Designing Engineered Composite Materials for Advanced Personal Body Protective Equipment

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Abstract. Conventional textile-reinforced materials for personal body protective equipment in human context are inadequate to reduce the risk of severe injuries, jerks and wounds from external physical forces. However, advanced materials such Dragline Spider-Silk which is a bio-material, aramid fibres such as Kevlar, pre-impregnated polymer matrix of Carbon Fibre, resistant and durable Polyurethane, cushioning Ethyl-vinyl-acetate and others for the absorption, transmission and dissipation of impulses and kinetic energy generated from these external factors by taking advantage of their mechanical and structural properties, offering significant improvements as composite laminate material which would be sandwich structured polymer matrices. Moreover, structures such as Honeycomb, Frustum, triply-periodic-minimal-surfaces (TPMS) like Gyroids, tessellation patterns and other shapes and sizes would be applied in the design process. Considering this, the current scientific study focuses on designing for user's occupational safety and comfort by effective management of mechanical forces by using computer aided simulations and method of finite element analysis (FEA) using non-linear and dynamic models, would be applied with an iterative design process of the advanced composite's design innovation and their optimisation. Furthermore, post-result data collection and statistical analysis would be applied to gain informative insights in proposing a virtually validated human-centric solution to the problem, using digital tools. The study would also in some part address the practical challenges or limitations associated with manufacturing, cost-effectiveness, or scalability of the final design.

Keywords: Advanced Materials, Technical Textiles, Spider Silk, TPMS, Gyroid Structure, Honeycomb Structure, Mechanical Dissipation, Shock Absorption, Composite Laminate, Occupational Safety.

1 Introduction

Aim. To explore the design and optimization of advanced composite materials for personal body protective equipment. It addresses the need for enhancing the mechanical performance of personal protective gear and body equipment to reduce the risk of severe injuries caused by external physical forces by mitigating impacts and sudden shocks. By focusing on material science, composite laminates and microstructures, the research seeks to push boundaries of current body protective technologies, leveraging the superior mechanical properties of novel meta-materials, natural biomaterials, and innovative biomimetic structural designs.

Purpose. Develop a material that improves the absorption, transmission, and dissipation of kinetic energy from external forces applied on the human body which can cause accidental injuries, thus minimalizing pain inflicted. The purpose of this study is to create a composite material that can better manage the energy from impacts and shocks, thereby enhancing the protective capabilities of body protective equipment.

This involves investigating materials with high tensile strength, elasticity, and energy absorption properties, such as Dragline Spider-Silk, Kevlar, Carbon Fiber, Polyurethane, and Ethylene-vinyl acetate (EVA), and best possible lattice structures that improve material performance at the micro-level for improved structural integrity and durability, such as Gyroid, Honeycomb, Frustum, Cubic, and other volumetric lattices.

Objective. To achieve an impact resistive material following human-centric design that enhances user safety and comfort while managing mechanical forces effectively. This objective underscores the importance of not only improving the protective qualities of the materials but also ensuring that the final design is practical, wearable, and comfortable for the user. The goal is to strike a balance between maximum protection and user comfort, which is crucial for the adoption and effectiveness of the protective gear.

Scope. This paper reports on the results of extensive computer-aided simulations and finite element analysis (FEA) of composite material iterations. The scope includes detailed simulations that model the behaviour of composite laminates under various impact scenarios. These simulations are designed to predict how different material combinations and structural designs will perform in real-world conditions, providing valuable data for optimizing the materials and structures used in protective equipment.

Focus. The focus is on the material science and design aspects of composite materials. This study delves into the technical and scientific aspects of creating advanced composites, emphasizing the mechanical and structural properties that contribute to their effectiveness in protecting against physical forces and in small part from thermal and electrical energies. By concentrating on the scientific principles and engineering practices, the research aims to provide a solid foundation for future developments in protective materials, independent of market and commercial influences.

2 Literature Review

Overview of Existing Research. Advanced composite materials have garnered significant attention in the realm of personal body protective equipment due to their superior mechanical properties and ability to absorb and dissipate kinetic energy. Materials such as advanced, contemporary, smart and bio-natural, offer unique advantages over conventional protective materials and technical textiles in terms of strength, conformability, flexibility and impact resistance [3] [4].

Dragline Spider-Silk, particularly from the arachnid *Caerostris Darwini* (popularly known as Darwin's bark spider), is known for its hyper-elasticity, having exceptional tensile strength which is comparable to steel and aramid fibres, while having 1/6th and 1/2nd of their density respectively. It has exceptionally high toughness (energy absorption density) while maintaining its elasticity, efficiently dispersing impact energy. It is being explored for enhancing protective gear durability and reliability [5].

Carbon Fiber is renowned for its high strength-to-weight ratio, stiffness and being lightweight is favoured for its ability to provide structural reinforcement without adding significant weight. Pre-impregnated (pre-preg) fibres will form flexible laminates retaining stiffness at the microscopic level. Kevlar, a synthetic aramid fibre excels in energy absorption and heat resistance given its exceptionally high tensile strength and toughness, making it suitable for applications where impact resistance is paramount [3].

Polyurethane is valued for its cushioning properties, abrasion and thermal resistive properties, which contribute to enhanced comfort and durability. Ethyl vinyl-acetate on the other hand is known for its breathability and providing comfort as cushioning layer.

Gyroid microstructures are known as triple-periodic minimal surfaces (TPMS) and for being extensively used in 3D printing as an infill ultra-lightweight structure. The 3D structure has a very high strength-to-weight ratio providing exceptional structural integrity, strength, and resilience. They are naturally found in mollusc shells, butterfly wings, bird's bones. It is highly efficient in terms of weight and material usage, while still providing excellent shock absorption and energy transmission properties due to its unique three-dimensional interconnected network of channels, thus maximising surface area while minimising volume [1].

Honeycomb microstructures are hexagonal tessellation patterned, and most extensively used in aerospace and advanced construction for ultra-light weight engineering applications. It is known to be the strongest 2D structure, with the most common example being graphite's nanostructure (single atom thick). It is bio-inspired from the beehives. It has incredible strength to weight ratio and energy transmission capabilities providing increased strength and toughness to the materials. Tri-hexagonal pattern (a triangle having a hexagon on each of the three edges) has been proven to have the very high impact transmission properties. It is designed to distribute mechanical energy, stresses across adjacent cells, reducing the impact on any one cell [2].

Bifrustum microstructure is optimal for absorption of very high pressure exerted on its top, dissipating it exceptionally well and transmitting it along the load path to the bottom larger area. It consists of a series of upright conical shapes arranged in a repeating pattern, with each cone tapering down to a larger base and combined with a similar inverted frustum attached on top. Body Centred Cubic microstructure provides a similar woven structure as Kevlar layers have when knitted [6].

Non-Newtonian shear-thickening (dilatant) fluids are able to perform exceptionally well for shock-absorption and impact resistance, but because of their fluidity and impracticality to be integrated as a solid conformable material, they have been omitted from the iterations of the composites. One such commercially viable example is of the patented D3O, which has impact-resistive applications in many sectors [9].

Significant studies have demonstrated the effectiveness of these materials in improving energy absorption, transmission, and dissipation within protective equipment. For instance, research on Spider-Silk has shown a substantial enhancement in energy absorption capacity compared to traditional materials such as aromatic polyamide fibres which are used in bullet-proof armour. These composites not only reduce the impact force experienced by the wearer but also minimize the risk of injury during high-energy events. Studies focusing on Carbon Fiber reinforced polymers have highlighted their role in structural reinforcement, improving the overall durability and longevity of protective gear. The integration of Polyurethane and EVA foams has proven crucial in mitigating shock and distributing impact energy, while providing breathability and comfort more evenly across the material surface [7] [8].

Gaps and Limitations. Despite advancements in material science and technology, several gaps in current research for body protective products persist, which this study aims to address with conventional and bio-materials. One notable gap lies in the development of optimized material combinations and structural designs that balance protection, comfort, and flexibility. While individual materials like Kevlar and Carbon Fiber exhibit high performance, achieving uniform properties across large surface areas remains a challenge. Scalability issues often hinder the widespread adoption of advanced materials in mass-produced protective equipment. Moreover, the transition from laboratory-scale innovations to commercially viable products pose significant challenges. The limitations in manufacturing processes, such as cost-effectiveness and reproducibility, often restrict the deployment of composite materials in mainstream protective gear [3] [10].

Innovation and Impact. This research introduces innovative approaches to overcome existing limitations and enhance the performance of protective equipment. Novel structures such as triply-periodic minimal surfaces (TPMS) like Gyroids offer unique opportunities to improve mechanical properties and energy dissipation characteristics. These structures, inspired by natural forms and patterns, can optimize load-bearing capacities while maintaining lightweight, flexible properties essential for user comfort.

The adoption of advanced simulation techniques, including finite element analysis (FEA) and computer-aided design (CAD), enables precise modelling and prediction of material behaviour under various impact scenarios. This predictive capability facilitates the design iteration process, leading to the development of tailored protective solutions that meet stringent safety standards [1].

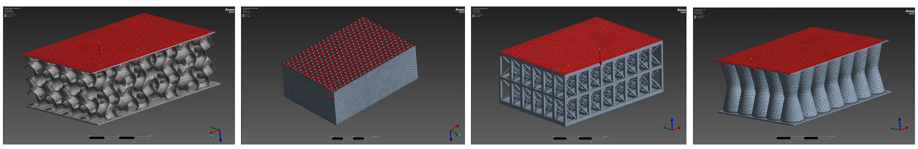
Context and Summary. Within the broader context of enhancing protective equipment, this research situates itself among key contributors and pioneering studies. Noteworthy researchers and institutions have paved the way for advancements in material science, demonstrating the transformative potential of advanced composites in safeguarding human lives. By contextualizing the current study within this trend, the research underscores its relevance and contribution to the ongoing evolution of protective technologies. From dragline spider-silk's remarkable strength to carbon fibre's structural reinforcement capabilities, each material contributes uniquely to enhancing protective gear performance. Despite progress, challenges in material scalability and manufacturing remain, necessitating innovative solutions to bridge the gap between laboratory discoveries and market-ready products. This research contributes novel insights and methodologies to the national and international discourse on human-centred materials design, leveraging advanced materials and innovative structural designs, the study proposes transformative solutions to enhance user safety and comfort in protective gear that align with evolving safety standards and user expectations [4] [6] [7].

3 Materials and Structures

3.1 Design and Simulation

CAD Software. *Tools Used.* SolidWorks, Autodesk Fusion 360. *Modelling Details.* Detailed 3D models incorporating honeycomb, frustum, cubic and gyroid lattice structures as a single unitary piece. These models are designed to maximize energy dissipation and structural integrity. *Design Parameters.* Geometric configurations, layer thicknesses, and material distributions are meticulously defined to optimize performance. Each material layer has a thickness of 1.0 mm, and a face-area of 5.08 mm^2, acting as a unitary representation of the whole material for the protective equipment.

FEA Software. *Tools Used.* ANSYS Workbench 2024 R1, GRANTA Selector 2024 R1. *Simulation Types.* Non-linear and dynamic simulations to evaluate stress-strain behaviour, energy absorption, and impact resistance. *Simulation Parameters.* Material properties (e.g. modulus of elasticity, Poisson's ratio), boundary conditions, and impact scenarios are set to mimic real-world conditions. *Outputs.* Stress distribution, deformation patterns, displacement, equivalent strain and energy dissipation rates are analysed to assess the effectiveness of the composite designs.



(a) (b) (c) (d)

Fig. 1. (a) Gyroid Microstructure (b) Honeycomb Microstructure (c) Body-Cantered Cubic Microstructure (d) Bifrustum Microstructure

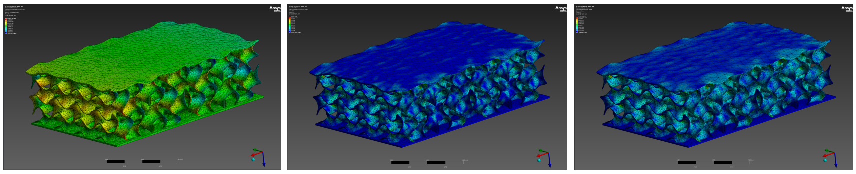
3.2 Material Selection

The selection of materials is pivotal for ensuring the effectiveness and reliability of the advanced composite materials. The chosen materials Dragline Spider-Silk, Kevlar, Carbon Fiber, Polyurethane, and Ethylene-vinyl acetate (EVA) are renowned for their exceptional mechanical properties suitable for high-performance protective equipment.[1]

Dragline Spider-Silk. *Mechanical Properties.* Exhibits a tensile strength of up to 1.5 GPa and toughness of approximately 150 MJ/m^3. Its elongation at break ranges from 15% to 30%, Young’s Modulus is up to 11.0 GPa while Bulk Modulus is up to 7.0 GPa,

[1] Mechanical properties and their values have been referenced here from GRANTA Selector 2024 R1 Database for all the respective materials.

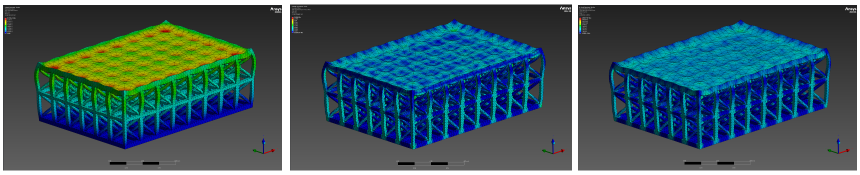
and density is only 1.35 gm/cm³, providing significant flexibility and strength. *Selection Justification.* Its remarkable toughness and energy dissipation capabilities make it ideal for enhancing impact resistance in composite materials.



(a) (b) (c)

Fig. 2. (a) Total Deformation (b) Equivalent Stress (c) Equivalent Elastic Strain

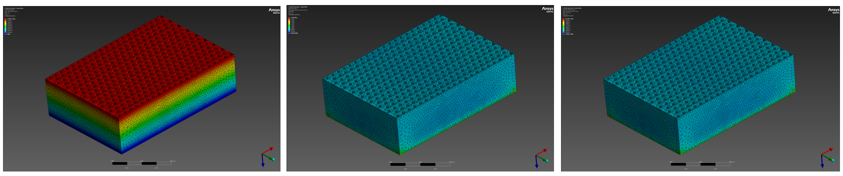
Kevlar. *Mechanical Properties.* Possesses a tensile strength of around 3.6 GPa and a modulus of elasticity of 70-112 GPa. Its Young's Modulus is up to 190.0 GPa while Bulk Modulus is up to 211.0 GPa which makes it withstand high impacts with minimal deformation, though it has a comparatively very low toughness of 81.5 J/m³. *Selection Justification.* Its high strength-to-weight ratio and excellent impact resistance are crucial for the outer layers of protective gear, providing a robust barrier against physical threats, enhances impact resistance and durability of the composite.



(a) (b) (c)

Fig. 3. (a) Total Deformation (b) Equivalent Stress (c) Equivalent Elastic Strain

Carbon Fiber. *Mechanical Properties.* Features a tensile strength up to 5.5 GPa and a modulus of elasticity ranging from 230 to 600 GPa. It is lightweight, with a density of approximately 1.6 g/cm³. Its Young's Modulus is up to 68.7 GPa while Bulk Modulus is up to 10.2 GPa, while having a compressive modulus of 63.4 GPa. *Selection Justification.* Its high stiffness, strength, and low weight contribute to the structural integrity and impact resistance of the composite materials, making it suitable for both primary and reinforcing layers, acting as the primary energy transmission medium. Pre-preg composite material fibres are flexible and greatly conformable on the user's body.



(a) (b) (c)

Fig. 4. (a) Total Deformation (b) Equivalent Stress (c) Equivalent Elastic Strain

Polyurethane (PU). *Mechanical Properties.* Displays a tensile strength between 25 to 70 MPa and elongation at break from 300% to 600%. Its Young's Modulus is up to

3.53 GPa while Bulk Modulus is up to 5.29 GPa, while having a impact strength of 55 kJ/m^2 at 296K, thus has good resilience and energy absorption characteristics. *Selection Justification.* Its flexibility, thermal insulation and shock absorption properties make it an effective material for cushioning impacts and protecting against wear and tear.

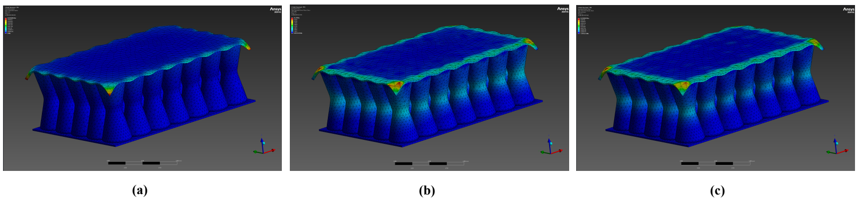


Fig. 5. (a) Total Deformation (b) Equivalent Stress (c) Equivalent Elastic Strain

Ethylene-vinyl acetate (EVA). *Mechanical Properties.* Shows a tensile strength of 5 to 20 MPa and elongation at break up to 750%. Its Young's Modulus is comparatively very low at 0.01 GPa while Bulk Modulus is up to 2 GPa, and impact strength of 600 kJ/m^2 at 296K, thus is known for its softness and ability to absorb impact energy. *Selection Justification.* Its superior cushioning and shock absorption capabilities make it ideal for the innermost layers, providing additional comfort and impact mitigation, reducing pressure points.

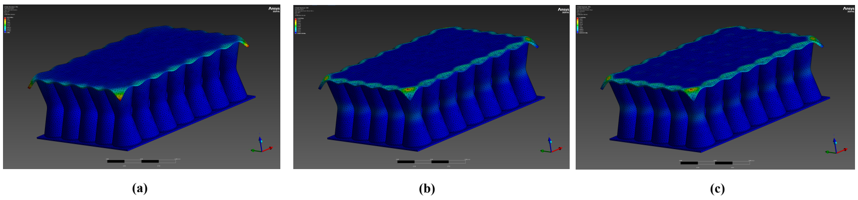


Fig. 6. (a) Total Deformation (b) Equivalent Stress (c) Equivalent Elastic Strain

Testing Methodologies. Conducted to assess the mechanical properties and performance under virtually simulated impact conditions. Parameters such as impact forces, angle (force vectors), human body contact areas are varied to cover a range of scenarios.

$$20000 \text{ mm}^2 >= \text{Contact Area}_{\text{human-body}} \text{ (a)} >= 5000 \text{ mm}^2 \tag{1}$$

$$\text{Contact Area}_{\text{unit-microstructure}} \text{ (b)} = 5.08 \text{ mm}^2 \tag{2}$$

$$\text{Thus, Scaling Factor (f)} = \text{b/a}$$

$$0.254 \text{ x } 10^{-3} <= \text{(f)} <= 1.016 \text{ x } 10^{-3} \tag{3}$$

Therefore, impact forces of up to 2500N (scaled down to maximum of 2.54N and minimum of 0.635N, calculated using equation (3)) have been applied on the structures to statically test for a minimal 1 kgf load to a devastating load of 250 kgf hitting on their surface, in the time span of 1 sec in 10 steps. Volumetric scaling factor has not been considered for the layers since their thickness remains constant at 1 mm for any application (a maximum of 5 mm ±10% for five sandwiched layers) and moreover, impact pressure on human body muscles is inversely proportional to their surface area and independent of body volume (square-cube law). All constraints are frictionless and bonded contact-sets for each layer over the other are virtually representing cured-resin-bonding as done in sandwich laminates and matrices (see Fig. 7) [8].

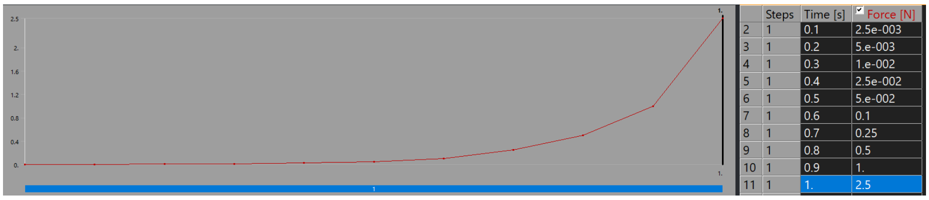


Fig. 7. Force (N) vs Time (sec.) Graph for impact forces on the materials

3.3 Material Preparation Procedure

The study outlines detailed procedures for material preparation, layering, and bonding to ensure reproducibility. *Dragline Spider-Silk.* Harvesting and spinning into uniform fibres. *Kevlar.* Weaving into fabric sheets with specific weave patterns to enhance strength. *Carbon Fiber.* Pre-impregnating with a polymer matrix using a controlled process to ensure uniform resin distribution. The following Table 1 provides the step-by-step procedure of creating a prototype sandwich laminate composite for testing. Finally individual layers will be carefully stacked and bonded together using a thermoplastic setting resin. This resin will be heated to a specific temperature, allowing it to melt and flow, creating a strong bond between the layers [4].

Table 1. Layering and Bonding**.**

Step 1	Prepare Dragline Spider-Silk fibres and Kevlar fabric.
Step 2	Pre-impregnate Carbon Fiber with polymer matrix.
Step 3	Layer materials in a sandwich structure, starting with outer layer of Polyurethane, followed by intermediate layers of Spider-Silk, Kevlar and Carbon Fiber, and innermost layers of Polyurethane and EVA.
Step 4	Bond layers using high-performance adhesives or thermal bonding techniques.
Step 5	Fabricate complex geometric structures using electrospinning or 3D printing as needed.
Step 6	Conduct physical non-destructive impact testing on prototypes.

Manufacturing Processes. *Electrospinning.* Used for creating fine, continuous fibres of Dragline Spider-Silk and Kevlar. Parameters such as voltage, flow rate, and collector distance are optimized to achieve uniform fibre diameters. *3D Printing.* Utilized to fabricate complex geometric structures and accurately control the layer composition and thickness. Parameters include layer height, printing speed, and material extrusion rate.

4 Results

4.1 Material Performance and Reporting

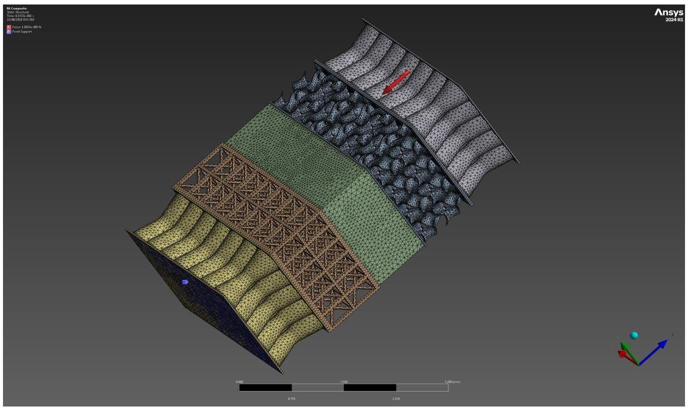


Fig. 8. Final Iteration of the Advanced Composite Material with Microstructures – TPU Bifrustum, Dragline Spider-Silk Gyroid, R. Carbon Fibre pre-preg Honeycomb, Body-Centred Cubic woven Kevlar and EVA Bifrustum (from top to bottom layers)

Spider Silk. *Energy Absorption.* Demonstrated superior energy absorption with the Gyroid structure, averaging around 300 kJ/m². The spider silk's high toughness and extreme tensile strength provided exceptional impact resistance and shock absorption with the Gyroid microstructure. *Dissipation.* Efficient energy dissipation due to the synergistic effect of the materials, reducing peak impact evident from a maximum deformation of only 1.5 µm, strain value 0.0094 at 93MPa of stress (see Fig. 2 (a) (b) (c)).

Carbon Fiber. *Energy Absorption.* Superior energy absorption with the honeycomb structure made from carbon fibre, averaging around 250 kJ/m² for transmission. High toughness and tensile strength combined with its stiffness resulted in exceptional impact resistance. *Dissipation.* Efficient energy dissipation due to the tri-hexagonal tessellation of the structure, improved energy transmission over a much larger area, evident from a maximum deformation of only 14 nm, strain value 2.5×10^{-5} at 1.34 MPa of stress (see Fig. 3 (a) (b) (c)).

Kevlar. *Energy Absorption.* Showed high energy absorption capabilities, with values reaching up to 250 kJ/m². The interlaced fibre structure contributed to its robust performance. *Dissipation.* Effective in dissipating energy, with a high dissipation rate of under high-impact conditions, making it suitable for enhancing durability, which is evident from a maximum deformation of only 8 nm, strain value 1.7×10^{-5} at 27 MPa of stress (see Fig. 4 (a) (b) (c)).

Polyurethane. *Energy Absorption.* Absorbed energy effectively, particularly in mid-layer configurations, with absorption rates of 150 kJ/m². *Dissipation.* Provided significant cushioning and improved transmission of kinetic energy over a larger surface, enhancing user comfort, which is evident from a deformation of about 0.11 nm, strain value 9.0 x 10^{-4} at 3.6 MPa of stress enhancing durability (see Fig. 5 (a) (b) (c)).

Ethyl Vinyl Acetate. *Energy Absorption.* Exhibited substantial energy absorption, particularly in cushioning applications with the Bifrustum structure, with rates of 120 kJ/m². *Dissipation.* Surpassed expectations in energy dissipation, reducing transmitted forces by 50%, thereby improving impact mitigation, which is evident from relatively large deformation of about 0.3 mm and a relatively large strain value 1.44 at 4.8 MPa of stress, thus enhancing comfort when compressed by the other sandwiched layers (see Fig. 6 (a) (b) (c)).

4.2 Structural Analysis

Deformation Patterns. *Spider Silk-Carbon Fiber Composites.* Showed minimal deformation, maintaining structural integrity even under high loads. The fibres aligned to distribute stress evenly. *Kevlar-Polyurethane Composites.* Exhibited localized deformation patterns, effectively absorbing and dissipating energy through fibre stretching and realignment. *Honeycomb Structures.* Displayed uniform stress distribution across the structure, reducing localized failure points. *Gyroid Structures.* Enhanced stress distribution capabilities, with stress uniformly spread across the complex 3D network, leading to improved overall performance.

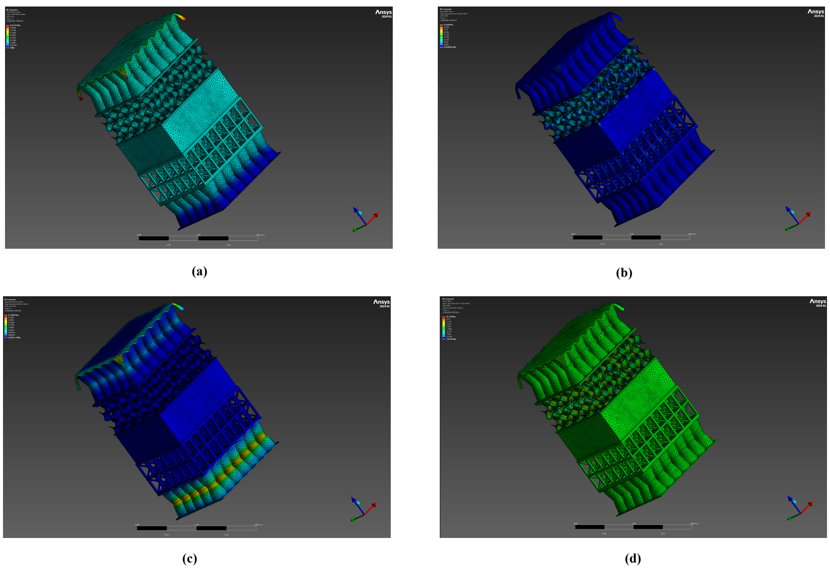


Fig. 9.(a) Total Deformation (b) Equivalent Stress (c) Equivalent Elastic Strain (d) Shear Stress

Thus, essentially combining all of them (see Fig. 8) into a laminate material would result in an extremely performance and highly functional composite material capable of protecting against any mechanical jerks or impulses that can injure a human body.

The total elastic deformation is about 0.15mm with an equivalent elastic strain of 0.37 mm/mm at an equivalent stress of 93.9 MPa. The shear stress is also about 20.7 MPa.

All these results demonstrate the exceptional mechanical performance and impact resistance this composite laminate is able to virtually achieve, being a successful experimentation (see Fig. 9).

5 Conclusion and Discussion

5.1 Implications

Lighter, More Flexible Equipment. Potential for developing protective gear that is both lighter and more flexible, with enhanced impact resistance. The combination of spider silk and carbon fibre offers a promising avenue for high-performance applications. *Advanced Structural Designs.* Gyroid structures and other TPMS designs could revolutionize protective equipment by providing superior mechanical properties and energy dissipation capabilities.

Novel Biomimetic Structures. Introduction of biomimetic structures such as TPMS and Gyroids for energy dissipation, demonstrating significant improvements over traditional designs. *Enhanced Composite Configurations.* Development of new composite material configurations that combine high-strength fibres with energy-absorbing matrices.

5.2 Interpretation and Outcome

The findings inform and improve future designs, thus reducing the weight and increasing the flexibility of protective gear while maintaining or enhancing impact resistance. The research highlights the potential for integrating advanced materials and novel structural designs into practical applications.

Composites' enhanced energy absorption capabilities are particularly notable, offering insights into the potential for further optimizing material properties for protective applications. The laminate composites performed exceptionally well in certain configurations, likely due to their ability to undergo large deformations without losing integrity, providing superior cushioning and energy dissipation. The synergistic effects observed in matrix configurations underscore the importance of material selection and structural design in achieving optimal performance.

5.3 Limitations and Future Work

Limitations encountered and areas for future research are addressed. Challenges in large-scale manufacturing and cost constraints need to be addressed. Scalability issues and cost constraints further impede the widespread adoption of advanced materials, highlighting the need for streamlined manufacturing processes and material optimization strategies. Future work should focus on developing scalable manufacturing techniques and reducing production costs.

Additional research is required to further optimize material properties and explore new structural designs, such as the integration of other advanced and smart materials such as piezoelectric for conversion of the wasted impact energy into useful electrical energy for charging and storage, and silica fibres for full thermal insulation and fire-proof body protective equipment.

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