ANALYSIS OF CHANGES IN THE STRENGTH OF THE SPACE FRAME OF THE FORMULA STUDENT VEHICLE

Paweł Fabiś, Władysław Leoniewski, Jędrzej Czapla, Krzysztof Kler

Summary

The study presents the design process and analysis of the spatial structure of the Formula Student vehicle. An important issue is such a concept of the vehicle frame that it is possible to design an optimal version of the front and rear axle suspension. Therefore, an important element of the design is the correct geometry of the frame around the mounting points of the front and rear suspension, and it will allow the use of electric vehicle drive. The analysis of the current frame structure has been compared to the previous structures created in the Silesia Automotive Student Science Club. Particular attention was paid to the weight of the element and its strength properties, and these parameters received the most attention.

Keywords:

Formula Student, space frame, 3D model, strength analysis

Citation:

Fabiś P., Leoniewski W., Czapla J., Kler K.: Analysis of changes in the strength of the space frame of the Formula Student vehicle. Motor Transport, 67(1), s. 29-36

DOI: 10.5604/01.3001.0053.9431

1. Introduction

A self-supporting body is an element of the vehicle responsible for safety. There it is possible to reduce the weight of the vehicle while maintaining the highest safety.

The most important parameters when designing a body for a racing car are weight and stiffness. Less weight allows you to get better acceleration, and the stiffness affects the precise control of the suspension geometry (so that the wheels adhere to the surface on which the vehicle is moving). Striking a balance between these assumptions is an art and science that he calls racing vehicle engineering.

The Formula Student car body made of steel pipes as a space frame is a solution known for many years and used in F1 cars or motorcycles. The structure consists of steel or aluminum pipes arranged in triangles to transfer the loads from the suspension, engine and aerodynamic elements. Pipes are subject to tension or compression, but do not bear any bending or torsional loads. This means that each point should be supported in three places. The pipes have a round section (for the greatest strength) or a square section for easier connection to the vehicle skin. The tubes are oriented in different directions to withstand forces anywhere.

2. Rules requirements

Formula Student regulations allow two options for designing the frame in racing vehicles [12]:

- structure made in accordance with the regulatory requirements, or
- an alternative construction, the construction of which must be supported by calculations, and the team must prove the correctness of the construction to the judges.

The frame for the presented Formula Student race car was created according to the regulations. It involves some fixed elements that must be placed in the frame. Their list are presented below:

- frame – a set of structures connecting and servicing all vehicle systems. It can be made as a welded structure, a combination of a welded and composite structure or a structure consisting of many welded structures,
- frame member – a minimum single piece of uncut, continuous pipe,
- main hoop – a headband located next to or just behind the driver's body,
- front hoop – a bar placed over the driver's legs, near the driver,
- roll hoop bracing supports- a structure connecting the shanks with the lowest ends of the shackle supports,
- front bulkhead – a front structure that protects the rider's feet. Impact atenuator is attached to it,
- side impact zone- the zone between the front and main headband. It should be at a distance of 240 and 320 mm from the lowest point of the frame,
- all pipe connections must be based on correct triangulation. All pipe connections should be in common nodes,
- shoulder harness mounting bar– element required to attach seat belts.

The vehicle frame should be designed on the basis of triangles, connecting pipes at nodes. The individual sections of the frame must be made of pipes with an appropriate wall thickness. Their dimensions are presented in Table 1.

Table. 1. The required minimum dimensions of pipes used for construction

Item or use	External dimensions x wall thickness
front and main hoop harness bar	round 25 x 2 [mm]
side impact structure, front bulkhead, hoop bracing, driver's restraint harness attachment, front bulkhead support, main hoop bracing supports, battery protection section (electric vehicles), traction components protection section (electric vehicles)	round 25 x 1,2 [mm]

The steel used to tubes should have properties not lower than:

- Young's modulus (E) = 200GPa,
- yield point (Sy) = 305MPa,
- ultimate strength (Su) = 365 MPa.

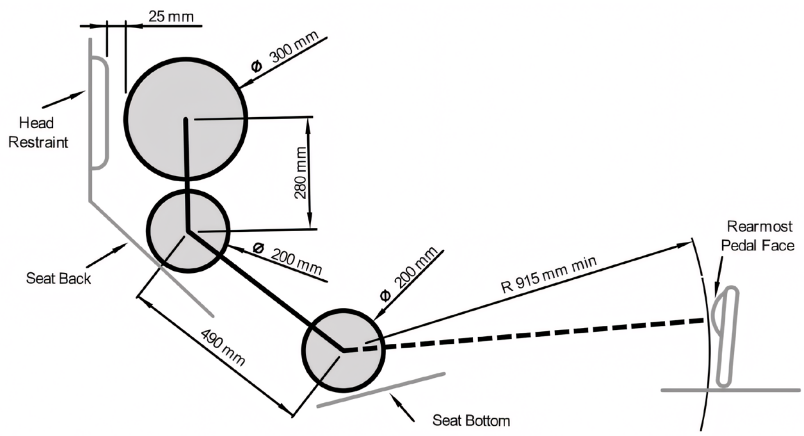
2.1. Requirements for the driver's position and space development

The process of designing the driver's space is heavily limited by the provisions of the regulations for safety reasons. It is dictated by the fact that the driver has the greatest possible protection during an accident.

The reason why the vehicle should have front and main hoop is sufficient safety. The main task of the hoops and the side impact zone is to prevent the driver's hands and head from contacting the ground during a possible rollover.

According to the regulations, the model showing a man from the 95th percentile, presented in Fig. 1, should fit freely into the vehicle.

Fig 1. Presentation of the required dimensions of the 95 percentile male template [11]

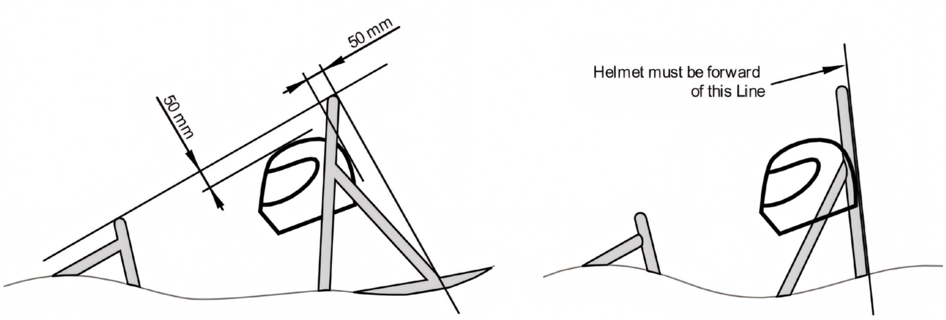


The centile is a statistical measure. It is a value that separates the parameters of a population in a certain ratio, below which a certain percentage of the results fall. Where the 95 percentile for the height of men in this case means the value at which 95% of men have a smaller height.

Placing such a template ensures that the structure will be fit for use by different people. The required number of drivers during the event is at least 4, each of which will be different.

There should be a distance of 2 inches between the helmet and the top hoop, and between the main hoop and the top of the main hoop. That is shown in Fig. 2.

Fig. 2. Required dimensions of the main hoop in the vicinity of the driver's head [11]



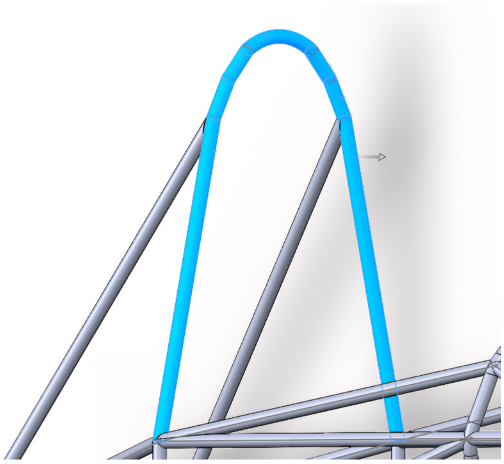
2.2. Main hoop

The main hoop is the element responsible for protecting the driver's head, located behind or above his head. It should be made of a single seamless pipe. In order to shape it without breaking the structure, the pipe is bent. It starts at the bottom of the frame and curves over the driver's head. It cannot be made of materials such as: titanium, aluminum or composite. It must be a steel pipe.

In side projection, the main hoop should not be more than 10° from the vertical. Any bends above its attachment point to the main hoop shall be stiffened to the structure node of the main roll restraint support. When looking towards the rear of the vehicle, the main bar can only be angled at 10 °, while looking towards the front it can be bent at any angle.

From the front of the vehicle, its vertical elements should maintain a minimum distance of 380 mm from each other at the point where the main hoop is attached to the down tube that will be part of the frame structure. It is necessary to support by two additional pipes, which form the stiffening of the supports. The brackets point to the rear lower part of the frame and end there and are fixed there. The main hoop brackets are stiffened on the right and on the left side of the frame. The bending of the main hoop is shown in Fig. 3.

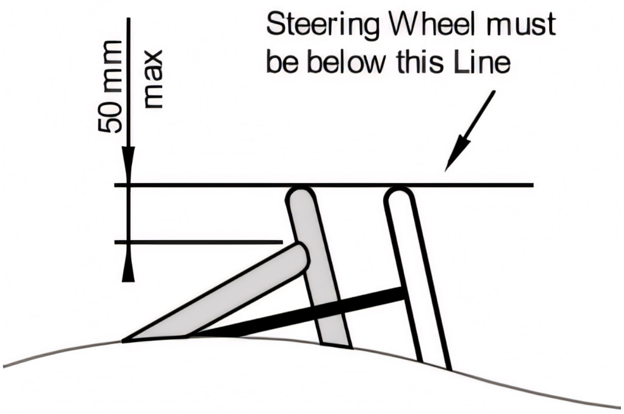
Fig. 3. Example showing the bending of the main hoop



2.3. Front hoop

The front hoop is a component placed above the driver's legs, reaching from the lowest point of the frame on both sides. It is used to protect the driver's legs and to mount the steering wheel and steering column on it. It should be made of a seamless metal pipe and designed in accordance with the principle of correct triangulation, which was described earlier. It can be made of more than one pipe and can be joined by welding.

Fig. 4. Correct location of the steering wheel [11]



The upper part should cover the upper part of the driver and his hands. It cannot limit visibility. There should be a minimum distance of 50 mm between the support of the upper part of the structure and the steering wheel in the side view, as shown in Fig. 4.

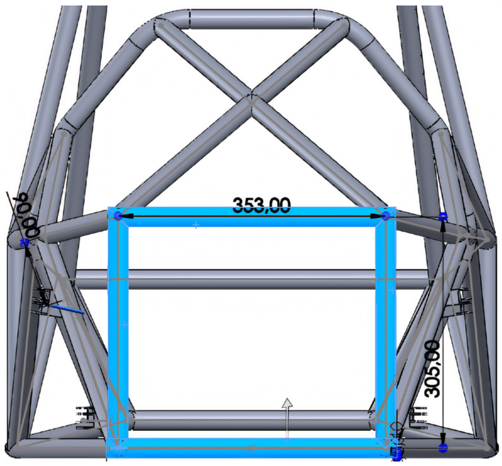
In the side view, none of the parts may exceed a slope of 20° from the vertical. This element must be supported by two pipes extending to the front of the vehicle on both sides. They should be arranged so as to cover the legs of the vehicle driver. These pipes should be located not more than 50 mm from the top of the hoop.

2.4. Front bulkhead

The front bulkhead is the part of the structure located at the very front of the vehicle frame in front of the front hoop. It is rectangular in shape with pedalbox and the driver's feet in its section. An absorber is built in front of the bulkhead.

The front bulkhead should meet several basic assumptions. The pedalbox placed in the vehicle must not touch the bulkhead when they are fully depressed. The bulkhead itself should be supported by at least 3 pipes on both sides of the structure. It should also be resistant to damage. The appearance of the front bulkhead (front) is shown in Fig. 5.

Fig. 5. Front view of the structure showing the front bulkhead.



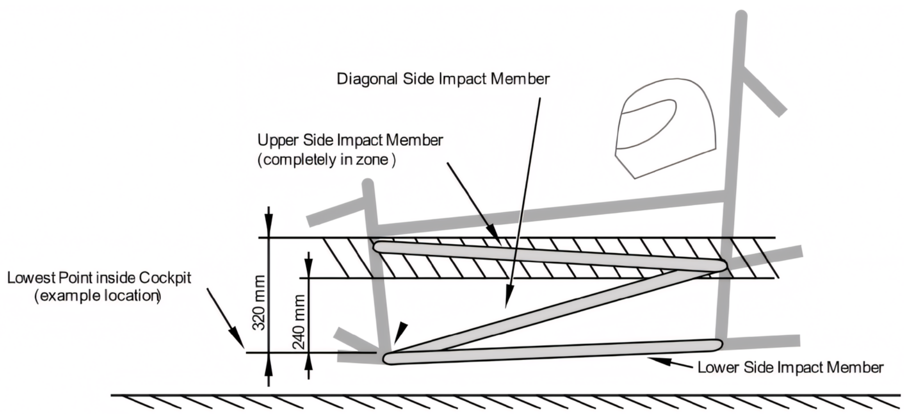
2.5. Side impact structure

The side impact structure is the section surrounding the driver on both sides of the body. Its pipe requirements are the same as in the previous sections.

The structure of the side impact structure should be made of three or more pipes placed on both sides of the driver seated in the normal driving position. The upper part of the side impact structure should:

- attach the front hoop to the main hoop.
- be completely in the area 240 to 320 mm from the lowest pipe that forms the structure of the side impact zone (Fig. 6).

Fig. 6. Construction of the side impact structure [11]



The lower part of the side impact structure must connect the bottom of the main and front roll bars. The diagonal elements of the side impact structure should connect the upper and lower parts of the side impact structure.

2.6. Templates

Templates are elements made of a sheet of metal of the appropriate thickness and dimensions that are used to control the space in specific places. They are inserted into the vehicle during the inspection before it is allowed to the competition. For this reason, they should be taken into account when designing the driver's space. There are two types of such measures: horizontal and vertical, described below.

The first template is placed horizontally in the driver seat space. It should be placed below the top of the side impact zone (Fig. 7). By making this measurement, the seat can be disassembled, as well as the steering wheel, steering column or upholstery.

The second plate (Fig.8b) is placed in the space where the driver's legs are located. It is inserted vertically towards the front of the vehicle 100 mm from the rearmost pedal.

3. Construction rules

Students of the Faculty of Transport and Aviation Engineering designed and built two Formula Student vehicles. The first was marked with the symbol WT-01, the second – WT-02. The latest design, described in this study, was designated WT-03e. Where the designation "e" refers to the vehicle in inversion with electric drive.

When creating the project, the design of the frame of the previous vehicle WT-02 (WT-01, was not considered) was important. When designing the frame for the WT-03e vehicle, the needs and design goals were determined:

- increasing the correlation between the suspension system and the frame structure,
- construction adapted to the most convenient location of the suspension fasteners,
- the design should allow the vehicle to achieve the smallest possible wheelbase of 1553 mm,
- easier getting in and out of the vehicle by tilting the front hoop by no more than 10 °.

Meeting the design assumptions determined the decision to select the appropriate material for the construction of the actual vehicle frame. The selection was based on the availability of the material among local suppliers, as well as the weldability of the steel. The selected material is 25CrMo4 steel, the parameters of which – in comparison to the regulations – are presented below in Table 2.

Table. 2. Properties of the selected steel compared to the regulations

	Regulations value [12]	Steel AISI 4130 (25CrMo4)
Young's modulus	200 GPa	210 GPa
Yield strength	305 MPa	460 MPa
Ultimate strength	365 MPa	560 MPa

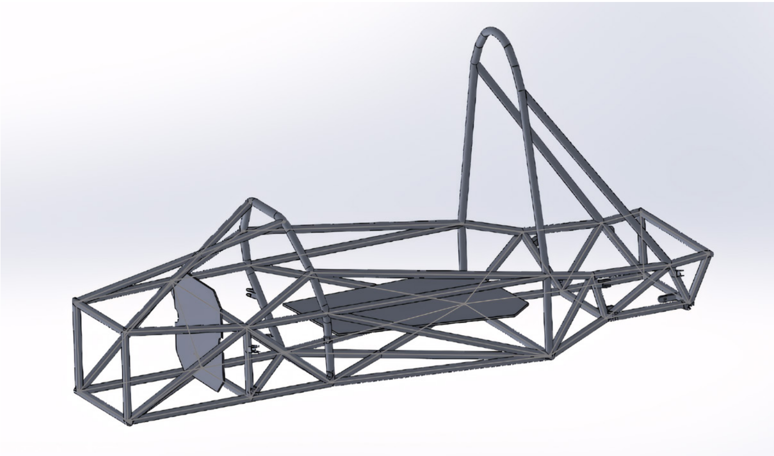
Along with the selection of the material, the thickness of the pipes walls for individual elements of the car's frame was determined. Due to the pioneering nature of the WT-01 project, the desire to guarantee a high level of driver safety, and the availability of material, pipes with walls thicker than required by the regulations were selected (Table 1). However, in the case of the WT-02 vehicle, where the priority was to obtain the lowest possible weight, the thicknesses were optimized to meet the regulatory requirements.

Table. 3. Selected dimensions of pipes for the WT-03e vehicle

Item or use	External dimensions x wall thickness
front and main hoop, harness bar	round 25,4 x 2,4 [mm]
side impact structure, front bulkhead, hoop bracing, driver's restraint harness attachment, front bulkhead support, main hoop bracing supports, battery protection section (electric vehicles), traction components protection section (electric vehicles)	round 25,4 x 1,65 [mm]

When designing the frame for the WT-03e vehicle, templates and their dimensions were taken into account from the very beginning, which predetermined the shape of the structure and allowed to design the vehicle perfectly, to use as little material as possible, which leads to the final weight of the structure.

Fig. 7. Setting of control measures WT-03e



Experience has been get from the previous two constructions, it was possible to create a frame that was simpler to manufacture, lighter, and better adapted to work with the suspension or a smaller drive system. The main hoop is now straight, not angled to the bottom of the structure. This eliminates the difficulties associated with the appropriate angle of bending the pipe to the final structure. The driver's space has been increased compared to previous designs, the front part with the driver's legs has been reduced. This allows much faster getting out, it also has an impact on the deformation of the structure in the event of a frontal impact, which will be shown in the research [7,8].

Fig. 8. Visualization of the vehicle frame WT-01 [7]

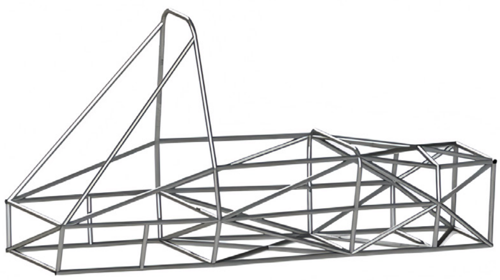
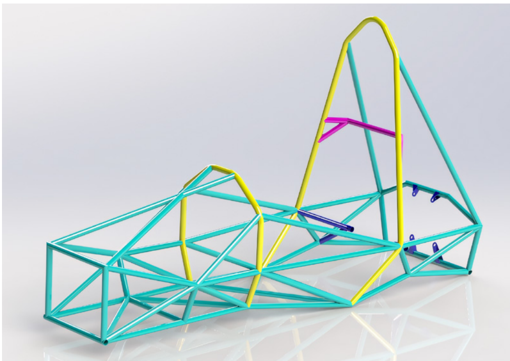


Fig. 9. Model of the WT-02 vehicle frame [8]



4. Simulation analysis of the WT-03e vehicle frame

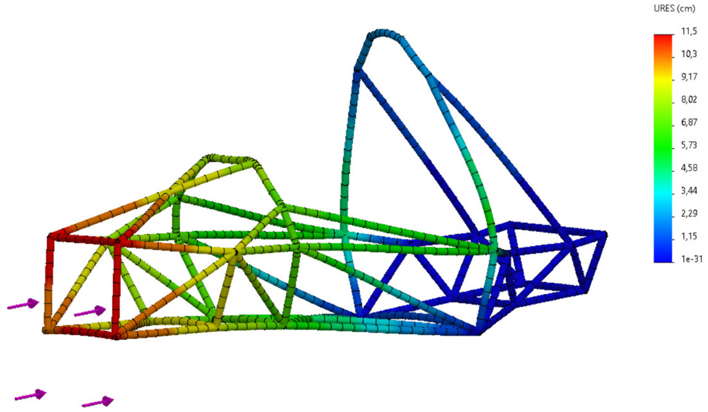
After the design was completed, the simulation was performed. Initial conditions were given such as:

- gravity,
- frontal force of 200 kN which is supposed to simulate a frontal collision,
- attachment of the structure to simulate in the rear section near the convergence of pipe nodes.

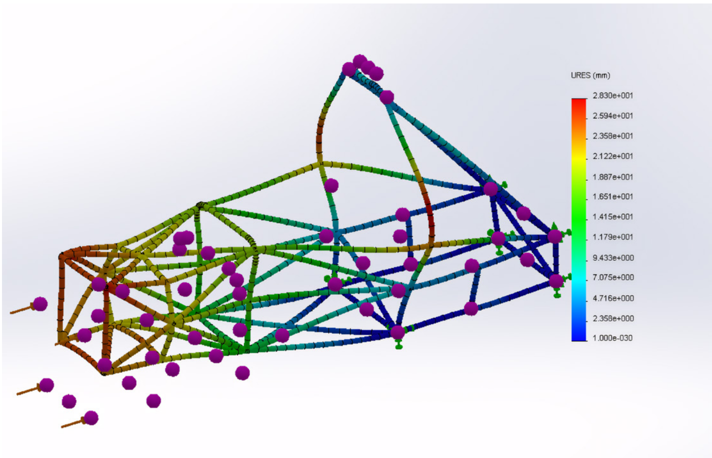
The result of the simulation was presented (Fig.10) as a displacement.

Fig. 10. Frame model displacement from simulation of the a) WT-03e, b) WT-01

a)

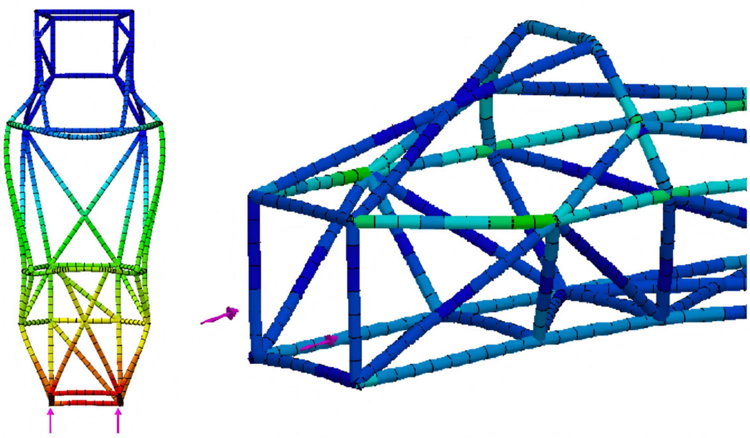


b)



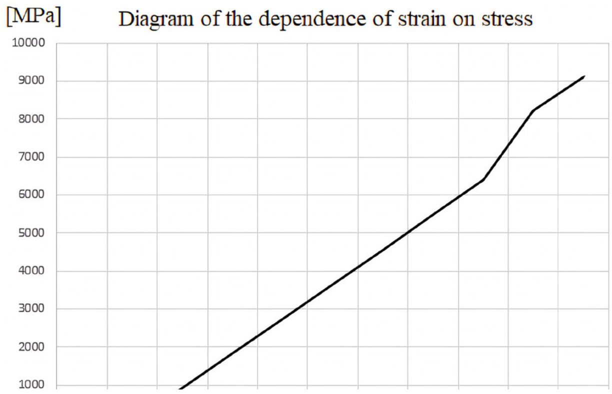
When examining the WT-03e frame, the focus was on the safety of the driver. As a result, it was decided to simulate a frontal collision without a front absorber. During a frontal collision, the frame rises upwards and the tubes of the structure itself deform outwards

Fig. 11. On the left, a view of displacements from above, on the right, the stress distribution



without causing any harm to the driver. This is the effect of a properly designed truss frame built according to the principle of correct triangulation. The greatest displacement occurred in the place where the frame diverges outwards, which means that in the event of an accident at high speed, the driver's legs will not be crushed. The maximum displacement occurring does not exceed 11 cm.

Fig. 12. Dependence of strain on stress of WT-03e frame



For example, the simulation of the WT-01 frame, which shows how much the new structures of the Silesia Automotive team have changed. Current constructions are subject to much less deformation. In the case of WT-01cars it was 28 cm, and in the case of WT-03e it is only 11.5 cm.

Summary

The analysis of the structure of the spatial frame made it possible to identify the critical nodes in which there was enough accumulation of loads. In addition, the nature of changes in the stiffness and deformation of the frame is presented. Based on this analysis, it was determined that the greatest deformations are located near the front part of the frame and the main rollbar. The size of these deformations fluctuate around 11.5 cm (force applied from the front of 200 kN). This value is more than twice smaller than the analogous deformation recorded for the WT-01 vehicle frame.

The design of the WT-02 vehicle frame took into account the safety aspects, so important in the Formula Student competition. The frame of the vehicle has been optimized in terms of engine size and the minimum number of pipes needed, which allowed to reduce structural deformation. The structure of the WT-02 frame has become light, modern and allows for further development, e.g. by installing an aerodynamic package.

The above assumptions were directly transferred to the frame of the currently designed vehicle. However, these requirements supplemented several other aspects. The WT-03e frame focused on increasing the driver's space and reducing deformation in the event of a possible frontal collision. The project was fully adapted to the assembly of the electric drive system. This made it possible to significantly narrow the rear part where the engine is mounted. These assumptions did not affect the strength parameters of the space frame, obtaining a compact, lightweight structure with high strength.

Bibliography:

1. Brown Matt. *Race car: Searching for the Limit in Formula SAE*. Oklahoma. Seven Car Publishing. 1 Edition. 2011.
2. Górska Ewa.: *Ergonomia*. Warsaw. OWPW, 2002
3. Newey Adrian. *How to build a car.* Harpent Collins 2017
4. Wicher Jerzy.: *Bezpieczeństwo samochodów i ruchu drogowego*. *Cars and traffic safety*. Warsaw: WKiŁ,2004
5. Milliken William F., Milliken Douglas L. *Race Car Vehicle Dynamics* Society of Automotive Engineers, Inc. Warrendale, Pa 1995
6. Zieliński Andrzej: *Konstrukcja nadwozi samochodów osobowych i pochodnych*. *Body cars and others construction*. Warsaw: WKiŁ, 2003
7. Hadula Przemysław. Saczko Sławomir. Fabiś Paweł. Optymalisation of the Formula Student cars frame. 2017. *Przegląd Mechaniczny*. Sheet 12/2017.p:46 – 50
8. Saczko Sławomir. 2013. „Bezpieczeństwo bierne pojazdu wyścigowego klasy Formuła Student – budowa kokpitu i absorbera energii zderzenia. Safety of the Formula Student race car –absorber and cocpit build". Master Thesis. Silesian University of Technology
9. „Definition of 95 percentile male, and percentile measures". Accessed: 2021. Available at.: https://dobryslownik.pl/slowo/centyl/212096
10. „Explanation of the truss frame". Accessed: 2021. Available at.: http://www.formula1-dictionary.net/chassis.html.
11. Formula Student Rules 2022.
12. Binetti de Gennaro P.: Chassis Design for Class 2. Project. 2017
13. Dodd C., Geneva N., Geneva P., Morris C.: Chassis Design Report. Master Project. University of Delaware FSAE team. 2017.
14. Stitt B., Brooks R., PellCal C.: Poly SAE Formula Electric Chassis. Master Project. San Luis 2015.
15. Sebastian A., Martinez F., Miyer A., Castrillon S, Suarez Castrillon A.: Analysis of the Chassis Structure of a Formula Student Racing Car. *International Journal of Engineering Research and Technology*. Volume 14, Number 10 (2021), pp. 1005-1017. DOI: http://www.irphouse.com
16. Oshinibosi A.: Chassis and impact attenuator design for formula student race car. University of Leeds, School of Mechanical Engineering. Master Project. 2012.
17. Wongchai B.: Front and side impact analysis of space frame chassis of formula car. *International Journal of GEOMATE*, March, 2020, Vol.18, Issue 67, pp. 168-174, 2186-2990. Japan, DOI: https://doi.org/10.21660/5528.
18. Rodrigues H.C., Herskovits J., Mota Soares C.M., Araujo A.L., Guedes J.M., Folgado J.O., Moleiro F., Madeira J.F.A: EngOpt 2018 Proceedings of the 6th International Conference on Engineering Optimization. *Springer*. 2018. DOI: https://doi.org/10.1007/978-3-319-97773-7.
19. Khan M.T.: „Design & manufacturing of FSAE chassis". *International Research Journal of Modernization in Engineering Technology and Science*. Volume:03. Issue:02. 2021. DOI: www.irjmets.com.
20. Edmund G.F., Salinas A.R.: „Introduction to Formula SAE Suspension and Frame Design." *SAE Technical Paper Series*, 1997.
21. Aird Forbes. *The Race Car Chassis*. New York, New York: The Penguin Group, 2008.
22. Canut F., Malcher L., Henriques A.: „Structural Analysis of a Formula SAE Chassis Under Rollover Loads". dic. 2015. DOI: 10.20906/CPS/COB-2015-0837

Paweł Fabiś
pawel.fabis@polsl.pl
Silesian University of Technology

Władysław Leoniewski
wladyslaw.leoniewski@gmail.com
Silesian University of Technology

Jędrzej Czapla
jedrcza030@student.polsl.pl
Silesian University of Technology

Krzysztof Kler
krzykle987@student.polsl.pl
Silesian University of Technology