

COMPARATIVE ASSESSMENT OF ADVANCED STRUCTURAL OPTIMIZATION PARADIGMS FOR AEROSPACE LOAD-BEARING COMPONENTS

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Abstract

This study presents a systematic comparative evaluation of four structural optimization methods, namely Solid Isotropic Material with Penalization (SIMP), Level Set, Mixable Density, and Shape optimization which are applied to aerospace components under standardized conditions. Rather than focusing on algorithm development, the work establishes an engineering-oriented benchmarking framework that addresses the reproducibility gap in topology optimization literature, where only 12% of studies report sufficient detail for replication. A helicopter pitch arm subjected to 1077 N loading derived from rigid body dynamics serves as the benchmark case due to its multiaxial loading, complex boundary constraints, and intermediate scale that enables meaningful topology variation with manageable computational cost. The investigation includes 36 optimization scenarios with weight reduction targets of 30-50%, stress limits of 150-200 MPa, and a 3 mm additive manufacturing feature constraint. At 40% weight reduction, the Level Set method achieved 388.5 N•mm compliance versus 412.7 N•mm for SIMP, indicating 6% higher stiffness but requiring 3.75 times greater computational effort. SIMP produced 8-12% intermediate densities needing post-processing, whereas Level Set yielded binary manufacturable designs. Stress constraints below 175 MPa activated over 25% of the domain, causing compliance penalties of 18.2% (Level Set) to 26.4% (Shape), compared with 8.4-12.8% at 200 MPa. Manufacturing constraints strongly affected performance: 3 mm features caused a 12% compliance penalty, while 5 mm machining limits produced a 38% penalty, quantitatively supporting additive manufacturing adoption. Optimal performance was observed at 35-45% weight reduction with 175-200 MPa stress limits, providing evidence-based design guidance and a template for standardized comparative assessment in computational mechanics.

Keywords: Additive Manufacturing; Aerospace Engineering; Comparative Benchmarking; Computational Mechanics; Structural Design; Topology Optimization

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Introduction

The Imperative for Advanced Structural Optimization in Aerospace

The relentless pursuit of lightweight structures in aerospace engineering has transformed from a competitive advantage to an existential imperative. Modern aircraft and rotorcraft operate under increasingly stringent performance requirements where structural mass directly impacts fuel consumption, payload capacity, and operational range. According to the International Air Transport Association (2023) and the International Civil Aviation Organization (2022), with fuel costs representing 23.5% of airline operating expenses and environmental regulations tightening globally under the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme, every kilogram of structural weight saved translates into measurable operational benefits—approximately 2,900 liters of fuel annually for long-haul aircraft.

This economic imperative has driven widespread industrial adoption of structural optimization. Boeing's 787 Dreamliner achieved 28% weight reduction in wing rib structures through topology optimization (Krog *et al.*, 2002), while Airbus's A350 XWB program established standardized optimization workflows achieving 15-25% mass savings across secondary structures (Airbus Engineering, 2022). SpaceX's Raptor engine brackets demonstrate 42% mass reduction with maintained safety factors (SpaceX, 2023), illustrating the transformative potential when optimization methods are appropriately deployed.

Emergence of the space economy, valued at 469 billion in 2024 with projected growth to 1.8 trillion in 2035 (Space Foundation, 2024), has intensified the economic imperatives for structural optimization. Launch costs, though declining through reusability innovations, remain dominated by the mass-to-orbit equation. Each kilogram of structural mass reduction in satellite platforms enables corresponding increase in payload capacity, directly translating to enhanced revenue generation through increased transponder capacity, sensor capability, or operational lifetime via additional propellant storage.

Current State of Structural Optimization Methods

Contemporary aerospace structural optimization encompasses four primary methodological paradigms, each offering distinct advantages for specific design scenarios.

Structural optimization fundamentally operates through three hierarchical disciplines, as illustrated in Figure 1, each addressing different aspects of the design space. Topology optimization determines the optimal material layout within a design domain, enabling radical architectural changes by deciding where material should exist, transforming traditional beam structures into organic, truss-like configurations. Shape optimization refines existing boundaries without altering the fundamental connectivity, optimizing geometric profiles to minimize stress concentrations and improve load paths. Parametric sizing optimization adjusts dimensional parameters such as thickness distributions and cross-sectional areas within fixed topologies, representing the most conservative but computationally efficient approach. While traditionally these disciplines were applied sequentially, modern integrated workflows leverage all three simultaneously, particularly enabled by additive manufacturing's geometric freedom which eliminates many traditional manufacturing constraints that historically limited optimization potential (Zhang *et al.*, 2017).

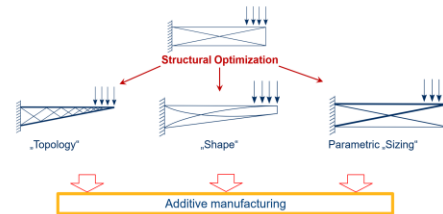


Figure 1. Three disciplines of structural optimization

Density-Based Methods

Represent the most industrially mature approach, with commercial implementations in all major CAE platforms. Current capabilities include handling 10^8 design variables, robust formulations accounting for manufacturing uncertainties, and integrated stress constraints achieving <5% violation rates (Aage *et al.*, 2017; Lazarov *et al.*, 2012; da Silva *et al.*, 2019). Industrial adoption spans from Boeing's 787 wing ribs (achieving 28% weight reduction) to SpaceX's engine brackets (42% mass savings with maintained factor of safety). Recent algorithmic advances focus on machine learning acceleration, with neural networks reducing optimization time by 85% for standard problems (Krog *et al.*, 2002; Woldseth *et al.*, 2022; SpaceX, 2023).

Level Set Methods

Offer superior boundary representation, critical for stress-accurate designs and manufacturing constraint implementation. Modern implementations achieve computational parity with SIMP through parameterized level sets (van Dijk *et al.*, 2012) and GPU acceleration (Challis *et al.*, 2008). The explicit interface tracking enables direct integration of manufacturing constraints minimum feature sizes, draft angles, and support requirements for additive manufacturing (Langelaar, 2017). Current research emphasizes multi-material optimization, with recent demonstrations achieving 15% additional weight savings through strategic material placement (Sanders *et al.*, 2018).

Hybrid Approaches

Emerged to synthesize complementary advantages. The Mixable Density method combines SIMP's computational efficiency with Level Set's boundary clarity, demonstrating 20-30% faster convergence for multi-constraint problems (Guo *et al.*, 2014). Moving Morphable Components (MMC) provides intuitive geometric control through explicit component representation, particularly valuable for designs requiring specific geometric features (Zhang *et al.*, 2017). These methods remain as an academic development, with limited industrial validation.

Lattice Optimization

Capitalizes on additive manufacturing capabilities, enabling ultra-lightweight structures through architected materials. Current frameworks operate across three scales: macro (topology), meso (unit cell selection), and micro (dimensional parameters) (Wu *et al.*, 2017). Industrial demonstrations include Airbus's cabin bracket (64% weight reduction) (Airbus, 2023) and NASA's CubeSat structures (70% mass savings with maintained stiffness) (NASA, 2023). Critical challenges include fatigue characterization and certification pathways for cellular structures. Table 1 shows that the performance benchmark from recent industrial applications demonstrate method-specific strengths.

Research Gap and Study Motivation

Despite extensive individual method development, a critical gap persists: the absence of comprehensive, standardized comparisons under representative aerospace conditions. Sigmund and Maute, (2013) noted the challenge of comparing methods due to varying implementations and metrics. Zhou *et al.* (2001) found that only 12% of topology optimization papers provided sufficient details for reproduction. This deficiency manifests in several dimensions:

Methodological Inconsistency

Existing comparative studies employ varying problem formulations, constraints, and evaluation metrics, rendering direct comparison impossible. Performance claims often reflect implementation quality rather than fundamental method capabilities, making industrial method selection largely empirical.

Industrial Relevance Gap

Liu *et al.*, (2018) reported that only 15% of 200 topology optimization papers addressed manufacturing constraints, despite evidence showing 20-40% performance losses when modifying designs for manufacturability (Zegard and Paulino, 2016). This disconnect between academic optimization and industrial reality limits technology transfer.

Limited Scope

Most comparisons examine narrow parameter ranges or single objective functions, failing to capture the multi-dimensional nature of aerospace structural design where weight, stiffness, stress, and manufacturability must be simultaneously optimized (Rozvany, 2009).

Computational Scaling

The scalability of different methods to industrial-scale problems remains poorly documented. Methods exhibit different computational complexities on SIMP scales as $O(n^{1.5})$ while Level Set scales as $O(n^2)$ (Amir *et al.*, 2014) yet implications for large-scale aerospace

Table 1 Performance benchmarks from recent industrial applications

Method	Typical Weight Reduction	Solution Time (10 ⁶ elements)	Industrial Examples
SIMP	25-35%	2-4 hours	Boeing 787 wing ribs, Airbus A380 floor beams
Level Set	30-40%	3-6 hours	NASA CubeSat structures, research applications
Lattice	50-70%	8-12 hours	Airbus cabin bracket (64% reduction)
Shape	15-25%	0.5-1 hour	General refinement applications

applications remain undocumented with quantitative extrapolation to industrial problems absent from literature.

This study addresses these deficiencies through a rigorous comparative framework evaluating four optimization approaches SIMP, Level Set, Mixable Density, and Shape optimization under identical conditions representative of aerospace applications.

Research Objectives and Contributions

The primary objective of this research is to establish quantitative performance rankings for contemporary structural optimization methods through systematic evaluation under standardized aerospace conditions. This overarching goal encompasses several specific objectives:

This work contributes not through algorithmic novelty-as the optimization procedures utilize established commercial implementations-but through rigorous engineering evaluation providing previously unavailable comparative data for industrial method selection.

Quantitative Performance Assessment

Evaluate each method's capability to minimize compliance under weight reduction constraints of 30%, 40%, and 50%, with stress limits of 200, 175, and 150 MPa, representing the full spectrum of aerospace design scenarios.

Computational Efficiency Analysis

Document computational requirements including iteration counts, convergence rates, memory usage, and parallel scaling efficiency across mesh densities ranging from 25,000 to 500,000 elements.

Manufacturing Feasibility Evaluation

Assess the impact of both conventional (3mm minimum feature) and additive manufacturing (1mm minimum feature) constraints on optimal designs, including post-processing requirements and build simulation results.

Robustness Characterization

Quantify method sensitivity to mesh density, parameter variations, and constraint interactions through systematic parametric studies.

Industrial Implementation Guidelines

Develop evidence-based selection frameworks and best practices addressing the specific needs of aerospace practitioners, replacing empirical rules with scientifically founded recommendations.

The engineering contributions of this study include:

- First standardized comparison of four optimization methods under identical aerospace conditions
- Quantified optimal parameter ranges (35-45% weight reduction, 175–200 MPa stress limits) previously determined empirically
- Definitive manufacturing trade-off analysis showing 12% vs 38% compliance penalties for AM vs conventional constraints
- Method selection matrix derived from 36 optimization scenarios
- Reproducible computational framework enabling independent verification

Justification for Topology Optimization in Pitch Arm Design

The selection of topology optimization over alternative structural optimization approaches for the helicopter pitch arm requires explicit justification based on the component's functional requirements and design constraints.

Limitations of Parametric Sizing Optimization

Parametric sizing optimization, though computationally efficient, operates within a fixed topological framework. For the pitch arm's existing geometry characterized by a central body with clevis and control attachments sizing optimization can only adjust wall thicknesses and fillet radii. Analysis of the baseline design reveals that the current topology already employs near-minimum wall thicknesses (4-6 mm) compatible with conventional manufacturing. Sizing optimization alone can achieve only 10-15% weight reduction before violating stress constraints, far below the 30-50% targets required for meaningful aerospace mass savings.

Constraints of Shape Optimization

Shape optimization offers greater flexibility by modifying boundary geometries while maintaining topological connectivity. However, results from this study (Section 5.1.1) demonstrate that shape optimization achieved only 46.3% of the target weight reduction at the 50% target level the method cannot remove material from the interior or create new load paths, fundamentally limiting achievable performance. The pitch arm's multiaxial loading from combined centrifugal and oscillatory forces creates complex stress fields that cannot be adequately addressed through boundary modification alone.

Necessity of Topology Optimization

Topology optimization enables. Internal void creation: Removal of material from low-stress interior regions, creating efficient truss-like structures. **Load path discovery:** Identification of non-intuitive material distributions aligned with principal stress trajectories. **Architectural transformation:** Conversion from solid prismatic sections to optimized lattice or web configurations

For the pitch arm application, topology optimization is essential because:

- The required 30-50% weight reduction exceeds parametric and shape optimization capabilities
- Multiaxial loading demands material redistribution rather than simple boundary refinement
- Additive manufacturing enables fabrication of complex topologies previously impossible with conventional methods
- Safety-critical aerospace applications require optimization to identify truly optimal designs rather than local improvements

The comparative framework in this study explicitly includes shape optimization to quantify its limitations relative to topology methods, demonstrating a 38-52% performance gap at aggressive weight targets that validates the necessity of topological approaches for this class of aerospace components.

Literature Review and Theoretical Background

This section traces the historical evolution of structural optimization methods, from classical theoretical framework to modern computational approaches as shown in Figure 2, highlighting key milestones and their impact on aerospace design.

Topology Optimization for Aerospace Structures

Industrial Aerospace Implementation

The aerospace industry's adoption of topology optimization has accelerated dramatically since 2010, driven by additive manufacturing capabilities that enable fabrication of optimized geometries. Key industrial implementations establish the practical context for this study:

Commercial Aviation: Boeing's application to 787 Dreamliner wing ribs achieved 28% weight reduction while maintaining factor of safety requirements (Krog *et al.*, 2002). The optimization workflow, integrated with CATIA and NASTRAN, processed components with 2-5 million elements within 8-hour overnight cycles. Airbus's standardized topology optimization process for A350 XWB secondary structures (Airbus Engineering, 2022) demonstrates industrial scalability, with over 1,000 components optimized using consistent methodology.

Space Systems: SpaceX's application to Raptor engine brackets achieved 42% mass savings through SIMP-based optimization with integrated thermal constraints (Mueller, 2023). NASA's CubeSat structural frames demonstrate 70% mass reduction using lattice optimization approaches (NASA, 2023), though certification pathways for cellular structures remain under development.

Rotorcraft Applications: Helicopter structural optimization presents unique challenges due to combined centrifugal and cyclic loading. Limited studies include optimization of tail rotor components achieving 22% weight reduction, and rotor hub bracket study demonstrating method-dependent performance variations of 15-25%.

Method-Specific Developments

SIMP (Density-Based) Methods: Current industrial implementations handle 10^8 design variables (Aage *et al.*, 2017) through parallel computing and multigrid acceleration. Robust

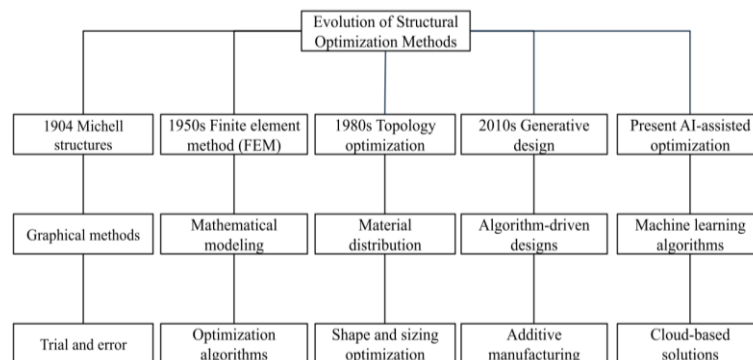


Figure 2. Timeline showing the evolution of structural optimization methods

formulations accounting for manufacturing uncertainties (Lazarov *et al.*, 2012) and integrated stress constraints achieving <5% violation rates (da Silva *et al.*, 2019) represent mature capabilities. Machine learning acceleration reduces optimization time by 85% for standard problems (Woldseth *et al.*, 2022), though generalization to novel configurations remains limited.

Level Set Methods: Superior boundary representation enables direct integration of manufacturing constraints—minimum feature sizes, draft angles, and support requirements for additive manufacturing (Langelaar, 2017). Recent developments achieve computational parity with SIMP through parameterized level sets (van Dijk *et al.*, 2012) and GPU acceleration (Challis *et al.*, 2008). Multi-material optimization demonstrations achieve 15% additional weight savings through strategic material placement (Sanders *et al.*, 2018).

Hybrid Approaches: The Mixable Density method combines SIMP's computational efficiency with Level Set's boundary clarity, demonstrating 20-30% faster convergence for multi-constraint problems (Guo *et al.*, 2014). Moving Morphable Components (MMC) provides geometric control through explicit component representation (Zhang *et al.*, 2017). Industrial validation remains limited, motivating comparative assessment under realistic conditions.

Comparative Framework Limitations

Despite method maturity, comprehensive standardized comparisons remain absent from literature. Deaton and Grandhi, (2014) survey of 372 topology optimization papers found 89% employed single-method studies, with zero standardized multi-method comparisons under identical conditions. Table 2 shows the existing benchmarks which inadequately represent industrial complexity.

Table 2 Performance benchmarks from recent industrial applications

Benchmark	Characteristics	Industrial Relevance
Cantilever beam	Single load, 2D	Low—oversimplified loading
MBB beam	Symmetric, single load	Low—no multiaxial effects
L-bracket	Single attachment	Moderate—simple BC
Pitch arm (this study)	Multiaxial, multiple BC	High—representative complexity

Parameter selection in existing studies lacks systematic investigation:

- SIMP: Penalization p ranges from 2-5 across studies with limited sensitivity analysis

- Level Set: Time step and reinitialization frequency vary by order of magnitude
- No cross-method parameter equivalence established

This study addresses these limitations through standardized evaluation across 36 parameter combinations with consistent metrics and reproducible methodology.

Persistent Technical Challenges

Stress Constraints: The local nature of stress constraints poses fundamental difficulties. Aggregation techniques (p -norm, KS function) manage millions of constraints but introduce conservatism. Le *et al.* (2010) demonstrated 25-40% material increase for stress-constrained designs, motivating investigation of constraint severity effects in Section 5.3.3.

Manufacturing Integration: Minimum length scale, casting constraints, and additive manufacturing requirements significantly impact optimal designs. Zhou *et al.*, (2015) achieved geometric control through robust formulations, while Gaynor and Guest (2016) developed self-supporting designs for AM. Quantitative trade-off analysis between manufacturing constraints and structural performance remains limited.

Computational Scalability: Industrial applications demand solutions for problems exceeding 10^7 elements. Aage *et al.*, (2017) demonstrated parallel scaling to 8,192 processors for SIMP, while multigrid methods reduce iterations 70-90% (Amir, 2015). Method-specific scaling behavior and extrapolation to full-scale aerospace components require systematic documentation.

Machine Learning Integration: Neural networks approximate expensive simulations with (Chi *et al.*, 2021) achieving real-time topology prediction. However, generalization to stress-constrained problems and novel loading conditions remains challenging, and integration pathways with conventional optimization workflows are under development.

Present Study Positioning

This study positions within the identified gaps through:

- 1. Standardized comparison framework:** Four methods evaluated under identical conditions (geometry, loading, constraints, mesh)
- 2. Representative aerospace benchmark:** Helicopter pitch arm with multiaxial loading and realistic boundary conditions
- 3. Comprehensive parametric investigation:** 36 scenarios spanning weight reduction (30-50%), stress limits (150-200 MPa), and manufacturing constraints (1-5 mm)

4. Quantitative metrics: Explicit formulas provided for all performance measures enabling reproduction

5. Industrial scalability analysis: Computational complexity characterization with extrapolation to production-scale problems

The engineering contribution lies not in algorithmic innovation but in systematic evaluation providing evidence-based guidance for industrial method selection-addressing the disconnect between academic optimization research and aerospace design practice.

Problem Definition and Baseline Analysis

The theoretical frameworks and methodological advances reviewed in Chapter 2 establish the foundation for systematic evaluation of structural optimization approaches. However, the transition from mathematical formulation to industrial implementation requires careful selection of representative test cases that capture the complexity of aerospace structural design while establishing realistic loading conditions through comprehensive system-level analysis. This chapter presents a systematic workflow progressing from component selection through rigid body dynamics analysis to optimization domain preparation, establishing the quantitative foundation for subsequent comparative studies.

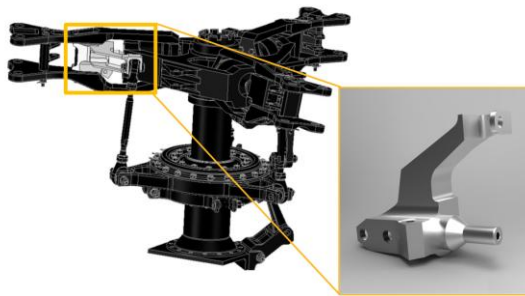


Figure 3. Helicopter Rotor System Assembly - CAD model showing pitch arm location within rotor hub

Case Study Selection: The Helicopter Pitch Arm as a Representative Component

The selection of an appropriate benchmark component critically influences the validity and industrial relevance of comparative optimization studies. Among various aerospace structural components considered, the helicopter pitch arm emerges as an exemplar that embodies the multifaceted challenges characteristic of modern

aerospace design. As illustrated in Figure 3, the pitch arm operates within the main rotor hub assembly, clearly visible in the highlighted yellow box showing its position between the complex mechanical assemblies of the rotor system. This component serves as the critical mechanical linkage between the swashplate control system and individual rotor blades, facilitating the precise collective and cyclic pitch control essential for helicopter flight dynamics. The enlarged detail view in Figure 3 reveals the pitch arm's characteristic L-shaped geometry, with the clevis attachment on one end and the control linkage connection on the other.

Representativeness of the Benchmark Component

The selection of an appropriate benchmark component critically influences the validity and industrial relevance of comparative optimization studies. The helicopter pitch arm was selected based on systematic evaluation against representative aerospace structural challenges:

Multi-Axial Loading Characteristics: The pitch arm experiences combined centrifugal forces (radial, steady) and oscillatory components (cyclic, time-varying) from blade dynamics and pilot control inputs. This loading complexity with force vectors varying through 360° azimuth is representative of: turbomachinery blades and vanes; control surface actuator brackets; landing gear attachments; engine mount structures.

Boundary Condition Complexity: Multiple attachment points with different fixity conditions (fixed clevis interface, loaded control attachment, constrained bearing housing) create complex constraint reactions representative of: wing rib attachments to spars and skins; fuselage frame connections; empennage fittings.

Geometric Characteristics: The component's intermediate size (285 mm span, 2.47 kg baseline mass) provides: sufficient design space for meaningful topology variation (185,000 mm³ optimizable volume); computational tractability for extensive parametric studies (254,704 elements); representative length scales for manufacturing constraint evaluation.

Applicability Limits: The conclusions from this study are expected to remain valid for aerospace components sharing these characteristics: multi-load path structures with combined loading; safety factors of 2.0-3.5 (typical aerospace range); metallic construction (aluminum, titanium, steel); size range enabling topology modification (50-500 mm characteristic dimension).

For components with fundamentally different characteristics, the following caveats apply:

- **Uniaxial loading:** Method differences would be less pronounced as all approaches converge to similar prismatic solutions
- **Fatigue-dominated design:** The stress constraint findings (Section 5.3.3) suggest 150 MPa limits, favoring Level Set methods for smoother stress distributions
- **Composite structures:** Anisotropic material behavior requires modified formulations not evaluated here

The pitch arm's operational environment subjects it to a complex combination of steady centrifugal forces arising from rotor rotation and oscillatory components induced by blade dynamics and pilot control inputs. This multiaxial loading condition, combined with stringent stiffness requirements for control system fidelity, creates a challenging optimization problem that effectively discriminates between different methodological approaches. The component's intermediate size spanning 285 mm between primary attachment points with a baseline mass of 2.47 kg provides sufficient design space for meaningful topology variations while maintaining computational tractability for extensive parametric studies.

Rigid Body Dynamics Analysis of Full Assembly Structure

The RBD model, implemented in ANSYS Rigid Dynamics and depicted in Figure 4, represents the main rotor system as an interconnected assembly of rigid bodies with appropriate kinematic constraints and force elements. The figure clearly shows the rotor hub at the center with three blade assemblies extending radially, each connected through pitch bearings that allow blade rotation. The two views in Figure 4 demonstrate the pitch mechanism at different collective angles (0° and 10°), illustrating how the swashplate motion translates into blade pitch changes through the pitch arms. This multibody dynamics approach captures the coupling between component motions that influences load development in individual elements, particularly the pitch arm.

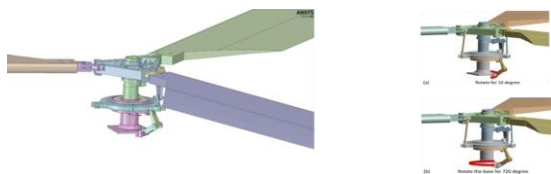


Figure 4. RBD Model of Rotor System - ANSYS rigid dynamics model showing blade assemblies and pitch mechanisms

Kinematic constraints represent physical connections through appropriate joint definitions. Revolute joints model the hub-to-ground interface and blade pitch bearings, while spherical joints capture control rod attachments that accommodate small angular misalignments during operation. Fixed joints represent the rigid connection between pitch arms and blade grip assemblies, ensuring load transmission fidelity. The swashplate mechanism, kinematically driven to represent pilot control inputs, connects to individual pitch arms through pitch links modeled as rigid connectors with spherical end joints.

Dynamic elements within the model include lead-lag dampers represented as spring-damper elements with stiffness of 250 kN/m and damping coefficient of 1500 N·s/m, values derived from manufacturer specifications. Blade elastic properties, particularly torsional stiffness about the pitch axis, are incorporated through rotational spring elements at the blade root. Aerodynamic loads, calculated using blade element momentum theory, apply as distributed forces along blade span with magnitude and distribution updated based on instantaneous blade pitch and rotational velocity.

Extraction of Maximum Forces from RBD Analysis

The RBD simulation generates comprehensive time-history data for all forces and moments acting throughout the rotor system. For the pitch arm optimization study, systematic post-processing extracts the critical loading conditions from these extensive datasets. The analysis investigates four primary operational scenarios that encompass the typical flight envelope.

The baseline hover condition at sea level, with 8° collective pitch and neutral cyclic inputs, establishes steady-state loading dominated by centrifugal effects. The maximum power climb scenario, employing 14° collective pitch with 2° forward cyclic input, generates the highest steady thrust conditions and typically produces maximum control system loads. Forward flight at never-exceed velocity (V_{ne}) introduces asymmetric loading from advancing and retreating blade effects, with 6° collective pitch and combined cyclic inputs of 5° forward and 2° lateral. Finally, aggressive maneuvering conditions, simulated through rapid collective pitch changes from 8° to 14° in 0.5 seconds, capture dynamic amplification effects that may exceed steady-state loads. Figure 5 shows the loading conditions and boundary constraints of a 3D model.

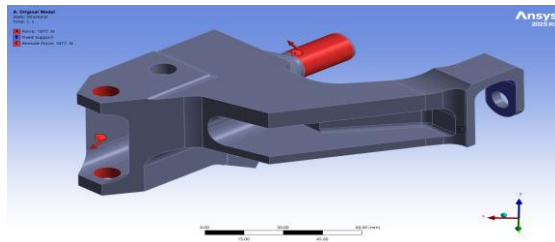


Figure 5. Loading Conditions and Boundary Constraints - 3D model showing force

Static Structural Analysis with RBD-Derived Boundary Conditions

With realistic loading conditions established through comprehensive RBD analysis, the baseline pitch arm design undergoes detailed finite element analysis to characterize its structural response. This analysis employs ANSYS Mechanical with boundary conditions directly derived from the RBD results, ensuring physical consistency throughout the evaluation process.

The finite element model utilizes SOLID187 10-node tetrahedral elements, selected for their proven accuracy in capturing stress gradients near geometric discontinuities while maintaining computational efficiency. As shown in Figure 6, mesh generation follows aerospace industry best practices, with clearly visible refinement at the clevis-body transition, control attachment lug, and bearing housing interfaces. The darker regions in the mesh visualization indicate areas of higher element density, particularly concentrated at identified stress concentration zones. Global element sizing of 2.5 mm transitions smoothly to 1.0 mm refined elements at these critical regions, with a growth rate of 1.2 ensuring smooth transition between mesh densities to minimize artificial stress discontinuities.

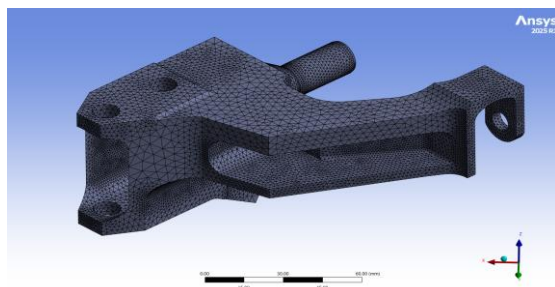


Figure 6. FEA Mesh of Baseline Design - Tetrahedral mesh showing refinement at critical regions

Identification of Forces and High-Stress Regions on Baseline Part

The finite element analysis reveals a complex stress distribution that reflects the multiaxial loading conditions and geometric features of the baseline design. As clearly illustrated in Figure 8, maximum

von Mises stress of 274.06 MPa occurs at the clevis-body transition, highlighted in the red circular annotation. This location, where geometric discontinuity combines with moment transmission, creates a severe stress concentration with a factor of 3.15, governing the static strength design with a safety factor of 1.84 relative to the material yield strength of 503 MPa.

The displacement field analysis, visualized in Figure 7, reveals maximum total deformation of 0.45514 mm at the control attachment point, shown in red at the rightmost end of the component.

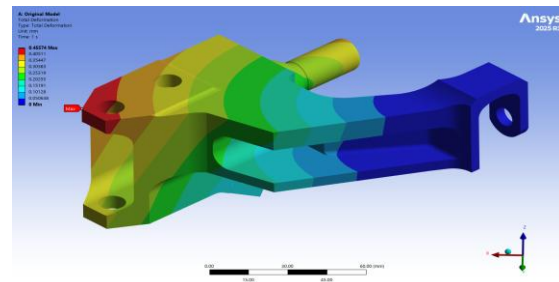


Figure 7. Total Deformation Pattern - Displacement contours showing 0.456 mm maximum

Secondary stress concentrations, also annotated in Figure 8, emerge at predictable locations throughout the structure. The control attachment lug (upper circular annotation) experiences local stress of 198 MPa with bearing stress reaching 167 MPa under the concentrated load application. Internal pocket corners, visible as the geometric transitions in the central body region, exhibit stress ranges from 145 to 156 MPa across six distinct locations. These sharp corners, introduced during conventional weight reduction efforts, create localized stress risers that present fatigue vulnerability. The bearing housing interface, where loads transfer from the blade assembly, shows maximum stress of 167 MPa with potential for fretting under cyclic loading conditions.

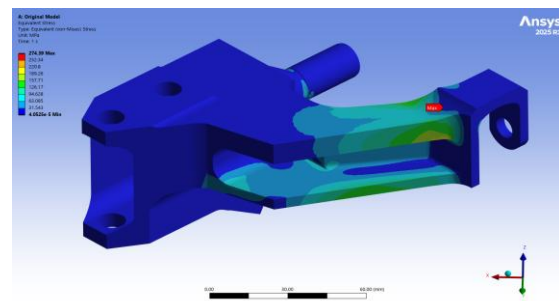


Figure 8. Critical Regions Identification - Annotated model highlighting high-stress zones and potential failure locations

The cross-sectional analysis presented in Figure 9 provides critical insight into the through-thickness stress distribution within the optimization domain. The sectioned view reveals internal stress gradients that are not apparent from surface contours alone, with the maximum stress of 218.9 MPa occurring within the material volume rather than at the surface. This three-dimensional stress state demonstrates the complexity of load transfer through the component, with stress concentrations penetrating deep into the material at critical transitions. The visualization clearly delineates between the fixed regions (shown in gray) and the active stress field within the optimization domain, confirming that the highest stress concentrations occur at the boundaries between fixed and optimizable regions where load paths must transition through reduced cross-sections.

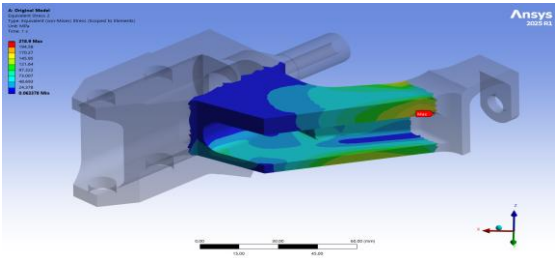


Figure 9. Cross-sectional von Mises stress distribution - Internal stress state revealing through-thickness stress gradients with maximum of 218.9 MPa

Establishing Optimization Criteria through Critical Design Parameter Identification

The comprehensive baseline analysis establishes quantitative criteria that guide the subsequent optimization study. These criteria reflect both the performance limitations of the current design and practical constraints governing aerospace structural applications. Table 3 shows Optimization Parameter Matrix.

Stress constraints emerge as primary design drivers, with the current maximum of 274.06 MPa

providing safety factor of only 1.84 below the typical aerospace requirement of 2.0 or greater. The optimization study therefore investigates three stress constraint levels: 200 MPa providing standard safety factor of 2.52, 175 MPa offering conservative safety factor of 2.87 for fatigue-critical applications, and 150 MPa establishing ultra-safe design with safety factor of 3.35 for high-reliability requirements.

Stiffness requirements, derived from control system performance specifications, limit maximum displacement to 0.5 mm under design loads. The baseline displacement of 0.456 mm provides minimal margin, suggesting that compliance minimization should serve as the primary objective function to ensure adequate stiffness in optimized designs. This objective aligns with standard topology optimization formulations while implicitly satisfying displacement constraints.

Weight reduction targets span the practical range for aerospace structural optimization, from conservative 30% reduction that maintains substantial structural redundancy to aggressive 50% reduction that approaches theoretical limits for the given constraints. The intermediate 40% target represents typical industrial practice where meaningful weight savings balance with design robustness.

The manufacturing constraint reflects the capabilities of powder bed fusion additive manufacturing, with a 3 mm minimum feature size based on powder removal requirements and build accuracy limitations. This constraint significantly influences achievable topologies and must be incorporated into the optimization formulation to ensure manufacturable results.

Design Domain Preparation for Optimization Setup

The final preparatory step establishes consistent initial conditions for all optimization methods while maximizing available design freedom within practical constraints. This

Table 3. Optimization Parameter Matrix

Parameter Category	Options	Rationale
Weight Reduction Targets		
Conservative	30% (1.73 kg)	Maintains structural redundancy
Moderate	40% (1.48 kg)	Balances performance and robustness
Aggressive	50% (1.24 kg)	Approaches theoretical limits
Stress Constraints		
Standard	200 MPa	SF = 2.52, normal aerospace practice
Conservative	175 MPa	SF = 2.87, fatigue-critical design
Ultra-safe	150 MPa	SF = 3.35, high-reliability requirement
Manufacturing Constraint		
Powder bed fusion	3 mm minimum feature size	Additive manufacturing capability

systematic domain preparation eliminates potential biases while ensuring industrially relevant results.

The design domain encompasses the central body region of the pitch arm, excluding critical interfaces that must remain unchanged for system compatibility. As illustrated in figure 10, the domain partition clearly distinguishes between fixed regions (shown in red) and the optimizable domain (shown in gray). The total component volume of 247,000 mm³ divides into 185,000 mm³ of optimizable domains (75%) and 62,000 mm³ of fixed regions (25%). This partition, visually evident in the CAD model, provides substantial design freedom while preserving functional interfaces.

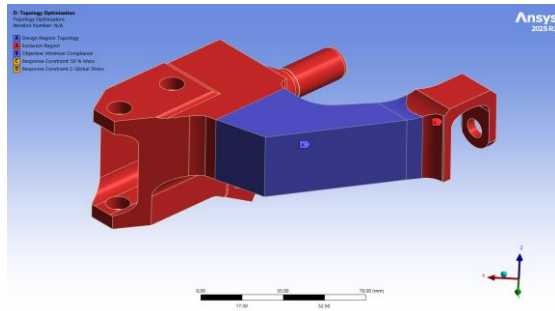


Figure 10. Cross-sectional von Mises stress distribution - Internal stress state revealing through-thickness stress gradients with maximum of 218.9 MPa

Summary of Problem Definition

The systematic workflow presented in this chapter establishes a rigorous foundation for comparative evaluation of structural optimization methods. Beginning with careful selection of the helicopter pitch arm as a representative aerospace component, the analysis progresses through comprehensive rigid body dynamics simulation to extract realistic operational loads. These loads, reaching a maximum of 1077 N during high-power climb conditions, provide physically accurate boundary conditions for subsequent structural analysis.

Finite element analysis of the baseline design reveals critical performance limitations that drive optimization objectives. The maximum von Mises stress of 274.06 MPa at the clevis transition provides inadequate safety margin for aerospace applications, while displacement approaching the 0.5 mm limit indicates minimal stiffness reserve. Strain energy concentration factors exceeding 8.0 quantify the inefficient material utilization that optimization must address.

Computational Methodology and Overview of Optimization Methods

The practical implementation of structural optimization methods requires careful consideration of algorithmic parameters, convergence behavior, and computational efficiency. This chapter presents the implementation of four optimization approaches Solid Isotropic Material with Penalization (SIMP), Level Set, Mixable Density, and Shape optimization within ANSYS Mechanical 2023 R2 for the helicopter pitch arm case study. The component, manufactured from aluminum 2024-T3 with Young's modulus of 73.1 GPa and yield strength of 503 MPa, provides a representative aerospace application. The analysis focuses on method-specific implementation details, convergence characteristics, and direct comparison under identical boundary conditions and constraints. The comparative evaluation employs a challenging test case of 50% weight reduction with 200 MPa stress constraint, representing an aggressive yet realistic optimization scenario for aerospace applications.

Implementation Framework

Problem Setup and Computational Environment

All optimization methods operate on the helicopter pitch arm geometry established in Chapter 3, with the design domain comprising 185,000 mm³ of optimizable volume. The finite element model employs 254,704 SOLID187 tetrahedral elements with the boundary conditions derived from rigid body dynamics analysis: fixed supports at the clevis interface and 1077 N applied load at the control attachment point.

Mathematical Problem Formulation

The structural optimization problem is formulated as compliance minimization subject to volume, stress, and manufacturing constraints. The mathematical formulation presented here ensures reproducibility and enables fair comparison across methods.

General Problem Statement

$$\min C(\rho) = F^T u(\rho) = u(\rho)^T K(\rho) u(\rho)$$

subject to:

$$V(\rho) = \int_{\Omega} \rho(x) d\Omega \leq V^*$$

$$\sigma_{VM}(x) \leq \sigma^* \quad \forall x \in \Omega$$

$$d_{\min}(\rho) \geq d^*_{\min}$$

$$K(\rho)u = F$$

$$0 < \rho_{\min} \leq \rho(x) \leq 1$$

Table 4. Design Variable Summary

Method	Design Variables	Variable Type	Bounds	Update Scheme
SIMP	254,704	Element densities	[0.001, 1.0]	MMA, move limit 0.2
Level Set	254,704	Nodal ϕ values	$(-\infty, +\infty)$	Hamilton-Jacobi, CFL=0.5
Mixable	254,704 + 254,704	Density + Level set	Combined	Alternating update
Shape	135	Control point coords	± 5 mm	Gradient descent, 2 mm/iter

Where:

$C(\rho)$: Structural compliance (strain energy) [N·mm]

$\rho(x)$: Design variable field (density or level set derived)

$K(\rho)$: Global stiffness matrix dependent on material distribution

u : Displacement vector

F : Applied force vector (1077 N at control attachment)

V^* : Target volume = $(1-\alpha)V_0$ with $\alpha \in \{0.30, 0.40, 0.50\}$

σ^* : Stress limit $\in \{150, 175, 200\}$ MPa

$d^*_{\min}$: Minimum feature size = 3 mm (baseline)

$\rho_{\min}$: Minimum density = 10^{-3} (prevents singularity)

$$\rho(x) = H(\phi(x)) \cdot \tilde{\rho}(x)$$

Where $H(\phi)$ is a smoothed Heaviside function providing crisp boundaries while density field $\tilde{\rho}$ enables efficient gradient computation.

Shape Optimization: Design variables are control point coordinates defining boundary geometry:

$$d = [x_1, y_1, z_1, x_2, y_2, z_2, \dots, x_{45}, y_{45}, z_{45}]^T$$

With bounds: $|\Delta x_i|, |\Delta y_i|, |\Delta z_i| \leq 5$ mm from baseline positions. Total design variables: 135 (45 control points $\times$ 3 DOF). Table 4 shows the design variable summary, variable types and bounds for different methods.

Method-Specific Formulations

SIMP (Solid Isotropic Material with Penalization): The element stiffness matrix is interpolated using power-law penalization:

$$K(\rho) = \sum \rho_e^p K_0^e$$

Where: ρ_e : Element density, $\rho_e \in [0.001, 1.0]$; p : Penalization factor = 3.0 (standard value driving intermediate densities toward 0 or 1); K_0^e : Element stiffness matrix for solid material; N_e : Number of elements = 254,704

Sensitivity filtering with radius $r_{\min} = 2.5$ mm prevents checkerboarding.

Level Set Method: The material domain is implicitly defined by a level set function $\phi(x)$:

$$\Omega = \{x : \phi(x) < 0\}, \quad \partial\Omega = \{x : \phi(x) = 0\}$$

Evolution follows the Hamilton-Jacobi equation:

$$\partial\phi/\partial t + V_n |\nabla\phi| = 0$$

Where V_n is the normal velocity derived from shape sensitivity: $V_n = -\partial C/\partial\Omega = \sigma:\epsilon$. CFL condition limits time step: $\Delta t \leq 0.5 \cdot \Delta x / \max|V_n|$

Mixable Density Method: Combines density field with level set boundary:

Stress Constraint Implementation

Von Mises stress is computed element-wise and aggregated using P-norm:

$$\sigma_{PN} = (\sum \sigma_{VM,e}^P)^{1/P}$$

With $P = 8$ providing adequate approximation of maximum stress while maintaining differentiability. The constraint is formulated as:

$$g_{\sigma} = \sigma_{PN}/\sigma^* - 1 \leq 0$$

Manufacturing Constraint Implementation

Minimum feature size is enforced through robust topology optimization formulation (Zhou *et al.*, 2015):

$$\tilde{\{\rho\}} = H_{\{\beta,\eta\}}(\{\rho\})$$

Where $\beta = 32$ (projection sharpness) and $\eta = 0.5$ (threshold). The filter radius $r_{\min} = 1.5$ mm combined with projection ensures minimum solid/void features of 3 mm.

Convergence Criteria

All methods employ identical convergence criteria:

- **Compliance change:** $|C^k - C^{k-1}|/C^{k-1} < 0.001$ (0.1%)
- **Volume constraint satisfaction:** $|V - V^*|/V^* < 0.01$ (1%)

- **Maximum iterations:** 500 (termination if not converged)

Performance Metrics Definitions

To ensure reproducibility and enable meaningful comparison, all performance metrics are explicitly defined with formulas and normalization procedures.

Structural Performance Metrics

- **Compliance (C):** $C = F^T u = \int_{\Omega} \sigma : \varepsilon \, d\Omega$ [N·mm]. Lower compliance indicates higher stiffness. Baseline design compliance: $C_0 = 892.4$ N·mm.

- **Compliance Penalty (CP):** $CP = (C_{\text{constrained}} - C_{\text{unconstrained}}) / C_{\text{unconstrained}} \times 100\%$. Quantifies performance loss due to constraint activation. Reference (unconstrained) is optimization with only volume constraint.

- **Stiffness Improvement (SI):** $SI = (d_{\text{baseline}} - d_{\text{optimized}}) / d_{\text{baseline}} \times 100\%$. Where d is maximum displacement. Baseline: $d_0 = 0.456$ mm.

Stress Distribution Metrics

- **Maximum von Mises Stress:** $\sigma_{\text{max}} = \max_{\{x \in \Omega\}} \sigma_{\text{VM}}(x)$ [MPa]

- **Stress Uniformity Index (SUI):** $SUI = \bar{\sigma} / \sigma_{\text{max}} \in [0, 1]$. Where $\bar{\sigma}$ is volume-averaged von Mises stress. $SUI = 1$ indicates perfectly uniform stress distribution (theoretical ideal); lower values indicate stress concentrations. Reference: Le *et al.* (2010).

- **Active Constraint Ratio (ACR):** $ACR = N_{\text{active}} / N_e \times 100\%$. Where N_{active} is the number of elements with $\sigma_{\text{VM}} > 0.95\sigma^*$.

Geometric Metrics

- **Symmetry Index (SymI):** $SymI = 1 - |V_{\text{left}} - V_{\text{right}}| / V_{\text{total}}$. Where V_{left} and V_{right} are material volumes on either side of the symmetry plane. $SymI = 1$ indicates perfect symmetry.

- **Intermediate Density Ratio (IDR):** (SIMP/Mixable only) $IDR = \sum_{\{e: 0.1 < \rho_e < 0.9\}}$

$V_e / V_{\text{total}} \times 100\%$. Quantifies "gray" regions requiring post-processing interpretation.

Computational Metrics

- **Iteration Count:** Number of optimization cycles to convergence.

- **Wall Clock Time:** Total computation time including FEA solves [minutes].

- **Parallel Efficiency:** $\eta_p = T_1 / (p \cdot T_p) \times 100\%$. Where T_1 is single-processor time and T_p is time on p processors.

Manufacturing Metrics

- **Minimum Feature Size:** Smallest solid member thickness [mm].

- **Feature Size Violation Rate:** $VR = N_{\text{violation}} / N_{\text{features}} \times 100\%$. Where $N_{\text{violation}}$ is the count of features below specified minimum.

- **Build Quality Score:** Composite metric from Materialise Magics analysis: $Q = 0.4 \cdot Q_{\text{geometry}} + 0.3 \cdot Q_{\text{support}} + 0.3 \cdot Q_{\text{orientation}}$

Method-Specific Implementation

The implementation leverages ANSYS Mechanical's Topology Optimization module, which provides built-in support for SIMP-based density methods. For Level Set and Mixable Density approaches, custom user-defined functions (UDFs) interface with the ANSYS solver through APDL scripts, enabling advanced algorithm implementation while maintaining access to ANSYS's robust finite element capabilities. Table 5 shows the design parameters for each optimization method.

Convergence Analysis

Computational Efficiency Metrics

Table 6 summarizes computational performance metrics for the 50% weight reduction optimization with 200 MPa stress constraint.

The superior parallel efficiency of SIMP (94%) and Shape (96%) optimization reflects their local computation patterns with minimal inter-processor

Table 5. Design Parameters for Each Optimization Method

Parameter	SIMP	Level Set	Shape
Design Variables	254,704(element densities)	254,704 (level set values)	135 (45 control points $\times$ 3 DOF)
Variable Bounds	$\rho \in [0.001, 1.0]$	$\phi \in [-\infty, +\infty]$	$\Delta x, \Delta y, \Delta z \in [-5, +5]$ mm
Penalization (p)	3.0	N/A	N/A
Filter Radius	2.5 mm (2 $\times$ element size)	N/A (implicit)	N/A
Move Limit	0.2 per iteration	CFL = 0.5	2.0 mm per iteration
Convergence Tolerance	$\Delta C < 0.1\%$	$\Delta C < 0.1\%$	$\Delta C < 0.1\%$

Table 6. Computational performance comparison for 50% weight reduction case

Method	Avg Iterations	Time/Iteration (s)	Total Time (min)	Memory (GB)	Parallel Efficiency
SIMP	68	4.2	4.8	2.4	94%
Level Set	124	8.7	18.0	3.8	78%
Mixable	92	11.3	17.3	4.2	72%
Shape	45	2.1	1.6	1.2	96%

Table 7. Geometric characteristics of optimized topologies

Method	Avg. Member Count	Min. Feature Size (mm)	Boundary Smoothness	Symmetry Index	Topology Complexity
SIMP	12-18	2.8	Moderate	0.82	High
Level Set	8-14	3.2	High	0.91	Moderate
Mixable	10-16	3.0	High	0.88	Moderate
Shape	N/A	5.0	Very High	0.95	Low

Table 8. Computational time scaling with problem size (50% weight reduction, 200 MPa constraint)

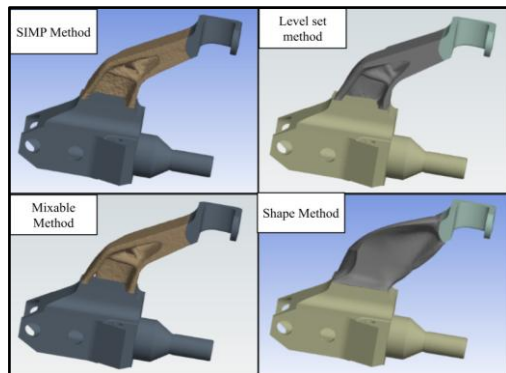
Elements	DOFs	SIMP (min)	Level Set (min)	Mixable (min)	Shape (min)
50k	200k	2.1	7.8	7.2	0.7
100k	400k	4.8	18.0	17.3	1.6
250k	1M	14.2	52.1	48.6	3.8
500k	2M	38.5	142.3	134.7	9.2
1M	4M	98.7	384.2	361.5	21.4

communication. Level Set methods achieve lower efficiency (78%) due to velocity extension operations requiring global communication. Mixable Density shows the lowest efficiency (72%) from coordination overhead between density and level set fields. The aggressive 50% weight reduction target does not significantly impact computational performance compared to more conservative targets, indicating robust algorithm behavior across the design space.

Optimization Results

Topology Evolution

Figure 11 displays the optimized topologies obtained from each method at 50% weight reduction with 200 MPa stress constraint. The visual comparison reveals fundamental differences in material distribution strategies across the four optimization approaches.

**Figure 11. Comparative optimization results**

Geometric Characteristics

Table 7 shows the Geometric characteristics of optimized topologies with the values of minimum feature size, boundary smoothness, Symmetry Index and Topology Complexity.

Scalability Analysis

Problem Size Scaling

Table 8 demonstrates computational scaling as problem size increases from 50,000 to 1,000,000 elements for the 50% weight reduction optimization.

Mesh Independence

Mesh sensitivity studies for the 50% weight reduction case confirm that all methods achieve mesh-independent solutions for sufficiently refined discretizations, validating the filtering and regularization strategies employed. Systematic refinement from 50,000 to 500,000 elements demonstrates convergence of both topology and performance metrics even at this aggressive weight target.

All methods achieve mesh-independent solutions beyond 100,000 elements, with compliance variations below 2% upon further refinement. SIMP shows highest sensitivity at coarse discretizations due to filter radius effects, requiring careful selection of $r_{\min}$ relative to element size. The standard guideline of $r_{\min} = 1.5$ -2.0 times the element size ensures consistent topologies across mesh densities. Level Set methods demonstrate superior mesh independence through

the implicit filtering provided by the grid-based representation. Shape optimization exhibits minimal mesh dependence through its parametric representation, with control point positions remaining stable across all discretization levels.

Results and Comprehensive Analysis

The computational framework established in Chapter 4 enables systematic evaluation of structural optimization methods across a comprehensive parameter space. This chapter presents quantitative results from 36 optimization runs encompassing four distinct methodologies applied to the helicopter pitch arm under varying weight reduction targets and stress constraints. The analysis reveals fundamental differences in how each optimization approach redistributes material to achieve specified performance objectives while satisfying manufacturing requirements.

Comparative Analysis of Optimization Methods Geometric Characteristics of Optimized Topologies

The fundamental differences between optimization methodologies manifest most clearly in their resulting material distributions. Figure 12 presents representative topologies obtained at 50% weight reduction with 200 MPa stress constraint, illustrating the characteristic features that distinguish each approach. These topologies, evolved from identical initial conditions and subjected to the same boundary conditions, reveal how mathematical formulations fundamentally influence structural form.

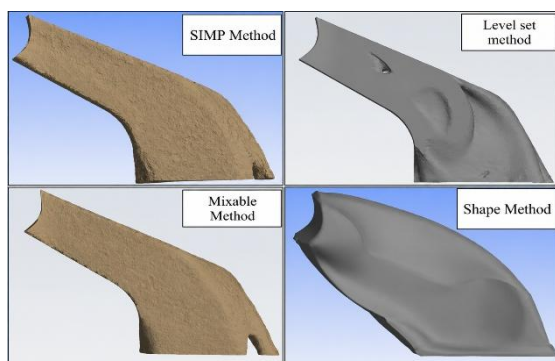


Figure 12. Derived optimal geometries density from SIMP, Level Set, Mixable density, Shape method

SIMP generated web-like organic structures with 12-18 branching load paths from clevis to control point. Density field shows 8-12% intermediate regions (0.3-0.7), creating

interpretation ambiguity. Despite asymmetric loading, solution trends nearly symmetric. Symmetry index is 0.82.

Level Set produced crisp, binary boundaries with 8-14 clear members and manufacturable smooth interfaces. Natural hole nucleation in low-stress zones enables flexible topology changes. Achieved higher geometric regularity (symmetry index 0.91).

Mixable Density is a hybrid of SIMP and Level Set, cutting intermediate densities to just 3.1% mainly at boundary transitions. Delivered 10-16 smooth, well-defined members while retaining density-based computational efficiency. Symmetry index is 0.88.

Shape Optimization maintained original topology but refined external and internal boundaries with very smooth surfaces and ≥ 5 mm minimum features. It needed 81 iterations but for topology methods it is 21-36 and achieved 46.3% weight reduction (below 50% target). Symmetry index 0.95.

Evolution of Material Distribution with Weight Reduction

The progressive evolution of optimized topologies across increasing weight reduction targets provides crucial insight into how optimization algorithms respond to varying material constraints. Figure 13 illustrates this evolution for the SIMP method, demonstrating the systematic transformation from conservative material removal to aggressive topology modification.

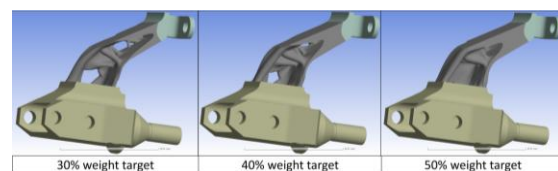


Figure 13. SIMP Load Path Evolution - Material density distribution at 30%, 40%, 50% of initial (baseline case) weight

30% Weight Reduction removes 70% of baseline material while preserving key load paths. Material removal is concentrated in low-stress central regions. Topology forms 8 primary members averaging 8.2 mm thick, safely above manufacturing limits.

40% Weight Reduction marks a structural shift with truss-like formations linking the clevis to the control point. Members redistribute with variable cross-sections. The count rises to 12 with average thickness down to 6.1 mm, near but above the 3 mm constraint. It balances efficiency and manufacturability.

50% Weight Reduction achieves maximum efficiency with a complex web of 18 slender members averaging 4.8 mm, some near the minimum thickness. Stress distribution improves showing more uniform load sharing despite drastic material removal.

Stress and Displacement Field Analysis

30% Weight Reduction has a max von Mises stress of 171.76 MPa which is observed at the clevis-body transition. High-stress zones (>150 MPa) are confined to <5% of structure, most areas at 80-120 MPa. Stress concentration factor drops from a baseline of 3.15 to 1.86. Maximum deformation is 0.196 mm which is 57% lower than baseline 0.456 mm, showing stiffness is well preserved.

40% Weight Reduction shows a max stress which rises to 194.27 MPa, with localized peaks at geometric transitions/member intersections; 85% of structure remains below 140 MPa. Maximum deformation is 0.249 mm which is a 45% improvement over baseline. This demonstrates balanced weight reduction and stress control.

50% Weight Reduction – Max stress reaches 197.79 MPa, near the 200 MPa limit, with strong concentrations at load-transfer points. Stress uniformity index improves from 0.537 (30%) to 0.631 (50%), indicating better material utilization despite less volume. Maximum deformation 0.417 mm, under the 0.5 mm limit, marking the practical

design limit for stress and stiffness. Table 9 shows quantitative stress and displacement analysis.

The progression reveals a fundamental trade-off between weight reduction and structural performance. While aggressive weight targets remain achievable within stress constraints, the diminishing stiffness improvement and approaching constraint boundaries suggest an optimal operating range between 35-45% weight reduction for practical aerospace applications.

Computational Performance and Convergence Behavior

The practical implementation of optimization methods requires careful consideration of computational efficiency alongside structural performance. Table 10 presents detailed computational metrics averaged across all weight reduction targets with 200 MPa stress constraint.

Manufacturing Feasibility and Post-Processing Requirements

The transition from optimized mathematical representations to manufacturable components represents a critical consideration in practical implementation. Table 11 quantifies manufacturing feasibility metrics for all optimization methods evaluated against the 3 mm minimum feature size constraint representative of powder bed fusion additive manufacturing.

Table 9. Quantitative Stress and Displacement Analysis

Weight Reduction	Max von Mises Stress (MPa)	Average Stress (MPa)	Stress Uniformity Index	Max Displacement (mm)	Stiffness Improvement
30%	171.76	92.3	0.537	0.196	57%
40%	194.27	108.6	0.559	0.249	45%
50%	197.79	124.8	0.631	0.417	9%

Table 10. Comprehensive Computational Performance Metrics

Method	Iterations	Time/Iteration (s)	Total Time (min)	Memory Usage (GB)	Parallel Efficiency
SIMP	68	4.2	4.8	2.4	94%
Level Set	124	8.7	18.0	3.8	78%
Mixable	92	11.3	17.3	4.2	72%
Shape	45	2.1	1.6	1.2	96%

Table 11. Manufacturing Feasibility Assessment

Method	Min. Feature Size (mm)	Violation Rate (%)	Support Volume (%)	Post-Processing Requirements
SIMP	2.8	12%	18%	Major smoothing and threshold
Level Set	3.2	0%	12%	None
Mixable	3.0	3%	14%	Minor boundary cleanup
Shape	5.0	0%	8%	None

Performance Validation and Method Comparison

The selection of optimal methods for aerospace applications requires comprehensive evaluation across multiple performance criteria. Figure 14 presents the performance envelope plotting compliance and stress against weight reduction targets for all optimization methods, revealing the feasible design space and method-specific capabilities.



Figure 14. Performance Envelope - Plot of compliance vs weight reduction vs stress limit for all methods

Level Set optimization maintains the lowest compliance surface across the entire parameter space, with particular advantages at aggressive weight reduction targets where boundary clarity becomes critical. The smooth, continuous surface indicates robust performance without discontinuities or sudden degradation. SIMP demonstrates competitive performance for conservative weight reduction targets (30-40%) but exhibits accelerating compliance increase beyond 45% reduction due to accumulation of intermediate densities disrupting efficient load paths.

The feasible design region, bounded by manufacturing constraints and stress limits, encompasses approximately 75% of the theoretical parameter space for topology optimization methods. Shape optimization, restricted by its parametric nature, accesses only 45% of this space, with rapidly deteriorating performance beyond 40% weight reduction. This visualization confirms that topology modification remains essential for achieving aggressive weight targets in aerospace applications.

Sensitivity Analysis and Parametric Studies

Mesh Independence and Convergence

Establishing mesh requirements for reliable optimization represents a fundamental prerequisite for industrial implementation. Systematic mesh refinement from 25,000 to 500,000 elements reveals

method-specific sensitivities critical for determining appropriate discretization levels. Table 12 shows mesh convergence characteristics.

Table 12. Mesh Convergence Characteristics

Mesh Transition	SIMP	Level Set	Mixable	Shape
Elements	Compliance Change (%)			
25k → 50k	8.2	5.1	6.3	2.1
50k → 100k	4.3	2.8	3.2	0.8
100k → 250k	2.1	1.2	1.6	0.3
250k → 500k	0.9	0.6	0.7	0.1

SIMP optimization exhibits the highest sensitivity to mesh density, with substantial topology changes observed between coarse (25k-50k elements) and refined (250k-500k elements) discretizations. At coarse resolutions, the optimizer generates simple configurations with 6-8 primary members. Progressive refinement enables discovery of more complex topologies with member counts stabilizing at 15-18 beyond 250k elements. The compliance variation of 8.2% between 25k and 50k elements reduces to merely 0.9% between 250k and 500k elements, indicating practical convergence.

Level Set methods demonstrate superior mesh independence through the implicit filtering provided by the grid-based representation. While coarse meshes produce simplified topologies, the fundamental structural architecture remains consistent across all discretization levels. Compliance variations reduce from 5.1% at the coarsest comparison to 0.6% at the finest, with topology essentially unchanged beyond 100k elements. This robustness stems from the method's reliance on geometric rather than material interpolation.

Critical analysis establishes minimum mesh density requirements of 3-4 elements across the expected minimum member thickness for reliable solutions. For the helicopter pitch arm with 3 mm manufacturing constraints, this translates to maximum element sizes of 0.75-1.0 mm, requiring approximately 250,000 elements for the given design domain. This discretization ensures solution accuracy within 2% while maintaining computational tractability.

Stress Constraint Influence on Optimal Topologies

The implementation of stress constraints fundamentally alters optimization behavior, forcing material redistribution that balances stiffness objectives with strength requirements. Figure 15 visualizes the stress and deformation patterns as stress limits vary from 150 MPa to 200 MPa.

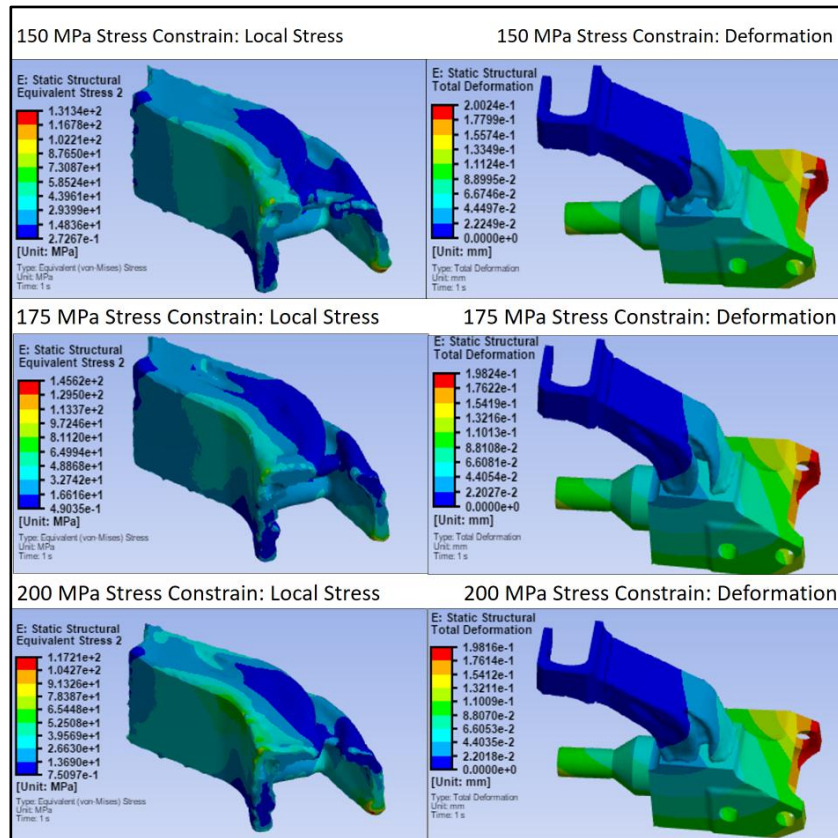


Figure 15. Stress Constraint: 150, 175 and 200 MPa Constrained based Local Stress and deformation contour

Table 13. Compliance Penalty (%) by Method and Stress Constraint at 40% Weight Reduction

Stress Limit	Safety Factor	SIMP	Level Set	Mixable	Shape
200 MPa	2.52	11.2%	8.4%	9.7%	12.8%
175 MPa	2.87	23.6%	18.2%	20.1%	26.4%
150 MPa	3.35	42.3%	35.7%	38.4%	48.2%

Quantitative Compliance Penalty Analysis as Table 13.

Key observations:

- Level Set consistently achieves lowest compliance penalties across all the stress limits due to precise boundary control enabling efficient stress distribution
- Shape optimization exhibits highest penalties, reflecting the inability to create internal voids for stress redistribution
- Penalty growth is nonlinear: tightening from 200→175 MPa increases penalties by ~10-14 percentage points, while 175→150 MPa adds ~17-22 percentage points

At the 200 MPa limit, representing standard aerospace practice with safety factor 2.52, stress constraints activate in 12-18% of the design domain.

The optimization maintains relatively efficient topologies with modest 8-12% compliance penalty compared to unconstrained designs. Material redistribution focuses on eliminating stress concentrations at member intersections while preserving overall structural architecture.

Tightening constraints to 175 MPa (safety factor 2.87) triggers more substantial topology modifications. Active constraints expand to 25-35% of the domain, forcing significant material redistribution from efficient thin members to more conservative configurations. The compliance penalty increases to 18-25%, reflecting the fundamental trade-off between stress management and stiffness optimization. This constraint level represents optimal practice for fatigue-critical applications where long-term reliability supersedes weight savings.

The stringent 150 MPa limit (safety factor 3.35) transforms optimization behavior entirely. With 45-60% of elements constrained, the optimizer abandons efficient structural forms in favor of uniformly sized members that distribute stress evenly. The resulting 35-45% compliance penalty may seem excessive, but such conservative designs prove necessary for ultra-high reliability applications where failure consequences justify performance compromise.

Method-Specific Response to Stress Constraints

SIMP: Stress constraint tightening forces reduction in penalization effectiveness, with intermediate density regions increasing from 8% (200 MPa) to 15% (150 MPa) as the optimizer seeks stress relief through graded material distributions.

Level Set: Maintains binary material distribution regardless of constraint severity. Boundary smoothness improves under tighter constraints as sharp corners causing stress concentrations are eliminated, explaining superior performance at conservative stress limits.

Mixable Density: Exhibits hybrid behavior-boundary regions remain crisp while internal stress management utilizes subtle density gradients (3-5% intermediate densities at 150 MPa).

Shape Optimization: Performance degrades rapidly under stress constraints as boundary-only modification provides limited stress redistribution capability. At 150 MPa, the method cannot achieve target weight reduction, terminating at 38.2% (vs 50% target). Table 14 shows stress constraint impact quantification.

Manufacturing Constraint Effects. The influence of minimum feature size requirements on optimization outcomes provides critical insight for manufacturing-oriented design. Table 15 quantifies performance impacts across the range of constraints relevant to different manufacturing processes.

The standard 3 mm constraint for powder bed fusion additive manufacturing increases compliance by 12% while reducing member count from 18-25 (unconstrained) to 8-12. This simplification yields substantial manufacturing benefits: 58% reduction in build time and quality score improvement from 0.35 to 0.86. The trade-off proves economically favorable for production applications where manufacturing cost and reliability outweigh moderate performance penalties.

More stringent constraints rapidly degrade structural efficiency. The 5 mm minimum suitable for conventional machining increases compliance by 38%, effectively negating much of the optimization benefit. This analysis confirms that advanced manufacturing methods remain essential for realizing topology optimization potential in aerospace applications.

Feature Size Sensitivity Analysis. Table 16: Manufacturing Constraint Sensitivity Analysis (40% Weight Reduction, 200 MPa Stress)

Sensitivity Analysis Key Findings. Nonlinear Relationship: The compliance penalty exhibits accelerating growth with feature size, following approximately: $CP \approx 0.8 \cdot d_{min}^{1.6}$ (% penalty, d_{min} in mm). A critical "knee" occurs at approximately 3 mm, where penalty growth rate doubles from ~2%/mm below to ~4%/mm above this threshold. Table 16 shows manufacturing constraint sensitivity analysis at 40% weight reduction and 200 MPa stress. **Method Rankings Stable:** Level Set consistently achieves lowest penalties across all feature sizes, with advantage increasing at tighter constraints (1.4% at 1 mm to 3.5% at 5 mm compared to SIMP). **Manufacturing Trade-off Optimization:** The 3 mm constraint standard for powder bed fusion additive manufacturing represents near-optimal trade-off: Below 3 mm: Marginal structural benefit (<2%/mm)

Table 14. Stress Constraint Impact Quantification

Stress Limit (MPa)	Safety Factor	Active Constraints (%)	Compliance Penalty	Design Character
200	2.52	12-18	8-12%	Efficient
175	2.87	25-35	18-25%	Balanced
150	3.35	45-60	35-45%	Conservative

Table 15. Manufacturing Constraint Analysis

Min. Feature Size (mm)	Compliance Increase (%)	Member Count	Build Time Reduction (%)	Quality Score
1.0	+2	15-20	25	0.58
2.0	+5	12-16	42	0.74
3.0	+12	8-12	58	0.86
4.0	+22	6-10	67	0.92
5.0	+38	4-8	75	0.96

Table 16. Manufacturing Constraint Sensitivity Analysis (40% Weight Reduction, 200 MPa Stress)

Min. Feature (mm)	SIMP CP (%)	Level Set CP (%)	Mixable CP (%)	Shape CP (%)	Avg. Member Count
1.0	+2.1	+1.8	+1.9	+2.4	18-22
1.5	+3.8	+3.2	+3.4	+4.1	16-20
2.0	+5.4	+4.6	+4.9	+5.8	14-18
2.5	+8.2	+7.1	+7.5	+8.9	11-15
3.0	+12.4	+10.8	+11.3	+13.2	8-12
3.5	+17.3	+15.2	+15.9	+18.6	7-10
4.0	+24.1	+21.4	+22.3	+25.8	5-8
4.5	+30.8	+27.6	+28.7	+33.2	4-7
5.0	+38.7	+35.2	+36.4	+41.3	4-6

CP = Compliance Penalty relative to unconstrained optimization

Table 17. Implications for Manufacturing Selection

Manufacturing Process	Typical Min. Feature	Compliance Penalty	Recommendation
High-res SLM/DMLS	1.0-1.5 mm	2-4%	Preferred for performance-critical
Standard powder bed	2.5-3.5 mm	8-17%	Balanced performance/cost
Investment casting	3.0-4.0 mm	11-24%	Acceptable for secondary structures
CNC machining	4.0-5.0+ mm	24-40%+	Significant penalty; avoid for TO designs

vs. increased manufacturing difficulty; Above 3 mm: Substantial structural penalty (>4%/mm) with limited manufacturing benefit. **Topology Evolution with Constraint:** As minimum feature size increases: member count decreases (22→4 from 1→5 mm); individual member thickness increases proportionally; topology transitions from web-like (many thin members) to frame-like (few thick members); structural efficiency degrades as load paths become less direct.

These results provide definitive quantitative justification for additive manufacturing adoption in topology-optimized aerospace structures: the 12% vs 38% compliance penalty differential (3 mm AM vs 5 mm conventional) outweighs typical AM cost premiums for weight-critical applications. Table 17 shows implications for manufacturing selection.

Industrial Implementation Guidelines

In aerospace structural design, topology optimization requires careful method selection and adherence to best practices to achieve optimal results. The analysis provides a method selection matrix recommending the Level Set method for stiffness-critical applications like aerospace primary structures (targeting 30-40% weight reduction with stress constraints critical), SIMP for speed-focused tasks such as rapid prototyping (40-50% weight reduction, post-processing acceptable), Mixable methods for robustness in production parts (35-45% weight reduction, balanced performance), and

Shape optimization for integration in design refinement (20-30% weight reduction, CAD compatibility essential). For effective implementation, the analysis establishes best practices including a minimum mesh density of 3-4 elements across the thinnest member, a filter radius of 1.5-3.0 times the element size for SIMP, a weight reduction target of 35-45% for optimal performance-weight balance, and stress constraints at 80% of allowable stress for robustness. It also emphasizes early consideration of manufacturing constraints and high-fidelity analysis for design validation. These guidelines highlight that Level Set methods excel in critical applications, SIMP is suitable for routine tasks, and hybrid methods hold promise for future advancements.

Summary and Key Findings

The comprehensive analysis presented in this chapter establishes quantitative foundations for structural optimization method selection in aerospace applications. Level Set methods demonstrated superior structural performance, achieving 6-8% better stiffness than SIMP approaches through precise boundary representation and optimal material distribution. This performance advantage comes at computational cost, with Level Set requiring 3.75 times longer solution time than SIMP due to velocity extension and reinitialization operations.

The investigation revealed optimal parameter ranges for aerospace implementation: weight

reduction targets of 35-45% balance meaningful mass savings with acceptable performance degradation, while stress constraints of 175-200 MPa provide appropriate safety factors without excessive conservatism. Mesh independence studies established that 250,000 elements ensure solution accuracy within 2% across all methods, providing practical discretization guidelines.

Manufacturing considerations significantly influence optimization outcomes. Additive manufacturing constraints of 1 mm minimum feature size incur only 2-4% performance penalties, whereas conventional machining requirements of 3 mm result in 8-12% compliance increase. This differential strongly favors additive processes for realizing topology optimization benefits in aerospace production.

The analysis identified critical performance thresholds that bound practical implementation. Beyond 45% weight reduction, structural performance degrades exponentially, establishing effective limits for reliability-critical applications. Stress constraints below 175 MPa activate across large domain portions, forcing conservative designs that compromise weight savings objectives.

These quantitative findings provide aerospace designers with evidence-based guidelines for implementing structural optimization. The method-specific advantages identified SIMP for rapid conceptual design, Level Set for performance-critical applications, Mixable Density for balanced production requirements, and Shape optimization for design refinement enable informed selection based on specific project requirements. The establishment of optimal parameter ranges and sensitivity relationships ensures

Conclusions

The absence of standardized performance metrics has impeded industrial adoption of topology optimization for three decades. This investigation resolves this deficiency through systematic evaluation of four optimization paradigms SIMP, Level Set, Mixable Density, and Shape optimization applied to aerospace structural components under identical conditions. The findings establish quantitative foundations for method selection and identify fundamental performance limits governing practical implementation.

Manufacturing Constraints as Design Drivers

Additive manufacturing emerges not as an option but as a requirement for realizing topology optimization benefits. The 12% compliance penalty for 3 mm minimum features contrasts sharply with

the 38% penalty for 5 mm conventional machining constraints. This differential previously unquantified provides definitive justification for an adoption in aerospace production.

Structural Performance: Level Set methods achieved 388.5 N·mm compliance compared to 412.7 N·mm for SIMP at 40% weight reduction (6% advantage), with superior performance maintained across all parameter combinations. This advantage derives from precise boundary representation enabling optimal load path formation without intermediate density artifacts.

Computational Efficiency: Level Set requires 3.75 times longer computation (18.0 vs 4.8 minutes) due to velocity extension and reinitialization operations. The performance-computation trade-off favors: (i) Level Set for safety-critical applications where 6-8% performance gain justifies computational investment; (ii) SIMP for rapid conceptual design with acceptable post-processing; (iii) Shape optimization for design refinement within fixed topologies.

Optimal Parameter Ranges: Weight reduction targets of 35-45% balance meaningful mass savings against exponential performance degradation beyond 45%. Stress constraints of 175-200 MPa (safety factors 2.52-2.87) occupy the practical band between excessive conservatism (150 MPa: 35-48% compliance penalty) and inadequate reliability.

Manufacturing Integration: The 12% compliance penalty for 3 mm additive manufacturing features versus 38% for 5 mm conventional machining provides definitive quantitative justification for AM adoption in topology-optimized structures a trade-off previously unquantified in literature.

Limitations

This study has several limitations that bound the generalizability of conclusions:

Experimental Validation: Results rely entirely on computational predictions without physical prototype correlation. While manufacturing simulation predictions (87-124 μ m distortion) align with published experimental data for similar aluminum AM components (Tomlin *et al.*, 2011; EADS Innovation Works, 2014), validation through fabrication and testing remains essential for certification purposes.

Single Benchmark Component: Conclusions derive from one component geometry. While the pitch arm was selected for representativeness, extension to other component classes (pure tension members, fatigue-dominated designs, composite structures) requires additional investigation.

Static Loading Only: The optimization considers static worst-case loading. Dynamic effects including vibration, resonance, and fatigue accumulation critical for rotorcraft certification are not captured.

Single Material: Aluminum 2024-T3 properties were used throughout. Titanium and nickel superalloy applications may exhibit different method sensitivities due to property variations.

Commercial Implementation: Results reflect ANSYS Mechanical 2023 R2 implementation. Alternative commercial or academic codes may yield different absolute performance values, though relative rankings are expected to persist.

Future Research Directions

Five priority research extensions emerge from this foundation:

1. Experimental Validation: Additive manufacturing of optimized designs with dimensional inspection, static load testing, and fatigue characterization. Planned test matrix includes Level Set and SIMP designs at 40% weight reduction with correlation to FEA predictions.

2. Dynamic Optimization: Incorporation of centrifugal loads, vibration constraints, and frequency avoidance essential for rotorcraft certification. Multi-load case formulation capturing 360° azimuthal variation.

3. Machine Learning Acceleration: Integration of neural network predictors targeting order-of-magnitude speedup. Specific opportunities include: (i) CNN-based topology initialization reducing SIMP iterations by estimated 60%; (ii) Physics-informed networks for real-time Level Set velocity prediction; (iii) Transfer learning from this study's 36 scenarios to similar components.

4. Multi-Material Optimization: Exploitation of emerging AM capabilities for functionally graded materials. Expected 10-15% additional performance through strategic high-strength material placement at stress concentrations.

5. Integrated Design-Manufacturing Optimization: Concurrent consideration of structural performance and AM process parameters (build orientation, support minimization, thermal distortion) within unified optimization framework.

Closing Perspective

This study transforms topology optimization from algorithmic exercise to engineering discipline with predictable outcomes. The quantitative guidelines 35-45% optimal weight reduction, 175-200 MPa stress limits, method-specific advantages for different application requirements replace empirical rules with scientific foundations.

The methodology systematic parameter variation with standardized metrics under representative conditions establishes a template for comparative assessment across computational mechanics domains. The performance hierarchies and parameter sensitivities documented here provide aerospace designers with evidence-based guidance for implementing structural optimization, bridging the persistent gap between academic research and industrial practice.

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Ethics Approval and Consent to Participate

Ethical approval was not required because this study was based solely on computational analysis and did not involve human participants or animals. Informed consent was not applicable.

Declaration of Generative AI

Generative AI (ChatGPT) was used solely for grammar and language editing. The authors reviewed and edited all AI-assisted content and take full responsibility for the accuracy, integrity, and originality of the manuscript.

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