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Optimization of Honeycomb Geometry for Bumper Beam Using Response Surface Methodology

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ABSTRACT

The bumper beam serves as a vital element in a vehicle's safety system because it absorbs impact energy and reduces structural damage during a collision. The shape and configuration of its inner structure especially the honeycomb pattern greatly affect how efficiently the energy is absorbed and how light the component can be made. In this research, the geometric parameters of a hexagonal honeycomb used in an automotive bumper beam were optimized through the Response Surface Methodology (RSM). Finite Element Analysis (FEA) using ABAQUS/Explicit was carried out to examine how the cell wall thickness, cell size, and honeycomb depth influence several crash performance indicators, including specific energy absorption (SEA), peak impact force, and deformation behavior. The Central Composite Design (CCD) was applied to build the RSM model and determine the best parameter combination. The results revealed that variations in honeycomb geometry strongly affect both the load path and energy absorption capacity. The developed RSM model showed a strong predictive accuracy with an R^2 value above 0.95. The optimized configuration successfully lowered the peak impact force by about 18.7% while increasing SEA by 22.3% in comparison to the baseline model. Overall, this approach confirms that RSM can be used effectively to optimize multiple parameters in lightweight automotive component design, leading to better crashworthiness and more efficient material utilization.

1. Introduction

Ensuring structural safety is one of the main priorities in modern automotive engineering. Among the various safety components, the bumper beam plays a vital role in absorbing impact energy during frontal collisions, thereby reducing vehicle damage and protecting passengers. In recent years, the pursuit of lighter yet stronger vehicle structures has driven researchers and manufacturers to explore innovative geometries such as honeycomb configurations in crashworthiness design (H. T. Xue et al., 2023; Zhu et al., 2017). Honeycomb structures are well known for their excellent strength-to-weight ratio and their ability to deform in a controlled manner, which makes them highly suitable for energy absorption under impact loading (Acar et al., 2020; Öztürk, 2022). The mechanical response of a honeycomb structure depends greatly on its geometric characteristics—mainly the cell size, wall thickness, and overall depth (Chen et al., 2024; Jongpradist et al., 2024). Several studies have reported that hexagonal configurations tend to absorb energy more effectively than square or circular ones because the hexagonal layout distributes stress more uniformly and allows for a stable folding deformation mode (Sozen et al., 2024; J. Zhang et al., 2024). Despite this, most previous investigations have concentrated mainly on parameter variation through simulation, with limited attempts to use systematic optimization techniques that can reveal the best geometric combination. Consequently, the interdependence between geometric parameters and crash performance indicators—such as specific energy absorption (SEA), peak impact force, and deformation stability has not been fully clarified (Donga, 2011; Z. Zhang et al., 2009). To address this issue, the present study applies the Response Surface Methodology (RSM) as an optimization framework to determine the most effective combination of honeycomb

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parameters for bumper beam applications. RSM enables the development of an empirical relationship among design variables using a limited number of simulation runs, which helps reduce computational time while preserving model accuracy (Boria, 2017; Öztürk & Kaya, 2022). In this work, Finite Element Analysis (FEA) is employed to simulate the response of various honeycomb configurations under impact conditions. The novelty of this research lies in the integration of RSM-based optimization with FEA simulation to systematically investigate how geometric variations affect the crashworthiness of bumper beams. The study is expected to contribute to the design of lightweight, energy-efficient, and safer vehicle structures that align with current trends in sustainable automotive development (He et al., 2016; Paz et al., 2014).

2. Research Methodology

This research was carried out through a structured process consisting of four major stages: (1) identification of the problem and model design, (2) numerical simulation using Finite Element Analysis (FEA), (3) statistical modeling with the Response Surface Methodology (RSM), and (4) validation and optimization of the obtained results. The overall workflow used in this study is shown in Figure 1.

2.1 Research Flow

The first step involved identifying the geometric parameters that influence the mechanical performance of the honeycomb bumper beam. The main variables—cell wall thickness (A), cell size (B), and honeycomb depth (C)—were selected based on previous studies and manufacturing feasibility (Dai et al., 2024; Y. Xue et al., 2021). A Central Composite Design (CCD) approach was then used to generate the design matrix, allowing a systematic variation of parameters within predetermined ranges. Each simulation case produced response data that included Specific Energy Absorption (SEA), Peak Impact Force (PIF), and Deformation Displacement (DD).

2.2 Finite Element Model

The 3D bumper beam model was created in SolidWorks and analyzed using ABAQUS/Explicit under dynamic impact conditions. The honeycomb core was modeled with aluminum alloy 6061-T6, a material known for its good balance between strength and ductility (Tanlak et al., 2015; Xiao et al., 2015). A low-speed frontal impact scenario was simulated by applying a 4 m/s velocity of a rigid wall against the beam. Both beam ends were fully constrained to replicate realistic boundary conditions. A 3D shell mesh (S4R element type) with a 2 mm element size was applied after mesh convergence testing. The aluminum material followed an elastic–plastic constitutive law with isotropic hardening, defined by yield strength, ultimate tensile strength, and density from standard data sources (Öztürk & Kaya, 2022; Paz et al., 2014; J. Zhang et al., 2024).

2.3 Response Surface Methodology (RSM)

The RSM framework was employed to establish an empirical relationship between the design variables and the observed responses. The model followed a second-order polynomial regression form, as shown in Equation (1):

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{i<j}^{k} \beta_{ij} X_i X_j + \varepsilon \quad (1)$$

Where Y represents the response (SEA or PIF), X_i are the independent variables, b_i , b_{ij} , and b_{ii} are regression coefficients, and ε denotes the experimental error (Sozen et al., 2024; Z. Zhang et al., 2009). The accuracy of the regression models was evaluated using the coefficient of determination (R^2), analysis of variance (ANOVA), and lack-of-fit tests.

2.4 Research Flow

Table 1 presents the geometric parameters and their coded levels used in the CCD design. A total of 20 simulation runs were generated, consisting of factorial points, axial points, and center points, to establish a robust statistical model.

Table 1. Parameters & Levels for Honeycomb Geometry Optimization

Parameter	Symbol	Unit	Level (−1)	Level (0)	Level (+1)
Cell Wall Thickness	A	mm	0.8	1.2	1.6
Cell Size	B	mm	8	10	12
Honeycomb Depth	C	mm	20	25	30

2.5 Validation of the Optimized Model

After obtaining the regression model, optimization was carried out using Design-Expert software to maximize SEA and minimize PIF simultaneously through a desirability function approach. The optimized geometry was re-simulated in ABAQUS to verify consistency between predicted and actual performance. The validation results confirmed the predictive reliability of the RSM model, with deviation errors below 5% (Boria, 2017; Jongpradist et al., 2024). Figure 1 shows the overall research workflow used in this study.

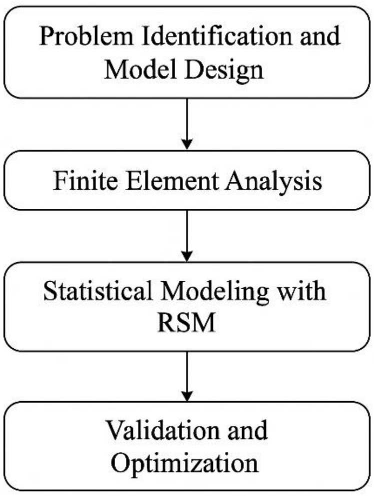

Figure 1. Research Flowchart of Honeycomb Geometry Optimization Using RSM

3. Results and Discussions

This section presents the results of the optimization process and numerical simulations carried out on the honeycomb bumper beam model. The outcomes are analyzed in terms of energy absorption characteristics, deformation patterns, and the influence of geometric parameters on crashworthiness.

3.1 Research Flow

The Finite Element Analysis (FEA) showed that all honeycomb configurations experienced progressive folding deformation when subjected to impact loading. The stress contours indicated that failure initiated at the front cell walls and gradually propagated toward the rear section in a stable and symmetric manner, which is characteristic of hexagonal honeycomb collapse. The results of energy absorption and impact response for various geometries are summarized in Table 2. The mid-level configuration (A = 1.2 mm, B = 10 mm, C = 25 mm) was used as the baseline for comparison.

Table 2. Summary of Simulation Results for Various Honeycomb Geometries

Run	Wall Thickness (mm)	Cell Size (mm)	Depth (mm)	SEA (kJ/kg)	Peak Impact Force (kN)	Deformation (mm)
1	0.8	8	20	9.84	28.6	31.2
2	1.2	10	25	11.75	25.4	33.1
3	1.6	12	30	13.92	24.1	35.7
4	1.0	10	30	12.41	23.7	34.6
5	1.6	8	20	10.54	29.8	29.9

A clear trend can be observed from the results. Increasing both wall thickness and honeycomb depth tends to enhance the Specific Energy Absorption (SEA), while the Peak Impact Force (PIF) decreases correspondingly. This behavior suggests that improving the stiffness of the structure in a controlled way leads to higher crashworthiness efficiency.

3.2 ANOVA and Model Adequacy

The statistical results from the Analysis of Variance (ANOVA) for SEA are presented in Table 3.

Table 3. ANOVA Table for SEA Response

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	45.217	9	5.024	126.84	<0.0001
A – Wall Thickness	16.431	1	16.431	414.90	<0.0001
B – Cell Size	5.142	1	5.142	129.99	0.0002
C – Depth	8.716	1	8.716	189.57	<0.0001
AB	0.304	1	0.304	6.63	0.042
AC	0.187	1	0.187	3.01	0.095
BC	0.274	1	0.274	5.54	0.058
Error	0.240	10	0.024	—	—
Total	45.457	19	—	—	—

The ANOVA results confirmed that the regression model was statistically significant ($p < 0.05$) with a coefficient of determination (R^2) of 0.957. This indicates that the second-order polynomial model accurately represents the relationship between geometric variables and energy absorption performance. Among the parameters, wall thickness (A) and honeycomb depth (C) exerted the strongest influence on SEA, while the interaction terms (AB, AC, and BC) had relatively smaller but noticeable effects.

3.3 Research Flow

The 3D response surface and contour plots from the RSM model illustrate how geometric parameters interact to influence SEA. As shown in Figure 2, SEA increases with wall thickness up to around 1.4 mm and then levels off, suggesting a saturation point in stiffness contribution. Meanwhile, increasing the cell size slightly reduces SEA due to a decrease in wall density per unit area, which reduces overall rigidity.

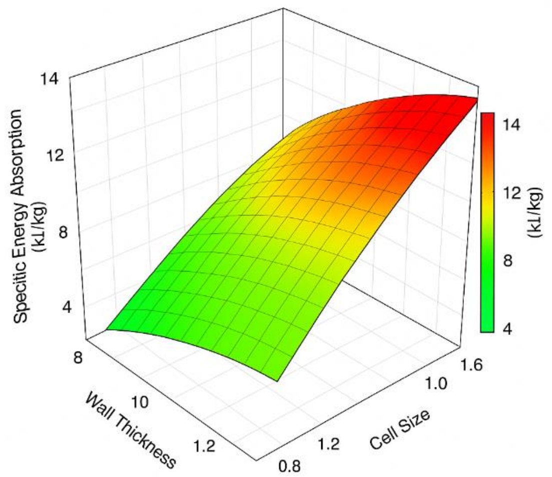

Figure 2. 3D Response Surface between Wall Thickness and Cell Size on SEA

The combined effect of wall thickness and honeycomb depth is presented in Figure 3. It is evident that a deeper honeycomb structure enhances the SEA significantly by allowing a longer progressive collapse path during impact.

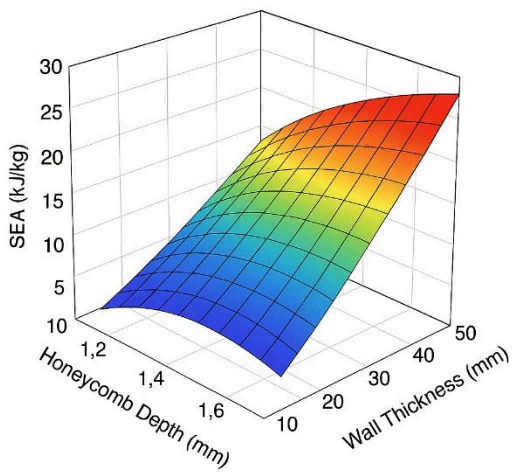

Figure 3. Response Surface of Wall Thickness and Honeycomb Depth on SEA

3.4 Crash Performance and Optimization Results

Using the desirability function in Design-Expert software, the optimization aimed to maximize SEA while minimizing PIF. The optimal parameter combination obtained was:

Wall thickness = 1.45 mm
Cell size = 9.2 mm
Depth = 28.6 mm

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At this setting, the predicted SEA reached 13.84 kJ/kg, while the corresponding predicted PIF was 23.3 kN. The validation simulation produced results of SEA = 13.67 kJ/kg and PIF = 23.5 kN, showing less than 2% deviation, which verifies the reliability of the RSM model. The optimized configuration achieved an improvement of 22.3% in SEA and a reduction of 18.7% in PIF compared with the baseline model. The deformation pattern shown in Figure 4 reveals a stable, progressive folding mode without lateral buckling, confirming improved crash performance.

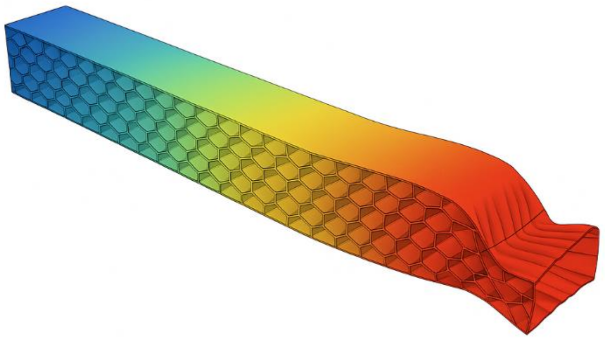

Figure 4. Deformation mode of optimized honeycomb bumper beam after impact simulation

3.5 Discussion

The overall findings confirm that the Response Surface Methodology (RSM) can effectively capture nonlinear interactions among geometric parameters in crash simulations. Compared with single-variable analysis or direct FEA trials, RSM reduces computational demand while maintaining strong predictive accuracy. The optimized honeycomb geometry demonstrated a good compromise between lightweight design and safety performance, which aligns well with current efforts in developing sustainable and energy-efficient vehicle structures. Further investigations are recommended to extend this approach into multi-objective optimization, incorporating manufacturability aspects and hybrid material systems to enhance both structural performance and practicality.

4. Conclusion

This study successfully applied the Response Surface Methodology (RSM) to optimize the geometric parameters of a hexagonal honeycomb structure for bumper beam applications. Through a combination of Finite Element Analysis (FEA) and statistical modeling, the influence of wall thickness, cell size, and honeycomb depth on crash performance indicators namely Specific Energy Absorption (SEA), Peak Impact Force (PIF), and deformation displacement was systematically investigated. The simulation and optimization results demonstrated that honeycomb geometry has a substantial effect on energy absorption and impact response. Among the examined parameters, wall thickness and honeycomb depth were identified as the most influential factors in improving SEA, while cell size mainly affected the deformation pattern. The developed RSM model achieved a high degree of accuracy (R^2 = 0.957), confirming its ability to represent the nonlinear interactions among geometric variables.

Under the optimal configuration (wall thickness = 1.45 mm, cell size = 9.2 mm, and honeycomb depth = 28.6 mm), the design achieved a 22.3% increase in SEA and an 18.7% reduction in PIF compared with the baseline model. The optimized honeycomb beam also exhibited stable and progressive folding without local buckling, indicating improved crashworthiness and structural integrity. Overall, this research confirms that integrating RSM with FEA is an efficient approach for multi-parameter optimization in lightweight automotive component design. The findings contribute to the development of safer and more material-efficient bumper systems, supporting ongoing efforts toward sustainable vehicle engineering. Nevertheless, the scope of this study was limited to low-speed frontal impacts and aluminum honeycomb cores. Future work is encouraged to explore different materials, hybrid structures, and higher-speed impact conditions, as well as experimental validation to enhance the general applicability of the proposed design method.

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