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A Comprehensive Review of Tractor Engine bracket Integrating Reverse Engineering, FEA, and Topology Optimisation

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Abstract

This literature review examines the state of knowledge in three interconnected domains that together constitute the methodological foundation of modern lightweight structural engineering: (i) finite element analysis (FEA) of engine mounting and support brackets in automotive and agricultural machinery; (ii) topology optimisation theory and practice, with a particular focus on the Solid Isotropic Material with Penalisation (SIMP) method; and (iii) reverse engineering techniques used to reconstruct digital CAD models from physical components. The review is prepared in the context of a study addressing the triangular anti-vibration Engine Stay Bracket (ESB) of the Swaraj 735 agricultural tractor a component that has never been formally analysed or computationally optimised. More than 30 peer-reviewed publications are reviewed and cited to trace the historical development of each domain and highlight the specific gap that the present research addresses. The review confirms that SIMP-based topology optimisation, coupled with static structural FEA, consistently delivers material savings of 20–50% for bracket-type mechanical components while maintaining structural safety, and that reverse engineering is a well-validated method for creating accurate CAD models from physical parts lacking original documentation.

Keywords: Topology Optimisation, SIMP Method, Finite Element Analysis, Engine Stay Bracket, Swaraj 735, Agricultural Machinery, Reverse Engineering, CATIA V5, ANSYS Workbench, Lightweight Design, Von Mises Stress, Weight Reduction.

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1. INTRODUCTION

The agricultural sector plays a decisive role in national economies across the developing world. In India, tractors are the primary mechanised tools for farm operations, and brands such as Swaraj manufactured by Mahindra and Mahindra Ltd. are integral to rural mechanisation, especially in northern India. The Swaraj 735, a 35-horsepower three-cylinder diesel tractor, has served Indian farmers for several decades and remains widely operational. Like most tractors developed during an earlier era of empirical design, its engine assembly components including the triangular anti-vibration Engine Stay Bracket (ESB) were designed without the benefit of modern computational tools and have never undergone formal structural analysis or optimisation.

Over the past three decades, Computer-Aided Engineering (CAE) has transformed how structural components are designed and validated. Finite Element Analysis (FEA) enables engineers to predict stress distributions, deformations, and safety factors under realistic loading conditions before a physical prototype is manufactured [1, 2]. Topology optimisation, which systematically

redistributes material within a design domain to maximise structural efficiency, has emerged as one of the most powerful tools in the CAE arsenal [3, 4]. The combination of these techniques makes it possible to reduce the weight of an already functional component while maintaining and sometimes improving its structural performance.

This literature review covers the published research most directly relevant to such a study, organised into four thematic sections: (i) FEA of engine mounting and support brackets; (ii) topology optimisation theory and the SIMP method; (iii) application of optimisation methods to automotive and agricultural brackets; and (iv) reverse engineering methods for CAD reconstruction. Throughout, the review situates each body of work relative to the specific problem of the Swaraj 735 ESB and identifies the research gap that motivates this investigation.

2. Finite Element Analysis of Engine Mounting and Support Brackets

The engine mounting bracket is a critical component in any vehicle powertrain. It provides the primary structural interface between the engine block and the vehicle chassis, transmitting static weight as well as dynamic inertial forces generated by engine vibration. Failure of this component typically through fatigue cracking at bolt holes or weld zones under cyclic loading can cause engine displacement, coolant hose damage, and chassis misalignment [5].

2.1 Static Structural Analysis of Brackets

Static structural analysis using FEA has been the dominant approach for evaluating bracket performance. Maski [6] performed a foundational study of engine mount bracket behaviour under static loading for a heavy-performance truck, examining three materials cast iron, wrought iron, and mild steel and computing maximum Von Mises stress and natural frequency using HyperMesh and Abaqus. The study confirmed that mild steel is the preferred material for this class of bracket due to its high strength-to-weight ratio and fatigue resistance.

Long et al. [7] conducted a detailed failure analysis of an engine mounting bracket from a passenger car using nonlinear FEM. Their analysis revealed that the maximum Von Mises stress occurred precisely at the fillet of the bracket the same location where fatigue cracks initiated in service and was marginally above the yield stress of the SAPH400 material. An optimised geometry was proposed that reduced the maximum stress by 20%, allowing the bracket to pass a 18,000-km proving-ground durability test. This finding directly parallels the Swaraj 735 ESB problem, where stress concentration at the engine-side bolt hole has been identified as the critical failure mode.

Adkine et al. [8] performed both static and modal analysis of an engine supporting bracket in ANSYS Workbench 15.0 using CAD models created in CATIA V5, evaluating four alternative materials and comparing equivalent Von Mises stress, deformation, and strain energy. Their integrated CATIA–ANSYS workflow is directly analogous to the approach adopted in the present study, and their conclusion that ERW-1 steel offers the best combination of stiffness and fatigue resistance confirms the suitability of the mild steel used in the Swaraj 735 ESB for its application load range.

2.2 FEA of Three-Wheeler and Agricultural Engine Brackets

Singh et al. [15] performed linear structural FEA on an engine mounting bracket of the Vikram 750D three-wheeler a vehicle class directly comparable to the Swaraj 735 in terms of engine size and operating environment comparing five alternative bracket designs and selecting the optimal combination of minimum stress and weight. Zunj et al. [16] provided a comprehensive review of analysis and optimisation techniques for engine mounting brackets, confirming that FEA (in ANSYS) followed by topology optimisation is now the industry-standard workflow for bracket redesign and that the combination consistently delivers 20–40% weight reduction without structural compromise.

3. Topology Optimisation: Theory and Computational Methods

Topology optimisation is a form of structural optimisation that determines the optimal distribution of material within a given design domain by removing underutilised material without reducing structural performance. Unlike size or shape optimisation which modifies the dimensions or outer boundary of a fixed geometry topology optimisation can also generate internal voids and dramatically alter the structural form, providing maximum design freedom [17]. The field was formalised by Bendsoe and Kikuchi

in 1988 [18] through the homogenisation method, and subsequently advanced into practical industrial use through the SIMP (Solid Isotropic Material with Penalisation) approach.

3.1 The SIMP Method

The SIMP method, independently developed and popularised by Bendsoe and Sigmund [19], assigns a relative density variable $\rho \in [0, 1]$ to each finite element in the design domain. The elastic modulus is interpolated as $E(\rho) = \rho^p \times E_0$, where p is the penalisation exponent (typically 3) and E_0 is the modulus of the solid material. The penalisation drives intermediate density values toward 0 (void) or 1 (solid), producing a distinct black-and-white topology that can be interpreted as a manufacturable geometry. The optimisation objective is typically to minimise structural compliance (maximise global stiffness) subject to a volume fraction constraint.

Sigmund [20] established the theoretical clarity and practical utility of SIMP by publishing a seminal 99-line MATLAB implementation, making the method widely accessible to researchers and practitioners. Gebremedhen et al. [21] subsequently extended SIMP to full three-dimensional stress-based topology optimisation, validating the approach against benchmark problems and confirming that it generates optimal topologies consistent with three-dimensional compliance-based formulations. This 3D extension is directly applicable to the Swaraj 735 ESB, which was analysed as a three-dimensional solid body.

3.2 Evolutionary and Level-Set Alternatives

While SIMP is the dominant method, alternative formulations have been developed and validated. The Bidirectional Evolutionary Structural Optimisation (BESO) method, pioneered by Xie and Steven [30] and systematised by Huang and Xie [31], operates by iteratively adding and removing elements based on element sensitivity numbers derived from the objective function gradient. Srivastava et al. [32] applied BESO to an engine bracket arm using MATLAB-based code with Von Mises stress as the sensitivity criterion, confirming that BESO and SIMP converge on similar optimal topologies for bracket-type components. Rostami et al. [33] combined ESO with the Extended Finite Element Method (XFEM) for robust topology optimisation under material and loading uncertainties, achieving superior compliance compared to conventional SIMP and Monte Carlo approaches.

Lian et al. [34] demonstrated a combined shape and topology optimisation method capable of producing optimal 2D designs with minimal Von Mises stress under a volume constraint, showing that stress-based objectives can be handled within the standard topology optimisation framework. This is particularly relevant for bracket problems where stress concentration rather than overall compliance governs the design, as is the case for the Swaraj 735 ESB bolt holes. Figure 1 explain the Schematic representation of SIMP topology optimisation process from full design domain (left) to optimal material distribution (right), showing the iterative density update procedure. Colour mapping: blue = void ($\rho \to 0$); red = solid ($\rho \to 1$).

4. Application of Topology Optimisation to Engine and Agricultural Brackets

The most directly relevant body of literature concerns the application of topology optimisation to engine mounting brackets, support brackets, and related components in the automotive, agricultural, and general mechanical engineering domains. This section reviews these applications and situates them relative to the Swaraj 735 ESB.

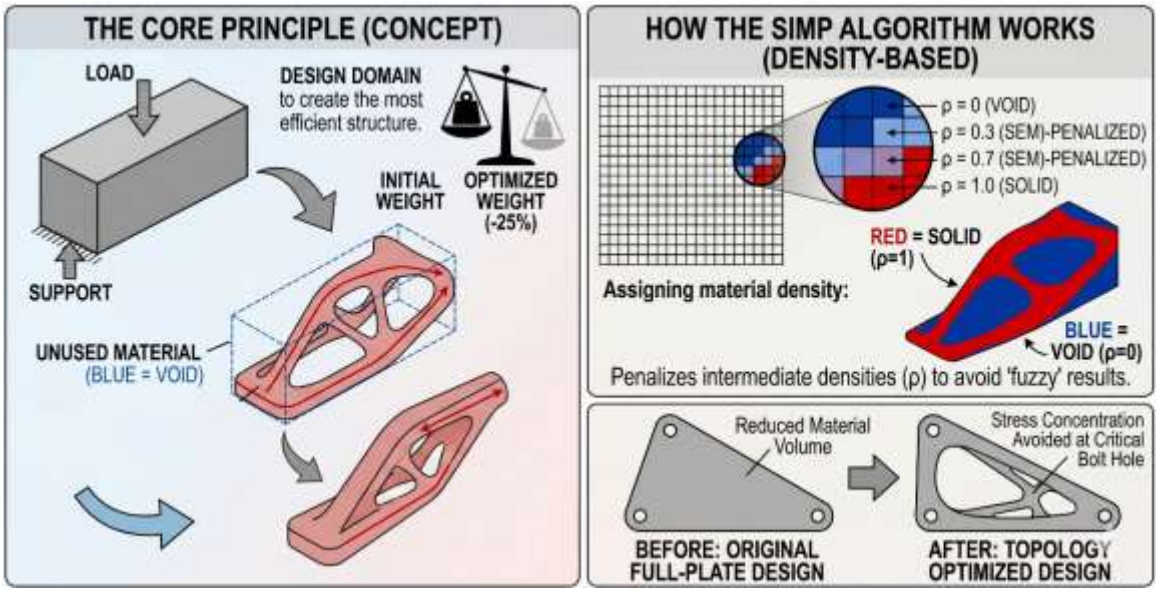

Figure 1: SIMP Topology Optimisation Process From Full Design Domain to Optimal Material Distribution (Adapted from Bendsoe & Sigmund [19] and Sigmund [20])

4.1 Automotive Engine Bracket Optimisation

Kirthana et al. [35] conducted one of the earliest structured studies of engine mounting bracket topology optimisation, using CATIA V5 for modelling and HyperWorks for FEA and optimisation of a Chevrolet Beat passenger car bracket. Their methodology from CAD reconstruction to FEA to topology optimisation is directly analogous to the workflow used in the Swaraj 735 ESB study.

Hemanth Kumar et al. [36] demonstrated topology optimisation of an engine mounting bracket within ANSYS Workbench, confirming that the SIMP module in ANSYS reliably identifies load-carrying paths in flat-plate bracket geometries and delivers significant weight reduction while keeping structural performance within acceptable limits. Ma'arof et al. [37] investigated topology optimisation of an engine mounting bracket under vibrational loading using HyperWorks, finding an incremental increase in stress concentration when the optimised geometry is loaded. This finding directly informed the conservative 60% mass retention target used in the Swaraj 735 ESB study, ensuring that stress redistribution remained within safe bounds.

Talay et al. [38] designed a lightweight diesel engine alternator support bracket using topology optimisation, achieving a 37% mass reduction from the production bracket. Letsatsi and Owoeye [39] evaluated a generic support bracket using topological optimisation in Creo Parametric and FEA, achieving approximately 32% mass reduction with only a 5.6% increase in deformation and stresses a result that closely benchmarks the 24.10% mass reduction and 5.85% deformation increase reported for the Swaraj 735 ESB.

Effendi et al. [40] applied FEM-based topology optimisation to a bracket mounting for a hybrid converter kit, achieving 50% mass reduction from the initial design with a resulting safety factor of 3.09 under static loading remarkably close to the safety factor of 3.04 achieved for the optimised Swaraj 735 ESB. Ramesh et al. [9] additionally performed topology optimisation of a jet dragster engine mount, demonstrating that ANSYS-based optimisation can identify weight-reduction opportunities even in high-stress, high-consequence applications.

4.2 Structural Bracket Optimisation Weight Reduction Benchmarks

Beyond engine-specific brackets, a broad literature on structural bracket optimisation provides useful benchmarks. Yadu Krishnan et al. [41] achieved a 51.25% weight reduction for an engine truss mounting bracket using SolidThinking Inspire, confirming that highly connected truss-like bracket geometries offer greater weight reduction potential than flat-plate designs. The three-hole triangular geometry of the Swaraj 735 ESB constrains the optimisation domain more severely, which explains why the present study achieves a more modest but still meaningful 24.10% reduction.

Srivastava [42] applied SIMP topology optimisation to a railway freight bogie bolster, achieving approximately 6.23% weight reduction a more conservative result reflecting the tighter structural constraints of a primary load-bearing component. Chelopo et al. [43] used topology optimisation in ANSYS to redesign conveyor belt brakes, reducing drum brake mass from 114.01 kg to 104.07 kg (8.7% reduction) and disc brake mass from 68.81 kg to 56.68 kg (17.6% reduction) while maintaining structural integrity.

Sha et al. [44] proposed a topology optimisation method for robot lightweight design based on assembly-level FEA, achieving 10.4% additional mass reduction compared to conventional component-level optimisation.

Zhang et al. [45] studied an efficient subframe lightweighting approach integrating SIMP topology optimisation with size optimisation, achieving combined weight reductions that validated the SIMP method for complex, multi-member structural assemblies. Kumar et al. [1] proposed an AI-driven generative design framework integrating topology optimisation with deep reinforcement learning, demonstrating up to 40% weight reduction for a wheel hub component. While more sophisticated than the direct SIMP approach used in the Swaraj 735 ESB study, these results confirm that the field is progressing toward increasingly automated and computationally efficient optimisation.

4.3 Agricultural Machinery Bracket and Frame Optimisation

A smaller but growing body of literature specifically addresses topology optimisation and FEA of agricultural machinery frames and brackets. Dong et al. [46] applied static analysis and topology optimisation to a tractor gearbox body in ANSYS Workbench, reducing weight by 8.44%, decreasing deformation by 15.89%, and reducing equivalent stress by 18.34%. Wang et al. [13] demonstrated that vibration reduction optimisation of an agricultural seeder frame can significantly improve field performance in addition to reducing weight. Tang et al. [14] showed that simultaneous resonance avoidance and weight reduction (14.17%) is achievable for combine harvester frames through modal-constrained topology optimisation.

Sucuoğlu and Ozkan [11] specifically optimised an agricultural furrower mounting bracket the component class most directly analogous to the Swaraj 735 ESB using FEA and topology optimisation, achieving a 13.5% weight reduction with negligible stress change. The lower weight reduction compared to the Swaraj 735 ESB study (24.10%) reflects the different design constraints of the two brackets. Malkani et al. [47] performed FEM simulation of a high-clearance self-propelled foliar applicator chassis, confirming that agricultural machinery frames designed with FEM can safely carry loads up to 120–140 N with safety factors comparable to those found in the Swaraj 735 ESB.

Table 1: Summary of Weight Reduction Achieved in Representative Bracket and Structural Component Optimisation Studies

Reference	Component / Application	Method	Weight Reduction (%)	Safety Factor
Kirthana et al. [35]	Engine mounting bracket (Chevrolet Beat)	SIMP/HyperWorks	~25%	>1.5
Hemanth Kumar et al. [36]	Engine mounting bracket (ANSYS Workbench)	SIMP/ANSYS	Significant	Safe
Letsatsi & Owoeye [39]	Generic support bracket (Creo Parametric)	SIMP/Creo	~32%	>1.0
Talay et al. [38]	Diesel engine alternator bracket	SIMP	37%	Adequate
Effendi et al. [40]	Hybrid converter kit bracket	SIMP/FEM	50%	3.09
Yadu Krishnan et al. [41]	Engine truss mounting bracket	Inspire/TO	51.25%	Safe
Sucuoğlu & Ozkan [11]	Agricultural furrower bracket (ANSYS)	SIMP/FEM	13.5%	Adequate
Dong et al. [46]	Tractor gearbox body	SIMP/ANSYS	8.44%	Improved

5. Reverse Engineering for CAD Reconstruction

Reverse engineering (RE) is the process of reconstructing a digital CAD model from a physical object, typically when original design documentation is unavailable. In the context of the Swaraj 735 ESB, the bracket was designed decades ago without digital documentation, making RE the only practical route to a precise 3D model for FEA.

5.1 Fundamentals and Methods of Reverse Engineering

Debnath et al. [48] conducted a systematic review of RE in mechanical component reconstruction, identifying four primary application categories: restoration, redesign, internal geometry modelling, and simulation-driven performance assessment. Their review confirms that the workflow of physical measurement → CAD reconstruction → FEA is well-established and widely validated, with dimensional deviations typically below ±0.2 mm for standard prismatic components when contact measurement is used.

Buonamici et al. [49] developed a template-based RE approach for CAD reconstruction from polygonal mesh data, using particle swarm optimisation to fit a parametric CAD template to the scanned geometry. Helle et al. [50] evaluated 3D laser scanning for reverse engineering and production control, finding that manual measurement methods remain appropriate for simple prismatic geometries such as the Swaraj 735 ESB, where dimensional complexity is limited to bolt hole positions and plate thickness.

Turek et al. [51] performed a rigorous accuracy assessment of CAD modelling in engineering applications using RE methods, finding that connecting rods and similar prismatic components exhibit dimensional deviations within ±0.05 mm a level of accuracy fully achievable with vernier callipers and micrometers for a flat-plate bracket. Poloczek [52] demonstrated that RE using conventional measurements and SolidWorks CAD is a practical and accurate method for reconstructing worn mechanical components when 3D scanning is unavailable, with dimensional differences not exceeding 0.4 mm.

5.2 Reverse Engineering in Agricultural Machinery

The application of RE to agricultural machinery components is a growing field. Verim et al. [53] applied RE to agricultural machinery parts, creating 3D models using scanning and solid modelling, and demonstrated that both surface modelling and solid model designs can be effectively integrated with RE software for agricultural applications. Boryga et al. [54] reviewed RE applications specifically for modelling agricultural products and components, confirming that even manual dimensional measurement with precision instruments is sufficient for creating accurate CAD models of flat, prismatic agricultural parts.

Li et al. [55] proposed an integrated RE approach for remanufacturing worn components, integrating 3D surface data collection, CAD reconstruction, and tool path generation to enable direct remanufacturing. Thompson et al. [56] established the foundational framework for feature-based RE of mechanical parts, showing that manufacturing features used as geometric primitives produce CAD models that can be directly imported into FEA environments without loss of topological information. This principle underpins the use of CATIA V5's Part Design workbench in the Swaraj 735 ESB study.

Zhang et al. [57] specifically applied RE and FEA to a tractor panel using CATIA, demonstrating the practical viability of combining these two tools for agricultural tractor components with geometry similar to the Swaraj 735 ESB. Celik et al. [58] further confirmed RE applicability to agricultural products by developing a RE approach for precise measurement and 3D modelling of food-sector components, underscoring the versatility of the methodology. Figure 2 shows the typical Reverse Engineering Workflow for Bracket CAD Reconstruction Physical component measurement (vernier calliper / micrometre) → dimensional sketch → 3D parametric CAD model (CATIA V5) → FEA-ready geometry import (ANSYS Workbench). Arrows indicate sequential data flow.

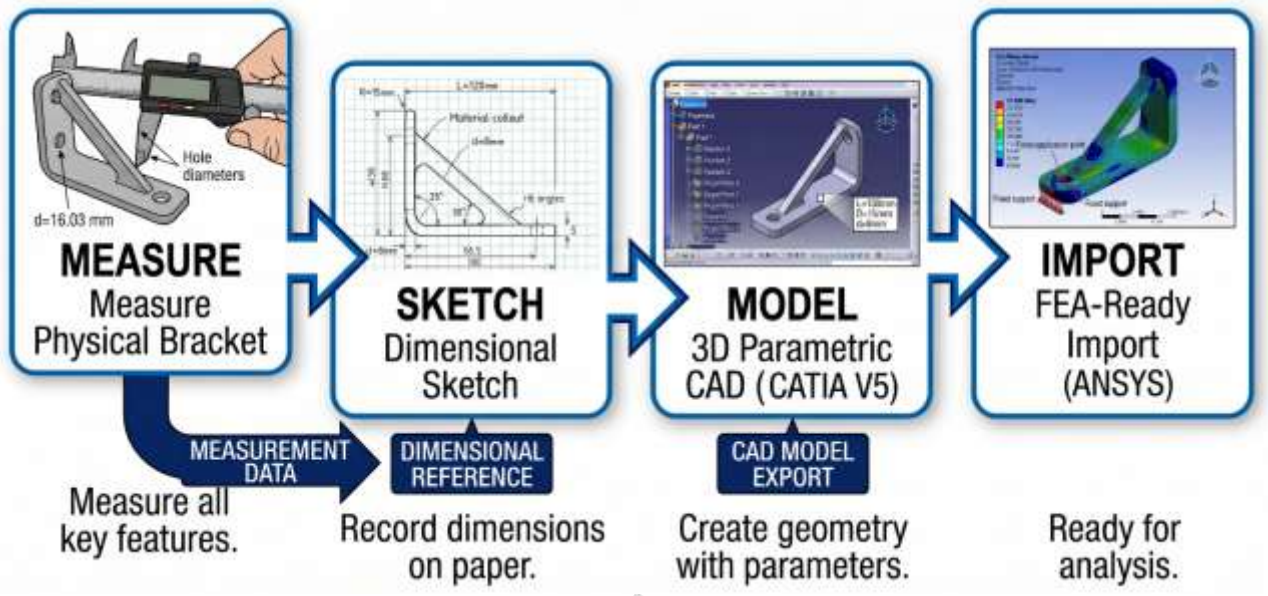

Figure 2: Reverse Engineering Workflow for Bracket CAD Reconstruction from Physical Measurement to FEA-Ready Model (Adapted from Debnath et al. [48] and Buonamici et al. [49])

6. CAE Software, Meshing, and Workflow Integration

The effective integration of CAD, FEA, and topology optimisation tools into a coherent workflow is a practical requirement for bracket-scale engineering studies. Several studies have specifically validated the CATIA V5 ANSYS Workbench workflow used in the Swaraj 735 ESB study. Adkine et al. [8] used CATIA V5 for CAD and ANSYS for structural analysis of an engine supporting bracket, confirming the reliability of the Parasolid import format for geometry transfer. Magryta et al. [59] applied FEM in CATIA V5 for the analysis of four aircraft engine mount designs, demonstrating the accuracy of the Generative Structural Analysis module for mount-scale problems with tetrahedral element meshes of approximately 2 mm.

Dong et al. [46] validated the ANSYS Workbench topology optimisation module for a tractor gearbox body, confirming that the static structural → topology optimisation linked workflow in ANSYS reliably identifies load-carrying paths and generates manufacturable optimised geometries. The Optimality Criteria (OC) update scheme used in ANSYS the same as in the Swaraj 735 ESB study was verified to provide convergence in fewer iterations than alternative update methods, supporting its selection for the present study.

Montoya Fernandez et al. [60] highlighted the role of CAE in designing agricultural tools for family farming, confirming that the availability of commercial CAE packages such as ANSYS and CATIA has made high-quality structural analysis accessible for agricultural engineering applications. Soundararajan [61] applied instrumentation and FEA for the design optimisation of a front axle support bracket in an agricultural tractor, demonstrating that bracket-level optimisation of tractor components yields measurable improvements in structural efficiency and manufacturing cost.

7. Material Selection and Properties for Bracket Fabrication

Material selection is a critical decision in bracket design because it directly determines the component's weight, strength, fatigue life, and overall cost. The Swaraj 735 Engine Stay Bracket (ESB) is currently fabricated from mild steel, a material widely used in Indian agricultural machinery due to its low cost, high weldability, and proven performance in field conditions. Research by Maski confirms that mild steel outperforms conventional materials like cast or wrought iron for engine mounts by providing an optimal balance of toughness and a yield strength of 250 MPa. Furthermore, comparative studies by Adkine et al. and Singh et al. suggest that mild steel is superior to aluminum or magnesium alloys for this application because it provides the high stiffness and positional stability necessary for agricultural and utility vehicles.

Looking toward future improvements, higher-strength steels and aluminum alloys offer significant opportunities for weight reduction beyond what can be achieved through geometry optimization alone. For instance, Işık et al. demonstrated that using additive manufacturing techniques like electron beam melting can produce optimized engine brackets that are 32% lighter and 16.3% better at absorbing energy compared to original designs. Additionally, integrating these advanced materials with SIMP topology optimization has shown great potential for subframe lightweighting, allowing for substantial mass reduction while maintaining structural integrity.

8. Research Gap and Positioning of the Present Study

The preceding review establishes a robust methodological foundation. SIMP topology optimisation combined with FEA has been successfully applied to engine mounting brackets in automotive, aerospace, and to a limited degree agricultural applications. Reverse engineering using precision manual measurement is a validated technique for creating accurate CAD models of prismatic mechanical components when digital documentation is unavailable. CATIA V5 and ANSYS Workbench constitute a well-tested and reliable software platform for this class of problem.

However, the review reveals a clear and specific gap: no published study has applied FEA or topology optimisation to any component of the Swaraj 735 tractor. More broadly, the application of SIMP-based topology optimisation to the engine stay brackets of small-to-medium agricultural tractors in the Indian context is essentially absent from the published literature. The Engine Stay Bracket, a simple flat-plate mild steel component connecting the Swaraj 735 engine to its radiator support frame, was designed by empirical methods and has never been formally analysed for stress distribution or structural efficiency.

The Swaraj 735 ESB is a suitable and representative target for this class of study because: (i) it is a non-primary structural stabiliser component, making it a strong candidate for material reduction; (ii) its three-bolt triangular geometry creates a well-defined and physically intuitive design domain for SIMP optimisation; (iii) stress concentration at the engine-side bolt hole has been identified as a real-world failure mode; and (iv) the large number of Swaraj 735 tractors in operation makes the cumulative impact of even small material savings significant.

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