COBEM UBERLÂNDIA 2019

ABCM Associação Brasileira de Engenharia e Ciências Mecânicas

25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

STRUCTURAL DIMENSIONING OF AN OFF-ROAD VEHICLE SUSPENSION THROUGH DROP TEST

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Abstract: *The present work presents an analytical modeling of the suspension vertical dynamics of an off-road vehicle and the methodology of experimental validation of the same. For this, a rapid and low complexity test was developed with the acquisition of data made through a compression load cell. With this methodology, it was possible to collect the conditions to be used in the project phase, in order to evaluate the changes related to the previous project and to verify improvement opportunities. With the adoption of the methodology presented, it was possible to improve the dimensioning of the suspension components for vertical impacts, being the most significant improvement in the knuckle which safety coefficient increased from 0,9 to 2,7.*

Keywords: *suspension, boundary condition, compression load cell, drop test*

1. INTRODUCTION

The suspension is the system responsible for the stability of the vehicle, absorbing, through its components, "irregularities of the terrain". For competition cars, it is desired that it behaves in a curve characterized by the oversteer tendency, because it allows it to make more closed turns.

To accomplish the suspension project of a vehicle it is necessary to analyze, mainly, the first two of the three dynamics below:

1. Vertical dynamics: it analyzes the comfort and the frequencies suffered;
2. Lateral dynamics: it analyzes the behavior of the car in the realization of curves
3. Longitudinal dynamics: analyze behavior during braking and acceleration

Once the dynamic part has been completed, kinematic modeling starts with specific software, such as Lotus Engineering.

1.1 Vertical dynamics

In vertical dynamics behavior, there are many variables, so it is necessary to pre-select some of them as natural frequency and springs and tires rates.

For the analytical modeling of the vertical dynamics of the suspension, it is necessary to first calculate the front and rear ride rates, that is a vertical force per unit displacement of the tires ground contact reference point relative to the chassis (Milliken, 1995). Besides that, given the tire rates, the wheel rates or wheel center rate is calculated.

1.2 Lateral dynamics

In order to analyze the lateral dynamics and the tendency of the chosen behavior, the lateral transfer of load is primordial. The understeer or understeer tendency is the sliding of the front to the rear, that is, the front of the car ends up skidding and the driver has no action, the car will continue to tangent the curve escaping out of it. Already the oversteer, is preferential in competition cars, the sliding of the rear in relation to the front and needs more experienced pilots because, as the rear skids, they need to give "anti-steering" so the car continues to tangentiate the curve.

The lateral load transfer, (Nicolazzi, 2008), happens when there is the shift of load from the inner wheel to the external wheel of the curve and it comes from different influences. The height of the roll center affects the side load transfer, because the higher the height, the greater the transfer. The roll axis is given by the line connecting the front and rear roll centers. During a turn maneuver, the vehicle rolls toward the outside of the vehicle, due to the centrifugal force resulting from the load transfer; this fact is called the rolling, quantified by the rolling angle or gradient. The rolling stiffness is the resistance that the body roll meets.

1.3 Kinematic modeling

There are some kinematic angles of great importance to the understanding of the study: the toe, camber, caster and kingpin inclination, because when quantified correctly, it aids the oversteer behavior. Toe in refers to the angle between the longitudinal axis of the vehicle and the lines of the center plane of the wheels. In curves, the wheels external to it are more loaded and govern the greater percentage of the trajectory. Camber is the slope of the plane of the wheel relative to a vertical passing through the center of the tire / track contact surface (Nicolazzi, 2008). Caster is the name given to the angle formed between the master pin of the vehicle tire relative to the vertical plane. Kingpin Inclination (KPI) or Steering Axis Inclination (SAI) is the angle between the center line of the kingpin and the center line of the wheel in a frontal view.

1.4 Signal processing

Signal processing is the name given to procedures used in data measured to reveal the information contained in the measurements. The three steps of the methodology of extracting the information of a signal are acquisition, processing and interpretation. These procedures are essentially constituted by transformations that are based in mathematics and are implemented with the use of digital techniques. The laws of physics or other models expressed in mathematical language comprise a first stage in which the process is characterized by a quantitative form (Souza et al, 2019).

Analog and continuous signal are represented by a single uninterrupted response whereas discrete ones are characterized by a data sequence. Therefore, the purpose of signal processing is to extract the information from a signal, especially when it is not feasible by direct observation (Shin, 2008).

For the acquisition of the value of vertical impact force is used a load cell of compression showed in Figure 1. It is used a commercial load cell acquired from the manufacturer HBM, which has four extensometers in the Wheatstone bridge configuration ensuring data accuracy and reliability. The force to be measured deforms the strain gauge being the deformation measured as a change in the electrical signal.

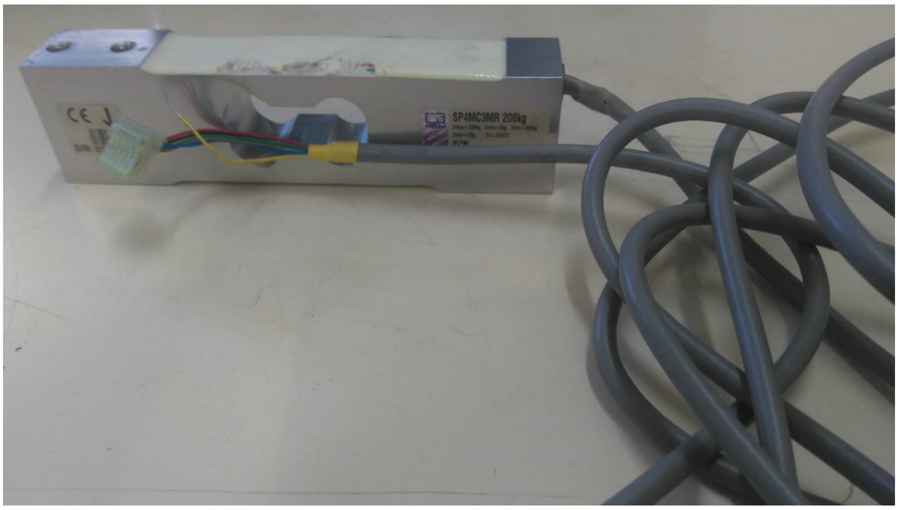

Figure 1. Load cell of compression used in test

1.5 Initial estimate of the ground/tire force

To estimate the tire/ground reaction force, a serious of physical principles are used (Reffatti, 2015). The first one is the energy conservation. It is calculated the potential energy of a body with mass m at a height h, then it is estimated its kinematic energy. It is assumed that immediately before the object reaches the ground, the potential energy will null while the kinetic is maximum. This way is possible to determine the speed of the body when reaching the ground. The next concept to be used is the amount of movement, the product between mass and speed.

The amount of movement of a body is equal to the impulse of the resulting force in a given time interval. Therefore, with the knowledge of the variation of the impulse and with an estimative of time, the force to be measured can be determined. The ease of measurement with a compression load cell helps speed up processing and output, reducing the time taken to get results, and ultimately reducing costs. (HBM, 2019).

1.6 Finite Element Method

The Finite Element Method is an approximate method of calculating continuous systems in which the continuous body is subdivided into a finite number of parts or elements, the nodes. A finite number of parameters specifies the mathematical model. In the problems of structural analysis, the unknown parameters are the nodal displacements.

The mathematical representation of the complete relation between all the nodal forces and nodal displacements in an element is done through a system of linear algebraic equations.

The conception of the mathematical model that represents the discretize structure is based on three fundamentals laws: balance of forces, compatibility of displacements and law of behavior of material. The displacement compatibility states that the ends of the element present on the same node are subject to the same displacement components. The determination of the rigidity of the structure constitutes the fundamental task of analysis in the calculation of the displacements of the structure (Filho, 2005).

2. METHODOLOGY

2.1 Suspension modeling

Initially, the vehicle was dynamically modeled by calculating the stiffnesses to the suspension roll to obtain the rolling gradient of the vehicle. With this value, graphically, the roll centers of the vehicle were found.

This was done using Lotus Engineering Software to model the kinematics of the suspension in order to minimize the bump steer effect. For this, in the front, worked, with the angles of camber, caster, toe e kingpin, the according with the Figure 2, 3, 4 and 5. Already for the rear, camber and toe. Thus, the suspension hardpoints were found. From them, you can scale the front and rear suspension arms in SolidWorks.

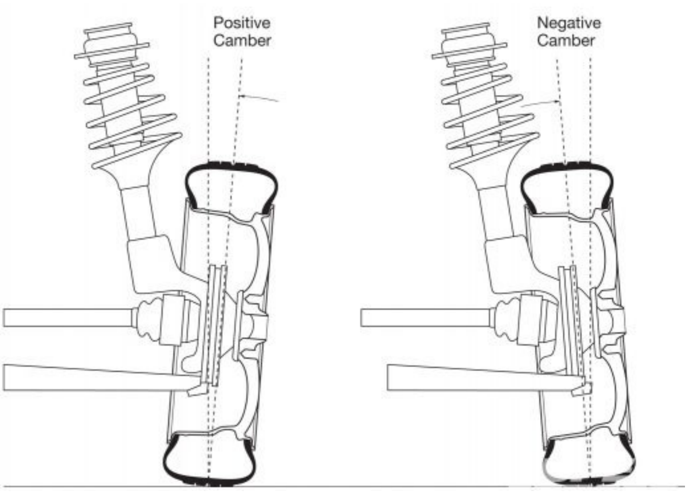

Figure 2. Camber Angle Illustration (Nicolazzi, 2008)

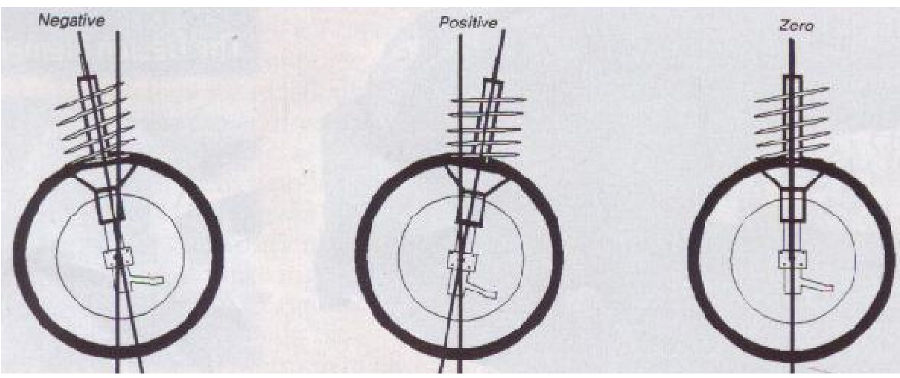

Figure 3. Caster Angle Illustration (Nicolazzi, 2008)

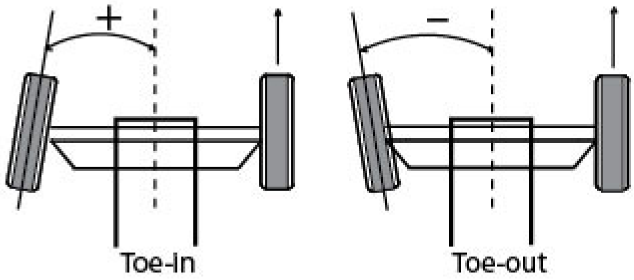

Figure 4. Toe Angle Illustration (Nicolazzi, 2008)

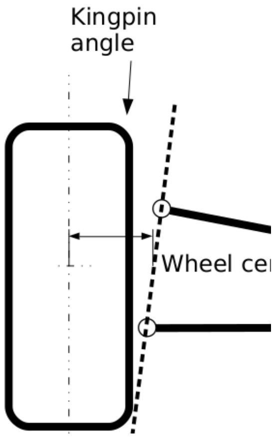

Figure 5. Kingpin Angle Illustration (Nicolazzi, 2008)

2.2 Experimental procedure

This was one of the first tests performed by the team using the load cell. Thus, an attentive reading of its manual was initially made, trying to understand its operation and potentialities.

The contact area of the load cell needed to be enlarged since it would be very difficult to align the tire with its sensitive part. The load cell already had 5 millimeters holes in some regions. In this way, holes of the same size were made in a 10 millimeters steel plate so that the instrument was fixed and consequently the contact area increased. That way, the whole area of the tire would trigger the mechanism in the fall of the vehicle, ensuring a better consistency of the data.

The calibration curve was not provided, so it was necessary to obtain it. Previously known mass rings (5, 10 and 15 kilograms) were used to create a graph and with the straight line of this equation obtained, it was possible to convert the electrical signal change in vertical force.

In order to guarantee the reliability of the data, it is necessary to ensure that the cell remains immobile throughout the experiments. Thus, double-sided tape was used to fix it to the floor, since the tests were performed in non-team dependencies. The car was hoisted in about 1 meter, with the use of a crane present in the laboratory of the Civil Engineering Department, which is capable of operating objects up to 3 tons. The Figure 2 shows the vehicle hoisted.

This height was chosen because it is very close to the maximum elevation of the obstacles present in the test track of the team as well as the ramps faced in the competitions BAJA SAE. At each outlet, the wheel of the car was always carefully aligned with the cell, as well as ensuring that the underside of the tire was at the correct distance from the ground.

Being all the steps verified, a student let go the rope and instantly the car fell on the load cell. In order to speed up the repeatability and avoid changing in the place-measuring device, the bridge operator would rotate the car in the air, so when it was desired to obtain the data for another wheel, the new alignment was performed with the vehicle suspended.

Figure 6. Car suspended 1 meter high from the ground, just before the fall

2.3 Analysis with the Finite Element Method

Collected the force value multiple times on each of the vehicle wheels, the arithmetic mean of values was calculated. Components that changed in relation to the suspension project used by the team in 2016 and 2017 years were evaluated such as suspension arms, front knuckle and rear suspension components besides other that were not altered such as axle tip, front and rear hubs.

Each of components has particular boundary conditions. The axle tip has a mesh refining in the axle variation sections where the bearings are present. At their location, free cylindrical supports in the tangential direction are used, fixed support at the axle end that is inside the knuckle as wheel as the remote force of the wheel (test withdrawal condition) applied at the other end. It is represented in the Figure 7.

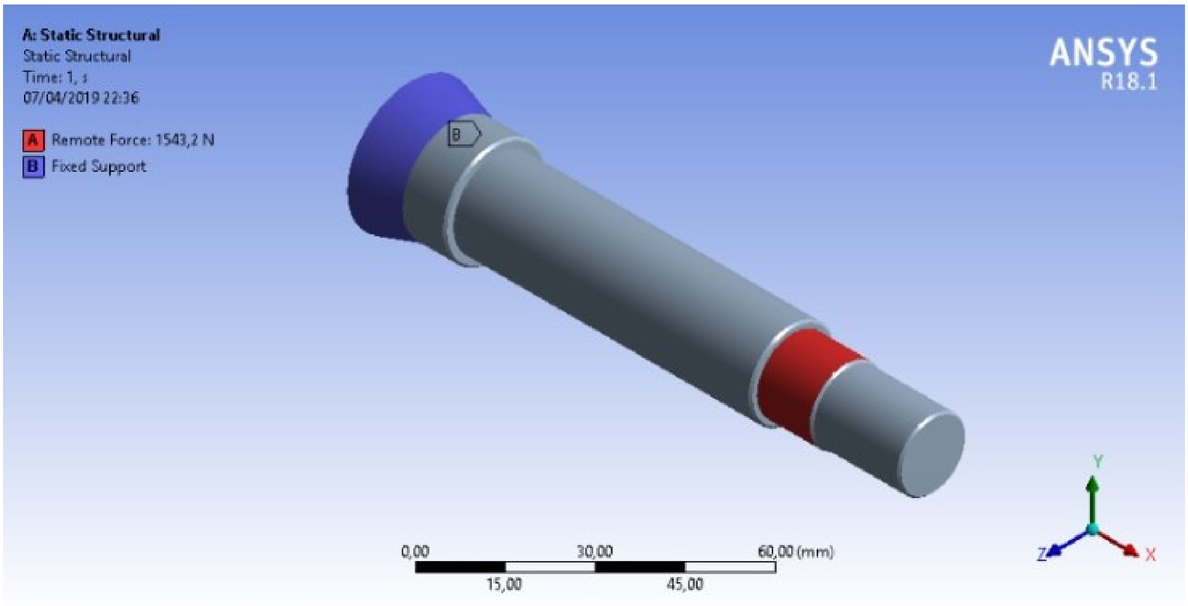

Figure 7. Boundary conditions of the analysis of the axle tip

In relation to the rear hub, cylindrical or fixed supports can be used in splines, remote force acting on holes applied relative to the wheel position. It is represented in the Figure 8.

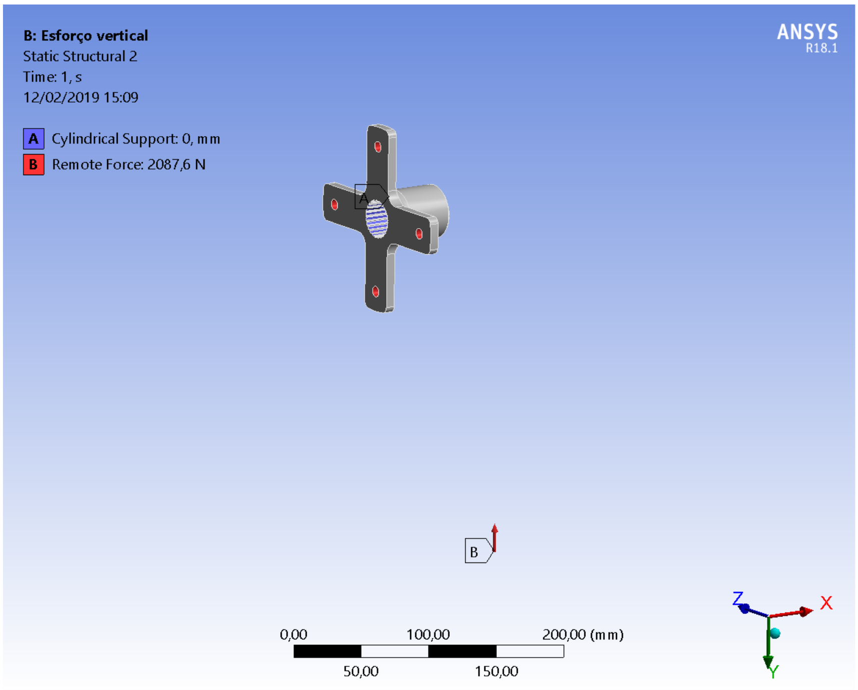

Figure 8. Boundary conditions of the analysis of the rear hub

The front hub has very similar conditions, being set in its central part embed also undergoing a solicitation of a remote force acting on holes that couple it to the wheel. It is represented in the Figure 9.

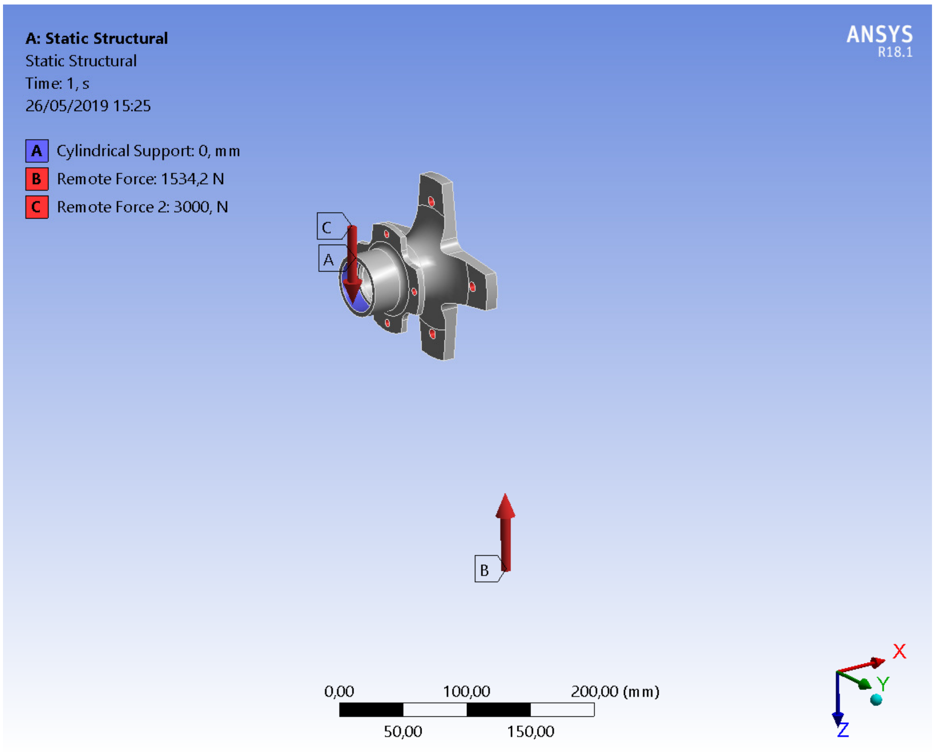

Figure 9. Boundary conditions of the analysis of the front hub

The boundary conditions for the analysis of the front knuckle, that are showed in the Figure 10, are free cylindrical supports in the tangential direction at the pivot point of the suspension arms and the steering arm coupling site; contact force of the ground/tire acting at the location of the axle tip as well as the braking force of the plunger at the support points of the brake caliper. This simulation has a particularity, since the reaction forces at the location where the eyes of the rod end are present is the entry condition for the analysis of the same.

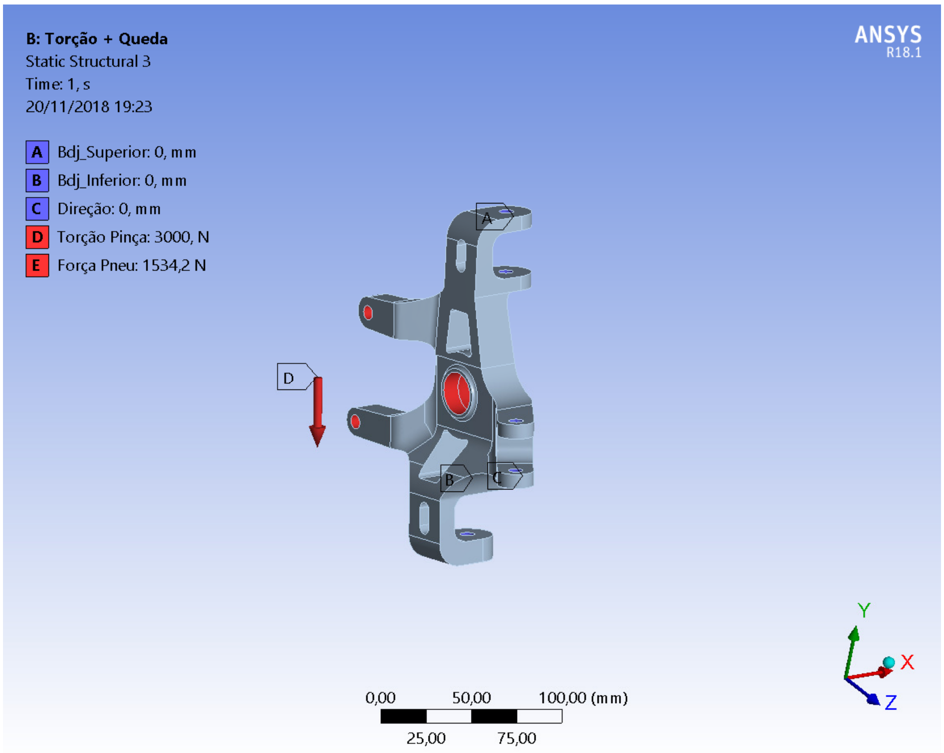

Figure 10. Boundary conditions of the analysis of the front knuckle

In the case of the suspension arms, shell elements are used since they very well portray the state of tensions acting on tubes and optimize the computational time of the analysis. In addition, to expedite the analysis, a rigid spring element with high stiffness is used at the location of the knuckle avoiding the need to import this geometry. In addition, free cylindrical supports are used in the tangential direction in tubes connecting the suspension arms to the chassis, restricted displacement in the vertical and lateral directions at the connection point of the suspension arms with the damper and reaction forces at the connection points of terminals to the knuckle. All this boundary conditions are showed in the Figure 11.

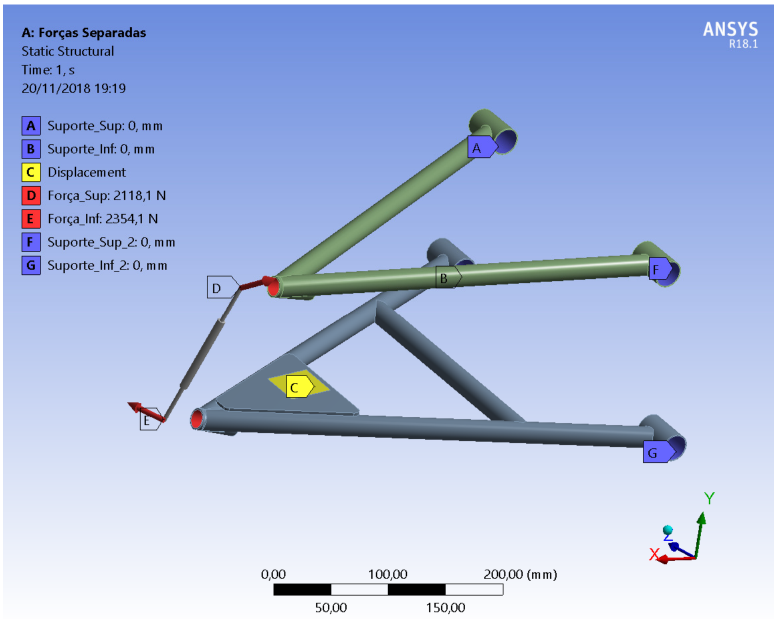

Figure 11. Boundary conditions of the analysis of the front suspension arms

For the rear suspension components, shell elements are also used. The other conditions are free cylindrical supports in the tangential direction at points of connection with the chassis, restriction of vertical and lateral movement at the location of connection of the suspension arms with the damper and application of tire force /ground contact force acting on the knuckle holes. It is represented in the Figure 12.

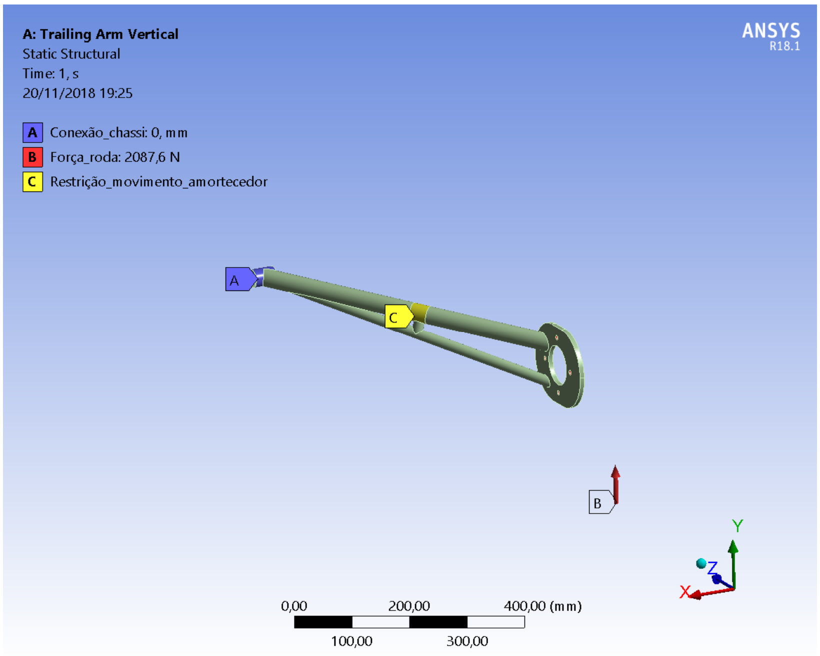

Figure 12. Boundary conditions of the analysis of the rear suspension arms

3. RESULTS AND DISCUSSIONS

Aiming at greater reliability of the data, the test was performed multiples times on each of the vehicle wheels. The graphs obtained were of force x time and the values used as boundary conditions in simulations are result of the arithmetic mean of all measurements. The Figure 13 contains the representation of one of its graphs for the front, and Figure 14 one representation of the graph for the rear.

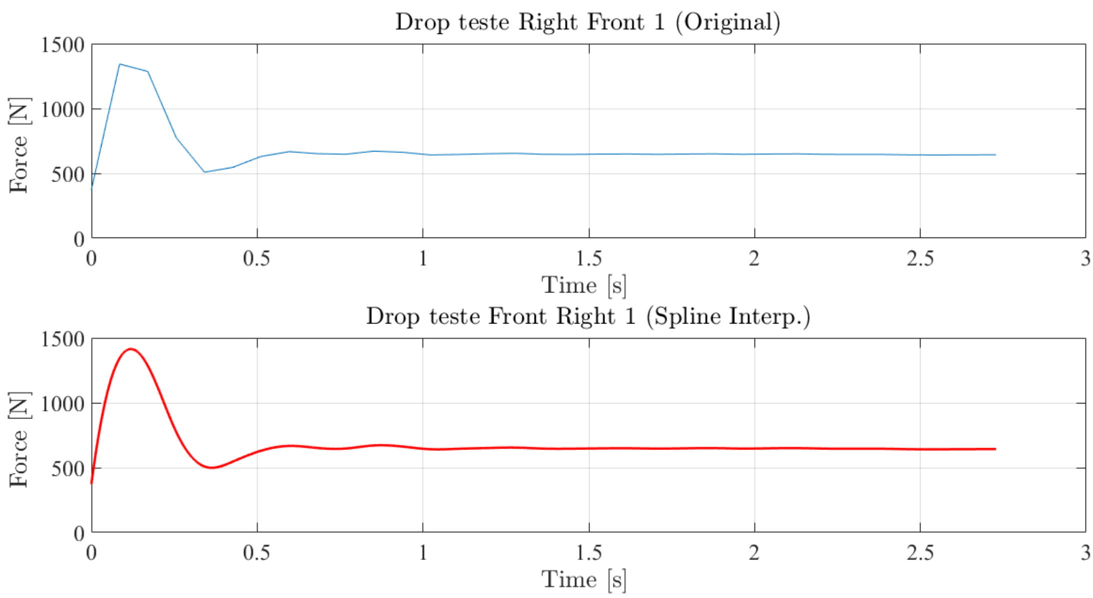

Figure 13. Curves of force x time in the first fall of the right front wheel

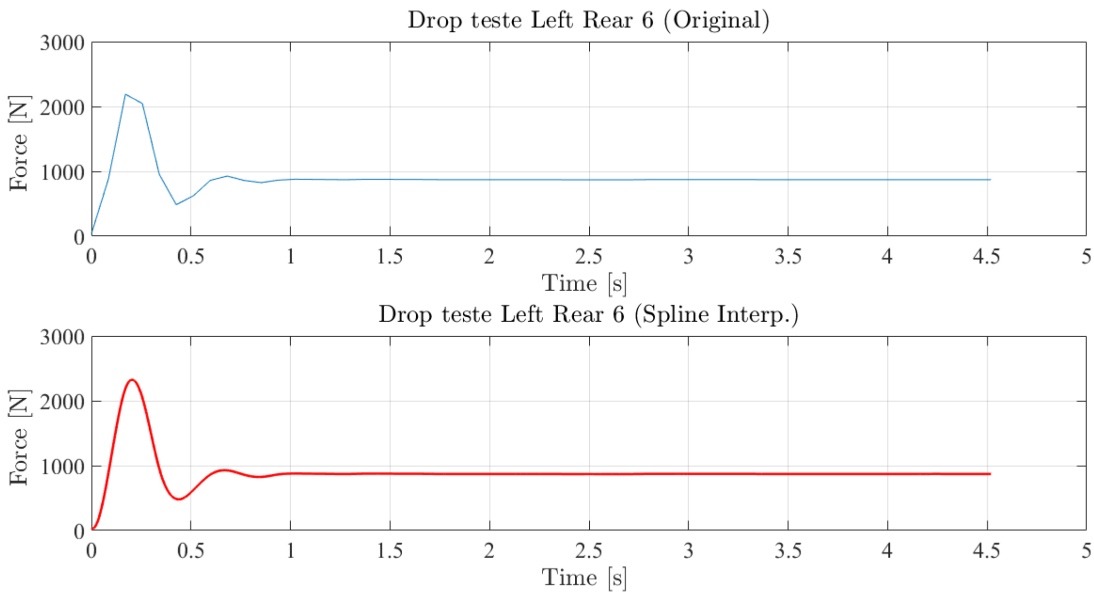

Figure 14. Curves of force x time in the sixth fall of the left rear wheel

The front and rear values are respectively 1534 N and 2087 N. Table 1 shows the tensions acting on components, their materials and reliability.

Table 1. Stress, materials and reliability of the suspension components of TEC Ilha BAJA team

Component	Old knuckle	New knuckle	Axle tip	Semi trailing-arm	Trailing-arm	Rear hub	Front hub	Old suspension arms	New suspension arms
Stress (MPa)	577	193	265	420	330	306	256	587	528
Material	Al 7075-T6	Al 7075-T6	AISI 8640	AISI 4130	AISI 4130	AISI 4340	Al 7075-T6	AISI 4130	AISI 4130
Safety factor	0.9	2.6	2.7	0.9	1.2	2.3	2	1	1.3

It is noted from Table 1 that the low safety factor referring to the old knuckle is due to the stress concentrators present in the geometry. The second, due to simpler geometry and de mass increase, was obtained a higher safety factor. For the axle tip and front and rear hubs, as there were no changes in the design, the comparison was not possible. In addition, the increasing in the safety factor of the trailing-arm was due to a change in the geometry, making it simpler and in the alteration of tubes, in the semi trailing-arm were used tubes of 1" of external diameter with 0.9mm of wall while in trailing-arm, ¾" with 1.25mm wall. In relation to the front suspension arms, the increase in the safety factor occurred due to the change in the lower point of the shock absorber with a steel sheet of 5mm base thickness to dissipate the impact energy.

4. CONCLUSIONS

Suspension is vital to the operation of any vehicle, especially off-roads due to obstacles they are submitted along their paths. There are multitudes of parameters that influence the dynamic and kinematic behavior of the vehicle, so each designer chooses its main variables by determining the values of others consequently.

The use of a compression load cell proved to be a valid alternative to collect the impact force values of the tire / ground contact acting on the vehicle in the 1m drop condition, height of the most critical ramp on the test track as well as in the competition. Another way of accomplishing the acquisition of boundary conditions would be the use of extensometers. For this, it would be necessary to move the vehicle to the team's test track what would require greater contingency of the team present in the test, could culminate in damage or failure of some component besides requiring the purchase of instruments that would be rarely used.

The calibration of the experimental apparatus with the use of washers is simple, and can be performed in the same place of the test instants before the execution of the same. Moreover, immediately after the fall of the vehicle, observing the collected values, it is possible to check if there was any inconsistency and several measurements can be taken, since hoisting the vehicle and realigning the wheel is done in a matter of minutes.

The described test was a more adequate methodology for the acquisition of the boundary conditions used in the simulations for vertical impacts than previous mathematical calculations that contained a series of simplifications. In addition, it is easily repeatable, which ensures more reliable data. That way, it was possible to use more accurate conditions, allowing a more adequate evaluation of the structural integrity of components. When analyzing the tension values as well as safety factor expressed in Table 1, it can be noticed that the new knuckle and the axis tip are oversized, two components being susceptible to structural modifications for future projects.

Acknowledgements: For the partnership UNESP - São Paulo State University “Júlio de Mesquita Filho” - Santander Bank, and Ilha Solteira Engineering Faculty for material and financial support and also the TEC Ilha BAJA SAE team for technical support and collaboration.

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6. RESPONSIBILITY NOTICE

The authors Mateus Coutinho de Moraes, Ana Caroline Garcia Feltrini de Souza and Miguel Ângelo Menezes are the only responsible for the printed material included in this paper.