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Impact Analysis of a Lattice Structure Based Design of Motorcycle Helmet Liners Using Finite Element Modelling

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Abstract

The fact that the number of motorcycle accidents is increasing in Malaysia means there is an urgent need of high-quality helmet designs that could offer better protection of head injuries caused by intense type of collision. In this research, the finite element analysis or FEA in ANSYS Workbench used to study the protective behavior of the foam-filled lattice core sandwich structure motorcycle helmet as compared to the traditional expanded polystyrene (EPS) liner structure of a motorcycle helmet. The study methodology entails extensive three dimensional finite element modeling of the traditional, as well as lattice core-filled helmet design including significant assignment of material properties, meshing, and boundary conditions that allow full three dimensional finite element modeling simulation of a realistic, three dimensional, 5 m/s, linear, side-region impact condition with dynamic loading, or appropriate ligament modeling and characteristics of the headform. The results of the simulation proved the excellent performance of the lattice core-filled helmet design a total of 75.9 percent decrease of deformation (0.19415 m to 0.046752 m), 97.9 percent decrease of equivalent elastic strain (2.2006 m/m to 0.046752 m/m), and much better stress management where stress dissipated fast when it reaches a peak equivalent stress of 132.92 MPa and quickly reduced against the sustained 16.176. Foam-filled lattice core helmets demonstrate significant enhancements in motorcycle crash protection through superior energy absorption, structural integrity, deformation resistance, and stress dissipation, thereby establishing a quantitative foundation for advancing future helmet safety standards.

1. Introduction

Motorcycle accidents represent one of the most significant public health challenges in Malaysia, where motorcyclists face disproportionately high risks of severe injury and death compared to other road users [1]. Statistical evidence reveals that motorcyclists are approximately 30 times more likely to suffer fatal injuries in traffic accidents, with head trauma being the predominant cause of fatalities and severe neurological damage [2]. This alarming mortality rate underscores the critical importance of advancing protective equipment technology, particularly motorcycle helmet design, to enhance rider safety and reduce the devastating impact of head injuries.

Traditional motorcycle helmets, while providing essential protection, demonstrate significant limitations in their energy absorption capabilities during high-velocity impacts and when subjected to complex forces encountered in real-world collision scenarios [3]. The conventional expanded polystyrene (EPS) foam liners commonly employed in these helmets exhibit restricted performance characteristics that compromise their effectiveness in severe impact situations [4]. This technological gap has created an urgent need for innovative helmet designs that can substantially improve energy dissipation and impact mitigation capabilities, particularly given the existing research on helmet impact behavior has primarily focused on conventional designs, leaving a significant knowledge gap in understanding the potential benefits of advanced structural configurations [5].

Recent breakthroughs in materials science and structural engineering have opened new avenues for helmet technology advancement through the development of foam-filled lattice sandwich structures. These hybrid designs represent a paradigm shift in protective equipment engineering, combining the structural advantages of lattice geometries with the superior cushioning properties of advanced foam materials [6]. Research has demonstrated that these innovative configurations can achieve remarkable improvements in energy absorption performance, with some studies reporting up to 64.75% enhancement in specific energy absorption values compared to traditional designs [7]. The gyroid lattice structure has shown superior performance with compressive strength reaching 76.51 MPa and energy absorption of 28.57 MJ m−3 under specific manufacturing parameters, while research has shown that incorporating auxetic honeycomb lattice structures along the perimeter of helmet liners can achieve superior energy absorption compared to conventional designs.

The integration of computational analysis methods, particularly Finite Element Analysis (FEA), has revolutionized the helmet design and evaluation process. This sophisticated computational approach enables researchers to simulate diverse impact scenarios and assess helmet performance characteristics without requiring extensive physical prototyping, thereby accelerating design optimization and reducing development costs [8]. Through FEA simulations, engineers can analyze complex stress distributions, deformation patterns, and energy dissipation mechanisms within foam-filled lattice structures under various impact conditions. Malaysian Safety Standards establish clear benchmarks for protective equipment effectiveness, mandating specific performance criteria that helmet designs must achieve to be considered acceptable for public use, with particular emphasis on maintaining structural integrity while effectively dissipating impact energy through controlled plastic deformation [9].

This research addresses these critical challenges by investigating the protective capabilities of foam-filled lattice sandwich construction motorcycle helmets through comprehensive finite element analysis. The study aims to quantify their impact behavior, assess peak headform acceleration values, and establish their effectiveness in reducing head injury risks compared to conventional helmet designs [10]. By evaluating the performance of these innovative structures under controlled impact conditions at 5 m/s velocity, focusing on linear impacts to the side region of the helmet, this research contributes to the advancement of motorcycle safety technology and provides valuable insights for future helmet manufacturing standards while addressing the urgent need for enhanced protective equipment in the context of rising motorcycle accident statistics [11].

2. Methodology

This research employs a comprehensive finite element analysis approach to evaluate the impact behavior of foam-filled lattice sandwich construction motorcycle helmets. The methodology encompasses a systematic process designed to quantify three parameters of total deformation, equivalent (von-Mises) stress, and equivalent elastic strain and assess protective capabilities through computational simulation, addressing the critical need for enhanced motorcycle helmet safety in Malaysia where motorcyclists face 30 times higher fatality rates.

2.1 Research Approach and Scope

The study focuses on evaluating helmet performance under controlled impact conditions at 5 m/s velocity, specifically analyzing linear impacts to the side region of the helmet. The research compares foam-filled lattice helmet performance against conventional EPS liner designs under identical impact conditions. The methodology incorporates analysis of biomechanical responses such as von Mises stress within the brain using finite element models, providing comprehensive understanding of injury risk associated with different helmet designs.

2.2 Computational Framework

The simulation setup utilizes ANSYS Workbench with Explicit Dynamics analysis, chosen specifically for its capability to handle high-speed, short-duration impact events characteristic of motorcycle accidents. The approach begins with geometry import of the helmet design incorporating both traditional EPS liner and innovative foam-filled lattice sandwich construction, with the process designed to assess impact performance under velocity speed of 5 m/s to simulate real-world crash scenarios.

2.3 Preprocessing Procedures

The material characterization process involves carefully specifying mechanical and physical properties for each helmet component using ANSYS Engineering Data Sources. The material definition encompasses three primary materials: inner foam liner with properties optimized for energy absorption, high-impact PC High Viscosity outer shell providing structural integrity, and lattice structures components acting as reinforcement framework. Critical material properties including mass density, Young's modulus, Poisson's ratio, and failure criteria are specified for each material, with properties obtained from material testing, literature, and standard material databases to ensure realistic finite element predictions.

Table 1 *Material Properties from the helmet Shell*

Property	Value	Unit
Density	1190	kg m^{-3}
Young's Modulus	2.32E+09	Pa
Poisson's Ratio	0.3912	
Bulk Modulus	3.5539E+09	Pa
Shear Modulus	8.3381E+08	Pa

The geometry input phase utilizes STEP (Standard for the Exchange of Product data) format to ensure compatibility and preserve 3D model integrity during import. The helmet model is initially created using SolidWorks CAD software, incorporating complex lattice geometry integrated with foam core, including detailed representations of helmet shell, lattice structure, and foam-filled regions. The imported geometry maintains all critical components accurately, serving as the foundation for finite element analysis and enabling detailed examination of helmet performance under various impact conditions.

Table 2 *Material Properties for the Lattice Core Liner*

Property	Value	Unit
Density	15	$kg{\cdot}m^{-3}$
Young's Modulus	5E+06	Pa
Poisson's Ratio	0.01	
Bulk Modulus	1.7007E+06	Pa
Shear Modulus	2.4752E+06	Pa
Specific Heat Constant Pressure, C_p	1210	$J{\cdot}kg^{-1}{\cdot}°C^{-1}$
Maximum Tensile Stress	5E+05	Pa
Maximum Equivalent Plastic Strain EPS	0.7	

2.4 Meshing Strategy and Quality Control

A finite element mesh was also created, and that is on linear Tetrahedral elements, which have a uniform global edge length of 9.0 mm and finally gives a total of 106,417 and 33,286 elements/nodes on the complete helmet assembly. The quality of mesh was determined using skewness requirements where more than 95 percent of elements were below 0.85 skewness value with an intention of ensuring that the solution was ensured in high stress gradient and in complex geometry areas. The meshing was progressively refined selectively in the areas around the shell out liner faces and the impact areas so as to obtain a balance between the expenditure on the computer resources and the quality of the results. The transition areas between element sizes were smoothed so that the element size did not change so abruptly and aspect-ratio checks were carried out to ensure that elements were not distorted too much. This method supplied an optimised mesh that gives one trustworthy forecast of deformation, stress and strain and at the same time sustains the computational performance in ANSYS Workbench.

Fig. 1 *Skewness mesh metrics Spectrum*

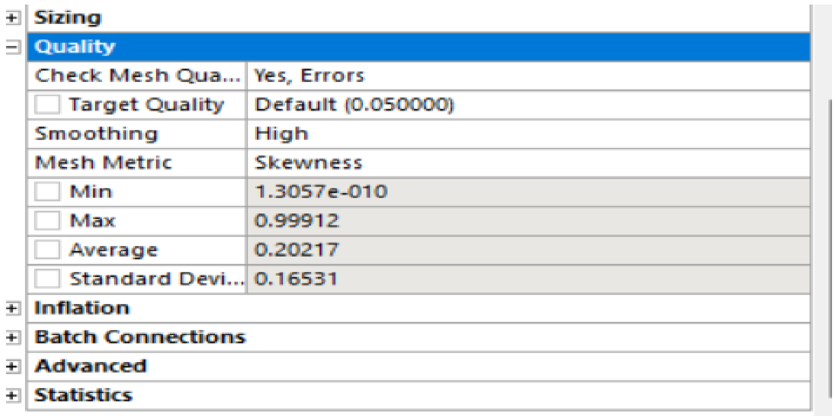

Fig. 2 *Meshing Quality*

2.5 Model Setup and Boundary Conditions

The boundary condition setup involves restricting specific helmet regions to replicate attachment to the head, with identification of regions corresponding to attachment points and establishment of specific identifiers for applying accurate border conditions. Initial conditions are established within Explicit Dynamic selection to ensure precise simulation outcomes, with one face treated as an attached surface extending to the ground plane using fixed area representation of rigid ground surface.

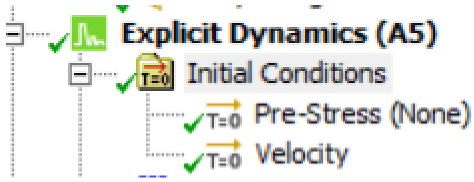

Fig. 3 *Initial Conditions of the model*

The loading condition establishment involves gravity-driven impact specification through drop height of 2000 mm, resulting in impact velocity of 6.2631 mm/ms in the +X direction. The loading conditions encompass impact situations including drops and surface impacts, with consideration of drop height, impact surface nature, model fixed points, and helmet orientation at contact time. Impact zones are modeled on three different helmet regions - top, side, and back - enabling analysis of deformation and stress patterns across multiple locations over 10 ms time scale.

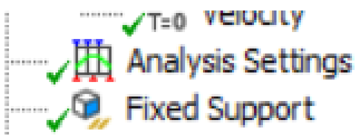

Fig. 4 *Selection of the conditions of the model*

The analysis configuration allows selection of total simulation duration with minimal time increment selection to improve model outcome precision. Specific output requests are chosen for model simulations, including Total

Deformation and Equivalent Stress parameters, with temporal parameters including time step controls and solver settings accessible through Analysis settings toolbar.

3. Postprocessing and Results Analysis

The postprocessing approach involves accessing results through toolbar results section upon simulation completion, with graph generation according to specified output demands. The lattice structure design simulation utilizes deformation plots demonstrating geometric alterations under applied forces, with stress plots examined to evaluate stress distribution according to helmet materials. Animation production illustrates impact forces when helmet strikes wall, providing comprehensive visualization of impact dynamics (Fig. 7).

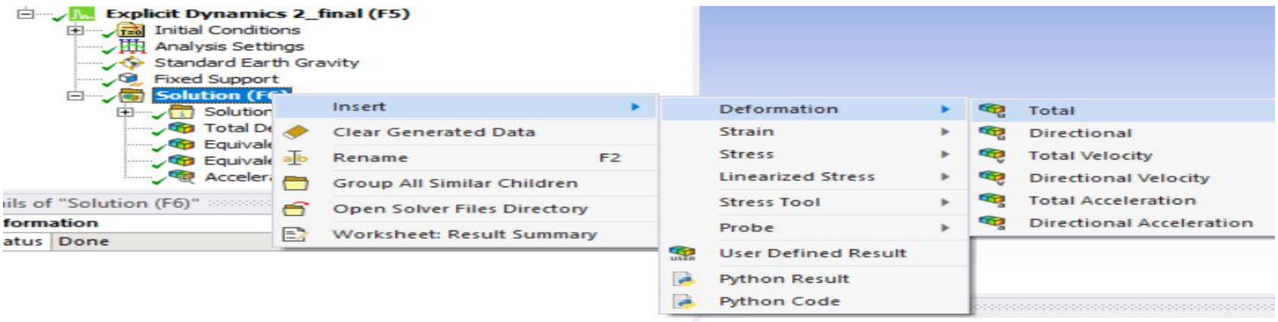

Fig. 5 *Specific results for the Simulation of the models*

3.1 Total Deformation

The helmet's total deformation contours reveal how each design manages impact energy. In the conventional helmet, peak displacement reaches 0.19415 m at 0.0329 s, with deformation localized in the crown region and gradually propagating outward as the EPS liner compresses. By contrast, the lattice-core design attains a maximum deformation of only 0.04675 m at 0.00581 s, with highly uniform, localized crushing of the lattice struts and minimal global deflection. These results illustrate the lattice's ability to absorb impact loads rapidly and restrict overall displacement, preserving shell integrity.

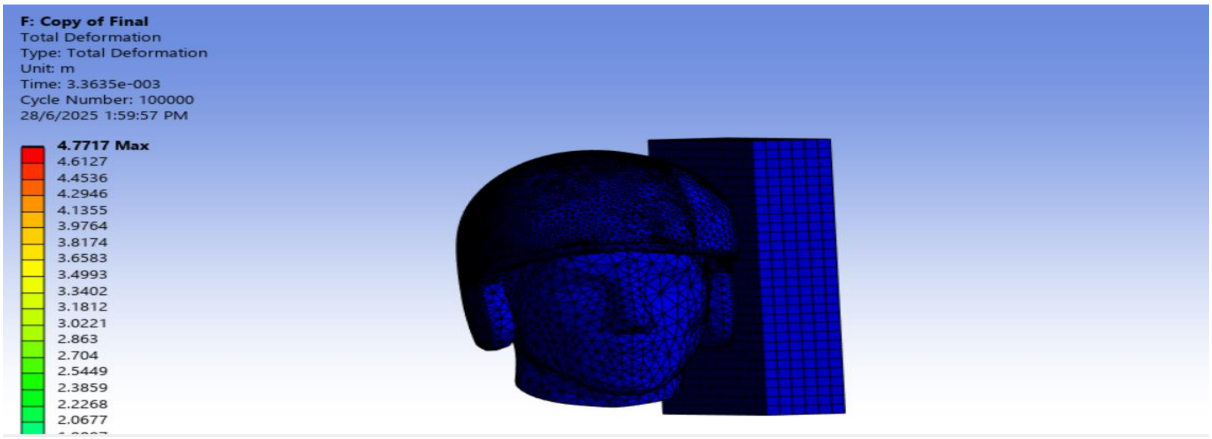

Fig. 6 *Total Deformation at 3.3635e-3s*

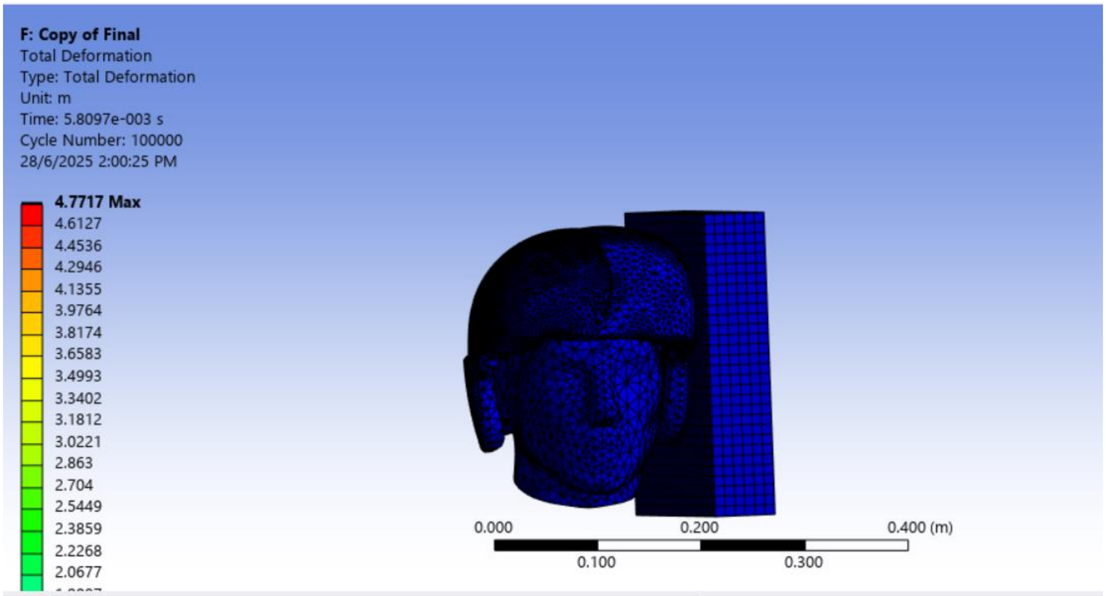

Fig. 7 *Total Deformation at 5.8097e-3s*

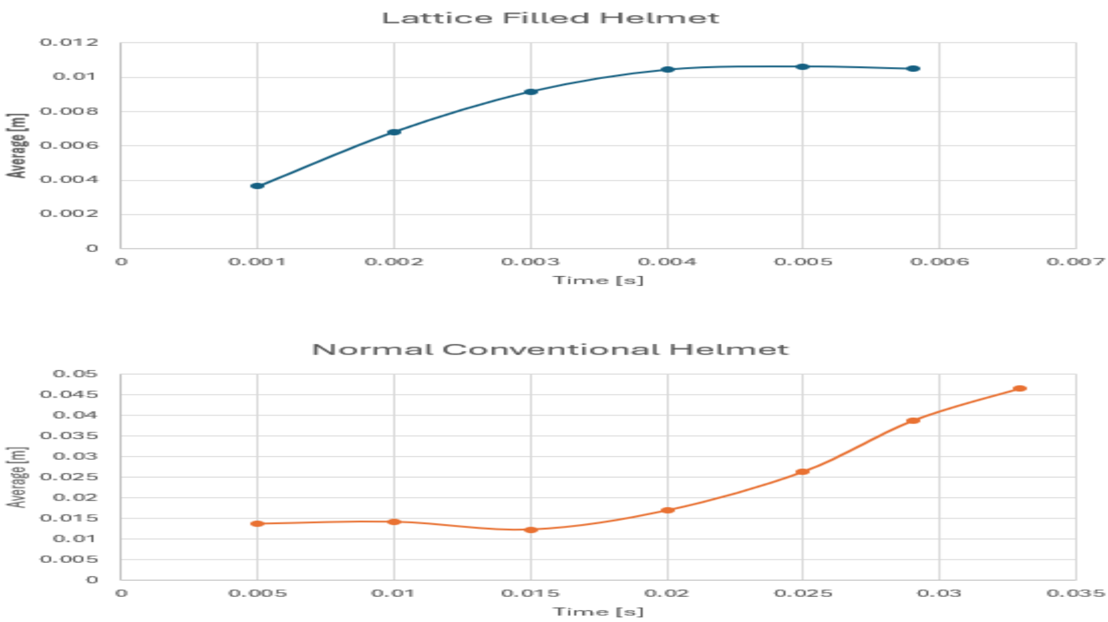

Fig. 8 *Comparison of Total Deformation vs. Time*

3.2 Equivalent (von-Mises) Stress

Stress distribution plots highlight the contrasting load-transfer mechanisms. The conventional helmet's outer shell builds up to 16.176 MPa at 0.02251 s, with stress concentrated at the shell–liner interface and slowly dissipating thereafter [12]. In the lattice core model, an instantaneous peak stress of 132.92 MPa occurs within 0.001 s, followed by rapid stress relaxation to under 0.01 MPa by 0.00581 s. This behaviour indicates that the lattice geometry channels impact forces through multiple load paths, focusing stresses into struts that then unload swiftly, unlike the sustained stress plateau in EPS foam designs.

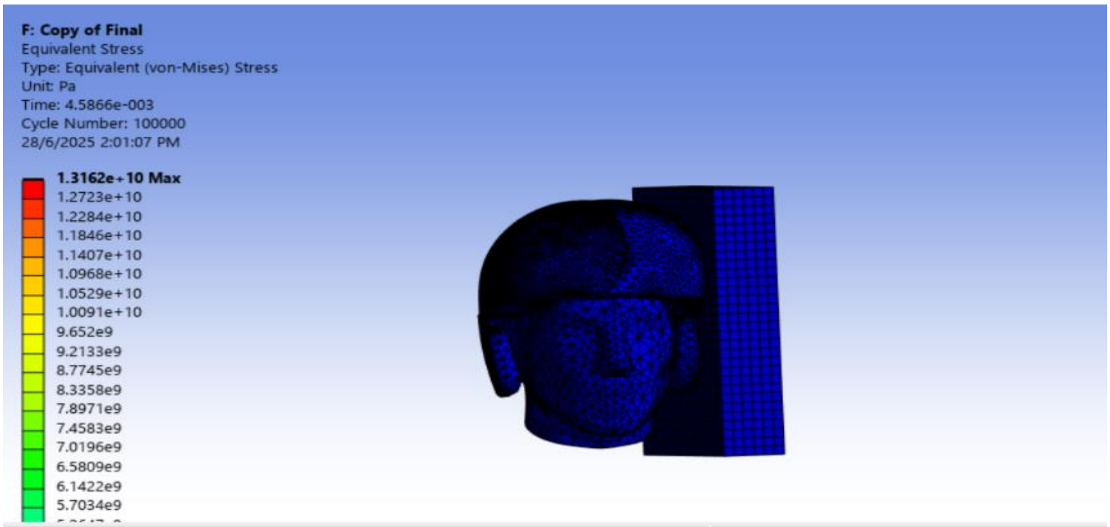

Fig. 9 *Equivalent (von-Mises) Stress at 4.5866e-3s*

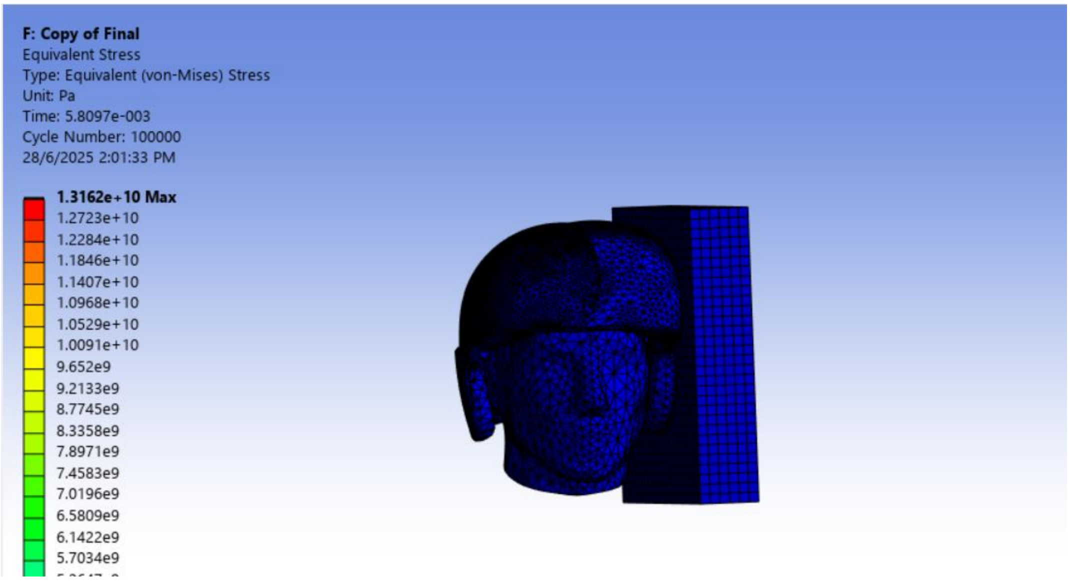

Fig. 10 *Equivalent (von-Mises) Stress at 5.8097e-3s*

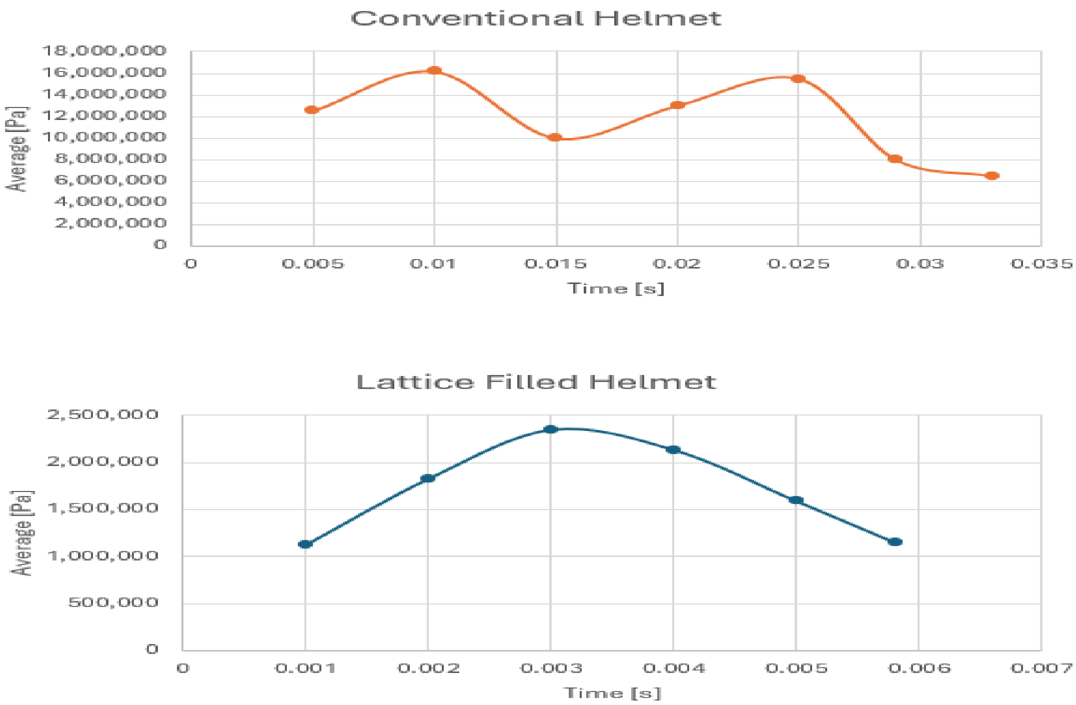

Fig. 11 *Comparison of Equivalent (von-Mises) Stress vs. Time*

3.3 Equivalent Elastic Strain

The elastic strain response further underscores structural resilience. In the conventional helmet, equivalent elastic strain climbs to 2.2006 m/m at 0.03117 s, with high strain zones in the EPS liner indicating plastic transition. The lattice core demonstrates a maximum elastic strain of only 0.04675 m/m at 0.00092 s, with the strain field confined to strut junctions and sustained without significant growth thereafter. This low, localized strain confirms the lattice's superior elastic recovery and minimal permanent distortion, essential for multi-impact applications.

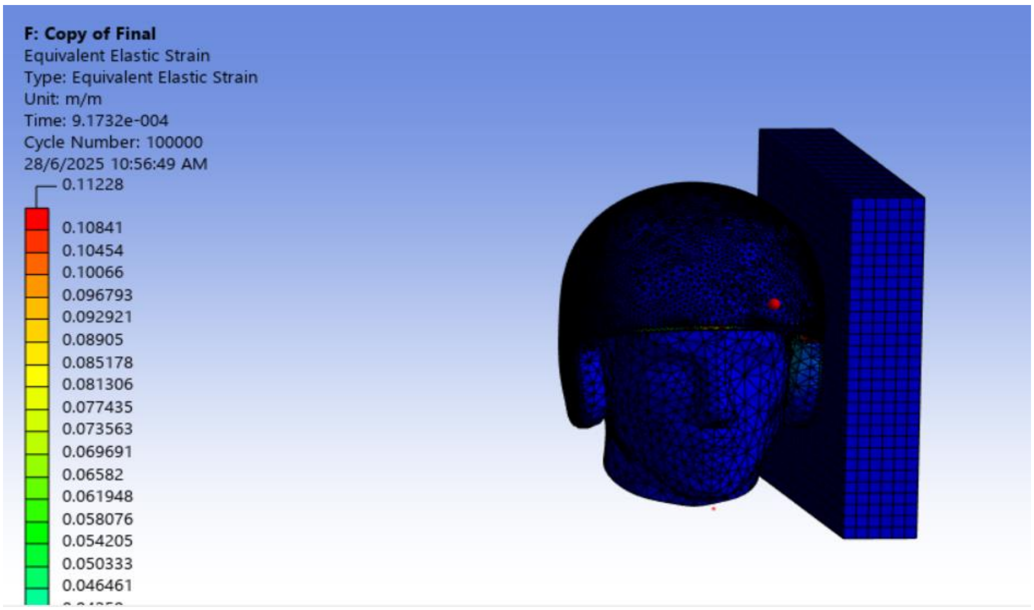

Fig. 12 *Equivalent Elastic Strain at 9.1732e-4*

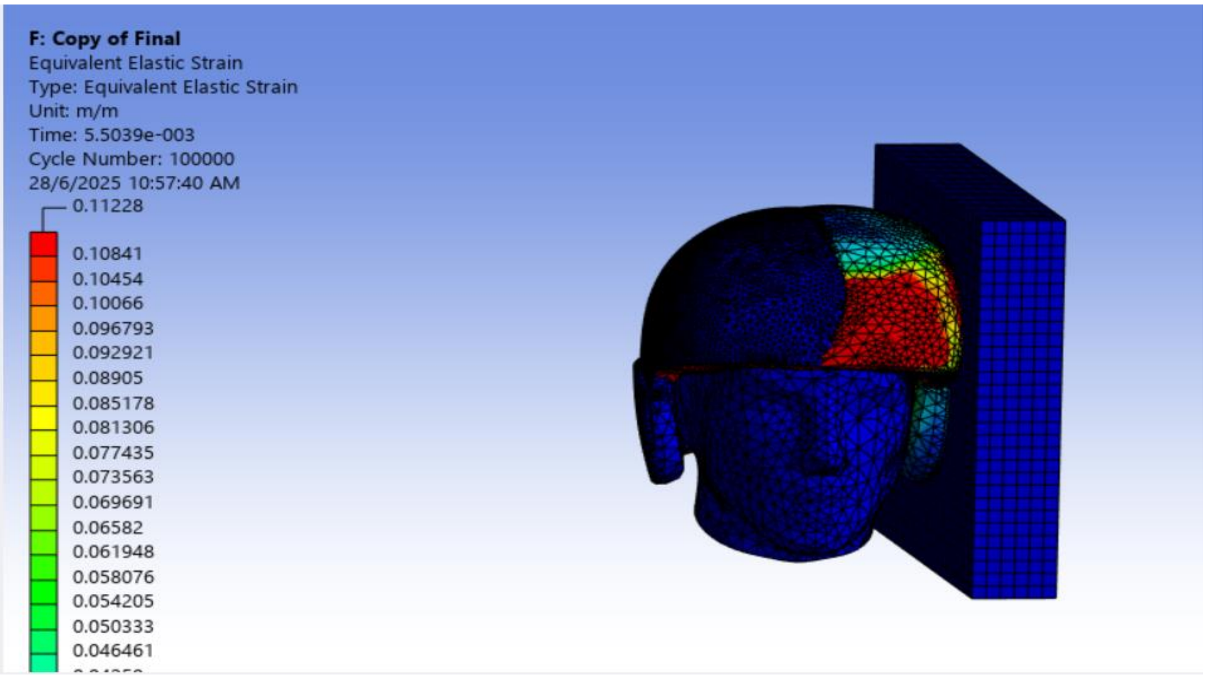

Fig. 13 *Equivalent Elastic Strain at 5.5039e-3s*

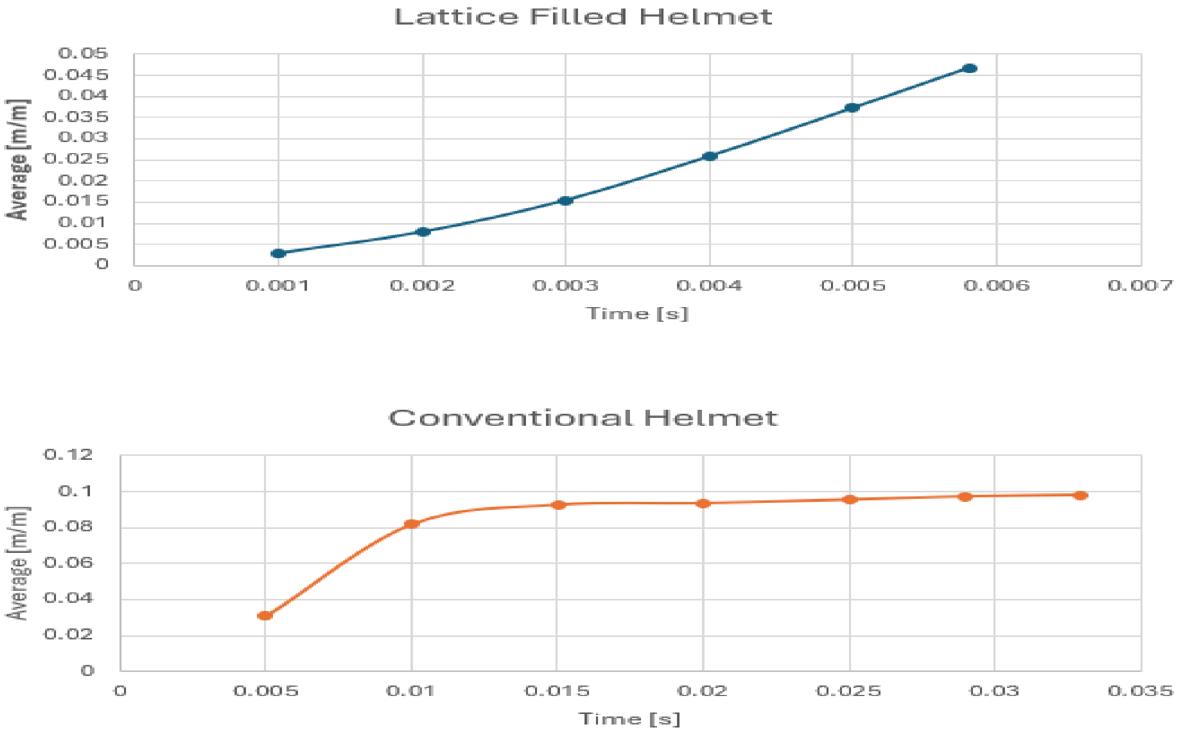

Fig. 14 *Comparison of Equivalent Elastic Strain vs. Time*

4. Conclusion

The finite element analysis state that foam filled lattice sandwich-construction of motor-cycle helmets are highly more effective than conventional EPS-lining ones in all significant safety measures. Maximum total deformation was reduced to 75.9 and equivalent elastic strain with 97.9 percent when using the lattice core design in comparison with the base on 0.046752 m and 0.19415 m and 2.2006 m/m, respectively. Most conspicuously, its stress capability management made it attain an immediate peak stress and rapidly decreased over 99% of the peak stress of 132.92 MPa within milliseconds unlike the gradual cumulative increase of 16.176 MPa plus creep rate in the regular helmetsClick or tap here to enter text..

A temporal study also shows that the temporal histories suggest that, although maximum lattice deformation is achieved about 27 times faster compared to conventional helmets, total displacement is significantly smaller, which shows very high energy absorption efficiency in a predictable deformation process through the multiple load-path phenomenon. This fact confirms the hypothesis that designed lattice geometries provide better protection of impact energy, having a strategic balance of localized crushing as well as global integrity. Foam-filled lattice core helmet, therefore, marks a paradigm change in the history of protective headgear bringing optimum reliable performance without compromising the feasibility of practical design.

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Conflict of Interest

There was no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: study conception and design: Nagulan Chanthiran, S. Kanna Subramaniyan; data collection: Nagulan Chanthiran; analysis and interpretation of results: Nagulan Chanthiran, S. Kanna Subramaniyan; draft manuscript preparation: Nagulan Chanthiran, S. Kanna Subramaniyan. All authors reviewed the results and approved the final version of the manuscript.

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