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Mass Reduction and Performance Testing of an Engine Bracket by Utilizing Topology Optimization and Generative Design Method

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Abstract

Engine mount bracket is an important component in a vehicle which secures the engine to the chassis. It plays a vital role in reducing vibrations. It is a bulky component operating under a variety of dynamic and static loading conditions. Therefore, optimizing the engine bracket in automobiles is essential, impacting the engine's efficiency and power output. One of the primary motivations for optimizing the bracket is weight reduction, which also improves material efficiency while lowering the manufacturing cost. Topological optimization is an iterative method where the material distribution of a body is calculated by computing varying loads and stresses within a design space. The topology optimization process was used to redesign the bracket to determine regions of mass reduction while maintaining the desired mechanical properties. Generative design algorithms are utilized to scrutinize a wide array of designs and are optimized for weight, stress, and machinability. Compared with traditional methods, generative design does not rely on the designer; rather, it runs different iterative processes to find the solution analytically. It hastens the design process as well as uncovers ingenious solutions that might not have been apparent through the traditional design process. This study provides a practical optimization technique, SIMP (Solid Isotropic Material with Penalization) employed using Solidworks software and generative design via Fusion 360. This research also highlights a comparative study of these techniques to acquire the finest optimization, showing its percentage of weight reduction, achieving it about 48.87% & 70.46% respectively of an engine bracket maintaining structural integrity of these components.

Keywords: Topology Optimization, Generative Design, Conceptual Modelling, Additive Manufacturing.

1. Introduction

The purpose of topological optimization is to enhance the efficiency of material usage within the defined design space. While shape optimization refers to the alteration of a design's external boundaries or surfaces, topological optimization involves calculating if a predefined design requires material at every point in the design space or not. Modifying a structure through this design process often leads to the formation of structures which are more complex and sometimes unheard of in simple engineering design.
Solid Isotropic Material with Penalization (SIMP) method is one of the most prominent methods used in topology optimization in order to find the most viable and efficient design of an object. This method works on a density-based process. Here, the material properties of the design are denoted as a continuous function of density which ranges from zero to one, where zero means the presence of void (no material) and one means the presence of material [1].

Governing Equations of the Density-Based SIMP Method

In the SIMP methodology, the process of topology optimization seeks to identify the most efficient allocation of material within a specified design domain, with the objective of minimizing a defined objective function, which is commonly structural compliance, while adhering to constraints regarding the total volume of material utilized. The material distribution is represented by a density variable ρ_e for each finite element e, where, $\rho_e \in [0,1]$, with 0 representing void (no material) and 1 representing solid material[2].
The compliance C is the objective function, representing the total strain energy of the structure, which is to be minimized:

$$C(\rho) = U^T K(\rho) U$$

U is the global displacement vector,
$K(\rho)$ is the global stiffness matrix that depends on the material density distribution ρ.

Stiffness Matrix and Penalization

The material stiffness for each element e is defined as:

$$K_e\ \rho_{(e)} = \rho_e^p\ K_e^0$$

where:

K_e is the stiffness matrix of the solid material for element e,

$\rho_{(e)}$ is the element density,

p ≥ 1 is the penalization factor, typically chosen as p=3, which pushes the design towards either 0 (void) or 1 (solid), avoiding intermediate densities.

The global stiffness matrix K(ρ) is assembled from the element stiffness matrices $K_e\ \rho_{(e)}$[3].

Volume Constraint

A common constraint in topology optimization is the volume constraint, which limits the total amount of material used. The constraint is defined as:

$$\frac{1}{V_0}\sum_{e=1}^{N}\rho_e\ v_e \leq V_f$$

Here,

V_0 is initial total volume of the model domain,

V_e is volume of element e,

V_f is desired fraction of initial volume (e.g., 30% material usage corresponds to V_f=0.3)

Optimization Problem

The overall optimization process for topology optimization using SIMP method can be formulated as:

$$\min C(\rho) = U^T K(\rho) U$$

$$K(\rho)U = F\ \ (Equilibrium\ constant)$$

$$\frac{1}{V_0}\sum_{e=1}^{N}\rho_e\ v_e \leq V_f \quad \text{(Volume constant)}$$

$0 \leq \rho_e \leq 1$, e=1…, N (Density bounds)

where F is the global load vector[4].

Penalization and Intermediate Densities

To avoid intermediate densities ($0<\rho_e<1$), a penalization factor p>1 is applied to the stiffness:

$$K_e\ \rho_{(e)} = \rho_e^p\ K_e^0$$

The penalization factor typically ranges from 3 to 4, ensuring a clear distinction between void and solid elements[4].

Here, the main goal is to reduce the weight of the engine bracket keeping the stiffness and safety factor constant. For this purpose, SIMP method is utilized.

2. Literature Review

No.	Author	Optimization Method Used	Key Findings	Mass Reduction	DOI
1	Yue Ma et al (2024)	SIMP (Solid Isotropic Material Penalization) method,	SIMP (Solid Isotropic Material Penalization) method, multi-objective optimization for a launcher bracket.	41.9%[5]	https://doi.org/10.61187/ita.v2i2.118
2	Hassan A. A. H. and Biswas B. (2024)	Topology optimization considering fatigue, using a penalization method (SIMP) for material distribution	Developed a lightweight automotive seatbelt bracket optimized for durability under dynamic and fatigue loads.	77%[6]	https://doi.org/10.3390/designs8050099
3	Margarida Mata, Mateus Pinto, José M. Costa(2023)	Generative design, Voronoi lattice optimization	Achieved a topologically optimized door handle design using AM for weight reduction and structural integrity.	Not specified	https://doi.org/10.24840/2183-6493_009-001_001620

4	Shannon L. et al (2022)	Topology optimization with the of Unity-in-variety concept and Gestalt Principles	Enhanced aesthetic appeal of topology-optimized designs by incorporating the principle of unity-in-variety, tested with Gestalt principles.	Not specified	https://doi.org/10.1007/s00158-022-03288-9
5	Deng J. and Cheng J. Y. G. (2012)	Multi-objective Optimization, GCMMA Method, Weighted Linear Sum Method	Minimizes compliance and thermal expansion, maximizes stiffness at optimal material volume, and addresses sensitivity to temperature variations.	70% mass reduction with porous configura-tions. 50% mass reduction, balanced structure[7].	https://doi.org/10.1007/s00158-012-0849-6
6	Nandanwar T. et al (2021)	Topology optimization done using Altair INSPIRE 9.5	Weight of the bell crank was reduced 28% and the weight of brake paddle was reduced to 211g from 363g.	28% (Bell crank) 41.87% (Brake Pedal)[8]	https://doi.org/10.1088/1757-899X/1123/1/012035

3. Design Specification and Modelling

Material: Gray Cast Iron
Hardness (Vickers): 161-321
Tensile Strength, Ultimate: 16700-102000 psi (115-700 MPa)
Tensile Strength, Yield: 9500-60900 psi (65.5-420 MPa)
Compressive Yield Strength: 83000-200000 psi (572-1380 MPa)

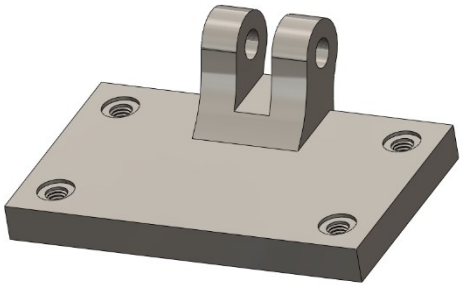


Figure 1: Basic Design of Engine Mount

Loading:

The bracket is supposed to be fixed with a rigid shaft connection passing through two cylindrical holes (Fig. 3). There are four similar holes for attaching the bracket with the desired Engine block. M6×1.0 sized metric bolts with a major diameter of 0.6cm and a pitch of 1 cm has to be used to fasten the bolt with the engine block and the rigid shaft. Per bolt has to withstand 1000kN (reversed) loading (Fig. 2). Using these parameters, the SIMP optimization technique is used to determine the optimized version of the Engine Bracket model.
Current mass of the part is 0.490961kg
Here, the meshing of the model was done using curvature-based mesh (Fig. 4) and the total number of nodes were found to be 252484 with 97.4% elements having aspect ratio of <3.
Two analyses were done. First, for a weight reduction of 30% and factor of safety 1.5 (Fig. 5), and the other at 60% mass reduction (Fig. 6) without any factor of safety constraint.

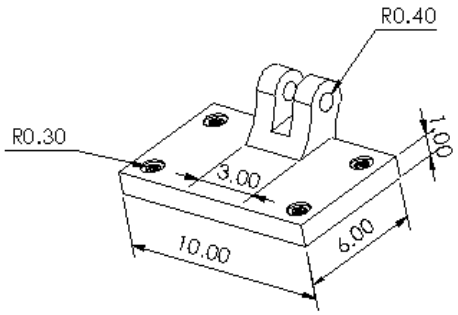


Figure 2: Dimensions of the Bracket (in cm unless specified)

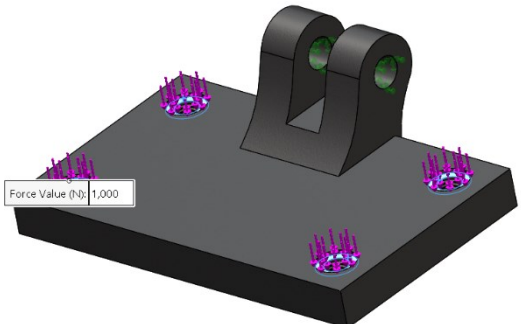


Figure 3: Loading of the bracket

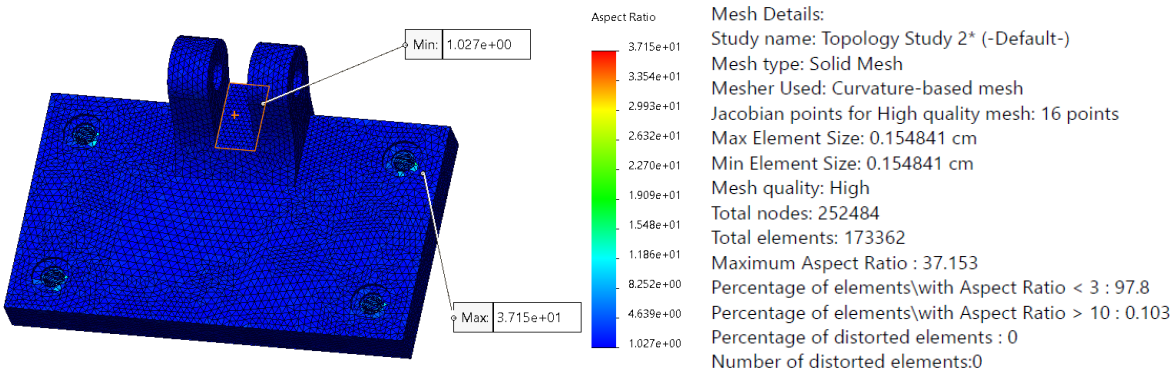


Figure 4: Mesh analysis of the model

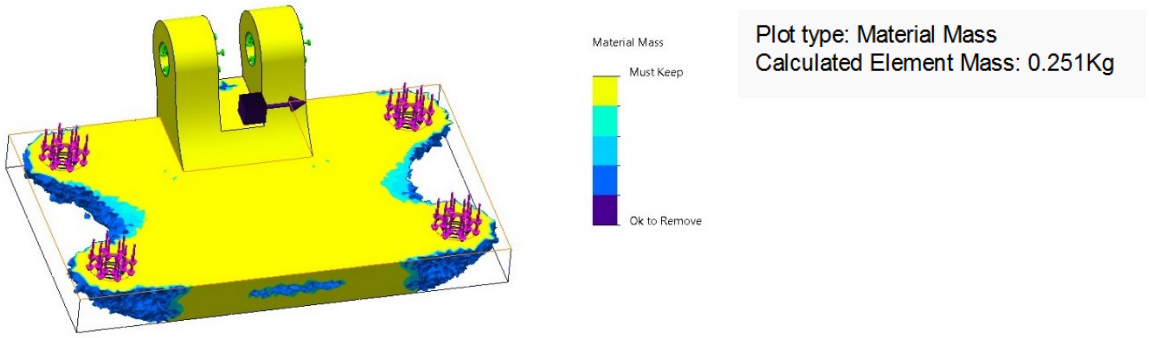


Figure 5: Mass Reduction parameter with 30% weight reduction and 1.5 Factor of Safety

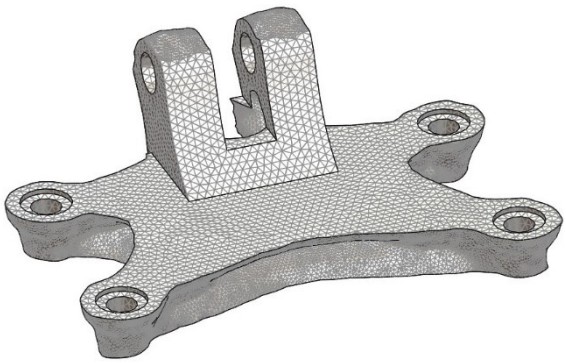


Figure 6: Final Model with 60% mass reduction

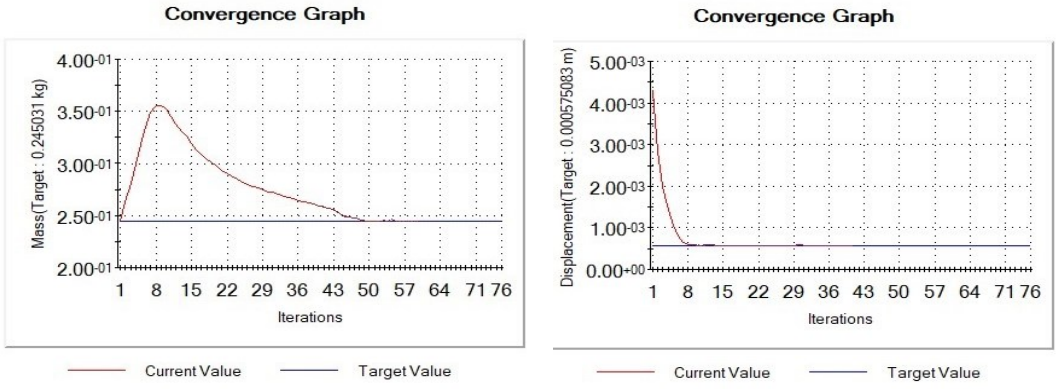


Figure 7: Convergence curve of mass and displacement criterion

Here, the graph converged at mass of 0.2453kg at 48-55 iterations and a displacement of 0.000575m at 8-10 iterations (Fig. 7).

Generative Design Modelling

The generative design method usually starts with an optimization phenomenon, where the goal is either maximizing or minimizing. This is represented as an objective function[8]:

$$\min_{x} f(x) subject\ to\ g_i(x) \leq 0, h_j(x) = 0$$

- $f(x)$: Objective function (Here, minimize weight and maximize strength)
- x: Design variables (Dimensions and material properties)
- $g_i(x)$: Inequality constraints (stress limits, manufacturing constraints, etc)
- $h_j(x)$: Equality constraint (geometric constraint)

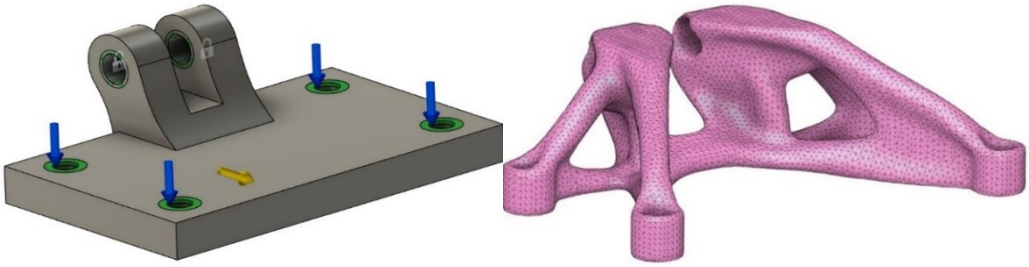


Figure 8: Initial loading and generated mesh of the engine bracket

Here, to conduct a generative design study, the model was loaded with Fusion 360 software and was given the same loading conditions (Fig. 8).

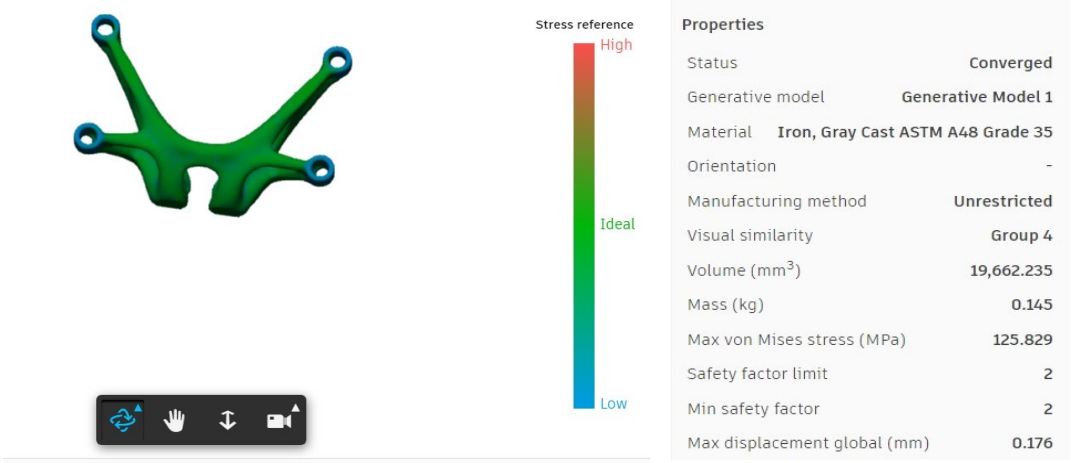


Figure 9: Mass and volume determination of generative designed model

4. Result

The initial mass was m_1 = 0.49096 kilograms
Mass after optimization process, m_2= 0.251 kilograms
Mass after generative design process, m_3= 0.145 kilogram (Fig. 9)

Initial Volume, V_1 = 68188.938 mm^3
Volume after mass reduction using optimization, V_2=47536.111 mm^3
Volume of generative design model, V_3=19662.235 mm^3

5. Discussion

The present study contrasts Topology Optimization via the SIMP method with Generative Design for the purpose of optimizing the mass of an engine bracket while preserving structural integrity. The SIMP method used here, attained a 48.87% mass reduction through iterative penalization of material distribution to reduce stress and strain energy, which is consistent with comparable research by Yue Ma et al. (2024), who reported a 41.9% decrease in mass. Generative Design process obtained a substantial 70.46% mass reduction by examining a wider spectrum of configurations, comparable to the reductions shown in the studies of Deng and Cheng (2012), which employed multi-objective optimization techniques.
This comparison emphasizes that although the SIMP method delivers reliable, iterative optimization for conventional structural objectives, Generative Design provides increased mass efficiency and adaptability. Therefore, Generative Design might be more appropriate when lightweight object and innovative structures are required.

6. Conclusion

This paper conducted a comparative study between topological optimization and generative design highlighting their governing formula and trade-off between the two techniques, where an engine bracket was modelled with grey cast iron to show the mass reduction performance for generative design and topological optimization. This paper demonstrated mass reduction of 48.87% at a factor of safety of 1.5 for topological optimization using SIMP method in Solidworks, whereas mass reduction of 70.46% at a factor of safety of 2 in generative design using Fusion 360, indicating a suitability for generative design for this loading condition and considering the mass reduction rate also exploring a wider array of design possibilities. While each method achieves mass reduction at an impressive rate, but approach should be made by desired design goals & manufacturing capabilities.

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