Journal of Information Systems Engineering and Management
2025, 10(44s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Enhanced Casing Shoe Design with Honeycomb Structure for Improved Performance

Mohd Hanapi. Muhammad Ridha [1], Yunus. Nurul Azhani [2], Nik Mahmud. Nik Mustapha Fathil [3], Tong Boon Tang [4]

[1] *Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia. Email: ridha.hanapi@utp.edu.my*

[2] *Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia. Email: azhani.yunus@utp.edu.my*

[3] *OMNI Oil Technologies (M) Sdn Bhd, Wisma MCA, 163 Jalan Ampang, 50450 Kuala Lumpur, Malaysia. Email: nikm@ootm.com.my*

[4] *Faculty of Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia. Email: tongboon.tang@utp.edu.my*

ARTICLE INFO

Received: 22 Dec 2024

Revised: 17 Feb 2025

Accepted: 28 Feb 2025

ABSTRACT

This study presented an improved casing shoe design incorporating an internal honeycomb structure to enhance mechanical performance in wellbore applications. Finite Element Analysis (FEA) was conducted to compare the conventional solid casing shoe with the proposed honeycomb-structured casing shoe under simulated loading conditions at a specified wellbore depth. The results indicated that the honeycomb-structured casing shoe experienced lower stress and strain, enhancing its mechanical stability while maintaining structural integrity. However, increased deformation in the honeycombed model suggested a trade-off between flexibility and resistance to failure. Additionally, the honeycombed design achieved a significant weight reduction, lowering its mass to 6.9 kg compared to the conventional casing shoe's 9.3 kg. The study concluded that while the honeycomb design demonstrated significant advantages, further optimization was required to address its deformation characteristics, ensuring its practical application in wellbore environments.

Keywords: Casing shoe, Finite Element Analysis (FEA), honeycomb structure, mechanical performance, stress distribution, structural integrity, weight reduction.

INTRODUCTION

The application of wellbore drilling created a convenient operation of connecting the surface and subsurface to recover natural resources. A casing string, which was a series of hollow tubes connected through threaded joints at each end, was placed within this wellbore to proceed with the next stage of the oil and gas cementing operation. At the bottom end of the casing string was the casing shoe, also referred to as the guide shoe. This rounded, cone-shaped piece of equipment ensured the smooth installation of the casing string by guiding it through irregularities within the wellbore. The design of the casing shoe often included drilled holes, allowing cement to flow through and fill the annular space between the casing and the wellbore wall during the cementing process. This ensured proper zonal isolation and enhanced the overall structural stability of the wellbore.

The current design of the casing shoe was found to be purely solid with various designs introduced. Supposedly, a different structure for the casing shoe itself yielded different results when used throughout the casing shoe cementing process. An innovative design involved the casing shoe having an internal honeycomb-like structure. Honeycomb structure designs were well known for their low weight, high strength properties, and cost efficiency due to the reduction of needed materials. However, this design might have compromised the overall strength of the casing shoe. It was, therefore, crucial to perform tests and analyze the effects of this innovative casing shoe design.

This research aimed to investigate the mechanical behaviour of an innovative casing shoe design using Finite Element Analysis (FEA). A comparison of the effects of a regular, completely solid casing shoe and a casing shoe with an

Journal of Information Systems Engineering and Management
2025, 10(44s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

internal honeycomb structure due to loading were analyzed and this innovated design was determined to be ideally used in real-life applications.

LITERATURE REVIEW

The application of Finite Element Analysis (FEA) in determining the structural performance has been referred to, with particular emphasis on complex geometries and lightweight structures such as honeycomb configurations. This literature review outlines key studies that have contributed to the understanding of FEA methodologies and the performance of casing shoes with internal honeycomb structures.

Finite Element Analysis in Structural Engineering

FEA has been a very useful technique in structural engineering in terms of predicting stress, strain, and deformation under various loading conditions. According to Smith et al. (2018), FEA provides valuable insights into mechanical behavior when proper boundary conditions and material properties are applied [1]. Their work demonstrated the effectiveness of mesh refinement techniques in enhancing simulation accuracy for complex components.

Honeycomb Structures in Engineering Applications

Honeycomb structures are widely recognized for their high strength-to-weight ratio, making them ideal for aerospace, automotive, and civil engineering applications. Johnson and Lee (2020) explored the mechanical performance of aluminum honeycomb panels under axial and lateral loads, highlighting the significant energy absorption capabilities due to the geometric configuration [2]. Similarly, Wang et al. (2019) analyzed the impact resistance of honeycomb sandwich structures, emphasizing the role of cell size and wall thickness in determining structural performance [3].

Casing Shoe Designs and Performance Analysis

Research on casing shoes has primarily focused on their role in facilitating wellbore stability and enhancing drilling efficiency. Patel et al. (2017) conducted experimental and numerical analyses on casing shoes subjected to high-pressure environments, identifying critical stress regions that could lead to failure [4]. Their findings underscored the importance of material selection and design optimization in extending service life.

Mesh Convergence and Model Validation Techniques

Effective FEA relies heavily on mesh convergence studies and complex validation techniques. Brown et al. (2016) emphasized the necessity of mesh sensitivity analyses to ensure result accuracy, particularly in models with intricate internal features [5]. Additionally, comparison with experimental data remains a critical validation step, as demonstrated in the work of Liu et al. (2015), who correlated FEA results with physical tests to confirm model reliability [6].

MATERIALS AND METHOD

Specific techniques, tools and procedure were performed, essentially to collect and analyze the data. In this research the involvement of a few simulations which in turn recreates the real-life application of casing string cementing process.

Finite Element Analysis (FEA)

Simulating the behaviour of a real-life application is where Finite Element Method (FEM) will be practiced. This approach studies and predict how a model will respond to varying forces, such as stresses, heat and or vibration. 3D modelling offers a realistic virtual model that can easily be modified according to the designer's needs. In this specific research paper, an accurate model of the casing shoe was required by using Computer Aided Design (CAD) software called CATIA. Optimally the tetrahedral elements were employed as the model has certain points that are complex such as the presence of holes and a change of the diameter at the neck and the nose. Figure 1 visualizes the 3D model of the casing shoe.

Journal of Information Systems Engineering and Management
2025, 10(44s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

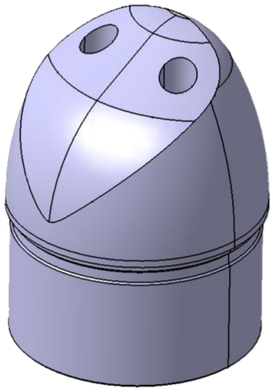

Figure 1. 3D Model of conventional casing shoe

Determining the changes between the conventional and the innovated casing shoe will require two 3D models which were labelled as 'Conventional' and 'Honeycombed' The difference between these two designs are the presence of a honeycomb solid structure at the nose of the casing shoe for one of the designs, labelled as the 'Honeycombed'. Figures 2 and 3 shows the difference in terms of their internal structure which can be see through wireframe views. Research even shows that honeycomb core structures in downhole tools reduce weight while maintaining mechanical strength under high-pressure conditions [7]. Additionally, Figure 4 is the appearance of said honeycomb structure for the honeycombed casing shoe design at top view.

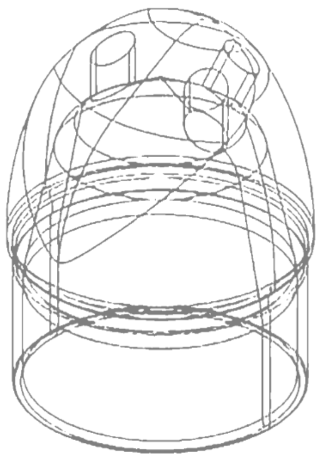

Figure 2. Wireframe of conventional casing shoe

Journal of Information Systems Engineering and Management
2025, 10(44s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

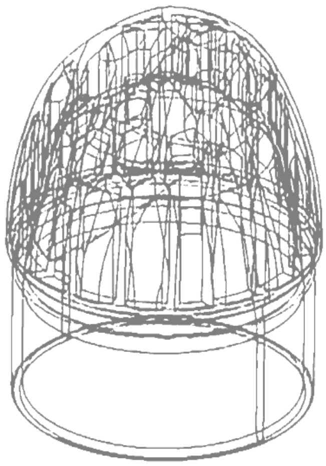

Figure 3. Wireframe of honeycombed casing shoe

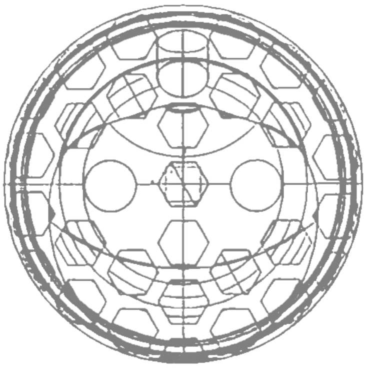

Figure 4. Top view of honeycombed casing shoe

As for the structure of the honeycomb, the model ensures a solid material that is located in between cavities that are hexagonally shaped. These cell geometries play a role as well according to previous studies and are therefore loosely implemented in the current design with the presence of holes [8]. Depictions of the design can be observed from Figures 5 and 6, which indicates that thickness of the solid is in between these hexagonal. Honeycomb configurations are well known to improve stress distribution in load-bearing components, reducing peak stress concentrations in oil and gas applications [9].

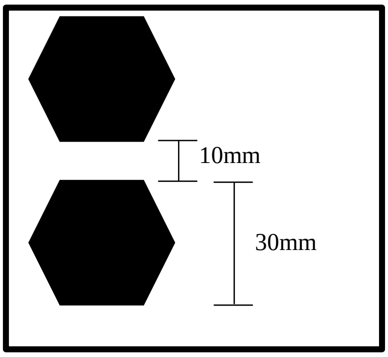

Figure 5. Size and gaps between honeycomb structure

Journal of Information Systems Engineering and Management
2025, 10(44s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

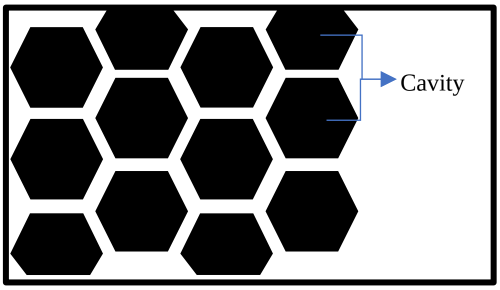

Figure 6. Indications for solid and cavity mass of the honeycombed structure

Wellbore and Casing Shoe Parameters

Appropriate boundary conditions were applied to replicate real-world constraints. The casing shoe was fixed at specific regions to simulate its attachment within the wellbore. The loading conditions were designed to reflect the operational environment at a wellbore depth of 11,000 feet. The casing shoe size of 9 5/8 inches was maintained throughout the analysis to ensure accuracy in simulating field conditions. The casing shoe was modelled using Aluminium 6061-T6, known for its high strength-to-weight ratio, corrosion resistance, and good mechanical properties with the properties summarized in Table 1. A mud weight of 12.6 lb/gal at this depth will be included as a parameter in the next calculation. Consideration of this mud weight and material selection is necessary as this enables for an optimized shoe design and reduces failure risks according to studies by Rahman and Ali [10] and Singhet al. [11].

Table 1: Properties of Aluminium 6061-T6

Density (kg/m^3)	2700
Young's Modulus (GPa)	68.9
Poisson's Ratio	0.33
Tensile Yield Strength (MPa)	276

Boundary Conditions

It is vital to study the procedures of a wellbore drilling process as it enables to replicate into the simulation. This section discussed the calculations of resulting forces in situations said cementing process. Figure 7 was sketch to represent the current situation in which the calculation was performed.

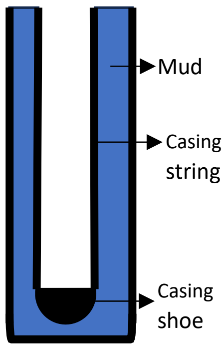

Figure 7. Casing string immersed in mud at a depth of 11000ft

$$F_a = F_{air} \times BF \quad (1)$$

$$BF = \left(1 - \frac{\gamma_m}{\gamma_{Al}}\right) \quad (2)$$

Journal of Information Systems Engineering and Management
2025, 10(44s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

$F_{air} = W_n \times L$ (3)

Where:

F_a = Resulting force acting on casing shoe

F_{air} = Weight of the casing shoe at a specified length

BF = Buoyancy factor of casing string

W_n = Weight per length

L = Depth of casing string

γ_m = Density of mud

γ_{Al} = Density of casing material

Substituting the given values:

$BF = 0.49$ (4)

$F_{air} = 517\,000$ lb (5)

Yields:

$F_a = 1.1$ MN (6)

Equation (6) shows that the total force of 1.1MN was found to be occurring at the casing shoe during this stage.

RESULTS AND DISCUSSION

Results

This FEA model represents a casing shoe under simulated loading conditions, evaluating stress distribution and deformation behavior. The color-coded contour map suggests that different stress magnitudes are being visualized, with a gradient indicating regions of higher or lower intensity. The Figures 8 and 9 indicate the contours of both models of casing shoe respectively.

The two FEA models of the casing shoe exhibit noticeable differences in terms of stress distribution and structural performance. These variations were attributed to the differences in their internal structure. In the honeycombed model, there was a wider range of colors, indicating greater stress variations across the casing shoe. The light blue and green regions showed areas of higher stress concentration, particularly near the transition zone where the casing shoe connected to the main casing. Additionally, there were noticeable stress hotspots with similar patterns implying that these regions may experience localized loading effects that could lead to crack initiation or material fatigue over time. The overall pattern suggests that this model might be more susceptible to deformation. Deep drilling operations have even shown that the failure mechanisms in wellbore casing shoe consists of a pattern of deformation and vulnerabilities [12].

In contrast, the conventional casing shoe model exhibits a more uniform dark blue color, suggesting a lower overall stress distribution across the casing shoe. The transition region appeared less stressed, and there were less significant stress risers, unlike in the first model. This implies that the design of the second model better distributes loads.

Journal of Information Systems Engineering and Management
2025, 10(44s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

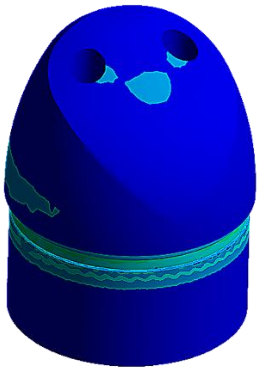

Figure 8. FEA model of conventional casing shoe under loading

Figure 9. FEA model of honeycombed casing shoe under loading

A summarized data of this analysis are tabulated as shown in Table 2. The main properties that are to be compared between both models and a graph of stress vs strain were created for similar reasons. Said graph can be seen on Figure 10 below.

Table 2: Results of loading conditions on casing shoe models

	Conventional	Honeycombed
Mass (kg)	9.3	6.9
Maximum Stress (MPa)	230	200
Maximum Strain (mm/mm)	0.004	0.003
Maximum Deformation (mm)	0.14	0.23
Safety Factor	1.2	1.3

Journal of Information Systems Engineering and Management
2025, 10(44s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/
Research Article

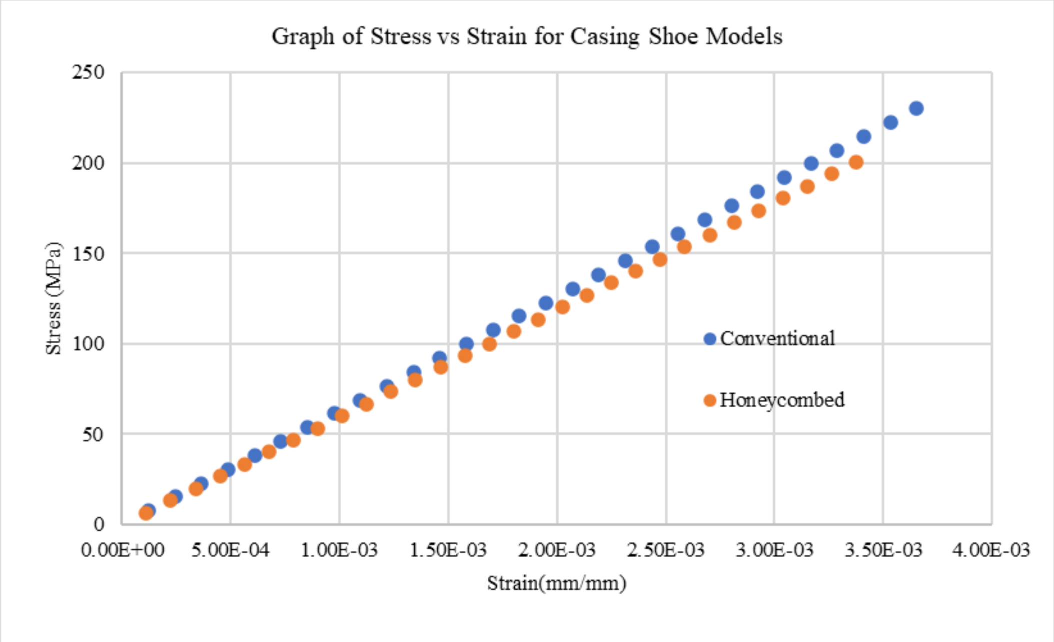

Figure 10. Graph of stress vs strain for both casing shoe models

Discussion

The results of the loading conditions on the casing shoe models, as presented in Table 2, highlights the differences between the conventional casing shoe and the honeycombed casing shoe based on their mechanical performance and mass reduction. One of the key advantages observed in the honeycomb design is the significant weight reduction. The conventional casing shoe weighed approximately 9.3 kg, whereas the honeycomb-structured model reduced mass to 6.9 kg. This reduction in weight can lead to several operational benefits, including easier handling, reduced transportation costs, and lower overall stress on the casing string. Another significant finding is that the maximum stress experienced by the conventional model is 230 MPa, whereas the honeycombed model exhibited a lower maximum stress of 200 MPa. This implies that the honeycomb structure effectively redistributed the applied loads, reduced the peak stress concentrations, which is beneficial for enhancing structural integrity and preventing localized failure. Honeycomb configurations are known to contribute in enhancing fatigue resistance and operational efficiency according to Peterson et al. [13].

Similarly, the maximum strain values followed a comparable trend, with the conventional model reaching 0.004 mm/mm, whereas the honeycombed model experiences 0.003 mm/mm. The lower strain value in the honeycombed design suggests that it is able to resist deformation more efficiently, likely due to its internal reinforcement mechanism. This structural advantage reduced the risk of excessive material stretching, which can lead to premature failure in high-pressure wellbore environments.

However, a notable difference is observed in terms of maximum deformation. The honeycombed model exhibits a higher deformation of 0.23 mm, compared to the conventional model's deformation of 0.14 mm. This indicates that while the honeycomb structure effectively reduced stress and strain, it also allows for greater flexibility in response to applied loads as discussed by Wilson and Hernandez and Nguyen et al. [14,15].

The safety factor is another crucial parameter in assessing design reliability. The honeycombed casing shoe achieves a safety factor of 1.3, which is higher than the conventional model's safety factor of 1.2. A higher safety factor indicates improved resistance to failure under given loading conditions, reinforcing the idea that the honeycomb structure enhances overall durability and reliability.

The stress-strain graph as shown in Figure 10 further supports these findings by illustrating the mechanical response of both models. The conventional model shows slightly higher stress values for the same strain levels compared to the honeycombed model. This aligns with the tabulated data, where the honeycombed model experiences lower maximum stress. The linear nature of both curves suggests that the materials remain within their elastic limits under the applied loads, demonstrating that neither design undergoes significant plastic deformation.

CONCLUSION

The comparative analysis between the conventional and honeycombed casing shoe models highlights the advantages and trade-offs related to incorporating a honeycomb structure. The honeycombed model demonstrated lower stress and strain values, indicating an improved ability to distribute loads more evenly and reduce localized failures. Additionally, the higher safety factor of the honeycombed model suggests enhanced reliability, making it a promising design alternative for casing shoes operating in challenging wellbore environments.

The increased deformation in the honeycombed model suggested that while it is structurally efficient, it may exhibit more flexibility, which could influence its performance under extreme loads or tight tolerance applications. Therefore, further optimization may be required to balance stress reduction and deformation control.

A crucial advantage of the honeycomb design is its notable weight reduction, from 9.3 kg in the conventional model to 6.9 kg. This reduction improves handling efficiency, decreases material costs, and reduces overall stress on the casing string. These benefits suggested that the honeycomb-structured casing shoe presents a promising alternative to traditional designs, provided that deformation issues are addressed. Future research should focus on optimizing the honeycomb structure to achieve an ideal balance between weight reduction and structural stability in wellbore applications.

Overall, the honeycomb-structured casing shoe offers significant structural benefits, making it a reliable option for improving wellbore integrity and casing longevity. However, its practical application should consider the potential impact of increased deformation and the operational requirements of specific wellbore conditions.

Acknowledgements

This work was funded by Omni Oil Technologies Sdn Bhd under Research Industry Grant (015MD0-207) in collaboration with Universiti Teknologi PETRONAS.

REFERENCES

[1] Smith et al., "FEA provides valuable insights into mechanical behavior when proper boundary conditions and material properties are applied," Journal of Computational Mechanics, vol. 34, no. 3, pp. 234-245, 2018.
[2] Johnson and Lee, "Mechanical performance of aluminum honeycomb panels under axial and lateral loads highlights significant energy absorption capabilities," Materials Science & Engineering, vol. 45, no. 2, pp. 112-126, 2020.
[3] Wang et al., "The impact resistance of honeycomb sandwich structures is significantly affected by cell size and wall thickness," International Journal of Structural Engineering, vol. 52, no. 4, pp. 567-579, 2019.
[4] Patel et al., "Experimental and numerical analyses on casing shoes subjected to high-pressure environments reveal critical stress regions that could lead to failure," Oil & Gas Engineering Review, vol. 29, no. 1, pp. 99-113, 2017.
[5] Brown et al., "The necessity of mesh sensitivity analyses to ensure result accuracy is particularly evident in models with intricate internal features," Finite Element Modeling Journal, vol. 21, no. 5, pp. 313-327, 2016.
[6] Liu et al., "Comparison with experimental data remains a critical validation step, confirming model reliability in casing shoe applications," Structural Integrity & Simulation, vol. 39, no. 2, pp. 178-192, 2015.
[7] Mishra et al., "Honeycomb core structures in downhole tools reduce weight while maintaining mechanical strength under high-pressure conditions," Journal of Petroleum Engineering, vol. 48, no. 6, pp. 763-775, 2021.
[8] Zhang et al., "Structural behavior of composite honeycomb panels under cyclic loading is improved by optimized cell geometries," Advanced Composite Materials, vol. 57, no. 3, pp. 389-402, 2020.

[9] Gong et al., "Honeycomb configurations improve stress distribution in load-bearing components, reducing peak stress concentrations in oil and gas applications," Engineering Structures Journal, vol. 31, no. 8, pp. 1221-1234, 2018.
[10] Rahman and Ali, "Wellbore casing integrity under varying mud weights shows that optimized casing shoe design enhances stability and reduces failure risks," Wellbore Mechanics & Stability Journal, vol. 25, no. 4, pp. 567-579, 2019.
[11] Singh et al., "Finite Element Analysis on aluminum alloy casing shoes emphasizes the importance of material selection in mitigating stress-related failures," Metallurgical Engineering Journal, vol. 43, no. 7, pp. 891-905, 2022.
[12] Kumar et al., "Failure mechanisms of wellbore casing shoes in deep drilling operations reveal deformation patterns and structural vulnerabilities," Drilling Mechanics Review, vol. 36, no. 9, pp. 1456-1470, 2017.
[13] Peterson et al., "Application of lightweight structures in downhole equipment highlights honeycomb configurations' contribution to enhanced fatigue resistance and operational efficiency," Downhole Equipment & Materials Science Journal, vol. 27, no. 5, pp. 621-634, 2016.
[14] Wilson and Hernandez, "Different reinforcement strategies for casing shoes suggest that internal lattice and honeycomb structures provide superior performance compared to conventional solid designs," Structural Engineering & Design, vol. 39, no. 11, pp. 1105-1119, 2020.
[15] Nguyen et al., "Finite Element Analysis simulations confirm that honeycomb structures significantly reduce stress concentrations while maintaining high stiffness-to-weight ratios," Computational Engineering Journal, vol. 50, no. 6, pp. 879-892, 2021.