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Material Optimization in Formula One Seat Fit Based on Structural and Biomechanical Analysis

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Abstract: *F1 drivers have reported that they suffer a long-term lower back pain due to 'Porpoising' effect, it is a series of bounce that is generated due to Aerodynamic downforce. This downforce is part of drag reduction principle that pulls the air underneath the vehicle, thereby creating an incredible speed of 200 to 230 mph. Also at 200 mph speed, the driver experiences a high amount G-forces up to six times during the race. This can be simply avoided by increasing the ground clearance of vehicle but at the same time it also reduces the max speed of the vehicle. Hence, without compromising the speed, Design optimization is done for driver's seat-fit through Computational methods of Biomechanical modelling and simulation for determining the optimum Seat Angle for Postural Ergonomics. As an additional Reinforcement and Shock absorption in seat material to protect driver's spine from the resulting dynamics, Material optimization is done by selecting Graphene as the suitable material over the existing Carbon fiber material. Finite element method was carried out for structural analysis of seat-fit model. The stress, strain and deformation values were found to be lesser in Graphene model when compared to Carbon fiber. The simulation results will provide a solution for eliminating the higher risk of spine injury or pathological condition of a sportsman and thereby improves the sporting performance.*

Key Word: *Motorsports, Computational Biomechanics, Ergonomics, Design optimization, Material optimization, Finite element analysis, Spine Injury prevention.*

I.INTRODUCTION

The lower back pain in F1 drivers is mainly caused due to Porpoising effect & G-forces. The four main factors identified from 4M – method (man, machine, material, method) can be optimized to improve the driver's pathological condition. The factors considered for improvement are Seat angle, Spine biomechanics, Posture & ergonomics, Shock absorption. Since seat angle determines the posture and ergonomics of the driver, and so angle modification approach was carried for optimum results. For Spine biomechanics, the kinematic analysis approach such as trunk flexion and its corresponding kinetics such as compression and shear forces are measured. For further reinforcement, material analysis was carried for various available composite materials from which the Graphene material is suggested to be more resistant to shock than existing carbon fiber material.

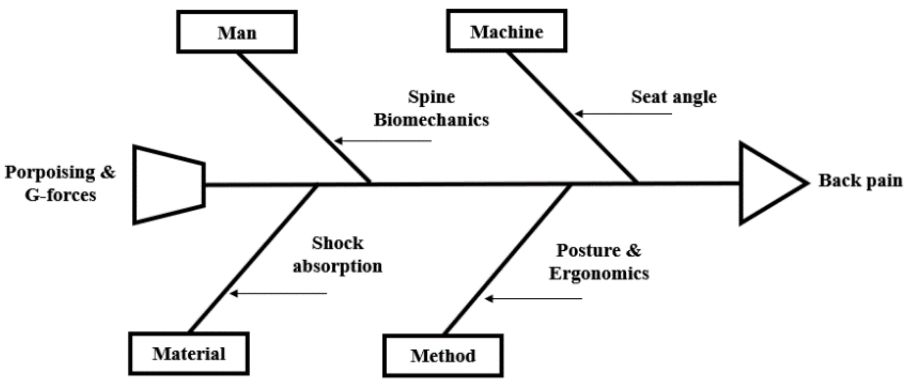


Figure 1. Fish bone representation of problem

1. The Proposing effect

The term 'Porpoising' is referred to a sea-dwelling mammal named as porpoise that's known to bob up and down in the sea surface while its swimming in the ocean. In F1, it's an aerodynamic phenomenon that affects the vehicle by pulling the air underneath for keeping the car close to the ground for achieving high speed in the racing track. The air entered will leave the rear part of vehicle, so in constant motion there a series of bounce is generated causing discomfort to the driver.

The FIA has revised the minimum ground clearance from 75mm to 90mm (75 + 15 mm) after this issue but higher off the ground can prevent porpoising and also creates less downforce, thereby decreasing the speed of a car.

2. G-forces

G-force is a physical phenomenon that is equivalent to one unit of gravity and this tends to be multiplied during the change in direction or velocity. In F1, the drivers experience high g-forces while performing acceleration, cornering and braking. The unit of g-force is 9.81 N. The average G-force in formula one is up to 6G max. In particular, 2G is experienced while accelerating, 5G at braking, 6G at the time of bouncing as well as cornering. The normal human threshold is 9G only for few seconds (measured for fighter jet pilot), where in this condition the body feels 9 times heavier and upward rapid pump of blood from heart to brain is experienced. However, this may lead to negative impact on human health.

II.LITERATURE REVIEW

The papers included in this literature review offer valuable insights into key areas spanning from the ergonomic design of Formula SAE race car cockpits to the optimization of Formula One racing cars and the integration of sustainability principles into automotive seat structures. Additionally, studies focusing on the ergonomics of Formula Student vehicles and truck driver seat comfort highlight the importance of human factors in vehicle design. Furthermore, investigations into advanced materials such as carbon fiber-graphene-reinforced hybrid polymer composites demonstrate the ongoing pursuit of innovative solutions to enhance vehicle performance and comfort.

1. **Mariotti and Jawad (2000):** This paper focuses on the ergonomic design of the Formula SAE race car cockpit. It likely delves into considerations such as driver comfort, accessibility of controls, and overall safety within the cockpit environment. The ergonomic aspect is crucial in ensuring that the driver can operate the vehicle efficiently and safely during races.

2. **Vadgama et al. (2015):** The paper discusses the design aspects of Formula One racing cars, likely covering various engineering considerations such as aerodynamics, materials selection, and performance optimization. Formula One cars represent the pinnacle of motorsport engineering, and understanding their design principles can provide valuable insights for engineers aiming to improve performance in similar contexts.

3. **Kinkead et al. (2016):** This study focuses on the design and optimization of Formula SAE vehicles. It likely discusses methodologies for improving vehicle performance through aerodynamic enhancements, weight reduction strategies, and chassis design optimization. Formula SAE competitions emphasize innovation and efficiency, making such optimization studies crucial for competitive success.

4. **Ahmad et al. (2017):** This paper discusses the ergonomics of Formula Student vehicles, which are similar to Formula SAE cars but geared towards university student teams. Ergonomics plays a vital role in ensuring that the vehicle is comfortable and easy to operate for the driver, which can ultimately impact performance and safety during competitions.

5. **Yuce et al. (2014):** This paper explores the design aspects of automotive seat structures with a focus on sustainability and reliability. Sustainable design practices are increasingly important in modern engineering to minimize environmental impact, while reliability ensures that automotive components meet performance requirements over extended periods of use.

6. **Chimote and Gupta (2013):** This paper discusses an integrated approach to improving truck driver seat comfort using ergonomics and Finite Element Method (FEM) analysis. Comfortable seating is crucial for long-haul truck drivers to prevent fatigue and ensure safety during extended periods of driving.

7. **Georgantzinos et al. (2020):** This study investigates the vibration analysis of carbon fiber-graphene-reinforced hybrid polymer composites using Finite Element Techniques. Such materials have potential applications in automotive components, where reducing weight while maintaining structural integrity and damping characteristics is essential for performance and comfort.

III.METHODOLOGY

The solution for the problem was carried out in two stages. In the first stage, 'Design optimization and Biomechanical analysis' and in the second stage 'Material optimization and structural analysis was carried out. Stage 1 is the corrective action and the Stage 2 is the preventive action approach.

1. Design optimization & Biomechanical analysis

- Seat fit model was designed in CATIA V5 – Part design module. Dimensions were based on FSAE Design rule edition – 2022.
- Human model (Manikin) with average height and weight of general population was assembled on the Seat in CATIA V5 – Human builder module.

- Posture editor in Human builder module was used to accommodate the seat fit with appropriate flexion angles of body segment.
- Load was defined as 75 kg acting downwards at Trunk (considering the average bodyweight of subject drivers).
- Finally, Human activity analysis module was selected, in which "Biomechanical single point analysis" tool was used to calculate the L4-L5 spine compression and shear limits.
- Above procedure was done for iteration of three angle variants such as 60°, 45° and 20° respectively.
- Results was compared for determination of optimum seat angle.

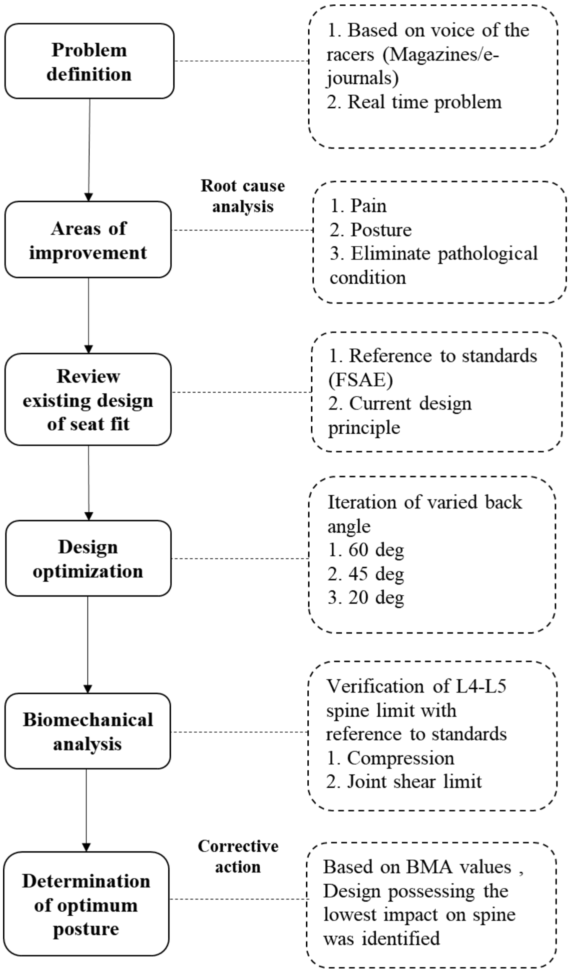


Chart 1. Flowchart for corrective action

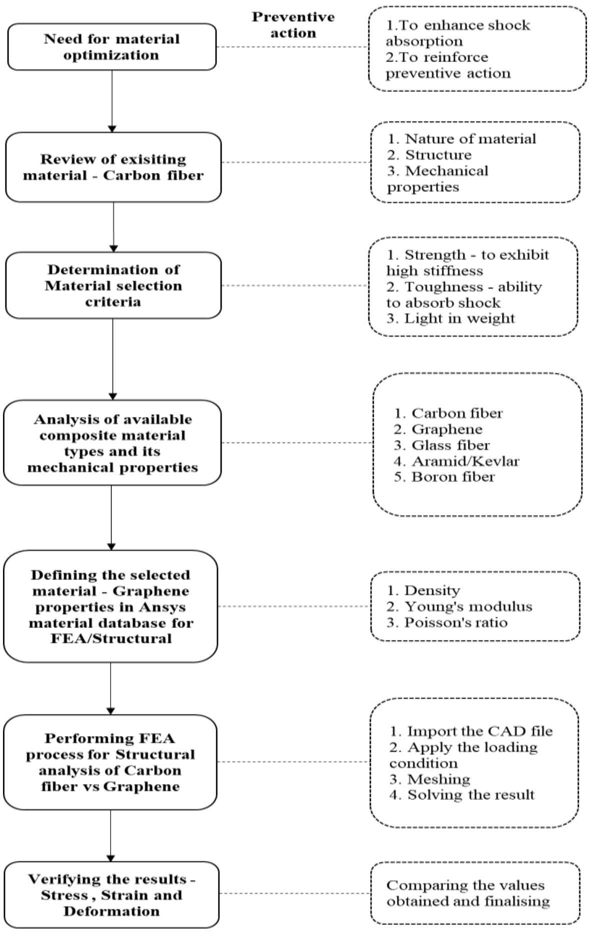


Chart 2. Flowchart for preventive action

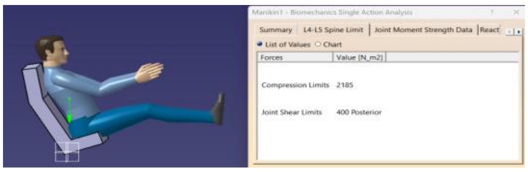
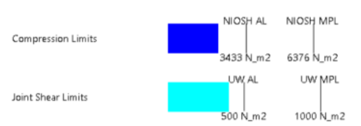
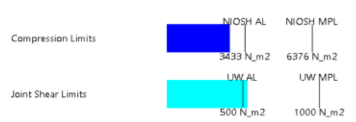
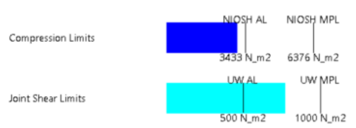
Biomechanical analysis of L4-L5 spine limit	Safety standards
	
	
	

Table 1. Biomechanical analysis in CATIA Human Builder & Human Activity Analysis

2. Material analysis & Selection of graphene

The existing material carbon fiber is a composite – reinforced polymer. Hence, other composite types were considered for comparison based on mechanical properties and Graphene was selected for its high strength and toughness characteristics.

S No	Material	Density [kg/m3]	Young's modulus [Gpa]	Poisson ratio	Remarks
1	Carbon fiber	1800	230	0.2	CF is the existing material currently used in F1 seats
2	Graphene	4717	342	0.19	Selected for simulation based on material properties and design criteria (high strength and toughness)
3	Glass fiber	1857	87	0.21	Other types of composites considered for comparison
4	Aramid/Kelvar	1400	140	0.37	
5	Boron fiber	2574	400	0.13	

Table 2. Material analysis based on the mechanical properties

3. Material optimization & Structural analysis

The finite element analysis takes place in three steps,

i. Pre-processing

- Defining the Engineering data (type of analysis)
- Material properties assignment
- Import the CAD geometry

ii. Solving – Mesh & Apply loading conditions

iii. Post processing – Verifying the simulation results

Detailed procedure for this experiment is given below,

- In Ansys workbench > select "Static structural" in the Analysis systems.
- In engineering data > Material database, the following material and its properties has to be defined,

S No	Material	Density [kg/m3]	Young's modulus [Gpa]	Poisson ratio
1	Carbon fiber	1800	230	0.2
2	Graphene	4717	342	0.19

Table 3. Material properties data

- **Import the CAD geometry from CATIA as .igs file**

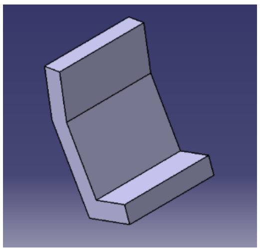


Figure 2. CATIA model of seat

- **Apply meshing to the discretize the solid model in form nodes and elements.**

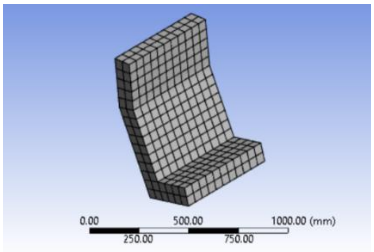


Figure 3. Meshing the model

- **Apply loading condition**

Fixed support: **Point A** – Bottom of the seat.
Force: **Point B** – Region where the driver's spine rest and loading takes place.

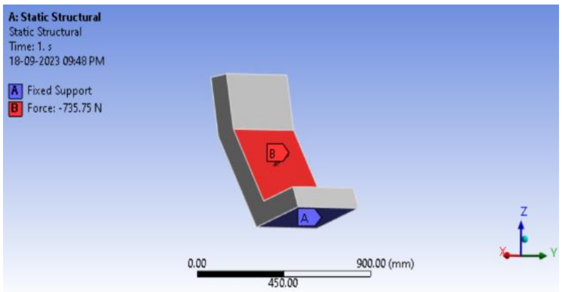


Figure 4. Loading condition

Load criteria:
Bodyweight = 75 kg
G-force = 9.81 N

⇨ 75kg x 9.81 N = -735.75 N ("-"sign indicates load in opposite direction)

- **Verify the results of**

I. Deformation
II. Stress
III. Strain
Following results were obtained for Carbon fiber and Graphene,

Carbon fiber – simulation results

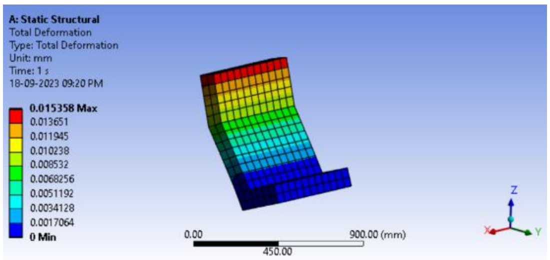


Figure 5. Total deformation

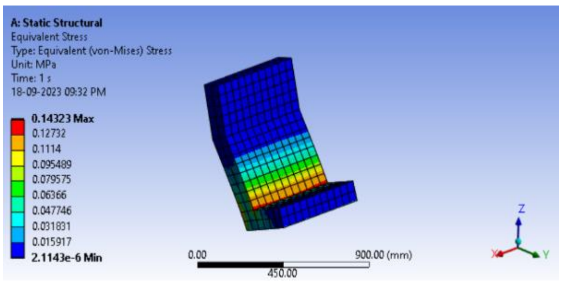


Figure 6. Equivalent stress

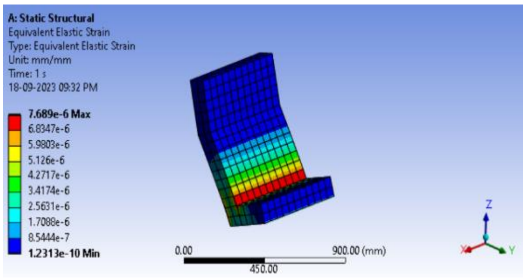


Figure 7. Elastic strain

Graphene – simulation results

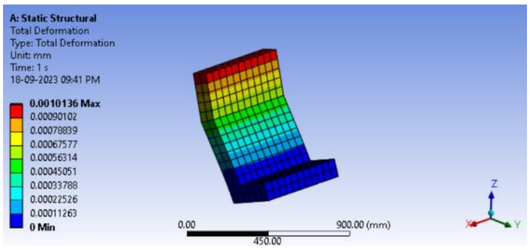


Figure 8. Total deformation

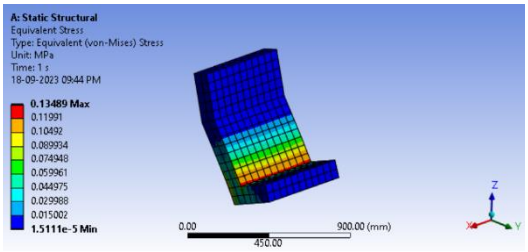


Figure 9. Equivalent stress

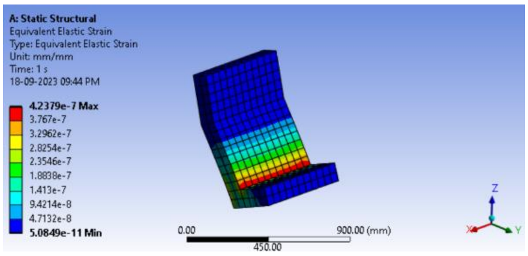


Figure 10. Elastic strain

IVRESULTS & DISCUSSION

In Biomechanical analysis and Design optimization, the compression and Joint shear limits of Lumbar spine - L4 L5 at angle 60° proves to the optimum seat fit posture for the driver. This nearly upright position protects the spine from compression induced shear loads during the porpoising effect and shear forces. Whereas, more flatter position i.e 20° is prone to higher level of load impact.

S No	Angle	G - Force [Taking 1G force = 1xbodweight as ref.]	L4-L5 spine limit (N)			
			Compression	Joint shear	Location	Result
1	60°	75 kg	2185	400	Posterior	Low
2	45°	75 kg	2747	531	Posterior	Medium
3	20°	75 kg	3081	773	Posterior	High

Table 4. Result of Design optimization & Biomechanical analysis

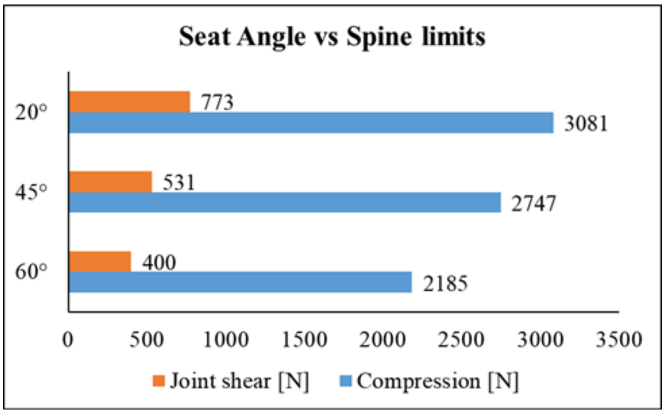


Chart 3. Graphical representation of Spine limits

In Material optimization, Graphene and carbon fiber model was simulated for Structural analysis by finite element method and compared for the values of Stress, Strain and Deformation. The total Stress value of Graphene model was 6% lower than Carbon fiber. Thus, Shock absorption is enhanced further in the selected material.

Load factors	Carbon fiber	Graphene	Result
Total deformation [mm]	0.01	0.001	Values <1 , negligible
Stress [pa]	143230	134890	Reduction of 6% of Stress in Graphene
Strain [mm]	7.689 e-6	4.237 e-7	Values <1 , negligible

Table 5. Result of Material optimization & Structural analysis

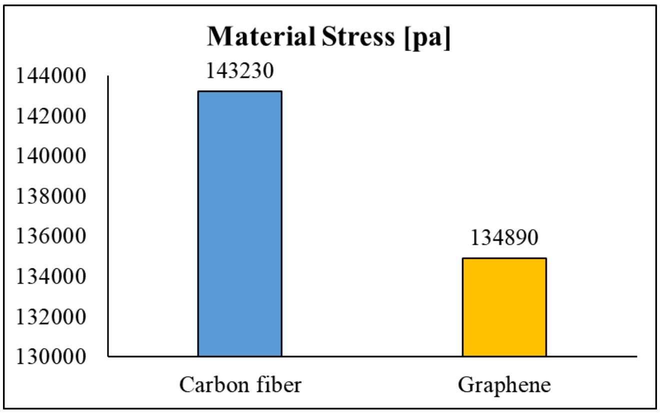


Chart 4. Reduction of stress in Graphene material

V.CONCLUSION

Hence, the simulation results have provided a clear solution for eliminating the higher risk of spine injury or pathological condition of a sportsman and thereby improving the sporting performance.

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