ABSTRACT

A Mini Baja is a special kind of four-wheeled vehicle used for recreational and exploration purposes. It is designed for off road usage and for endurance of a rough terrain. In many aspects it is similar to an All-Terrain Vehicle (ATV) except that it is much smaller in size and has safer rollover capabilities. Besides these any successful mini baja vehicle should also be easily transported, easily maintained and fun to drive. An international competition is organized by the Society of Automotive Engineers (SAE) for universities throughout the world to design and fabricate their vehicles and then compete against each other. This project was aimed to develop the design of a chassis which is safe, ergonomic and has the lowest possible weight. Competitiveness of the vehicle in terms of ruggedness and maneuverability has also been kept in mind. A preliminary design was first prepared keeping in mind the guidelines issued by SAE[1]. Indian standards[2] for driver space have been incorporated and a PVC mock-up was developed to evaluate the driver ergonomics. A proper suspension type was then selected and designed as per the requirements of the vehicle. The CAD modeling of the frame and other components was done. This design was checked by Finite Element Analysis after estimating the load and the weight of the frame optimized. A rollover analysis was then carried out to ensure safety in such a situation. The Rollover Analysis involved evaluating static stability and ensuring compliance with the pertinent Indian Standards[3,4]. Hence, after ensuring safety, the design was finalized and the frame was then manufactured after procuring the pipes from the market.

Keywords: Mini Baja, Chassis, Suspension, Roll Over, ATV, FEM

CERTIFICATE

We, Mr. Vijay Jain and Mr. Manvinder Singh, are submitting this report detailing work done during 2nd semester 2004-2005 in course ME320S. We have written this report and all material taken from other sources (books, manuals, internet, other theses, etc.) has been fully acknowledged.

Vijay Jain	Manvinder Singh
2002277	2002245

Date:

Mr. Mr. Vijay Jain and Mr. Manvinder Singh have worked under my supervision during 2nd semester 2004-2005. This report accurately reflects the work done by the students and conforms to the editorial requirements.

Dr. Sudipto Mukherjee
(Supervisor)

Date:

ACKNOWLEDGEMENTS

We would like to express our extreme gratitude towards Dr. Sudipto Mukherjee, Associate Professor, Mechanical Engineering Department. The support and enthusiasm shown by our guide constantly acted as a source of inspiration to us and motivated us to achieve the goals of the project.

This effort also received immense support from professionals in the field of performance vehicles, prominently Mr. Nipun Chabbarwal, Mr. Raj Kapoor, Mr. Jayesh Desai and also from Mr. Aarush of Autopsyche. We would like to thank all of them.

We would also like to thank the staff of the Computer Aided Graphical Instruction (CAGI) laboratory of the Mechanical Engineering Department. In the end we would like to express gratitude towards Mr. Tushar Gavade and Mr. Abhishek Dwivedi for their help in gaining understanding of certain subjects involved in the project.

Vijay Jain

Manvinder Singh

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LIST OF SYMBOLS

E	Energy
Exy	Youngs Modulus
F	Force
FS	Factor of Safety
g	Acceleration Due To Gravity
H	Height of Centre of Mass
ID	Inner Diameter
M	Mass
OD	Outer Diameter
S	Strength
SMAX	Maximum Von Mises Stress
SSF	Static Stability Factor
T	Track Width
ν	Poisson's Ratio

Subscripts

y	Yield
t	Tensile
i	'i'th component
d	Design
in	Incorporated

CHAPTER 1 INTRODUCTION

1.1 Motivation and objectives

1.1.1 Motivation

An international Mini Baja design competition is organized by the Society of Automotive Engineers(SAE), Mini Baja is an intercollegiate engineering design competition for undergraduate and graduate engineering students. The object of the competition is to simulate real-world engineering design projects and their related challenges. SAE has laid down certain guidelines[1] for designing and fabrication of mini bajas. According to these guidelines all mini bajas are to use the same Briggs & Stratton ® 10HP engine. Thus the chassis design becomes very important. Typical capabilities on basis of which these vehicles are judged are hill climbing, pulling, acceleration & maneuverability on land as well as water. This project aims to design the chassis for a mini baja according to the SAE guidelines.

1.1.2 Objectives

The project was aimed to design the frame & suspension of the Mini Baja which is of minimum possible weight and allows for the construction of a mini baja that is safe, rugged and easy to maneuver and conforms to all Indian established standards & guidelines issued by SAE. The design of the frame and the suspension and have been successfully completed as per the requirements.

1.2 Problem statement

To Design and carry out Finite Element Analysis and Rollover Simulations for a Mini Baja Chassis.

1.3 Plan of Work

The Plan of Work for the project was divided into 5 major stages. Initially, we prepared a preliminary design based on specifications given[1]. This then was tested for driver space by building a plastic mock-up model using PVC pipes. It was then followed by modeling the chassis in Pro/E. This design was then checked using Finite Element Analysis in Ansys and further optimized in terms of weight and safety. Simultaneously, a suspension type was selected and its design carried out. A rollover analysis was carried out to ensure safer rollover capabilities.

1.4 METHODOLOGY

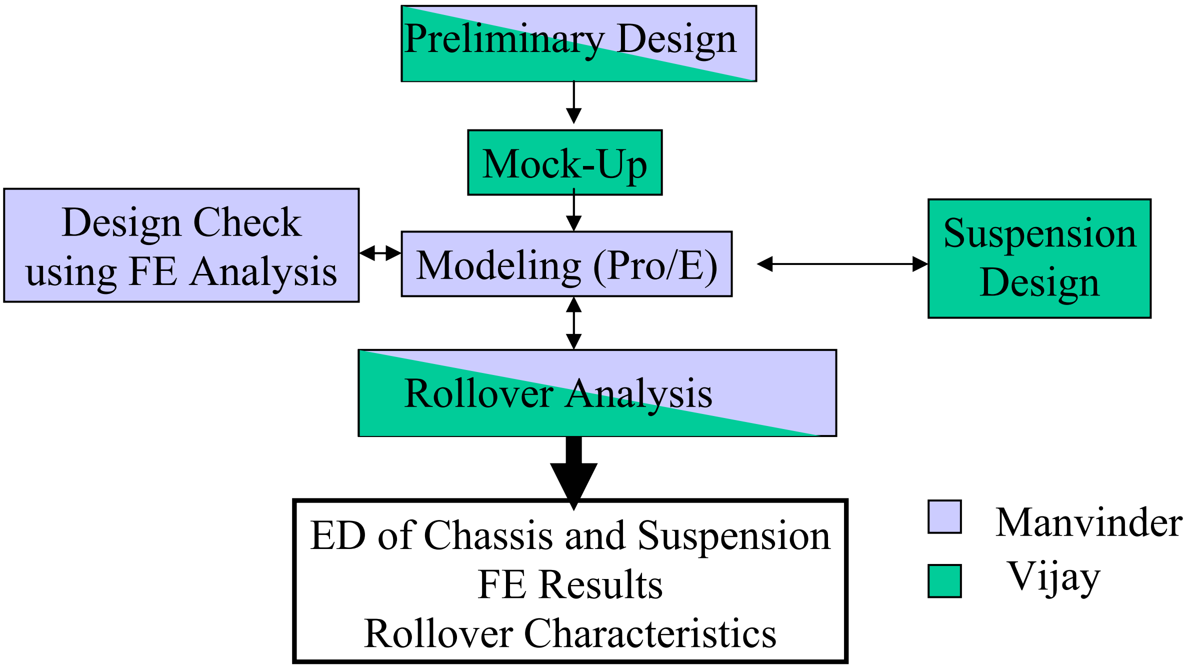


Figure 1.1: Methodology of the project

1.5 GANTT Chart

Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Research	■	■	■	■	■					■	■	■	■	
Preliminary Design		■	■	■										
Pro/E Modeling			■	■	■	■	■				■	■		
FEA on ANSYS						■	■	■	■	■				
Roll Over Analysis									■	■	■			
Suspension Design											■	■	■	
Report Submission										■	■	■	■	■

Figure 1.2 GANTT Chart

Research: Study of SAE guidelines, established standards, search for previous work done.

Preliminary Design: Preparation of preliminary design of frame & suspension.

Pro/E Modeling: CAD modeling of chassis in Pro/E. Modeling of additional components like tires, engine etc.

FEA on ANSYS: Finite Element Analysis of the Chassis & study of previous work done in rollover simulations.

Roll Over Analysis: Ensuring safety in case of roll-over through simulations.

Suspension Design: Selecting a suitable suspension type and developing its design.

Report Submission : Preparation of Final Report.

1.6 Expected outcome

The expected deliverables for the project were Engineering Drawings of the frame and suspension of the Mini Baja. The project has successfully met its aims.

The Engineering Drawings are presented in Appendix D.

1.7 Organization of the Report

This report is divided into nine chapters.

Chapter 1 introduces the concept of a mini baja as well as details the motivations, objectives and the work plan of the project.

Chapter 2 presents a detailed review of the existing literature and the work done at IIT Delhi which is relevant to the project. The novelty of this project has also been explained.

In **Chapter 3**, a preliminary design is developed and CAD Models have been prepared using this design.

In **Chapter 4** this design is then checked after estimating loads and applying these conditions on Finite Elements Models of the frame using ANSYS V7.0, the details of which are presented.

In **Chapter 5**, this dissertation proposes a suspension design after a careful analysis of existing systems.

In **Chapter 6**, this design is evaluated in terms of rollover stability. IT contains the results of FE analysis using standardized loading conditions and the calculations for determining chance of rollover.

Chapter 7, details the manufacturing of the chassis using the developed design.

Chapter 8, concludes this dissertation with a discussion on the deliverables and recommendations for future work.

CHAPTER 2: REVIEW OF PAST WORK

2.1 An overview

The Society of Automotive Engineers organizes an inter-collegiate competition in which various universities from all around the world build a mini-baja to compete against each other. Being a competitive exercise, every university has to develop its own design without any kind of professional help or knowledge sharing. This project is an attempt to design the chassis of a Mini Baja from a scratch and based on the guidelines given by SAE [1], certain practices by the Off-road vehicles industry and the concepts of mechanical engineering. This chapter lists the courses and the modules in the IIT curriculum that were useful, the related work done at IIT Delhi and other works that acted as sources of knowledge for this project.

2.2 Theoretical background

Courses that are relevant with respect to the project are listed below:

AM110N: Mechanics

- Work Elements: Rollover Analysis
- Relevant Course Modules: Kinematics and Dynamics of a rigid body, Euler's Equations.

ME110N: Graphic Science

- Work Elements: Preliminary Design, Pro/E Modeling, Preparation of Engineering Drawings.
- Relevant Course Modules: Orthographic Projections, Rules and conventions for sectioning, CAD.

AM217N: Mechanics of Solids

- Work Elements: Finite Element Analysis, Design modification.
- Relevant Course Modules: Theories of Failure, Stress and Strain Analysis, Bending of beams, Mechanical Properties of materials.

ME203N : Kinematics of Machinery

- Work Elements: Suspension design, Rollover Analysis,
- Relevant Course Modules: Motion Analysis of planar mechanisms by analytical and computer aided methods.

ME204N : Dynamics of Machinery

- Work Elements: Suspension design
- Relevant Course Modules: Free and Forced Vibrations.

ME210P: Mechanical Engineering Drawing

- Work Elements: Pro/E Modeling
- Relevant Course Modules: CAD, Assembly Drawings, Drawing standards and conventions.

ME301N: Mechanical Engineering Design

- Work Elements: Devising the work plan and elements, Suspension Design.
- Relevant Course Modules: Design Procedure, Application of theories of failure to design, Spring Design, Factors of Safety.

ME441N: Computer Aided Manufacturing

- Work Elements: Pro/E modeling (and exporting of model)
- Relevant Course Modules: Design on Pro/E

AM493: Finite Element Methods for Stress Analysis

- Work Elements: Finite Element Analysis
- Relevant Course Modules: Introduction, FEA for stress analysis, Solution of solid mechanics problems using FE packages.

2.3 Recent Work

The SAE guidelines prevent any design sharing between the university teams. Dissertations that may be useful or pertinent to the work elements of designing a mini baja have been discussed in sub-section 2.4. Although hundreds of universities throughout the world have Mini Baja Design Teams, the knowledge generated is proprietary and a new knowledge base is to be developed by this project.

2.4 Work done at IIT Delhi

No recent works pertaining to Performance vehicle design or Off-Road vehicle design were found. However the following dissertations are relevant to certain elements of the project:

- Nayak [5] carried out rollover simulations of a RTV. The Rollover of a Rural Transport Vehicle (RTV) was simulated. Rigid body simulations were carried out using MADYMO. This is preceded by a preparation of mathematical model considering the whole vehicle as a rigid body and also generation of a Finite Element Model. A basic understanding of the procedure of a rollover simulation was understood from this dissertation.
- Bose and Gupta [6], carried out Finite Element Analysis of a Child Restraint System in car crash situations. This dissertation was treated as a model for carrying out an Finite Element Analysis of the frame and understanding the various steps involved.

2.5 Summary of Past Work

This is the first project in the field of design of an off-road vehicle that is being undertaken at the institute. Some projects have been completed in the field of rollover analysis and FE analysis at IIT Delhi. Though Mini Bajas have been developed by many universities throughout the world, the designs are not in public domain. To design the chassis of the vehicle, most universities develop a preliminary design and check the design using Finite Element Packages such as IDEAS, ALGOR, ABAQUS and ANSYS.

This work will be the first ever project aimed at designing an Off-Road Vehicle at IIT Delhi. It will further create a knowledge base for future attempts at designing performance vehicles. This design can then be used to manufacture a Mini Baja and participate in the global Mini Baja competition organised by SAE annually.

CHAPTER 3 DEVELOPMENT OF A PRELIMINARY DESIGN

3.1 The Mini Baja Guidelines

SAE has laid down a set of guidelines and rules [1] that every vehicle should follow. These guidelines are based on recommendations and tests conducted by design professionals. For creating a preliminary design these guidelines were followed to include members in the frame of the chassis. No additional members were added initially, so that the frame with the minimum weight is obtained.

The following elements are to be included in the design of the frame

Rear Roll Hoop	(RRH)
Lateral Diagonal Bracing	(LDB)
Roll Hoop Overhead members	(RHO)
Lower Frame Side members	(LFS)
Side Impact members	(SIM)
Front Bracing members	(FBM)
Fore-Aft Bracing members	(FAB)
Lateral Crossmember	(LC)

The Rules for these members can be seen in Appendix A.

The dimensions of these elements were selected keeping in mind the rules laid down by SAE. No additional members were added. A method of adaptive designing was used wherever possible and considerations were made for the ergonomics of the driver. The finalized dimensions of these members can be seen in the Pro/E Model as shown in Section 3.4.

These members were included in the preliminary design and the minimum possible section was taken i.e.,

OD = 25.4cm

ID =21.2cm

Material: AISI1020 Mild Steel.

The guidelines for these are given in Appendix A.

3.2 Adequate Operator Space

In the previous sub-section, dimensions of certain members were decided using standards published by the International Standards Organisation. These standards are:

- ISO 7250 Basic Human Body measurements for Technological Design.
- ISO 3411 Human Physical Dimensions of operators and minimum operator space envelope.

These standards facilitated the weaving of a vehicle frame around the human body.

3.3 Testing by building a Mock-Up

A Mock-Up of the preliminary design was prepared using dimensions selected in sections 3.1 & 3.2. The mock-up was built using PVC pipes of diameter 25.4cm and the joints were formed using insulation tape.

The objectives of building the mock-up were the following:

- To assess the preliminary design for driver ergonomics.
- To improve the designs aesthetic senses.
- To get a hands on feel of the design.
- To make sure the design meets the requirements of a 5 second exit in accident situations.

Figure 3.1 Picture of chassis prototype in side view

Figure 3.2 Picture of chassis prototype in side view

Figure 3.3 Picture of chassis prototype in front view

The Preliminary design was found to meet all the above objectives.

3.4 Modeling of preliminary design in Pro/Engineer

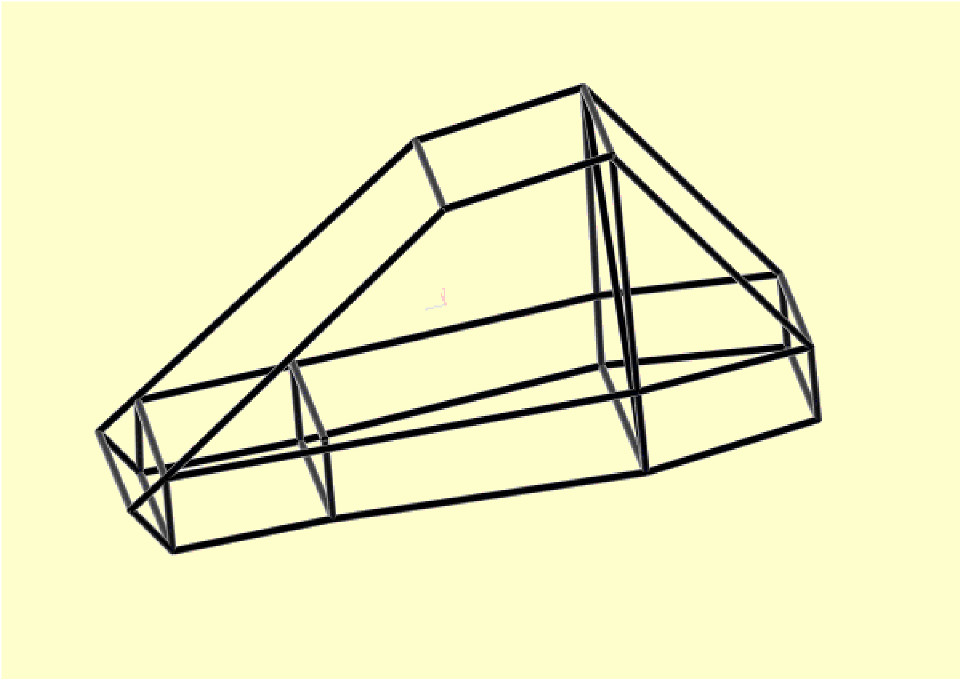


Figure 3.4 Pro/E model of frame

The Preliminary design was then modeled using Pro/Engineer and the figure above shows snapshots of the Pro/E Model.

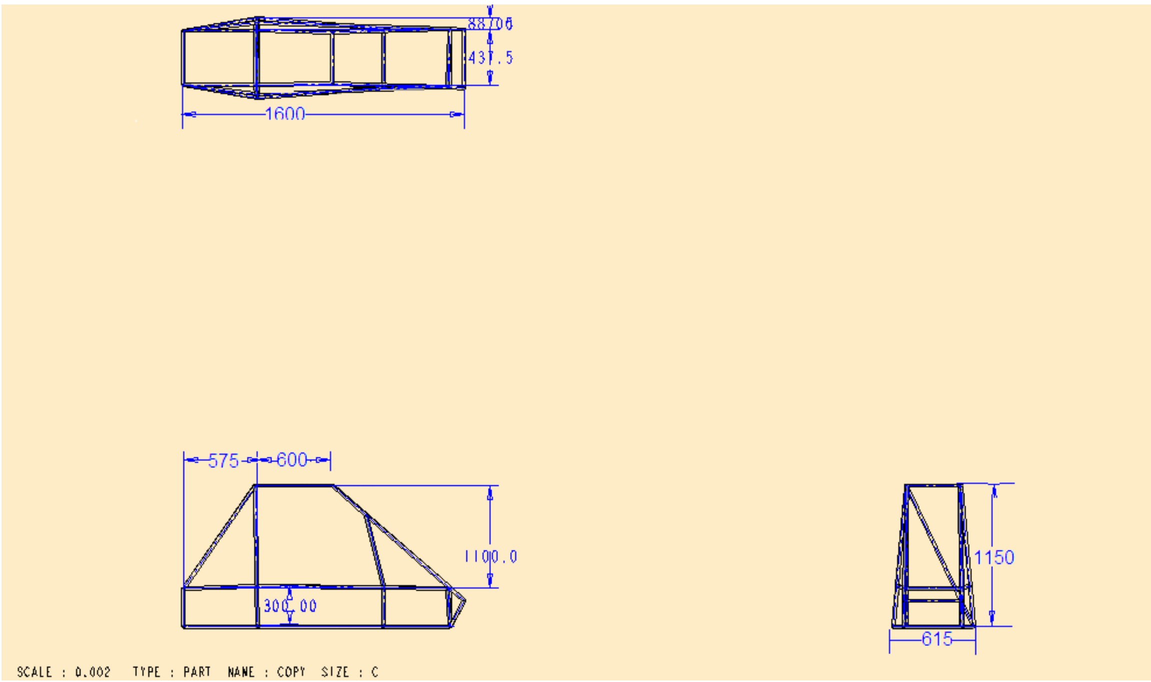


Figure 3.5 Orthographic projections of CAD model

CHAPTER 4 FINITE ELEMENT ANALYSIS OF THE CHASSIS USING ANSYS

4.1 Force estimation for loading conditions

4.1.1 Estimation of Impact Force

For a perfectly inelastic collision,
Energy Transferred,

$$DE = ½ (m_1m_2/m_1+m_2)(u_2-u_1)^2 \quad (4.1)$$

Where, M_1 and M_2 are the two colliding masses with velocities u_2 and u_1 respectively. Since both m1 and m2 are two vehicles with similar masses and the vehicle m2 is at rest,

=> $m_1=m_2$ & $u_2=0$

$$=> \quad DE = 1/4\ m_1u_1^2 \quad (4.2)$$

Now,
F = DE/t
Where 't' is impact time.

$$F = ¼ * m_1u_1^2 * 1/t \quad (4.3)$$

Weight of vehicle = 200kg
Weight of driver = 75Kg
M_1 =200 + 75 =275 Kg

Maximum Speed of Vehicle, u_1 = 10m/sec
In most crashes t is of the order of 100 ms.

⇨ $F = 275 /4 *10^2 /.1$
⇨ F = 6875 N

- Hence for design purposes force is taken to be 7000N.

- Also, design output is for no plastic deformations. The vehicle should remain in the elastic region.
- The Safety of the driver in case of crash is taken care of by safety equipment which includes special helmets, foam padding on bars and seat belts.
- The Design Factor of Safety, FS_d was taken as 2. This relatively high value is taken to account for the uncertainty in the nature of forces.

4.1.2 Estimation of Wheel Bump Forces

An assumption is made that when the vehicle passes over a bump, the entire weight of the vehicle will turn into two point loads at the two points where the wheel force is transmitted to the chassis, through the suspension. The worst case will be when the suspension fails and the entire force is transmitted. As the requirement is not for the Chassis to fail in case the suspension fails.

These two point loads will be equal to the weight of the chassis.

Hence, 2F = m1 * g

F = ½ m1 * g

F= ½ * 275 * 10

F = 1375 N

Hence, Designing for F = 1.1 * 1375 = 1500N (approx). Where 1.1 is the Stress Factor of Safety.

4.1.3 Estimation of Loading Forces While Heaving

The Entire Weight of the vehicle will be transmitted to the two points in each case.

Hence F =1500N (similar to previous case)

4.1.4 Forces In Case of Rollover

Another situation can arise when the Chassis undergoes rollover. Hence the same force as that in 4.1.1 is applied. i.e., F =7000N.

The safety in case of rollover will be dealt with separately in Chapter 6 and suitable forces will be applied. This force of 700N is applied at the top front corner points of the Chassis.

4.2 Finite Element Modeling

In order to carry out a design check of the preliminary design developed in Chapter 3 using Finite Element Analysis a finite element model was developed using the package ANSYS. The geometric model in Pro/E was converted onto IGES format which was then imported in ANSYS. Two Models are used for the analysis, a) Full Model and b) Half Model. The Full model is imported from Pro/E by converting into IGES file consisting of datum Points and Lines.

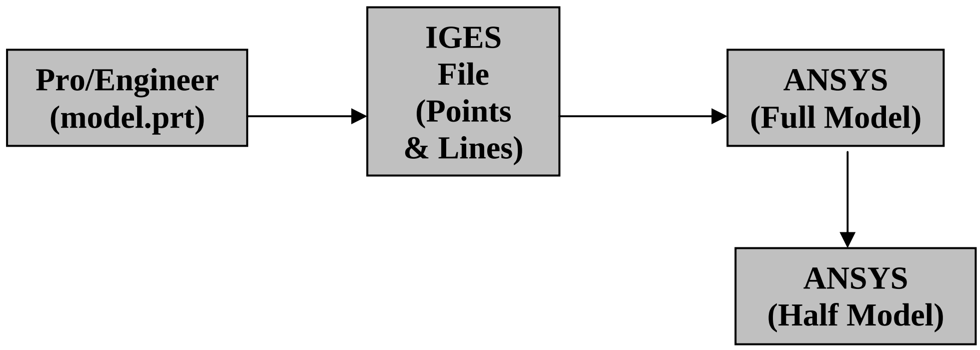


Figure 4.1: Importing the model into ANSYS

Material properties defined below were applied and the model was meshed using BEAM4 Line Elements. These are elements are based on the Euler-Bernoulli beam theory and have 6 degrees of freedom at each node. The meshing was done by dividing each linear member into ten divisions having equal lengths. The material properties of the tubes are given below.

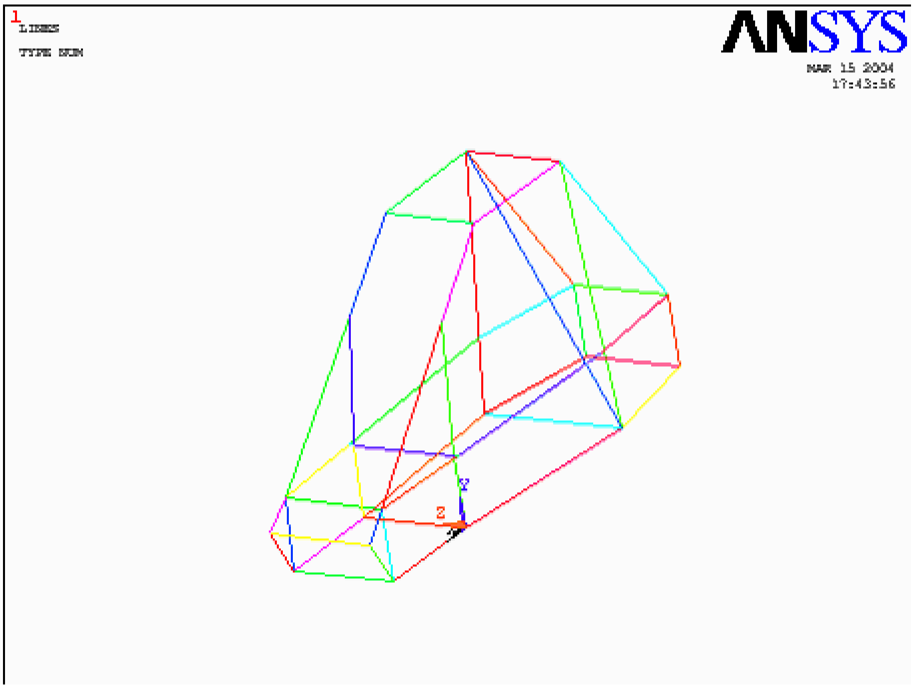


Figure 4.2: Full Model in Ansys

a) Full Model

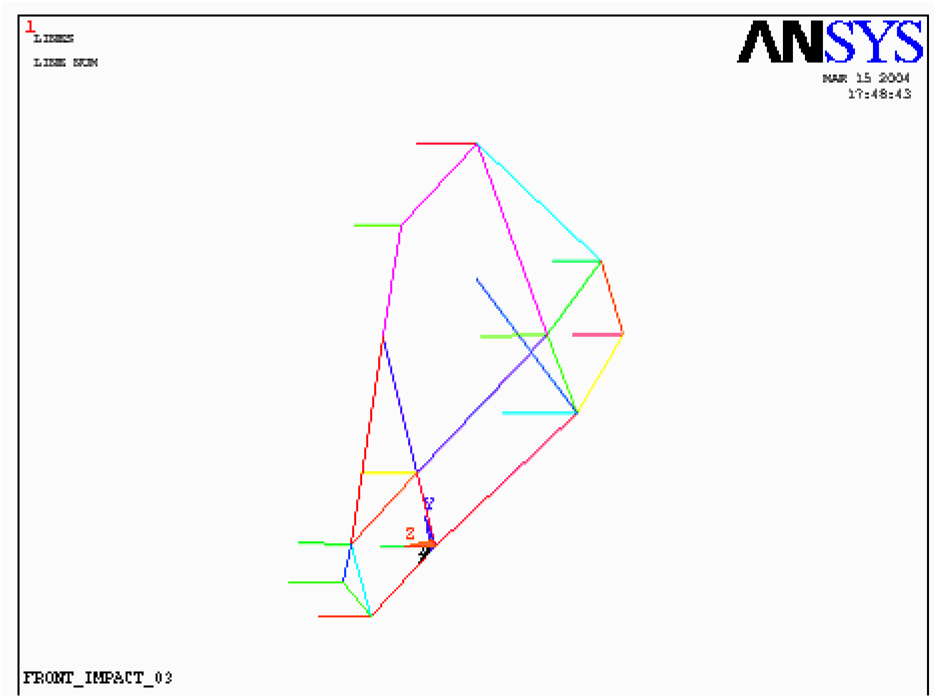


Figure 4.3: The Half Model in ANSYS

b) Half Model

For Simplicity each line is meshed into equal sized elements for both Full Model and Half Model.

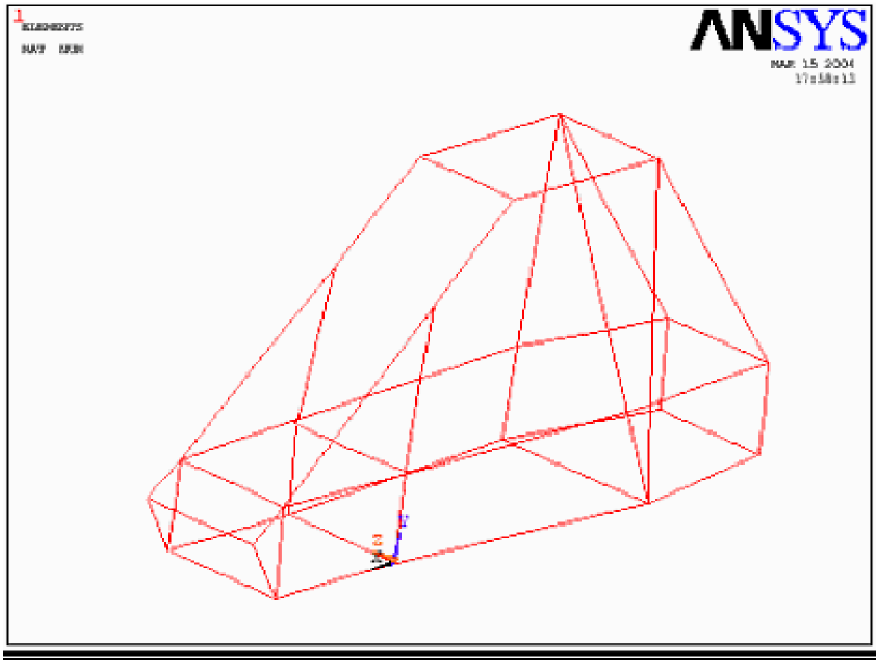


Figure 4.4: Meshed Full Model

470 Elements

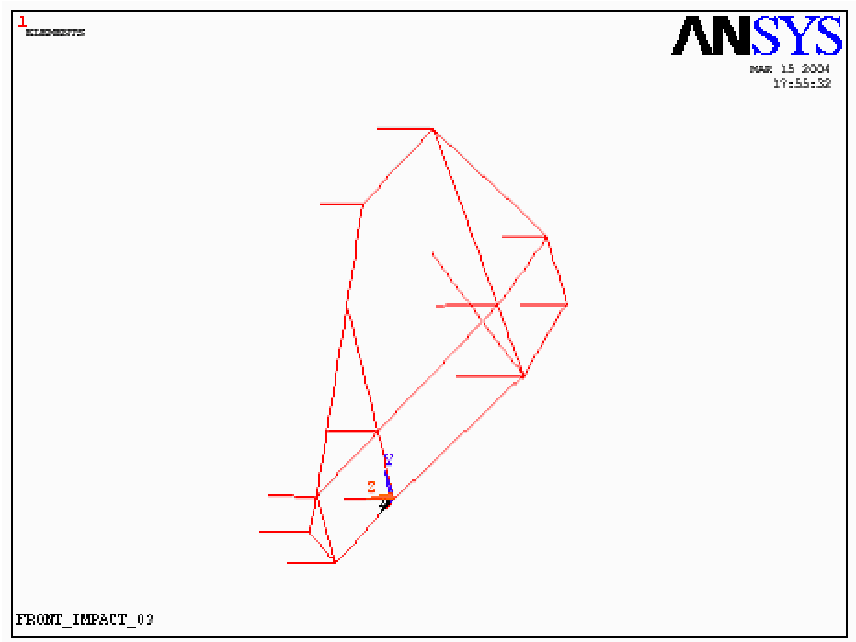


Figure 4.5: Meshed Half Model

300 Elements

4.3 Element Attributes for FEA

4.3.1 Elements

3D Elastic Beam Elements (Beam4)

Line Elements

Based on Euler-Bernoulli Beam Theory

6 DOF

4.3.2 Material Properties

Linear, Elastic, Isotropic

Exy=2.08 x 10^{11}

ν= 0.28

4.3.3 Element Properties

AREA = 8.03E-5

IZZ = 5.96E-9

IYY = 5.96E-9

TKZ = 0.021

TKY = 0.021

IXX = 1.19E-8

ADDMASS = 6.153

4.4 The Finite Element Analysis

The aim is to carry out a design check of the given Mini Baja chassis under estimated loading conditions and to minimize the weight of the frame keeping a Safety Factor of 2. Material of the tubes is AISI 1020, Hot Rolled with properties[6] :

Sut = 379 Mpa

Syt = 207 Mpa

Density = 7800 Kg/m^3

The following tests were used to check the design

1) Front Impact
2) Rear Impact Test
3) Front Wheel Bump
4) Rear Wheel Bump
5) Heave
6) Rollover

4.4.1 Front Impact Test

- Model Used: Half Model
- Loading: F= 7000N on Front Corner.
- Boundary Conditions:
  1. Symmetry (Plane normal to Z axis)
  2. Suspension Mounting Points

     Uy=Uz=0
  3. Rear Corner Points

     All DOF=0

Results:

- Stress:

  Max Stress= -0.77720E+08 Pa = 77.77 MPa

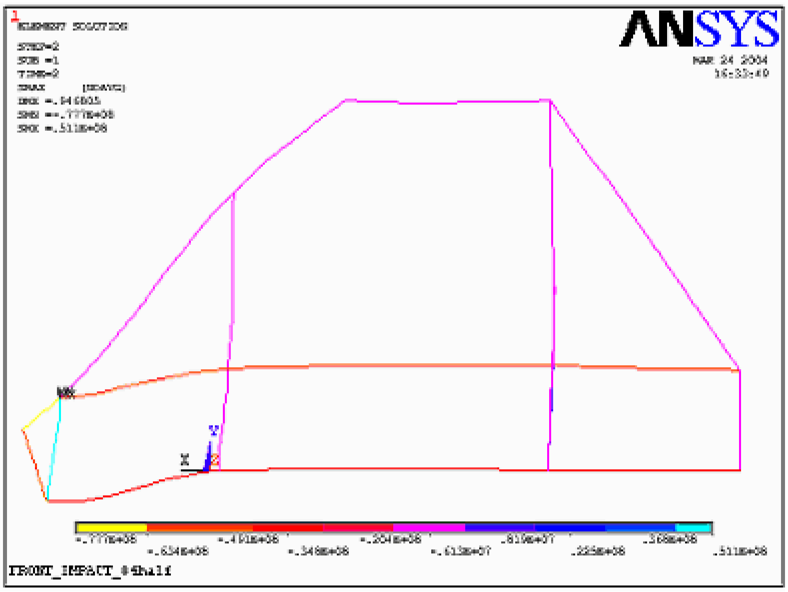


Figure 4.6 : Stress Distribution upon Frontal Impact

- Deformation

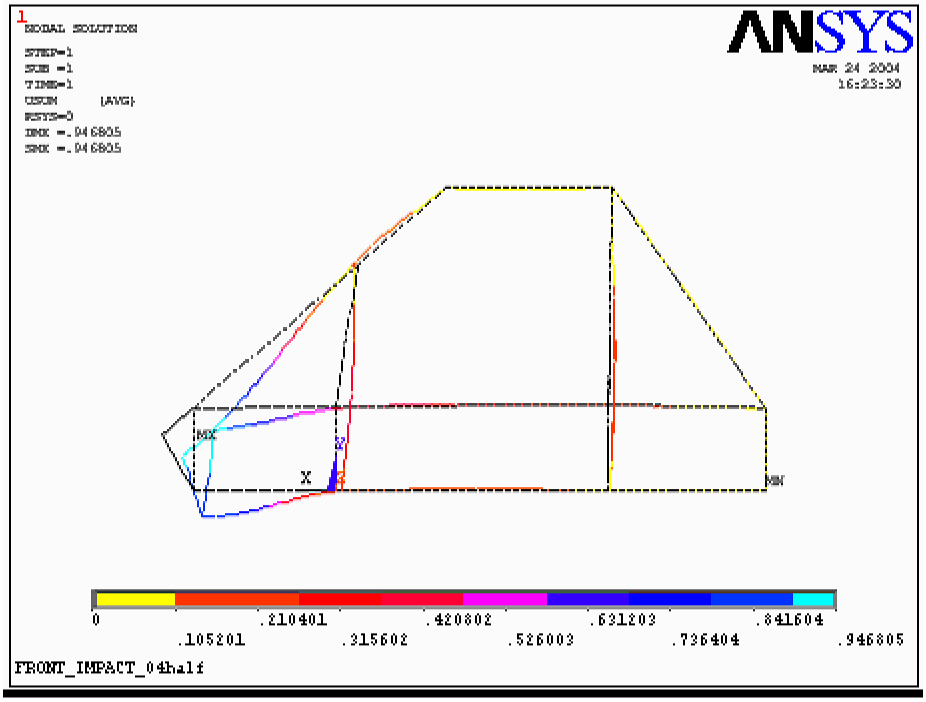


Figure 4.7: Elastic Deformation upon Frontal Impact

- Factor Of Safety:

  Incorporated Factor of Safety = Syt/Smax
  = 207/77.77
  = 2.69
  > 2

  Hence, the Chassis will be safe under Frontal Impact.

4.4.2 <u>Rear Impact Test</u>

- Model Used: Half Model
- Loading: F= 7000N on Rear Corner.
- Boundary Conditions:
  1. Symmetry (Plane normal to Z axis)
  2. Suspension mounting points

     Uy=Uz=0

3. Front Corner Points

   All DOF=0

4. Top Front Corner

   All DOF=0

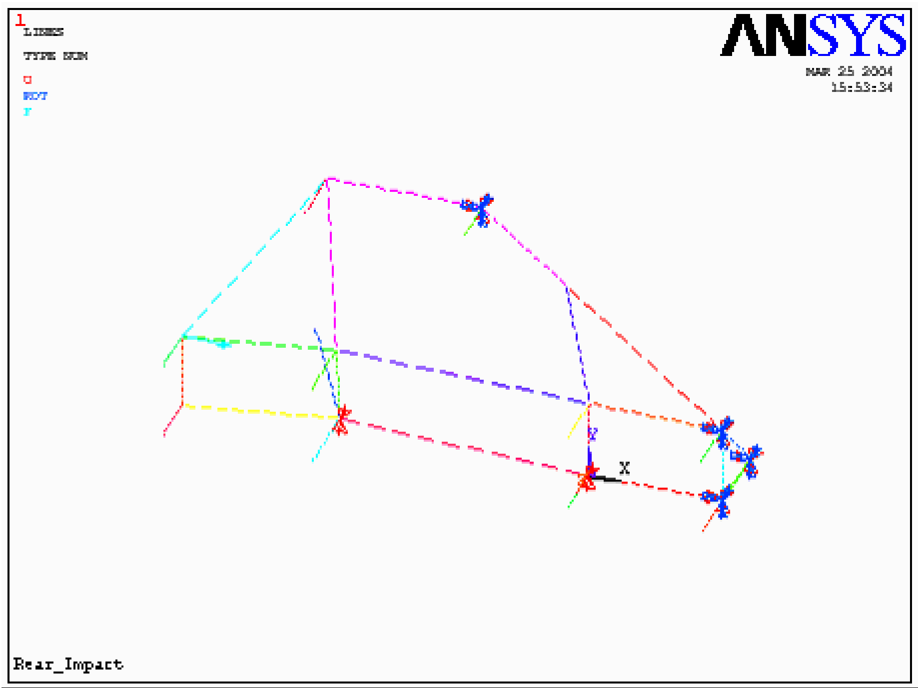


Figure 4.8: Constraints for Rear Impact

Results:

- Stress

  Max Stress= -0.89308E+08 Pa = 89.31 MPa

- Deformation

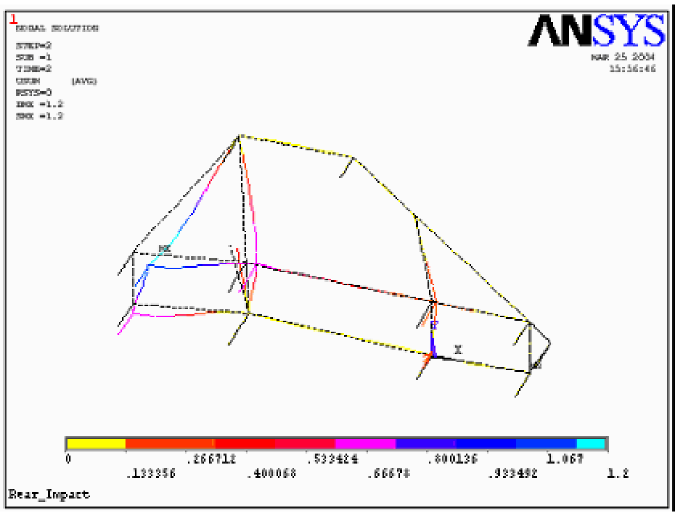


Figure 4.9: Deformation upon Rear Impact

- Factor of Safety:

Incorporated Factor of Safety = Syt/Smax

= 207/89.31

= 2.32

> 2

Hence, the Chassis will be safe under Rear Impact.

4.4.3 <u>Front Wheel Bump Test</u>

- Model Used: Full Model

- Loading: F= Weight=1500N on front wheel.

- Boundary Conditions:
  1. All DOF =0 at Rear Wheels and Opposite Front Wheel.

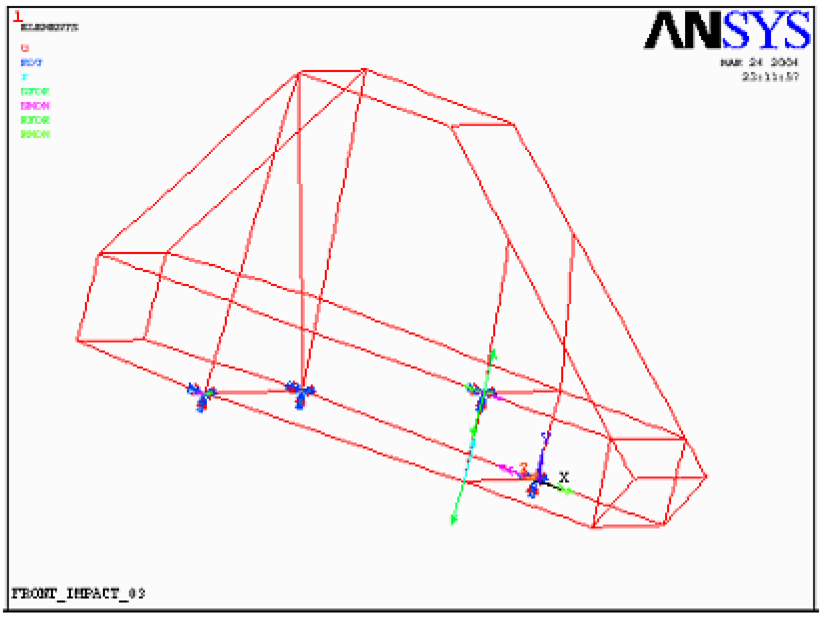


Figure 4.10: Constrains for Front Wheel Bump Test

Results:

- Stress

Max Stress= -0.31175E+08 = 31.17 Mpa

- Factor of Safety

Incorporated Factor of Safety = Syt/Smax
= 207/31.17
= 6.64
>> 2

Hence, the Chassis will be safe during a Front Wheel Bump.

4.4.4 Rear Wheel Bump Test

- Model Used: Full Model
- Loading: F= Weight=2500N (Vehicle + Driver Weight) on Rear Right Wheel .
- Boundary Conditions:
  1. All DOF =0 at Front Wheels and Rear Left Wheel

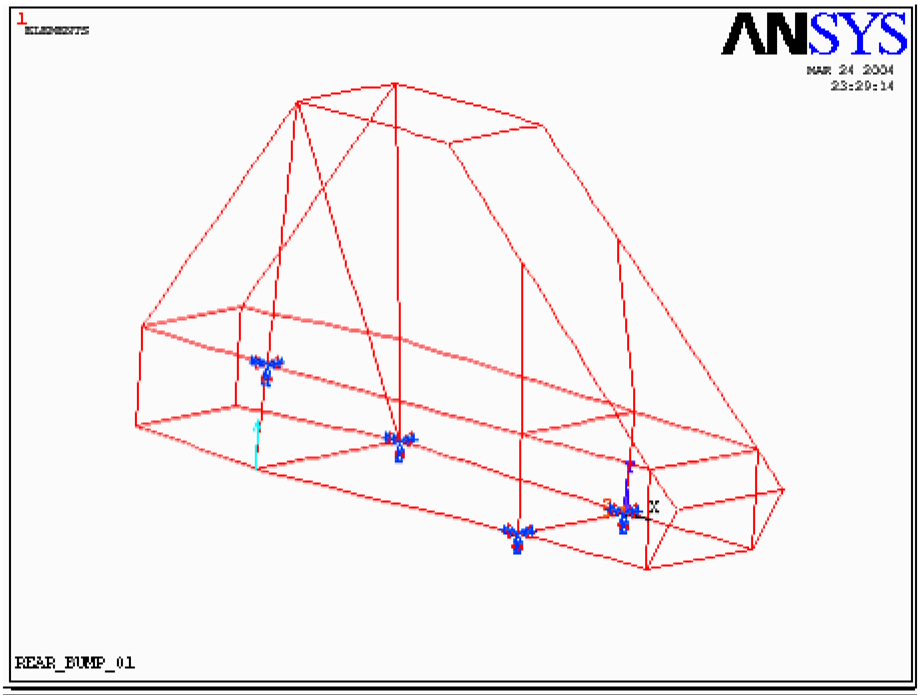


Figure 4.11: Constraints for Rear Wheel Bump Test

Results:

- Stress

  Max Stress= 0.31264E+08= 31.27 MPa

- Factor of Safety

  Incorporated Factor of Safety = Syt/Smax

  = 207/31.27

  = 6.62

  >> 2

  Hence, the Chassis will be safe during a Rear Wheel Bump.

4.4.5 Heave Loading

- Model Used: Full Model
- Loading: F= 2 X Weight=3000N is to be supported.

  Force on Two Front Corner Points= F/2 =1500N

  Force on Two Rear Corner Points= F/2 =1500N

- Boundary Conditions:

  All DOF =0 on all Kypts on the Upper Surface of the Frame.

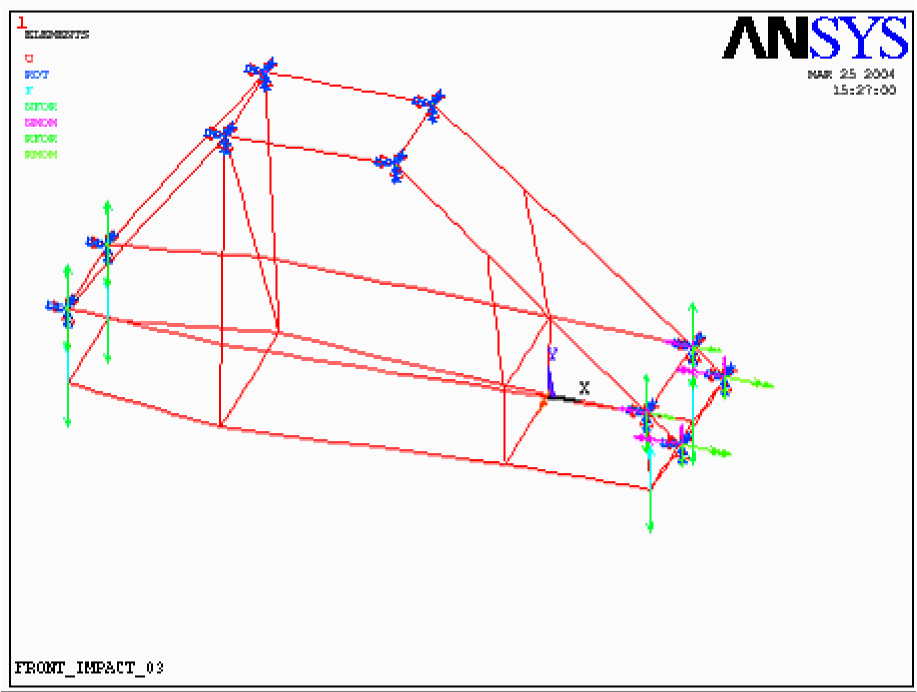


Figure 4.12: Constraints for Heave Laoding

Results,

- Stress

  Max Stress= 0.16352E+09 = 163.52 MPa

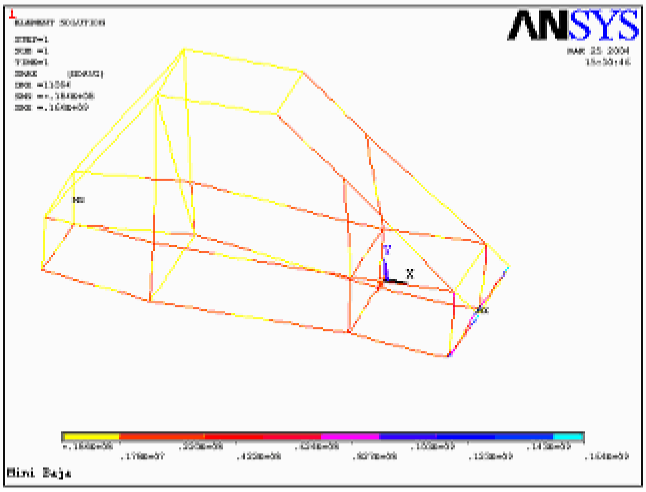


Figure 4.13: Stress Concentrations for Heave Loading

- Factor of Safety

  Incorporated Factor of Safety = Syt/Smax

  = 207/163.5

  = 1.26

  < 2

The model needs to be improved by adding more members upfront to decrease chances of failure under heave loading.

4.4.6 Rollover Loading

- Model Used: Full Model
- Loading: F= 7000N on Top Front Points
- Boundary Conditions:

  All DOF =0 on all Keypts on the Bottom Members of the Frame.

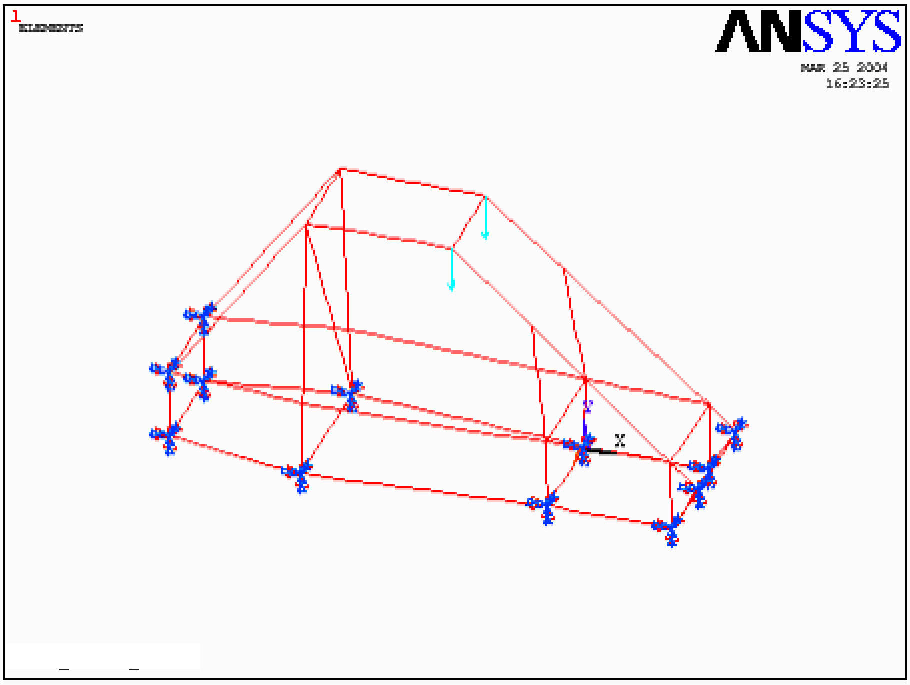


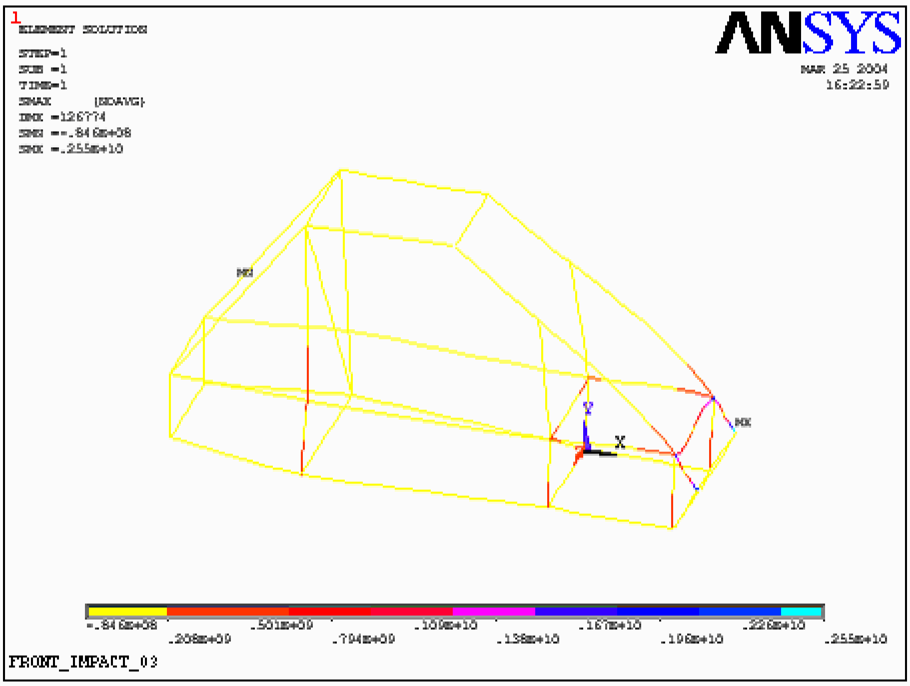
Figure 4.14: Constraints for Rollover Loading

Results,

- <u>Stress:</u>

  Max Stress= 0.25505E+10 = 2550.5 Mpa

- <u>Stress Distribution</u>



- Factor of Safety,

$$\text{Incorporated Factor of Safety} = \text{Syt/Smax}$$
$$= 207/25505.5$$
$$= 0.08$$
$$< 2$$

Clearly, the model will fail. This can be attributed to stress concentration at front bulkhead corners.

4.4.7 Test Results

S.No.	TEST	FSin	RESULT	REMARKS
1	FRONT IMPACT	2.69	No Yielding	Slight Tilt Towards Right. Possibly due to RH Bracing
2	REAR IMPACT	2.32	No Yielding	Safe
3	FRONT WHEEL BUMP	6.64	No Yielding	Safe
4	REAR WHEEL BUMP	6.62	No Yielding	Safe
5	HEAVE	1.26	FSin < 2. Chances of failure at front bulkhead corners.	Stress Concentration should be reduced.
6	ROLLOVER IMPACT	0.08	Failure at Front Bulkhead Corners	Stress Concentration to be reduced.

Table 4.1: Results of FEM Analysis

4.4.8 New Model

Proposed Changes

1. There was found to be stress concentration at front bulkhead points. Since the purpose is not designing for crush, this can be removed
2. Using pipe bends instead of corner points at the top two points.
3. Shifting of Front Aft Bracing.
4. Changing dimensions of rear portion to accommodate needs of engine design.

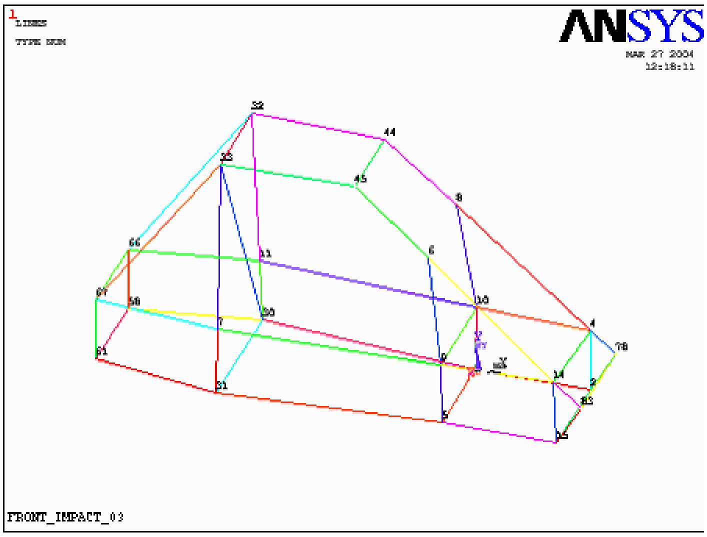


Figure 4.15: Proposed changes in frame

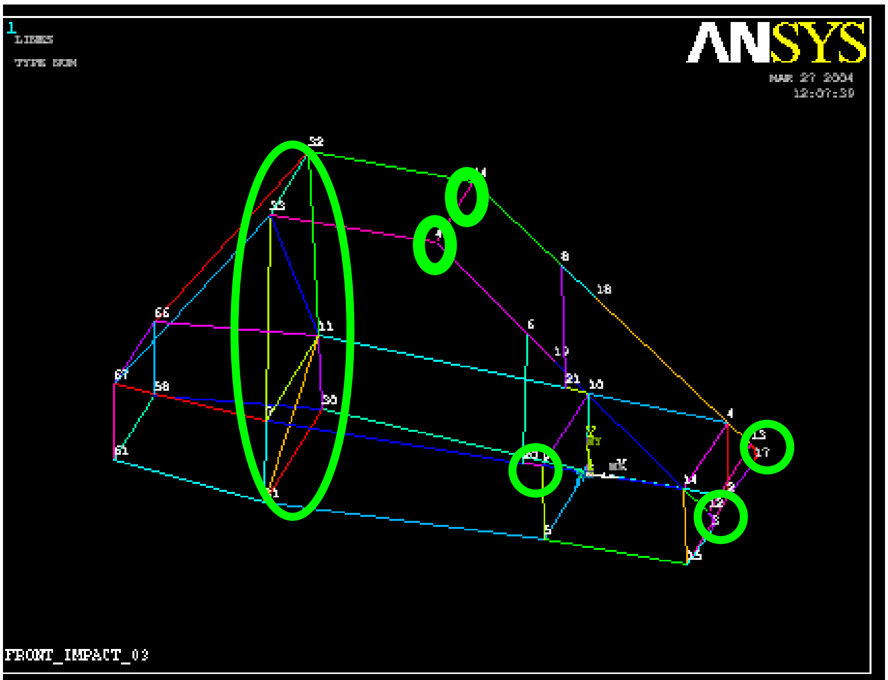


Figure 4.16: Locations of proposed changes in frame

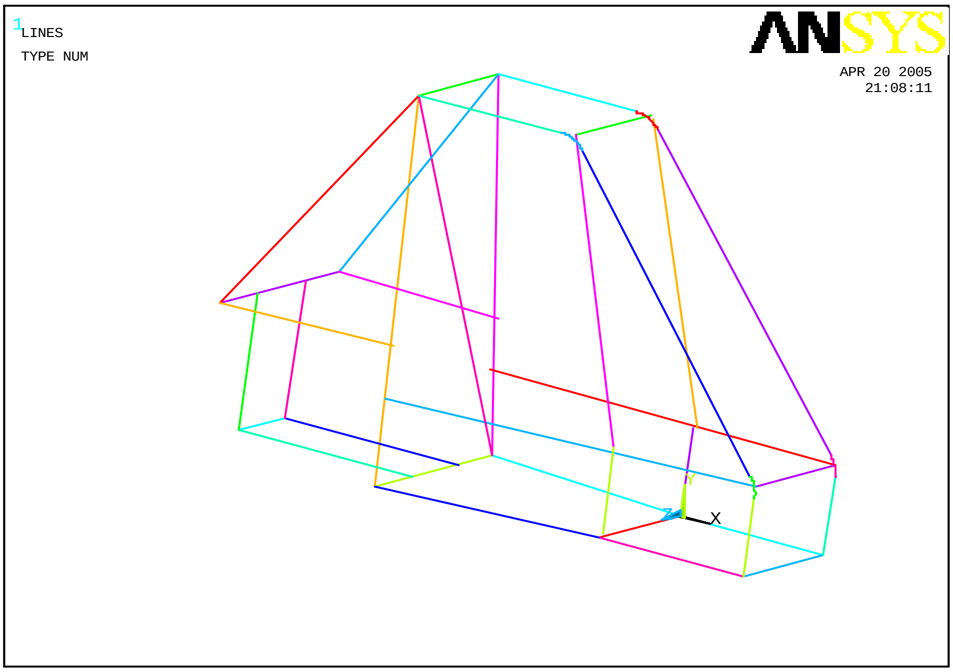


Figure 4.17 New Model developed

4.4.9 Testing of New Model

- Rollover Test

Maximum Stress= -0.85069E+08 = 85.07 MPa

Factor Of Safety = 207/85.07= 2.43

Hence, the new model is safe in case of rollover.

- Heave Loading Test

Maximum Stress= 0.15941E+09 = 159.41 MPa

Factor Of Safety = 207/159.41= 1.3

Hence, the new model is still not satisfactory when it comes to heaving. Adding further members shall add to weight and cost of the frame. Thus it is recommended that hitch points should be put up a few cms away from the front corners to prevent such a loading situation.

Appendix B contains the sample result file for the elemental table of maximum stress. The results were read from these elemental tables. The results in Appendix B are for the Front Impact Test shown in Subsection 4.4.1.

4.5 Making Modifications in Pro/E Model

The final acceptable model obtained after the finite element analysis was again remodeled in Pro/Engineer. The model is shown in the figure below:

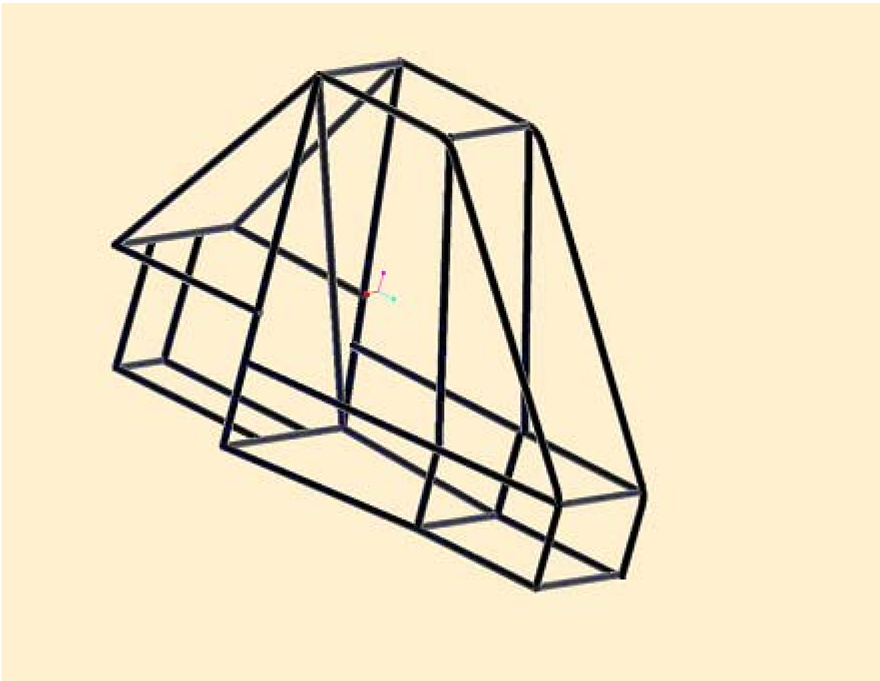


Figure 4.18: The new frame modeled in Pro/E,

CHAPTER 5: SUSPENSION DESIGN

5.1 Study of Suspension Types and Selection

5.2 Spring Design

5.3 A-Arm Design

5.3.1 Introduction

The design of the arms in the wishbone suspension is to be checked for failure under the loading forces present at the wheel. For this purpose, a Finite Element Analysis is carried out and used to obtain a minimum weight design which does not yield in the worst loading conditions as defined below. The Arm is first modeled using Pro/Engineer. This geometric model is then imported into Pro/E for preparing a Finite Element Model. After applying suitable constraints and forces, the Von Mises Stresses are obtained. These are compared with the Yield Strength values for the specified material and design changes are made.

5.3.2 First Design for Suspension A-Arm

- Configuration

  Wishbone type A-arm for both front and rear suspension

- Design Input:

  A preliminary design of a wishbone type A-Arm designed on the basis of :
  - Material Availability for pipes.
  - Minimum Weight
  - Adapting Design from current practices.
  - Design for Manufacturability: The suspension arm consists of a U-Bend of a hollow pipe. The lower portion of the U is semi-circular. This U-Bend is welded to the steel plate. The wheel shall be connected to the steel plated using a steel rod of suitable diameter.

- Material Selection :

  For U-Bend

SAE1430 Alloy Steel Pipes

Syt =343Mpa

OD=28mm

ID=24mm

For Plate & Rod:

C-30 Steel, Normalised

Syt = 345 MPa

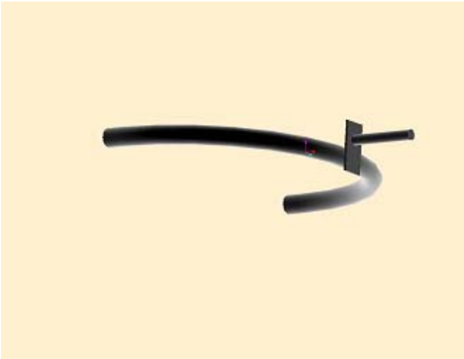


Figure 5.5 A-Arm in Pro/E

- Finite Element Model in ANSYS

Element Type: SOLID 45, 8-noded Brick

Loads

- 450N upward(+y)direction (=Weight of Chassis & Tires on each arm)
- 150N in (-x) backward direction the at the rod end.
- Ends of U-B end are constrained to move.

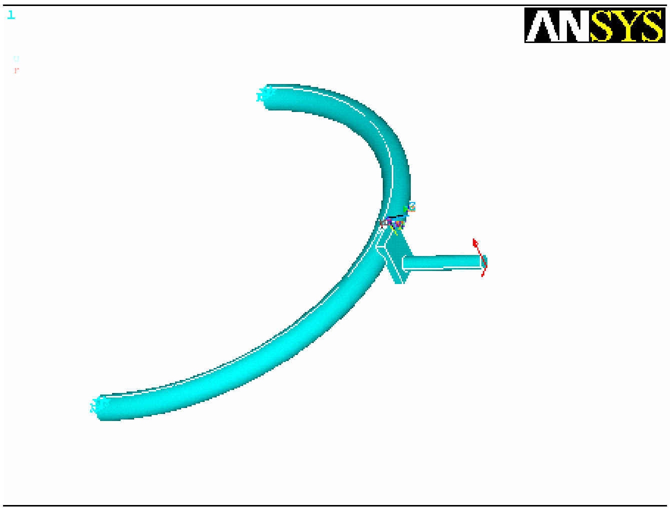


Figure 5.6 Solid Model of A-Arm in ANSYS

- <u>Results</u>

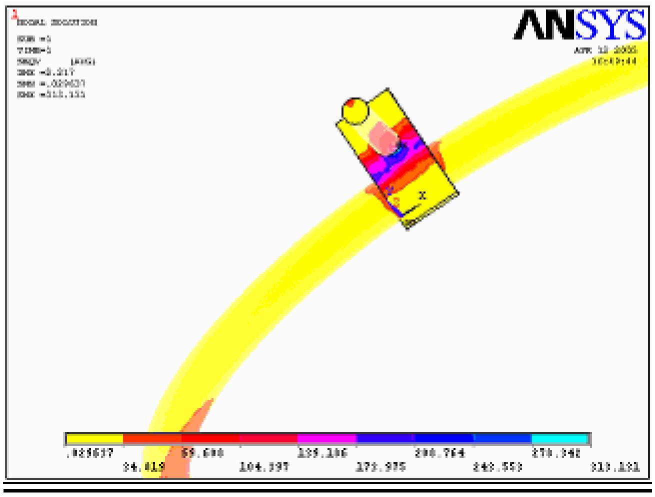


Figure 5.7 Stress Concentration in A-arm

Maximum Von Mises Stress =322.6 Mpa

Yield Strength= 345 Mpa

Hence Factor of Safety = 1.1, which is not good enough.

Hence this design does not satisfy our requirements.

- <u>Proposed Changes & Results</u>

- Since the Plate does not hold and has high stresses, the thickness is required to be increased form its current value f 3mm.
- Since the Stresses on the U-Bend are relatively low, we can decrease the OD & ID to minimize weight.

- New Material for U-Bend : ASTM 106 Grade B
  OD=26.7mm
  ID=20.9mm
  Syt=321.7Mpa

- In the next iteration the plate thickness was increased to 10mm.To further reduce the weight, the length of the steel plate was decreased form the edges by 7mm and 13mm at the two edges.

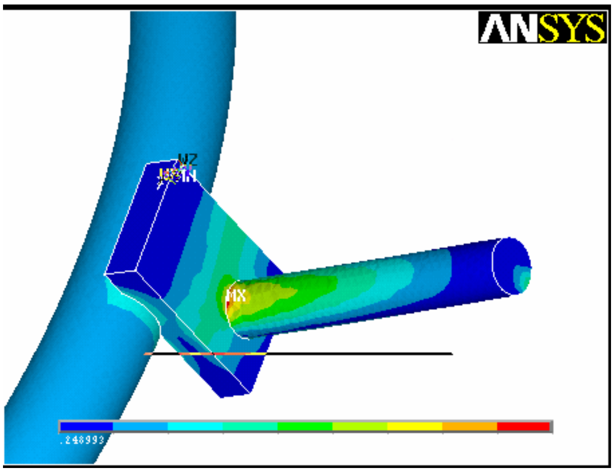


Figure 5.8: Stress distribution for redesigned A-arm

Maximum Von Mises Stress = 138.2Mpa
Factor of Safety = 345/138.2= 2.49

- Obtained Design
  => Steel Plate Dimensions = 53 x 35 x 10
  => For the U-Bend, ASTM 106 Grade B
  OD=26.7mm
  ID=20.9mm

Syt=321.7Mpa

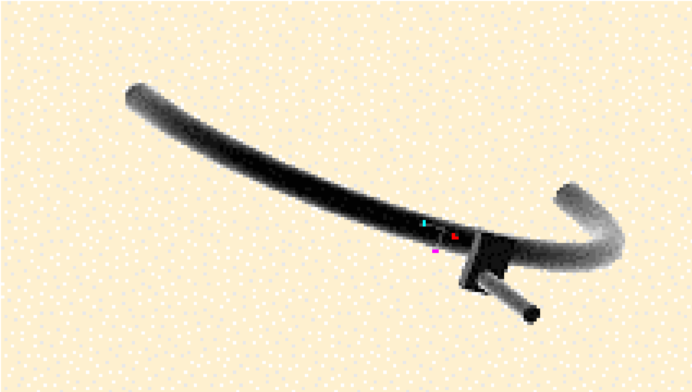


Figure 5.9 The safe design remodeled in Pro/E

5.3.3 Designing for Manufacturability

From the available manufacturing sources it was found that the obtained design would not be suitable to manufacture for the following reasons.

- Pipe Bends: Pipe bending was not available for tubes of diameter 450 mm. The closest possible die was of 300mm.
- Insufficient Weld Strength: The weld strength obtainable from commonly obtainable processes is not good enough. To withstand the raised stresses at the welds.

Thus a new design was required to be developed which incorporates these issues. Thus the first design was rejected.

5.3.4 Second Design of A-arm

Following the feedback from manufacturing, a new design was developed for the A-arm. Separate designs were made for rear arms and front arms as it was found that rear arms require greater length as more. These designs were modeled in Pro/Engineer and imported into ANSYS by converting them into finite element models.

- Modeling of A-arms,

The arms were modeled using Pro/Engineer.

The Material chosen was

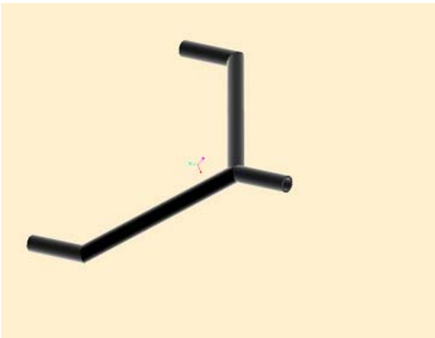
With,

OD= 26.7mm

ID = 21.1mm

Syt= 321.7 MPa

For, the rear arm the length of the tubes were increased by 175mm as the rear members of the frame where the rear suspension arms would be mounted are at a further distance of 175 mm. The distance between he two mounting mounts for both the arms was taken to be 450mm.


(a)

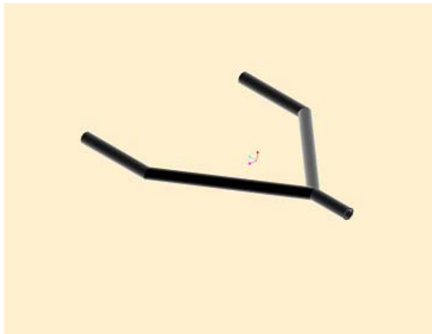

(b)

Figure 5.10: (a) Model of Front Suspension A-Arm
(b) Model of Rear Suspension A-Arm

- Loading Condition.

Total Weight of vehicle + human = 2750 N

Number of Suspension Arms = 4 *2 = 8

Assuming equal forces on all arms,

Static Upward Force on each arm,

F_{ys}= Total Weight/ Number of Arms

F_{ys}= 2750/8= 344N

Since the suspension may be subjected to dynamic loads which can have a maximum value equal to twice the static load,

Hence, $F_y = 2 * F_{ys} = 2 * 344 = 688$ N

Also, due to rolling motion and friction there will be a load in the direction of motion, which was estimated as 0.3 times the normal load where 0.3 is the estimated co-efficient of friction.

$F_x = 0.3 * F_y$

$F_x = 0.3 * 688$

$F_x = 210$N

- Boundary Conditions
  - All DOF =0 at the two mounting points
  - Forces F_y and F_x at rod end.

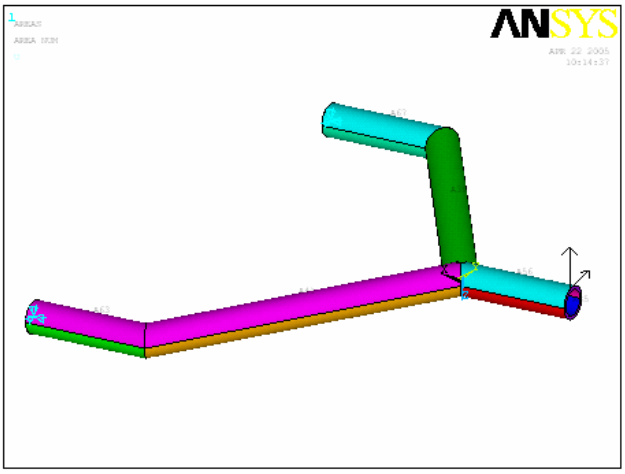


Figure 3.11: Boundary Conditions on Suspension Arm

o

- Results:
  - Front Arm

The Stress Distribution obtained is shown in the figure below:

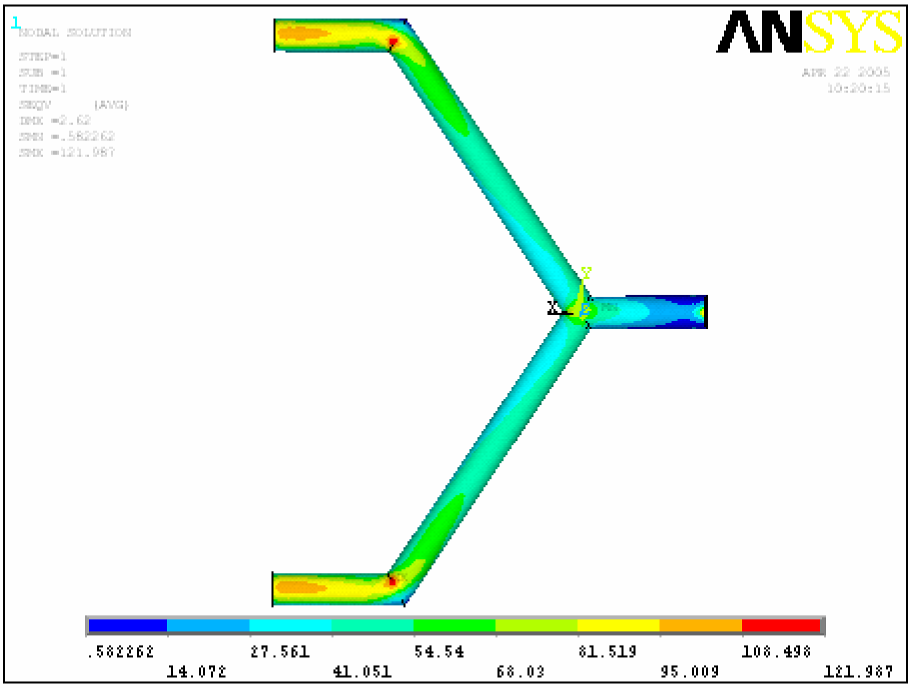


Figure 5.12: Stress distribution in Front A-arm

Maximum Von Mises Stress, Smax = 121.987 Mpa

Syt = 321.7 Mpa

FSin = Syt / Smax = 321.7/121.987 = 2.64

FSin/FSd =2.64/2 = 1.32

The design for the front suspension arm was found to be within acceptable limits.

- Rear Arm

The Stress Distribution obtained is shown in the figure below :

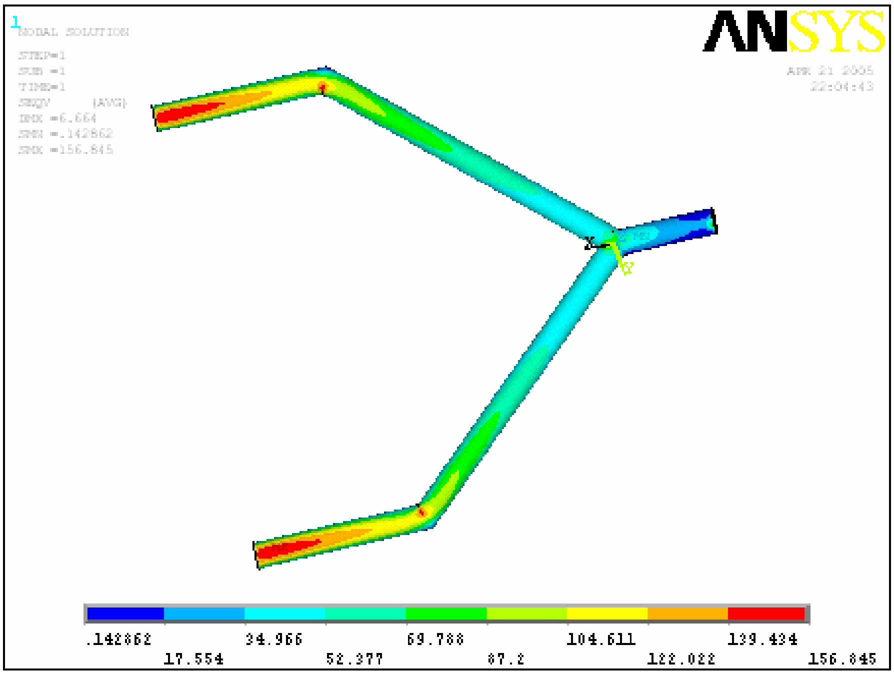


Figure 5.13: Stress distribution in rear suspension A-arm

Maximum Von Mises Stress, Smax = 156.845 Mpa

Syt = 321.7 Mpa

FSin = Syt / Smax = 321.7/156.845 = 2.05

FSin/FSd =2.05/2 = 1.03

The design for rear suspension arm was found to be within acceptable limits.

5.4 Finalizing Suspension Design

The design in developed in Section 5.3.4 was found to be satisfying all requirements and was found to be withstanding failure due to bending forces as seen from the results of finite element analysis. Thus this design was finalized. The engineering drawings for this design were made and are presented in Appendix D of this dissertation. Separate dimensions were used to for the front and rear arms.

The Suspension and arms were along with the spring were modeled and assembled with the frame of the Mini Baja.

CHAPTER 6 ROLLOVER ANALYSIS

6.1 Rollover Safety Test

6.1.1 Rollover Safety as defined by IS 11821

IS 11821 defines a set of tests and acceptance conditions for agricultural tractors in case of rollover. The same tests were simulated with the help of Finite Element Simulations on the model of the Mini-Baja and the acceptance conditions were applied.

The loading conditions defined by the standard are given below. In these conditions, Mt is the weight of the vehicle which in this case is estimated to be 200Kg

- The loading condition for longitudinal loading is defined as follows:

  The Strain Energy absorbed by the protective structure is equal to or greater than the required input energy in joules (Es). Where

  $$Es=1.4Mt$$

  $$Es=1.4*200=280 \text{ J}$$

- For crush loading at the front and rear of the protective structure, the force Ft is applied, where

  $$Ft=20Mt$$

  $$Ft=20*200=4000\text{N}$$

6.1.2 Finite Element Analysis for Rollover Safety

Using the same model as previously used for the FE Analysis of the Baja the loads calculated above were applied.

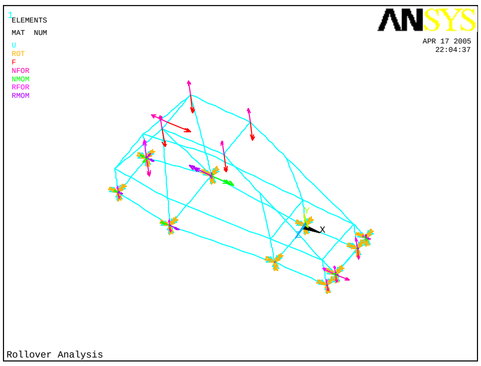


Figure 6.1: The Constraints applied to the Solid Model in Ansys

Upon solving this model, the deformed shape of the vehicle was obtained as shown below. This is then compared by the Clearance Zone defined by IS11821. If any part of the protective structure enters the clearance zone, then the vehicle fails to meet acceptance conditions.

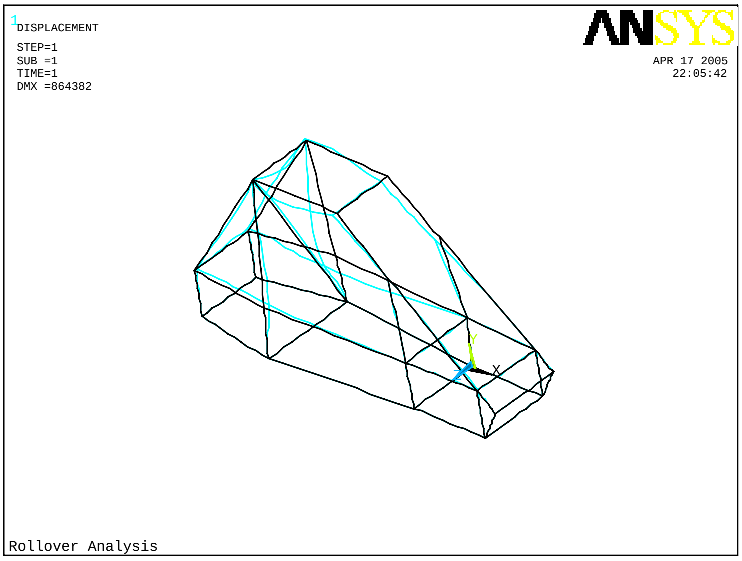


Figure 6.2: The Deformed Model

6.1.3 Results

Maximum Deflections:

$U_x = 0.608$mm

$U_y = 1.808$mm

$U_z = 8.6$mm

6.1.4 Acceptance Condition

The Acceptance condition for the vehicle is satisfied if none of the members enters the clearance zone. The Inner most rectangle that could be formed in the clearance zone has a height of 840mm.

6.1.5 Conclusion

The deflections obtained by the simulations were found to be very small and the protective structures do not enter the clearance zone. The height of the structure after the deflections was found to be 982mm, which is greater than the stipulated 840mm Thus, the Mini Baja conforms to IS11821 with respect to Rollover Safety.

6.2 Determination of Centre of Mass

In order to check the propensity of the Mini Baja to undergo tripped rollover, the height of the centre of mass of the vehicle is required. This was found by treating various components in the vehicle as point masses and estimating the location of these masses from the supporting elements in the frame.

S.No	Component(s)	Mass (m_i)	Height of Pt Mass (h_i)
		Kg	mm
1	Frame	40Kg	200
2	Tyre Assembly	4*20=80Kg	175
3	Suspension System	5*4=20Kg	200
4	Driver Mass	75 Kg	500
5	Engine, CVT, Transmission	45 Kg	400
6	Steering System and other equipment	15 Kg	450

Table 6.1: Component weights in the Mini Baja

Total Weight, M = Σm_i = 275 Kg

Height of Centre of Mass, H = $\Sigma m_i h_i / M$ = 320.77mm

6.3 Calculation of Static Stability Factor

Based on the track conditions, the Mini Baja is expected to face a situation of tripped rollover. To evaluate the propensity of tripped rollover the NHTSA method of evaluating the Static Stability Factor (SSF) is used.
(http://www.nhtsa.dot.gov/cars/testing/ncap/Rollover/Index.htm)

$$SSF = T/2H \quad (6.1)$$

Where,

T= Track Width

H= Height of Centre of Mass

H=320.77mm(Section 6.2)

T= 175

⇨ SSF= 1750/2*320.77

⇨ = 2.72

This would entitle it to a 5 star rating and the probability of rollover is less than 10%. Appendix C contains details on obtaining the rollover probabilities from the SSF.

CHAPTER 7 MANUFACTURING THE CHASSIS

CHAPTER 8 CONCLUSIONS AND RECCOMENDATIONS FOR FUTURE WORK

8.1 Conclusions

8.2 Recommendations for Future Work

Similar projects can be undertaken for other aspects involved in the fabrication of the Mini Baja namely drive-train, transmission, steering, safety equipment, assembly of components etc.

For optimizing the design it would be of great use if the motion of the vehicle can be simulated based on the track surface, the vehicle design and other parameters. Such a project will be helpful in making design decisions which can improve speed, ruggedness and maneuverability.

8.3 Learning from the Project

The project involved a real life design problem and provided an immense experience in the field of contemporary performance vehicle design. This effort also gave an insight into Computer Aided Engineering (CAE) and how it can be used to solve trivial as well as complicated problems in mechanical engineering.

In this project, the theory learnt so far in the curriculum was made use of in a large number of situations. Various concepts from the courses in the curriculum including Machine Design, Mechanical Engineering Drawing, Solid Mechanics, Finite Element Methods for Stress Analysis, Dynamics of Machinery etc. were used in the different modules of the project. The knowledge in these fields was further enhanced during this effort. Knowledge was gained in the use of Finite Element Methods, CAD and Design for Manufacturing.

The indirect benefits from this project include lessons in professional ethics, following of International and National standards in engineering and project management.

LIST OF REFERENCES

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[3] ISO 3411 Human Physical Dimensions of operators and minimum operator space envelope.

[4] Nayak, Ashish, 2004, "Crash Simulation of a RTV", M-Tech Thesis, IIT Delhi.

[5] Bose, Dipan and Gupta, Rahul, 2001, "Finite element analysis of child restraint system in car crash situations." B-Tech Project, IIT Delhi.

[6] Norton, R.L., 2004, *Machine Design*, Pearson Education, Singapore.

[7] IS 11821 Method of test and acceptance conditions for protective structures of agricultural tractors.

[8] Ghosh, Amitabha and Malik, Asok Kumar, 2002, T*heory of Mechanisms and Machines,* East-West Press, New Delhi.

[9] Kazimi, S.M.A, 2002, *Solid Mechanics,* Tata MacGraw-hill, New Delhi.

APPENDIX A SAE GUIDELINES AND RULES

The elements of the roll cage are:

Rear Roll Hoop	(RRH)	Rule A.1
Lateral Diagonal Bracing	(LDB)	Rule A.2
Roll Hoop Overhead members	(RHO)	Rule A.3
Lower Frame Side members	(LFS)	Rule A.4
Side Impact members	(SIM)	Rule A.5
Front Bracing members	(FBM)	Rule A.6
Fore-Aft Bracing members	(FAB)	Rule A.7
Lateral Crossmember	(LC)	Rules A.3-5

A.1. Rear Roll Hoop (RRH)

Rear Roll Hoop shall be attached to the Lower Frame Side members (LFS) at a point behind the driver's seat. These junctions define Point AR on the right side and point AL on the left side. The driver's seat may not intrude into the plane(s) of the RRH.

The upper junctions in straight-tube construction shall define points BR and BL. (See R1A) If bent-tube construction is used, points BR and BL will occur at the upper end of each bend. (See R1B) The radii of the upper bends at the tube center may not be greater than 5". Points B shall be located above the driver's seat by a minimum of 41 inches and behind the drivers head as defined in section 4.1.3.

The RRH shall extend upward vertically +/-20 degrees from points A to points B. (See R1C)

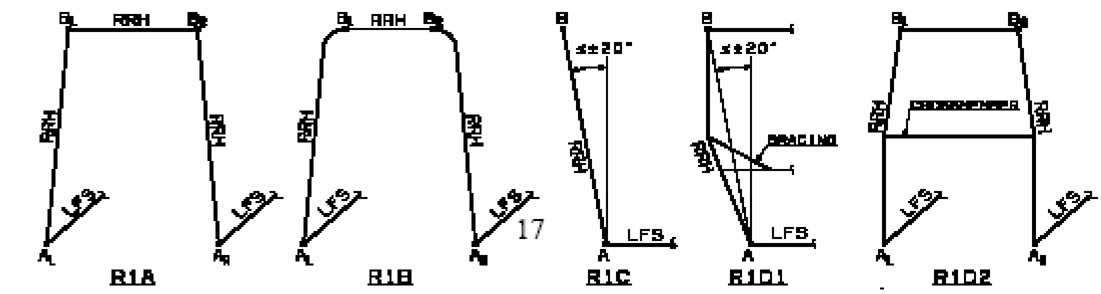


Figure A.1: RRH Bracing

If the RRH is defined by more than one plane or if the RRH verticals are not straight in a rear view, sound engineering practice must apply. (See R1D)

A.2. Rear Roll Hoop Lateral Diagonal Bracing (LDB)

Lateral Bracing for the Rear Roll Hoop shall begin at a point along the vertical portion of the RRH within 5" vertically of point BL or BR and extend diagonally to a point no farther that

2” above point AR or AL respectively. (See R1E) The angle between the vertical of the RRH and the LDB must be no less than 20 degrees. Lateral bracing may consist of two or more members if needed. (See R1F)

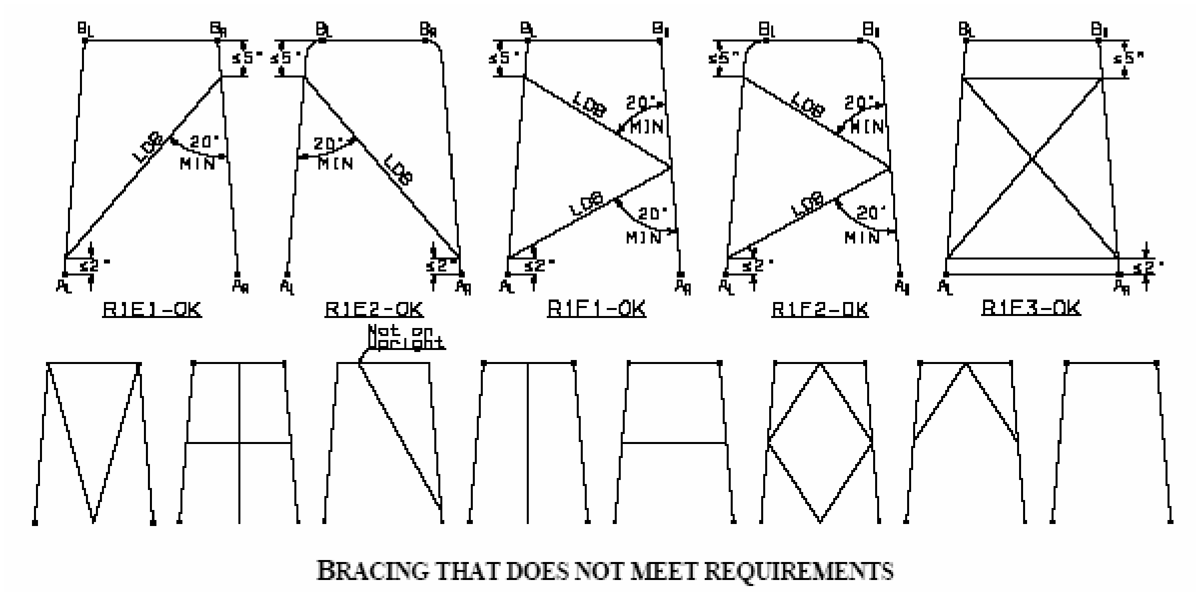


Figure A.2 LDB specifications

A.3. Roll Hoop Overhead members (RHO)

Roll Hoop Overhead members shall join the RRH within 2 inches vertically or laterally of points B and extend generally horizontally to points C. (See R2A) The RHO shall be located above the drivers seat by a minimum of 41 inches and points C shall be located forward of the drivers seat by a minimum of 12 inches as defined in section 31.3. (See R2B) Points CR and CL shall be joined by a lateral Crossmember (LC). (See R2A)

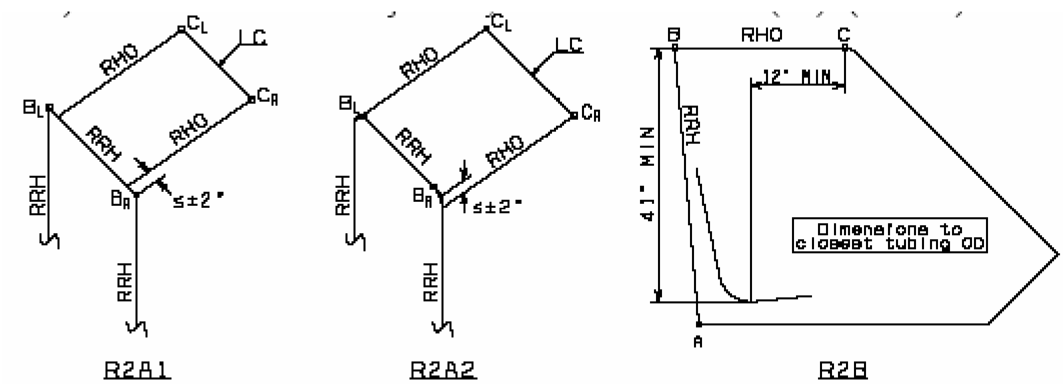


Figure A.3 RHO Specifications

A.4. Lower Frame Side members (LFS)

Lower frame side members shall join the RRH at points A and shall extend forward and generally horizontal to points AF forward of the drivers heal. A lateral Crossmember (LC) shall join point AFR to point AFL. (See R3)

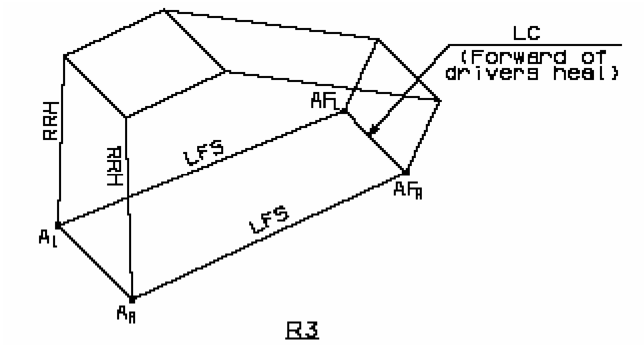


Figure A.4 LFS specifications

A.5 Side Impact members (SIM)

Side impact members shall join the RRH at points S and extend generally horizontal to points SF forward of the drivers toes. (See R4A) The SIM shall be between 6" and 12" (as measured vertically) above the lowest part of the seat in contact with the driver. From any direction, there shall be at least 2" clearance between the SIM and the driver's hips. Points SFR and SFL shall be joined by a lateral Crossmember (LC).

NOTE: The driver's feet must be behind the plane created by points AFR,L and SFR,L.

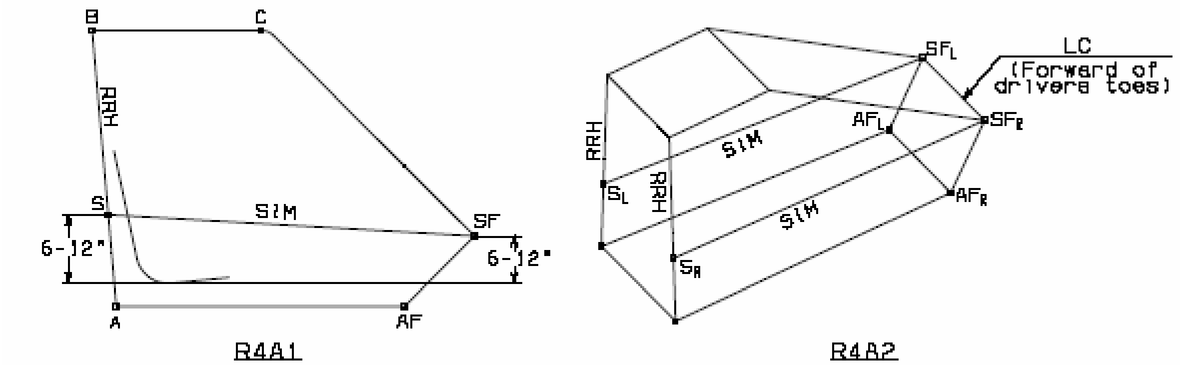


Figure A..5 SIM specifications

A.6. Front Bracing members (FBM)

Front bracing members shall join the RHO, the SIM and the LFS. (See R5A) The upper Front Bracing members (FBMUP) shall extend generally downward and forward and join points C on the RHO to the SIM at or behind points SF. The angle between the FBMUP and the vertical shall be less than 45 degrees.

At the point where the FBMUP joins the SIM, the lower Front Bracing members (FBMLWR) shall extend generally downward and join the SIM to the LFS at or behind points AF. The angle between the FBMLWR and the vertical shall be less than 45 degrees.

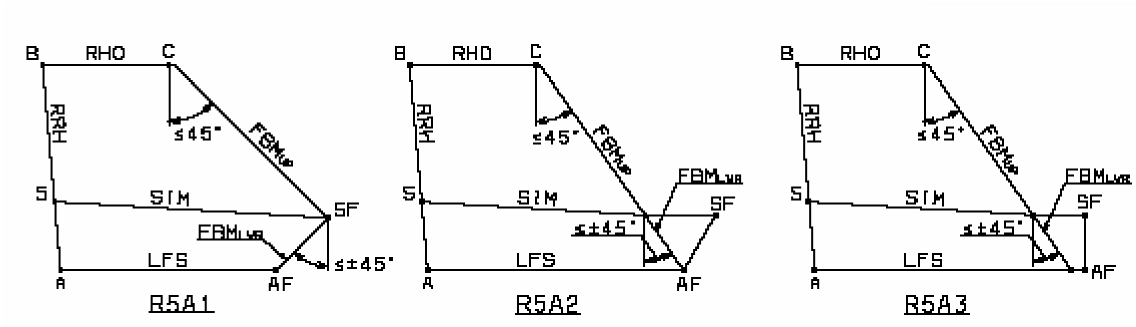


Figure A.6 FBM specifications

A.7. Fore-Aft Bracing members (FAB)

Fore-Aft bracing members shall be provided for the cage using either of the following methods:

Front Fore-Aft Bracing

Front FABUP shall extend generally downward from points D and join the FBMUP to the SIM at points E. The angle between the Front FABUP and the FBMUP shall be at least 30 degrees. (See R6A)

Front FABLWR must join points E and the LFS. (See R6A) The angle between the Front FABUP and the Front FABLWR must not be greater than 15 degrees in a side view. If two FABLWR members are needed, the angle between the two members must not be greater than 90 degrees. (See R6B)

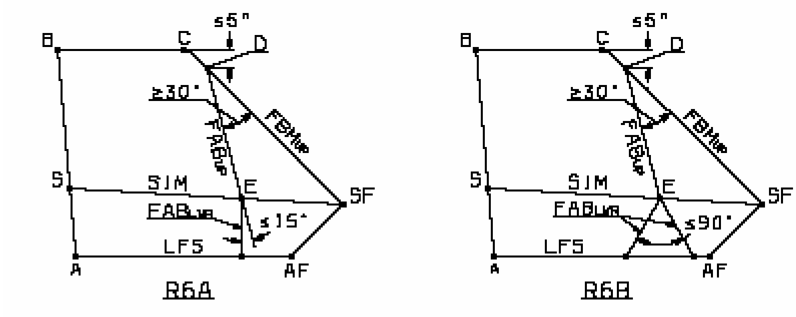


Figure A.7 Front FAB specifications

Rear Bracing

From a side view, construction must be entirely of contiguous triangles, with the maximum length of any member not to exceed 32” between attachment points. A bent tube not exceeding 28” between attachment points may be considered as one side of a triangle.

Rear bracing must as a minimum include FAB Upper, FAB Mid (a generally horizontal brace per side connecting FAB Up or FAB lwr to the RRH), and FAB Lower (See: Rrh 1–4 ok, Rrh 1–2 not ok). Additionally, at least one horizontal Crossmember (HMX) must connect the left and right sides of the rear bracing, attached within 15” of the center of the outer perimeter (as viewed from the side) of the rear bracing. (See HXM Lateral OK.)

Rear bracing must attach within 2” of Br and Bl, extend rearward beyond all engine componentry, and connect at or below Sr and Sl to the RRH. The lower attachments (at or below Sr and Sl) must be connected directly to the RRH (may not be inboard). (See below)

NOTE: Bent tube construction must not show any signs of stress tear or buckling. Please be aware that if your roll cage shows any problems in the bend area your team will need to fix it before you are allowed to compete.

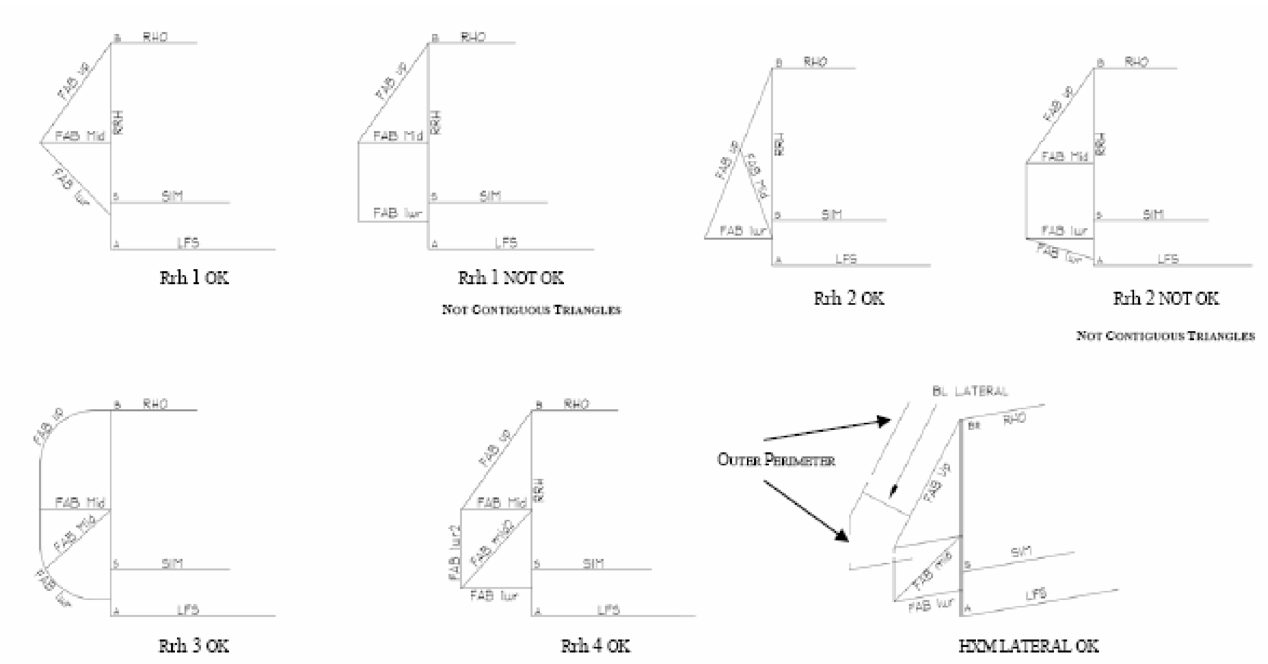


Figure A.8 Rear FAB specifications

A.8 Driver Head Clearance

For driver head clearance, the roll cage must extend a minimum of 104.14 cm (41 inches) above the seating surface to the bottom of the upper roll cage tubes measured vertically using the Template in Figure 1. The template radiused bottom should be placed in the joint of the seat base and the seat backrest and positioned vertically. The template “tee” top describes the projection of the required clearance height forward and rearward. While the clearance height forward is fixed by the template, the clearance height rearward must be extended in each design over the helmet top of a seated and secured driver. Taller drivers may be accommodated by lengthening the template vertical member and raising the entire clearance height envelope above the 104.14 cm (41 inches) minimum.

Head Clearance - Minimum

In all cases, a minimum of 12.7 mm (5 inches) vertical clearance must be provided from the helmet top of the team’s tallest driver to the bottom of the roll cage top tubes or members.

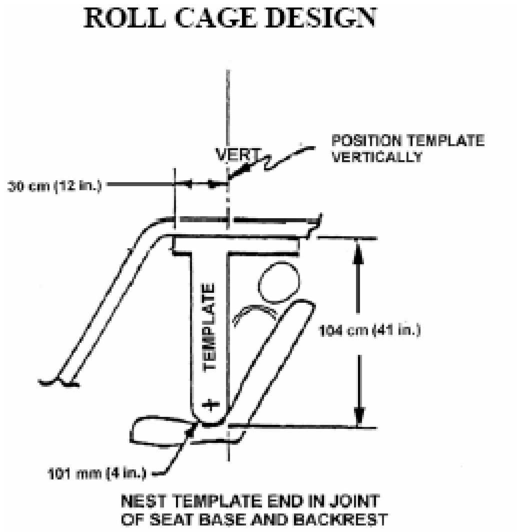


Figure A.9 Head Clearance specifications

A.9 Roll Cage & Bracing Materials

The material used for all of the required roll cage members must, as a minimum, be either:

(a) Circular steel tubing with an outside diameter of 25.4 mm (1 inch) and a wall thickness of 2.10mm (0.083 inch) and a carbon content of at least 0.18.

(b) Steel members with at least equal bending stiffness and bending strength to 1018 steel having a circular cross section having a 25.4 mm (1 inch) OD and a wall thickness of 2.10 mm (0.083 inch). The bending stiffness and bending strength have to be calculated about an axis that gives the lowest value. Bending stiffness is proportional by the EI product and bending strength is given by the value of SyI/c, (for 1018 steel the values are; Sy= 370 Mpa (53.7 ksi) E=205 GPa (29,700 ksi).

APPENDIX B ELEMENTAL TABLE RESULTS FOR FRONT IMPACT TEST

******* POST1 ELEMENT TABLE LISTING *******

STAT ELEM	CURRENT SMAX
1	-0.28676E+08
2	-0.28677E+08
3	-0.28678E+08
4	-0.28679E+08
5	-0.28680E+08
6	-0.28680E+08
7	-0.28679E+08
8	-0.28678E+08
9	-0.28677E+08
10	-0.28676E+08
11	0.11341E-08
12	0.11305E-08
13	0.14434E-08
14	0.20729E-08
15	0.15647E-08
16	0.15647E-08
17	0.12518E-08
18	0.31295E-09
19	0.0000
20	0.0000
21	0.51143E+08
22	0.51142E+08
23	0.51142E+08
24	0.51141E+08
25	0.51141E+08
26	0.51142E+08
27	0.51143E+08
28	0.51143E+08
29	0.51144E+08
30	0.51144E+08
31	0.18777E-08
32	0.21906E-08
33	0.18777E-08
34	0.12518E-08
35	0.78237E-09
36	0.0000
37	0.0000
38	0.0000
39	0.0000
40	0.0000
41	0.31295E-09

***** POST1 ELEMENT TABLE LISTING *****

STAT ELEM	CURRENT SMAX
42	0.39119E-09
43	0.39119E-09
44	0.23471E-09
45	0.15647E-09
46	0.0000
47	0.0000
48	0.0000
49	0.0000
50	0.0000

51	0.46079E-07
52	0.81961E-09
53	-0.21916E-07
54	0.97550E-09
55	0.23924E-07
56	0.12210E-08
57	0.23853E-07
58	-0.22508E-07
59	-0.67486E-07
60	0.13721E-09
61	1493.6
62	1246.9
63	1000.3
64	753.64
65	506.99
66	260.33
67	13.683
68	230.13
69	476.78
70	723.44
71	0.0000
72	0.0000
73	0.0000
74	0.0000
75	0.0000
76	0.0000
77	0.0000
78	0.0000
79	0.0000
80	0.0000
81	0.11191E+07
82	0.11190E+07

***** POST1 ELEMENT TABLE LISTING *****

STAT ELEM	CURRENT SMAX
83	0.11189E+07
84	0.11188E+07
85	0.11187E+07
86	0.11188E+07
87	0.11189E+07
88	0.11190E+07
89	0.11191E+07
90	0.11191E+07
91	0.39119E-10
92	0.39119E-10
93	0.19559E-10
94	0.19559E-10
95	0.19559E-10
96	0.19559E-10
97	0.19559E-10
98	0.19559E-10
99	0.19559E-10
100	0.19559E-10
101	0.61123E-12
102	0.61123E-12
103	0.0000
104	0.0000
105	0.0000

```
 106   0.0000
 107   0.0000
 108   0.0000
 109   0.0000
 110   0.0000
 111  0.73862E+06
 112  0.73836E+06
 113  0.73809E+06
 114  0.73820E+06
 115  0.73847E+06
 116  0.73873E+06
 117  0.73899E+06
 118  0.73925E+06
 119  0.73952E+06
 120  0.73978E+06
 121 -0.59103E+08
 122 -0.59103E+08
 123 -0.59103E+08
```

***** POST1 ELEMENT TABLE LISTING *****

```
 STAT    CURRENT
 ELEM    SMAX
 124 -0.59103E+08
 125 -0.59103E+08
 126 -0.59103E+08
 127 -0.59103E+08
 128 -0.59103E+08
 129 -0.59103E+08
 130 -0.59103E+08
 131 -0.29122E+08
 132 -0.29122E+08
 133 -0.29122E+08
 134 -0.29122E+08
 135 -0.29122E+08
 136 -0.29122E+08
 137 -0.29122E+08
 138 -0.29122E+08
 139 -0.29122E+08
 140 -0.29121E+08
 141  0.49471E-11
 142  0.49471E-11
 143  0.49471E-11
 144  0.49471E-11
 145  0.49471E-11
 146  0.49280E-11
 147  0.49471E-11
 148  0.24640E-11
 149  0.24640E-11
 150   0.0000
 151  0.97796E-11
 152  0.97796E-11
 153  0.97796E-11
 154  0.97796E-11
 155  0.97796E-11
 156  0.14669E-10
 157  0.97796E-11
 158  0.48898E-11
 159  0.48898E-11
 160  0.48898E-11
```

161 -0.58178E+06
162 -0.58179E+06
163 -0.58179E+06
164 -0.58179E+06

***** POST1 ELEMENT TABLE LISTING *****

STAT	CURRENT
ELEM	SMAX
165	-0.58180E+06
166	-0.58180E+06
167	-0.58180E+06
168	-0.58180E+06
169	-0.58180E+06
170	-0.58180E+06
171	-0.77720E+08
172	-0.77719E+08
173	-0.77719E+08
174	-0.77719E+08
175	-0.77718E+08
176	-0.77718E+08
177	-0.77718E+08
178	-0.77717E+08
179	-0.77717E+08
180	-0.77716E+08
181	0.80324E-09
182	0.87032E-09
183	0.26067E-09
184	0.40482E-09
185	0.27119E-09
186	0.59778E-09
187	0.36866E-09
188	0.39590E-09
189	0.48922E-09
190	0.70085E-09
191	-0.28793E+08
192	-0.28793E+08
193	-0.28793E+08
194	-0.28793E+08
195	-0.28793E+08
196	-0.28793E+08
197	-0.28793E+08
198	-0.28793E+08
199	-0.28793E+08
200	-0.28793E+08
201	-0.58638E+08
202	-0.58639E+08
203	-0.58640E+08
204	-0.58640E+08
205	-0.58641E+08

***** POST1 ELEMENT TABLE LISTING *****

STAT	CURRENT
ELEM	SMAX
206	-0.58641E+08
207	-0.58641E+08
208	-0.58640E+08
209	-0.58639E+08
210	-0.58639E+08

211	0.95034E+06
212	0.95031E+06
213	0.95028E+06
214	0.95025E+06
215	0.95022E+06
216	0.95019E+06
217	0.95016E+06
218	0.95014E+06
219	0.95017E+06
220	0.95020E+06
221	0.55621E+06
222	0.55614E+06
223	0.55608E+06
224	0.55601E+06
225	0.55595E+06
226	0.55589E+06
227	0.55582E+06
228	0.55576E+06
229	0.55569E+06
230	0.55563E+06
231	0.52001E-07
232	0.46103E-07
233	0.55957E-07
234	0.67295E-07
235	0.62975E-07
236	0.48715E-07
237	0.43739E-07
238	0.31154E-07
239	0.11120E-07
240	0.16429E-08
241	-0.59492E+08
242	-0.59492E+08
243	-0.59492E+08
244	-0.59492E+08
245	-0.59492E+08
246	-0.59492E+08

***** POST1 ELEMENT TABLE LISTING *****

STAT ELEM	CURRENT SMAX
247	-0.59492E+08
248	-0.59492E+08
249	-0.59492E+08
250	-0.59492E+08
251	-42423.
252	-43258.
253	-44093.
254	-44928.
255	-45763.
256	-46598.
257	-45780.
258	-44945.
259	-44110.
260	-43275.
261	0.73907E+06
262	0.73883E+06
263	0.73859E+06
264	0.73835E+06
265	0.73812E+06

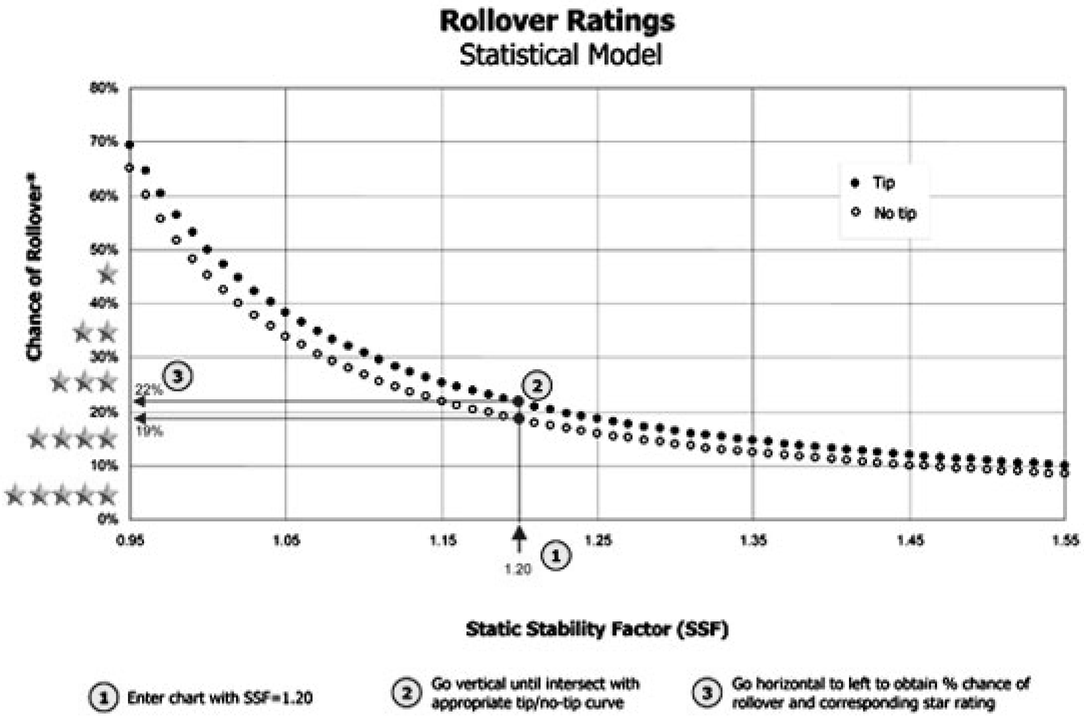
266 0.73816E+06
267 0.73839E+06
268 0.73863E+06
269 0.73887E+06
270 0.73911E+06
271 0.18220E-09
272 0.19032E-09
273 0.14370E-09
274 0.32799E-09
275 0.10519E-09
276 0.17404E-09
277 0.74983E-10
278 0.88483E-10
279 0.86221E-10
280 0.50194E-10
281 -0.59080E+08
282 -0.59081E+08
283 -0.59081E+08
284 -0.59082E+08
285 -0.59082E+08
286 -0.59083E+08
287 -0.59083E+08
***** POST1 ELEMENT TABLE LISTING *****
STAT CURRENT
ELEM SMAX
288 -0.59082E+08 289 -0.59081E+08
290 -0.59081E+08
291 -0.78131E+06
292 -0.78136E+06
293 -0.78141E+06
294 -0.78146E+06
295 -0.78151E+06
296 -0.78156E+06
297 -0.78162E+06
298 -0.78165E+06
299 -0.78160E+06
300 -0.78155E+06

MINIMUM VALUES
ELEM 171
VALUE -0.77720E+08

MAXIMUM VALUES
ELEM 30
VALUE 0.51144E+08

APPENDIX C CORRELATION BETWEEN STATIC STABILITY FACTOR AND ROLLOVER RISK

The National Highway and Traffic Safety Administration(NHTSA) recommends all consumers to use Static Stability Factor (SSF) to calculate the risks associated with tripped rollover for a vehicle. Tripped rollover is a rollover which a vehicle undergoes after colliding with small obstacles. 95% of all rollovers are believed to be tripped rollovers. The graph shown below can be used to determine the probability of rollover.



FigureC.1: SSF vs Chance of Rollover
http:www.nhtsa.dot.gov

In the above procedure,

$$SSF = t/2H$$

Where, ‘t’ is the track width and ‘H’ is the height of the centre of mass.

APPENDIX D ENGINEERING DRAWINGS