Design, Analysis and Optimization of Suspension System for an Off Road Car

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Abstract— **Suspension is one of the most vital sub-systems of an automobile. The basic function is to isolate the driver from the road shocks. Secondary function includes load transfer, lateral stability and providing adequate wheel travel ensuring ergonomics and driver comforts. The study describes design, analysis and optimization of a suspension system for an off-road buggy. The aim is to compete in SAE INDIA Baja competition. The suspension is designed for a rough terrain giving optimum camber, caster, toe, anti-dive, Roll Centre and Ackermann geometry variations. Compliance studies, effect on suspension bushings, transmissibility of different forces, vibration analysis, quarter car modeling has been carried out. Shock absorber, spring design and mounting considerations are also put forward. The geometry of the suspension has been modelled in commercial software package Lotus Shark. The finite element analysis of various suspension components are done in commercial software ANSYS 14.**

Keywords—Double wishbone, Mc Pherson, Camber, Ackermann, roll center, quarter car modelling, finite element analysis.

I. INTRODUCTION

Baja SAE India is an intercollegiate design competition organized by the Society of Automotive Engineers (SAE). The competition is open for undergraduate and graduate engineering students. The dynamic events include endurance race, hill climbs, maneuverability events, and suspension & traction events. The goal is to design, build, test and race a single seat off-road car following SAE guidelines. The subsystems include chassis, analysis, suspension and transmission. A well-engineered car is a fine blend of sound engineering concepts put into practice in all the subsystems. 25 motivated students work in different sub systems around the year with the aim to build a winning off-road buggy.

Suspension in itself is a vital sub system of the car. It is the term given to the system of springs, dampers, linkages that isolates the chassis and driver form shock induced by the terrain. It determines how unsprung mass is connected to the sprung mass and how they interact with each other [1]. Constant feedback was collected from chassis and transmission subsystem to decide on the hard points for suspension. Various geometric and non-geometric parameters like camber, castor, toe, roll Centre variation, Ackermann geometry, track width, wheelbase are considered in detail. This paper describes the work done by the suspension team of NITK Racing-Junkyard maniacs to build “JM VII” for SAE Baja India 2014.

The paper explains design methodology and flow in a systematic manner. The basic procedure of suspension design consists of the following steps:

- Selecting various design targets.
- Selecting the type of geometry.
- Choosing hard points.
- Analyzing the loads in suspension.
- Designing springs and dampers.
- Designing the structure of different components.
- Analyze and reiterate.

Second section talks about the front suspension as well as steering and various design parameters related to them. Third section describes rear suspension. Fourth one captures the vibration analysis; quarter car modeling and some miscellaneous studies conducted for the optimization of suspension which includes bush studies and variable ride height concept. Fifth section describes FEA results of various suspension components. Conclusion, acknowledgment and references follow it.

II. FRONT SUSPENSION AND STEERING

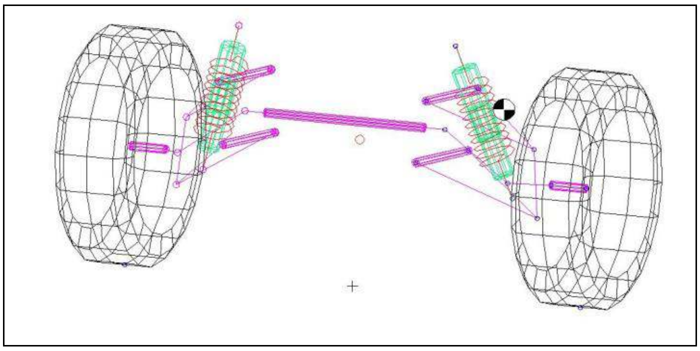

Fig. 1. Front suspension assembly

The main objective of the front suspension is to provide the maximum wheel travel in bump as well as in droop [5]. Moreover it should provide better grip when it comes to cornering. Design also has to be compatible with nose design. Front suspension is coupled with steering and both are interdependent [5]. We need to have some base values to start

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off with. Hence we fix the turning radius, wheelbase and find out the required track width.

Suspension coupled with steering should provide better directional stability [4]. Also good controls of geometric parameter like camber, toe is aspired hence Double wishbone geometry with parallel and unequal arms were identified as the most suitable configuration. During cornering inner wheel undergoes droop while outer wheel undergoes bump this should practically decrease the contact patch of the wheels.

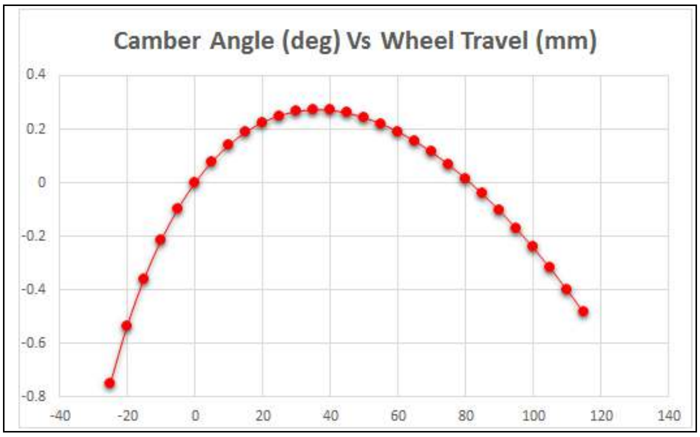

Fig. 2. Camber variation

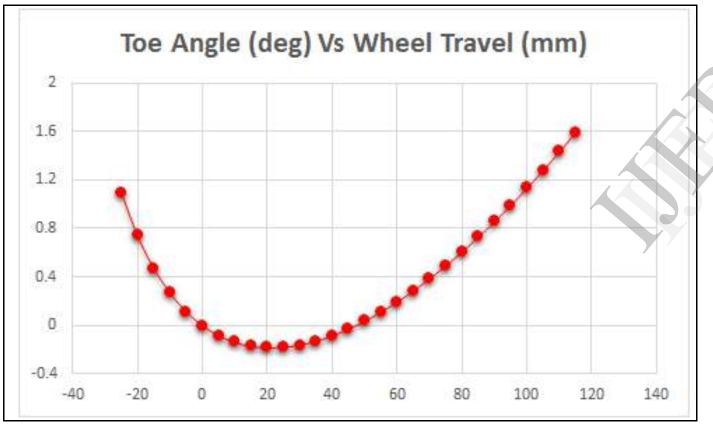

Fig .3. Toe variation

This can be overcome using unequal A-arm lengths [5]. Unequal arms ensure lesser camber variations hence large patch of tire will remain in contact with ground resulting in better traction.

Static camber of 0^0 is set but when the car get loaded with the driver a small amount of negative camber is induced, improving cornering stiffness of the tire. Static camber setting can be done using ball joint threads. Care should be taken not have large negative angle to avoid excessive tire wear [2].

Caster is maintained 0^0 throughout. Positive Kingpin Inclination is kept via knuckle design to impart self-centering effect for the steering and reduce positive camber gain on bumps [1]. Dynamic Toe-angle variation is kept low giving better handleing .However static toe-angles can be varied using tie-rods. Toe setting can be done as required i.e. toe-in for straight line stability however toe-out for manueurvability to decrease the effective turning radius proved useful for our team. Roll-Centre is kept above the ground, lower than rear to Impart under steer characteristics [5].

Coil over springs with adjustable pre loads were used. Motion ratio of 0.6 was used such that the spring compresses by $1/6^{th}$ amount of wheel travel giving better ride quality. Front suspension is kept softer than rear for better performance.

Optimum strut angle is chosen w.r.t. vertical to increase the effectiveness of the spring. However in the side view it is placed vertical.

$$K_s = 4 * \pi^2 * MR^2 * M_s * RF^2 \qquad (1)$$

Where, K_s = spring rate; MR = Motion Ratio;
M_s = Sprung Mass; RF = Ride frequency;

Ride frequency of around 1.99 Hz was calculated using relation (1). Ride frequency of front is kept lower than the rear. .Anti-dive and anti-squat is not considered since the velocity and accelerations involved are not very high.

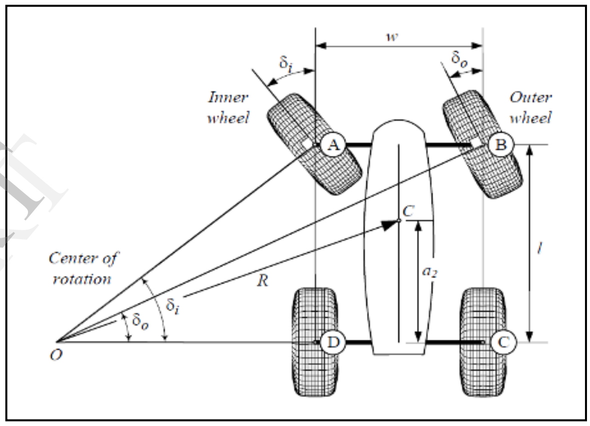

Fig. 4. Ackermann Steering

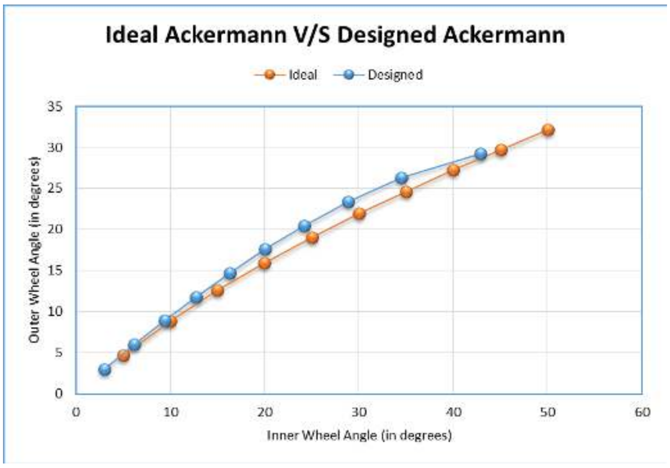

Fig. 5. Ideal v/s Designed Ackermann

The steering system must provide a feel (of front tires) and a sense (of contact patch) to the driver. Components must be rigid enough not to undergo deflections. Steering response of

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the vehicle is made fast by giving proper KPI, Caster and Trail values.

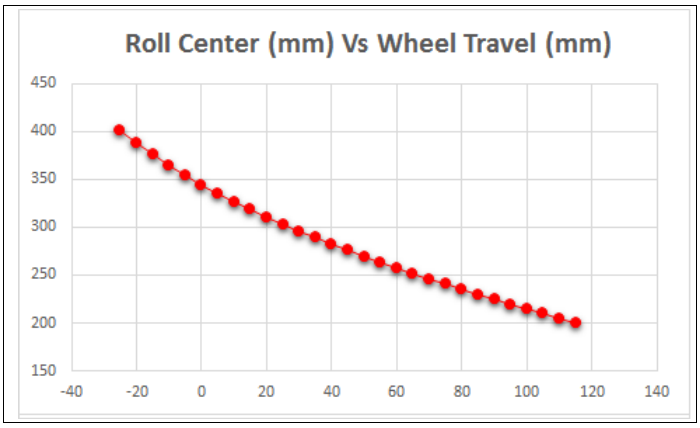

Fig. 6. Roll Center Variation

Rack and pinion manual steering system has been chosen. There are many steering geometries, of which Ackermann geometry has been chosen. It is when a vehicle goes around a corner; the inward wheel turns bit more than the outward to effectively complete the cornering without slipping [7]. The following relations hold good for Ackermann geometry.

$$\cot \delta_0 - \cot \delta_i = \frac{w}{l}$$

$$R = \sqrt{a_2^2 + l^2 \cot^2 \delta}$$

$$\cot \delta = \frac{\cot \delta_o + \cot \delta_i}{2}$$

R = Turning radius (mm)
w = Track-width (mm)
l = Wheel-base (mm)
δ_o = Outer Locking Angle (degree)
δ_i = Inner Locking Angle (degree)
Percentage Change in Turning Radius: $\Delta R = 2.249$ %

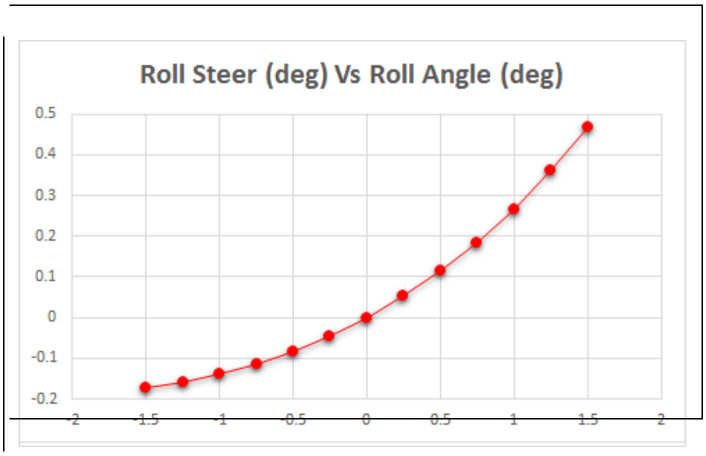

Fig. 7. Roll steer variation

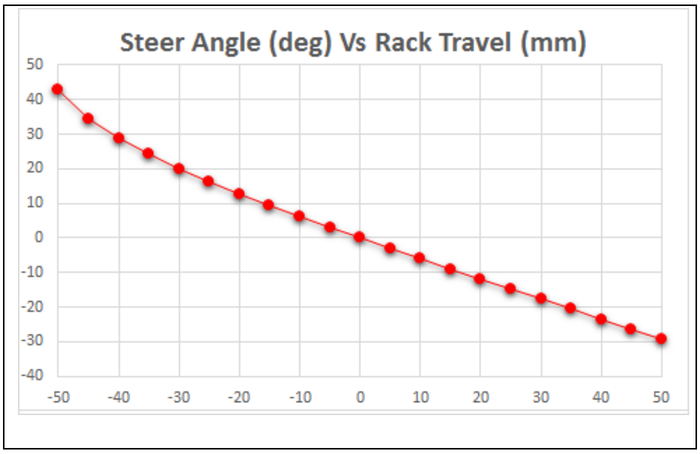

Fig. 8. Steer Angle variation

Since suspension and steering acts as a coupled system the tie rod length, steering arm length affects the overall suspension response. Position of rack and the length of the tie rod were chosen so as to minimize the dynamic toe changes [1]. A slight change in the position of inboard point of tie-rod either above or below the Ideal center will lead to roll steer. And a slight change in the position of inboard point of tie-rod either inward or outward to axis of line joining inner upper and lower wishbones will lead to bump steer. It is ensured that minimum bump steer and roll steer is present.

III. REAR SUSPENSION

When it comes to rear suspension the objective were no different from the front however compatibility with transmission was given high priority. CVJ cups used for powering the wheels don't allow very large angular movement of the shafts, hence the propeller shafts had limited travel, and suspension travel had to be restricted too [4]. Team in the past have faced problem of propeller shaft getting disconnected during the race. The static angle was set using gearbox height as a parameter.

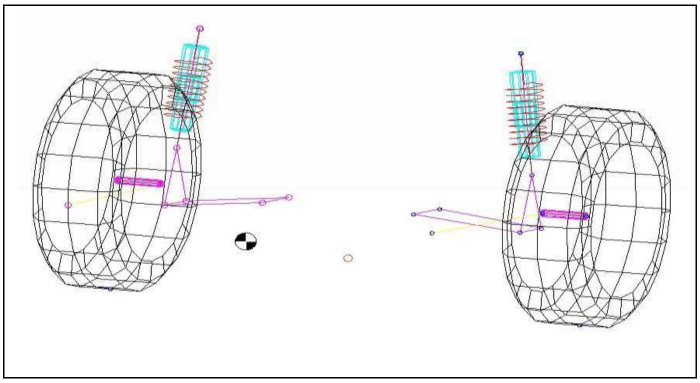

Fig. 9. Rear Suspension Assembly

McPhersons strut with a toe link was chosen as an optimum geometry for the application. Since it involves only one arm the unsprung mass is considerably less thus response of the suspension system is better. Serviceability and packaging is also good considering lesser linkages. Conventional McPherson's geometry is known to have a motion ratio

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nearly one [3], however we have modified the design ensuring motion ratio of around 0.8 giving better ride qualities. Half track-width of 600 mm is used.

During cornering load transfers take place to the outer wheels and large patch of tire need to stay in contact with ground to ensure better traction and hence stability[4]. Therefore camber variation is kept minimum. Static camber without driver is kept zero, but with the driver negative value is ensured giving better lateral stability. However static value can be changed using Heim joint threads.

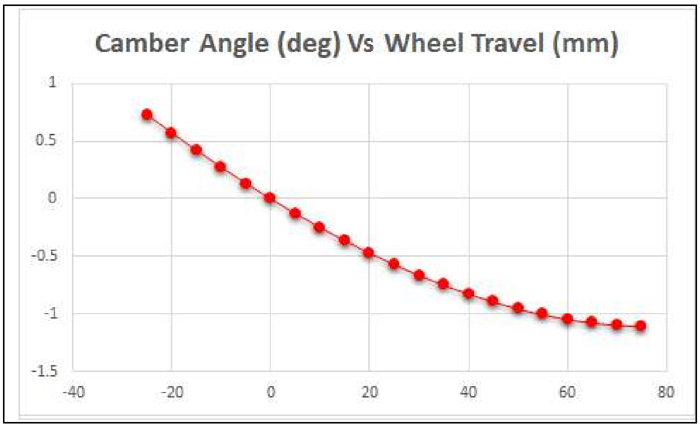

Fig. 10. Camber Variation

Toe change is eliminated in the design since the drive shaft is a rigid member which restricts any toe variation. Static value can be set using toe link. Castor and king pin inclination (KPI) are kept zero for stability purpose.

Roll center is a point in which lateral forces developed by the wheels are transmitted to the unsprung mass without producing roll [5]. Suspension was set up to minimize the roll center migration. Also roll moment was less since the distance between CG and roll center is less, hence rolling tendency is less on corners, allowing tighter corners reducing corner radius.

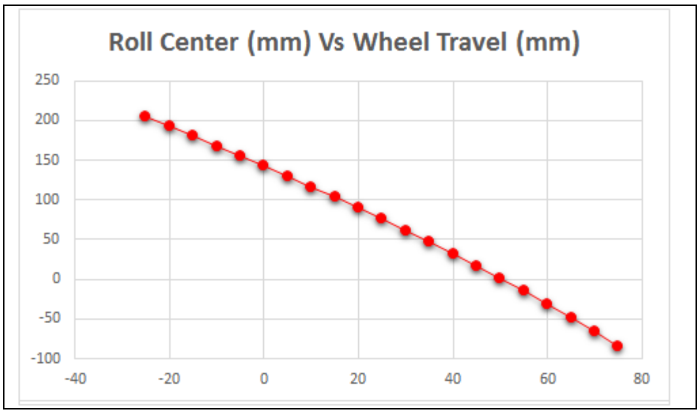

Fig. 11. Roll Centre Variation

Coil over spring with dampers were used to absorb the shocks. Struts are mounted such that it is inclined in the direction of force acting on it thus making them more efficient. It was noticed that one strut was undergoing buckling hence two of them were used in parallel configuration as seen in fig 14. Ride frequency for rear was calculated as 2.33Hz using equation (1). The energy stored in the springs has to be dissipated in some form, dampers dampens the oscillations and stabilizes the system. Damping coefficient value for a passenger car is around 0.2-0.3, however off road car need higher damping of around 0.5 for better road holding characteristics.

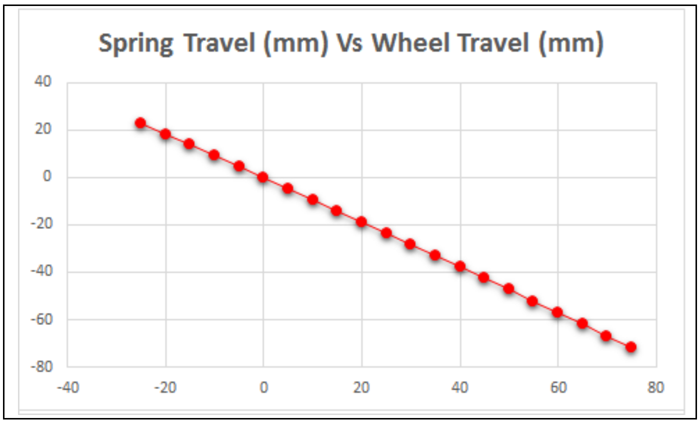

Fig. 12. Spring Travel

IV. Miscellaneous Studies

Bush is basically an isolating material which provides interface between two metals allowing certain degree of movement. The papers shows the study on different bush types and designs .We experimented with three bush designs ; nylon bushes, gun metal bushes and brass pipe embedded into a rubber bush. Nylon bush were satisfactory since it was easy to machine, compliant enough, provided good damping, easy to assemble, however it performed good for a short time and wore out very easily, also were costly, and had to be replaced over and again.

Fig. 13. Gun metal, Rubber with Brass pipe respectively.

Fig. 14. Nylon bushes

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Gun metal bushes were resistant to wear, easy to machine, however could not dampen the vibrations, were costly, and difficult to assemble. Rubber bushes with brass pipe were identified as the best. They were easy to work with, rubber could dampen out the vibrations, brass was resistant to wear. Good performance, cheap prices were few advantages. It basically combined advantages of two above mentioned bush types.

A Simple and smart way of passively varying the ride height of the vehicle was adopted. The multiple strut mounting points were provided. Three at the bottom and three at the top mount. Hence strut could be assembled in six different ways to get different ground clearances. Team used high ride height during endurance; however lower for hill climb.

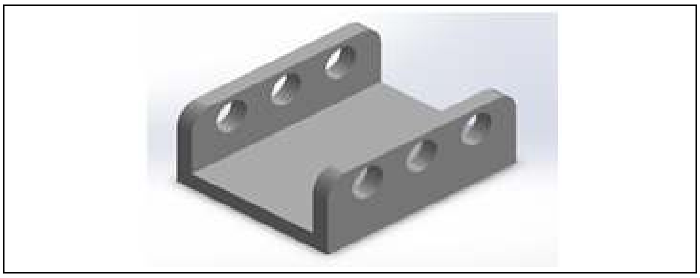

Fig. 15. Strut Mounting Bracket

Quarter car modeling has been done using MatLab® to study the effects of road inputs on the driver's seat, sprung mass, unsprung mass. Input is sudden elevation of 0.2 m which excites the suspension systems and results are plotted as displacement and velocity Vs time graphs.

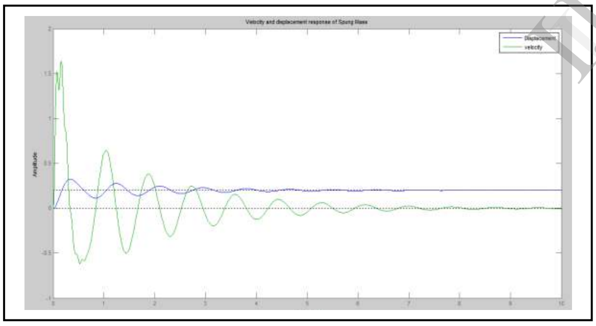

Fig. 16. Response of Sprung mass

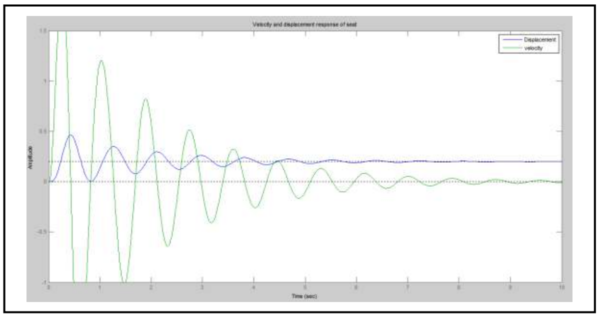

Fig. 17. Response of seat

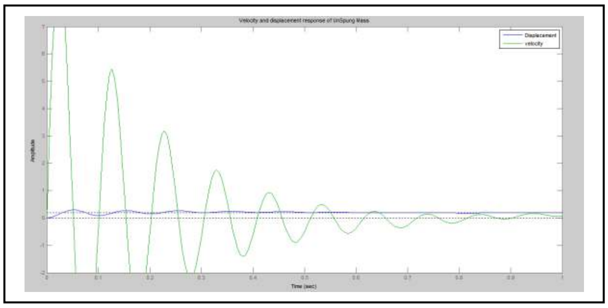

Fig.18. Response of unsprung mass

V. ANALYSIS

Once the design is satisfactory the calculation of forces acting and analysis of wishbone is very important for any progression in the fabrication phase. Various forces along with their line of actions are obtained from Lotus shark force transmissibility model.

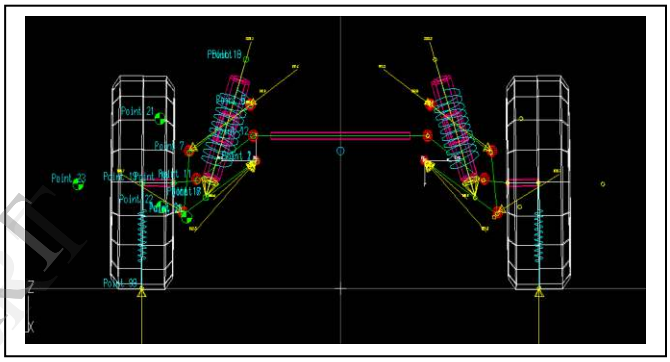

Fig. 19. Forces at different points

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Assumptions made in the analysis: Material is isotropic, linear. Static analysis is used to determine the deflections, stress-concentrations in the structure caused by applied loads or impacts. The hard-points of the suspension system are taken from the designed iteration. Since the Outer, inner and upper points of an A-arm can be joined infinitely; it is joined such a way that it is structurally strong enough to take all the loads acting on it. Wishbones have been analyzed for bump and braking scenario. Appropriate Mesh size is considered after several iterations and Convergence is ensured. There are few constraints that come into picture while iterating like optimum space for placing struts, minimal stress concentration etc. Factor of safety of more than 1.5 has been obtained in all the cases from analysis which is necessary for an ATV.

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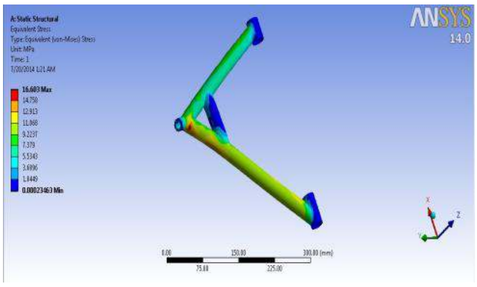

Fig. Front lower *(Braking)*

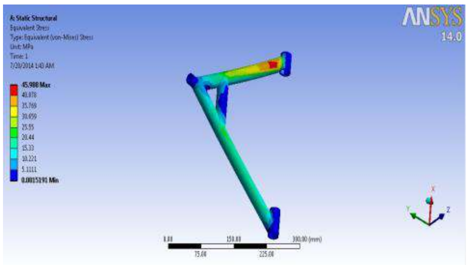

Fig. Front lower *(Bump)*

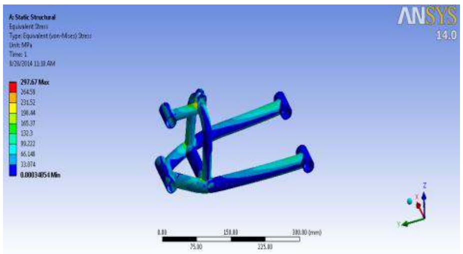

Fig. Rear *(Bump)*

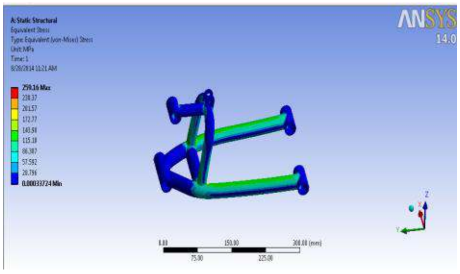

Fig. Rear *(Braking)*

Fig. 20. Stress concentration

VI. ACKNOWLEDGMENT

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VII. CONCLUSION

The use of Lotus shark in the modeling was inevitable and helped a lot to reiterate and obtain satisfactory results. User friendly user interface make it much easier to carry out various analysis and visualize the geometry. Simple MatLab® coding helped us to get important data needed. Analysis of wishbones helped to structurally strengthen them without using excess material. The designed suspension was found to give satisfactory wheel travel in the front. The steering system was responding very well and turning radius of around 2.6m was obtained easily. The Unique design of the rear wishbone was
well appreciated as it gave good performance satisfying all the aims we had at the back of our minds while designing it. Thus we performed well in the suspension and traction event at SAE INDIA BAJA 14 held at Pithampur. We were one of the fastest in the same event.

VIII. REFERENCES

[1] William F. Milliken, Douglas Milliken, 1994."Race Car Vehicle Dynamics," SAE International.
[2] Reza, N. Jazar, "Vehicle Dynamics," Springer publications, 2nd edition.
[3] Optimum.com," Optimum Kinematics Help files," Vehicle dynamics solutions.
[4] Thomas D. Gillespie, 1992. "Fundamentals of Vehicle Dynamics," SAE International.
[5] Carroll Smith, 1978. "Tune to win: The art and science of race car development and tuning."
[6] Lotus Cars Ltd. "Getting Started with Lotus Suspension Analysis," Version 3.11
[7] 7. Steering Dynamics.

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