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Project Methodology of a Baja SAE Chassis Based on Lateral Load Transfer

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Abstract - *Torsional stiffness relates the torsional deflection of the structure when subjected to a pure torque acting on the longitudinal axis of the vehicle. Thus, torsional stiffness is one of the main design criteria for a chassis. The problem of finding the best relationship between chassis stiffness, weight and cost is of great importance in the development of both high-performance cars and popular vehicles (cost and consumption efficiency). The influence of chassis torsional stiffness on kinematic and dynamic suspension behaviors is still poorly explore and there are few studies in the literature referring to this approach for BAJA SAE vehicles. Thus, this work seeks to evaluate the design methodology used in the chassis design of TEC Ilha BAJA team to be use in 2019 and 2020 by evaluating the addition of mass and influence on lateral load distribution.*

Keywords: *project methodology, torsional stiffness, lateral load distribution*

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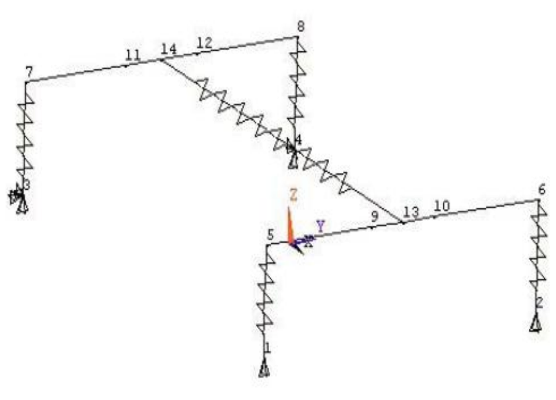
I. Introduction

Chassis is defined as the base structure of a motor vehicle on which it is built. It has the function of containing, supporting and connecting the other parts of the vehicle. Ideally, the first purpose of a car's chassis is to connect the four wheels with a rigid frame to both the bending and the twist by supporting all components and absorbing all loads without deflection. In addition, it must connect suspension systems, protect the pilot against accidents, transmit workloads and accommodate powertrain components, among other auxiliary systems. (Moraes et al, 2018).

The torsional stiffness of a chassis is a paramount information, as it relates to the vehicle's dynamic responses and is usually modeled by connecting the axles through a torsion spring. Increasing the torsional stiffness of a racecar's chassis optimizes handling, with the optimum adjustment being the one in which the rolling stiffness is only due to the suspension (Thompson et al, 1998). Factors such as drivability and vibration are critical, as a stiffer structure implies less vehicle deformation along the way. The problem is determining the best relationship between chassis rigidity, weight and cost, which is of great importance in both the development of high-performance cars and popular vehicles (cost efficiency and consumption).

The model of (Riley et al, 2002) deals with the determination of an ideal range of torsional stiffness. The chassis is modeled with infinite stiffness, in addition the stiffness coefficient of the springs, installation ratio and torsional stiffness of other suspension components such as stabilizer bars and knuckles are considered, thus obtaining an equivalent total stiffness, as shown in Figure 1.

Figure 1 – Representation of Riley & George's model



Reference: (Riley et al, 2002)

Then the chassis torsional stiffness varies so that only a percentage of the previously obtained stiffness is achieved. The literature, (Riley et al, 2002) and (Seward, 2014), recommends that the chassis should guarantee a total rigidity of the set between 80 and 90% of the extremely rigid case.

The torsional stiffness of a chassis can be measured in several ways. Each mode consists of the basic principle of securing one end of the chassis and applying a torsional moment to the other so that torsion occurs and is measured (Moraes et al., 2017). A typical test involves twisting the chassis, measuring its angular variation and then returning it to the starting point. To validate, the value obtained is compared to the stiffness of the structure calculated in an analytical model (Thompson et al., 1998). Thus, the torsional angle is measured for a respective torsional moment.

The force created when the car turns and the normal tire load has a nonlinear reaction. Increasing a lateral load applied to an axle decreases bending stiffness and influences handling. As normal load increases, an increase in lateral load is achieved, but this gain decreases as the normal component increases. Lateral load transfer is a function of the stiffness distribution for the sprung mass (rolling stiffness), unsprung mass as well as the position of the rolling axis.

The lateral load distribution is typically modified by changing the CG height or wheelbase to change wheel clearances or when you use wheel hub spacers. The load transfer has the contribution of the unsprung mass as well as the sprung mass which is subdivided into a portion related to lateral force and another related to the torsion angle (Danielsson et al, 2015). The unsprung mass includes unsupported components. suspension, such as wheels, bumpers and brake subsystem.

The lateral load distribution of the suspended mass is composed of a component of the lateral forces caused by the car's steering. They act on the rolling center (points where there is a coupling between forces acting on the sprung and unsprung mass) of each axle and these are determined by the suspension kinematics, so this part is known as the kinematic component.

The other fraction refers to the centrifugal force of inertia that generates a moment, causing the suspended mass to roll to the outside of the curve. When this happens, the outer spring of the suspension compresses while the inner part extends. Spring forces have a reaction, which is the elastic component of the load distribution. As the chassis rolls, the center of gravity of the suspended mass is shifted to the side, creating a moment that increases lateral load transfer.

The torque that the suspension makes when the body rolls trying to return it to its original position at the vehicle's angle of rotation around a longitudinal axis defines the rolling stiffness. This factor is directly related to weight distribution and its adjustment can be made using stabilizer bars. The terms that influence the lateral load transfer distribution are the fraction of the rolling time (rolling moment) generated by the suspended mass and front axle strength, force applied to the axle in addition to the effect of the unsprung mass.

For models that take into account chassis torsional stiffness, this is approached as a torsion spring. It is coupled in series with the rolling resistance of the front and rear axles (Sampò, 1991). According to (Milliken, 1995), when comparing the rolling stiffness of the front and rear axles with the torsional stiffness of the chassis, it must resist approximately the difference between the distribution rates between the front and rear rotation rates. However, studies that are more recent have shown that there is a proportionality between suspension roll stiffness and chassis torsional stiffness, a multiple number that varies with each design (Deakin et al, 2000).

II. Methodology

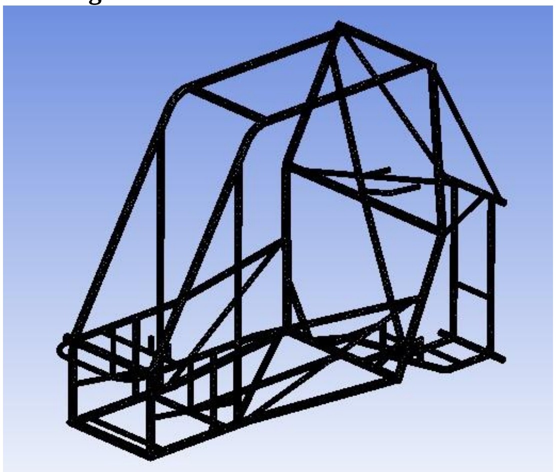
Finite element simulations are performed using the Ansys software provided by ESSS and the equations that will allow the study were implemented in Octave.

For the analyzes performed on the prototype chassis, shell elements are generally used for tube modeling to obtain a uniform mesh and facilitate geometry processing during simulation. In the process of converting geometry to shell, the thickness of the pipes is defined (wall). The mesh used was generated using Relevance Factor 50 and the Proximity and Curvature function to define the size of the mesh elements resulting in distinct node and element values for each of the chassis models. Figure 2 represents the mesh of the final chassis drawing and Table 1 contains the mechanical properties of SAE 4130 steel pipe material.

Table 1 - Mechanical Properties of SAE 4130 Steel

Property	Value
Density	7,850 Kg/m3
Young's modulus	205 GPa
Poisson's ratio	0.285
Tensile yield strength	552 MPa
Tensile ultimate strength	731 MPa

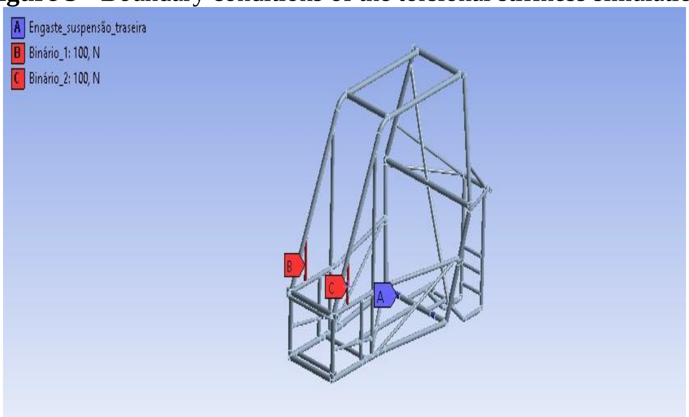
Figure 2 - Finite element chassis model



Reference: Authors, 2019.

First will be determined the torsional stiffness of each configuration. The boundary conditions are shown in Figure 3.

Figure 3 - Boundary conditions of the torsional stiffness simulation



Reference: Authors, 2019.

The chassis is embedding to rear suspension points and a torque of forces is applied to the front shock absorber points. Next, the lateral load distribution will be evaluated by comparing the error between models that consider the chassis with infinite torsional stiffness (Milliken, 1995) and what considers each chassis torsional stiffness (Sampò, 1991).

The mass variation along with the modeling error is evaluated considering the chassis torsional stiffness to estimate the lateral load distribution, seeking a configuration that allows the suspension to work correctly (having a minimally rigid structure).

Measurements were made using the "Directional Deformation" tool in the X and Y directions, varying the force from 100N to 1,000N. With the simulation results, a Torque x Angular Deformation graph was constructed.

Torque and angular deformation were calculated as follows:

$$T = F\,L \qquad (1)$$

Besides that:

$$\theta = \frac{\tan^{-1}(|y_{max}| + |y_{min}|)}{180\ L/\pi} \qquad (2)$$

Which:

T: Torque [Nm]; L: Distance between the two applied forces [m]; θ: angular strain [°], y_{max}: maximum strain in Y direction [m] and y_{min}: minimum strain in Y direction [m].

(Deakin et al., 2000) inspired the methodology used to obtain the curve: frontal lateral load transfer as percentage of total lateral load transfer x frontal roll stiffness as percentage total roll stiffness. Initially, the values of the directional deformations obtained through the simulations are entered for each chassis model. Then the rolling stiffness of the suspension is calculated considering the springs, stabilizer bar and the tires. The same procedure applies to the rear suspension, calculating the rolling stiffness of the shock absorber springs and stabilizer bars, such as the rolling caused by the tires and finally the total rolling stiffness of the car. In order to calculate the load transfer, it is necessary to inform a set of data related must be entered: the mass on the front and rear axle, the lateral acceleration as well as the height of the center of gravity.

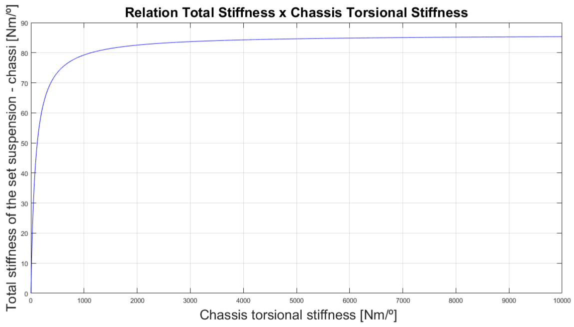
To plot the curve described in this methodology, the roll stiffness distribution on the front axle ranges from 5% to 5%. The rear roll value, the front, chassis and rear torsional angles as well as the new lateral load distribution on the front axle are calculated simultaneously. The literature contains a series of equations that allow estimating lateral load transfer without considering the torsional stiffness of the chassis. So the ideal distribution was based on (Milliken, 1995).

III. Results And Discussions

For the chassis to be used in 2019 and 2020, a 20% mass reduction target was set against the previously used prototype, which had a mass of 31.75 kg. Thus, a maximum of 25.4 kg was sought and the torsional stiffness was expected to result in a maximum difference of 8% in lateral load distribution between the model that considers the infinitely rigid chassis and what estimates this magnitude considering the torsional stiffness.

With the knowledge of the vertical spring stiffness as well as the vehicle installation ratio it was possible to calculate the equivalent stiffness of the set which resulted in 135 Nm / °. Thus, the chassis must ensure equivalent rigidity between 108 and 121.5 Nm / °. Figure 4 contains the representative curve of the Riley & George model for the TEC Ilha Baja 2019-2020 project, which to follow the literature recommendations must have a torsional stiffness between 550 and 1,200 Nm / °.

Figure 4 – Curve representative of Riley & George's model for TEC Ilha Baja 2019-2020 chassis



Fonte: Autores, 2019.

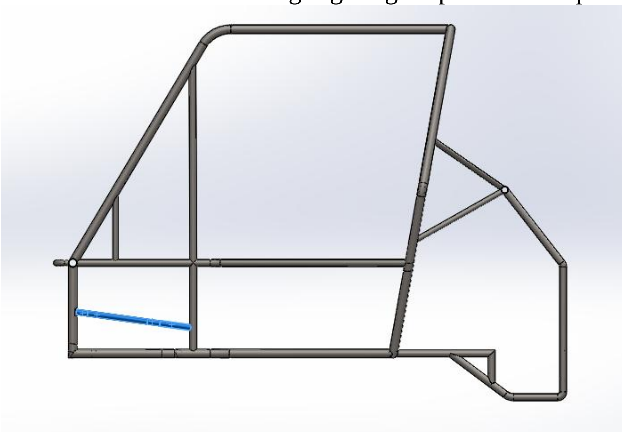
3.1 – Analysis of lateral load distribution

Initially the two permissible floor arrangements by the regulation were analyzed. The first resulted in an initial chassis mass of 23.8 kg, while the second 24.23 kg. It was opted for the first because of the mass as well as this configuration also facilitate the construction of the prototype.

The first four models sought to evaluating not only the torsional stiffness but also the stress distribution at the suspension connection points with the chassis. Images 5-9 contain the analyzed settings. At first, there is only one ¾" outer diameter tube with 1.47 millimeters wall attaching the upper points of the suspension arms. However, the acting stress resulted in a safety factor of 0.73.

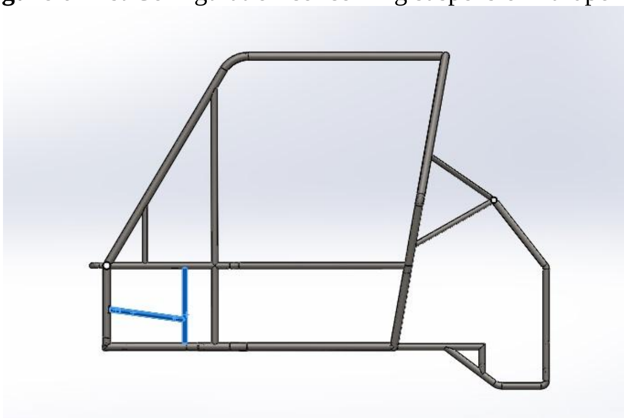
Thus, configurations were tested by adding a 1" outer diameter pipe with 0.9 mm wall, varying angles and layouts. Mass and torsional stiffness results are shown in Table 2.

Figure 5 - Initial model side view highlighting suspension hardpoint brackets



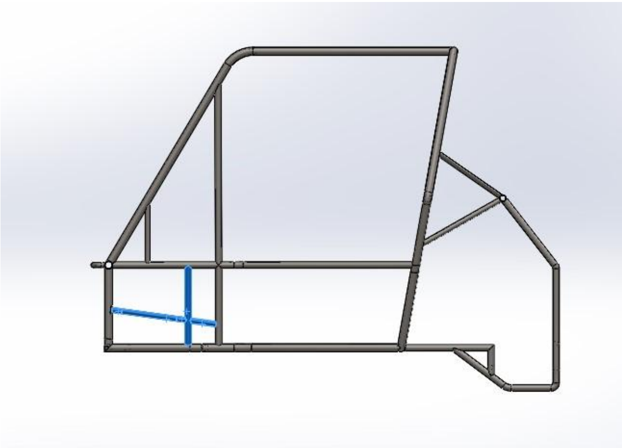
Reference: Authors, 2019.

Figure 6 - 1st Configuration concerning suspension hardpoints



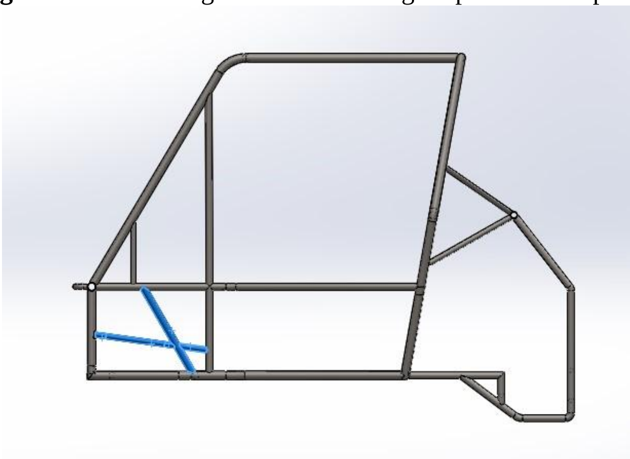
Reference: Authors, 2019.

Figure 7 – 2nd Configuration concerning suspension hardpoints



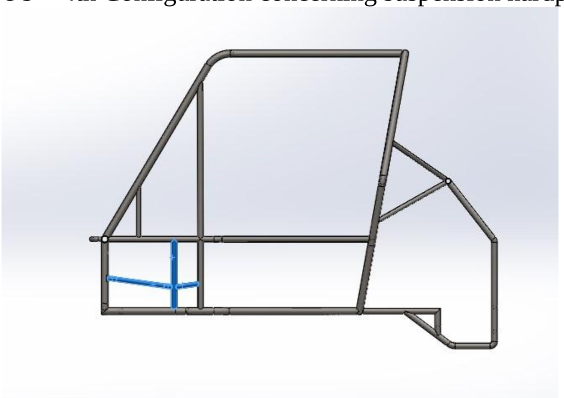
Reference: Authors, 2019.

Figure 8 – 3rd Configuration concerning suspension hardpoints



Reference: Authors, 2019.

Figure 9 – 4th Configuration concerning suspension hardpoints



Reference: Authors, 2019.

Table 2 - Results analysis related to suspension locking's.

Description	**Mass(kg)**	**Torsional stiffness (Nm/º)**
Initial model	23.8	578.25
1st configuration	24.02	583.53
2nd configuration	24.13	596.31
3rd configuration	24.16	365.19
4th configuration	24.48	595.1

There was no significant change in mass, torsional stiffness and lateral load distribution at this stage and stress distribution was the most relevant criterion. Thus, we opted for the 2nd configuration. Next, the roof locking possibilities were evaluated.

Table 3 - Results analysis related to roof locking.

Description	**Mass(kg)**	**Torsional stiffness (Nm/º)**
Diagonal	24.61	627.93
Transverse	24.38	610.86
X	25.08	651.94

Continuing, the locks were evaluated in the lateral region of the project.
The diagonal locking showed the best results, resulting in a 3.3% increase in mass, torsional stiffness of 7.9% and lateral load distribution error from 9.1% to 8.5%. So, it was initially added.

Table 5 - Results analysis related to lateral locking.

Description	**Mass(kg)**	**Torsional stiffness (Nm/º)**
Diagonal	25.08	1,168.4

V	25.22	1,253.93
X	25.87	1,226.19
Vertical	25.31	727.54

Increases in torsional stiffness were most significant in this region and the choice consisted of diagonal locking connecting the SIM to the LFS. With it, there was a 5.1% increase in vehicle mass, but the torsional stiffness increased by 102% and the lateral load distribution error decreased to 7%.

The next step was to evaluate the locks at the rear of the vehicle. About ten configurations have been verified, varying not only the locking configurations in relation to the torsional stiffness, but also to ensure the structural integrity of the chassis, as this region is subject to constant engine stress as well as CVT shifting and the elements of motion transmission.

Table 4 - Analysis results related to rear locks.

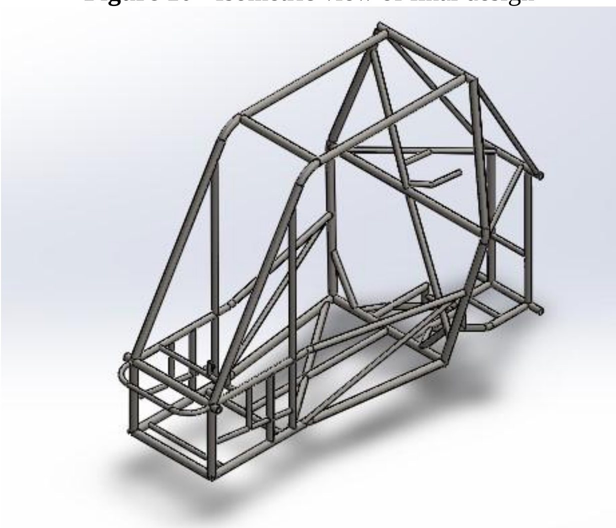
Description	Mass(kg)	Torsional stiffness (Nm/º)
Fitting adaptation	24.98	1,168.7
Fitting adaptation 2	25.22	1,186.6
Fitting adaptation 3	25.24	1,183.7
Angle lower tubes 10º	25.35	1,169.03
Diagonal locking engine support	25.54	1,172.5
Diagonal locking cradle	25.55	1,170.2
Angle upper tubes 25º	25.38	1,170.05
Angle upper tubes 30º	25.42	1,169.21
Rear discontinuous locking	25.82	1,175.41
Rear continuous locking	25.97	1,177.53

No locking was added to this region, since stiffness increases and improvement in lateral load distribution were not significant. The final configuration has an angulation at the top of 25 °.

3.2 – Selection of the final design

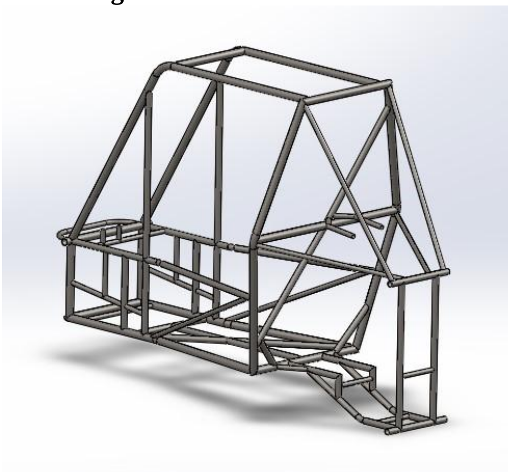
The locking between SIM and LFS allows a clear improvement in the vehicle's dynamic and kinematic performance. However, further analysis was required to evaluate whether combining this locking with the roof would result in a significant improvement in vehicle performance. The increase in torsional stiffness was 9.6% and the error minimization of 7% increased to 6.9%. Thus, the addition of 2% mass (0.48 kg) proved unnecessary, opting only for locking on the side of the vehicle. Figures 10, 11, 12 and 13, they contain the views of the final drawings.

Figure 10 - Isometric view of final design



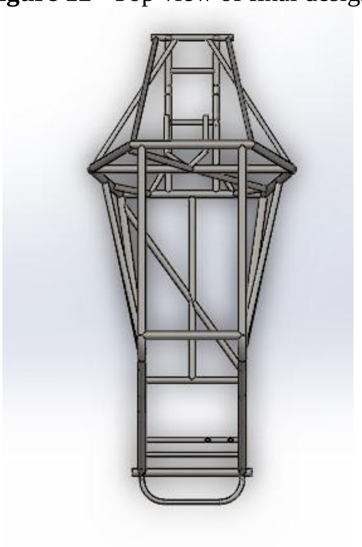
Reference: Authors, 2019.

Figure 11 - Isometric rear view



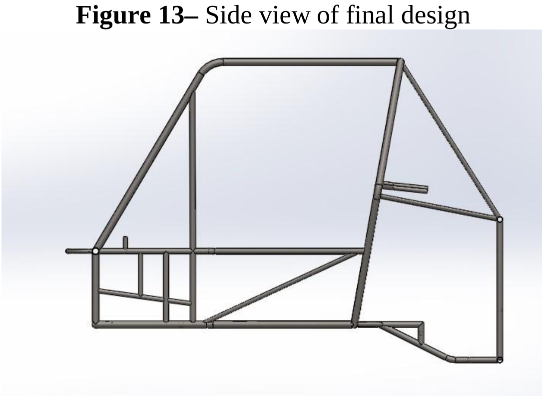
Reference: Authors, 2019.

Figure 12– Top view of final design



Reference: Authors, 2019.

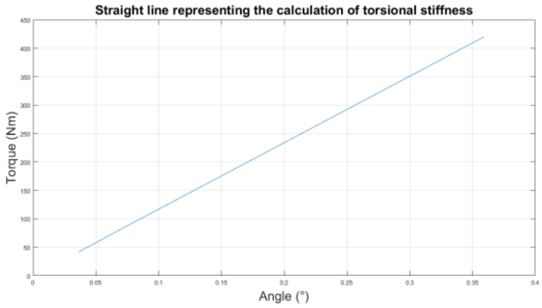
Figure 13– Side view of final design



Reference: Authors, 2019.

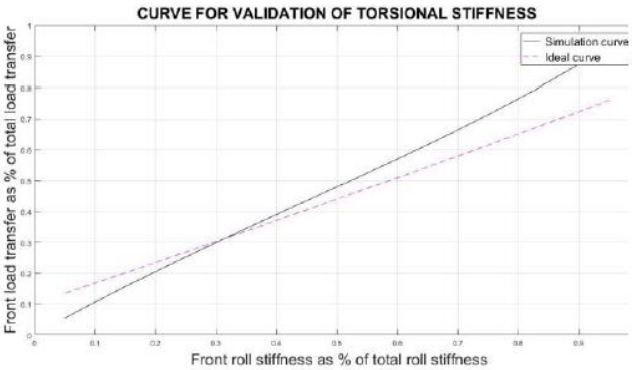
The figure 14 contains the straight line Torque x Angle, whose linear coefficient is the chassis torsional stiffness, and Figure 15 contains the lateral load transfer curve as % of total lateral load transfer x frontal roll stiffness as % of total roll stiffness, as (Deakin, 2000), which uses the concepts already mentioned in the methodology.

Figure 14 - Representative line of the torsional stiffness calculation



Reference: Authors, 2019.

Figure 15 - Frontal lateral load transfer as % of total lateral load transfer x Frontal roll stiffness as % of full roll stiffness



Reference: Authors, 2019.

IV. Conclusion

The final chassis configuration has a mass of 25.4 kg reaching the target of 20% mass reduction previously established of this subsystem and its torsional stiffness of 1,169.03 Nm / ° allowed the load distribution error to decrease from 9% to 7.1%. This allowed the chassis to become a stiffer platform for working not only of the suspension but also for the other subsystems of the vehicle. Therefore, the evaluation of this parameter contributes positively to the prototype performance.

There are still few studies on the relationship of chassis torsional stiffness and suspension rolling stiffness, but it is agreed that each car has its ideal relationship. Recent studies have concluded that there is a direct proportion between these quantities and not between the suspension rolling difference and chassis torsional stiffness, as in (Milliken, 1995). For the suspension design used between 2019 and 2020 by the TEC Ilha Baja team, a chassis with torsional stiffness approximately 2 times greater than the rolling stiffness of the suspension would make the lateral load distribution very close to ideal.

The calculation of torsional stiffness is an important design parameter and the objective of this paper is to present a new methodology for chassis design developed that was used by TEC Ilha Baja team. The development of a mathematical model to evaluate how torsional stiffness influences lateral load distribution is another tool to evaluate the impact of adding new locking's to vehicle performance in relation to lateral dynamics and mass. This is an initial model, containing a number of simplifications, so its development needs to be continued.

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