



# Advanced Multidisciplinary Engineering Journal AMEJ

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Journal Homepage

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## Impact Resistance and Buckling Mitigation in Hybrid Textile–Polymer Composite Helmets

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### ABSTRACT

This study presents an innovative approach to protective helmet design by integrating textile-reinforced polymer composites with structural geometries inspired by ancient Egyptian wrapping techniques. Finite element analysis was employed to examine the influence of fabric strip layouts on stress distribution and to support the development of the proposed helmet architecture. A polyester–jute hybrid configuration (H2) helmet was subsequently fabricated and experimentally evaluated under repeated vertical drop-weight impacts. Its performance was compared with pure jute (H1), pure cotton (H3), and conventional thermoplastic (H4) helmet shells. The H2 configuration demonstrated outstanding structural resilience, withstanding 20 consecutive impacts ranging from 14.71 J to 51.80 J and absorbing a cumulative impact of 738.69 J with very low measurable permanent deformation of 0.2 cm. In contrast, the pure jute shell failed during the first impact due to severe delamination and strip separation, while the cotton and thermoplastic reference shells exhibited permanent residual deformations of 1.5 cm and 1.3 cm, respectively. The superior performance of the H2 configuration is attributed to the combined effect of vertical load-carrying fabric strips and circumferential confinement provided by a horizontal reinforcement strip at the helmet rim, which improves load redistribution, delays local buckling, and enhances impact energy absorption. The findings demonstrate the potential of sustainable hybrid textile–polymer composites as lightweight and efficient structural solutions for advanced protective headgear applications.

### PAPER INFORMATION

#### HISTORY

**Received:** 2 March 2026

**Revised:** 20 May 2026

**Accepted:** 22 June 2026

**Online:** 27 June 2026

#### MSC

68T07; 68R10; 94A60; 68M15

#### KEYWORDS

Hybrid Textile Composites;  
Protective Helmets;  
Mitigating Buckling;  
Impact Damage Assessment;  
Indentation Severity Index.

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## 1. INTRODUCTION

The design of protective helmets has undergone a significant transformation in the past decade, driven by concurrent advances in textile engineering, advanced fabric architectures, and polymer composites. As the primary barrier against mechanical trauma, the choice of reinforcing fibre type remains central to helmet design, directly governing impact energy mitigation, structural durability, lightweight execution, and ergonomic user comfort. Traditionally, high-performance synthetic aramid fibres, specifically Kevlar, have served as the industrial benchmark for personal protection due to their exceptional tensile strength and energy dissipation mechanisms [1]. However, contemporary studies have increasingly highlighted the pivotal role of ultra-high-molecular-weight polyethylene (UHMWPE) and basalt fibres, which offer superior localized ballistic resistance and enhanced thermal stability under extreme operational conditions [2, 3]. Recent literature emphasizes that continuous fibre selection strongly dictates macroscale load-transfer mechanisms and the resultant biomechanical head protection, underscoring the vital need to develop optimized hybrid composite systems [4, 5]. Experimental investigations consistently validate these material dynamics. For instance, Kamble et al. [6] demonstrated that glass fibre-reinforced epoxy helmet shells performed effectively under low-velocity drop configurations, whereas carbon fibre variants provided significantly higher structural stiffness, albeit at a prohibitive manufacturing cost. Concurrently, natural lignocellulosic fibres, such as flax, jute, and hemp, have been widely studied for sustainable, eco-friendly helmet designs, offering advantageous biodegradability and cost-effectiveness despite exhibiting lower intrinsic mechanical strength compared to their synthetic counterparts [7, 8]. Nanotechnological interventions have further augmented natural and synthetic fibre performances; specifically, the cross-linking of nano-clay and graphene platelets into polymer matrices has been shown to significantly improve localized impact resistance and multifunctionality [9, 10]. Furthermore, finite element modeling (FEM) has emerged as a fundamental tool for simulating dynamic helmet impacts, demonstrating that precise fibre orientation and stacking sequences exert a dominant influence on transient stress distribution patterns [11, 12]. Modern structural configurations, including 3D woven fabrics and auxetic cellular architectures, have similarly proven effective in facilitating superior multi-axial shock absorption and localized dynamic responses [13, 14].

Beyond the fibrous reinforcement, the choice of the continuous resin matrix plays an important role in defining structural performance, where thermoset resin systems like epoxies yield high structural rigidity, while thermoplastic matrices provide enhanced fracture toughness and damage tolerance [15]. To guarantee strict safety compliance and structural repeatability, standardized head form testing protocols, such as the ASTM F1446 standard, strictly govern the evaluation of protective headgear [16]. Concurrently, automated manufacturing methodologies, including vacuum-assisted resin transfer molding (VARTM) and automated fibre placement (AFP), have significantly enhanced structural consistency while reducing internal void formation [17, 18]. Driven by modern operational environments, current design paradigms are also shifting toward the integration of smart wearable technologies, requiring flexible composite architectures capable of embedding sensor arrays without inducing premature structural delamination [19]. Furthermore, ecological sustainability has transitioned into a core engineering priority, with bio-based resins and fully recyclable continuous fibres being actively investigated to minimize lifecycle environmental footprints without compromising user safety benchmarks [20]. In the context of sustainable vehicular protection, recent research has specifically evaluated the structural feasibility of fabricating commercial motorcycle helmets from sustainable organic substrates, including flax, hemp, sisal, and bamboo continuous architectures [21, 22]. Cotton networks, though inherently limited by lower tensile thresholds, have been successfully treated via specialized chemical mercerization to enhance interfacial adhesion and reinforcement efficiency [23]. To eliminate synthetic chemical dependencies, completely bio-based resins, including lignin-derived binders, have been formulated to yield entirely natural eco-composites [24]. Architecturally, natural cellular cores such as expanded cork have been proposed as sustainable replacements for conventional expanded polystyrene (EPS) liners to manage impact energy attenuation [25]. Nevertheless, attaining rigorous international safety certifications (e.g., DOT, ECE, and Snell metrics) remains an ongoing engineering challenge, as natural fibre-reinforced composites must reliably mirror the dynamic energy dissipation profiles of established synthetic materials [26]. Consequently, structural hybridization strategies that strategically combine natural technical fibres with highly localized synthetic reinforcements offer an optimal compromise between high mechanical strength and ecological sustainability [27, 28]. However, critical operational hurdles persist, particularly regarding raw natural fibre quality variability and progressive environmental degradation due to weathering and moisture absorption [29, 30].

To date, numerical and experimental efforts have sought to characterize the crashworthiness of natural fiber assemblies under dynamic loads; for instance, explicit dynamic simulations of bio-composite helmets have demonstrated promising energy absorption capabilities [31]. Nevertheless, thin-walled composite shell geometries remain highly susceptible to localized structural instability, collapse, and severe post-buckling degradation under

repeated dynamic impacts [32]. This challenge becomes more critical under repeated impact conditions, where accumulated damage may trigger premature buckling failure. Addressing these coupled challenges of energy dissipation and buckling mitigation requires innovative material layering and structural confinement strategies that have not been fully realized in current literature.

To establish a robust structural foundation, several recent scholars have explored the broader applications of advanced fiber-reinforced polymers in personal protective equipment. Singh and Behera [4] provided a developmental overview of protective helmet evolution, emphasizing the critical role of material hybridization. Similarly, Dolez et al. [5] analyzed recent advancements in protective textiles, noting that fiber configuration directly governs dynamic energy distribution, while Kamble et al. [6] experimentally verified the structural viability of cost-effective composite helmet shells. Building on these foundations, the structural response of composite shells under low-velocity and repeated impacts has been widely investigated using both experimental and numerical approaches. Sun et al. [33] evaluated the dynamic response and damage accumulation in laminated composites under repeated low-velocity impacts, and reported matrix cracking and delamination, which severely compromise post-impact residual stiffness. To mitigate such dynamic degradation, Wu et al. [34] explored the incorporation of engineered high-density polyethylene air-bubble cushioning fabrics within Type I construction helmets, noting a significant reduction in the peak acceleration transmitted to the headform during repeated sequential strikes. Concurrently, dynamic durability evaluations are not restricted to polymeric systems; Gao et al. [35] tracked the microstructural damage evolution, fatigue life, and crack propagation behaviors under repeated impact loading in metallic protective shells. Furthermore, to address complex trauma profiles, La Fauci [36] introduced a novel tangential impact absorption safety liner utilizing shear thickening fluids to systematically mitigate rotational acceleration and shear damage.

The transition toward natural and hybrid fiber reinforcements represents a major change in thinking in personal protective equipment engineering. High-performance synthetic architectures have been benchmarked alongside treated natural alternatives to optimize the balance between ecological sustainability and mechanical resilience. Recent investigations by Sanjay et al. [37] highlighted that chemical treatment, such as alkalization and silane coupling, significantly enhanced the interfacial shear strength between natural lignocellulosic fibers and polymer matrices, effectively delaying premature delamination under compressive dynamic loads. Furthermore, Rajesh et al. [38] successfully demonstrated that hybridizing natural jute or flax layers with external plies of synthetic fibers creates a typical skin-core effect to stabilize multi-axial impact.

In contrast to conventional outer-synthetic architectures, our developed paradigm strategically positions the treated natural jute as the outer energy-dissipating shell, backed by a highly ductile woven polyester inner lining to optimize shielding mechanics and eliminate structural fragmentation.

Previous studies have explored stiffening strategies to delay local buckling in thin-walled structures through circumferential reinforcements and optimized load-path configurations. However, these approaches have not been investigated in textile strip-based helmet architectures and are given in **Table 1**.

**Table 1: Comparative matrix of recent protective helmet literature**

<b>Materials</b>	<b>Manufacturing</b>	<b>Structure design</b>	<b>Main finding</b>
Laminated synthetic composites	Compression molding and autoclave curing	Multidirectional laminated continuous plies	Tracked progressive damage accumulation under repeated low-velocity impacts; unconfined laminates suffered severe interlaminar delamination.[33]
High-density polyethylene / Air-bubble cushioning fabrics	Thermal bonding and layer lamination	Integrated polymeric bubble liners in protective helmets	Successfully enhanced secondary impact energy absorption but significantly increased overall helmet thickness and bulkiness.[34]
Titanium alloy (TC18) structures	Hot forging and heat treatment processes	Metallic protective shells	Analyzed microstructural damage evolution and fatigue life under high-velocity repeated impact loading conditions.[35]

Materials	Manufacturing	Structure design	Main finding
Polymeric shells / Shear Thickening Fluids (STF)	Liquid impregnation and chemical sealing	Integrated fluid-filled safety liners	Developed a novel tangential impact absorption system to effectively mitigate rotational acceleration and shear damage.[36]
Chemically treated natural fibers	Hand layup with chemical surface modification	Continuous quasi-isotropic laminate sheets	Chemical treatment optimized fiber-matrix adhesion but failed to mitigate global structural buckling.[37]
Natural-synthetic hybrid layers	Vacuum-assisted resin infusion	Skin-core structural sequencing	Hybridization delayed ply slippage; however, localized seam degradation remained a critical issue under dynamic impact.[38]

Despite these extensive historical and modern advancements, a critical research gap persists in current literature. While modern composite engineering emphasizes uniform, quasi-isotropic laminate layups, the structural potential of localized textile wrapping configurations—particularly those inspired by historical structural concepts, such as ancient Egyptian wrapping techniques—remains fundamentally under-explored. Traditional structural paradigms often struggle with localized macro-instabilities under severe vertical compressive loads, where protective shells are highly susceptible to sudden buckling failure. Consequently, the correlation between targeted strip geometry, circumferential confinement rings, and buckling prevention under high-energy impact profiles remains a critical unaddressed domain. The primary objective of this study is to evaluate the impact resistance and buckling mitigation of an innovative, lightweight hybrid textile polymer composite helmet shell utilizing multi-directional fabric strip architectures inspired by historical structural concepts. Specifically, this work focuses on developing a distinct hybrid polyester–jute configuration and systematically characterizing its structural integrity and progressive deformation mechanics under repeated low-velocity impact loads.

The core scientific novelty of this research lies in its inverted hybrid structure and edge reinforcement. Unlike conventional synthetic shells, this design strategically places a treated natural jute fabric network on the outside as the energy-dissipating shell, backed internally by a ductile woven polyester lining. To prevent local buckling, a horizontal fabric strip is integrated around the rim to act as a structural stiffening ring. The physical protective capacity of the fabricated shells is then experimentally validated through repeated drop testing adapted to ASTM F1446-20 parameters [16] on a standardized alloy headform conforming to the EN 960 specification [39].

## 2. MATERIALS AND METHODS

### 2.1 Materials

In this study, high-performance textile fabrics were selected as the primary reinforcements to optimize the structural integrity of the composite helmet shell. The reinforcing phase consisted of three distinct pure textile categories to evaluate the comparative constructive interaction of synthetic-natural hybridization: woven jute, woven pure cotton, and woven polyester fabrics. The matrix phase utilized was a polyester resin chemically cured using a dedicated hardener in a mixing ratio of 100:1 parts by weight, and the target fiber-matrix weight fraction was strictly maintained at approximately 50:50 wt.% to ensure optimal fiber-matrix constructive interaction and structural rigidity. To provide a precise baseline for the macro-mechanical response of the helmet shells, the structural parameters of the three discrete reinforcing fabrics were quantified as systematically detailed in **Table 2**.

A strip width of 30 mm was adopted as a practical fabrication parameter to achieve stable handling and consistent coverage of the hemispherical mold. The number of layers for each fabric type was adjusted to obtain helmet shells with comparable overall thickness and structural integrity before testing.

**Table 2: Technical specifications of the fabric reinforcement strips**

Fabric Material Type	Weave Style	Fabric Density (g/m <sup>2</sup> )	Warp Density (Ends/cm)	Weft Density (Picks/cm)	Nominal Strip Width (mm)	Nominal Fabric Thickness (mm)	Number of layup layers
<b>Woven Jute</b>	Plain	708(3.1) *	4.0(0.0) *	4.0(0.0) *	30.0	2.0(3.4) *	1
<b>Woven Polyester</b>	Plain	737(1.7) *	4.0(0.0) *	4.0(0.0) *	30.0	2.0(2.7) *	1
<b>Woven Cotton</b>	Plain	240(2.2) *	28.0(1.2) *	28.0(1.3) *	30.0	0.4(3.1) *	5

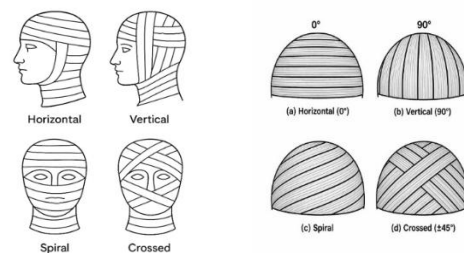
\* Coefficient of variation (CV%)

## 2.2. Fabrication and Wrapping Techniques

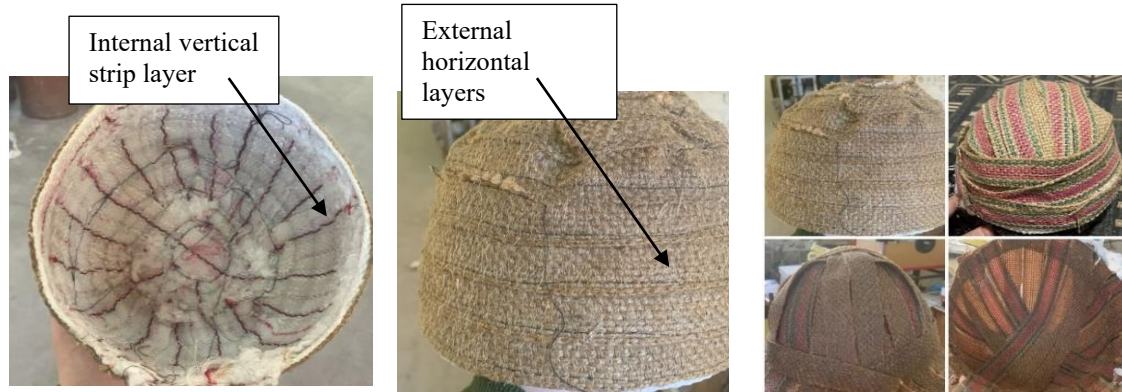
The fabrics were cut into uniform strips along the warp and weft directions to prevent edge fraying and enhance the mechanical interlocking at the interfaces. For the modified hybrid arrangement, specific stitching patterns (straight and zigzag) were applied using a high tenacity polyester thread to reinforce the longitudinal and circumferential paths. The helmet shells were fabricated using a head form mandrel (size EN 960) as a template. Four distinct wrapping models inspired by ancient textile practices were implemented, as systematically illustrated in **Figures 1 and 2**.

1. **Horizontal (Circumferential 0°):** wrapping parallel to the headform rim, prioritizing hoop-stress confinement.
2. **Vertical (90° Crown-to-Base):** Meridian strips intersecting at the apex, maximizing vertical load-bearing capacity.
3. **Spiral (Helical):** wrapping at a progressive 45° helix angle, facilitating semi-isotropic stress propagation.
4. **Crossed (Bi axial ±45°):** Intersecting diagonal strip networks, establishing high shear resistance.

For the Hybrid Modified Arrangement, a primary layer of vertical stripes was combined with a horizontal circumferential stripe at the rim. The layers were integrated using a secondary stitching process to form a cohesive preform before resin infusion.



**Figure 1. Wrapping models inspired by ancient Egyptian textiles and corresponding fibre orientation patterns used in composite helmet layups: (a) horizontal (0°), (b) vertical (90°), (c) spiral, and (d) crossed (±45°).**



**Figure 2. Composite helmet layups fabricated using the hand lay-up technique, showing strip orientation and structural arrangement**

### ***2.3. Composite Manufacturing Process***

The composite helmet shells were fabricated utilizing a conventional hand lay-up technique. To ensure a uniform distribution of the matrix and minimize potential structural defects, the liquid polyester resin was manually applied and spread sequentially across the aligned fabric strips. Manual pressure was carefully applied to each wrapped layer during the lamination sequence to eliminate entrapped air pockets, prevent localized void formation, and facilitate thorough resin impregnation throughout the multi-layered textile configuration. Following the manual consolidation process, the prepared prototypes were left to cure under ambient laboratory conditions ( $24 \pm 2^\circ\text{C}$  and  $60 \pm 5\%$  relative humidity) for 24 hours.

### ***2.4. Characterization and Performance Evaluation***

The structural thickness of the helmet shells was evaluated using a high-precision digital caliper to verify dimensional uniformity. The mean shell thickness was determined to be  $4.2 \pm 0.3$  mm for the H2 hybrid configuration. Concurrently, the final weight of the cured H2 hybrid prototype was directly measured using a calibrated laboratory electronic scale, yielding a precise weight of 326.79 g as shown in **Figure 3**. This absolute mass demonstrates a highly competitive, lightweight structural solution that achieves robust mechanical protection without adding ergonomic burden compared to conventional industrial protective headgear.

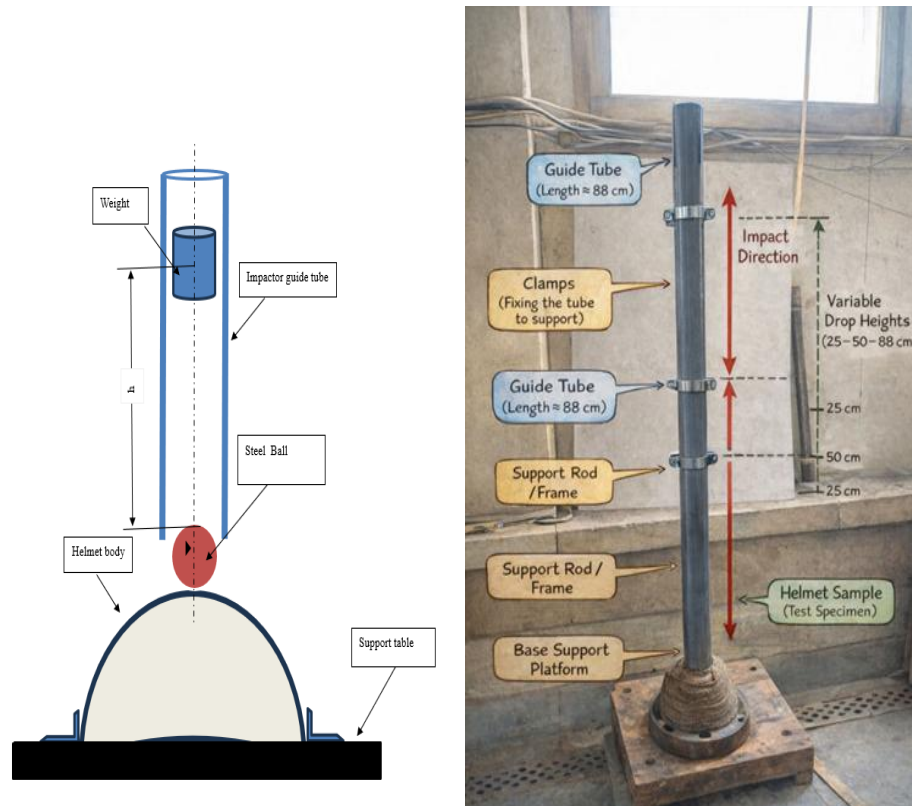


**Figure 3: Direct physical mass quantification of the hybrid textile-polymer composite helmet (H2 configuration) utilizing a calibrated laboratory electronic scale.**

## 2.5. Experimental Impact Methodology

### 2.5.1. Impact Testing Apparatus

Impact testing was executed utilizing a custom-engineered vertical drop-weight impact tower as illustrated in **Figure 4**. The apparatus is comprised of a rigid vertical twin-guide rail assembly designed to minimize frictional losses during the falling phase. The impactor assembly features a total falling mass of 6.0 kg, terminating in a high-carbon steel hemispherical striker with a nominal diameter of 50 mm.



**Figure 4.** Experimental setup of the guided drop-weight impact apparatus

### 2.5.2. Impact Energy Control

The dynamic impact energy delivered to the composite shell was calibrated by varying the physical drop height ( $h$ ) of the falling weight. The potential energy was calculated according to Equation (1):

$$E = m \cdot g \cdot h \quad (1)$$

Where:

- $E$ : impact energy (J)
- $m$ : total falling mass (6.0 kg)
- $g$ : gravitational acceleration ( $9.81 \text{ m/s}^2$ )
- $h$ : mechanical drop height (m)

Three distinct mechanical drop heights 25 cm, 50 cm, and 88 cm, were utilized to generate controlled low-to-high velocity impact energies of 14.71 J, 29.43 J, and 51.80 J per individual drop sequence, respectively.

### 2.5.3. Dynamic Data Acquisition and Testing Protocol

The drop-weight impact testing setup was designed to evaluate the damage response of composite materials under sudden mechanical loading. The system uses a falling weight that operates in a vertical path to deliver controlled impacts from its guided impactor that follows a dedicated path within a protective structure. The impactor base features a steel ball tip, which directs its force to a small area of the composite sample to replicate actual contact situations such as tool drops, or debris strikes. The composite specimen is securely positioned on a support fixture that stabilizes it during impact and ensures consistent energy transfer. The drop height adjustment system enables users to control sample impact energy, which facilitates testing of various composite configurations. The testing system allows researchers to examine failure modes through the observation of indentation and delamination, matrix cracking, and fibre fracture, which reveals essential information about material impact resistance and structural integrity. Figure 4 shows the setup where:

- Helmets were mounted on a rigid head form fixture to replicate real boundary conditions.
- The impact location was fixed at the crown region (most critical zone).
- The impactor was released from the predefined height without initial velocity.
- All experimental test configurations were repeated 3 times to ensure statistical validity

### 2.6. Indentation Severity Index (ISI) Formalization

To establish a quantitative, scientifically objective methodology for assessing damage accumulation under repeated dynamic impacts, an Indentation Severity Index (ISI) ranking system was developed. Rather than relying on qualitative visual descriptions, the physical degradation of the composite helmet shells was categorized on a normalized scale from 1 (elastic/undamaged state) to 5 (catastrophic structural penetration), and it is intended as a simplified classification tool for helmet indentation damage. This localized classification methodology is adapted and modified based on the multi-criterion structural damage ranking frameworks and the Composite Damage Severity Index (CDSI) formalized by El Messiry et al. [40]. The definitive morphological damage features and corresponding physical indentation depth criteria are systematically outlined in **Table 3**.

**Table 3: Quantitative Criteria of the Indentation Severity Index (ISI)**

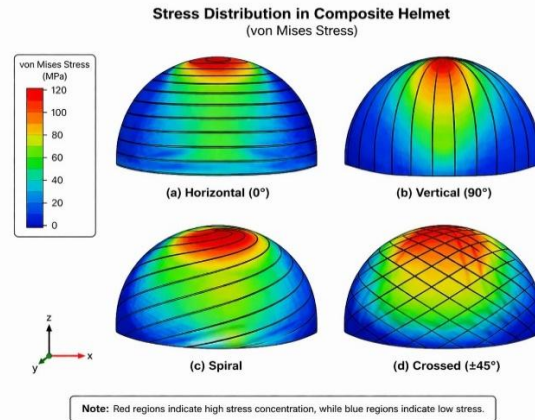
ISI Level	Classification	Residual Indentation Depth ( $\delta_{\text{final}}$ )	Morphological Damage & Failure Criteria
1	Fully Elastic / Undamaged	$\delta_{\text{final}} = 0.0 \text{ mm}$	Zero macroscopically detectable surface indentation; no internal resin micro-cracking; complete elastic energy recovery.
2	Minor Microscale Damage	$0.0 \text{ mm} < \delta_{\text{final}} \leq 2.0 \text{ mm}$	Shallow plastic surface depression; localized resin micro-cracking at the strike zone; zero fiber fracture.
3	Moderate Interlaminar Damage	$2.0 \text{ mm} < \delta_{\text{final}} \leq 8.0 \text{ mm}$	Intermediate residual crater depth; initialization of localized interlaminar delamination; matrix cracking propagates to adjacent strips.
4	Severe Structural Degradation	$8.0 \text{ mm} < \delta_{\text{final}} \leq 15.0 \text{ mm}$	Significant localized depression; macroscopic fiber slippage and localized fiber breakage; extensive delamination and stitch rupture.
5	Catastrophic Structural Failure	$\delta_{\text{final}} > 15.0 \text{ mm}$ or Penetration	Complete rupture of the reinforcement layers; full-thickness structural penetration; catastrophic split along the stitching boundaries.

Following the termination of the dynamic events, the permanent (residual) indentation depth ( $\delta_{\text{final}}$ ) was measured using a digital depth gauge featuring an instrument precision of  $\pm 0.01$  cm. To ensure high spatial accuracy, a high-resolution 3D surface scanning system was utilized on selected samples to reconstruct the post-impact topographical maps of the damaged crown zone.

### 3. RESULTS AND DISCUSSION

#### 3.1. Comparative Stress Distribution Analysis of Different Fabric Strip Layouts

The structural behavior and macro-mechanical response of composite helmet shells under dynamic apex loading are directly governed by the fabric reinforcement layout. The finite element analysis results, systematically presented in the stress field contours of **Figure 5**, indicate a strong dependency on the physical orientation of the wrapped reinforcing textile strips.



**Figure 5. FEA stress distribution contours under impact for different wrapping layouts**

- For the Horizontal Wrapping ( $0^\circ$ ) configuration, the induced von Mises stress field is highly localized around the immediate apex strike zone. Because the high-strength reinforcement runs exclusively along the circumferential paths, the shell lacks continuous load-bearing fiber pathways along the longitudinal meridian axes to transfer the vertical impact energy to the rigid base support. This layout creates severe localized transverse shear stresses along the inter-strip boundaries, resulting in premature inter-ply slippage and macroscale delamination.
- The Vertical Wrapping ( $90^\circ$ ) model also demonstrates effective stress transmission along the vertical meridian fiber paths. The compressive load is guided axially from the crown directly to the rim support. Due to the complete absence of circumferential hoop constraints, the compressive stress induces outward lateral displacements, generating a symmetric primary buckling mode under low structural thresholds.
- The Spiral Wrapping model facilitates a more distributed, diagonal stress path across the hemispherical geometry. This layout shares the dynamic forces across multiple intersecting strip boundaries due to complex torsional-flexural coupling interactions.
- The Crossed Wrapping ( $\pm 45^\circ$ ) geometry exhibits a highly uniform, grid-like stress dissipation pattern. The intersecting diagonal networks effectively mitigate apex stress build-up by transferring the impact energy symmetrically across all four quadrants.

**Table 4** presents a comparative performance evaluation of the different wrapping arrangements under top and side impact conditions, illustrating their directional strength, structural anisotropy, and overall multi-directional energy dissipation efficiency.

**Table 4. Comparative Stress Distribution in Helmet Fabric Strip Arrangements**

Arrangement Model	Vertical Force Response (Top Impact)	Horizontal Force Response (Side Impact)	Overall Performance Characteristics
<b>Horizontal Wrapping</b>	Weak axial resistance; stress concentrates at junctions	Strong hoop resistance; distributes lateral stresses effectively	Highly anisotropic; strong only under side loads
<b>Vertical Wrapping</b>	Strong axial load transfer: fibres aligned with the force	Weak circumferential resistance; prone to lateral deformation	Directional strength; vulnerable to side impacts
<b>Spiral Wrapping</b>	Balanced stress distribution: diagonal fibres reduce concentration	Moderate resistance; shares stresses across orientations	Quasi-isotropic: a compromise between vertical and horizontal
<b>Crossed Wrapping</b>	Strong multi-directional reinforcement; grid-like dissipation	Strong shear and torsional resistance; minimizes crack propagation	Best overall isotropy among the evaluated layouts; enhanced multi-directional stress distribution


Based on the comparative stress distribution analysis, the polyester/ jute hybrid helmet was designed by combining the advantages of vertical load transfer and circumferential confinement. This design concept was subsequently validated through experimental impact testing.

**3.2. Damage Progression and Indentation Analysis under Repeated Impacts**




The progressive damage accumulation of the fabricated composite helmets was evaluated under sequential drop-weight impact testing. All experimental test configurations were repeated three times to ensure statistical validity. The average mechanical values and their corresponding standard deviations ( $\pm$  SD) are summarized in **Table 5**, while the comparative deformation behavior is illustrated in **Figure 6**, where the damage severity is mapped against the cumulative energy applied to the various helmet designs.

**Table 5. The progressive damage accumulation of the fabricated composite helmets under sequential drop-weight impact testing**




**H1 - Jute lay-up**

Stage	Height (cm)	Hits	Energy/hit (J)	Stage energy (J)	Cumulative energy (J)	Observed response	
Single impact	25	1	14.71	14.71	14.71	Catastrophic delamination and strips separation on first hit. <b>ISI level 5</b>	




**H2 – Polyester/ jute hybrid**

Stage	Height (cm)	Hits	Energy/hit (J)	Stage energy (J)	Cumulative energy (J)	Observed response	
Stage 1	25	5	14.71	73.58	73.58	No visible damage, fully elastic. <b>ISI level 1</b>	
Stage 2	50	5	29.43	147.15	220.73	No visible damage, fully elastic. <b>ISI level 1</b>	
Stage 3	88	10	51.80	517.97	738.69	Simple localized resin cracking at the strike zone <b>ISI level 2</b> <b>Av. Indentation depth: 0.2± 0.04 cm</b>	

**H3 - Cotton sample**

Stage	Height (cm)	Hits	Energy / hit (J)	Stage energy (J)	Cumulative energy (J)	Observed response	
Stage 1	25	5	14.71	73.58	73.58	Progressive localized matrix cracking and indentation. <b>ISI level 3</b> <b>Av. Indentation depth: 1.0± 0.1 cm</b>	
Stage 2	50	5	29.43	147.15	220.73	Matrix yielding and progressive depth expansion: 1.4±0.15 cm <b>ISI level 4</b>	
Stage 3	88	10	51.80	517.97	738.69	Severe permanent deformation; local fibre slippage. <b>ISI level 4</b> <b>Indentation depth: 1.5±0.1 cm</b>	

**H4 - Plastic reference**

Stage	Height (cm)	Hits	Energy/hit (J)	Stage energy (J)	Cumulative energy (J)	Observed response	
Stage 1	25	5	14.71	73.58	73.58	No visible damage <b>ISI level 1</b>	
Stage 2	50	5	29.43	147.15	220.73	Localized plastic yielding. <b>ISI level 3</b> <b>Indentation depth: 1.0±0.12cm</b>	
Stage 3	88	10	51.80	517.97	738.69	Deep localized plastic crater at the apex strike zone. <b>ISI level 4</b> <b>Indentation depth: 1.3±0.08cm</b>	

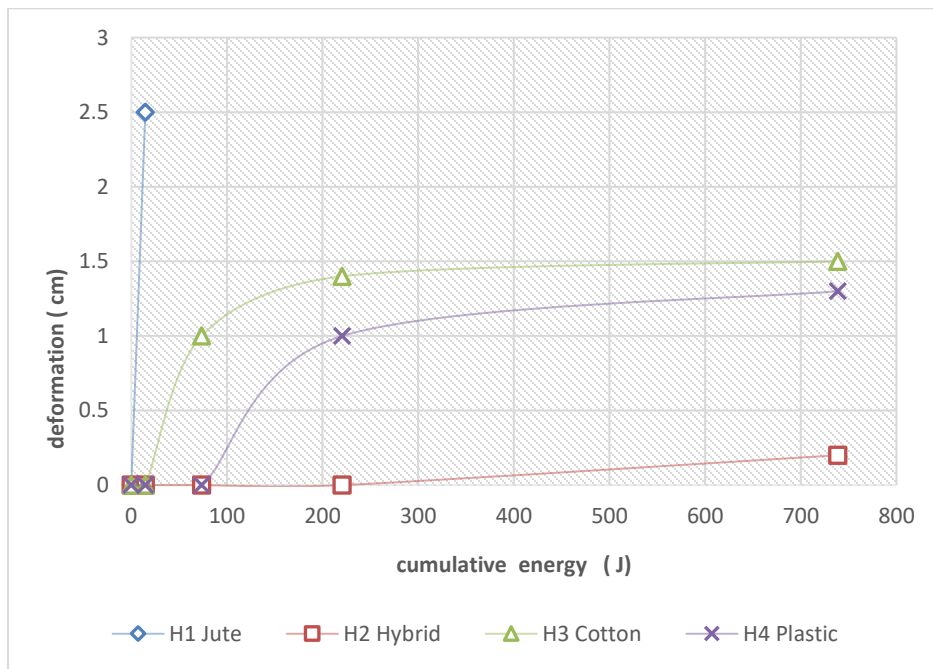


Figure 6. Effect of cumulative impact energy on deformation response of different composite helmets

### 3.2.1. *Pure Jute Helmet (H1)*

The pure natural jute layup (H1) exhibited low dynamic toughness and poor interlaminar shear strength under impact loading. As detailed in Table 5, the unconfined H1 shell failed on the first hit, followed by immediate structural collapse. Because the jute fibers lack high ductility and are not confined by synthetic fibers or horizontal rim bands, the shear stresses generated along the inter-strip boundaries quickly exceeded the interlaminar fracture toughness of the resin. This triggered extensive delamination and strip separation, placing the H1 configuration directly at ISI Level 5 (Catastrophic Structural Failure). This brittle response suggests limited fiber–matrix interaction under high-energy loading.

### 3.2.2. *Polyester-Jute Hybrid Helmet (H2)*

In sharp contrast, the modified polyester–jute hybrid (H2) achieved exceptional structural durability. The H2 shell completed the entire testing sequence, absorbing a cumulative dynamic energy of 738.69 J over 20 repeated hits. High-precision digital caliper measurements confirmed a residual indentation depth of only 0.2 cm, maintaining a consistent ISI Level 2 (Minor Microscale Damage).

This superior performance is scientifically justified by three cooperating mechanical mechanisms:

- 1- **Hybrid Shielding:** The ductile, high tenacity woven polyester strips on the inner face act as a structural shield. Under impact, the polyester fibers undergo progressive elastic deformation, distributing the dynamic forces over a wider area and protecting the natural jute from high interlaminar shear stresses.
- 2- **Stitch-Locking of Seams:** The high-density zigzag lock stitching likely contributes to limiting delamination propagation outside the immediate localized strike zone.
- 3- **Hoop Confinement Ring:** The circumferential horizontal strip acts as a stiffening belt. By suppressing the lateral outward bulging of the vertical meridian strips, it forces the composite shell to dissipate the dynamic energy via localized microscale viscoelastic damping within the polymer matrix.

### 3.2.3. *Cotton Helmet(H3)*

The pure cotton reinforcement shell (H3) exhibited a highly progressive, ductile failure mode. As recorded in Table 5, the indentation depth increased from 1.0 cm at Stage 1 to a final depth of 1.5 cm at Stage 3, corresponding to ISI Level 4 (Severe Structural Degradation). Because cotton fibres exhibit high elongation-at-break, the H3 shell avoided brittle shattering; instead, it deformed predictably, absorbing the impact energy through extensive fiber slippage and progressive matrix cracking.

### 3.2.4 *Plastic Helmet (H4)*

The industrial thermoplastic helmet (H4) exhibited rigid structural behavior but suffered from permanent plastic deformation under repeated loading. The H4 shell developed a localized permanent indentation of 1.0 cm at Stage 2, which increased to 1.3 cm at Stage 3 (ISI Level 4). While the H4 shell prevented tearing, its monolithic structure lacked multi-directional fiber paths to redistribute stress, resulting in a localized plastic crater at the apex strike zone.

## 3.3. *Structural Performance Relative to International Protective Helmet Standards*

To evaluate the practical feasibility of the developed composite configurations, their experimental impact performances were compared directly against the requirements of international safety standards, namely EN 397 [41] and EN 1078 [42]. Both standards dictate that the peak force transmitted to the headform must not exceed safety limits, and the shell must resist penetration, limiting permanent deformation to  $\leq 2.5$  cm. The comparative compliance assessment compiled in **Table 6** demonstrates the outstanding safety margins of the H2 Hybrid configuration. Even under extreme repeated impact energies (738.69 J cumulative, which significantly exceeds the single-impact energy demands of standard testing), the H2 hybrid maintained structural integrity with 0.2 cm of residual deformation. This confirms that combining historic wrapping geometries with modern hybrid composites yields a lightweight shell that demonstrates structural integrity and deformation behavior consistent with selected shell performance criteria

commonly associated with these standards. Concurrently, the H3 Cotton and H4 Plastic configurations achieved basic compliance by keeping their final permanent deformations (1.5 cm and 1.3 cm, respectively) below the 2.5 cm standard limit, though both suffered from permanent localized damage. Conversely, the pure jute shell (H1) failed to meet the minimum standards, as its catastrophic brittle delamination violates the core structural integrity and safety criteria mandated for protective headgear.

**Table 6. Comparative Commentary: Helmet Impact vs. Standards**

Helmet Type	Observed Deformation (cm)	Standard Allowable Deformation / Failure Criterion	Compliance Assessment	Technical Comment
H1	Structural Failure at 14.7 J	Must withstand $\geq 50$ J without structural failure	<b>Non-compliant</b>	Structural failure at low energy suggests poor bonding and insufficient toughness. Not suitable for protective use.
H2	0.0-0.2	$\leq 2.5$ cm deformation	<b>Excellent</b>	No deformation between (50-100) J indicates outstanding energy absorption and structural integrity. It demonstrates superior impact tolerance under the tested conditions.
H3	1.0–1.5	$\leq 2.5$ cm deformation	<b>Acceptable</b>	Maintains consistent deformation across all energies, showing good cushioning and controlled energy dissipation. Suitable for moderate-impact protection.
H4	0.0–1.3	$\leq 2.5$ cm deformation	<b>Good</b>	Slight deformation at low energies and stable at high energies. Indicates rigid shell behavior with limited energy absorption but strong resistance to penetration.

## 4. CONCLUSIONS

This study developed and evaluated lightweight hybrid textile-reinforced composite helmet shells utilizing structural wrapping configurations inspired by historical boundary constraint techniques. The following conclusions were drawn:

- Finite element stress analysis was employed to examine the influence of fabric strip layouts on stress distribution paths and to support the development of the proposed helmet architecture. Horizontal layouts exhibited localized stress concentration near the impact zone, whereas vertical layouts improved axial load transfer but showed reduced circumferential restraint. Crossed layouts provided the most uniform multi-directional stress distribution among the evaluated configurations.
- These observations served as the design rationale for the development of the H2 hybrid helmet, which combines vertical load-carrying strips with circumferential confinement. The vertical meridian strips act as axial load-bearing columns, while the external circumferential horizontal strip at the rim establishes a high-stiffness perimeter boundary condition.
- The engineered polyester–jute hybrid (H2) configuration, weighing only 326.79 g, withstood the repeated drop-weight impact program, absorbing a cumulative impact energy of 738.69 J over 20 consecutive drops (including 10 hits at 51.80 J) and resulting in final residual deformation of only 0.2 cm. This performance corresponds to ISI Level 2 (Minor Microscale Damage) according to the proposed Indentation Severity Index (ISI) ranking system.
- In contrast, the unconfined pure natural jute shell (H1) suffered catastrophic brittle delamination and strips separation (ISI Level 5) during the first impact. The cotton shell (H3) and the commercial thermoplastic helmet (H4) exhibited progressive localized yielding and permanent plastic deformation, resulting in final residual indentations of 1.5 cm and 1.3 cm, respectively (ISI Level 4).
- The H2 hybrid shell demonstrated structural performance consistent with key deformation and integrity requirements commonly associated with EN 397 and EN 1078 helmet standards, highlighting the potential of green hybrid composites for protective headgear applications.

- Overall, the results demonstrate that the integration of natural and synthetic textile reinforcements within a boundary-constrained architecture can significantly enhance impact resistance while maintaining low structural weight, providing a promising pathway for the development of sustainable protective helmet systems.

## 5. RECOMMENDATIONS FOR FUTURE WORK

To expand upon the findings of this research, future studies should subject the developed hybrid shells to oblique impact and rotational acceleration testing to evaluate their capacity to mitigate rotational acceleration, which is a primary contributor to traumatic brain injuries (TBIs).

## DISCLOSURE STATEMENT

The authors certify that they have no known competing interests, whether financial or non-financial, that could have influenced the outcomes or presentation of this research.

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