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Optimization of helmet shell thickness for motorcycle safety
Optimización de diseño de carcasa de casco para la seguridad de las motocicletas

Cruz-Jaramillo Iván Lenín
Tecnológico Nacional de México
Tecnológico de Estudios Superiores de Tianguistenco
Departamento de Investigación y Desarrollo Tecnológico
E-mail: breaking_182@hotmail.com
https://orcid.org/0000-0002-7832-1686

Samano-Guadarrama Víctor Leonardo
Tecnológico Nacional de México
Tecnológico de Estudios Superiores de Tianguistenco
Departamento de Investigación y Desarrollo Tecnológico
E-mail: victor_201821072@test.edu.mx
https://orcid.org/0009-0007-9436-1710

Piña-Díaz Armando Josué
Instituto Politécnico Nacional, México
Escuela Superior de Ingeniería Mecánica y Eléctrica Unidad Zacatenco
Departamento de Ingeniería en Control y Automatización
E-mail: apinad@ipn.mx
https://orcid.org/0000-0002-2723-6369

Abstract

Head injuries resulting from motorcycle accidents are a common cause of serious mortality. The most common injuries in motorcycle accidents are: head trauma, brain injuries, spinal cord injuries, facial injuries, neck injuries, and spinal cord injuries. The helmet is a fundamental piece of equipment to protect the head during a motorcycle accident. In general, a modern motorcycle helmet comprises a rigid outer shell made of thermoplastic or fiberglass to decrease the energy of the initial impact caused by the accident. Using 3D CAD modeling, the helmet shell is designed, allowing the controlled discretization of the helmet with hexahedral type elements to be able to perform the numerical simulation under the boundary conditions established in the NOM-206-SCFI/SSA2-2018 standard. Each scenario is carried out under the same boundary conditions and maintaining the mechanical properties of the ABS shell. The only parameter of variation is the thickness of the shells (4, 6, 8, and 10 mm). Simulations are performed for 20 ms, during which the strain, stress, and internal energy are obtained. The results show that as the thickness of the helmet increases, the unitary deformation decreases; the stresses, regardless of the thickness, reach a value of 34.3 MPa, reaching the elastic limit of the ABS; however, the stresses are dissipated over a larger area and the zone of maximum stresses decreases. The energy absorbed by the helmet increases with respect to the increase in thickness; from 2-4 mm it increases by 11.6 J, from 4-6 mm by 11.4 J, and from 8-10 mm by 8.35 J. As the thickness of the helmet increases, the amount of energy absorbed continues to increase, but the rate of increase decreases beyond 8 mm, so it is not feasible to continue increasing the thickness. The thickness of 8 mm offers an optimal balance between energy absorption and efficiency in terms of material and weight.
Keywords: Motorcycle helmets, finite element analysis, passive security, thickness, impact testing.

Resumen

Las lesiones en la cabeza resultantes de accidentes de motocicleta son una causa común de mortalidad grave. Las lesiones más comunes en los accidentes de motocicleta son: traumatismos craneoencefálicos, lesiones cerebrales, lesiones de la columna vertebral, lesiones faciales, lesiones del cuello y lesiones de la medula espinal. El casco es una pieza fundamental para salvaguardar la cabeza durante un accidente de motocicleta. En general, un casco de motocicleta moderno comprende una carcasa rígida exterior hecha de termoplástico o fibra de vidrio para disminuir la energía del impacto inicial, causada por el accidente. Mediante el modelado 3D en CAD se diseña la carcasa del casco, permitiendo generar el discretizado controlado del mismo con elementos tipo hexaédricos para poder realizar la simulación numérica bajo las condiciones de frontera establecidas en la norma NOM-206-SCFI/SSA2-2018. Cada escenario se realiza bajo las mismas condiciones de frontera y manteniendo las propiedades mecánicas de la carcasa de ABS. El único parámetro de variación es el espesor de las carcasas (4, 6, 8 y 10 mm). Las simulaciones se realizan durante 20 ms, durante los cuales se obtienen las deformaciones unitarias, esfuerzos y energía interna. Los resultados muestran que conforme se incremente el espesor del casco la deformación unitaria disminuye; los esfuerzos, independientemente del espesor, alcanzan un valor de 34.3 MPa, llegando al límite elástico del ABS; sin embargo, los esfuerzos se disipan en una mayor área y la zona de esfuerzos máximos disminuye. La energía que absorbe el casco aumenta respecto al incremento del espesor, de 2-4 mm aumenta 11.6 J, de 4-6 mm 11.4 J y 8.35 J de 8-10 mm. A medida que se aumenta el espesor del casco, la cantidad de energía absorbida sigue aumentando, pero la tasa de aumento disminuye pasando los 8 mm, por lo que no es viable continuar aumentando el espesor. El espesor de 8 mm ofrece un equilibrio óptimo entre la absorción de energía y la eficiencia en términos de material y peso.
Descriptores: Casco de motocicleta, análisis elemento finito, seguridad pasiva, espesor, prueba de impacto.

Introduction

Riding a motorcycle carries significant risks of fatal accidents, especially for novice riders (Kardamanidis *et al.*, 2010). Head injuries resulting from motorcycle accidents are a common cause of serious morbidity and mortality (Liu *et al.*, 2008). The most common injuries in motorcycle accidents are head trauma, brain injuries, spinal cord injuries, facial injuries, neck injuries, and spinal cord injuries (Tabary *et al.*, 2021).

The need for a "crash helmet" arose shortly after the widespread introduction of the motorcycle in the 1900s. Companies with names like Triumph in England and Harley Davidson in the US came to fill a need for this new means of transportation that was much cheaper than the automobile (Newman, 2005).

In general, a modern motorcycle helmet comprises a rigid outer shell made of thermoplastic or fiberglass to decrease the initial impact energy caused by the accident (Yu *et al.*, 2011). The main components of the helmet are the foam liner and the shell. The function of the foam is to absorb most of the impact energy, while the function of the carcass is to resist the penetration of any foreign object when touching the head and causing direct damage to the skull, decreasing the impact load by a wider foam area, thus increasing the energy absorption capacity of the foam liner. Manufacturers design their helmets based on experimental verification (Shuaeib *et al.*, 2002).

Numerous helmet analyses have been conducted to evaluate various aspects of helmet performance. One of these studies focused on determining the protective capability of the chin bar, for which a 4 mm thick ABS shell was used (Chang *et al.*, 2000). Dynamic numerical analyses have been performed in accordance with DOT FMVSS 218 standards, using LS-DYNA software to optimize and ensure the helmet's impact absorption capability. In these studies, two different scenarios were simulated, varying the thickness of the foam padding in the helmet. The thickness of the foam was found to be a crucial factor in the maximum acceleration experienced by the head (Agrawal *et al.*, 2018). Impact tests were also carried out on motorcycle helmets using COSMOS software. These tests included impacts at different speeds and in various positions, comparing two materials: PVC and ABS (Sadaq *et al.*, 2014). In Ansys, both dynamic and static analyses were conducted to evaluate the performance of helmets with a consistent thickness of 30 mm, using various materials including Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), Polystyrene, ABS + PC plastic, and Epoxy E-Glass. The findings concluded that both ABS and Polycarbonate offer effective movement during collisions and provide adequate protection against damage (Shankar *et al.*, 2021). In LS-DYNA, materials such as carbon fiber, glass fiber and Kevlar fiber, each with a thickness of 2 mm, have been analyzed (Kostopoulos *et al.*, 2002).

Similarly, non-traditional materials such as fiber-reinforced composites (FRC) and glass fibers have been employed. The mechanical properties of these fiber-reinforced composites are comparable to those of conventional materials. Results demonstrate that fiber-reinforced composites are a viable option for helmet applications (Thomas *et al.*, 2017). Additionally, epoxy composites reinforced with glass fibers offer superior mechanical properties compared to current helmet materials. A hybrid composite, incorporating jute, bamboo, E-glass, and coconut shell powder as fillers, has also been developed (Naidu & Rao, 2021).

Honeycomb structures with a thickness of 5.9 mm constructed from polypropylene have been designed and analyzed as replacements for EPS foam to evaluate their performance. These honeycomb structures feature polypropylene walls with a thickness of 0.1 mm and are coated with a 4 mm layer of ABS (Kholoosi & Galehdari, 2019).

The helmet is of vital importance to guarantee the safety of motorcycle users. In this work, Acrylonitrile Butadiene Styrene plastic (ABS) is implemented for the manufacture of the helmet shell and altering the thickness to obtain the optimal one.

Methodology

The design is based on the size of the head circumference, opting for a medium size of 7.5 inches (60 European size) (Diario Oficial de la Federación, 2018). Following the development of the hull parameterization sketch, modeling is performed using a Computer-Aided Design (CAD) software. Within this mechanical design software, surface tools are employed to extrude the sketch and create the helmet model. The helmet design is divided into three sections: the jaw, the middle part, and the upper section. Using the CAD tool's sewing function, these three sections are combined to form a single piece. Generate the model of the full-face helmet (Figure 1).

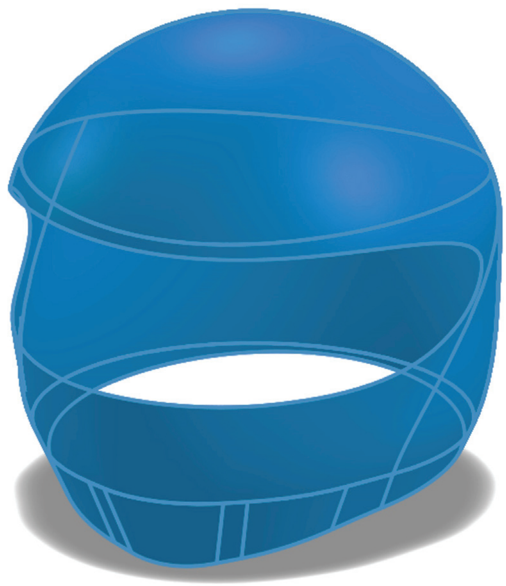

Figure 1. Modeling of helmet shell with surface tools

The completed design, initially created as a surface model without thickness, is processed using the "Thicken" tool to add various thicknesses for analysis. Four different thicknesses (4 mm, 6 mm, 8 mm, and 10 mm) are applied, generating a distinct model for each. These models are saved in Parasolid file format, which is compatible with HyperMesh 14.0 for further editing. In HyperMesh, each model is discretized into 2D, as depicted in Figure 2, before being mapped into 3D. After discretization, the models are exported to the LS-DYNA® software, where impact analysis scenarios are assembled.

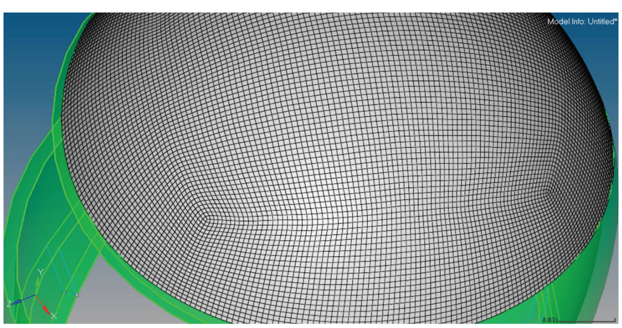

Figure 2. Discretization process in HyperMesh

The same analysis scenario is applied to all four thicknesses, with consistent boundary conditions and mechanical properties for ABS, to assess the effects of thickness variations. The boundary conditions adhere to the NOM-206-SCFI/SSA2-2018 standard (Diario Oficial de la Federación, 2018). According to these standards, a flat block with a diameter of 127 mm and a thickness of 25 mm is used. This block is modeled as a solid cylinder with the specified dimensions and discretized into 72 elements across the diameter and 10 elements through the thickness (Figure 3).

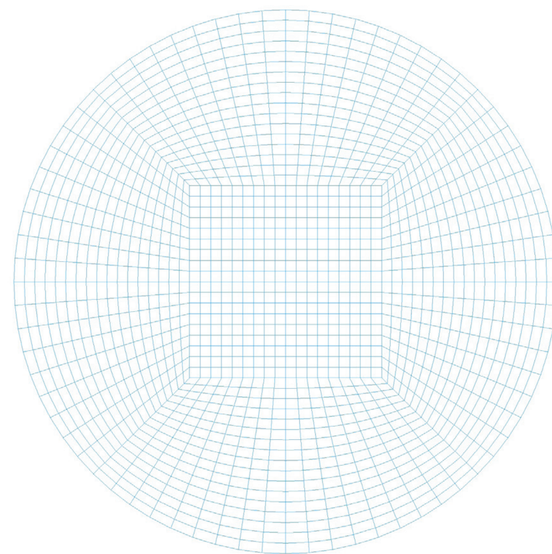

Figure 3. Mesh of flat impactor block

The block material assignment is A36 steel, with the following mechanical properties; density of 7.85x10-6 kg/mm^3, Young's modulus of 200 GPa, yield strength of 0.25 GPa, and a Poisson's ratio of 0.32 (Hibberler, 2006).

According to the standard, the block is dropped from a height of 1829 mm and is positioned 10 mm away from the helmet in the test setup. Using the equations for free fall, the impact velocity is calculated as follows (Tippens, 2000):

$$v = \sqrt{2g * h}$$

Substituting the given values into equation (1), obtain:

$$v = \sqrt{2\left(9.806\,e^{-3}\, {mm}/{ms^2}\right) * 1819mm} = 5.972\, mm/ms$$

ABS is a rigid thermoplastic known for its high resistance to heat and impact. It is commonly used for the outer shell of motorcycle helmets due to its mechanical properties: a density of 1.2x10-3 g/mm3, Young's modulus of 2 GPa, yield strength of 34.3 MPa and a Poisson's ratio of 0.37 (Totla *et al.*, 2020; Jacob *et al.*, 2016).

With the mechanical properties defined for the A36 steel block and the ABS material used for the helmet shell, boundary conditions were established. A gravitational acceleration of 9.806 m/s² and an initial helmet speed of 5.972 mm/ms were set. The bottom of the impacted block was fixed to prevent displacement, positioning it 10 mm away from the top of the helmet. Additionally, contact conditions between the helmet and the block were defined as Surface to Surface (Figure 4).

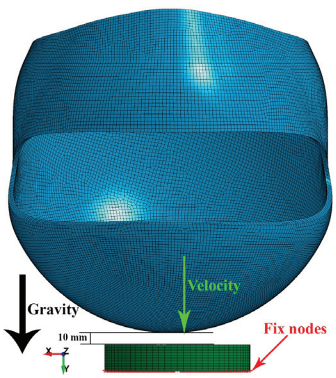

Figure 4. Simulation scenario with 4 mm thickness

Discussion and analysis of results

The simulations were conducted over 20 ms, with data recorded every 0.5 ms. Figure 5 illustrates the impact kinematics from a top view, with the block concealed to highlight the stresses generated in the helmet shell. Three key moments are shown: at 2 ms, when the helmet first contacts the block; at 3 ms, when the maximum stress due to the impact is reached; and at 4 ms, when the rebound effect begins.

As shown in Figure 5, the maximum stress occurs at 3 ms, reaching 34.3 MPa, which is the yield strength of the ABS material. This peak stress value remains consistent regardless of the helmet thickness; however, the area experiencing maximum stress decreases and dissipates more effectively across the upper surface. At 4 ms, when the helmet rebounds, a thickness of 4 mm maintains a larger area with stresses of 33.3 MPa. As the thickness increases, the color scale indicates lower stresses, and the affected area diminishes.

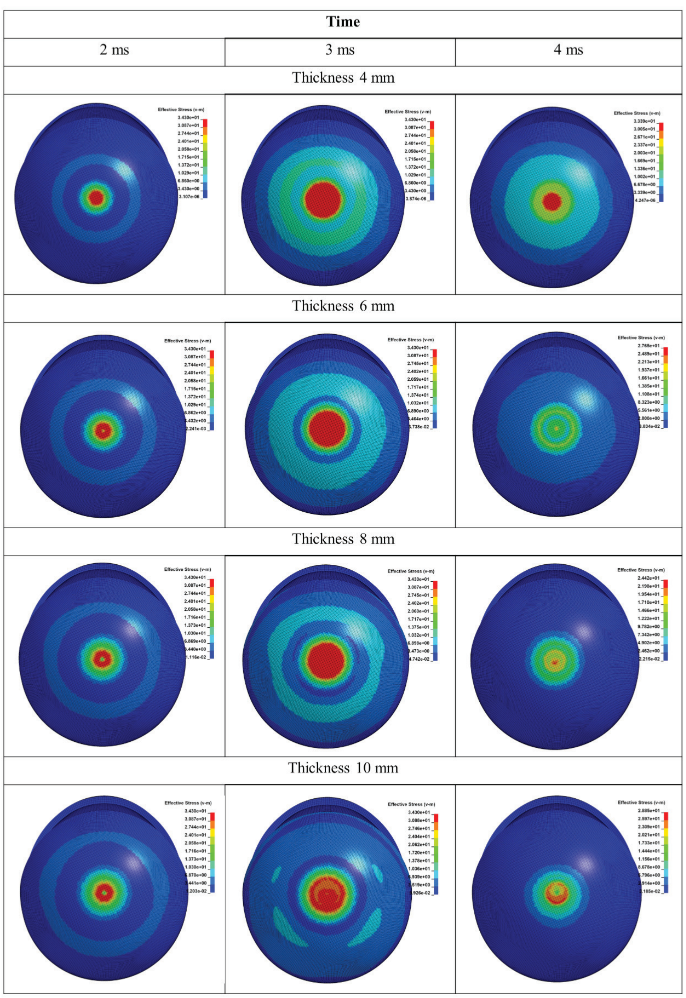

Figure 5. Stresses obtained during the impact to the shell helmet with the steel block

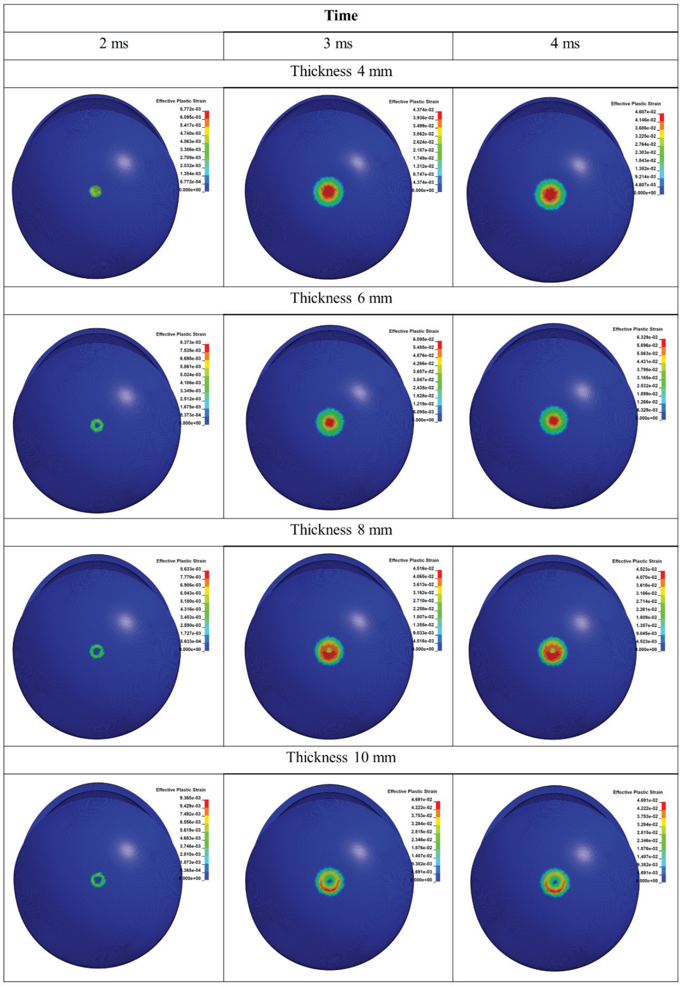

Figure 6. Strain obtained during the impact to the shell helmet with the steel block

In the same way, Figure 6 displays the strain caused by the various shell thickness.

Figure 6 shows that at 2 ms, strain begin to appear, increasing with the thickening of the shell, reaching a value of 0.009365 for a thickness of 10 mm. At 3 ms, with a thickness of 4 mm, a strain of 0.04374 is observed; when increased to 6 mm, the strain rises to 0.06095. However, the area of maximum strain decreases. For thicknesses of 8 mm and 10 mm, the strain obtained are 0.0451 and 0.04691, respectively, with the trend of decreasing maximum strain areas as the thickness increases. At 4 ms, the maximum strain is recorded, which remains constant throughout the 20 ms duration of the simulation. The strain observed are 0.0467 for 4 mm, 0.06329 for 6 mm, 0.04523 for 8 mm, and 0.04691 for 10 mm, following the same pattern of reduction in the areas of maximum strain.

Using the maximum values of stress and strain recorded every half millisecond during the 20 ms simulation, stress-strain graphs were generated to describe the behavior of each of the analyzed shell thicknesses (Figure 7).

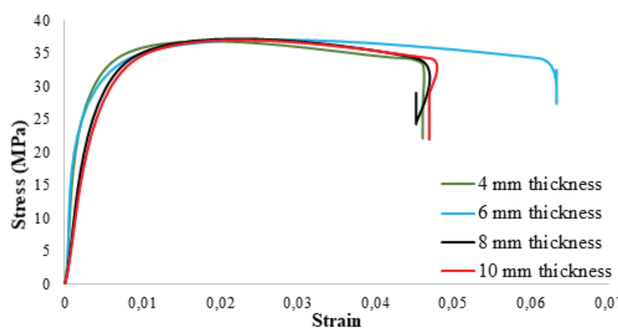

Figure 7. Stress-strain graphs

As shown in Figure 7, the stress-strain graphs for all analyzed thicknesses remain below the yield strength of ABS, thus staying within the elastic region. The strain varies around 0.046, except for the 6 mm thickness, where an increase to 0.063 is observed.

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An important parameter to consider is the internal energy of the helmet shell, as a higher internal energy value indicates a greater capacity of the helmet to absorb impact, thereby reducing the transmission of energy to the skull and, consequently, decreasing the risk of injury. Figure 8 shows a comparison of the internal energy for each of the analyzed helmet shells.

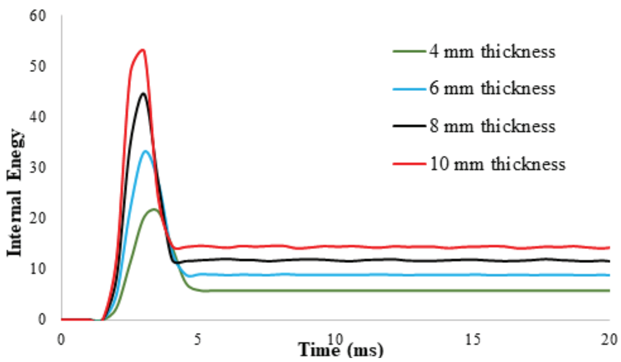

Figure 8. Internal energy of the helmet shells

The values presented in Figure 8 indicate that, although the amount of energy absorbed by the helmet increases with increasing thickness, the rate of increase shows a decreasing trend. Specifically, the helmet absorbs an additional 11.6 J when increasing the thickness from 2 to 4 mm, 11.4 J when increasing from 4 to 6 mm, and 8.35 J when increasing from 8 to 10 mm.

The boundary conditions shown in Figure 4 were modified by reducing the distance between the block and the top of the helmet shell from 10 mm to 0.2 mm and increasing the initial velocity from 5.972 mm/ms to 7.5 mm/ms. The analysis was conducted with a casing thickness of 4 mm. At 0.5 ms, the stresses began at a value of 34.3 MPa, reaching a maximum stress, while the strain started at 0.001723. At 3 ms, the maximum strain was observed at a value of 0.0551, at which point the stresses began to decrease, measuring 33.9 MPa (Figure 9).

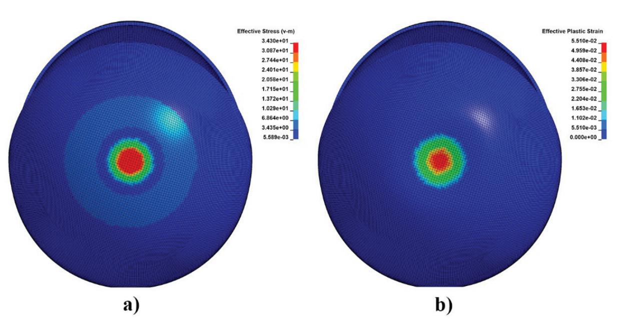

Figure 9. Maximum values: a) stress at 0.5 ms, b) strain at 3 ms

Based on the maximum values obtained for stress and strain every millisecond during the simulation, a graph was created comparing the 4 mm shells. This comparison shows that, in both analyses, the yield strength of 34.3 MPa is reached. However, a change in the slope inclination is evident: it decreases with an increase in velocity, resulting in a strain increase from 0.046 to 0.055.

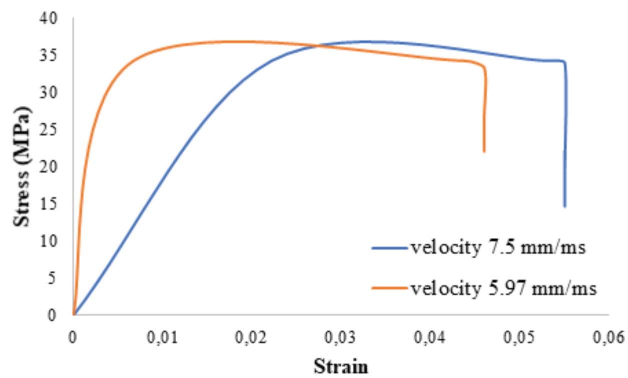

Figure 10. Maximum values: a) stress at 0.5 ms, b) strain at 3 ms

To validate the results, a comparison was made with the simulation carried out by Pinnoji *et al.* (2010) in which the same mechanical properties of ABS were used, a shell thickness of 4 mm and a speed of 7.5 mm/ms. Table 1 presents the results obtained in this research in relation to those reported by Pinnoji *et al.* (2010). This comparison allows to verify the consistency of the findings and to highlight the validity of the model used.

Table 1. Comparative of performance parameters helmet 4 mm shell at 7.5 mm/ms

Helmet	Equivalent plastic strain in shell	Effective stress in shell (Mpa)	Internal energy in shell before rebound (J)
By Pinnoji	0.04	34.3	30.5
This research	0.05	34.3	29.7

Conclusions

As the shell thickness is reduced, the helmet becomes lighter, which improves comfort for the wearer; however, this leads to greater deformations and a lower energy dissipation capacity in the event of an impact. In contrast, greater thickness provides better protection, although excessive thickness can be uncomfortable during prolonged use and even lead to neck injuries.

The results indicate that, as the helmet thickness increases, the amount of energy absorbed continues to increase, but the rate of increase tends to slow down. The smallest variation in absorbed energy occurs when increasing from 8 to 10 mm. From a design and efficiency perspective, it is not advisable to continue increasing helmet thickness beyond 8 mm, as the improvements in energy absorption become less and less significant. This suggests that a thickness of 8 mm may offer an optimal balance between energy absorption and efficiency in terms of material and weight.

References

Agrawal, V., Kumrawat, R., Sheikh, R., & Jain, S. (2018). Safety assessment of motorcycle helmet using finite element analysis. *International Journal of Computational Research and Development*, 3(1), 174-181.

Chang, C. H., Chang, L. T., Chang, G. L., Huang, S. C., & Wang, C. H. (2000). Head injury in facial impact a finite element analysis of helmet chin bar performance. *J. Biomech. Eng.*, 122(6), 640-646. https://doi.org/10.1115/1.1318905

DOF-Diario Oficial de la Federación. (2018). Gob.mx. Retrieved on February 2023 https://dof.gob.mx/nota_detalle.php?codigo=5524337&fecha=29/05/2018

Hibberler, R. C. (2006). *Mecánica de materiales*. 6th ed. México: Pearson Educación. 894 p.

Jacob, A., Faria, C., Cardoso, G., Reis, K., Motta, M., Meneghetti, T., & Shibli, A. (2016). Evaluation of helmet protection during impact of head to ground and impact of an object to head using finite element analysis. *Journal of Safety Engineering*, 5(1), 8-16. http://10.5923/j.safety.20160501.02

Kardamanidis, K., Martiniuk, A., Ivers, R. Q., Stevenson, M. R., & Thistlethwaite, K. (2010). Motorcycle rider training for the prevention of road traffic crashes. *Cochrane Database of Systematic Reviews*, 10, CD005240. https://doi.org/10.1002/14651858.CD005240.pub2

Kholoosi, F., & Galehdari, S. A. (2019). Design, optimisation and analysis of a helmet made with graded honeycomb structure under impact load. *International Journal of Crashworthiness*. https://doi.org/10.1080/13588265.2018.1506605

Kostopoulos, V., Markopoulos, Y. P., Giannopoulos, G., & Vlachos, D. E. (2002). Finite element analysis of impact damage response of composite motorcycle safety helmets. Composites Part B. *Engineering*, 33(2), 99-107. https://doi.org/10.1016/S1359-8368(01)00066-X

Liu, B. C., Ivers, R., Norton, R., Boufous, S., Blows, S., & Lo, S. K. (2008). Helmets for preventing injury in motorcycle riders. *Cochrane Database of Systematic Reviews*, 1, CD004333. https://doi.org/10.1002/14651858.CD004333.pub3

Naidu, A. L., & Rao, P. R. (2021). Structural analysis of hybrid reinforced composite for industrial safety helmet. *Journal of Cardiovascular Disease Research*, 12(3), 1558-1562.

Newman, J. (2005). The biomechanics of head trauma and the development of the modern helmet. How far have we really come. In Proceedings of the IRCOBI Conference, 10.

Pinnoji, P. K., Mahajan, P., Bourdet, N., Deck, C., & Willinger, R. (2010). Impact dynamics of metal foam shells for motorcycle helmets: Experiments & numerical modeling. *International Journal of Impact Engineering*, 37(3), 274-284. https://doi.org/10.1016/j.ijimpeng.2009.05.013

Sadaq, S., JunaidiMdA, R., *et al.* (2014) Impact test on motor cycle helmet for different impact angles using FEA. *International Journal of Engineering Trends and Technology*, 12 (6), 278-281. http://dx.doi.org/10.14445/22315381/IJETT-V12P254

Shankar, S., Nithyaprakash, R., Praveen, S., Kumar, S. S., & Sriram, A. M. (2021). Analysis of motor cycle helmet under static and dynamic conditions considering different materials. *Materials Today: Proceedings*, 43, 1098-1102. https://doi.org/10.1016/j.matpr.2020.08.327

Shuaeib, F. M., Hamouda, A. M. S., Hamdan, M. M., Umar, R. R., & Hashmi, M. S. J. (2002). Motorcycle helmet: Part II. Materials and design issues. *Journal of Materials Processing Technology*, 123(3), 422-431. https://doi.org/10.1016/S0924-0136(02)00047-X

Tabary, M., Ahmadi, S., Amirzade, M. H., Shojaei, M., Asl, M. S., Ghodsi, Z., & Rahimi, V. (2021). The effectiveness of different types of motorcycle helmets-A scoping review. *Accident Analysis & Prevention*, 154, 106065. https://doi.org/10.1016/j.aap.2021.106065

Thomas A., Suresh, P., Jafrin-Thilak, A., Subramani, N. (2017) Impact analysis on composite helmet by using FRC and Glass

Fiber by using ANSYS. *International Research Journal of Engineering and Technology*, 4(3), 1629-1634.

Tippens, P. (2000). *Física-Conceptos y Aplicación*. 5b Ed. McGraw-Hill Companies.

Totla, S. K., Pillai, A. M., Chetan, M., Warad, C., Vinodkumar, S. K., Patil, A. Y., & Kotturshettar, B. B. (2020). Analysis of helmet with coconut shell as the outer layer. *Materials Today: Proceedings*, 32, 365-373. https://doi.org/10.1016/j.matpr.2020.02.047

Yu, W. Y., Chen, C. Y., Chiu, W. T., & Lin, M. R. (2011). Effectiveness of different types of motorcycle helmets and effects of their improper use on head injuries. *International Journal of Epidemiology*, 40(3), 794-803. https://doi.org/10.1093/ije/dyr040

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