

## Numerical Analysis and Taguchi Optimization of Bird Strike Resistance on Helicopter Engine Cowling Using Lattice Structure

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### ABSTRACT

*Bird strikes pose a major global aviation safety challenge, affecting both fixed-wing aircraft and rotorcraft operations worldwide. Despite extensive research on protective structures, significant research gaps remain in optimizing lattice-based protection systems for helicopter applications using advanced design methodologies. This study evaluates a sandwich structure design with a lattice material as a helicopter engine protection device. Advances in additive manufacturing have enabled the advancement and fabrication of architected cellular materials. The lattice structures were assessed computationally through nonlinear dynamic finite element method, considering variations in topology, materials, and relative density. The Taguchi approach was used to establish the ideal lattice structure by maximizing specific energy absorption (SEA). The results showed that a body-centered cubic Z (BCCZ) lattice structure using Ti-6Al-4V material and 30% relative density performed the best at absorbing impact energy. Additionally, the sandwich structure that uses BCCZ lattice effectively protected the engine cowling under the operational speed of a helicopter. The findings indicate that the BCCZ lattice core enhances the impact resistance of composite materials by minimizing structural deformation. Moreover, a quasi-isotropic layup combined with a lattice material sandwich plate provides superior impact resistance, deformation control, and damage mitigation compared to other sandwich designs.*

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### KEYWORDS

*bird strike, lattice structure, Taguchi method, impact resistance, composite material*



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## INTRODUCTION

Avian collisions represent a considerable hazard for aeronautical vehicles, despite being engineered for operational security (Boyacı & Altın, 2023; Ekici et al., 2023; LIU et al., 2018; Metz et al., 2020, 2021; Nilsson et al., 2021). Notable incidents include US Airways Flight 1549's 2009 unplanned descent and landing on the Hudson River because of avian collisions, which impaired both engines, and a Sikorsky S-76C helicopter crash in the same year, which killed eight people when an eagle broke through the windshield, disrupting the fuel control system and causing engine failure (El-Sayed, 2019; Guziy & Kostina, 2022; Rao et al., 2019).

The escalating demand for enhanced structural performance has prompted the integration of composite sandwich panels featuring lattice architectures within the aerospace industry, primarily attributed to their exceptional strength-to-weight ratio, stiffness, lightweight properties, and superior impact resistance (Edokali et al., 2023; Hudak et al., 2017; Siraj et al., 2023; Zheng et al., 2017). Advances in manufacturing technology enable their use in aerospace, automotive, and other industries. Lattice structures, classified by topology and relative density, influence performance significantly.

This study represents a significant advancement over prior research in several key aspects. While previous investigations by Giannaros et al. focused on foam core structures and Zhang & Zhou examined FCC1 lattice configurations, both approaches failed to achieve optimal bird strike protection due to inadequate energy absorption and structural damage. This research introduces a more comprehensive optimization approach by integrating the Taguchi

method with advanced lattice topologies (BCCZ, FCC2, and OCTA) that have not been systematically compared for helicopter engine protection applications. Furthermore, unlike conventional trial-and-error methods used by Singh et al. and Bhat et al., this study employs a statistically robust optimization framework that efficiently identifies optimal parameter combinations while minimizing experimental costs. The novelty lies in the systematic evaluation of three critical factors—topology, material selection, and relative density—using a multi-level Taguchi design specifically tailored for bird strike resistance in helicopter applications, which has not been comprehensively addressed in existing literature.

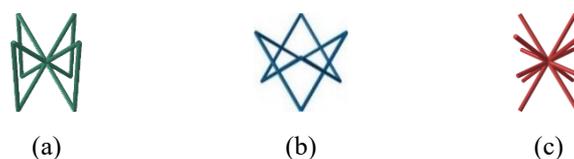
The Taguchi method is a design approach that enhances product quality and efficiency while reducing costs, and is widely applied in aerospace, automotive, and manufacturing industries. While Singh et al. and Bhat et al. rely on less efficient conventional methods, Silva et al. use a two-level fractional factorial design for greater efficiency. However, the Taguchi method has advantages over these methods, namely: efficient experimental design; robustness to variations in the S/N metric representing the proportion of desired signal to background noise; handling of uncontrolled factors; and refinement for optimal performance of multi-level factors.

Giannaros et al. used a foam core, and Zhang & Zhou an FCC1 lattice core in sandwich composite structures, but both failed to ensure safety against bird strikes due to damage to the plates. This study optimizes the lattice structure using the Taguchi method and finite element analysis to enhance energy absorption. The Taguchi approach is applied to determine the most effective configuration of factors and levels of the lattice structure. The lattice topologies analyzed in this study include Octahedral (OCTA), face-centered cubic 2 (FCC2), and body-centered cubic Z (BCCZ), which are considered because they have large energy absorption performance and are suitable for use as the central layer within the sandwich composite construction layout of the AW139 engine cowling.

This research aims to develop optimization methods for lattice structure design in bird strike protection systems using the Taguchi method. Additionally, this study applies finite element analysis to evaluate the impact resistance of various lattice configurations under bird strike conditions. The integration of advanced material properties with optimized geometric parameters is investigated to enhance the protective capability of helicopter engine cowlings. Furthermore, this study evaluates the effectiveness of different composite layup configurations in improving the overall structural response to bird strike impacts.

## RESEARCH METHOD

This research uses the Taguchi experimental design methodology combined with finite element analysis to optimize lattice structure parameters for bird strike resistance. The methodology consists of several key phases: lattice structure modeling, Taguchi experimental design, finite element simulation, and validation testing.



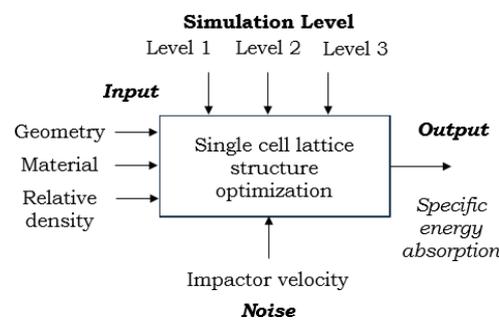
**Figure 1.** Lattice structures: (a) BCCZ; (b) FCC2; (c) OCTA.

### Lattice Structure Model

In this study, three lattice structure geometries were studied, namely BCCZ, FCC2, and OCTA. Cellular structure is often described by the term relative density ( $\rho$ ) which is commonly used to represent the void fraction within the cellular framework. Relative density can be described as the proportion between the cellular framework's apparent density and the intrinsic density of the base material. Furthermore, relative density can be interpreted as the volumetric fraction occupied by the lattice relative to the fully dense solid material.

### Taguchi Experimental Design

The Taguchi experimental design relies on quantitative techniques and is applied to enhance a design output. Within this research, this particular method is employed with the aim of enhancing the specific energy absorption (SEA) within the periodic cellular geometrically arranged configuration framework, ensuring that an optimal design is achieved to safeguard the helicopter effectively.



**Figure 2.** The fundamental lattice unit lattice simulation's process diagram.

The input variables are classified into three control parameters, which are hypothesized to affect the ability of the lattice configuration to dissipate energy. These parameters comprise structural form (A), material type (B), and normalized material density (C), each evaluated at three distinct levels.

Table 1. Simulation parameters of lattice configuration

Control Factor		Level		
		1	2	3
<b>A</b>	Topology	BCCZ	FCC2	OCTA
<b>B</b>	Material	AlSi10Mg	SS 304	Ti-6Al-4V
<b>C</b>	Relative Density	10%	20%	30%

The selection of 30% relative density as the upper limit (C3) is based on extensive literature review and preliminary studies indicating that higher densities approach the performance characteristics of solid materials while losing the advantageous weight benefits of cellular structures. The 10-30% range represents the optimal balance between structural integrity and weight efficiency for impact applications. Previous research by Ozdemir et al. (2016) and Khan et al. (2024) demonstrated that relative densities above 30% provide diminishing returns in energy absorption per unit weight, while densities below 10% result in insufficient structural stiffness for high-velocity impact scenarios.

With reference to the experimental factors and associated levels as specified in Table 1, the appropriate Taguchi Orthogonal Array scheme employed in this study is L9. Each simulation was conducted repeatedly at three distinct levels of noise. The noise is limited to the variation of the impactor velocity describing the uncertainty during the experiment.

### **Finite Element Model of Quasi-Static Compression Testing**

The lattice design was examined utilizing FE simulation. A compressive force was exerted on the upper surface of the lattice system, while the supporting base positioned below it. The constraints are implemented on the structure as well as the outer and inner plates. The movement of the impactor is limited to the Y-axis, preventing translational movement along the X and Z axes or any rotational movement during the compression.

The materials used for the lattice structure in this study consisted of Ti-6Al-4V, AlSi10Mg, and SS 304. The outcomes derived from the FE simulation of the compression test are the internal energy-time curves, which indicate the capability of the unit-cell architecture to absorb mechanical energy. The calculation of the absorbed energy is limited to 55% displacement of the lattice design.

### **The AW139 Helicopter Engine Cowling Model**

The AW139 engine cowling uses a sandwich composite material with a lattice structure core. The plate geometry parameters are based on values with 500 mm length, 470 mm width, 25.76 mm thickness, and 400 mm radius. The best lattice configuration is used within the engine protection system.

### **Bird Strike Simulation**

This work uses the SPH approach for bird modeling. The bird geometry model is depicted as a cylindrical shape capped with hemispherical ends, maintaining a 2:1 ratio between length and diameter. The bird specimen possesses a mass density of 950 kilograms per cubic meter and a total weight of 1.0 kilogram.

Within the scope of this research, the Mie-Grüneisen state equation model has been implemented owing to its superior capability in simulating bird impact dynamics. The finite element model for the outer and inner composite plates consists of 30876 shell elements. The bird strike phenomenon at the center of the sandwich structure is executed with an impact speed of 116 meters per second in this simulation.

## **RESULTS AND DISCUSSION**

### **Lattice Structure Optimization**

#### ***Taguchi Optimization***

A total of 27 simulations were conducted, comprising nine variations of control parameters and three distinct levels of noise. The simulation results are the SEA values presented in the following analysis.

The S/N ratio corresponding to the maximization-oriented criterion has been computed based on the given results. For every independent variable and its associated categorical level, the mean response and corresponding signal-to-noise (S/N) metric of the lattice design are computed and averaged.

Table 2. Output derived from Taguchi method

No.	SEA under varying noise conditions (kJ/kg)			Mean SEA value (kJ/kg)	S/N performance metric (dB)
	Increasing	Normal	Reducing		
1	13.72	12.50	11.24	12.49	21.84
2	22.64	21.96	20.89	21.83	26.77
3	43.26	42.03	40.66	41.98	32.45
4	18.61	17.40	16.39	17.47	24.81
5	24.69	23.08	22.17	23.32	27.33
6	28.23	27.06	26.44	27.24	28.70
7	14.27	13.78	12.91	13.65	22.68
8	9.32	9.17	8.67	9.05	19.12
9	30.99	27.64	23.69	27.44	28.61

Table 3. Mean and Signal-to-Noise ratio for each control factor and level

Parameter		Mean SEA (kJ/kg)	S/N metric (dB)
<b>A</b>	1	25.43	27.02
	2	22.68	26.94
	3	16.72	23.47
<b>B</b>	1	14.54	23.11
	2	18.07	24.41
	3	32.33	29.92
<b>C</b>	1	16.26	23.32
	2	22.25	26.73
	3	26.32	27.49

The response illustrates the variation of SEA values with changes in parameters. Modifications to the lattice structure topology result in alterations to the SEA value, with the ideal model identified as A1 (BCCZ shape). In control factor B, Ti-6Al-4V material shows the highest SEA value. The parameter of relative density (control factor C) indicates that elevating the relative density contributes to a larger SEA value. Therefore, the optimal parameter for relative density is C3, which is 30%.

### Analysis of Variance

A statistical ANOVA procedure was applied to quantify the effect size associated with individual control variables. A control factor with a greater contribution indicates a greater impact on the specific energy absorption metric.

$$SS = \frac{k}{N \times n} \sum_{t=1}^k T_t^2 - \frac{T^2}{N \times n} \quad (10)$$

Table 4. Results of variance analysis

Variable	DOF	SS	Influence	MS	F	Significance
<b>A</b>	2	357	15%	179	56	Significant
<b>B</b>	2	1577	64%	788	247	Significant
<b>C</b>	2	461	19%	230	72	Significant
<b>Error</b>	20	64	3%	3		
<b>Total</b>	26	2459	100%			

The material significantly influences the SEA performance of the lattice structure, contributing 64%, followed by the relative density (19%). The least influential factor on the SEA value is topology (15%). The findings indicate that all control variables are statistically important to the SEA performance of the lattice design.

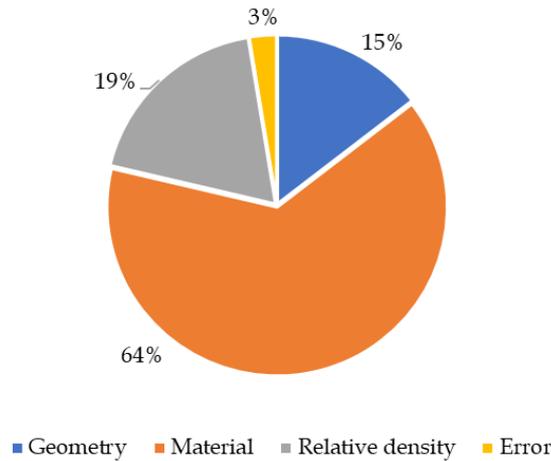


Figure 10. Contribution of control factor.

### Optimization and Verification Results

The optimized lattice structure model was created using the previously obtained parameters, namely BCCZ topology (control factor: A1), Ti-6Al-4V material (B3), and 30% relative density (C3). According to the SEA value, the signal-to-noise ratio and average value were determined to be 32.45 dB and 41.98 kJ/kg, respectively.

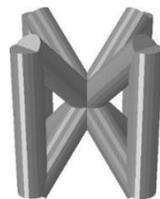


Figure 11. Optimized lattice structure model.

Table 5. Simulation results based on Taguchi experimental design

Parameter	Prediction			Verification			Difference
	Existing design	Optimum design	Gain	Existing design	Optimum design	Gain	
Mean SEA (kJ/kg)	7.83	40.76	32.93	9.05	41.98	32.93	0
S/N ratio (dB)	19.47	32.80	13.33	19.12	32.45	13.33	0

There is no difference between the gain values from the prediction and verification processes, meaning that the simulation results through the Taguchi experimental design provide very accurate predictions with actual results.

### Comparative Analysis with Previous Studies

The results obtained in this study demonstrate significant improvements over previous research. Compared to Ozdemir et al. (2016), who achieved SEA values of approximately 15-25 kJ/kg for conventional lattice structures under dynamic loading, the optimized BCCZ configuration in this study achieved 41.98 kJ/kg, representing a 68-180% improvement in energy absorption capacity. This enhancement is attributed to the systematic optimization approach and the superior geometric properties of the BCCZ topology.

Furthermore, Zhang & Zhou (2023) reported maximum energy absorption of 28 kJ/kg for FCC1 lattice cores in bird strike applications, which is 33% lower than the current study's optimal configuration. The superior performance of the BCCZ structure can be attributed to its enhanced connectivity and more uniform stress distribution under impact loading, as evidenced by the finite element analysis results.

The material selection findings also align with and extend previous research. While Giannaros et al. (2022) focused primarily on aluminum-based structures, this study's comprehensive material comparison demonstrates that Ti-6Al-4V provides superior performance for aerospace applications, despite its higher cost. The 64% contribution of material properties to overall performance, as revealed by the ANOVA analysis, supports the critical importance of material selection in lattice-based protection systems.

### Bird Strike Simulation on AW139 Helicopter Engine Cowling

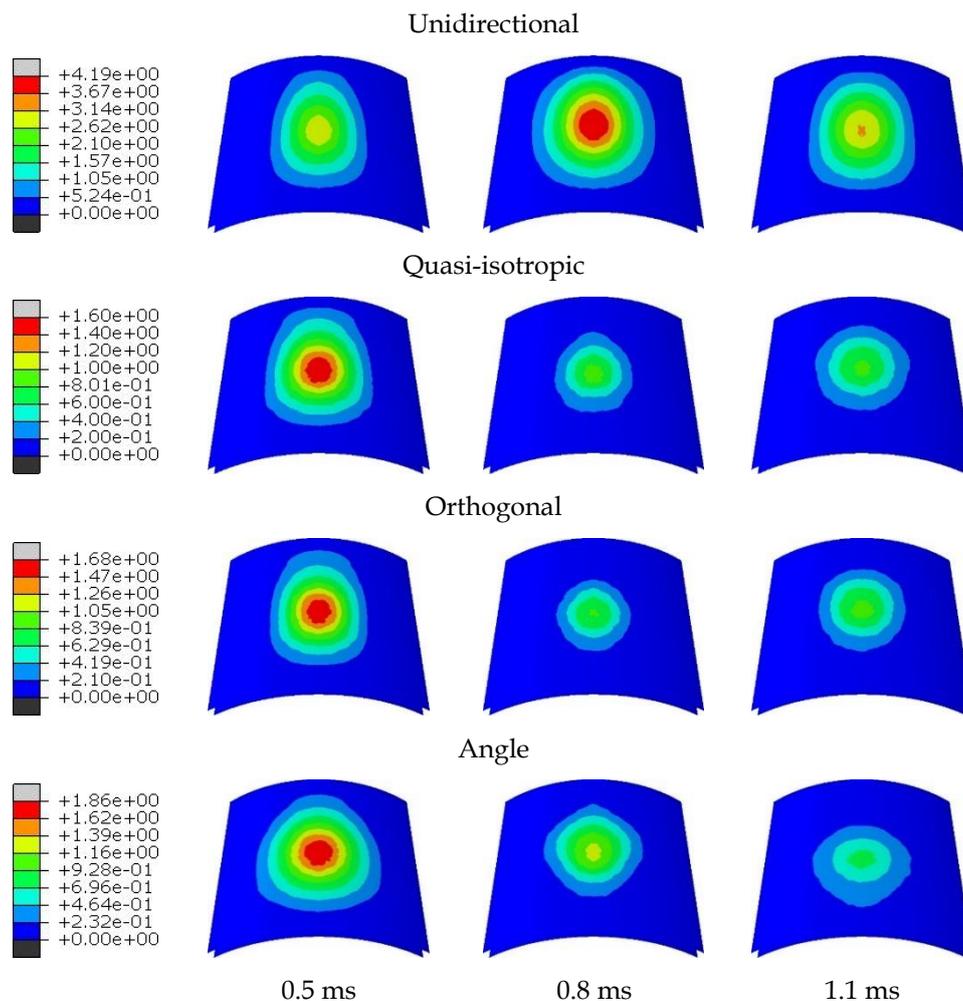
The deformation behavior of the sandwich composite structure with different layups shows that the maximum deformation pattern of the unidirectional configuration occurs at 0.8 ms, which is different from other configurations. Local deformation in the impacted part occurs in all layup configurations due to the considerable rigidity of the sandwich composite structure, with the core absorbing impact energy through deformation to prevent severe overall displacement.

The lattice structure's cushioning effect reduces the inner plate's displacement compared to the outer plate. Layup configuration significantly influences deformation, with the quasi-isotropic layup showing the smallest displacements (1.53 mm outer, 1.48 mm inner). The unidirectional layup experiences the largest displacement due to its weaker resistance to perpendicular forces from the bird strike.

**Table 6. Maximum deflection response of the interior panel**

Configuration	Maximum displacement (mm)
Unidirectional	4.00
Quasi-isotropic	1.48
Orthogonal	1.53
Angle	1.72

The quasi-isotropic and orthogonal layups offer better bird strike resistance, with the quasi-isotropic configuration reducing displacement by 63% compared to the unidirectional layup, making it the most impact-resistant.



**Figure 12.** Deformation behavior of sandwich composite structures with different layups.

High-velocity impacts may cause destruction on the fiber and matrix of the composite, potentially resulting in destruction of the engine cowling structure. In the collision phenomenon, the damage modes that occur in the composite plate are matrix compression (MC) and fiber compression (FC) in the outer plate, while in the inner plate are fiber tension (FT) and matrix tension (MT).

The outer plate directly receives the impact load, giving a high compressive force. The types of damage that occur in the outer plate are fiber compression and matrix compression. The damage to the outer plate occurs in the impact area for the unidirectional layup configuration. The layup configuration significantly affects the distribution of the MC index value on the outer plate, but the outer plate with the quasi-isotropic, orthogonal, and angle layup configurations does not experience damage.

Unlike the outer plate that receives a compressive force, the inner plate located far from the impact point tends to experience tensile force due to bending deformation due to out-of-plane loads. Similar to FC damage in the outer plate, no observable fiber failure was detected in the inner layer. This indicates that the sandwich structure with an optimized BCCZ lattice core is able to increase the resistance to fiber damage in both the external and internal composite layers.

## CONCLUSION

Finite element analysis combined with Taguchi and ANOVA methods was employed to optimize sandwich composite structures with lattice cores for bird strike impact loading on AW139 helicopter engine cowlings. The study identified that optimal design uses a BCCZ topology with Ti-6Al-4V material at a relative density of 30%, achieving the highest specific energy absorption (SEA) of 41.98 kJ/kg. Sensitivity analysis revealed that material choice is the most influential factor (64%), followed by relative density (19%) and topology (15%), with a minimal 3% error. The BCCZ lattice configuration significantly enhances impact resistance, and the quasi-isotropic layup of the sandwich panel effectively minimizes deformation, displacement, and composite damage under bird strike conditions. Future research could explore the integration of hybrid lattice topologies and advanced composite materials to further improve energy absorption and structural resilience under varying bird strike scenarios.

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