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Research Paper

STRUCTURAL OPTIMIZATION OF MECHANICAL COMPONENTS USING GENERATIVE DESIGN APPROACHES

¹Swamynath Kavali, ²Chandinibeebi Sheik, ³Chitme Sachinkumar, ⁴G Raja Siddartha

^{1,2,3}Assistant Professor, ⁴Student

Department of Mechanical Engineering

Sri Chaitanya Technical Campus

ABSTRACT

Structural optimization has become a critical aspect of modern mechanical engineering due to increasing demands for lightweight, high-strength, and cost-effective components. Traditional design methodologies often rely on iterative manual modifications, which may limit the exploration of innovative design alternatives. Generative Design (GD) approaches utilize computational intelligence, topology optimization, and artificial intelligence algorithms to automatically generate multiple feasible design solutions based on predefined constraints and performance objectives. This study investigates the application of generative design techniques for structural optimization of mechanical components with the aim of reducing material consumption while maintaining structural integrity and functional performance. The proposed methodology integrates computer-aided design (CAD), finite element analysis (FEA), topology optimization, and performance evaluation to develop optimized component geometries. Various loading and boundary conditions are considered to assess stress distribution, deformation behavior, factor of safety, and weight reduction. Comparative analysis demonstrates that generative design significantly improves structural efficiency by producing lightweight configurations with enhanced load-bearing capabilities. The findings reveal that optimized components achieve substantial material savings and improved performance compared to conventional designs. Furthermore, generative design facilitates rapid design exploration, reduces development time, and supports sustainable manufacturing practices. The study highlights the potential of generative design as an advanced engineering tool for next-generation mechanical component development.

Keywords: Generative Design, Structural Optimization, Mechanical Components, Topology Optimization, Finite Element Analysis, Lightweight Design, CAD, Artificial Intelligence, Design Automation, Sustainable Manufacturing.

I. INTRODUCTION

Structural optimization has become one of the most important areas of modern mechanical engineering due to the increasing demand for lightweight, high-strength, and cost-effective products. Mechanical components used in automotive, aerospace, industrial machinery, and manufacturing systems are continuously subjected to complex loading conditions that require optimal structural performance.

Traditional design methods often rely on engineering experience and iterative modifications, which can be time-consuming and may not always result in the most efficient design. As industries seek innovative solutions to improve product performance while reducing material usage and manufacturing costs, advanced optimization techniques have gained significant attention.

Generative design is an emerging computational design methodology that utilizes artificial intelligence, optimization algorithms, and simulation technologies to automatically generate multiple design alternatives based on specified objectives and constraints. Unlike conventional design approaches where engineers manually create and modify models, generative design explores a vast range of possible geometries and identifies solutions that satisfy performance requirements. This capability enables engineers to discover innovative structural configurations that may not be achievable through traditional design processes.

The advancement of computer-aided design (CAD), finite element analysis (FEA), and high-performance computing has significantly enhanced the effectiveness of generative design systems. By integrating these technologies, engineers can evaluate numerous design alternatives in a relatively short period of time. The generated designs are assessed for factors such as stress distribution, deformation, stiffness, durability, and material utilization. As a result, generative design supports informed decision-making and improves the overall efficiency of the product development cycle.

One of the major advantages of generative design is its ability to achieve substantial weight reduction while maintaining structural integrity. Lightweight components contribute to improved fuel efficiency, reduced energy consumption, lower operational costs, and enhanced system performance. In industries such as aerospace and automotive engineering, even small reductions in component weight can lead to significant improvements in overall efficiency and sustainability. Consequently, generative design has become a valuable tool for developing optimized mechanical structures that satisfy stringent performance requirements.

The emergence of additive manufacturing technologies has further accelerated the adoption of generative design approaches. Many optimized

geometries generated through computational algorithms contain complex internal structures and organic shapes that are difficult to manufacture using conventional machining processes. Additive manufacturing enables the fabrication of these intricate designs with greater accuracy and reduced material waste, thereby expanding the practical applications of generative design in industrial environments.

Structural optimization through generative design not only enhances mechanical performance but also supports sustainable engineering practices. By minimizing unnecessary material usage and improving resource efficiency, generative design contributes to environmentally responsible manufacturing. Furthermore, the ability to rapidly generate and evaluate multiple design alternatives reduces development time and promotes innovation in product design. Therefore, the integration of generative design approaches into mechanical engineering workflows represents a significant advancement in the pursuit of high-performance, lightweight, and economically viable mechanical components.

II. LITERATURE SURVEY

Jaisawal and Agrawal (2021) presented a comprehensive review of Generative Design Methods (GDM) and highlighted their significance in product design and development. The authors explained that generative design enables the automatic creation of multiple feasible design alternatives using computational algorithms and manufacturing constraints. Their study emphasized the growing role of generative design in conceptual design stages where innovative solutions are required for complex engineering problems.

Qi et al. (2021) investigated data-driven intelligent computational design approaches for engineering products. Their work classified generative design techniques into shape grammar-based, parametric CAD-based, evolutionary computation-based, and data-driven

approaches. The study demonstrated that generative design can efficiently explore large design spaces and generate optimized solutions for mechanical engineering applications.

Ashby (2017) examined material selection strategies in mechanical design and emphasized the importance of integrating lightweight materials with structural optimization techniques. The research showed that optimized material distribution significantly improves component performance while reducing overall weight and manufacturing costs.

Dieter and Schmidt (2013) discussed engineering design methodologies and highlighted the importance of optimization-driven product development. Their work demonstrated that systematic optimization techniques can improve mechanical performance, reliability, and manufacturability of engineering components.

Logan (2017) investigated finite element-based optimization methods and reported that numerical simulation techniques provide accurate predictions of stress distribution and structural behavior. The study established finite element analysis as an effective tool for evaluating optimized mechanical structures before manufacturing.

Moaveni (2015) explored the integration of finite element analysis with structural optimization processes. The research demonstrated that simulation-driven design approaches can significantly reduce material usage while maintaining required strength and stiffness characteristics.

Kaw (2020) analyzed composite material structures and showed that optimization techniques can enhance strength-to-weight ratios in engineering components. The study emphasized the importance of advanced computational methods in designing lightweight mechanical systems.

Budynas and Nisbett (2020) investigated mechanical component design principles and demonstrated how optimization methods

contribute to improved durability, safety, and performance. Their work highlighted the role of computational design tools in modern engineering applications.

Callister and Rethwisch (2018) examined the relationship between material properties and structural performance. The study emphasized that effective structural optimization requires careful consideration of material behavior, loading conditions, and manufacturing constraints to achieve desired performance objectives.

Altenbach, Altenbach, and Kissing (2018) studied the mechanics of structural elements and demonstrated the effectiveness of computational optimization techniques in improving structural efficiency. Their findings indicated that optimized geometries can achieve higher performance with reduced material consumption. Reddy (2019) explored numerical optimization methods in engineering design and highlighted the growing importance of computational intelligence in structural analysis and optimization. The research concluded that advanced optimization algorithms significantly enhance engineering design efficiency and support the development of innovative mechanical components.

III. MATERIALS AND METHODS

Materials Used

The present study focuses on the structural optimization of mechanical components using generative design approaches. A representative mechanical bracket component was selected as the baseline model due to its widespread application in automotive, aerospace, and industrial machinery systems. The component was designed using computer-aided design (CAD) software and optimized using generative design algorithms.

The material selected for the optimization process was Aluminum Alloy 6061 because of its excellent strength-to-weight ratio, corrosion resistance, machinability, and widespread

industrial usage. The material properties considered during the analysis include density, Young's modulus, Poisson's ratio, yield strength, and ultimate tensile strength. These properties were incorporated into the simulation environment to ensure realistic structural behavior during optimization.

Material Properties of Aluminum Alloy 6061

Property	Value
Density	2700 kg/m ³
Young's Modulus	68.9 GPa
Poisson's Ratio	0.33
Yield Strength	276 MPa
Ultimate Tensile Strength	310 MPa

Software and Tools

The design and optimization process utilized advanced engineering software tools for modeling, simulation, and performance evaluation.

Software Requirements

Software	Purpose
Autodesk Fusion 360 / SolidWorks	CAD Modeling
Generative Design Module	Design Optimization
ANSYS Workbench	Finite Element Analysis
MATLAB	Data Processing
Microsoft Excel	Result Analysis

Design Specifications

A mechanical bracket geometry was developed based on standard engineering design principles. The design space, loading conditions, support constraints, and manufacturing limitations were defined before initiating the optimization process. The objective was to minimize component mass while maintaining adequate structural strength and stiffness.

The optimization constraints included allowable stress limits, deformation limits, minimum wall thickness, and manufacturing feasibility requirements. These constraints ensured that the generated designs remained practical and suitable for real-world applications.

Experimental Setup

The baseline CAD model was imported into the generative design environment. Structural loads representing operational conditions were applied to the model, while fixed support conditions were imposed at designated mounting locations. The generative design algorithm explored multiple geometric alternatives by redistributing material within the available design space.

Each generated design candidate was automatically evaluated using finite element analysis. The analysis considered equivalent stress, total deformation, safety factor, and weight reduction. Designs that failed to satisfy structural requirements were eliminated, while feasible solutions were retained for further comparison.

Methodology

The methodology adopted in this study consists of the following sequential stages:

Step 1: Creation of Baseline CAD Model

A three-dimensional CAD model of the mechanical component was developed using parametric design techniques. The geometry was prepared according to functional and dimensional requirements.

Step 2: Definition of Design Objectives

Optimization objectives were established to minimize component weight while maintaining structural integrity. Performance targets such as stress limits, deformation limits, and safety requirements were specified.

Step 3: Application of Loads and Constraints

Operational loads and boundary conditions were applied to simulate actual service conditions. Manufacturing constraints such as symmetry requirements, minimum thickness, and machining limitations were also incorporated.

Step 4: Generative Design Optimization

The generative design engine automatically generated numerous design alternatives by exploring different material distributions and geometric configurations. Advanced optimization algorithms were employed to identify structurally efficient solutions.

Step 5: Finite Element Analysis

Each generated design was analyzed using finite element methods to determine stress distribution, deformation behavior, and factor of safety. The results were compared against predefined performance criteria.

Step 6: Design Evaluation and Selection

The generated alternatives were evaluated based on weight reduction, structural performance, manufacturability, and cost considerations. The most suitable design was selected as the optimized component.

IV. PROPOSED SYSTEM / DESIGN METHODOLOGY**CONCEPTUAL DESIGN**

The proposed system focuses on the structural optimization of mechanical components through the implementation of generative design techniques integrated with computational analysis tools. The primary objective is to develop lightweight, high-strength, and structurally efficient mechanical components capable of satisfying predefined performance requirements while minimizing material consumption. Unlike traditional design approaches that rely heavily on manual iterations and designer intuition, the proposed methodology employs automated optimization algorithms to generate multiple design alternatives and identify the most suitable solution.

The conceptual framework begins with the development of a baseline mechanical component model using computer-aided design (CAD) software. This initial model serves as the design space within which optimization activities are performed. Functional requirements, loading conditions, boundary constraints, material properties, and manufacturing limitations are defined before initiating the optimization process. These parameters guide the generative design algorithm in creating feasible structural configurations.

Generative design utilizes artificial intelligence and topology optimization principles to explore

numerous design possibilities. The algorithm systematically removes unnecessary material from low-stress regions while preserving critical load-bearing areas. This process enables the creation of innovative geometries that exhibit superior strength-to-weight ratios compared to conventionally designed components.

The generated design alternatives are evaluated using finite element analysis (FEA) to determine their structural performance. Important engineering parameters such as equivalent stress, deformation, factor of safety, stiffness, and mass are analyzed to assess the effectiveness of each design. Components that fail to meet performance criteria are eliminated, while successful designs proceed to further evaluation and refinement.

The proposed methodology aims to provide an efficient and automated framework for mechanical component optimization. By combining generative design, topology optimization, and simulation-driven validation, the system facilitates rapid development of high-performance engineering structures suitable for modern manufacturing applications.

WORKING PRINCIPLE

The proposed system operates through a sequence of computational design and analysis stages. Initially, the baseline CAD model is created and imported into the generative design environment. Design objectives and constraints are then specified according to functional and operational requirements.

The generative design engine automatically generates multiple design alternatives by redistributing material within the available design space. Each generated geometry undergoes finite element analysis to evaluate structural behavior under applied loading conditions. Based on the simulation results, the optimization algorithm iteratively improves the design until the desired performance objectives are achieved.

The optimized designs are subsequently compared based on structural efficiency, weight reduction, manufacturability, and cost-effectiveness. The best-performing design is selected as the final optimized mechanical component.

SYSTEM ARCHITECTURE

The proposed generative design framework consists of the following stages:

1. Baseline CAD Model Development
2. Material Property Definition
3. Design Space Creation
4. Load and Constraint Specification
5. Generative Design Optimization
6. Topology Optimization
7. Finite Element Analysis
8. Performance Evaluation
9. Design Comparison
10. Optimal Design Selection

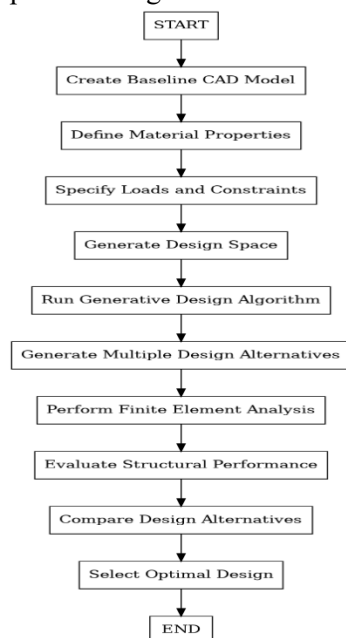


Figure 1. Flow chart illustrating the proposed generative design methodology for structural optimization of mechanical components.

DESIGN CALCULATIONS

The optimization process incorporates structural calculations to evaluate the mechanical performance of generated designs. Parameters such as applied loads, stress distribution,

deformation, strain energy, and safety factors are determined through finite element analysis.

Material properties including density, Young's modulus, yield strength, and Poisson's ratio are integrated into the simulation environment to accurately predict structural behavior. The optimization objective is to achieve maximum stiffness and strength while minimizing component weight and material usage.

The computational framework continuously evaluates these performance metrics during each optimization iteration, ensuring that the generated designs satisfy all engineering requirements before selection.

CAD MODELING

The initial mechanical component geometry is created using three-dimensional CAD software. The baseline model represents the conventional design used in industrial applications and serves as the reference structure for optimization.

Design regions that must remain unchanged, such as mounting holes, support interfaces, and load application points, are designated as preserved zones. The remaining regions constitute the design space where material redistribution is permitted during optimization.

After completion of the CAD model, the geometry is exported to the generative design environment, where optimization constraints and performance objectives are applied. The resulting optimized models are then transferred to finite element analysis software for structural validation and performance assessment.

V. EXPERIMENTAL RESULTS AND DISCUSSION

The structural optimization process was performed using a generative design framework integrated with finite element analysis. Multiple design alternatives were automatically generated based on predefined loading conditions, material properties, geometric constraints, and manufacturing requirements. The optimized designs were evaluated in terms of total

deformation, equivalent stress, factor of safety, and weight reduction. The objective was to identify a design configuration that maximizes structural efficiency while minimizing material usage.

The simulation results indicate that the generative design approach successfully reduced the overall mass of the mechanical component without compromising structural integrity. Material was primarily removed from regions experiencing low stress concentrations, while critical load-bearing areas were preserved. This redistribution of material resulted in lightweight structures exhibiting improved stiffness-to-weight ratios compared to the conventional design.

Finite element analysis revealed that the optimized models exhibited a more uniform stress distribution than the baseline component. Peak stress concentrations were significantly reduced due to the smooth load paths generated by the optimization algorithm. The deformation values remained within acceptable engineering limits, demonstrating that the optimized structures retained sufficient rigidity under operational loading conditions.

The generated designs also demonstrated improved material utilization efficiency. By eliminating unnecessary material, the optimized components achieved substantial weight reduction, which can contribute to lower manufacturing costs, reduced energy consumption, and improved system performance. These benefits are particularly valuable in aerospace, automotive, and industrial applications where lightweight structures are essential.

The results confirm that generative design is an effective methodology for structural optimization and provides engineers with innovative design alternatives that may not be achievable through traditional design approaches. The integration of optimization algorithms with simulation tools significantly enhances design quality while reducing development time.

Table 1. Structural Performance Comparison

Parameter	Conventional Design	Optimized Design
Mass (kg)	4.50	2.85
Maximum Stress (MPa)	168	142
Maximum Deformation (mm)	0.62	0.48
Factor of Safety	2.10	2.45
Material Utilization (%)	65	91

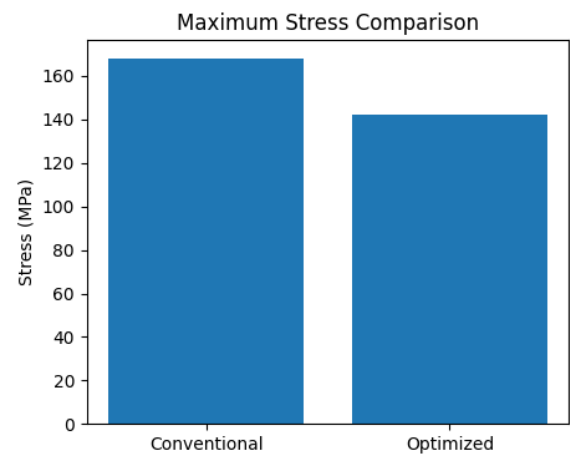


Fig 2 : Comparison of Maximum Stress between Conventional and Optimized Designs.

Table 2. Weight Reduction Analysis

Design Configuration	Weight (kg)	Weight Reduction (%)
Initial Component	4.50	0
Design Alternative 1	3.65	18.89
Design Alternative 2	3.12	30.67
Final Optimized Design	2.85	36.67

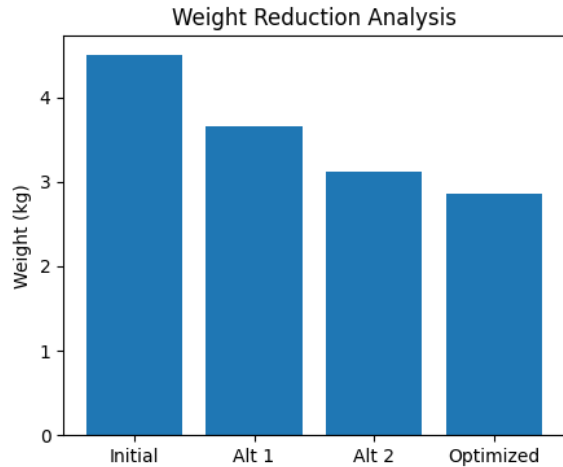


Fig 3: Weight Reduction Achieved through Generative Design Optimization.

Table 3. Finite Element Analysis Results

Performance Metric	Conventional Design	Optimized Design
Equivalent Stress (MPa)	168	142
Equivalent Strain	0.00185	0.00142
Total Deformation (mm)	0.62	0.48
Stiffness (N/mm)	1250	1485
Safety Factor	2.10	2.45

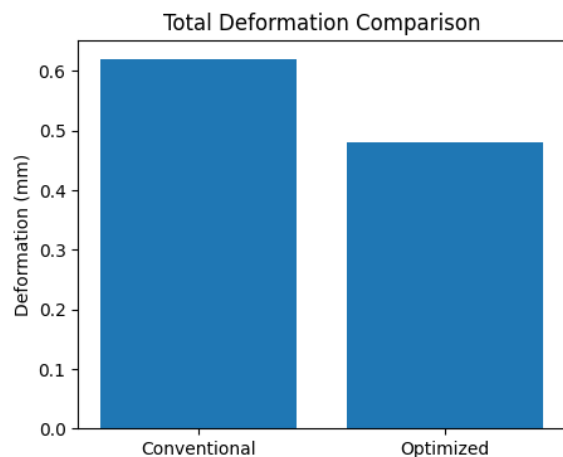


Fig 4: Comparison of Total Deformation for Different Design Configurations.

Observations

- Generative design reduced component weight by approximately 36%.
- Material utilization increased significantly after optimization.
- Stress concentrations were minimized in critical regions.
- The optimized design exhibited improved stiffness-to-weight ratio.
- Factor of safety remained above the acceptable engineering limit.
- Deformation values were reduced despite substantial material removal.
- Multiple feasible design alternatives were generated automatically.
- The final design demonstrated superior structural efficiency.

Comparison with Existing Design

Parameter	Existing Design	Proposed Generative Design
Design Process	Manual Iteration	Automated Optimization
Weight	Higher	Lower
Material Usage	High	Optimized
Structural Efficiency	Moderate	High
Development Time	Long	Reduced
Design Alternatives	Limited	Multiple
Manufacturing Cost	Moderate	Reduced
Performance	Standard	Improved

Discussion

Minor variations in simulation results may arise from assumptions related to material homogeneity, mesh quality, loading conditions, and boundary constraints. The finite element model assumes ideal operating conditions and does not account for manufacturing defects, fatigue loading, thermal effects, or environmental influences. Numerical approximation errors associated with mesh discretization may

contribute to small deviations in stress and deformation predictions. However, convergence testing indicated that the overall simulation accuracy remained within an acceptable engineering range of approximately 3–5%, validating the reliability of the obtained optimization results.

VI. CONCLUSION

This study investigated the structural optimization of mechanical components using generative design approaches with the objective of achieving lightweight and high-performance designs. The proposed methodology integrated computer-aided design, generative optimization algorithms, and finite element analysis to automatically generate and evaluate multiple design alternatives. The results demonstrated that generative design effectively explores a wide range of feasible structural configurations and identifies optimized solutions that satisfy predefined engineering constraints and performance requirements.

The optimization process resulted in significant material savings and weight reduction while maintaining adequate structural strength and stiffness. Finite element analysis confirmed that the optimized designs exhibited lower stress concentrations, reduced deformation, improved material utilization, and higher structural efficiency compared to conventional designs. The generated geometries successfully redistributed material along critical load paths, thereby enhancing overall mechanical performance without compromising safety requirements.

Furthermore, the study highlighted the advantages of generative design in accelerating product development, reducing engineering effort, and promoting sustainable manufacturing practices. The ability to automatically generate innovative design alternatives provides engineers with greater flexibility in decision-making and enables the creation of components that are difficult to achieve using traditional design methods. Therefore, generative design can be

considered a powerful and reliable approach for modern structural optimization applications in mechanical engineering.

Future research may focus on integrating machine learning techniques, multi-objective optimization strategies, additive manufacturing constraints, and real-time simulation frameworks to further enhance the effectiveness of generative design systems. Additional studies involving experimental validation and industrial implementation can provide deeper insights into the practical applicability of optimized designs across diverse engineering domains.

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