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APPROACH TO VERIFICATION OF A ROLL CAGE SURVIVAL SPACE WITH FINITE ELEMENT ANALYSIS

Abstract: In the study, the extensive validation of the original project of roll cage construction designed according to FIA standards is presented. In order to test the impact protection of the vehicle occupant site the verification of survival space was performed. For that purpose, a standardized manikin was utilized. The crashworthiness of the structure was examined by means of Finite Elements discrete model over a number of dynamic explicit simulations. The roll cage was in particularly designed for the passenger car. The important finding from the study is the need for additional side impact energy absorption ability of the cage.

Keywords: design of roll cage, FEM, dynamic simulation, crash test, explicit

1. INTRODUCTION

Safety equipment remains invaluable in today's motorsport. Hight severity of rally accidents forced to undertake thorough research for the sake of improving the safety in racing vehicles. There exists an ongoing trend in inventing and testing of new crashworthy materials, seats improvements, interior design adaptations as well as roll cage constructions [1].

Fig. 10. Destroyed Mitsubishi Lancer Evolution during Pikes Peak Hill climb 2012 [2]

Jeremy Foley's famous crash during Pikes Peak International Hill Climb (Fig. 10) was the inspiration to investigate the last-mentioned case – construction of roll cages. This kind of safety structure consists of a number of steel tubes welded together. The assembly is then not only welded, but also bolted to the chassis. Additionally, using this kind of connection significantly increases rigidity of the vehicle.

There are published many articles addressing the issue of roll cage crashworthiness utilizing FIA standards and aimed mainly at side structure energy-absorbing capability [3]. Nevertheless, majority of papers presents static analyses, such as quasi-static loading of the main hoop [4]. The minor part containing the dynamic analysis covers only a single side impact scenario which includes the collision with pole or tree [5]. Nevertheless none of them include verification of vehicles occupant survival space.

2. MATERIALS AND METHODS

The article presents the analysis a construction designed by the Authors according to FIA standards [6]. The dynamic analysis was selected to reflect real accident scenarios. Also, the driver's survival space was investigated whether interrupted during the performed crashes. For this purpose, a standardized manikin has been introduced into the simulations. General shape and dimensions of the used test dummy are according to Official Journal of the European Union for Commercial Vehicles Crash Testing [7]. The lack of complexity of the dummy is explained by the fact that it was used only to verify the survival space. The extensive biomechanics study was redundant for the studied case.

2.1. Geometric model of the roll cage

The paper presents the design of a custom roll cage utilizing combination of reverse engineering as well as traditional means of engineering design. On the basis of 3D lasers scan of the vehicle (Fig. 11) as well as technical documentation a geometric model of roll cage has been designed by the Authors (Fig. 12).

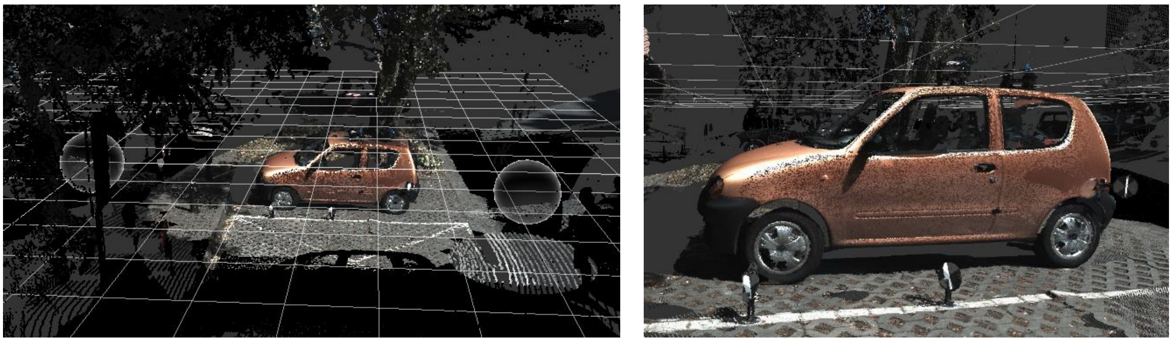


Fig. 11. Full view of scanned Fiat Seicento and its surroundings and magnified view of the car

The standard according to which the structure is designed allows for the choice of pipes dimensions and formed intersections as well as types of reinforcements. For the roll cage investigated in this paper the choice of tubing diameter was the following: for the main and front hoop Ø 50 mm x 2 mm and for the other pipes Ø 40 mm x 2 mm.

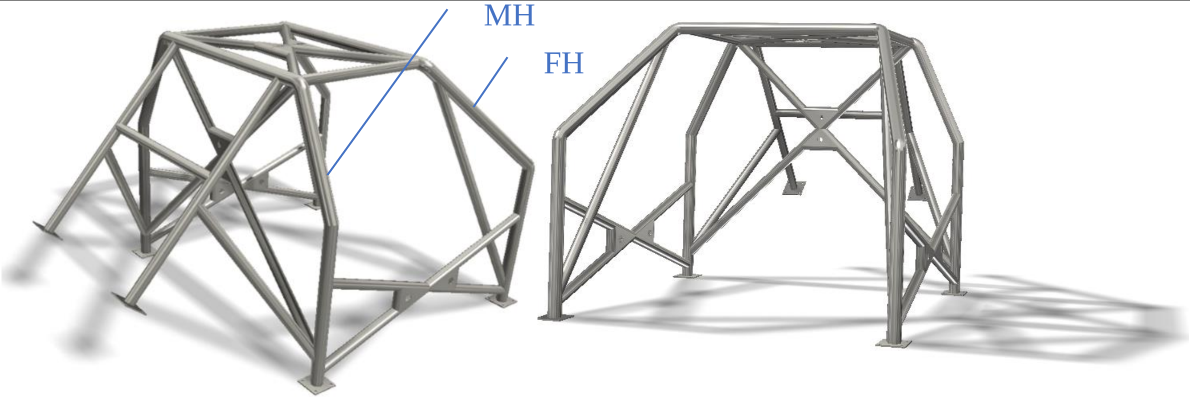


Fig. 12. 3D model of the roll cage with indicated main hoop (MH) and front hoop (FH)

Moreover, the self-prepared model of manikin was also introduced to all simulations. Both models have been subsequently discretized (Fig. 13). In order to save the computation time 2D shell elements were employed [8].

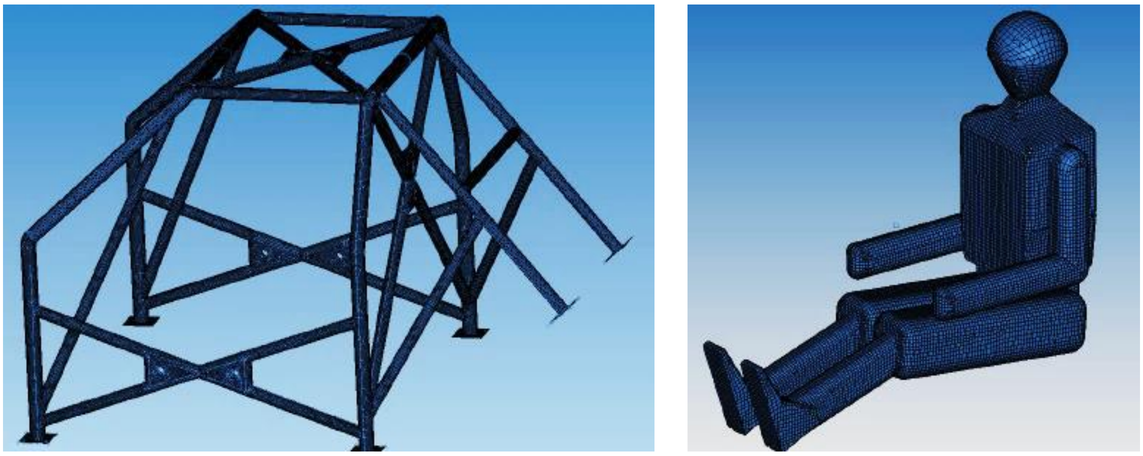


Fig. 13. Discrete models of roll cage and dummy

Model discretization was under particular focus since the explicit solver was utilized for all the simulations. The use of the explicit solver requires fulfillment of the Courant-Friedrichs-Lewy condition which emphasizes the importance of mesh size as it influences the computational time [9].

Accordingly, the average size of applied mesh was set to be 5 mm which resulted in the mesh consisted of 123948 and 25277 elements for roll cage and dummy respectively. Nevertheless, the quality of the manikin's mesh was negligible, due to the fact that its deformation was not examined. Figure 3 presents the meshed models.

Table 4. Mechanical properties of S355JR steel grade according to DIN EN 10 025 (1994-03-00) [10]

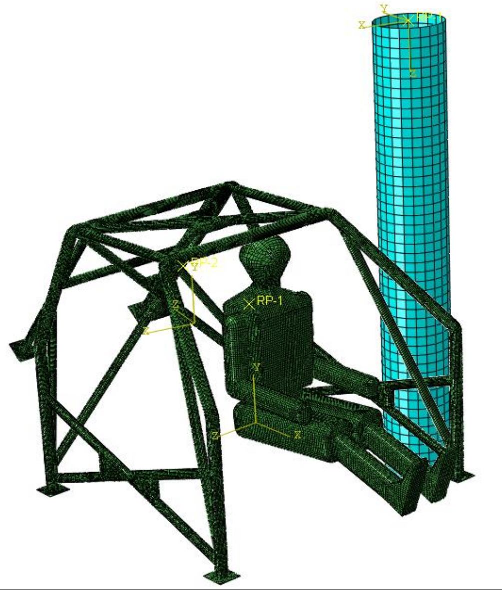
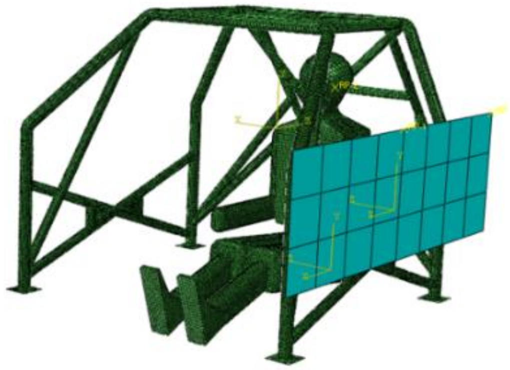
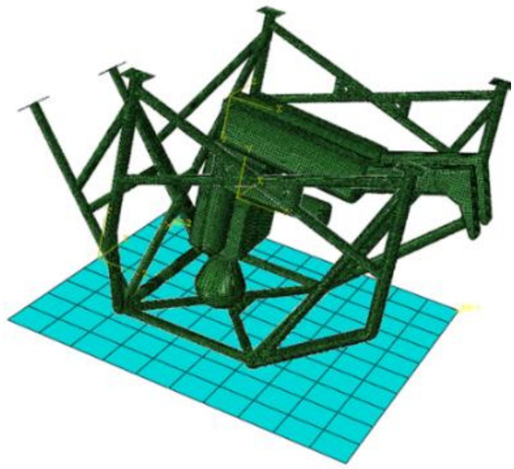
Material	**Type**	$\mathbf{R_m}$ [MPa]	$\mathbf{R_e}$ [MPa]
S355JR	Steel	510	355

The material assigned to the roll cage structure was S355JR steel. Not only does it offer high weldability (Carbon Equivalent Value ≤ 0.45 [10]), but also satisfactory tensile and yield properties. Table 4 presents the selected mechanical properties of S355JR grade. The investigated discrete model does not include welded joints representation. The model is a macro scale one, therefore it does not recreate all real loading conditions.

2.2. Simulation boundary conditions

The study contains three different accident scenarios (Table 5). Two of them verify the side impact protection offered by the structure. During the last one, the cage is subjected to a roof collision.

Table 5. Simulation setup description

Setup name	Short description	Illustration
Side impact – pole *(Setup A)*	**Collision with a pole** The rigid pole of 254 mm diameter. The cage sideways velocity set to 8.8 m/s. The angle between the direction of motion of the cage and its longitudinal centerline equal to 75º.	
Side impact – wall *(Setup B)*	**Collision with a wall** The rectangular wall of 1500 mm width and 500 mm height. The crash proceeded at velocity equal to 13.3 m/s.	
Roof impact (*Setup C)*	**Collision with ground** The initial vertical velocity of cage equals to 8.8 m/s.	

3. RESULTS

The results of the simulations setups described in the Table 5 are displayed in the Table 6. The pictures were chosen to ensure the overall view of the simulation in general as well as detailed manner.

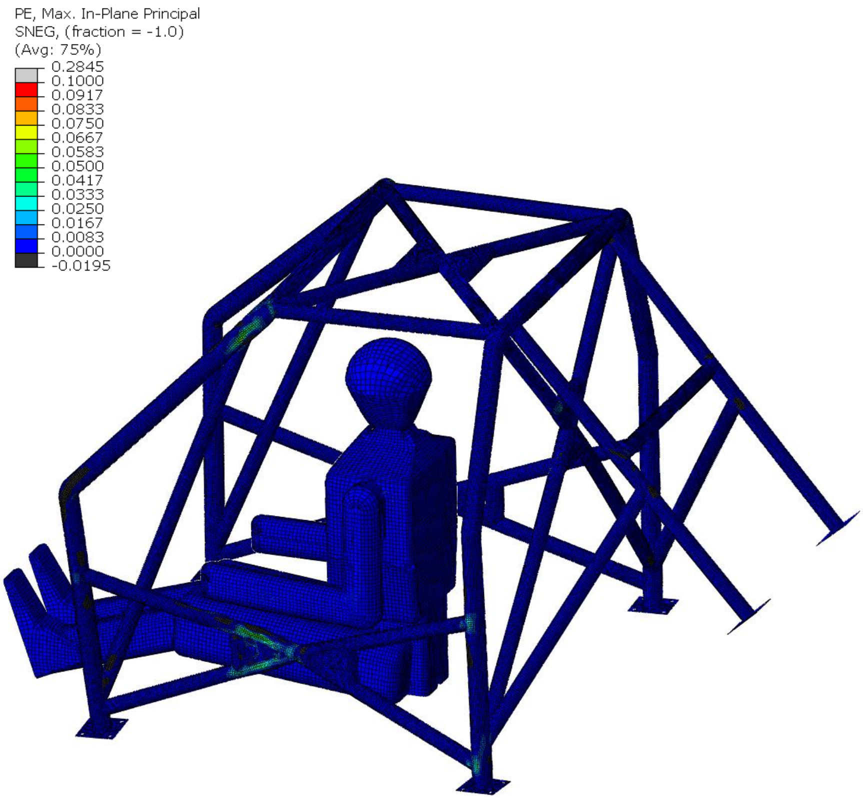
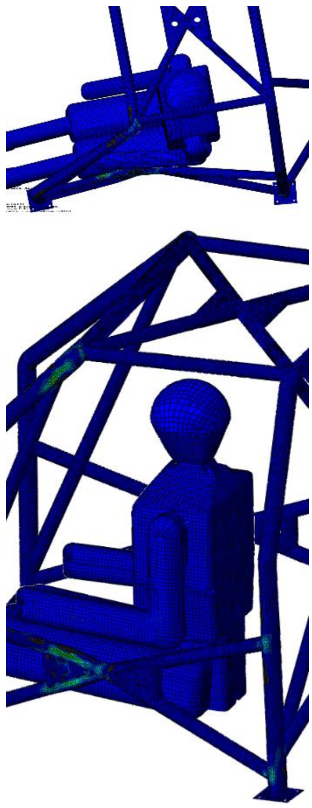
During the course of the first simulation (Setup A: side impact – pole) the side reinforcements become deflected up to the point they get in contact with the manikin. The dummy is hit by the side pipes in its left arm. Also, plastic strain of the structure can be witnessed during this crash scenario.

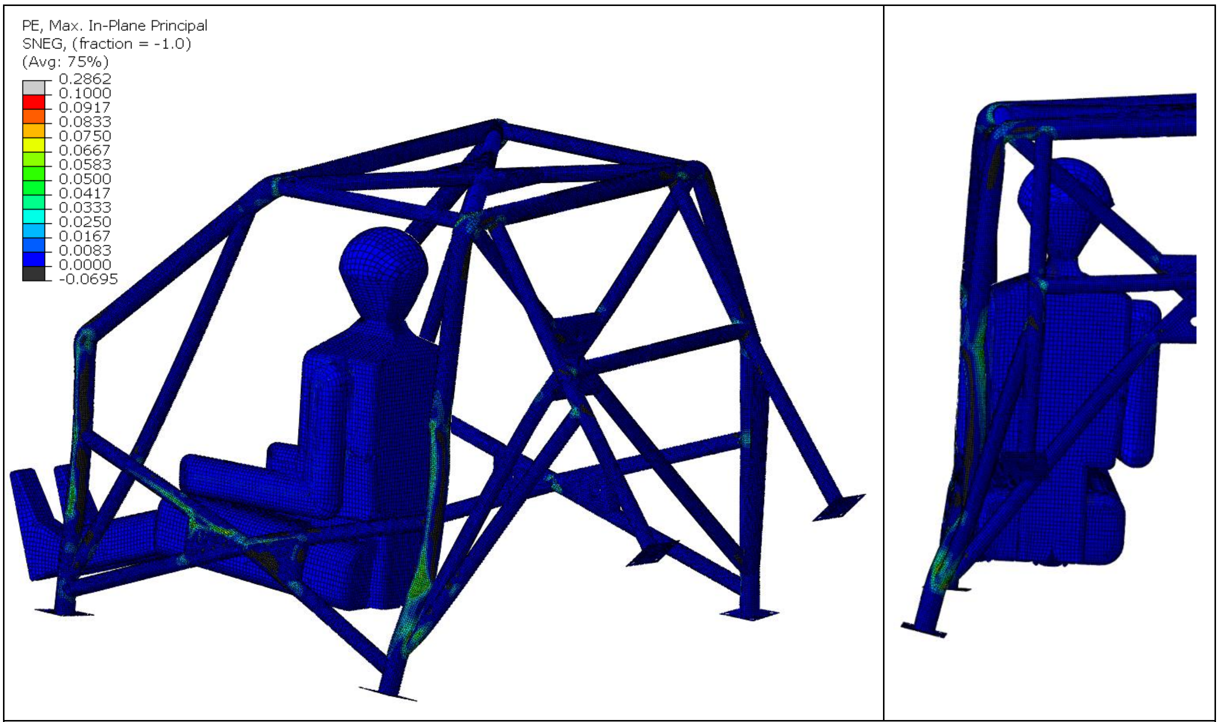
During this second crash test simulation (Setup B: side impact about the wall), the manikin survival space not only is interrupted by the piping, but also by the wall. Graphical representation is given below. Plastic strain is also observed during the second side impact. The manikin is also hit in the left arm, as for the pole collision scenario.

During the roof impact the survival space of the dummy remained intact. Setup C in Table **6** depicts the effect of the crash. As shown, the yield point of the S355 steel grade is exceeded only locally.

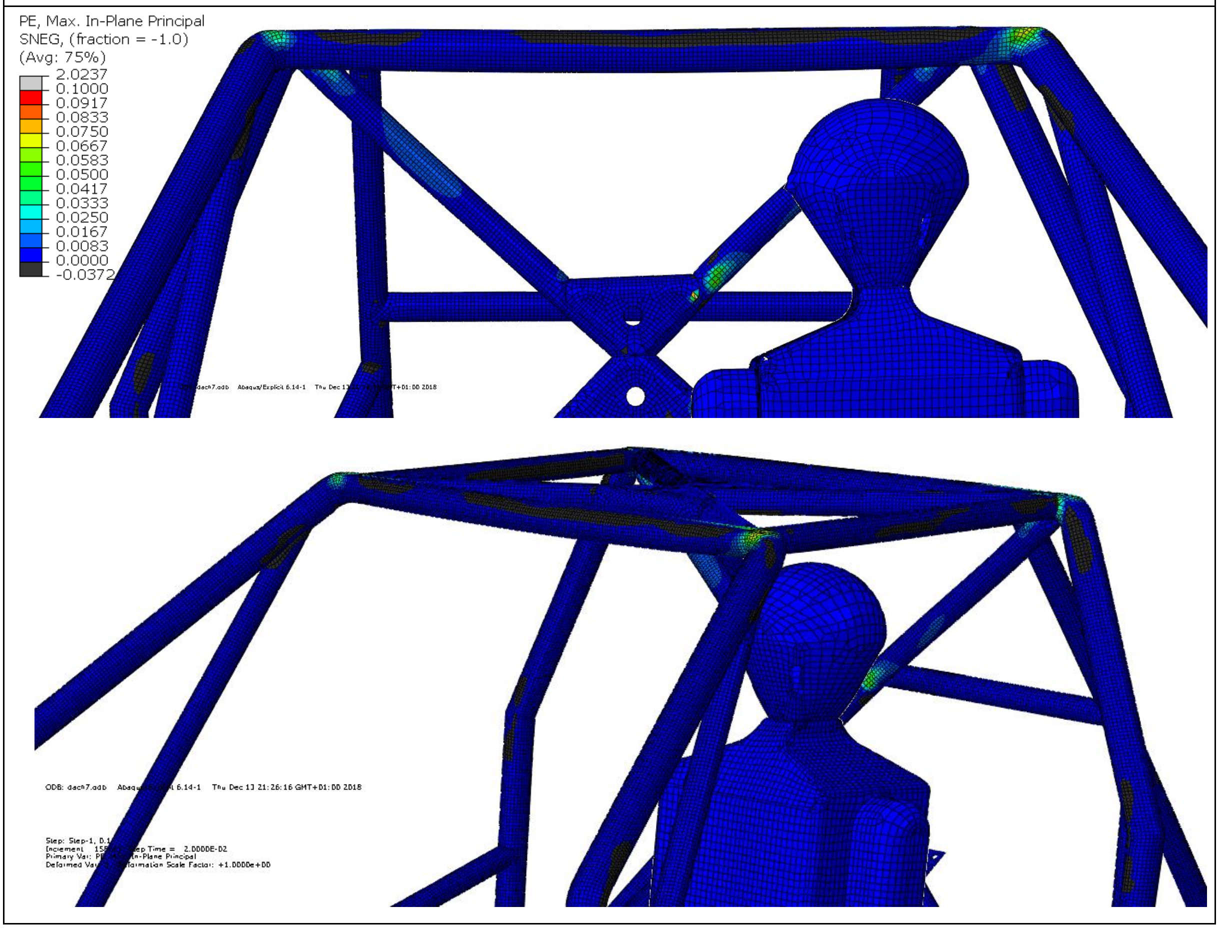
The last scenario shows satisfactory results. The cage withstands the load occurring during the roof impact with the velocity equal 8.8 m/s. A remark can be made that the cage would also withstand the load occurring during a rollover.

Table 6. Simulation results, plastic strain presentations [mm/mm]

General view	**Detailed view**
Setup A: Side impact – pole	
	
Setup B: Side impact – wall	



Setup C: Roof impact



3.1. Energy conversion

Every performed simulation was stable, namely the decrease of kinetic energy is proportional to the increase of internal energy (phase A and B). The occurrence of kinetic energy in phase C is due to the fact that the structure was bounced off the immovable object. the absolute value of the difference between internal and kinetic energy remained constant. Total energy, however stayed the same. Figure 14 displays the energy vs time exemplary graph for the pole side impact in particular. The graphs for all the remaining simulations were very similar. Energy transformation can be divided into 3 following stages set according to the moment of impact: A – before the impact, B – during impact, C – after the impact.

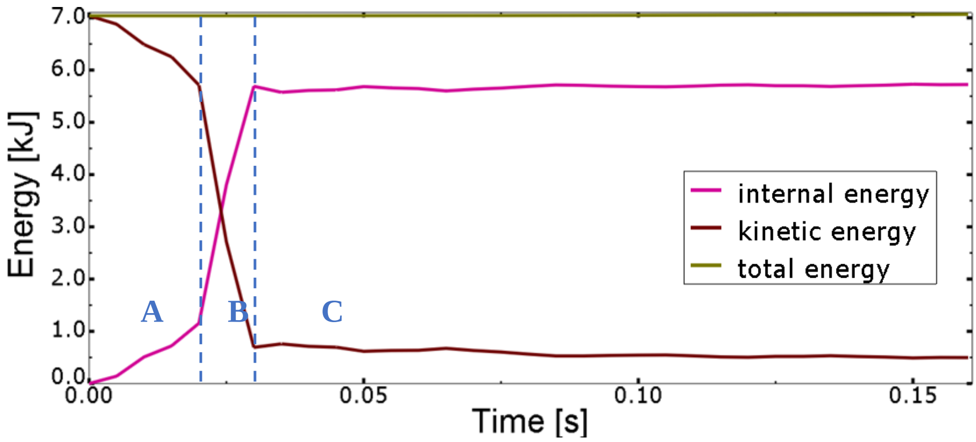


Figure 14. Energy vs time graph for the side impact against pole

4. CONCLUSIONS

Literature overview focused at the statistics of motorsport accidents helped to locate the weak spots of the roll cage structure. The gathered information directly indicated the course of performed research.

The tests confirm the already existing research concerning side impact protection system in rally cars. The roll cage has been designed according to the FIA standards, however the protection of the vehicle occupant is not sufficient. The structure significantly reduces the risk of fatal injuries, but does not eliminate serious ones. Current design of the door bars subjected to the combined loads during the side impact has very low energy absorption ability. The distance between the driver and the exterior object during a crash is approximately 200 mm. The kinetic energy has to be dissipated over this distance, which is a very challenging task to accomplish.

The dynamic tests have proven that the cage designed according to current standards does not withstand loads occurring during both investigated side impacts. There is visible interruption of manikin survival space in 2 out of 3 cases. The vehicle occupant remains intact only in the roof impact simulation. The easiest and most available alteration of the structure is the change of steel grade used for the cage tubing. Implementation of steel with higher yield point than S355 will undoubtedly reduce the deformations occurring in the structure.

The direction of research should be focused on development areas such as chassis or implementation of energy absorbers. Adding new members to the door-bar structure or increasing their cross-section area is not a satisfactory idea. This solution will increase the structure’s weight dramatically, substantially hindering the vehicle performance.

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WSTĘPNA WERYFIKACJA PRZESTRZENI BEZPIECZNEJ KLATKI BEZPIECZEŃSTWA PRZY UŻYCIU METODY ELEMENTÓW SKOŃCZONYCH

Streszczenie: Praca przedstawia badania dotyczące zweryfikowania konstrukcji autorskiego projektu klatki bezpieczeństwa do samochodu osobowego zaprojektowanej zgodnie z obowiązującymi standardami FIA. Zaproponowane rozwiązanie poddano testom dynamicznym w celu zbadania odporności na zdarzenia używając Metody Elementów Skończonych. W celu sprawdzenia przestrzeni bezpiecznej kierowcy użyto standardowego manekina. Uzyskane wyniki sygnalizują, że pomimo zachowania wytycznych ze standardu FIA klatka nie oferuje wystarczającej ochrony kierowcy w przypadku zderzeń bocznych.