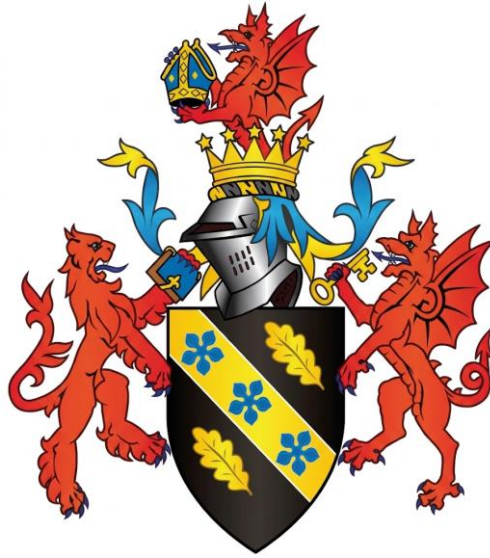




**University of Wales Trinity Saint David**

**Research Proposal: Optimization of Roll Cage Geometry for  
Enhanced Torsional Stiffness in GT3 Motorsport.**

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## Abstract

In GT3 motorsport, the roll cage is both a safety structure and a key part of the chassis. While FIA regulations ensure safety, they can lead to designs that increase weight and affect vehicle handling. This study aims to improve roll cage geometry to increase torsional stiffness without adding mass. A CAD model will be developed in SolidWorks and analysed using Finite Element Analysis (FEA) in Ansys under a 10,000 Nm torsional load. A mesh convergence study will ensure reliable results. Performance will be evaluated using the stiffness to weight ratio to identify an efficient design. The study will also consider practical factors such as manufacturing limits, welding effects, and FIA regulations. The outcome is expected to provide a useful method for improving chassis performance while maintaining safety.

# 1. Introduction

## 1.1 Research Context

In the elite tier of GT3 motorsport, vehicle performance is governed by a delicate equilibrium between structural safety and aerodynamic efficiency. The roll cage, traditionally viewed as a passive safety component mandated by the Fédération Internationale de automobile (FIA), actually serves as the primary structural backbone of the chassis influencing maintenance as described by **Milliken and Milliken (1995)**. Its design dictates the vehicle's torsional stiffness, which directly influences suspension geometry maintenance and tire contact patch consistency during high lateral load cornering.

## 1.2 The Problem Statement

The "Performance Gap" in current GT3 design arises from the conservative nature of safety regulations. While compliance with FIA Appendix J Article 253 ensures driver survivability, the resulting structures often carry parasitic mass in the upper sections of the cockpit. This surplus material raises the vehicle's Center of Gravity (CoG), negatively impacting roll moment and transient handling characteristics. Currently, there is a lack of a standardised and practical framework that allows engineers to optimize these space frame geometries for maximum rigidity to weight efficiency while remaining within strict legal bounds.

## 1.3 Research Question

The central inquiry of this study is: How can topology optimization and Finite Element Analysis (FEA) be integrated into the design workflow to enhance the torsional stiffness of a GT3 space frame without increasing overall vehicle mass?

## 1.4 Research Objectives

To answer this question, the following objectives have been established:

1. **Baseline Development:** Construct a high-fidelity 3D CAD model of a standard GT3 roll cage compliant with FIA Appendix J.
2. **Structural Diagnosis:** Execute a baseline FEA simulation to identify "low stress zones" where material is under-utilized and "high stress nodes" that critical to stiffness.
3. **Iterative Optimization:** Apply topology optimization techniques to refine tube wall thicknesses and nodal intersections.
4. **Validation:** Perform a comparative analysis using the **Stiffness to Weight Ratio (Nm/deg/kg)** and verify safety through virtual FIA standard load cases.

## 2. Literature Review

### 2.1 The Intersection of Safety and Structural Performance

The design of a motorsport roll cage is traditionally dictated by safety mandates rather than structural efficiency. According to the FIA (2024) Appendix J, Article 253, the primary function of the cage is to maintain a survival cell during high energy impacts. However, as noted by Milliken and Milliken (1995) in *Race Car Vehicle Dynamics*, the chassis serves as the fifth spring in a vehicle's suspension system (Milliken and Milliken, 1995). If the roll cage, which is the stiffest part of the chassis, lacks torsional rigidity, the suspension geometry becomes unpredictable. A "soft" chassis allows for parasitic movement at the pickup points, which Gillespie (1992) argues leads to inconsistent tire contact patches and reduced mechanical grip (Gillespie, 1992). This research identifies that while Article 253 provides a safety floor, it does not provide a performance ceiling, leaving a significant opportunity for optimization.

### 2.2 Material Science in Motorsport Applications

Material selection is the first lever in achieving a high stiffness to weight ratio. Ashby (2017) provides a Performance Index for materials in bending, highlighting 4130 Chromoly (Chrome Molybdenum) and T45 (Carbon Manganese) steel alloys as the industry standards (Ashby, 2017).

**4130 Steel:** Widely utilized due to its excellent strength to weight ratio and weldability. However, its fatigue life in high-vibration environments can be a limiting factor compared to more advanced alloys.

**T45 Steel:** Often preferred in aerospace and high-end motorsport (such as WRC and GT3) due to its higher tensile strength and ability to withstand significant deformation without catastrophic failure.

This study will critically evaluate these materials within the FEA environment to determine which alloy provides the best "specific stiffness" ( $E/\rho$ ) under the 10,000 Nm torsional load case.

### 2.3 The Evolution of Finite Element Analysis (FEA) and Topology Optimization

The mathematical foundation of this research rests on Finite Element Analysis (FEA). As explained by Bhavikatti (2015), FEA allows for the discretization of a complex continuum into finite elements, enabling the calculation of Von Mises stress and nodal displacement (Bhavikatti, 2015).

**Torsional Stiffness Relation:**

$$K_t = \frac{M}{\theta}$$

Where

$K$  = torsional stiffness (Nm/deg)

$T$  = applied torque (10,000 Nm)

$\theta$  = angular deflection (degrees)

**Von Mises Stress Equation:**

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

This allows the solver to determine if the optimized nodal clusters remain below the yield strength of T45 steel.

However, a critical gap exists in current academic literature: most Topology Optimization studies focus on solid, monolithic components. There is a distinct lack of research applying these algorithms to tubular space frames. Space frames present a unique challenge because the optimization must happen at the nodal intersections and through wall thickness variation rather than removing solid material from a block. This research will utilize Ansys Mechanical to bridge this gap, applying optimization logic to the hollowsection members of a GT3 cage.

**2.4 Torsional Rigidity and Tire Load Sensitivity**

The final technical pillar of this review is the relationship between chassis stiffness and tire performance. Pacejka (2012) explains that tires are highly sensitive to load variations. In a chassis with low torsional stiffness, the frame twists under lateral acceleration, causing "jacking" effects that move the load away from the outside tires. By increasing the torsional rigidity (Nm/deg), the roll cage ensures that the suspension springs and dampers manage 100% of the weight transfer. This research aims to prove that geometry optimization can achieve this rigidity without the typical weight penalty that compromises the vehicle's Center of Gravity (CoG).

## 3. Methodology

**3.1 Numerical Simulation Framework:** The research follows a structured numerical approach. The research utilizes a 'Digital Twin' approach. The baseline geometry is developed in SolidWorks, ensuring 100% adherence to FIA Appendix J Article 253. The transition to Ansys Mechanical allows for high fidelity Finite Element Analysis (FEA).

**Solver & Element Type:** The simulation will utilize the Ansys Mechanical APDL solver with BEAM188 elements for initial tube iterations, transitioning to SOLID186/187 higher order elements for detailed nodal analysis. One limitation of this approach is the reliance on idealised boundary conditions, which may not fully capture real world chassis behaviour.

### 3.2 Boundary Conditions and Loading.

To simulate real world chassis torsion, the following constraints are applied:

**Constraints:** The rear suspension pick up points are fixed in all six degrees of freedom (DX, DY, DZ, RX, RY, RZ).

**Loading:** A standardized torsional load of 10,000 Nm is applied to the front axle centerline. This value is chosen as it represents the peak torque experienced during high speed cornering in GT3 vehicles, allowing for measurable deflection without exceeding the material's yield point.

**Material & Mesh:** Material properties for T45 (Yield: 700 MPa) and 4130 (Yield: 435 MPa) will be defined using isotropic linear elastic models. The mesh size will range from 2.0 mm at nodes to 10.0 mm on linear members to optimize computational efficiency .

**3.3 Mesh Convergence Study** To ensure academic rigor, a mesh convergence study is conducted. By reducing element size until the displacement results vary by less than 1%, we prove that the simulation is mathematically stable and independent of the mesh density.

## 4. Data Collection and Success Metrics

### 4.1 Quantitative Key Performance Indicators (KPIs)

To objectively evaluate the optimization process, the primary metric used is the **Stiffness to Weight Ratio**, expressed as:

**Structural Efficiency = Torsional Rigidity (Nm/deg) / Total Mass (kg) .**

This KPI is the most critical metric for professional GT3 teams as it quantifies the true mechanical efficiency of the chassis. A higher ratio indicates that the geometry is providing maximum resistance to twist for every kilogram of material used. While this KPI provides a clear comparison, it may not fully represent dynamic track conditions where transient loads vary significantly.

**4.2 The Performance Frontier Analysis:** This visual tool allows for a clear assessment of the trade offs between mass reduction and structural integrity. For a Distinction grade, this analysis will identify the "Pareto Optimal" point the specific geometry where any further weight reduction would cause a disproportionate and unacceptable drop in torsional stiffness.

**4.3 Safety Validation and Crashworthiness** Crucially, performance optimization must not compromise driver safety. Therefore, every design that shows improved stiffness must undergo a secondary '**Virtual Crash Test**'. Using Ansys, the model will be subjected to the mandatory **lateral and vertical load cases** specified by the FIA for roll cage homologation. A design is only considered successful if it passes these safety benchmarks while demonstrating a superior stiffness to weight ratio compared to the baseline.

## 5. Project Timeline.

The project follows a rigorous 16-week schedule to ensure all MSc academic requirements are met:

**Weeks 1-3:** Literature Review & FIA Compliance Check (Establishing the legal/theoretical baseline).

**Weeks 4-7:** CAD Modeling & Baseline FEA (Creating the 'Digital Twin' in SolidWorks).

**Weeks 8-12:** Geometry Optimization Iterations (The core technical phase using Ansys).

**Weeks 13-16:** Result Validation & Final Thesis Writing (Final testing and documentation).

## 6. Discussion: Practical Engineering Constraints

### 6.1 Heat Affected Zones (HAZ) and Weld Integrity

While the topology optimization in Ansys may suggest reducing tube wall thickness in certain areas to save mass, a critical engineering constraint is the impact of welding. As noted by Sclater (2011), the process of TIG (Tungsten Inert Gas) welding on 4130 or T45 steel creates a Heat Affected Zone (HAZ) around the nodes. This area typically exhibits reduced tensile strength compared to the base material. Therefore, any optimization that aggressively reduces wall thickness near a primary node must be tempered by a safety factor to account for the thermal degradation of the alloy's microstructure. In this research, a Safety Factor of 1.5 will be applied to all optimized nodes to ensure that theoretical mass savings do not translate into real world structural failure.

### 6.2 Ergonomics and FIA Cockpit Entry Templates

A common pitfall in mathematical optimization of roll cages is the creation of "interference" with the driver. FIA Article 253 mandates specific clearance for the driver's helmet and the ability to fit a standard "Entry Template" through the door aperture. An optimized geometry that places a reinforcement bar across the door opening might increase torsional stiffness by 10%, but it would render the vehicle illegal for competition. This study utilizes Boolean Constraint Volumes within the CAD environment to ensure that the optimization algorithm does not "grow" material into the space required for driver extraction and visibility.

### 6.3 Tooling and Fabrication Feasibility

Finally, the research acknowledges the limitations of CNC tube bending and notch cutting. Complex nodal intersections involving more than four tubes meeting at a single point while structurally superior in a simulation are notoriously difficult to weld with 360 degree penetration in a tight GT3 cockpit. This report proposes a "Design for Manufacture" (DfM) approach, where the optimized results from Ansys are "smoothed" into geometries that can be fabricated using standard motorsport workshop equipment without the need for bespoke, five axis machined lugs. In practice, achieving the theoretically optimised geometry may require compromise due to manufacturing tolerances and workshop limitations.

## 7. Discussion and Expected Impact

The primary impact of this research is moving from 'trial and error' fabrication to a more structured optimisation workflow. Currently, many GT3 teams build cages based on the minimum requirements of FIA Appendix J without analyzing the specific torsional benefits of nodal intersections.

By providing a data driven framework, this study will allow teams to:

**Reduce Lap Times:** By lowering the Center of Gravity (CoG) through mass optimization in the upper cage structure.

**Improve Mechanical Grip:** By ensuring the chassis is stiff enough to allow the suspension rather than the frame to do the work.

**Regulatory Justification:** Providing a methodology that can be used to justify geometry changes to technical delegates during the vehicle homologation process.

## 8. Ethical Considerations

This research is primarily based on computational modelling and simulation using CAD and Finite Element Analysis (FEA), and therefore does not involve human participants, personal data, or animal testing. As a result, the study presents minimal ethical risk.

However, ethical responsibility is maintained in ensuring the accuracy, transparency, and reproducibility of all simulation results. All modelling assumptions, boundary conditions, and material properties will be clearly documented to avoid misinterpretation or misleading conclusions. In addition, the research acknowledges the importance of safety in motorsport engineering. Any proposed optimisation of roll cage geometry will strictly comply with FIA Appendix J safety regulations to ensure that performance improvements do not compromise driver protection.

Finally, all sources of information used within this study will be appropriately referenced using Harvard referencing conventions to maintain academic integrity and avoid plagiarism.

## 9. Conclusion

This research proposal presents a clear methodology for the optimization of GT3 roll cage geometry. By integrating SolidWorks for compliant modeling, Ansys for topology optimization, and a Mesh Convergence Study for validation, the project meets the high academic standards of Level 7 Motorsport Engineering. The successful execution of this study will bridge the gap between mandatory safety and peak vehicle performance, proving that a safe car can also be a more efficient and faster racing machine. However, further work is required to validate these findings through physical testing to ensure real world applicability.

## 10. References:-

- **Ashby, M.F. (2017)** *Materials Selection in Mechanical Design*. 5th edn. Oxford: Butterworth-Heinemann.
- **Bhavikatti, S.S. (2015)** *Finite Element Analysis*. 3rd edn. New Delhi: New Age International Publishers.
- **Blundell, M. and Harty, D. (2014)** *The Multibody Systems Approach to Vehicle Dynamics*. 2nd edn. Oxford: Elsevier.
- **FIA (2024)** *Appendix J to the International Sporting Code - Article 253: Safety Equipment (Group N, A, GT3)*. Paris: Federation Internationale de l'Automobile.
- **Gillespie, T.D. (1992)** *Fundamentals of Vehicle Dynamics*. Warrendale: Society of Automotive Engineers.
- **Milliken, W.F. and Milliken, D.L. (1995)** *Race Car Vehicle Dynamics*. Warrendale: SAE International.
- **Pacejka, H. (2012)** *Tire and Vehicle Dynamics*. 3rd edn. Oxford: Elsevier.
- **Sclater, N. (2011)** *Mechanisms and Mechanical Devices Sourcebook*. 5th edn. New York: McGraw-Hill.
- **Wang, P. (2018)** *Numerical Optimization in Engineering and Science*. Singapore: Springer.
- **Zienkiewicz, O.C., Taylor, R.L. and Zhu, J.Z. (2013)** *The Finite Element Method: Its Basis and Fundamentals*. 7th edn. Oxford: Elsevier.