DESIGN AND ANALYSIS OF FORMULA STUDENT FRAME

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Abstract: *The entire process of designing the frame of Formula student for Student formula team "FIN Racing team" from University of Kragujevac, is in several stages presented from the perspective of industrial design. Formula student is a small racing car, based on construction of the Formula One. Due to security issues, there is a number of regulations that must be respected in the construction and design of this Formula vehicle. The frame is designed in the "CATIA" software , in which the structural analysis of the load using the finite element method is performed. Based on facted analysis, optimal conception of fame is suggested.*
Keywords: *design, frame chassis, Formula student.*

1. INTRODUCTION

Industrial design is creative activity, which goal is to define the formal quality of industrial produced products. This formal qualities contain outside shape, but they especially refer to structural and functional elements, and relations beetwen them, which one system make into the whole assembly [1]. The most important factors of industrial design in mechanical engineering, which directly affect to final product are: function, purpose, structure, type of manufacturing and technologically, size, mass, kind of material, ergonomic requests, security, functional safety, aesthetic requests in type of shape, color and visual comunication, number of products, delivery deadline, planed quality, durability. Some of these factors are contained in case of the design of Formula student frame, which is the main task of this paper.

1.1 Basic consideration of vehicle Formula Sudent

SAE - Society of Automotive Engineers has started the international competition, more than three deceny ago, where students from the technical faculties all around the world, represent their Univesities in specific way – to make the bolids based on Formula One design. The main goal of competition is to apply the asquired knowledge in practice, so the young people can gain specific kind of training and experience, which will prepare them for future profession. Student teams have the special task to design, build and test the prototypes of vehicles. Due to security issues, there is a number of regulations that must be respected in the construction and design of the formula, in order to gain the permit for competition. The biggest limitation (from regulations) means that team must use the powertrain with maximum value of 600 cm^3. Reducing the intake manifold to 22 mm is the second biggest limitation. The selection of the outside dimensions and shape and their compatibility with all systems is very important not only for aesthetic but for better perfomance of vehicle (aerodynamic, stability control, speed and acceleration).

1.2 Metodology of designing process

Before the process of design of Formula sudent had started, the science and profession papers were analysing, which is written on this topic. In the paper [2] the methode of manufacturing Formula student frame is described. When the frame had made physicaly, experimental test of torsional stiffness was done, and then the precision value of torsional stiffness is determined . The paper [3] based on previously refference and contain the comparation between numerical method of analysis with final elements (FEM anlysis) and experimentally method of defining the torsional stiffness. In paper [4] dynamic frequency analysis of frame is done. Also, the principe of manufacturing frame using clamping tools, which are made of wood, is shown.

The researching enabled detail overview for all aspects of analysis of this kind of product, and therefore collecting the most of necessary information. It was necessary to examine the way to access to the designing space frame, all important factors which are important for design process and their priorities [5]. Design process begins with idea to develop the new product, and it ends with tested prototype. The mechanical designer meets with different problems in design process. It is necessary to go through several successive, clearly defined phases, in order to reach the optimum designing solutions to set up a technical task. The main phases of design process are: elaboration of given task, conceiving the frame construction, forming the constrction, optimisation and detailed designing [6].

2. ELABORATION OF TASK AND DEFINITION OF REQUESTS

2.1 Consideration of Formula Student frame

The frame of vehicle is very important part, and, until design process of vehicles, it paid special attention, because it is loaded with very high loads (static and dynamic). Projecting and manufacturing represent big challenge, because many factors affect on its final version. Space frame (which is the most used kind of frame in Formula student vehicles) represent very complex tubular truss construction, on which we can notice, separate and define its main elements, which are shown on Figure 1.

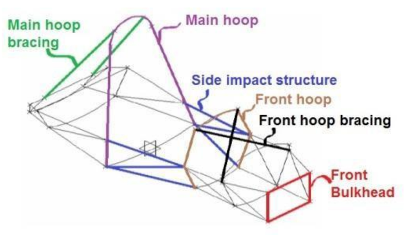

***Figure 1 -** Main elements of frame* [3]

Engineering development of designing frame is based on the method of connecting thin-wall tubes in knots. Accordingly, the schedule of elements (tubes) is very important, but their method of connecting in knots is important too.

2.2 Specification of limitations

Many factors affect on frame desing, to a lesser or greater extent. It is completly impossible to apsolutely satisfy all requests, so first it must determine the priority of all the influencing factors. Main goal for mechanical designer is to design the frame in order to satisfy all the pre-defined requests, but the final design of frame must have as much as possible low mass, and high strength. Also, it is tendency for vehicle to have as much as possibly better performance, which are the most depend of geometry of final frame. Below in this paper, the main factors which affect on frame design process will be described.

Minimal mass is most important request. The main tendency is for complete vehicle to

have as much as possible low mass, and therefore every element or system on formula vehicle must have the lowest possible mass. According to researching of other world

Formula student teams, the request for minimal mass of frame constrction will be set to 35 kg.

Strength is very complex request, which demand detail researching in area of mechanics and material resistance. Main indicator for strength of frame construction is test of torsional stiffness, which is shown on Figure 2, because the frame is most critical when torsion stress is applied, caused by inertial forces during the cornering on the track. Torsional stiffness is skill, that frame can resist to load, which appear during the apply of moment of torsion.

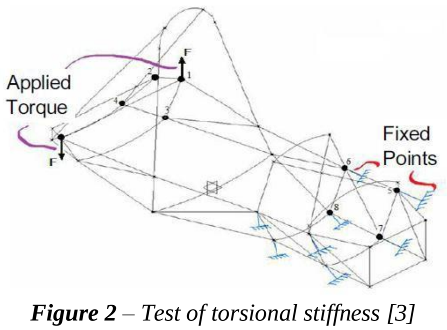

***Figure 2** – Test of torsional stiffness [3]*

It is defined as relation between moment of torsion and angle of torsion. Based on researching of practise expirience in world, the minimal request of torsiona stiffness for frame is 1500 Nm/° [3].

Proposition for Formula student competition is official document which consists of the set of rules, that students must follow in order to design and manufacture vehicle Formula student. The rules contain a request about geometry, cross section of tube, material for tubes, security rules and other simulary requests [6]. The tubes for frame are defined with outside dimater of 25 mm, and with three different thickness: 1.5 mm, 1.8 mm and 2.5 mm.

Aerodynamic. For this request, it is main tast to set up outside shape and geometry of frame, in order for better airflow and achievement better aerodynamic properties. Main tendency is to make an ideal aerodynamic shape for frame, which is populary called the „shape of tear".

Space limitation is factor, which has very big influence on frame design. It is necessary to determine all outside dimensions of all systems and elements, and preliminary plan their schedule and positions, in order to have more efficiency conception of frame construction. One of the space limitations is the position of driver inside the vehicle (Figure 3).

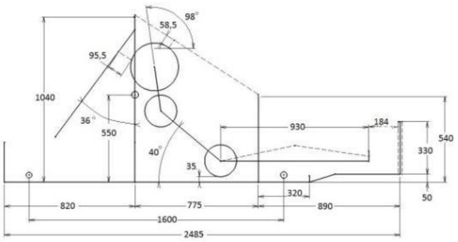

Figure 3 - *Sketch of driver position* [7]

The other factors, which affect final design of frame, are: technologically, ergonomy, installating and dismantling, the work conditions, low brunt height and aesthetics.

3. DESIGN PROCESS OF FRAME

3.1 Conceiving of frame construction

The first step in development process of preliminary variant of frame is to design and position basic roll hoops of frame, based on driver ergonomy and determined wheelbase (Figure 4). Based on limitations from propositions, it is necessary to plan in detail whole conception of vehicle, because it partially conditions all other systems. The wheelbase and geometry of connection for suspension system are set [7].

Figure 4 - *Positioning of basic roll hoops* [7]

According to geometry of suspension system, clearance of vehicle Formula student (vertical distance measured between the lowest point of vehicle and ground) will be between 35 mm and 45 mm. Accordingly, elements of side impact structure will be designed (Figure 5).

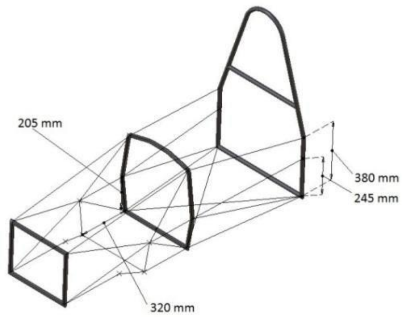

Figure 5 - *Design sketch of side frame elements* [7]

The next phase in design process of frame is conceiving back frame part (Figure 6), which is located behind the driver, where is situated a powertrain of vehicle Formula student.

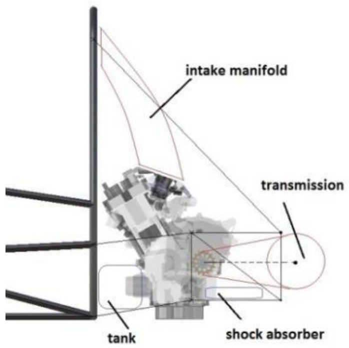

Figure 6 - *Sketch - conceiving back frame part* [7]

This part of frame is the most complex part of frame, because many factors and space limitations, which are not predicted at all, affect on it. In back part of frame are located engine with gearbox, intake system, exhaust system, fuel supply system, rear suspension system and transmission.

3.2 Reconstruction of back frame part

According to this redistribution of back suspension system (due to bad evaluation), the geometry of back frame part will be changed as much as necessary. Based on detail analysis of space, design of bracing for main roll hoop will be changed, and partially design of back roll hoop. All other elements in this part of frame won't be changed. The main idea is to form the construction, which contains together one point on frame for fixing the engine, and connect bracing for main roll hoop and back roll hoop (Figure 7).

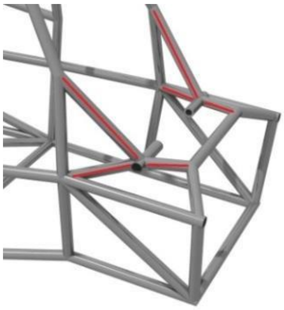

Figure 7 - *Reconstructed back part* [7]

3.3 Preliminary variant

On Figure 8 reconstructed preliminary varinat is shown, which completely satisfies all pre-defined requests from the list of requests currently [7].

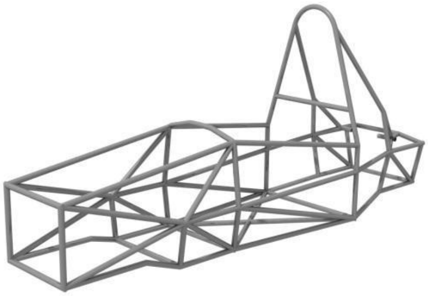

Figure 8 -*Preliminary variant* [7]

The information of preliminary variant of frame construction are obtained from software package „CATIA“, and they are shown in tabel 1 bellow.

Table 1. *Information for preliminary variant of frame construction* [7]

Criterion	**Value**
Brunt height	268,41 mm
Mass redistribution	48% - 52%
Frame mass	31,36 kg
Frame lenght	2320 mm
Frame width	645 mm
Frame height	1065 mm

4. ANALYSIS OF THE LOADS

Frame, as a main construction of any vehicle, has one of the functions to absorb and transfer all the loads, which are applied on vehicle. The loads, which are applied to frame, can be classified in this way: the weights of all elements and systems of vehicle, resistant forces during the motion of vehicle, force caused by driver weight, intertial dynamic forces, which are applied during the motion of vehicle, forces caused by steering, forces caused by braking and accelerating, impact forces [8]. Static loads are caused by: weight of engine, transmission and body, and all other system which are connected to frame, and alos by driver weight (Figure 9). Their forces intensity for static load are equal to:

$$F_S = m \cdot g \text{ [N]}$$

Dynamic loads are caused by forces and moments, which are applied during the motion of vehicle – inertial forces and moments, and their intensity is equal to:

$$F_i = m \cdot a \text{ [N]}$$

After detailed theoretical and experimental analysis, and classification of all loads which are applied to frame of vehicle, it can be concluded that the most critical load is centrifugal force. Centrifugal force applies in cornering, and it stresses the frame mostly with torsioanl moment, which can reach up to 800 Nm [3].

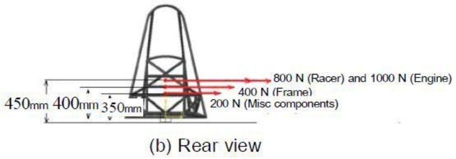

Figure 9 - *Scheme* of *frame loads* [3]

4.1 Computer analysis of the loads

Analysis of the loads will be done using the Finite element methode in software package „CATIA". Finite element method – FEM analysis represent the numerical method for structural analysis, which is used for gaining approximation results for wide range of engineering problems [9]. Test of torsioanl stiffness, which represents simulation of frame torsion, will be done. Torsional stiffnes is considered as the most important test, because it simulates torsion on the back part of the frame during the braking, accelerating and cornering, when the biggest loads and displacements (deformations) are applied. The test principle is shown on Figure 2, where the front part of frame is fixed with stacionary bracing, and the forces which are appeared due to inertial centrifugal force (*F*=1800 N) are applied to the back part of the frame, is shown on Figure 2. Frame is also loaded with static forces, with real distribution. Results of displacement (deformation) are shown on Figure 10, with diferent colors. Chosen material for the frame is strucutural steel *S355 j2g3* (Su=560 MPa, Sy=355 MPa).

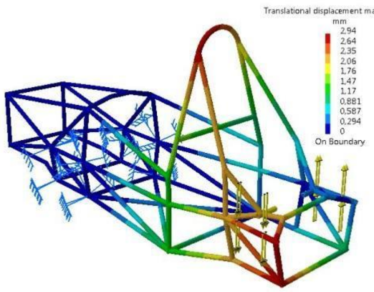

Figure 10 *- Results of displacement* [7]

The biggest displacement on frame is on the top of main roll hoop, and it equals 2,94 mm in the worst case. The vaule of displacement in the zone where moment is applied equeals 2,81 mm, so the value of torsion angle equals θ=0,618. Torsional moment is $T=F\cdot l$=1800·0,53=954 Nm, and so the torsional stiffness is equal to: $K=T/\theta$=954/0,618=1559 Nm/°.

Results of Von Mises stress under the applied moment of torsion, are shown in figure 11 in different colors. The biggest value is located in down and left or right knot (it depends on direction of torsional monent) of front roll hoop, and it equals σ_{max}=134,8 MPa.

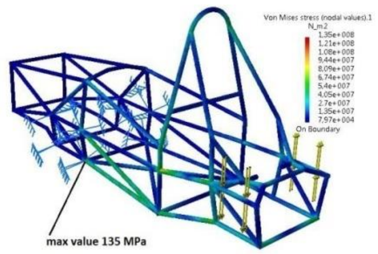

Figure 11 *- Results of Von Mises stress* [7]

After test of torisonal stiffness, on request from propositions, test with barrier impact simulation is done, which is shown in **Figure** 12. Value of imact force equals 150 kN.

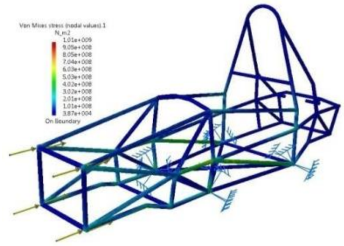

Figure 12 *- Barrier impact simulation* [7]

The results are not satisfied, because value of stress (σ=1010 MPa) is bigger that value of Ultimate (Tensile) strength of chosen material (Su=560 MPa). In order to increase security, it is necessary to reinforce front part of frame.

5. FINAL DESIGN

5.1 Optimisation of frame

After detailed consideration from aspect of frame computer analysis of the loads, it can be concluded from Figure 12, that the frame can be critical due to the strong impact into the barrier. Accordingly, the front part of frame is reinforced, as it is shown in figure13.

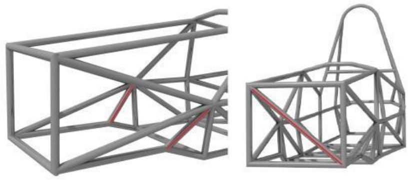

Figure 13 *- Reinforcement of front part* [7]

After significantly reinforcing of the front part of frame (shown in Figure 13), it is necessary to do again computer analysis of barrier impact with the same conditions. When the results of second analysis are gained, it can be concluded that value of displacement of front part of frame equals d=9,93 mm (less than 25 mm), and maximal value for Von Mises stress equals σ_{max}=541 MPa (less than 560 MPa). This result, now, completely satisfies the test request from propositions.

The back part of frame is also reinforced, with adding one transversely tube on the top of the main roll hoop, in order to increase torisional stiffness. After reinforcing, value of torsional stiffness equals 1967 Nm/° (before reinforcing the value of torsional stiffness equaled 1559 Nm/°).

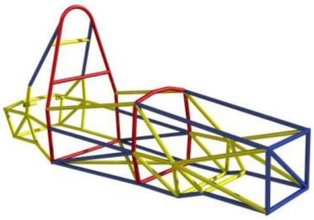

Figure 14 *- Final design of frame* [7]

After the whole design process of the frame construcion and the process of optimisation, the final design is shown in Figure 14, with different colors for different thickness of tubes. Tubes with cross section Ø25x2.5 mm are shown with red colors (main and front roll hoops, and shoulder harness attachment). Tubes with cross section Ø25x1.8 mm are shown with blue color, and tubes with cross section Ø25x1.5 mm are shown with yellow color, which contains all other elements [7]. The information of final design are shown in Table 2.

Table 2 *- Information for final design of frame construction* [7]

Criterion	**Value**
Brunt height	267,01 mm
Mass redistribution	49% - 51%
Frame mass	33,061 kg
Torsional stiffness	1967 Nm/°

6. CONCLUSION

After the whole design process, from colecting all necessary informations, through the optimisation process to the final design, all criterions are satisfied. Frame is designed with mass below 35 kg, and value of torsional stiffness above 1500 Nm/°, and beside this, ergonomy for driver is quite satisfied. According to the first analysis of loads, preliminary variant is additionally reinforced, and now the test of torisional stiffness is completely satisfied, as well as simulation of barrier impact. This solution of frame construction represents a prototype, which is result of researching and development during the few months, from Formula student team "FIN Racing team", University of Kragujevac in Serbia. In order to improve and optimise this solution of Formula student frame, it is necessary to perform next detailed researching and analysing.

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