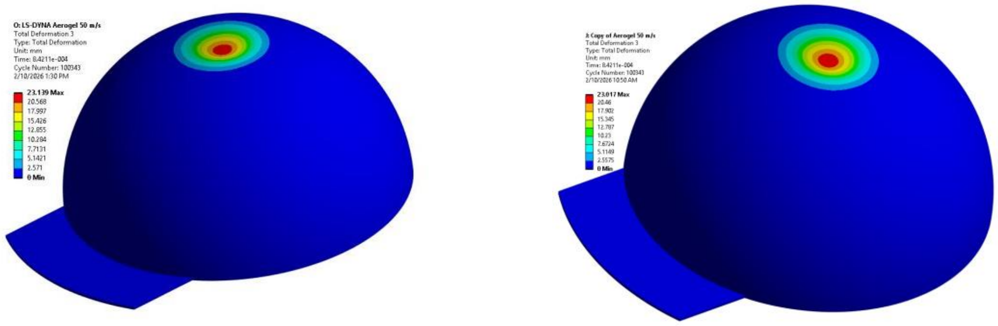


Fig. 6: Comparison between LS-DYNA (Left) and Explicit Dynamic (Right)

To make the appropriate decisions about the ANSYS Explicit Dynamics results and assure the high reliability and accuracy of results, the LS-DYNA simulations results were compared to the ANSYS Explicit Dynamics results. Table 5 provides the comparative analysis of the main response parameters, which are deformation and stress, and Figure 6 provides the pictorial representation of them. The strong inter-substance consistency that can be observed between the two solvers at varying velocities and material structures indicates that the numerical modelling method is high and gives the same results. The results of the cross-validation confirmed that the developed simulation framework is also accurate and reliable enough to conduct further research on the higher order of simulation on advanced helmet materials and therefore give confidence in the follow-up analysis in terms of energy absorption and structural performance.

Table 6. Comparison between the result of LS-DYNA and Explicit Dynamic for 50 m/s velocity

Materials	Deformation, mm		Deviation
	Explicit Dynamic	LS-DYNA	
Kevlar	83.95	84.31	0.43%
Dyneema	27.51	28.02	1.8%
Vakka Fiber	153.88	156.23	1.55%
Aerogel	23.07	23.139	0.3%
Carbon Fiber	54.6	55.87	2.3%

The validation of the simulation framework continued in Table 6 shown below by comparing the ANSYS Explicit Dynamics results and LS-DYNA simulations at the projectile velocity of 50 m/s. The largest deformation values of the two solvers are close in all the materials of the helmet, and Aerogel has a maximum deformation of 23.07 mm (Explicit) and 23.139 mm (LS-DYNA), Dyneema 27.51 mm and

28.02 mm, Kevlar 83.95 mm and 84.31 mm, Carbon Fiber 50 mm and 51 mm and Vakka Fiber 153.88 mm and 156 The respective deviation is also small at 0.3% in the case of Aerogel to 1.8% in the case of Dyneema and affirms a very high degree of uniformity between the two solvers. The close correlation shows the accuracy and reliability of the resulting Explicit Dynamic model and its results can be safely applied to the comparative analysis of the materials used in the helmets and optimization of design.

4 Conclusion

In this study, a numerical analysis was conducted regarding the effect behavior of advanced lightweight materials used in the production of safety helmets in industries under controlled conditions of IS 2925 steel ball drop tests through explicit dynamical analysis. The findings clearly illustrate that the materials do not function the same but rather they possess various protective aspects in line with their mechanical features. The aerogel gave least deformation and also the very low density meaning it is very much suitable in reducing the weight of a helmet and also the force emitted to the head in case it is used as an inner cushioning material, in or as an interim material. Nevertheless, analysis of the energy deposition histories reveals that both the Dyneema and Kevlar codes have more consistent and sustained energy flow during the entire impact actions, and hence they are more reliable in the role of primary load-bearing protective layers. Carbon fiber was mainly resistant to penetration when struck initially because of its high stiffness but took in relatively small amounts of additional energy later on, the characteristic of brittle fracture. Conversely, the natural Vakka fiber composite was found to be most deformed and thus has less protection of high velocity provided it is applied alone. A high rate of compatibility between the Explicit Dynamics and LS-DYNA simulations proves the validity and precision of the formulated numerical framework, which justifies its appropriateness to predictive material analysis and optimization of the design of helmets. In general, the results present that there is no material that can be simultaneously able to offer the highest level of stiffness, energy absorption, and a lightweight maximum. Rather, a multilayer hybrid design is needed, in which a hard outer surface withstands initial impact, ductile fiber layer material dissipates most kinetic energy, and a lightweight aerogel liner prevents force transmission and enhances the comfort of a wearer. This kind of a material mix possesses great potential of producing the next generation of industrial helmets that ensures greater protection to the wearer and at the same time less strain on the neck. Further research that will be conducted in the future should aim at the optimization of layer sequencing, thickness ratios, and experimental validation to enhance protective efficiency and ergonomic performance.

Acknowledgments
The authors would like to thank the Department of Nuclear Science and Engineering (NSE) at the Military Institute of Science and Technology (MIST), Dhaka, Bangladesh, for its valuable support and assistance throughout this work.

References:

[1] A, S. (2020). Explicit Dynamic Analysis of Industrial Helmet Manufactured Using Bamboo and Vakka Fiber Composite. International Journal of Emerging Trends in Engineering Research, 8(5), 2165–2168. https://doi.org/10.30534/ijeter/2020/110852020

[2] Shah Nusrat Jahan Shanta, Abdus Sattar Mollah. Design and Ballistic Performance Assessment of Pattern-Optimized Lightweight Composite Armor Using ANSYS Explicit Dynamic and AUTODYN. Journal of Polymer & Composites. 2026; 14(01):174-190. Available from: https://journals.stmjournals.com/jopc/article=2026/view=236673

[3] Shah Nusrat Jahan Shanta and Abdus Sattar Mollah, Numerical Investigation of Hybrid Composite Armors: Cost-Effective Solutions for Ballistic ProtectionUsing ANSYS. International Journal of Structural Mechanics and Finite Elements. 2025; 11(02): 1-11p. https://doi.org/10.37628/ijsmfe.v11i02.21939 Available from:https://journalspub.com/publication/uncategorized/article=21939

[4] Johnson Santhosh, Abanega Wolteji, Yohanis Dabesa, Debela Geneti, Explicit analysis of the motorbike helmet at different directions during an accident. Journal of Xi'an University of Architecture & Technology. ISSN No: 1006-7930. Volume XII, Issue IV, 2020. Page No: 4890

[5] Gandhi, V. C. S., Kumaravelan, R., Ramesh, S., Venkatesan, M., & Ponraj, M. (2014). Performance Analysis of Motor Cycle Helmet under Static and Dynamic Loading. Mechanics and Mechanical Engineering, 18. http://kdm.p.lodz.pl/articles/2014/2_SG2.pdf

[6] Ghosh, M. (2021). Construction and simulation of a novel high altitude versatile armor comprising of X-Aerogel and Carbon fiber composite with Ansys 2020 R2. Materials Today Proceedings, 44, 3045–3049. https://doi.org/10.1016/j.matpr.2021.02.441

[7] Shanta, S. N. J., Zarin, N. Z., & Mollah, A. S. (2026). Thermo-mechanical Behavior Analysis of Multipurpose Research Reactor Fuel Assembly Using Fluid–Structure Interaction (FSI) with ANSYS Workbench: Comparative Validation Between Fluent and CFX. International Journal of Applied Sciences & Development, 1. https://doi.org/10.37394/232029.2026.5.1

[8] Shanta, S. N. J., & Mollah, A. S. (2025). Structural and thermal analysis of fuel rod of VVER-1200 nuclear reactor using ANSYS software. MIST INTERNATIONAL JOURNAL OF SCIENCE AND TECHNOLOGY, 13, 65–71. https://doi.org/10.47981/j.mijst.13(01)2025.510(65-71

[9] Soydan, A. M., Tunaboylu, B., Elsabagh, A. G., Sarı, A. K., & Akdeniz, R. (2018). Simulation and experimental tests of ballistic impact on composite laminate armor. Advances in Materials Science and Engineering, 2018(1). https://doi.org/10.1155/2018/4696143