Impact Behaviour of Existing Bicycle Helmet Subjected to Drop Test

Mohamad Irfan Farhan Mohd Nawi[1], Mohd Norihan Ibrahim @ Tamrin[1]*

[1] *Faculty of Mechanical and Manufacturing Engineering*
   Universiti Tun Hussein Onn Malaysia, Batu Pahat, 86400, MALAYSIA

*Corresponding Author: norihan@uthm.edu.my
DOI: https://doi.org/10.30880/rpmme.2024.05.01.003

Abstract

A bicycle helmet is a crucial piece of safety equipment that serves to protect the head from injury during accidents. In this research, the focus is on investigating the deformation behavior and impact capability of commuter bicycle helmets with and without liners using Finite Element Analysis (FEA). Based on actual measurements, two commuter helmet models with a shell thickness of 0.4 mm made of polycarbonate (PC) and an inner thickness of 25 mm made of Expanded Polystyrene (EPS) were created. The drop tests simulated a free fall from a height of 1.5 meter with a constant gravity acceleration of 9.81 m/s^{-2}. The commuter helmet shell was examined in the first simulation run, while the drop test parameters for the helmet with an inner were run in the second simulation. Output parameters such as displacement, equivalent stress, and strain were analyzed. The simulated data from both commuter helmet models was compared to determine the differences, providing insights into the deformation behavior and impact capability of the bicycle helmets with and without liners This research aims to contribute to the understanding of bicycle helmet performance in drop tests and inform future designs and improvements in bicycle helmet technology.

1. Introduction

The head is a major source of serious and fatal injuries in bicycle accidents, which makes cyclists a particularly vulnerable category of road users. Head injuries pose a significant challenge to society, as they can result in immediate and prolonged effects. Additionally, when it comes to severe injuries sustained by bicyclists, the head is the body region most affected. So far, helmets have been the primary means of protecting against head injuries.

From the previous study of [1] have explored that the existing bicycle helmet still have a lack whether the utilization of helmets is linked to injuries to the face or neck. Specifically, a recent analysis revealed that wearing helmets provided protection against upper and middle facial injuries. Further investigation is needed to identify potential limitations in the existing bicycle helmet designs, including assessing the impact resistance of materials used and evaluating ergonomic aspects. In terms of helmet design, there are two key components that require heightened attention which is the outer shell and the external layer (liner) of the bicycle helmet. Modern bicycle helmets commonly feature a rigid outer shell made from materials such as Polycarbonate (PC), ABS, or composite materials. These composite shells exhibit anisotropic behavior, in contrast to the isotropic behavior of thermoplastic shells. This allows them to better withstand impact forces, while the inner disperses the applied force [2],[3].

Finite Element Analysis (FEA) has been used to examine the improvement of bicycle helmet performance, particularly in oblique road impacts [4]. The application of Finite Element Analysis (FEA) is one such technique used to evaluate a bicycle helmet's performance in a real-life accident. The performance and characteristics of different types of bicycle helmets can be examined through drop test analysis using simulation software, which considers factors such as helmet design and materials used. This allows for a thorough study of how these helmets behave under impact scenarios, providing insights into their protective capabilities. Drop test studies involve assessing how an object or assembly responds to impact when dropped onto a rigid or flexible surface, such as the floor. This analysis allows for a detailed examination of how the object or assembly behaves upon impact, including factors such as deformation, stress distribution, and strain. As a result, it is necessary to conduct additional research to enhance our understanding of existing bicycle helmet behavior when dropped to the flat surface.

2. Material and Methods

The deformation behaviour and impact capabilities of commuter bicycle helmets with and without liners were investigated using finite element analysis (FEA). The analysis was split into three phases, which were geometry development, numerical solution, and result interpretation. SolidWorks 2021 was used in this research to do a drop test analysis simulation and obtain the results. The initial stage was to build a bicycle helmet model, specifically a commuter helmet. The outer shell was composed of thermoplastic polycarbonate, and the interior liner was made of expanded polystyrene (EPS) [5]. The mechanical properties and values of polycarbonate are shown in Table 1.

Table 1: *Properties of Polycarbonate (PC)*

Density	Young's Modulus	Poisson's Ratio
1200 Kg/m^3	$2.2 \times 10^9 \text{N/m}^2$	0.37

2.1 Geometry Development

The study's goal was to model the commuter helmet and examine the colour contour on its surface after impact on a flat surface, along with deformation, equivalent stress, and strain values. The drop test was conducted in accordance with the EN1078 standard for bicycle helmets and involved a 1.5-meter drop at a constant velocity of 9.81 m/s^2. The outside shell of the commuter helmet was made of polycarbonate, and the inside inner was made of expanded polystyrene (EPS). Polycarbonate (PC) is a lighter and more flexible outer shell material than ABS, while EPS is designed to absorb forces after an impact by deforming, protecting the wearer's head from direct contact with hard surfaces [6]. To assure the validity of the data simulation, the commuter helmet dimensions were based on an existing commuter helmet size. The commuter helmet's outer shell and inner were created using SolidWorks 2021 software. Table 2 shows the parameters used for the drop test analysis.

Table 2: *Parameters used for the drop test analysis*

Shell material	Liner material	Shell thickness (mm)	Inner thickness (mm)	Gravity (m/s^2)	Drop height (m)
PC	EPS	0.4	25	9.81	1.5

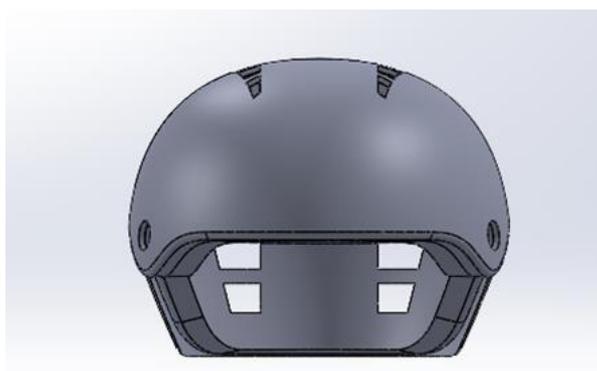**Fig. 1:** *Modelled commuter helmet for drop test*

2.2 Mesh Generation

Meshing is an essential component in the simulation process that impacts the accuracy of the results because it manages the arrangement of discrete points on a model. Elements with different shapes, such as square and triangular, can be used to allow for more accurate meshes in places of high stress concentration, where greater accuracy is required, especially when the shape geometry of model structures is complex. A tetrahedral mesh was used in this case to ensure accuracy of deformation, equivalent stress, and strain values. Tetrahedral components are used to fill the volume of a part with solid elements and are great for large objects. The tetrahedral hybrid mesh type utilizes a triangle surface mesh and then adds tetrahedral volume elements and generally combines with boundary layers. Figure 2 shows the mesh generation at the commuter helmet.
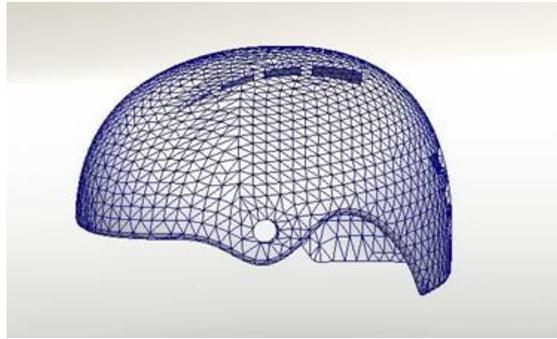

Fig. 2: *Mesh generation at the commuter helmet*

2.3 Boundary Conditions and Output Parameter

The boundary conditions for bicycle helmet drop testing are essential to assessing the helmet's performance and assuring its safety. The boundary conditions for drop tests of commuter helmets with and without inner padding were set to a constant acceleration of 9.81 m/s2 in this study. The free fall drop test height was set at 1.5 metres, which corresponds to a speed of roughly 16.1 m/s (50 km/h) for a drop test cycling helmet [7]. Therefore, the boundary conditions for drop tests of bicycle helmets should be designed to simulate real-world impacts as closely as possible to ensure that the helmet is subjected to a realistic range of forces and conditions. Figure 3 shows the setting parameters of height and acceleration.
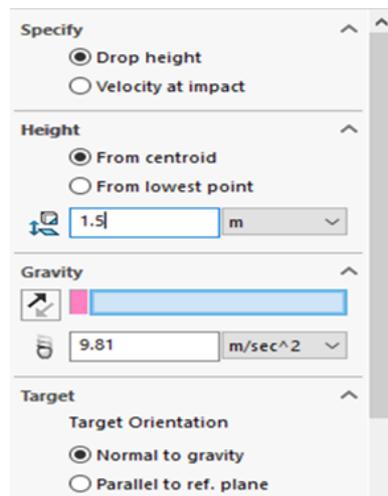

Fig. 3: *Setting parameters of height and acceleration*

The commuter helmet will be dropped from three different angles during the drop test: the front side, the crown or top side, and the back side. This method enables the evaluation of the helmet's performance in various impact scenarios. The results of the drop impact test on these three important impact points for the three helmet types can provide useful information about the helmet's capacity to withstand impacts from varied angles. Figure 4 shows the impact points for (a) crown; (b) front; (c) back.
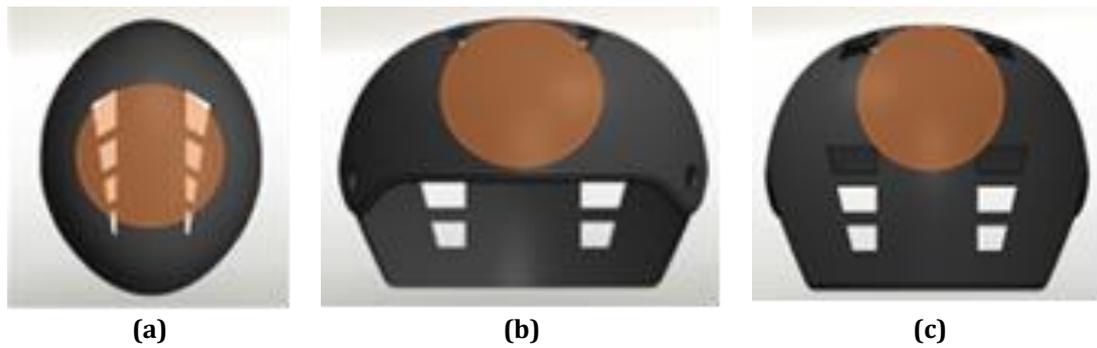
(a)   **(b)**   **(c)**

Fig. 4: *Impact points (a) crown; (b) front; (c) and back (right)*

The output parameters of bicycle helmet drop testing provide important insights into their performance and safety. These tests generate stress distribution, deformation, and strain measurements, which are essential in determining the helmet's ability to protect the wearer during collisions. The stress distribution analysis, which often relies on the Von Mises stress value, assists in determining the maximum stress that the helmet can withstand [8]. This value is compared to the helmet's Young's modulus, and if the stress exceeds this limit, the helmet structure is considered fail. Deformation measures analyse how the shape of the helmet changes afterwards impact, demonstrating its ability to absorb and distribute energy. Furthermore, when combined with finite element analysis, strain measurements enable the identification of possible fatigue or overload conditions on the helmet, allowing for extensive structural examination for design validation [7].

3.   Result and Discussion

Drop test analysis has been simulated using SolidWorks finite element analysis to investigate the impact capability of existing bicycle helmet and to analyses the deformation behaviour of bicycle helmet with a liner and without liner.

   The results obtained from the drop test simulation for a helmet with an inner and without an output parameter of deformation, equivalent stress, and strain were compared to investigate the impact capabilities of a bicycle helmet due to a drop on a flat surface. The result obtained for each drop test is the minimum and maximum values of deformation, equivalent stress, and strain. The drop test simulation can also help to determine the most and least affected locations on the bicycle helmet through the colour contour generated from the drop test simulation. The evaluation will be done on the front, crown, and back side components of an existing bicycle helmet.

3.1 Commuter helmet without inner

The simulation was conducted using all of the parameters and boundary conditions, and the predicted result was obtained. When the commuter helmet was dropped on a flat surface, the colour areas revealed the following: the blue zone represents the minimum affected area and minimum value, while the red region represents the most impacted area and the most deformation on the top, front, and back sides of the helmet.
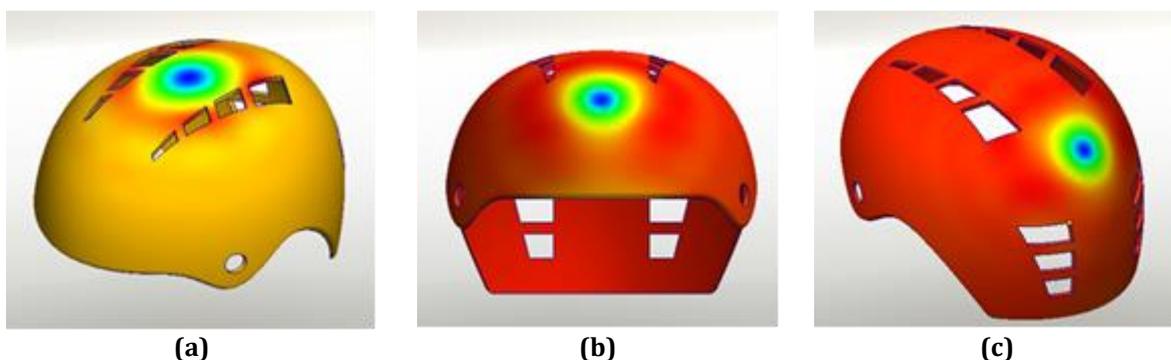

(a)   **(b)**   **(c)**

Fig. 5: *Displacement and colour contour commuter helmet shell (a) top; (b) front; (c) and back*
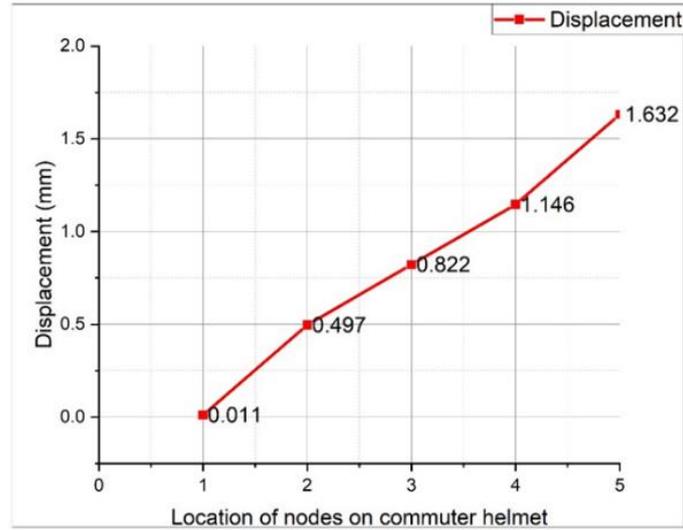
Fig. 6: *Mean displacement at five nodes from three probe commuter helmet shell*

In a single drop analysis, data can be gained for other parameters too including the minimum and maximum values of equivalent stress and the behaviour of commuter helmet structures when impacted on a flat surface. The behaviour of the structure of the commuter helmet without inner equivalent stress can be seen through the colour contour on Figure 7 for the top, front, and back sides of the helmet, where the blue colour region is the minimum value, and the red contour is the maximum value.
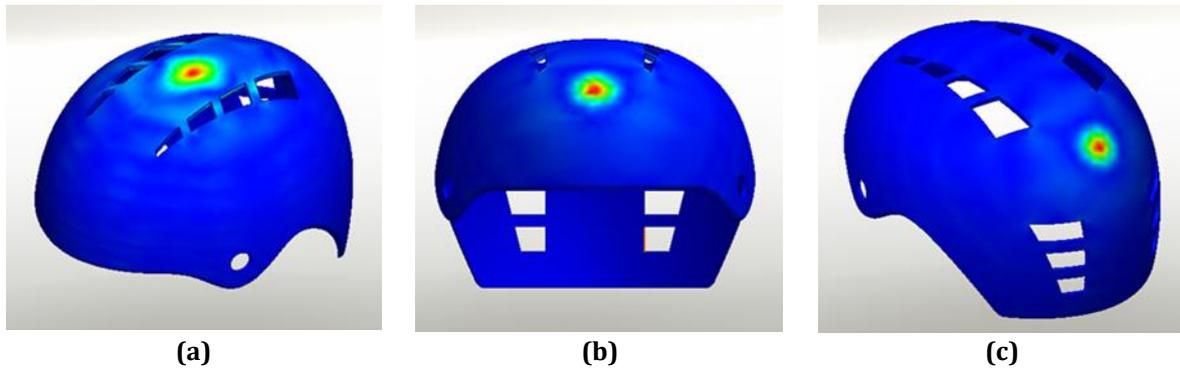

(a)   **(b)**   **(c)**

Fig. 7: *Equivalent stress and colour contour at the top, front, and back side commuter helmet shell*
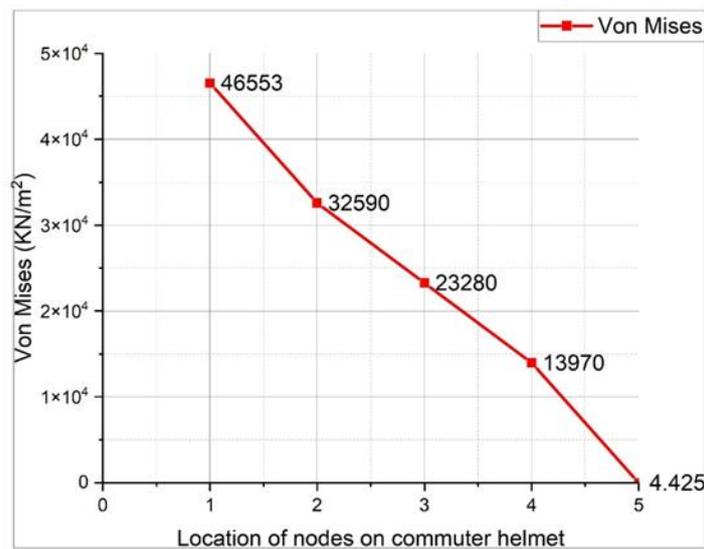

Fig. 8: *Von Mises mean generated at five nodes from three probe commuter helmet shell*

From the drop test, values of minimum and maximum for the strain commuter helmet without inner structure could be collected to show the behaviour of the commuter helmet without inner structure when dropped from a height of 1.5 meters. The colour contour in the Figure 9 demonstrated the affected area for the structure, where the blue colour region is the least affected and the red colour region is the most affected.
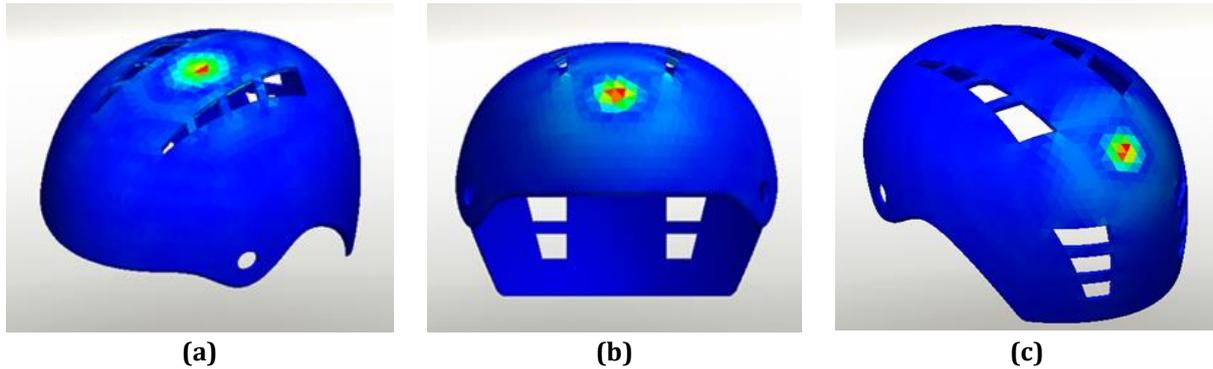

(a)   **(b)**   **(c)**

Fig. 9: *Strain and colour contour commuter helmet shell (a) top; (b) front; (c) back*
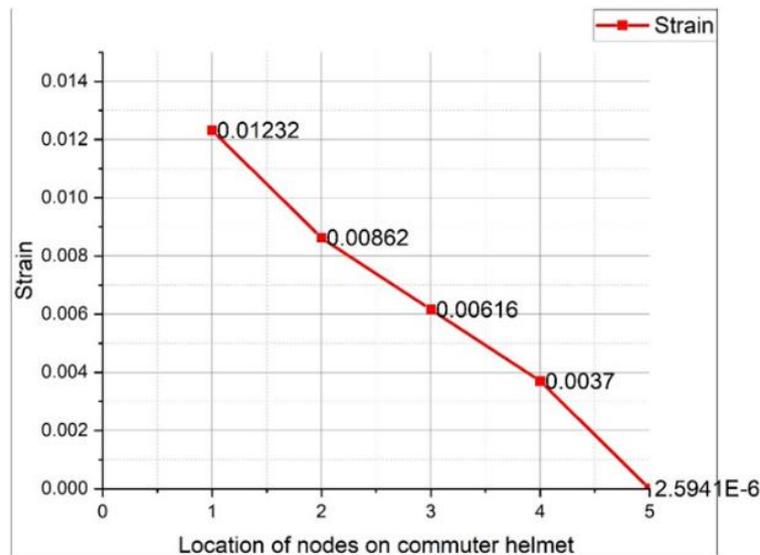

Fig. 10: *Strain mean generated at five nodes from three probe commuter helmet shell*

Table 3: *Data collected from existing commuter helmet shell*

Part	Stress (KN/m²)		Displacement (mm)		Strain	
	Min	Max	Min	Max	Min	Max
Top	2.141	28790	0.00515	1.794	$1.544e^{-6}$	0.0091
Front	0.985	53700	0.01964	1.542	$4.363e^{-7}$	0.0133
Back	10.150	57170	0.00820	1.560	$5.802e^{-6}$	0.0146

3.2 Commuter helmet with inner

The simulation for the commuter helmet with an inner foam liner was configured and run using appropriate parameters and boundary conditions. This simulation was conducted similarly to the commuter helmet without an inner foam, which is the standard drop test analysis method. For this specific test, the inner foam was fabricated from expended polystyrene (EPS) and combined with the outer shell made from polycarbonate.

In this simulation, the minimum and maximum values of deformation, equivalent stress, and strain were collected to investigate the deformation behaviour and impact capability of commuter bicycle helmets with inner thoughts on the colour contour of the commuter helmet structure, where the minimum value will be in the blue colour region and the maximum value will be in the red colour region [9].
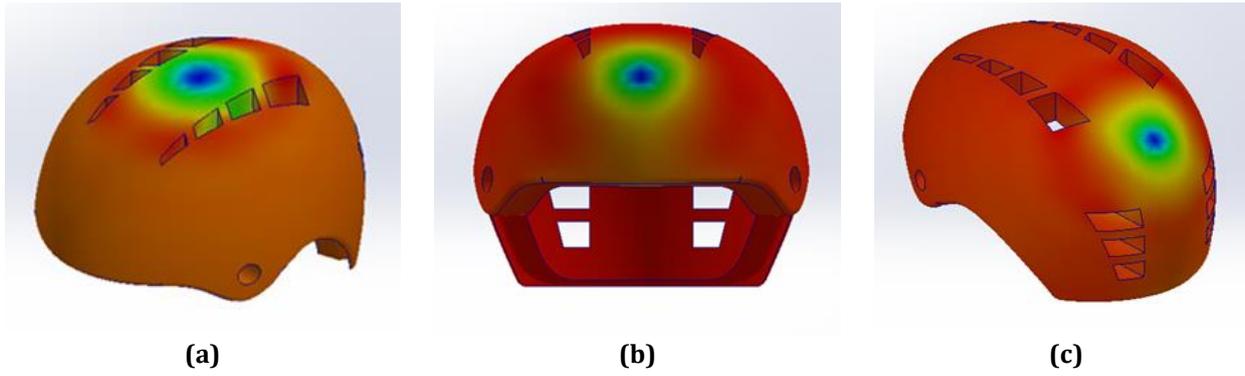
Fig. 11: *Displacement and colour contour commuter helmet (a) top; (b) front; (c) back*
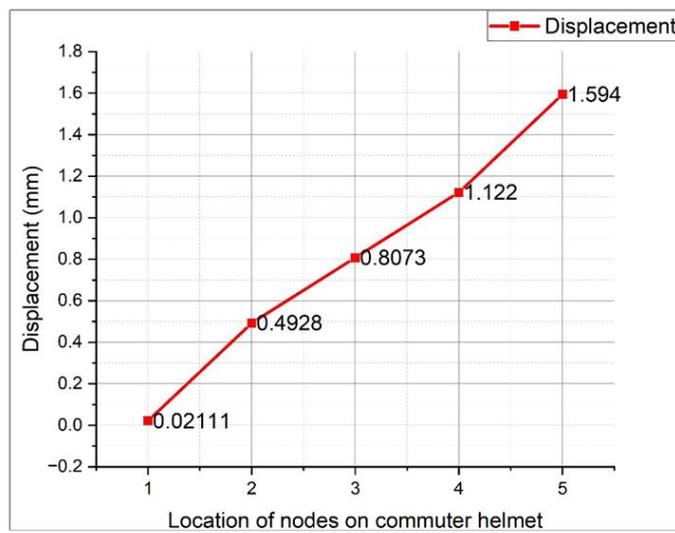

Fig. 12: *Mean displacement at five nodes from three probe commuter helmet*

Figure 13 shows the colour contour of minimum and maximum values for the equivalent stress and behaviour commuter helmet with inner at the top, front, and back sides for value of equivalent stress after undergoing a drop test.
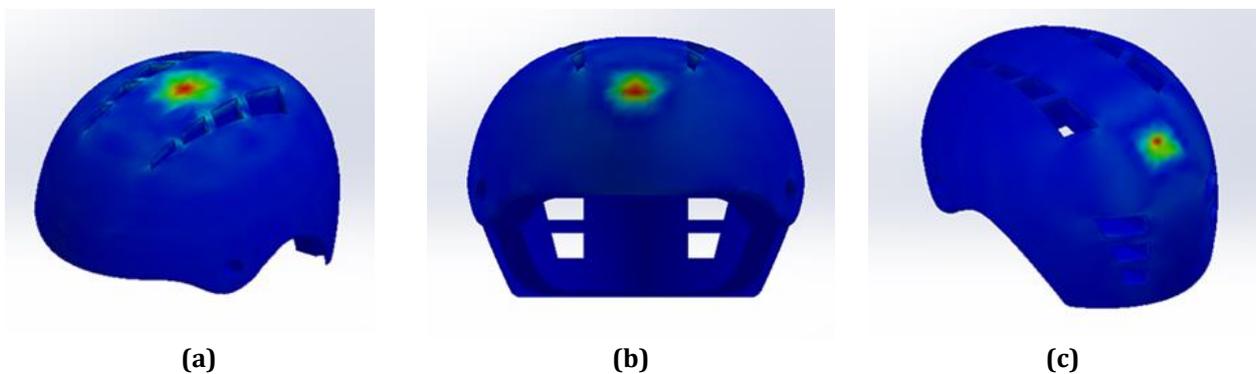

Fig. 13: *Equivalent stress and colour contour commuter helmet (a) top; (b) front; (c) back*
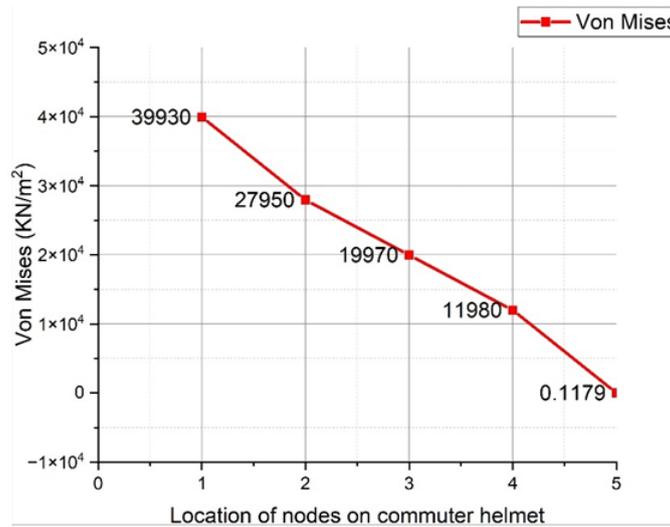
Fig. 14: *Von Mises mean generated at five nodes from three probe commuter helmet*

The analysis of the helmet's performance during the impact test involves calculating total strain energy under drop test analysis been shows in the Figures below to demonstrate the behaviour of outer shell and inner of the helmet.
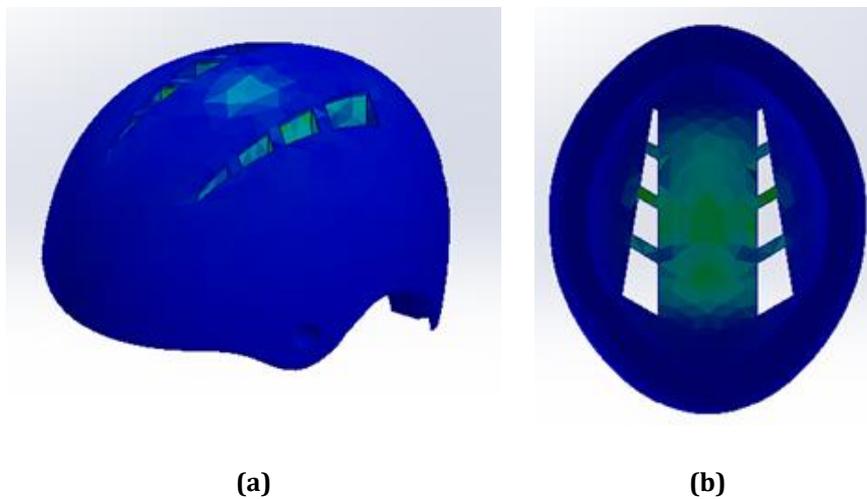

(a) **(b)**

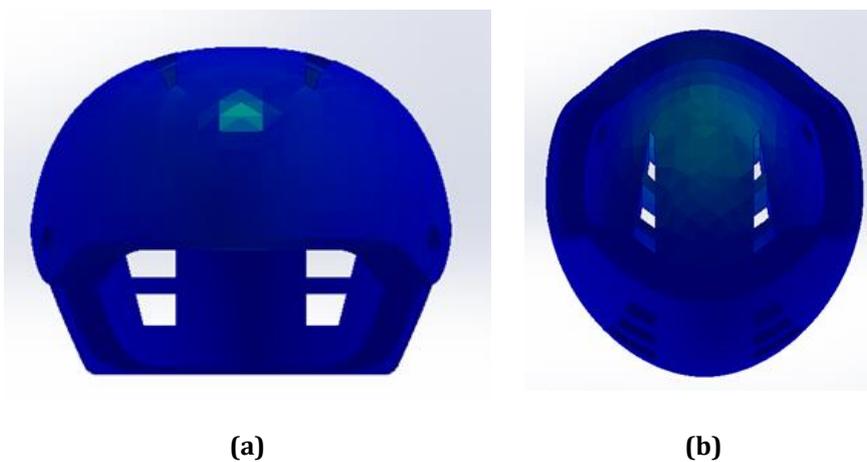**Fig. 15:** *Strain and colour contour at the top side commuter (a) shell; (b) inner*

(a) **(b)**

Fig. 16: *Strain and colour contour at the front side commuter helmet (a) shell; (b) inner*
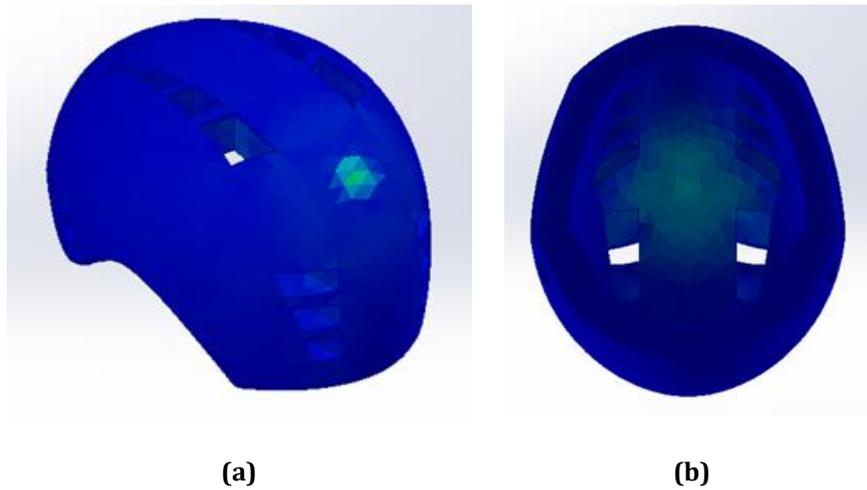
(a)   **(b)**

Fig. 17: *Strain and colour contour at the back side commuter helmet (a) shell; (b) and inner*
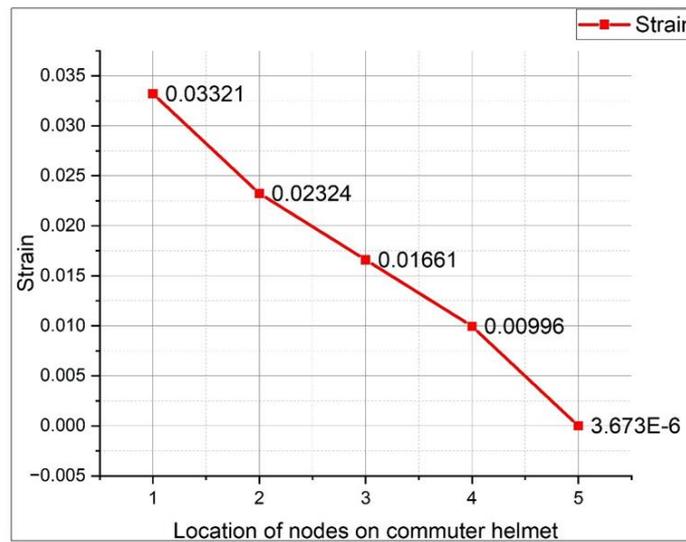

Fig. 18: *Strain mean generated at five nodes from three probe commuter helmet*

Table 4: *Data collected from existing commuter helmet with inner*

Part	Stress (KN/m²)		Displacement (mm)		Strain	
	Min	Max	Min	Max	Min	Max
Top	0.0513	23650	0.0138	1.684	3.434e⁻⁶	0.0236
Front	0.0103	44050	0.0381	1.518	5.238e⁻⁷	0.0410
Back	0.2922	52080	0.0114	1.579	7.061e⁻⁶	0.0351

3.3 Comparison of helmet with inner and without inner

The deformation behavior of existing commuter helmets with inner and without inner is discussed in this section in term of deformation, equivalent stress and strain. These analyses are particularly relevant to proof the effectiveness of inner foam of commuter helmet to reduce the impact to the bicyclist head during impact or collision. The value obtains of deformation, equivalent stress and strain for those two models has been calculated to the mean and percentage difference from the three locations of the commuter helmet for easier to gain the data and make a comparison between commuter helmet with inner and without inner.

Penerbit
UTHM

Table 5: *Commuter helmet without inner and with inner comparison*

Helmet Condition Output Parameter	Commuter helmet without inner	Commuter helmet with inner	Percentage difference between commuter helmet without and with inner (%)
Displacement (mm)	1.632	1.594	2.35
Equivalent Stress (KN/m²)	46553	39930	15.32
Strain	0.012	0.033	93.33

Table 5 shows that the difference in the value of deformation, equivalent stress, and strain for commuter helmers without inner and inner where displacement is the lowest and the difference for strain is the highest. In terms of displacement, the commuter helmet without an inner has greater deformation than the commuter helmet with an inner. Based on the graph comparison for the displacement for commuter helmets without inner and with inner that is shown in the Figure 19, the maximum displacement for commuter helmets without inner is 1.632 mm and the minimum value for commuter helmets without inner is 0.011 mm. For the maximum value of the commuter helmet with inner, it shows the value is 1.594 mm and the minimum value is 0.02111 mm. The commuter helmet shows a decrease in displacement of 2.35% based on a margin of percentage difference in the displacement or deformation from both models. Commuter helmets with inner layers, particularly those incorporating expanded polystyrene (EPS) foam, exhibit superior deformation resistance and energy absorption compared to helmets lacking inner layers. The EPS foam effectively absorbs impact energy, reducing both helmet and head displacement.
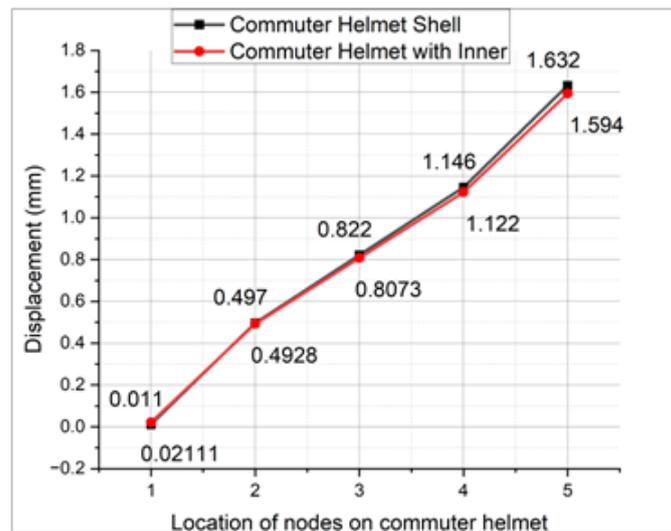

Fig. 19: *Difference of displacement between commuter helmet with inner and without inner*

Figure 20 shows the difference in equivalent stress between commuter helmets with inner and without inner, where the maximum and minimum values for commuter helmets without inner are 46553 KN/m2 and 4.425 KN/m2, respectively, and the maximum and minimum values of commuter helmets with inner are 39930 KN/m2 and 0.1179 KN/m2, respectively. In drop test simulations, helmets with inner liners demonstrated a 15.32% higher stress tolerance, ensuring resilience against forces and penetration. The combination of a polycarbonate (PC) shell and EPS foam minimises structural stress on the head, surpassing the protective capabilities of a standalone polycarbonate shell.
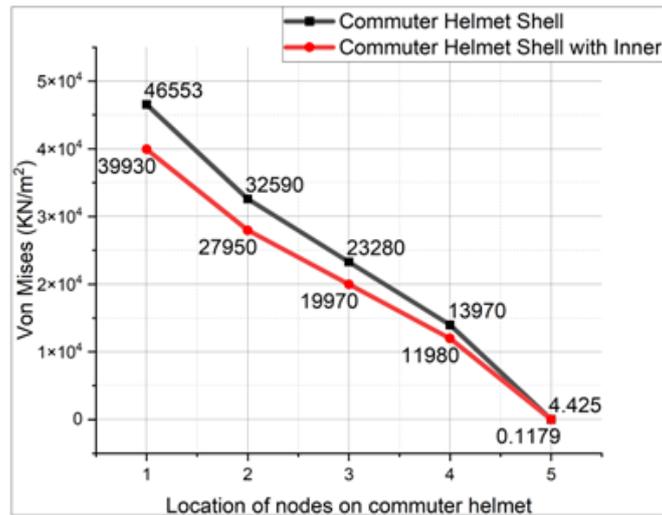
Fig. 20: *Difference of equivalent stress between commuter helmet with inner and without inner*

The difference in strain between commuter helmets with and without inners was plotted in a graph on the figure 21 to make it easier to illustrate the difference in strain value between commuter helmets without inners and with inners. Based on the graph, the maximum value for a commuter helmet without an inner is 0.0123 and the minimum value is 2.594 x 10-6. The maximum and minimum values of the strain on a commuter helmet are 0.03321 and 3.673 x 10-6, respectively. The inner helmet with EPS foam experiences a 93.33% higher strain due to EPS's brittle nature and plastic deformation during a drop test. EPS's ability to distribute impact energy over a larger area reduces the force transmitted to the head, enhancing overall protection [10]. Evaluating stress and displacement through drop tests is vital for assessing helmet performance and effectiveness in mitigating head injuries during impacts.
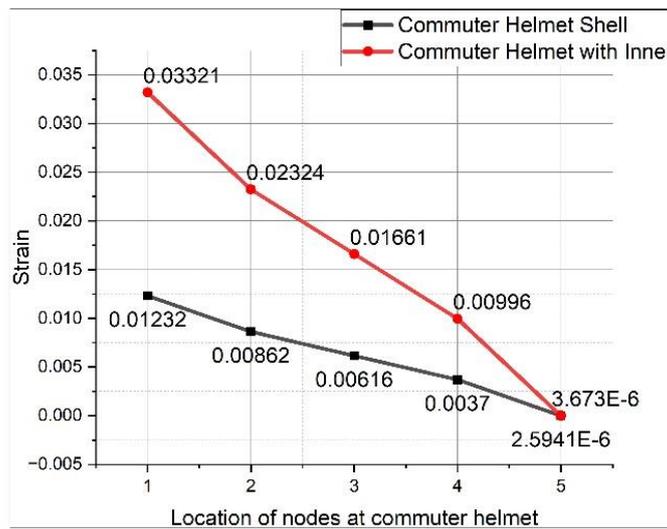

Fig. 21: *Difference of strain for commuter helmet with inner and without inner*

4. Conclusion

Finally, this study used SolidWorks 2021 to successfully simulate a drop test of commuter helmets with and without inner, offering important insights into their performance. The data show that adding inner padding to a commuter helmet improves its performance significantly, resulting in lower deformation rates, equivalent stress, and a higher strain rate as compared to helmets without inner padding. This is because the inside padding absorbs and distributes the energy from the hit, thereby protecting the wearer's head. This study's parametric study emphasizes the importance of the helmet's inner as an essential component in reducing deformation and stress. The overall performance of the helmet can be improved by including inner padding, making it more effective in assuring the wearer's safety. This research also highlights the prospect for utilizing

computational methods such as Finite Element Analysis (FEA) and software simulations to study the performance of bicycle helmets under different conditions. Designers and manufacturers may work together to produce more effective and protective bicycle helmets by knowing the capabilities of commuter helmet shells and the benefits of adding inner padding. This study contributes to ongoing efforts to improve bicycle helmet design and safety regulations, reducing the risk of head injuries and supporting sustainable transportation.

Acknowledgement

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Mohamad Irfan Farhan Mohd Nawi, Mohd Norihan Ibrahim**; data collection**: Mohamad Irfan Farhan Mohd Nawi**; analysis and interpretation of results:** Mohamad Irfan Farhan Mohd Nawi, Mohd Norihan Ibrahim**; draft manuscript preparation:** Mohamad Irfan Farhan Mohd Nawi, Mohd Norihan Ibrahim. All authors reviewed the results and approved the final version of the manuscript.*

References

[1]   J. Olivier and P. Creighton, "Bicycle injuries and helmet use: A systematic review and meta-analysis," Int J Epidemiol, vol. 46, no. 1, pp. 278–292, Feb. 2017, doi: 10.1093/ije/dyw153.

[2]   M. Fahlstedt et al., "Ranking and Rating Bicycle Helmet Safety Performance in Oblique Impacts Using Eight Different Brain Injury Models," Ann Biomed Eng, vol. 49, no. 3, pp. 1097–1109, Mar. 2021, doi: 10.1007/s10439-020-02703-w.

[3]   S. H. Marwan, M. A. M. Wahi, A. H. Abdullah, and M. H. Mazlan, "FINITE ELEMENT ANALYSIS OF PROTECTIVE BICYCLE HELMET & DUMMY HEAD UNDER DYNAMIC LOADING," J Fundam Appl Sci, vol. 10, no. 4S, pp. 870–881, 2018, doi: 10.4314/jfas.v10i4s.251.

[4]   J. Hutchinson, C. Rogers, J. Bish, K. Friedman, A. Sances, and S. Kumaresan, "FINITE ELEMENT ANALYSIS OF A BICYCLE HELMET."

[5]   L. Dahlin and E. L. Regnström, "Linear Impact of Bicycle Helmet-Experimental Testing and FE-modelling KTH Thesis Report THE SCHOOL OF ENGINEERING SCIENCES."

[6]   V. Saroha, B. S. Pabla, and S. S. Bhogal, "Characterization of ABS for enhancement of mechanical properties," International Journal of Innovative Technology and Exploring Engineering, vol. 8, no. 10, pp. 2164–2167, Aug. 2019, doi: 10.35940/IJITEE.J9379.0881019.

[7]   C. Moses Büth, N. Barbour, and M. Abdel-Aty, "Effectiveness of bicycle helmets and injury prevention: a systematic review of meta-analyses," Scientific Reports 2023 13:1, vol. 13, no. 1, pp. 1–10, May 2023, doi: 10.1038/s41598-023-35728-x.

[8]   J. Abderezaei, F. Rezayaraghi, B. Kain, A. Menichetti, and M. Kurt, "An Overview of the Effectiveness of Bicycle Helmet Designs in Impact Testing," Front Bioeng Biotechnol, vol. 9, p. 718407, Sep. 2021, doi: 10.3389/FBIOE.2021.718407/BIBTEX.

[9]   F. Abayazid, K. Ding, K. Zimmerman, H. Stigson, and M. Ghajari, "A New Assessment of Bicycle Helmets: The Brain Injury Mitigation Effects of New Technologies in Oblique Impacts," Ann Biomed Eng, vol. 49, no. 10, pp. 2716–2733, Oct. 2021, doi: 10.1007/S10439-021-02785-0/TABLES/8.

[10]   S. K. Bhudolia, G. Gohel, and K. F. Leong, "Impact performance of innovative corrugated polystyrene foam for bicycle helmets," https://doi.org/10.1177/0021955X20965215, vol. 57, no. 6, pp. 849–862, Oct. 2020, doi: