Design and Optimization of Roll Cage for Pick-Up Truck
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Abstract:
Our study aims to design and optimize roll cage for a pick-up truck. The roll cage is a structural base which protects the occupants in case of impact and rolls over and also prevent flexing of chassis. Here we are going to deal with design of roll cage and considering various loading test like front impact, side impact, rear impact roll over as well as modal analysis. We have focused on every point of roll cage to improve performance of vehicle without failure of roll cage and also optimizing it for reducing its weight and maintaining desired centre of gravity to maintain stability at turns.

I. INTRODUCTION
The objective of the study is to design and develop the roll cage for Pick-up truck. The design factor contains safety, easy manufacturing, durability & maintenance of the frame and a compact, lightweight & ergonomic design.

This paper focus on various loading tests like Front Impact, Rear Impact, Side Impact, Roll over to check whether the roll cage can bear all types of impacts. A software model is prepared in Solidwork software. Later the design is analysed against all modes of failure by conducting various simulations and stress analysis with the aid of Ansys Software. Based on the result obtained from these tests the design is modified accordingly. The vehicle is required to have a combination of frame and roll cage consisting of steel members.

As weight is critical in a vehicle powered by engine a balance must be found between the strength and weight of design. To best optimize this balance the use of solid modelling and finite element analysis (FEA)

II. DESIGN AND DEVELOPMENT
The design and development process of roll cage involves various factors namely material selection, cross section determination and finite element analysis.

One of the key design decision of frame is to increase the safety, reliability and performance in any automobile design is material selection. To ensure that the optimal material is chosen, extensive research was carried out and compared with materials of multiple categories. The key categories of comparison are strength, weight and cost.

III. MATERIAL SELECTION
To build roll cage steel must be used according to the rules. There are many different types of steel available. We selected three material for our roll cage AISI 304, AISI 1018 and AISI 4130. We performed analysis on roll cage of each material and after analysis we selected material AISI 4130 steel for our roll cage.

The roll cage will be made from tubular sections. Tubular sections offer superior loading capabilities per kg when compared to solid sections or square sections.

Table.1. The table below shows properties of AISI 4130:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength (Sₚ)</td>
<td>945 [MPa]</td>
</tr>
<tr>
<td>Yield Tensile Strength (Sₚₜ)</td>
<td>740 [MPa]</td>
</tr>
<tr>
<td>Modulus of Elasticity (E)</td>
<td>205 [GPa]</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>7850</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.285</td>
</tr>
<tr>
<td>Shear Modulus [MPa]</td>
<td>80000</td>
</tr>
</tbody>
</table>

IV. ROLL CAGE DESIGN
For designing the roll cage we considered the dimension of truck for which the roll cage need to be designed. The various points considered for designing the roll cage are the wheel base, track width, weight of vehicle. It is also necessary to keep weight of the roll cage as low as possible to achieve better acceleration. It is necessary to keep the centre of gravity of the vehicle as low as possible to avoid toppling. Once modeling of the roll cage structure is done by using Solidwork, the designed roll cage is then evaluated in the Solidwork itself to have an idea of the physical parameters of the roll cage.

V. ANALYSIS METHODOLOGY
Once modeling of the roll cage structure is done by using Solid work, this design is checked by Finite Element Analysis. Ansys Workbench has been used for this purpose. A coordinate file is created in notepad and that has been imported in Ansys via import geometry, then specified material.
VI. FEM ANALYSIS

As the Roll cage was developed by plotting key points, so every member of the roll cage is considered to be properly constrained at every joint. After finalizing the frame along with its material and cross section, it is very essential to test the rigidity and strength of the frame under severe conditions. The frame should be able to withstand the impact, torsion, roll over conditions and provide utmost safety to the driver without undergoing much deformation. Following tests were performed on the roll cage: (1) Front Impact, (2) Rear Impact, (3) Side Impact, (4) Roll over, (5) Torsional.

FRONT IMPACT ANALYSIS
This analysis is done to simulate those conditions when the vehicle may hit a tree, another vehicle or a wall. Under such conditions, the amount of forces generated reacts at the front most portion of vehicle.

During dynamic condition,
We assume collision occurs and maximum speed of vehicle i.e. 80kmph = 22.22m/s
Suddenly it hits the wall within 0.25 sec and deacceleration is given by
V = u + at
V = 0
U = 22.22 m/s
T = 0.2
Therefore a = 111.1m/s²
Now according to newtons second law of motion
F = m x a
Therefore F = 1920 x 111.1
= 213120 N
Therefore we will be applying force of 213 kN along Z axis because it is the maximum force acting on roll cage during front impact.

SIDE IMPACT ANALYSIS
Side impact analysis is done to check the strength of the roll-cage in the case of accident involving the vehicle hit by another car from side. The force is applied on the side most members of the vehicle and fixing suspension pick up points.
Assuming our vehicle is stationary and another vehicle speed of 55kmph will strike us from side then deacceleration is given by
V = u + at
U = 55kmph = 15.3 m/s
T = 0.2 (time of impact)
Therefore a = 76.5 m/s²
According Newtons second law of motion force of impact is given by,
F = 1920 x 76.5 = 146880N
Therefore applying force of 146.88KN along X axis in negative direction.

REAR IMPACT ANALYSIS
The rear impact analysis is done for analysing the rigidity of a roll cage in case of a collision of the vehicle from back side when some another car hits. The force is applied on the rear part of the vehicle and fixing suspension pick up points.
Assuming another vehicle at 60kmph hit our stationary vehicle then deacceleration is given by,
V = u + at
U = 60 kmph = 16.67m/s
t = 0.2 (time of impact)
therefore a = 83.33m/s²
Now according to newtons second law of motion force during impact is given by,
F = 1920 x 83.33
= 160000 N
Therefore applying force of 160 kN along Z axis in positive direction.

ROLL OVER ANALYSIS
The roll over analysis is done for analysing the overhead structure of roll cage to check whether it will absorb the force during roll over and prevent intrusion of parts and protect driver during accident.
For roll over we are applying force equal to weight of vehicle since force applied by the ground on roll cage will be equal to weight of vehicle.
Therefore F = 1920 x 9.81 (m x g)
= 18835 N
Therefore applying force of 18835 N along Y axis in negative direction.

TORSIONAL ANALYSIS
Torsional analysis of the roll cage was done to find the torsional stiffness of the roll cage during cross bumps at front and rear. The main aim of this analysis was to have greater roll
cage stiffness to sustain dynamic suspension loads. We assume that load is acting 60 : 40 that is 60 percent at front and 40 percent at back axle.

Therefore \( F = 0.6 \times 1920 \times 9.81 \)
\[ = 11301 \text{ N} \]

Applying the force on front axle equally but opposite in direction

Calculation for torsional stiffness

Roll cage weight = 172 kg
Truck weight = 1920 kg
Force of 1G = 1 \times 9.81 \times 1920
\[ = 18835 \text{ N} \]

\( \text{Torque} = \text{force} \times \left(\frac{1}{2} \text{ of track width}\right) \)
\[ = 15068 \text{ N-m} \]

\( \Theta = \text{Angle of deflection} = \tan^{-1} \left(\frac{\text{vertical displacement}}{\left(\frac{1}{2} \text{ of track width}\right)}\right) \)
\[ = \tan^{-1} \left(\frac{13.57}{800}\right) \]
\[ = 0.9717 \]

Torsional stiffness \((k) = \frac{\text{Torque}}{\text{angle of deflection}} \)
\[ = \frac{15068}{0.9717} \]
\[ = 15505 \text{ Nm/degree} \]

**OPTIMIZATION OF MODEL**

Design optimization is more than reducing weight. It’s about maximizing performance and efficiency of material application while minimizing life-cycle cost. Finite Element technology provides us with tools for structural design optimization throughout several design phases. So we optimized the model in terms of deformation since deformation is high for our model. So we redesigned the model so that the deformation is reduced and again analysis is performed on our model. The front and rear pipe diameter was increased from 1 inch to 1.5 inch. Similarly, the members which are not subjected to much load was decreased from 1 inch to 0.5 inch In this model we replaced the pipes which are subjected to higher deformation with increased diameter pipes. Similarly the pipes which are not subjected to much force are replaced by decreased diameter pipes. Now to check whether the deformation is reduced or not analysis is performed of this model and results are compared with the previous model result.

**VII. RESULTS**

The below results are comparison between optimized and 1st model

<table>
<thead>
<tr>
<th>IMPACT</th>
<th>1ST MODEL</th>
<th>OPTIMIZED MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRONT</td>
<td>165</td>
<td>27.68</td>
</tr>
<tr>
<td>SIDE</td>
<td>8.42</td>
<td>2.97</td>
</tr>
<tr>
<td>REAR</td>
<td>77.69</td>
<td>5.27</td>
</tr>
<tr>
<td>ROLL OVER</td>
<td>19.46</td>
<td>4.68</td>
</tr>
<tr>
<td>TORSIONAL</td>
<td>13.46</td>
<td>6.55</td>
</tr>
</tbody>
</table>

From analysis;

- Stress induced for torsional impact = 642.17 MPa
- Strength of material = 740 MPa
- FOS = 740/642.17 = 1.2
- Since the factor of safety for automobile goes up to 8 therefore our design is satisfactory and valid

- Stress induced for roll over = 387 Mpa
- Strength of material = 740 MPa
- FOS = 740/ 387 = 1.92

- Stress induced during front side and rear impact = 1152 MPa
- Strength of material = 740 MPa
- FOS = 740/1152 = 0.65

Since FOS goes up to 8 our roll cage is safe and valid since FOS is under the limit therefore roll cage is safe

**VIII. CONCLUSION**

The safety of vehicle increases by adding roll cage to the vehicle. FEA results show that AISI 4130 is better material for roll cage compared to that of AISI 304 and AISI 1018 . From results it is clear that most of the force during impact is absorbed by the roll cage thus protecting vehicle and driver during accident. From this project we can conclude that optimization increases efficiency of roll cage.

**IX. REFERENCES**

[1]. A.Subic “Modal analysis of bus roll cage structure for optimum rollover design”


[5]. Sudeep Roy, Rishabh Srivastava and Devesh Kumar “Roll Cage Design for an All-Terrain Vehicle with Reduced Weight and Improved Strength” Journal of Material Science and Mechanical Engineering (JMSME) Volume 2, Number 10; April-June, 2015

[6]. Akshay Murkute “Structural Optimization Of Sae Baja Car Frame”