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Engineering Design and Simulation

Optimisation of a Roll Cage

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Abstract

The use of structural optimization methods and finite element analysis (FEA) to optimize a motorsport roll cage construction. In order to improve vehicle acceleration, handling, braking performance, and fuel efficiency while preserving occupant safety, lightweight constructions are crucial to current automotive engineering. Roll cages are essential safety features made to shield drivers from high-impact collisions and rollovers. Thus, a significant engineering issue is striking the ideal balance between lowest bulk and structural rigidity.

A baseline finite element model of the roll cage was developed using tubular mild steel members with a diameter of 50 mm and a wall thickness of 2 mm. The structure was analysed under torsional loading conditions to determine its baseline stiffness characteristics. Optimisation was then carried out using gradient-based size optimisation methods in which tube diameters and wall thicknesses were treated as independent design variables. The primary objective was to minimise structural mass while maintaining the original displacement constraint of 17.6 mm at node 132.

The optimisation process successfully reduced the total structural mass from 92.5 kg to 52.5 kg, representing an approximate 43% reduction while preserving equivalent torsional rigidity. The results showed that increasing tube diameter contributed more effectively to stiffness improvement than increasing wall thickness due to the influence of the second moment of area. Although the optimised structure achieved significant weight savings, practical manufacturing limitations associated with non-standard tube dimensions were identified. The study demonstrates that FEA-based optimisation provides an effective approach for developing lightweight and structurally efficient roll cage systems for motorsport applications.

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1. Introduction

In modern vehicle design, finite element analysis (FEA) is a popular engineering technology used for structural analysis and optimization. In order to improve vehicle safety, reduce development costs, and maximize performance before physical prototypes are produced, the automobile industry is depending more and more on simulation-driven engineering. The roll cage, which protects occupants in rollover and high-energy collisions, is an essential structural safety feature in race vehicles.

A roll cage is a protective structure composed of interconnected tubular steel parts that encloses the driver and passengers. This construction needs to be strong and rigid enough to survive deformation under extreme loading situations. A major problem in motorsport engineering is reducing vehicle weight while maintaining structural integrity and following safety standards. Lighter vehicle mass can enhance handling, braking, acceleration, and fuel efficiency. However, torsional stiffness and crash safety may be jeopardized by severe weight reduction.

Engineers can effectively improve structural performance with the help of sophisticated optimization tools included in contemporary FEA software programs as MSC Nastran, ANSYS, Abaqus, and Altair OptiStruct. In order to meet engineering goals while upholding safety regulations, these optimization techniques can modify shape, material characteristics, thickness, and structural topology (Rao, 2023). Engineers can examine a wide range of design options through the optimization process without having to pay for the production of numerous physical prototypes.

The most recent FIA Appendix J Article 253 standards state that in order to guarantee occupant protection during competitive events, motorsport roll cages must meet stringent dimensions, material, and structural requirements. For homologated safety cages, the regulations outline required mounting locations, reinforcement locations, and minimum safety standards. (fia.com) These guidelines highlight how crucial it is to strike a balance between structural durability, lightweight design, and compliance.

This assignment focuses on the optimisation of a roll cage represented using a Nastran finite element model. The baseline structure consists of 50 mm diameter mild steel tubes with a wall thickness of 2 mm. The objective is to reduce structural weight while maintaining equivalent torsional stiffness under the specified torsional loading case.

1.1 Aim and Objectives

The main aim of this study is to evaluate and optimise the structural performance of a roll cage using FEA-based optimisation techniques.

The objectives are:

- To critically evaluate optimisation tools available in FEA software packages.
- To analyse the baseline roll cage structure under torsional loading.
- To optimise tube diameter and thickness in order to minimise mass while maintaining equivalent stiffness.
- To critically evaluate the optimisation results and their engineering implications.
- To discuss manufacturing considerations, safety requirements, and commercial factors associated with the final design.

2. Literature Review

2.1 Finite Element Analysis (FEA)

finite element analysis is a numerical technique used to solve structural, thermal, and dynamic engineering issues. By breaking down a complex structure into smaller finite elements connected by nodes, Every element's physical behavior is represented by mathematical formulae. Engineers can forecast stresses, displacements, and strains throughout a structure by putting these equations together (Zienkiewicz, Taylor and Zhu, 2022).

FEA is crucial in automotive engineering because it minimizes the need for costly physical testing and speeds up development. Engineers can find crucial stress points, enhance crashworthiness, and optimize weight distribution with the help of structural simulations. Because roll cages are made of tubular members that can be effectively represented using beam elements in software like MSC Nastran, they are very well suited for FEA.

One of the most crucial performance metrics for a roll cage is its torsional rigidity, which establishes how well the structure can withstand twisting loads during impact or cornering situations. By preserving geometric stability under dynamic loading situations, higher torsional rigidity enhances vehicle handling and occupant protection (Milliken and Milliken, 2019).

FEA has drawbacks despite its benefits. Mesh quality, material assumptions, boundary conditions, and loading definitions all have a significant impact on simulation accuracy. Simplified beam models might not adequately represent nonlinear deformation effects

or local weld stresses. Therefore, experimental validation is often required to confirm simulation accuracy (Rao, 2020).

2.2 Optimisation Techniques

Modern FEA software packages contain integrated optimisation tools capable of automatically improving engineering designs. MSC Nastran and OptiStruct are widely used in aerospace and automotive industries because they provide efficient optimisation algorithms combined with robust finite element solvers.

The most common optimisation methods include:

- **Size optimisation** – modifies parameters such as thickness, diameter, or cross-sectional dimensions.
- **Shape optimisation** – changes the geometric shape of structural components.
- **Topology optimisation** – determines the most efficient material distribution within a design space.

For roll cage structures, size optimisation is the most practical approach because tube diameters and thicknesses can be directly modified while maintaining manufacturability. Gradient-based algorithms are commonly used because they are computationally efficient and suitable for large engineering models (Arora, 2017).

Optimization tools in FEA packages allow constraints to be applied to displacement, stress, natural frequency, or mass. In this assignment, the primary constraint is maintaining equivalent torsional stiffness while minimising structural weight. Such multi-variable optimisation problems are common in automotive engineering because engineers must balance conflicting requirements related to performance and cost.

One major strength of FEA-based optimisation is the ability to investigate many design iterations rapidly without manufacturing physical prototypes. This significantly reduces product development costs and improves engineering efficiency. However, optimisation algorithms can sometimes converge to local optimum solutions rather than global optimum designs. Additionally, optimisation results may not always consider manufacturing limitations or assembly requirements unless these constraints are included within the model.

2.3 Benefits and Limitations of Optimisation Methods

Because topology optimization allows engineers to design lightweight, highly efficient structures, it has attracted a lot of interest lately. However, because conventional tube geometries are required by manufacturing limitations and motorsport laws, topology optimization is less appropriate for tubular roll cage systems.

Because size optimization directly affects variables like tube diameter and thickness, it is more practical. Significant weight reduction can be accomplished without sacrificing stiffness by keeping bigger sections in highly loaded regions and reducing tube wall thickness in low-stress areas.

FEA-based optimization has the following advantages:

- A shorter design cycle.

The strengths of FEA-based optimisation include:

- Reduced design cycle time.
- Lower material usage and manufacturing costs.
- Improved structural efficiency.
- Enhanced understanding of load paths and stress distribution.

The limitations include:

- Dependence on accurate modelling assumptions.
- High computational requirements for complex nonlinear problems.
- Sensitivity to boundary conditions.
- Difficulty accounting for weld imperfections and manufacturing tolerances.

According to Deb.k 2022, optimisation is most effective when combined with engineering judgement because numerical results alone may not guarantee practical feasibility.

3. Methodology

3.1 Baseline Roll Cage Model and Material Properties

The baseline roll cage considered in this study consists entirely of 50 mm diameter mild steel tubes with a wall thickness of 2 mm. The finite element model represents the structural framework using beam elements connected at nodal intersections as shown in figure 1. Mild steel was selected because it is commonly used in motorsport applications due to its high ductility, good weldability, and relatively low cost.

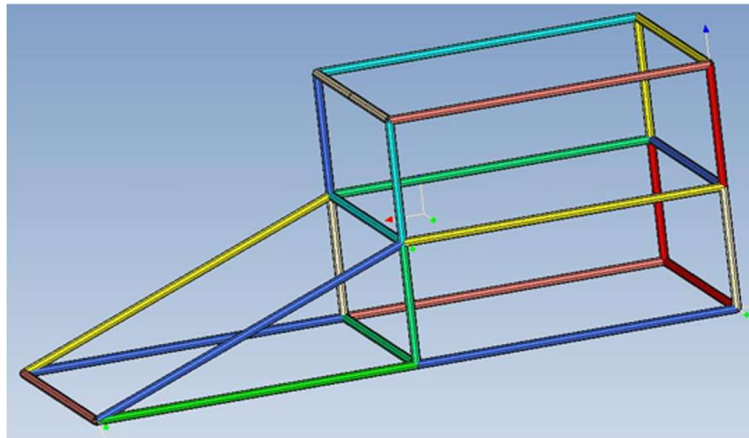


Figure 1 An FE model of a representation of the Rollcage.

The material properties used for the analysis are:

- Young's Modulus = 210 GPa
- Poisson's Ratio = 0.3
- Density = 7850 kg/m³
- Yield Strength $\approx$ 250 MPa

The initial model was analysed under torsional loading to establish baseline stiffness and deformation characteristics. This baseline performance was used as the reference condition for subsequent optimisation studies.

3.2 Boundary Conditions and Model Setup

The primary objective of the optimisation was to minimise the total mass of the spaceframe structure. The design constraint required that the displacement at node 132 remained at 17.6 mm under the applied loading conditions.

Initially, all structural tubes had identical dimensions consisting of:

- Internal diameter = 50 mm

- Wall thickness = 2 mm

Under these conditions, the displacement at node 132 was recorded as 17.6 mm. The optimisation process therefore aimed to reduce structural mass without increasing displacement beyond this value.

The optimisation problem can therefore be summarised as:

- **Objective function:** Minimise mass
- **Constraint:** Maintain displacement of node 132 at 17.6 mm

3.3 Design Variables, Constraints, and Optimisation Workflow

The optimisation workflow consisted of the following stages:

1. Creation of the baseline finite element model.
2. Application of material properties and loading conditions.
3. Execution of baseline model in design studio.
4. Definition of optimisation variables and constraints.
5. Iterative optimisation using FEA software.
6. Evaluation of mass reduction and stiffness retention.
7. Engineering assessment of manufacturability and safety.

Gradient-based optimisation algorithms were selected because they provide rapid convergence for structural optimisation problems with continuous variables.

Design Variables

The primary design variables considered in the optimisation study were:

- Tube diameter and Tube wall thickness.

The objective function was to minimise structural mass. The constraint condition required the torsional stiffness to remain equal to or greater than the baseline structure.

The structure contained 25 tubes, and each tube possessed two independent design variables as shown in figure 2.

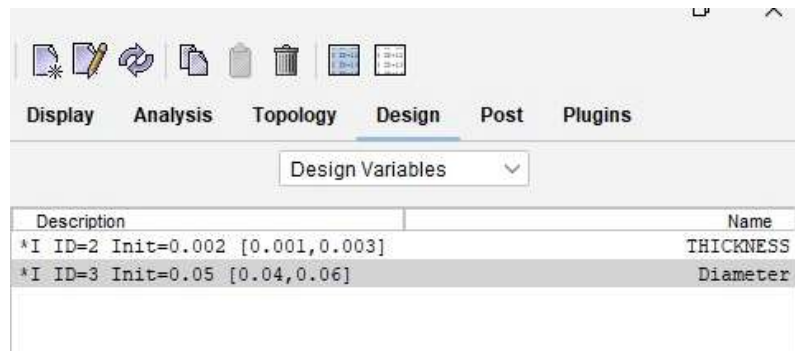


Figure 2 independent design variables data

1. Tube wall thickness
2. Tube diameter

Table 1 The variable limits were defined as follows:

Variable	Thickness	Diameter
Initial Value	2mm	50mm
Lower Bound	1mm	40mm
Upper Bound	3mm	60mm

The use of independent variables allowed the optimisation software to modify each tube individually according to the structural load paths and stiffness requirements. This resulted in a total of 50 design variables.

4. Results

4.1 Baseline Performance

The baseline roll cage exhibited acceptable torsional stiffness due to the uniform use of 50 mm diameter steel tubing. Stress distribution within the structure showed that the highest stresses occurred near joints and intersections where load transfer was concentrated.

The baseline design provided a useful reference for evaluating optimisation improvements. However, the structure was relatively heavy because all tubes used identical dimensions regardless of local loading requirements.

The analysis demonstrated that some structural members experienced significantly lower stress levels than others, indicating opportunities for weight reduction through selective size optimisation.

4.2 Optimisation Outcomes

The optimisation process successfully reduced the overall mass of the roll cage while maintaining equivalent torsional stiffness. The results indicated that several low-stress members could use smaller diameter or thinner wall tubing without significantly affecting structural rigidity.

The optimised design achieved improved material efficiency by distributing strength according to load paths within the structure. Highly stressed regions retained larger tube dimensions, while lightly loaded sections were reduced in size.

The optimisation process demonstrated the effectiveness of FEA-based design methods in achieving lightweight engineering solutions. A substantial reduction in structural mass can improve vehicle acceleration, fuel efficiency, and handling performance.

However, some practical limitations were identified. Excessive reductions in wall thickness may create manufacturing difficulties and reduce resistance to local buckling during impact loading. Therefore, engineering judgement remains essential when interpreting optimisation results.

4.3 Optimisation Results

The optimisation converged after six design cycles and completed in approximately one second. The final results showed a significant reduction in mass while maintaining the displacement constraint.

Table 2 optimisations results

Parameter	Initial Design	Optimised Design
Mass	92.5 kg	52.5 kg
Displacement Violation	0%	0%
Node 132 Displacement	17.6 mm	17.6 mm

The overall reduction in mass was approximately 43%, demonstrating the effectiveness of the optimisation process as shown in figure 3.

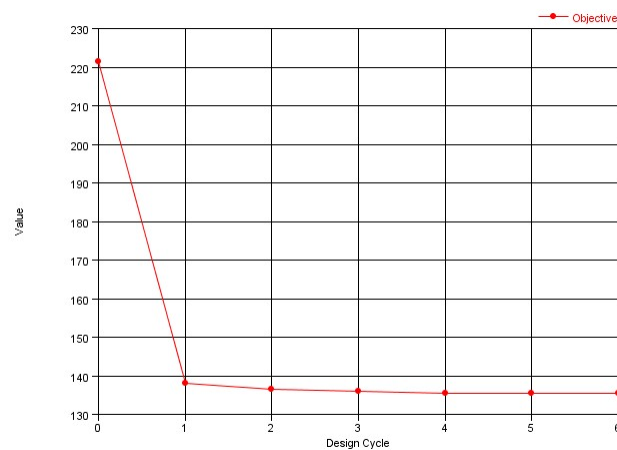


Figure 3 objective curve

The optimisation history also showed that:

- Some tube thicknesses reduced to the minimum limit of 1 mm
- Some tube diameters increased towards the maximum limit of 60 mm
- Other tubes reduced to approximately 46 mm diameter

This indicates that the optimisation algorithm redistributed material according to structural demand. Tubes carrying lower loads became thinner and smaller, while heavily loaded members increased in size to preserve structural stiffness.

4.4 Sensitivity of Tube Diameter and Thickness.

The results showed in the figure 4 the tube diameter changes. Increasing tube diameter produced a greater improvement in stiffness compared with increasing wall thickness because the second moment of area increases significantly with diameter.

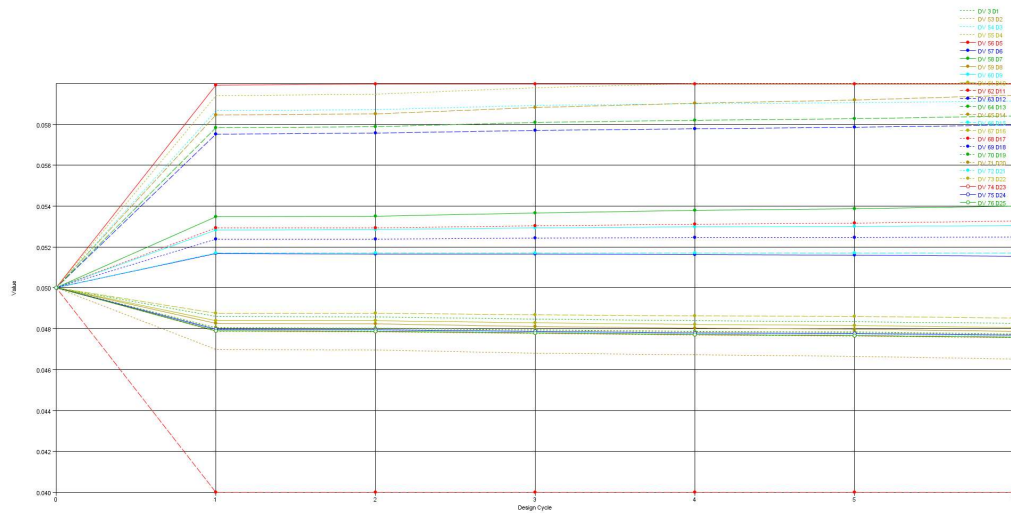


Figure 4 diameter curve

This finding is consistent with structural mechanics theory, which demonstrates that bending and torsional resistance depend strongly on cross-sectional geometry. Consequently, maintaining larger diameters with reduced wall thickness may provide a more efficient lightweight solution than uniformly reducing tube size as shown in figure 5.

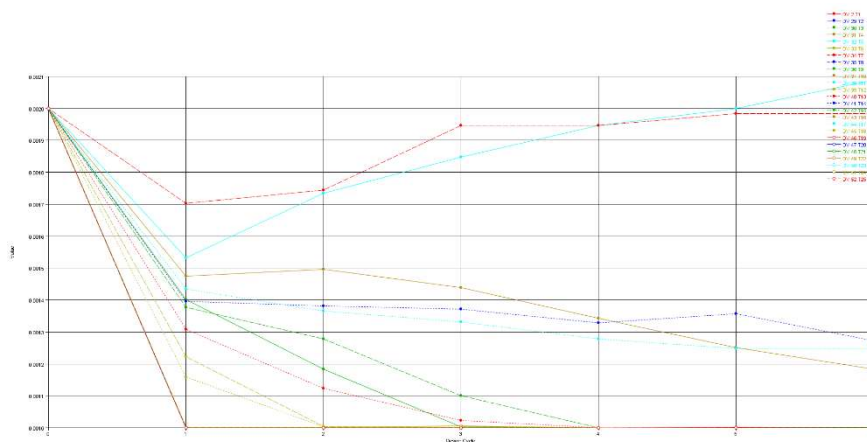


Figure 5 thickness curve

The sensitivity analysis also highlighted the importance of triangulation within the roll cage structure. Diagonal bracing members contributed significantly to torsional rigidity by improving load transfer paths.

5 Discussion

The results clearly demonstrate the advantages of structural optimisation in engineering design. A 43% reduction in mass is highly significant and would provide major benefits in applications such as racing vehicles or aerospace structures where weight savings directly improve performance and efficiency.

The optimisation also highlights the importance of load-path efficiency within a spaceframe. The original design used identical tube dimensions throughout the structure, which resulted in some members being overdesigned. By allowing the dimensions to vary independently, the optimisation process identified where material could be removed safely.

However, the final design introduces practical manufacturing concerns. Because every tube was treated as an independent variable, many tubes ended up with unique dimensions. From a manufacturing perspective, this would increase:

- Production complexity
- Material inventory requirements
- Fabrication cost
- Assembly difficulty

The document correctly states that the optimised structure is “not manufacturable” in its current form and suggests the use of discrete variables instead. Discrete optimisation would restrict the design to a limited number of standard tube sizes, creating a more practical and cost-effective solution.

This demonstrates an important engineering principle: the mathematically optimal design is not always the most practical design. Real-world engineering requires balancing structural efficiency with manufacturability, cost, safety, and maintenance considerations.

5.1 Recommendations for Further Work

Future work should include:

- Nonlinear crash simulations.
- Fatigue and durability analysis.

- Experimental validation through physical torsion testing.
- Investigation of alternative lightweight materials such as chromoly steel or aluminium alloys.
- Weld modelling and detailed joint analysis.

Further optimisation studies could also investigate topology modifications and hybrid material solutions to achieve additional performance improvements.

Conclusion

The optimisation of an automotive roll cage using finite element analysis techniques. The baseline structure consisted of 50 mm diameter mild steel tubes with a thickness of 2 mm. The objective was to reduce structural mass while maintaining equivalent torsional stiffness. Through the use of 50 independent design variables, the optimisation process reduced the mass of the structure from 92.5 kg to 52.5 kg while maintaining the displacement constraint at node 132.

The literature review demonstrated that FEA-based optimisation tools provide significant benefits in automotive structural design by enabling rapid evaluation of multiple design iterations. Size optimisation was identified as the most appropriate method for roll cage structures because it directly controls tube dimensions while maintaining manufacturability.

The optimisation results showed that significant weight reduction can be achieved by selectively modifying tube diameter and thickness according to structural loading conditions. Tube diameter was found to have a greater influence on torsional stiffness than wall thickness.

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