DESIGN AND CRASHWORTHINESS ANALYSIS FOR A RALLY VEHICLE ROLL CAGE

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Abstract: *This paper studies the protective features of automotive roll cages in cases of frontal, side and rollover impacts. A comparison is needed between structures made of circular section pipe and structures made of square section pipe. Both roll cage variants comply with FRAS (Federația Română de Automobilism Sportiv) regulations and they are being subjected to nonlinear dynamic analyses.*

Keywords: *roll cage, impact analysis, frontal, side, rollover*

1. Introduction

The impact simulation is aimed at comparing roll cages made of pipes of different sections, also studying the influence of the materials chosen to achieve maximum performance. Specialized studies on the impact performance of roll cages do not take into account the possibility of making structures using square section pipes. Crash test analysis normally involves the collision of a real vehicle with human dummies in order to determine the physical damage, which is expensive and time consuming. Using the finite element method (FEM) we can obtain results similar to reality, which can be validated by experimental data.

2. Design and analysis tools

2.1 Solidworks

The 3D models in solidworks are all started by creating a base 3D sketch based on the real parameters of a vehicle (in this case the Ford Fiesta RS WRC).

The precise dimensions can be incorporated and altered as desired based on the size and location on the geometry. Solidworks has the abilty to co-relate dimensions and location to provide control over parallelism, tangecy, perpendicular and concentricity which provides us a better dimensional preview before designing an object.[1]

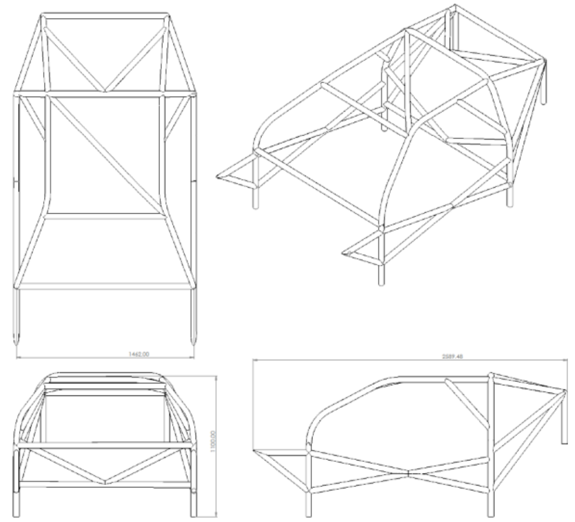

Figure 1: *Roll cage sketch using solidworks*

The roll cage complies with the rules and recommendations regarding their construction established by the FRAS [2].

2.2. Solidworks - simulation

The structural analysis has been very difficult to achieve before simulation softwares. This tool enables us to define a 3D structure on which we can apply many different loads, constrains, it allows us to choose the structures materials or modify their properties of a customized material.

3. Material selection

In this study, three different materials were chosen for the roll cage analysis. Table 1 shows the characteristics of the chosen materials.

Table 1. *The characteristics of the chosen materials*

Material	Stellite T40 steel	7075 Aluminum alloy	Composite material
Young's modulus [GPa]	442	70	520
Poisson's ratio	0.3	0.32	0.2
Yield strength [MPa]	732	480	1200
Tensile strength [MPa]	900	560	590
Density [kg/m^3]	7700	3000	2700

4. Finite element analysis

The finite element method is a theoretical way to analyze the behavior and characteristics of a material or geometry.

The obtained structures were analyzed in the case of frontal, lateral and overturning impacts, using both circular and square section pipes, made from the previously mentioned materials.

All the roll cage variants were divided into finite elements by using the Mesh tool, their quality being high.

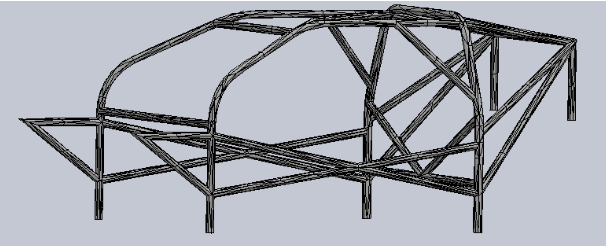

Figure 2: *Meshed roll cage made of circular section pipes*

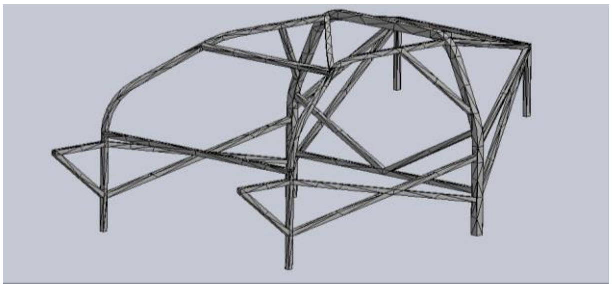

Figure 3: *Meshed roll cage made of square section pipes*

In establishing the impact parameters, the mass of the structure was chosen to be constant, without taking into account the material it is made of, equal to the mass of the entire vehicle on which it is mounted (1200 kg) and the kinetic energy dissipated after the collision will be determined.

$$E_C = \frac{m \cdot v^2}{2} \qquad (1)$$

where: E_c – kinetic energy [J];
m – vehicle mass [kg];
v – velocity [m/s].

5. Analysis results and discussion

5.1. Frontal impact

For the frontal impact, the initial speed was established at 13.3 m/s.

The stresses that appeared in the material can be seen in the following figures. For the frontal impact, both constructive versions of the roll cage were simulated, successively with the specified materials.

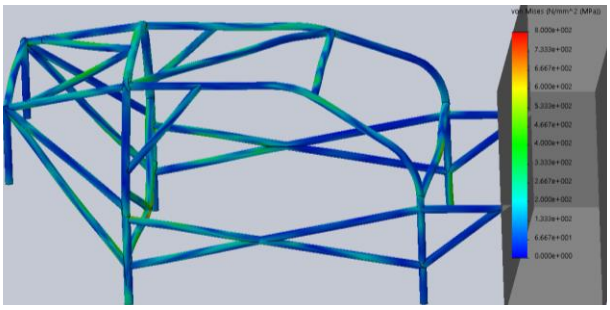

Figure 4: *Stress occurring in the aluminum alloy roll cage (circular section pipe)*

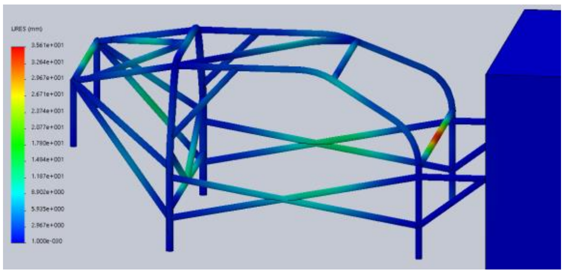

Figure 5: *Displacement occurring in the aluminum alloy roll cage (circular section pipe)*

The safety factor of the roll cage structure is calculated by the ratio between the yield strength of the material and the average normal stress resulting from the analysis.[3]

Maximum stresses with values above the yield strength of the materials occur due to the stress singularity in the finite element simulation.

Table 2: *Results obtained from the simulations of the frontal impact of the circular section pipe structure*

Material	Aluminum alloy	Steel	Composite material
Maximum stress [MPa]	1897	1921	5154
Average normal stress [MPa]	129.99	231.84	168.94
Average displacement [mm]	3.9976	5.3017	3.0978
Maximum displacement [mm]	35.609	50.699	21.062
Safety factor	3.69	3.15	7.10

Table 3: *Results obtained from the simulations of the frontal impact of the square section pipe structure*

Material	Aluminum alloy	Steel	Composite material
Maximum stress [MPa]	2583	3024	4810
Average normal stress [MPa]	207.35	362.11	211.85
Average displacement [mm]	5.9159	2.6279	2.4575
Maximum displacement [mm]	28.408	15.498	17.533
Safety factor	2.31	2.02	5.66

The model does not take into account the welding properties and the amount of welding at the joints of the elements.[4]

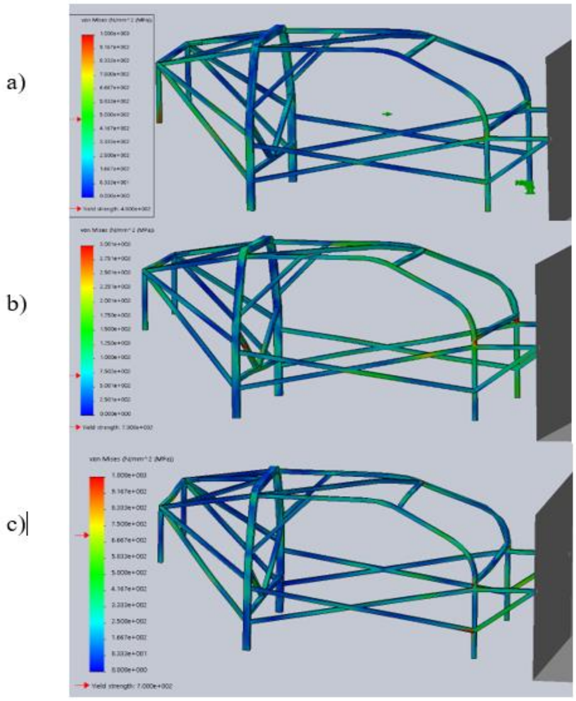

Figure 6: *Stress occurring in the square section pipe (frontal impact): a) aluminum alloy; b) steel; c) composite material*

A comparative study is carried out between the circular and square section pipe structures.

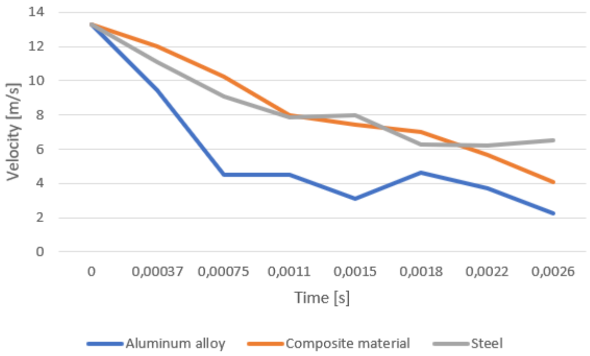

Figure 7: *Velocity-time graph for circular pipe (frontal impact)*

In the graph presented above, it can be seen how the speed of movement varies during the impact, depending on the material of which it is made.

At the same time, it can be observed that the roll cage made of aluminum alloy presents a more sudden reduction in the speed of movement compared to the other materials.

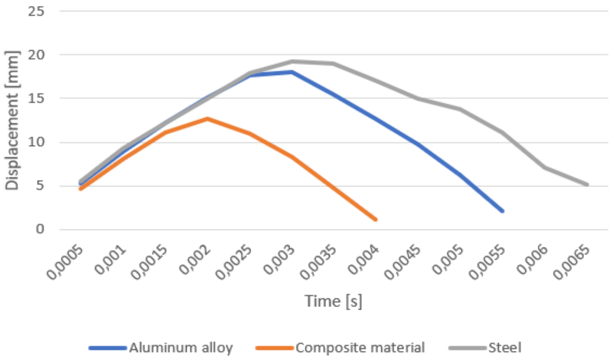

Figure 8: *Displacement-time graph for circular pipe (frontal impact)*

From the results represented in Fig. 7 and Fig. 8, it can be seen that the composite material shows the smallest deformations, and the least aggressive deceleration is achieved by the composite material as well.

Table 4: *Values of kinetic energy dissipated in the circular section pipe structure for frontal impact*

Material	**Aluminum alloy**	**Steel**	**Composite material**
Dissipated kinetic energy	103.06944 kJ	83.07 kJ	96.2925 kJ

Table 5: *Values of kinetic energy dissipated in the square section pipe structure for frontal impact*

Material	**Aluminum alloy**	**Steel**	**Composite material**
Dissipated kinetic energy	62.98776 kJ	94.35906 kJ	79.83936 kJ

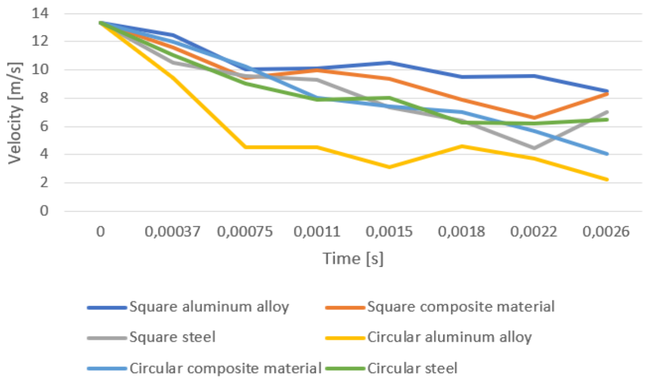

Figure 9: *Velocity-time graph. Comparison between pipe section and chosen material (frontal impact)*

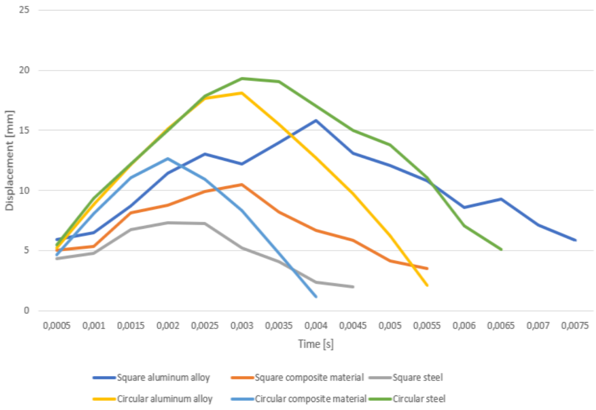

Figure 9: *Displacement-time graph. Comparison between pipe section and chosen material (frontal impact)*

5.2. Side impact

For the side impact, the travel speed of 8.8 m/s was established. The collision is carried out with a non-deformable fixed barrier in close proximity to the main safety beam.

The results were obtained in a similar way to those of the frontal impact, the stresses and displacements were extracted by the same method as in the previous case.

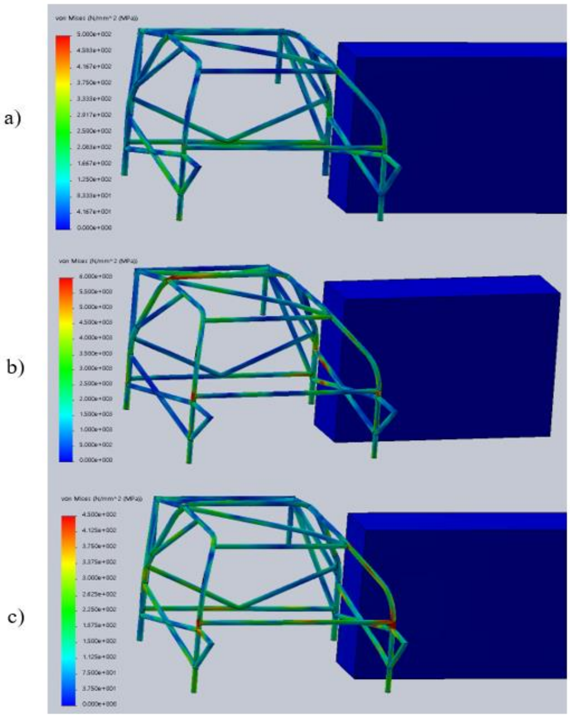

Figure 10: *Stress occurring in the circular section pipe (side impact): a) aluminum alloy; b) steel; c) composite material*

Table 6: *Results obtained from the simulations of the side impact of the circular section pipe structure*

Material	**Aluminum alloy**	**Steel**	**Composite material**
Maximum stress [MPa]	6628	18542	4810
Average normal stress [MPa]	93.297	624.7	211.85
Average displacement [mm]	3.1724	7.2769	2.4575
Maximum displacement [mm]	17.172	41.084	17.533
Safety factor	12.21	1.71	5.66

Table 7: *Results obtained from the simulations of the side impact of the square section pipe structure*

Material	**Aluminum alloy**	**Steel**	**Composite material**
Maximum stress [MPa]	3723	10534	2719
Average normal stress [MPa]	122.08	557.84	130.1
Average displacement [mm]	7.2803	3.3782	2.4112
Maximum displacement [mm]	72.99	30.309	19.677
Safety factor	3.93	1.31	9.22

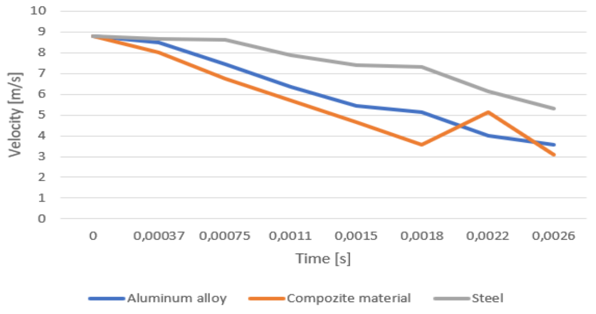

Figure 11: *Velocity-time graph for circular pipe (side impact)*

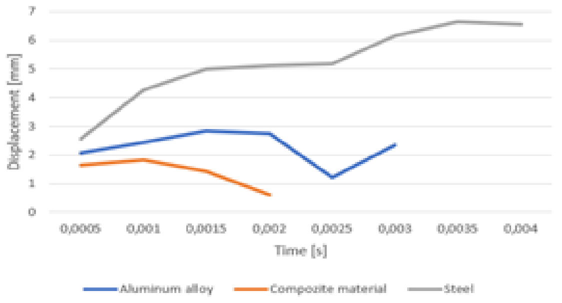

Figure 13: *Displacement-time graph for circular pipe (side impact)*

Considering the resulting data represented in Fig. 10 and Fig. 11 we can state that in the case of the present application, the performance of the composite material structure is being followed because it presents the least displacement and a similar deceleration with the other materials.

Table 8: *Values of kinetic energy dissipated in the circular section pipe structure for side impact*

Material	Aluminum alloy	Steel	Composite material
Dissipated kinetic energy	38.81706 kJ	29.48256 kJ	40.77206 kJ

Table 9: *Values of kinetic energy dissipated in the square section pipe structure for side impact*

Material	Aluminum alloy	Steel	Composite material
Dissipated kinetic energy	41.1357 kJ	37.70856 kJ	44.064 kJ

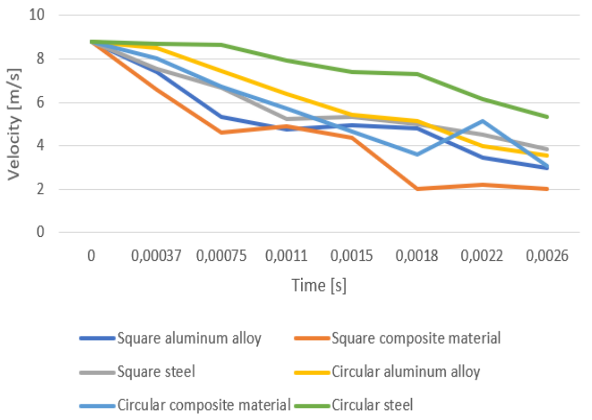

Figure 12: *Velocity-time graph. Comparison between pipe section and chosen material (side impact)*

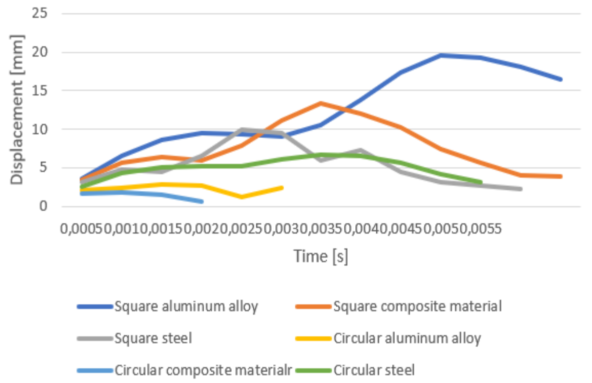

Figure 13: *Displacement-time graph. Comparison between pipe section and chosen material (side impact)*

5.3. Rollover

Due to the fact that the roll cage is intended especially to protect the passengers in case of overturning, in the nonlinear dynamic analysis, the value of 20 m/s was chosen as the speed of the vehicle.

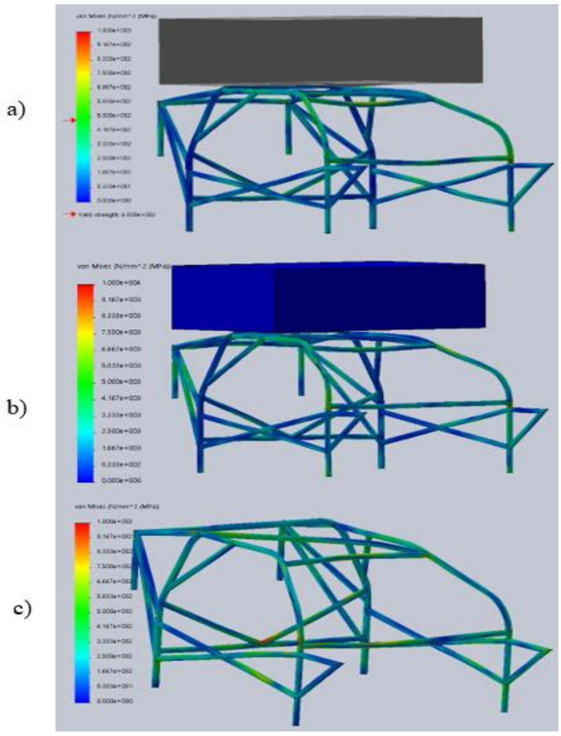

Figure 14: *Stress occurring in the circular section pipe (rollover): a) aluminum alloy; b) steel; c) composite material*

Table 10: *Results obtained from the simulations of the rollover case of the circular section pipe structure*

Material	Aluminum alloy	Steel	Composite material
Maximum stress [MPa]	1166.2	9843.1	1791
Average normal stress [MPa]	168.8	801.4	227.02
Average displacement [mm]	5.9233	2.6591	4.6867
Maximum displacement [mm]	48.346	43.686	35.289
Safety factor	2.84	0.91	5.22

Table 11: *Results obtained from the simulations of the rollover case of the square section pipe structure*

Material	Aluminum alloy	Steel	Composite material
Maximum stress [MPa]	3788.7	6048.8	1624
Average normal stress [MPa]	291.99	614.22	142.489
Average displacement [mm]	18.065	13.558	16.475
Maximum displacement [mm]	85.238	90.212	50.456
Safety factor	1.64	1.19	8.42

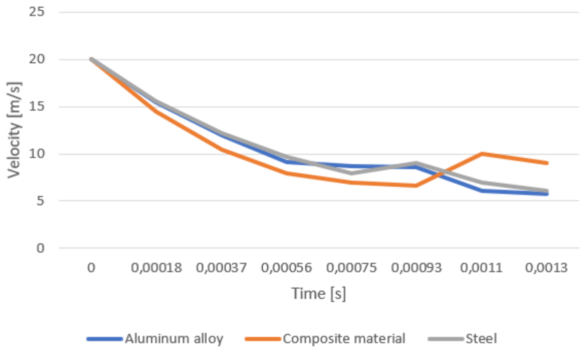

Figure 15: *Velocity-time graph for circular pipe (rollover case)*

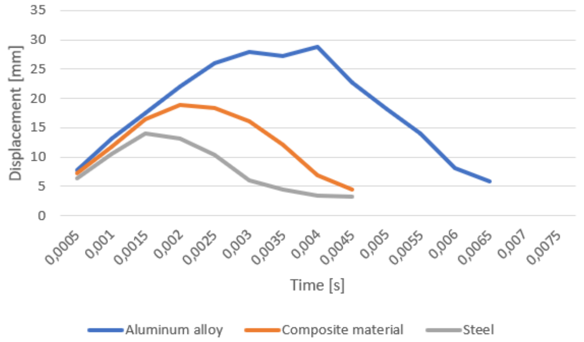

Figure 16: *Displacement-time graph for circular pipe (rollover case)*

From the graphs shown in Fig. 13, Fig. 14 and the values given in table 6, it can be stated that in the case of overturning, the values of the travel speeds during the impact are relatively similar. Performance related to keeping passengers safe, without the possibility of them coming into contact with the deformed structure, has been shown to be optimal for the structure made of steel.

Table 12: *Values of kinetic energy dissipated in the circular section pipe structure for rollover case*

Material	Aluminum alloy	Steel	Composite material
Dissipated kinetic energy	219.816 kJ	218.038 kJ	190.967 kJ

Table 13: *Values of kinetic energy dissipated in the square section pipe structure for rollover case*

Material	Aluminum alloy	Steel	Composite material
Dissipated kinetic energy	210.347 kJ	179.227 kJ	208.723 kJ

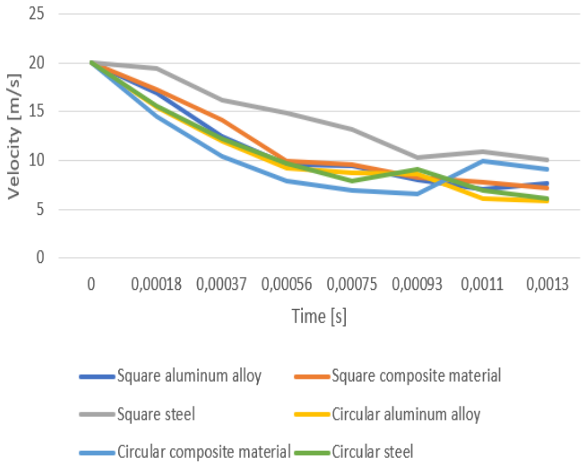

Figure 17: *Velocity-time graph. Comparison between pipe section and chosen material (rollover case)*

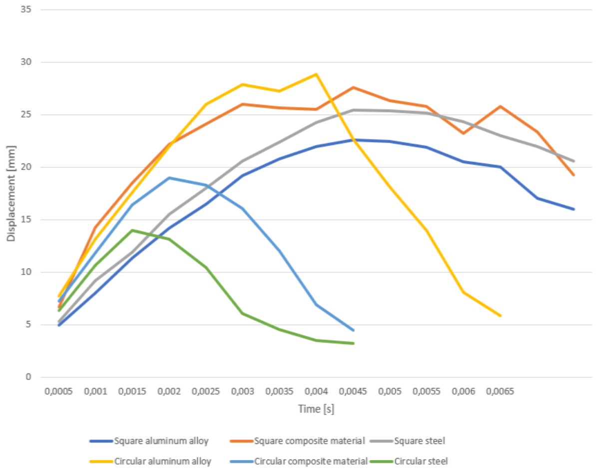

Figure 18: *Displacement-time graph. Comparison between pipe section and chosen material (rollover case)*

6. Conclusions

After checking the results obtained from the simulation through nonlinear dynamic analysis of the roll cage variants presented in the previous chapter, the following conclusions can be drawn:

- for frontal impact with a fixed non-deformable barrier, the use of components made of square section pipe is preferred due to the fact that, in this case, the kinetic energy resulting during the collision is dissipated in a way appropriate to the purpose of maintaining the safety of the passengers. In this impact version, it is preferred that the roll cage is made of Stellite T40 Steel.
- for the side impact, the performances related to the dissipation of kinetic energy are, again, better for the structure made of square section pipe. The material that presented the best characteristics this time is the epoxy matrix composite material reinforced with carbon fiber.
- for the case of rolling, from the analysis carried out at the speed of 20 m/s it appears that both structures behaved in a similar way, the largest deformations occurring in the structures made of square section pipe. From the values of the maximum stresses that appear in the material, we can state that in case of overturning, the structure made of steel of circular section will fail due to the fact that the value of the yield limit of the specified material is exceeded. At the same time, it is observed that under the same analysis conditions, using the same parameters, the value of the stresses in the material obtained for the roll cage made of square section pipes falls within the value of the maximum stress of the material. The roll cage can be optimized to achieve satisfactory results in conditions where travel speeds exceed 70 km/h.

References

1. [T. Safiuddeen,2020] T. Safiuddeen, P. Balaji, S. Dinesh, B. M. ShabeerHussain, and M. R. Giridharan, “Comparative design and analysis of roll cage for automobiles,” Materials Today: Proceedings, vol. 39. pp. 183–200, 2020

2. F. R. de A. Sportiv, “Anexa A Norme privind constructia de Roll Cage.pdf.” FRAS
3. [V. U. J. Shubham Kolhe,2016] V. U. J. Shubham Kolhe, “Roll cage design and analysis for formula student race car.” International Journal of Engineering Sciences & Research Technology, Pune, pp. 717–732, 2016.
4. [S.S. Vineet Felix Rodrigues,2015] S.S. Vineet Felix Rodrigues, Abel Antony, “Roll cage - regulation V/S Requirement - Design and Testing Analysis.” International Journal of Research in Mechanical Engineering, Mumbai