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Enhancing Structural Safety: Analysis of Roll Cage Models in Rally Cars

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ABSTRACT:

The structural integrity of rally cars heavily relies on the effectiveness of roll cages in mitigating damage during side impacts and roll-overs, crucial for ensuring driver safety. This study undertakes a comprehensive analysis of various roll cage models, emphasizing the positioning of individual members to optimize safety measures. Six distinct models are scrutinized to assess maximum deformation and von Mises stress, pivotal factors in determining the structural robustness of roll cages. Utilizing Fusion 360 software, the roll cage models are meticulously constructed, followed by rigorous analysis employing the static structural module in ANSYS. This analytical approach aims to provide insights into the performance and resilience of different roll cage configurations under varying impact scenarios. The investigation delves into critical aspects such as load-bearing capacities during side impacts and roll-overs, with a keen focus on minimizing cabin deformation to enhance driver safety. By employing advanced computational methods and simulation tools, this study

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contributes to the advancement of structural safety measures within rally car design and engineering..

KEYWORDS:

Roll Cage Design & Analysis, side impact, roll-over, Fusion 360, Ansys Workbench.

1. Introduction

Auto racing stands as one of the most perilous sports, where even the slightest error or stroke of misfortune can lead to fatalities or severe injuries. Constructing a roll cage in compliance with the essential requirements outlined by motor sport federations like the Federation of Motor Sport Clubs of India (FMSCI) serves as a crucial means to elevate driver safety. Governing bodies in car racing, such as the FIA or FMSCI, possess the flexibility to establish regulations either based on performance or technological standards.

Adhering to these regulations, Roll-Over Protection Systems (ROPS) or Roll cages must adhere to numerous criteria and configurations for their design, manufacture, and installation in various vehicle types—be it production, touring, or sports automobiles. These regulations encompass specifics like roll cage tube dimensions, material choices, incorporation of gussets, and required outcomes such as factor of safety and minimal forces during a side impact.

A roll cage, serving as a protective frame within a vehicle, aims to safeguard occupants from harm or fatality in the event of an accident. While different racing organizations have distinct specifications, many align closely with the FMSCI guidelines. Meanwhile, a roll bar, a single bar positioned behind the driver, provides basic rollover protection. Some modern convertibles utilize a robust windscreen frame as a roll bar due to the absence of a protective top. Additionally, a roll hoop, essentially a roll bar spanning the passenger's shoulder width, can be installed behind both headrests.

Constructed from high-strength steel and engineered to withstand impacts, roll cages are classified into two types: welded and bolted. Welded joints offer superior strength, while bolted joints allow for more flexibility. This analysis considers six different configurations as shown in figures 1 and 2 and evaluates their efficacy.

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(a) (b) (c)

Fig. 1: (a) 4-point roll cage (b) 6-point roll cage (c) 8-point roll cage

(a) (b) (c)

Fig. 2: (a) 5-pointrollcage, (b) 7-pointrollcage, (c) 10-pointrollcage

A crash test involves destructive testing to verify the compliance of various modes of transportation or interconnected systems and components with safe design standards in terms of crashworthiness and compatibility. Factors such as deformation patterns, acceleration, and projected harm by human body models are used to assess crashworthiness prospectively and retrospectively. After real collisions occur, crashworthiness is further evaluated by examining the risk of injuries.

Side-impact tests pose high risks of fatality due to insufficient crumple zones in cars to absorb impact forces before occupants are harmed. Meanwhile, rollover tests evaluate a car's ability to sustain itself in a dynamic accident, particularly assessing the pillars supporting the roof. Dynamic rollover tests have been suggested as alternatives to static crush testing.

To mitigate costs, engineers often conduct computer model testing by simulating crash scenarios, refining vehicle or barrier designs before physical crash tests due to their expenses. Roll cage configurations in this study are affixed to a ladder frame chassis for experimental analysis.

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The current study aims to select the optimal roll cage by conducting static structural analysis of roll cage geometry under natural boundary conditions and assessing the outcomes.A. Pavlovic et al. [1] specifically analyzed the influence of material characteristics on vehicle stiffness and found that using quality steels (such as EU1.0401) better meets safety conditions (<50 mm displacement) compared to low carbon steels (EU1.0309). Vineet Felix Rodrigues et al. [2] discussed the methodology for designing, fabricating, and testing a roll cage for Aston Martin DB9 rallying. They employed two 3-D models for finite element analysis (FEA) to comprehend roll cage performance when subjected to static side loads, aligning theory, experiment, and FEA results for validation.

B. Subramanyam et al. [3] focused on dynamic loads applied to the roll cage during normal driving conditions and analyzed the roll cage's torsion rigidity. Their analysis suggested that roll cages can absorb high-energy impacts while managing deceleration rates, providing recommendations for mild steel and carbon-fiber skins in a tabular space frame for student formula SAE car roll cages. Their analysis laid the groundwork for designing and analyzing student formula car roll cages.

Several studies [4-10] explored roll cage design, employing advanced accident modeling approaches [11-18].

2. Design and analysis of roll cage

Taking ergonomic considerations a roll cagewas modelled in Autodesk Fusion 360. The inner tube dimension of the entire roll cage is taken as 3mm and every member of the roll cage is created with the support of the roll-bar.

2.1 Finite Element Analysis

The whole analysis part is done by using static structural system in the ansys workbench. The entire geometrical model was discretised by model option. Mesh was generated using the face meshing operation.

2.2 Boundary Conditions

Loads are applied to obtain results of roll over and side impact crash test.

2.2.1 Roll Over

A load of 2500 N is applied at the top junction along the Y direction. As shown in the figure 3 the load is applied to all the roll cage models respectively.

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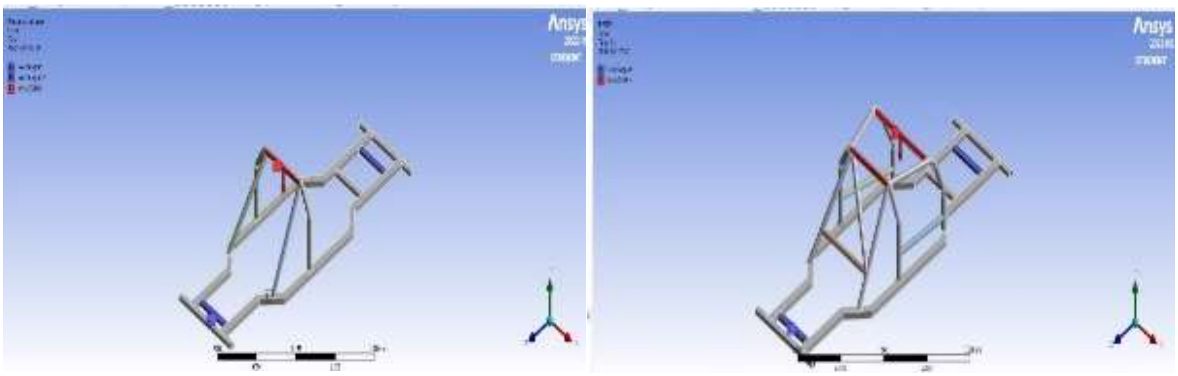

Fig. 3: Top Load in 4-Point Roll Cage & 10-Point Roll Cage Respectively

2.2.2 Side Impact

A load of 2500 N is applied at the Side junction along the X direction. As shown in the figure 4the load is applied to all the roll cage models respectively.

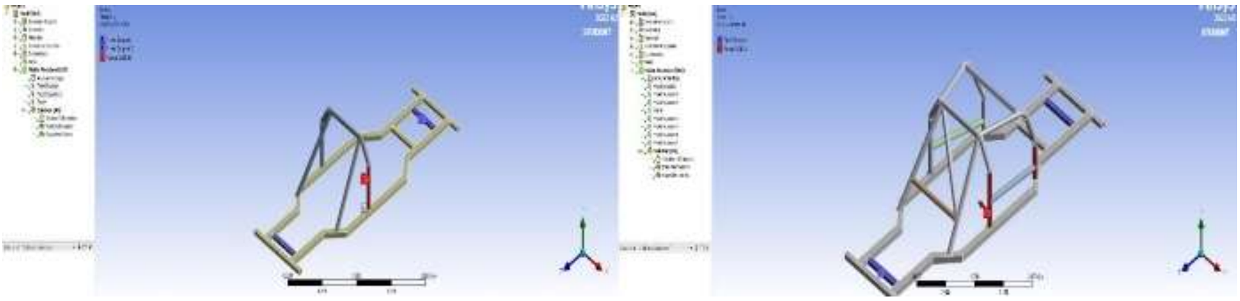

Fig. 4: Side Impact in 4-Point Roll Cage & 10-Point Roll Cage Respectively

2.3 Material Properties

The material we considered for the analysis is structural steel whose properties are already predefined in the ansys workbench. The materail properties are given in table 1.

Table 1 Structural Steel Properties

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Property	Value	Unit
Material Field Variables	Table	
Density	7850	kg m^-3
Isotropic Secant Coefficient of Thermal Expansion		
Isotropic Elasticity		
Strain-Life Parameters		
S-N Curve	Tabular	
Tensile Yield Strength	2.5E+08	Pa
Compressive Yield Strength	2.5E+08	Pa
Tensile Ultimate Strength	4.6E+08	Pa
Compressive Ultimate Strength	0	Pa

3. Analytical Results

3.1 Analysis at top junction of roll cage

From the table 2 of roll-over results, we can observe that 10-Point roll cage is having less deformation and von misses stress values i.e. 0.00024128 & 1.2245e7 respectively. So using 10-point roll cage is the safest way to protect the drivers in-case of accidents.

Table 2: Roll Over Results

S.no	Model	Load (N)	Von Misses (pa)	Total Deformation (m)
1	4 Point Roll Cage	2500	3.5525e7	0.00039906
2	5 Point Roll Cage	2500	4.043e7	0.00038752
3	6 Point Roll Cage	2500	3.1928e7	0.00023146
4	7 Point Roll Cage	2500	1.2433e7	0.00024545
5	8 Point Roll Cage	2500	1.8893e7	0.00031438
6	10 Point Roll Cage	2500	1.2245e7	0.00024128

Von-Misses stress Results for Top Junction are shown in figure 5 for 4 point and 5 point roll cages, in figure 6 for 6 point and 7 point roll cages, figure 7 for 8 point and 9 point roll cages.

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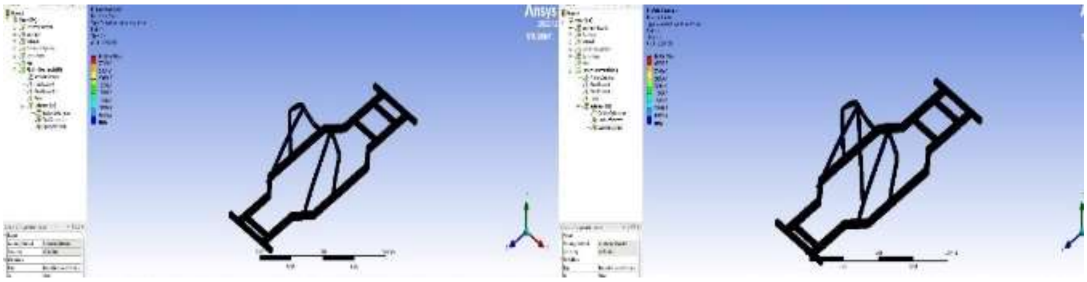

Fig. 5:Stress in 4-point & 5-point Roll Cages at Top junction

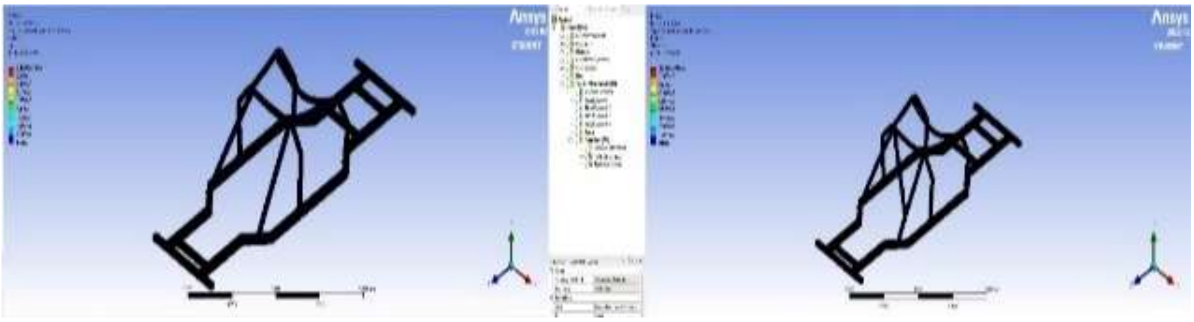

Fig. 6 :Stress in 6-point & 7-point Roll Cages at Top junction

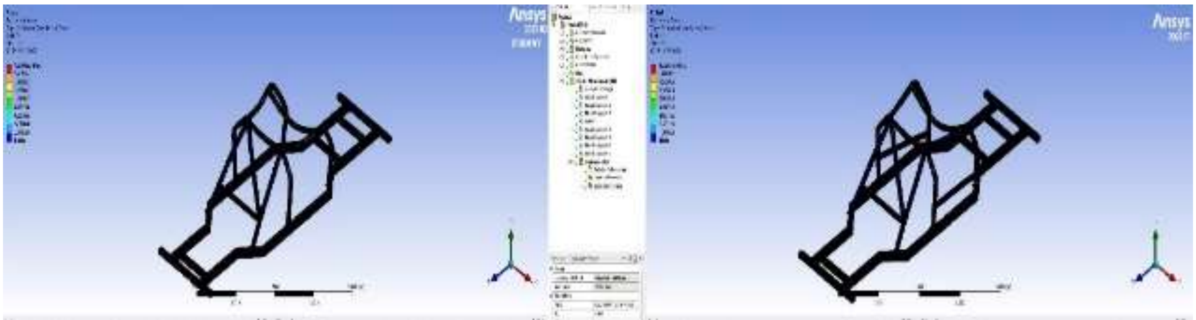

Fig. 7 :Stress in 8-point & 10-point Roll Cages at Top junction

Total Deformation results for Top Junction are shown in figure 8 for 4 point and 5 point roll cages, in figure 9 for 6 point and 7 point roll cages, figure 10 for 8 point and 9 point roll cages.

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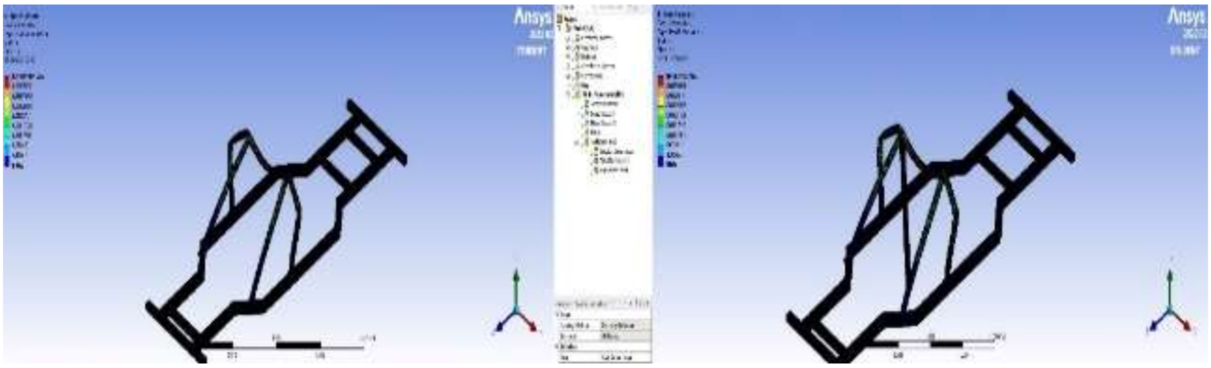

Fig. 8:Deformation in 4-point & 5-point Roll Cage at Top Junction

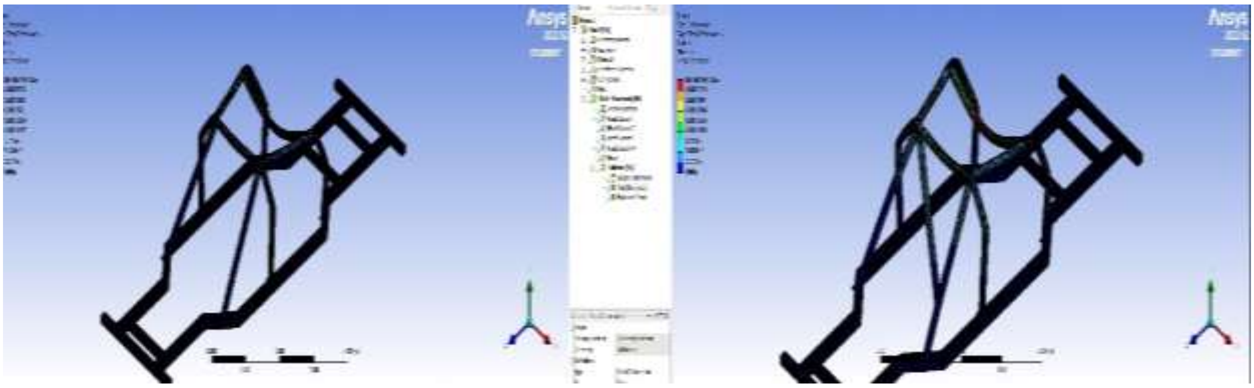

Fig. 9:Deformation in 6-point & 7-point Roll Cage at Top Junction Resp.

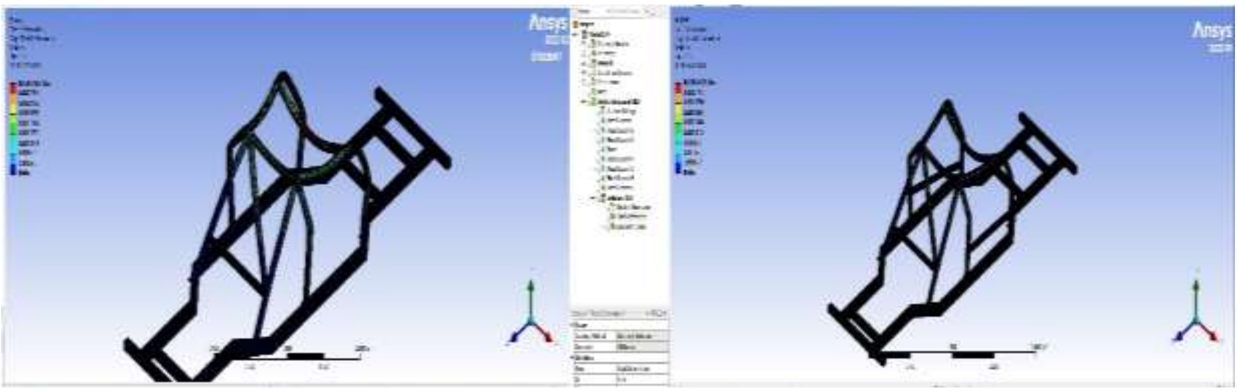

Fig. 10:Deformation in 8-point & 10-point Roll Cage at Top Junction Resp.

3.2 Analysis at side junction of roll cage

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S.no	Model	Load (N)	Von Misses (Pa)	Total Deformation (m)
1	4 Point Roll Cage	2500	4.0429e7	0.0011426
2	5 Point Roll Cage	2500	2.942e7	0.00018567
3	6 Point Roll Cage	2500	2.4005e7	0.0002027
4	7 Point Roll Cage	2500	1.5295e7	0.000099417
5	8 Point Roll Cage	2500	1.5531e7	0.000090233
6	10 Point Roll Cage	2500	1.8183e7	0.000086826

Table-3 Side impact results

From the above table of side impact results, we can observe that 10-Point roll cage is having less deformation and von misses stress values i.e. 0.000086826 & 1.8183e7 respectively. So using 10-point roll cage is the safest way to protect the drivers in-case of accidents.

Von-Misses stress Results for side Junction are shown in figure 11 for 4 point and 5 point roll cages, in figure 12 for 6 point and 7 point roll cages, figure 13 for 8 point and 9 point roll cages.

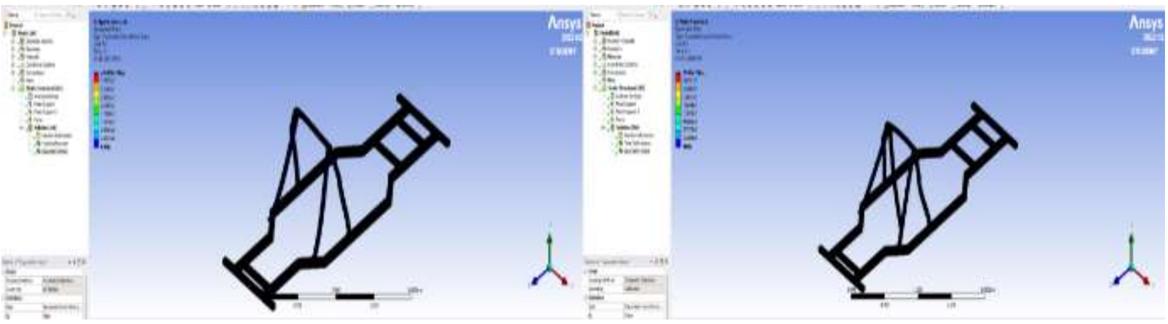

Fig. 11: Stress in 4-point & 5-point Roll Cages at Side junction

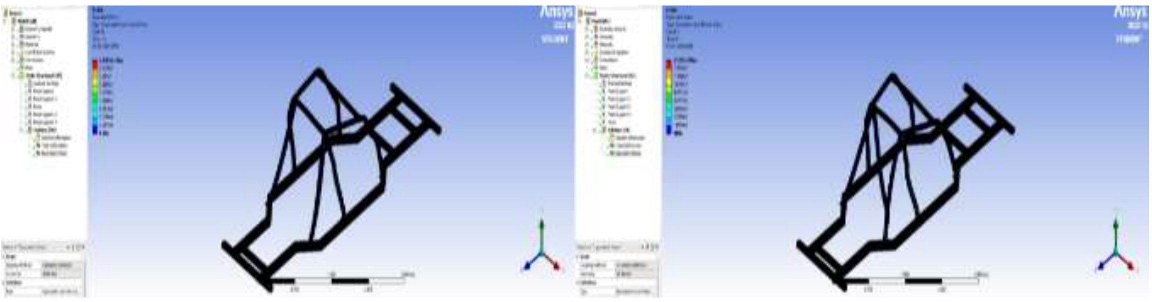

Fig. 12:Stress in 6-point & 7-point Roll Cages at Side junction

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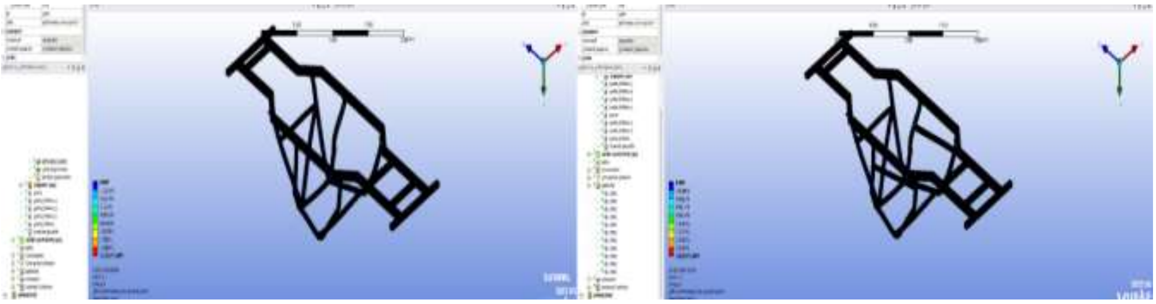

Fig. 13: Stress in 8-point & 10-point Roll Cages at Side junction

Total Deformation results for side Junction are shown in figure 14 for 4 point and 5 point roll cages, in figure 15 for 6 point and 7 point roll cages, figure 16 for 8 point and 9 point roll cages.

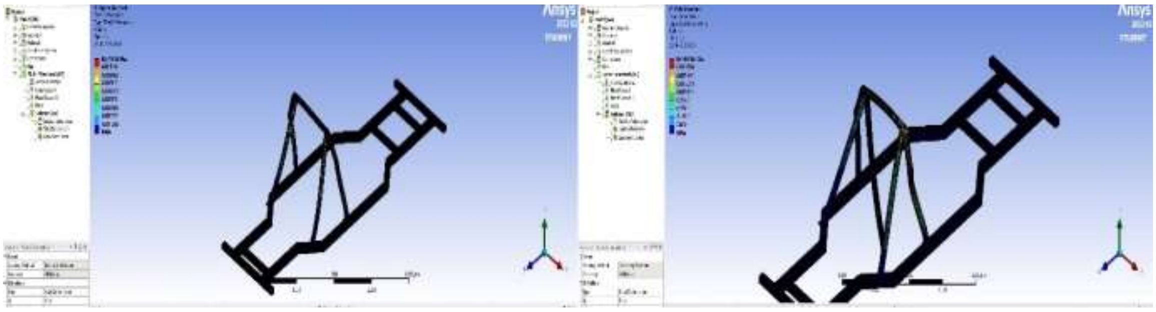

Fig. 14:Deformation in 4-point & 5-point Roll Cage at Side Junction

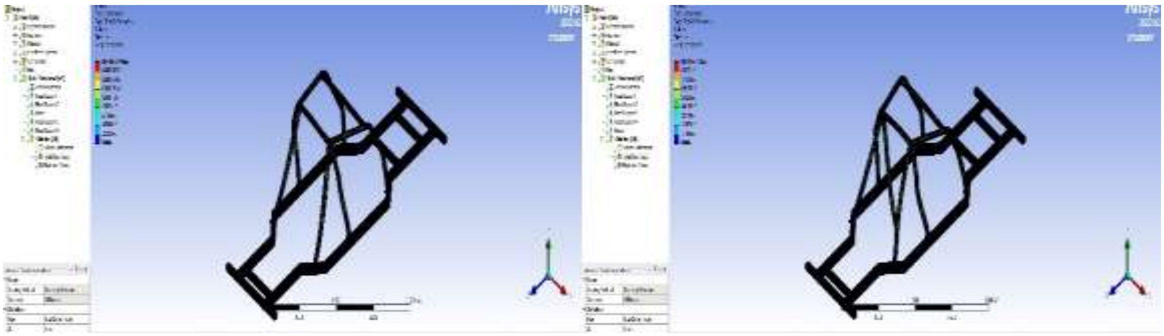

Fig. 15:Deformation in 6-point & 7-point Roll Cage at Side Junction

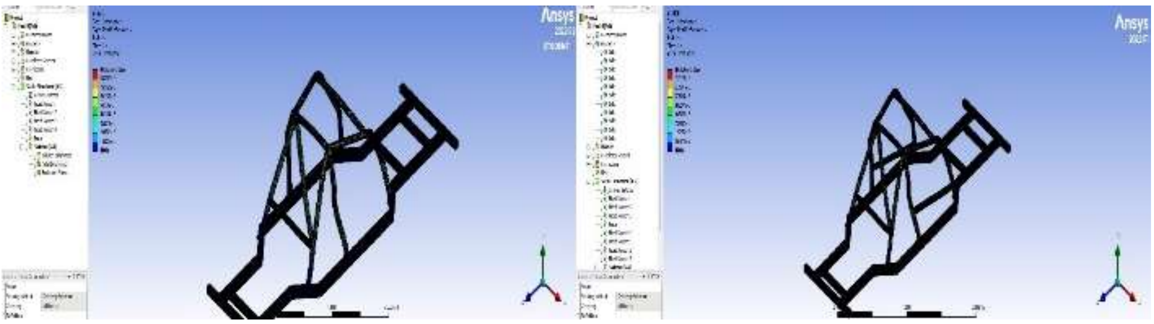

Fig. 16:Deformation in 8-point & 10-point Roll Cage at Side Junction

3. Conclusion

The roll cage is an essential tool for occupant protection during a rally race, adding to the rigidity of the car's body frame. Nonetheless, a careful design validation is required to guarantee significant benefits.

In the crash test, the roll bar was a key component. It has protected the passenger area and given the chassis extra muscle.

Depending on the size and speed of the vehicle, the car will actually experience side impact loads and roll-over loads of more than 2500 N. Hence, the best method to construct these roll cages would be to let the user design them so that they can bear such minimal stresses.

Table-4 Overall Result Comparision

Model	**Side impact**		**Top impact**	
	Von Misses	Total Deformation	Von Misses	Total Deformation
4 Point Roll Cage	4.0429e7 Pa	0.0011426 m	3.5525e7 Pa	0.00039906 m
5 Point Roll Cage	2.942e7 Pa	0.00018567 m	4.043e7 Pa	0.00038752 m
6 Point Roll Cage	2.4005e7 Pa	0.0002027 m	3.1928e7 Pa	0.00023146 m
7 Point Roll Cage	1.5295e7 Pa	0.000099417 m	1.2433e7 Pa	0.00024545 m
8 Point Roll Cage	1.5531e7 Pa	0.000090233 m	1.8893e7 Pa	0.00031438 m
10 Point Roll Cage	1.8183e7 Pa	0.000086826 m	1.2245e7 Pa	0.00024128 m

The roll cage with the most cross members is the safest one to use in a rally car i.e. 10 point roll cage, according to the experimental results of the roll over analysis and side impact analysis, which show that by increasing the number of cross members present in the roll cage, the von-misses stress and the total deformation have been decreased.

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