Formula Student car chassis – research on the torsional stiffness

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Abstract. In the article, the torsional stiffness of a formula student's space frame was analyzed. The article mainly focuses on the comparison of the stiffness between different frame designs, which were used in three consecutive formula student cars designed by the weracing™ team as well as a comparison of the result of two calculation methods. The calculations were made in computer-aided engineering software, i.e. ABAQUS dedicated to analyzing Finite Elements models. The assumption for analysis was to check the rotation of the frame after applying a 5000 Nm load. The torsional load was introduced by first fixed the four rear bulkhead joint and then subsequently applying a force couple to the upper front wishbone mounts. Having a distance between joint from the central line and torque moment, the force for specific nodes can be calculated. The calculation for each model was performed. The obtained differences result from the construction of frames and applied methods of calculations.

1 Introduction

In the field of vehicle engineering, especially in the context of sports car design, investigating the torsional stiffness of the frame plays a crucial role in ensuring excellent control and safety under extreme operating conditions. Buggies, racing cars, and other sports vehicles require an optimized frame design that guarantees both precise handling during cornering and minimizes deformations under the influence of forces during dynamic driving.

In the many research of racing vehicles, torsional stiffness of the chassis plays a crucial role, ensuring precise steering and stability during extreme driving conditions [1-7]. While torsional stiffness is the predominant factor, vibrations also impact the vehicle's behavior. Past studies on the influence of vibrations on vehicle construction have shown that, although they may be less significant than torsional stiffness, they can still affect the overall performance of the vehicle. In [8] AFSV (articulated frame-steered vehicle) and HPS (hydro-pneumatic suspension) were applied in the research on the torsional stiffness of the vehicle within the context of a three-dimensional dynamic model. The study included an analysis of the influence of HPS parameters on the steering behavior of AFSV, encompassing directional stability and ride comfort, which was crucial for optimizing the vehicle's design in terms of torsional stiffness.

Some researchers [9] have focused their research on the impact of vibrations on racing vehicles. Their work has included analyzing how vibrations can affect the dynamic parameters of the vehicle and how to minimize the negative effects of these vibrations on performance and driving comfort. An important aspect is also the distribution of forces in the chassis during braking [10]. Thus, while torsional stiffness remains a crucial element, understanding and controlling vibrations constitute an additional area of research aimed at optimizing the overall construction of a racing vehicle. In the construction of vehicles of this type, reverse engineering is often employed [11]. Applications for investigating the torsional stiffness of frames also extend to increasing accessibility for people with disabilities by creating solutions for three-wheeled vehicles that they can maneuver more efficiently than wheelchairs [12].

The article presents simulation-based studies on the torsional stiffness chassis of three successive Formula Student vehicles generations designed by the whiteEagle Racing team. Numerical simulation studies of the structural models, developed using the finite element method, were conducted on models created with beam elements in the HyperMesh preprocessor, and calculations were performed using the ABAQUS solver.

1.1 Formula Student

Formula Student is a design competition aimed at students from technical universities worldwide. The task for students is to design and build a racing car and then participate in competitions with other teams. Students undertaking the Formula Student project must imagine that they have been hired by an automotive company to design a prototype of an affordable racing car for weekend driving. The competition consists of two parts, static and dynamic. During the first part, students must present their product to the judges. They are evaluated on cost, innovation, and presentation skills. In the dynamic part of the competition, the acceleration of the vehicle, its manoeuvrability, fuel consumption, and reliability are assessed. The competitions take place worldwide, on prestigious racing tracks. The whiteEagle Racing team has twice participated in competitions in England held at the Silverstone circuit.

Fig. 1. The Race Car and Drivers of the whiteEagle Racing Team.

1.2 The chassis of the Formula Student race car

The main task of the supporting structure of the Formula SAE car is to ensure the driver's safety. The spatial frame of the car influences both active safety, by ensuring a relatively constant position of the suspension mounting points, and passive safety, by providing the proper structural strength. The spatial supporting structure of the vehicle allows for seamless mounting of essential vehicle components. Furthermore, the car frame bears all external loads acting on the vehicle.

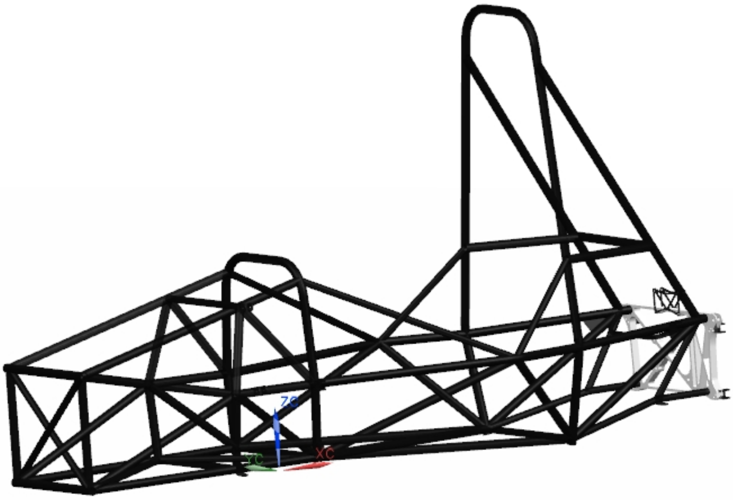

Fig. 2. The frame model designed by the WhiteEagle Racing team.

The support structure of each Formula SAE vehicle must be designed in accordance with the regulations, specifying the diameters and thicknesses of most tubes. The frame must consist of a minimum of elements as detailed in the illustration Fig. 3.

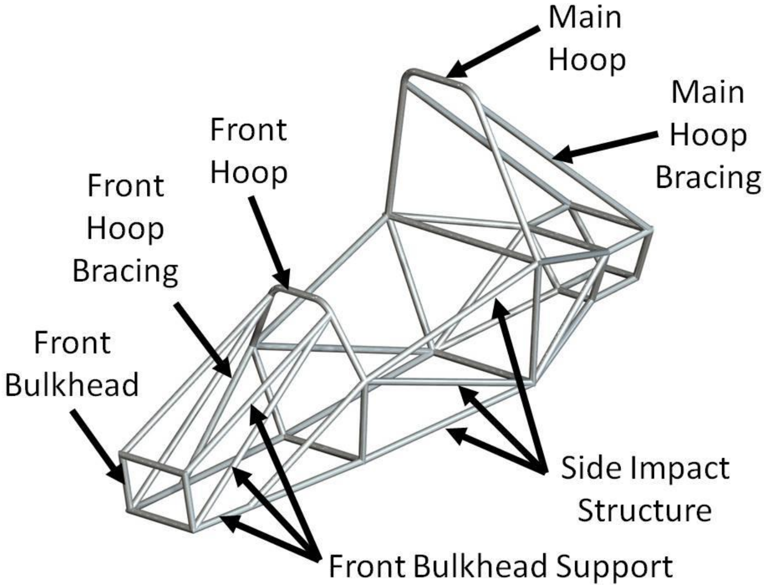

Fig. 3. A reference design of the car frame with specification of elements required by the competition regulations.

Torsional stiffness is defined as the ratio of the twisting moment of the frame to the corresponding angle of twist according to formula (1).

$$k_{\varphi} = \frac{M_s}{\varphi} \tag{1}$$

The frame must exhibit sufficiently high torsional stiffness so that its interaction with the suspension ensures maintaining contact of all wheels with the road surface. The suspension is designed assuming that the frame is an ideally rigid body. Therefore, situations where frame deformations have a noticeable impact on the suspension kinematics should be avoided.

2 Simulations

2.1 Determining the torsional moment acting on the frame

The torsional moment arises when there are reactions of different magnitudes in the wheels of one axle. In the extreme case, the difference in these reactions is equal to the total reaction of that axle, which is synonymous with lifting one of the wheels off the road surface.

Assuming an equal distribution of loads on both axles, a vehicle mass of 250 kg, and a front wheel track of 1650 mm, we can easily calculate the torsional moment (2) of the frame.

$$\mathrm{M_s} = \frac{1650}{2} \cdot \frac{\mathrm{m} \cdot \mathrm{g}}{2} \approx 1000[Nm] \tag{2}$$

The obtained torsional moment illustrates the static load acting on the race car. In reality, during driving, there are also dynamic loads that need to be taken into account by introducing an appropriate coefficient. In this case, the following (3) dynamic coefficient has been adopted.

$$n_s=2 \tag{3}$$

Assuming a safety factor m=2, the maximum moment acting on the vehicle has been calculated (4).

$$\mathrm{M_s} = 1000 \cdot \mathrm{n_s} \cdot \mathrm{m} = 5000[Nm] \tag{4}$$

Therefore, since the goal of the study is to compare the torsional stiffness of individual designs, it was decided to use the same load for all examined support structures.

2.2 Finite Elements simulation

To conduct a finite element analysis, it was necessary to prepare a discretized model and then apply boundary conditions appropriate to the considered situation. A linear-elastic analysis was performed using the ABAQUS program. The models were entirely made up of beam elements with a length of 5 mm. The frame was fixed at the rear axle, meaning that three degrees of freedom of the mounting points of the rear suspension were restrained. The forces intended to generate the torsional moment (4) were applied at the mounting points of the front upper suspension arms. The analysis was carried out for three designs.

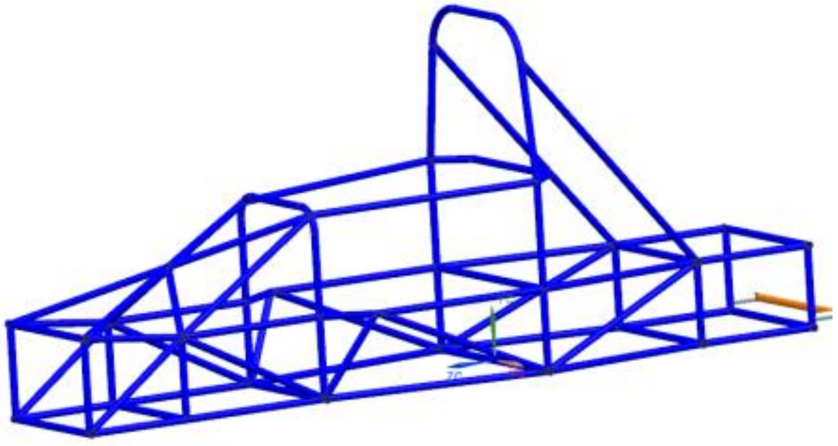

Fig. 4. The first model of the frame built by the WhiteEagle Racing team.

To determine the angle of frame twist, the displacement of a node at the point where the force was applied was recorded. Knowing the displacement and the distance between the suspension mounting point and the axis of the frame, the angle of frame twist was calculated using basic mathematical relationships. By dividing the value of the torsional moment (4) by the angle of frame twist, the torsional stiffness of the respective frames was calculated. Figures 4 and 5 show the results of torsional stiffness and the mass of the individual designs.

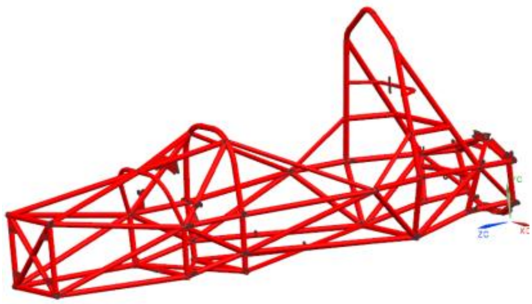

Fig. 5. The second model of the frame built by the WhiteEagle Racing team.

Table 1. Comparison of parameters characterizing spatial frame designs for Formula Student race cars.

Project number	Vehicle curb weight [kg]	Frame weight [kg]	Torsional stiffness [Nm/°]
1	362	40	1740
2	242	37	2652
3	220	32	2392

3. Results and discussion

Formula Student cars, like all racing vehicles, should be characterized by relatively high body structure stiffness. Vehicles participating in Formula SAE competitions typically have stiffness in the range of 1400-3400 Nm/°. The torsional stiffness of all frames designed by the WhiteEagle Racing team falls within the mentioned range. Subsequent designs differ in weight and torsional stiffness. The natural evolution involves striving for maximum torsional stiffness with minimal frame weight. As illustrated by the above results, the team designs progressively lighter structures each year while maintaining high torsional stiffness.

It should be expected that simulation study results may deviate from real-world performance. To verify the calculated simulated values of designed spatial frames' parameters, a setup for experimental torsional stiffness testing of Formula Student car frames will be constructed during the "Generation of the Future" project.

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