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ANALYSIS OF INJURIES OF A DRIVER OF A ROLL CAGED CAR SUSTAINED DURING A ROLLOVER CRASH

Abstract: The aim of the study is to analyze the extent of injuries sustained by the driver during a crash rollover. A safety cage for 1996 Dodge Neon was designed following FIA guidelines as well as a seat. 50th percentile male HYBRID III ATD model was utilized. The crashworthiness of the test setup and verification of the injury measures were examined utilizing the Finite Elements Method in LS-DYNA software. Biomechanical injury measures that were investigated include neck normal and shear force and chest deflection.

Keywords: injury measures, roll cage, crashworthiness, ATD, hybrid III, LS-DYNA

1. INTRODUCTION

The rollover crash in rallies is characterized by a relatively small – 10% fatality rate (Figure 1). As a comparison, the most popular group of accidents which is caused by an impact to a tree or post has a 52% death rate (for 67 investigated cases as shown in the literature [1]). The reason why a rollover causes significantly less harm to the vehicle occupant is that the roll cage turns out to be very effective in the energy absorption and consequently, saves successfully lives of both drivers and co-drives.

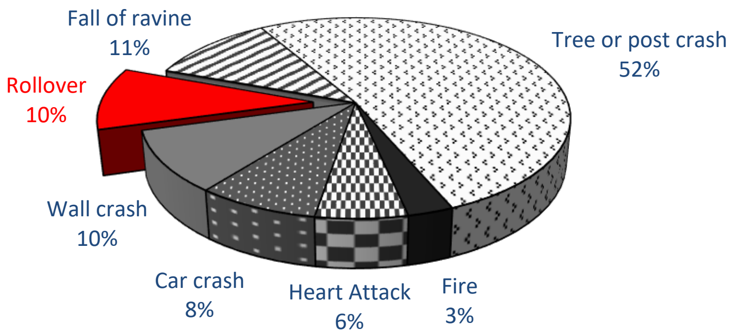

Figure 1. Fatalities per scenario in 67 investigated rally crashes adapted from [1]

The subject of the car rollover crash has been broadly investigated by the researchers [2]–[10] both numerically and in real-life conditions. To the knowledge of authors, only one paper includes tests of the car equipped with a roll cage [8]. That roll cage [8] is modelled as a simplified beam structure. For this reason, the main subject of the presented paper is to focus on the proper shape of the structure as well as its discretization accuracy as it is not widely investigated yet. Additionally, this study covers three injury measures: neck normal force, neck shear force, and chest deflection. In terms of future research, neck injury criteria (Nij), head injury criterion (HIC) measures [8], [9] can be also considered.

2. MATERIALS AND METHODS

2.1. Roll cage and racing seat

The paper presents the design of a custom roll cage for 1996 Dodge Neon. Based on the car model [11] as well as technical documentation, a geometric model of a roll cage structure has been designed by the Authors (Figure 2a). Dimensions of the tubes used for the cage model are specified in the following way: for the main and front rollbars diameter Ø 45 mm and thickness 2.5 mm, for other pipes Ø 40 mm x 2 mm.

The next important step was the design of a racing seat. The surface model of the seat (Figure 2b) was prepared basing on the already existing seat produced by the OMP company, which is following the latest FIA regulations [12].

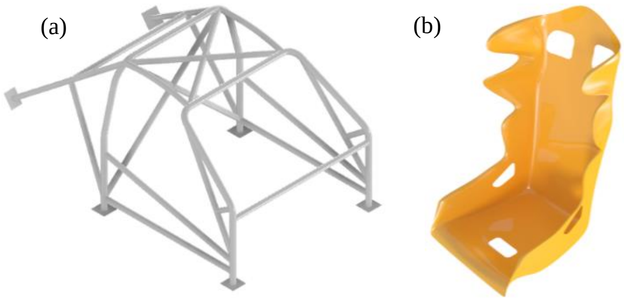

Figure 2. Roll cage (a) and seat models (b)

Table 1. Mechanical properties of 25CrMo4 steel grade according to [13]

Material		25CrMo4
Type		Steel
Tensile Strength	**R_m MPa]**	740
Yield Point	**R_e [MPa]**	590
Young Modulus	**E [GPa]**	210
Poisson Ratio	**υ [-]**	0.3
Density	**ρ [g/cm^3]**	7.85

The seat originally should be made of composite material, but for the sake of complexity reduction, the same material is assigned to both roll cage and seat. The material specified in the FIA J appendix is the weldable steel with a minimum yield point (**R_e**) of 350 MPa, which, however, does not have satisfactory performance as a roll cage construction material as proven in the previous paper [14]. Among suggested roll cage materials characterized by better mechanical properties [15], 25CrMo4 steel grade, with properties shown in Table 1, was chosen for the research. The multi-linear plastic material model was implemented into LS-DYNA software basing on the stress-strain curve shown in [16]. Emphasis is given to roll cage and seat models discretization (Figure 3a, b). The middle surface of the roll cage was needed to be extracted to apply the 2D mesh. In the case of the seat model this operation was omitted, due to the fact that I was originally designed as a surface model. Application of 2D shell elements (4-node quadrilateral elements and 3 node triangle elements where necessary) allowed to majorly save the computational time [17]. This is a very common practice when two dimensions are very large in comparison to the third one for example in sheet metal parts [18]. The size of the applied mesh was 5 mm for the roll cage and 10 mm for the seat, which resulted in the total number of elements equal to 123 065 and 11 085, respectively.

2.2. 1996 Dodge Neon and HYBRID III ATD

The vehicle model utilized for the research is 1996 Dodge Neon (Figure 3c). Although the model represents a passenger vehicle, the weight properties and overall dimensions fit the properties of the rally car. Additionally, the interior trim is removed which is typical for a competition vehicle. The full validated finite element model was developed and released by NCAC [11]. The model of the car is equipped with concentrated mass nodes that substitute components such as engine or gearbox. The model representing the human body is the Hybrid III male 50th percentile dummy FEM model (Figure 3d) which was previously validated in the literature for the purpose of rollover crashes [7], [10].

2.3. Simulation setup

The setup contains manikin, seat, and roll cage, all inserted into the car (Figure 3e). The manikin is restrained by a 5-point harness designed by the authors (red rectangle in Figure 3e). The harness was fitted and its length was adjusted using LS-PrePost Seatbelt fitting module.

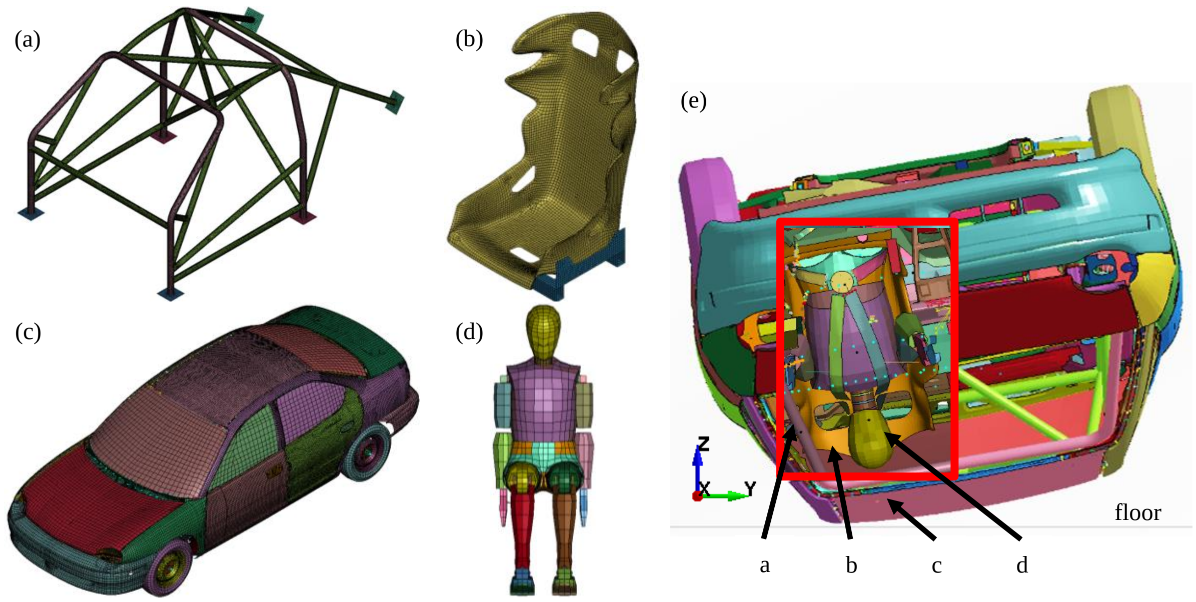

Figure 3. Meshed model of roll cage (a), seat (b) 1996 Dodge Neon and Hybrid III FAST (c) and 50th percentile male dummy (d) building simulation setup (e) showing harness

The initial boundary conditions for the two cases (Table 2) differ in assigned lateral (y-direction) and vertical velocities (z-direction). In both simulations, the initial roll rate is assigned to be 225 deg/s, and setup is tilted at 10 deg to the ground. Also, gravity is taken into consideration. Similar impact conditions were observed in [8].

Table 2. Initial boundary conditions for case 1 and 2

Case	Lateral velocity [m/s]	Vertical velocity [m/s]	Initial roll rate [deg/s]	Initial angle [deg]
1	-3.6	-2.3	225	10
2	-5.4	-3.5	225	10

3. RESULTS AND DISCUSSION

The termination time for the simulation was set to be 150 ms. The car body deformed extensively up to the point when the roll cage started to absorb the impact and at that moment the roll cage construction proved its crashworthiness and successfully protected the occupant's survival space. In both cases, the plastic deformation of the roll cage structure was not observed. Through the course of both simulations (Figure 4, Figure 5), there was no contact recognized between the dummy's head and the car body or roll cage. It is shown in the literature [9], that the dummy head in the car not equipped with the safety cage when subjected to rollover exhibits roof contact.

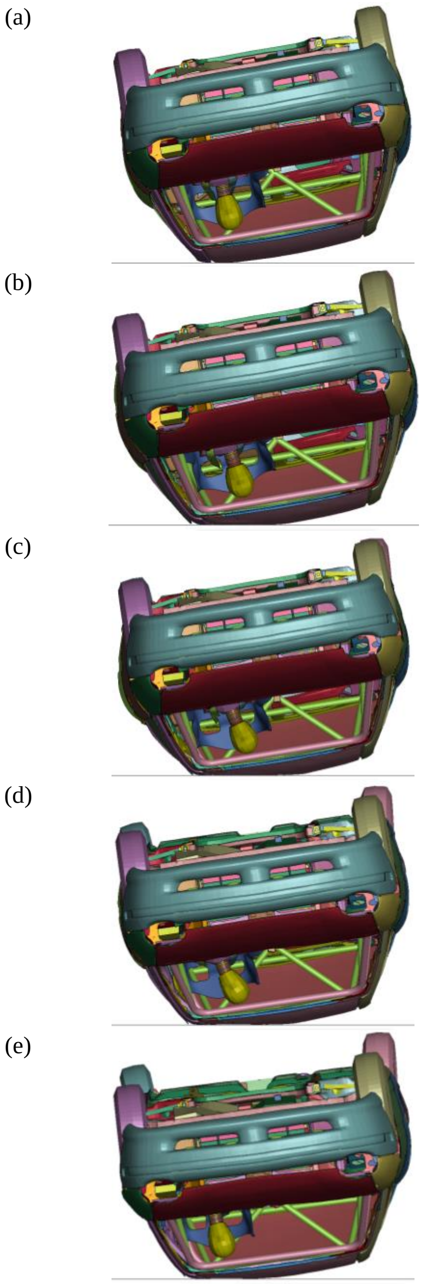

Figure 4. Simulation results of case 1 for the selected timeframes: 8 ms (a), 32 ms (b), 52 ms (c), 82 ms (d), 106 ms (e)

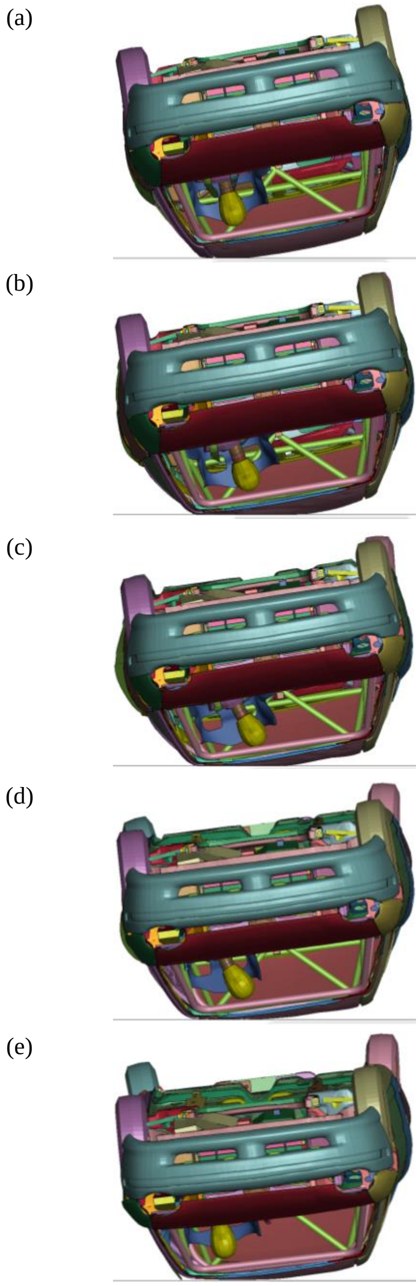

Figure 5. Simulation results of case 2 for the selected timeframes: 8 ms (a), 32 ms (b), 52 ms (c), 82 ms (d), 106 ms (e)

Additionally, literature shows that the limbs do interact with the surroundings [9]. That random motion is caused by the inertia and is observed also in the presented cases. In case 1

(Figure 4), only the contact of the left arm with the door is detected. It evidences low impact velocity and hence low crash severity. For case 2 (Figure 5), the dummy movement includes also contact of lower legs with the roll cage which is caused by assigning higher initial velocity.

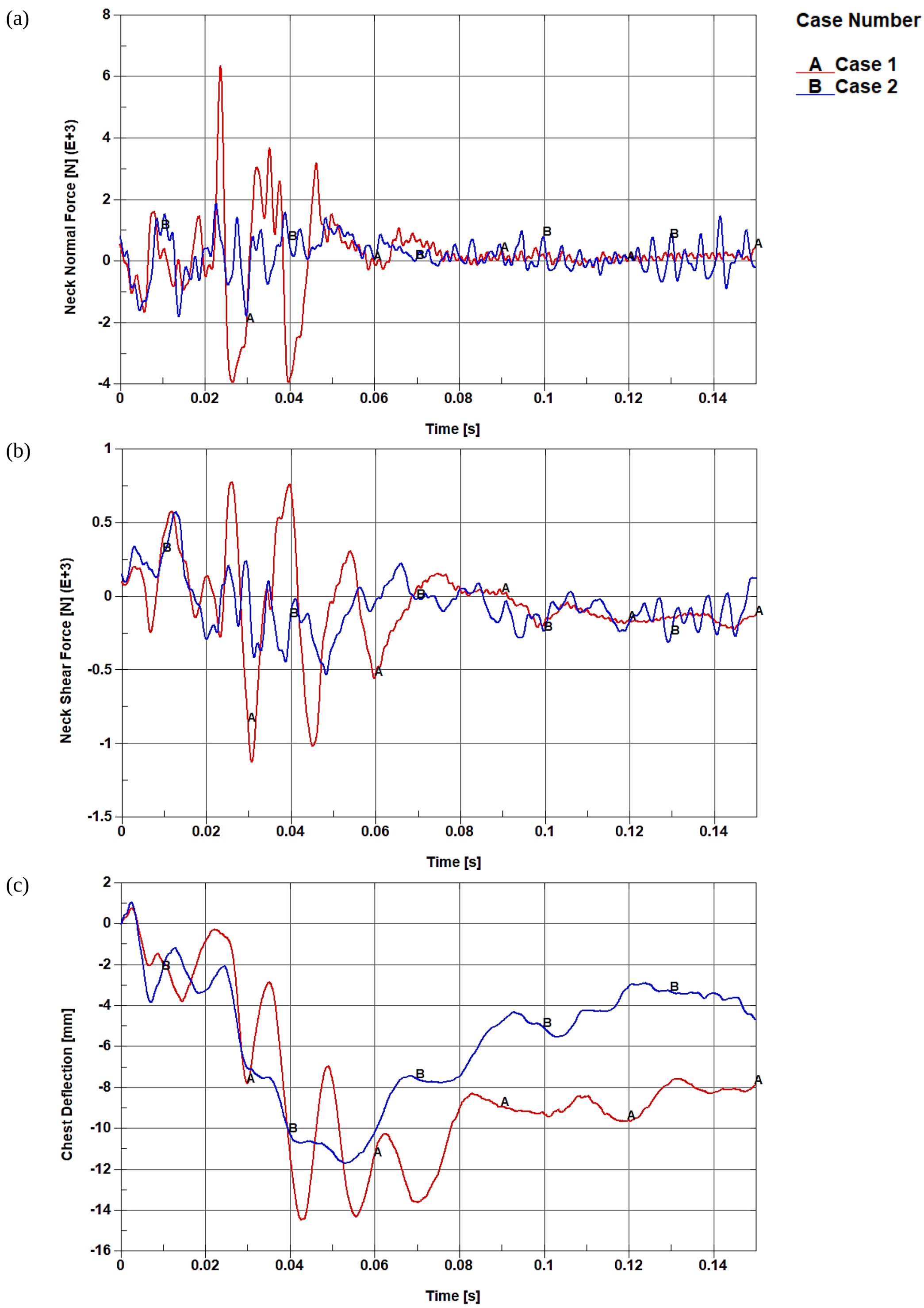

Figure 6. Time history of neck normal force [kN] (a), neck shear force [kN] (b) and chest deflection [mm] (c)

Aside from the manikin dynamics, the biomechanical injury measures being neck normal force, neck shear force, and chest deflection were investigated.

The values of the normal (Figure 6a) and shear neck forces (Figure 6b) are smaller than the ones obtained during tests of a non-caged vehicle [9], where the head-roof contact occurred. The peak values for the neck normal force are the following case 1: nearly 6.4 kN tension and

4.0 kN compression, case 2: about 9.0 kN tension, nearly 1.8 kN compression. The shear neck force values are approximately 25% of normal forces values (average for both cases). The exact values of maximum neck shear forces are case 1 – 1120 N, case 2 – 578 N.

The chest deflection time history graph (Figure 6c) shows satisfactory results for both impact cases. The maximum chest deflection values for case 1 and 2 are observed to be to 14.4 mm and 11.7 mm, consecutively which is lower than the recommended critical value by NHTSA of chest deflection of a mid-sized male (represented in this paper by Hybrid III 50th percentile dummy model) being 63 mm [19]. It is believed that the lack of movement of the manikin's body is caused by the application of 5-point harness. Typically, the usage of ordinary seatbelts when having an accident lead to occurring submarining effect [20]. In the investigated setups, the manikin remained properly restrained during the whole course of the crash.

4. CONCLUSIONS

Literature overview focused on the statistics and testing methods of rollover crashes assisted in indicating the course of the presented research. The performed finite element simulations confirmed the rollover crashworthiness of roll caged vehicles. It is shown that the injury measures are lower than the ones occurring in studies concerning non-caged cars. The most satisfactory remark is that no contact of the dummy head with the surroundings was witnessed.

Since the values of the injury measures obtained in the simulations are low, it may be reasonable to test the setup for more severe initial boundary conditions. Most of all, it may be of high importance due to the application of roll cages in motorsport where the overload is a routine.

It was observed, that the manikin model obtained from LSTC Software Corporation exhibits high instability during the preliminary runs at higher velocities. For that reason, in case of assigning higher initial velocities, the simulations can be also updated with a more sophisticated manikin model, for instance, THUMS (Total Human Model for Safety).

Literature shows extensive research on non-caged vehicles and this research proves the need for testing the caged ones since the application of the roll cage highlights different problems. For that reason, future research should be aimed at adding the helmet and HANS (Head and Neck Support System) to the setup as this equipment is currently mandatory in motorsport, similarly as in [21], [22].

Additionally, with the selected safety features, it would be advisable to check the Head and Neck Injury Criteria. The models of current vehicles on the market would be also better to test.

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ANALIZA OBRAŻEŃ DOZNANYCH PRZEZ KIEROWCE SAMOCHODU WYPOSAŻONEGO W KLATKĘ BEZPIECZEŃSTWA PODCZAS DACHOWANIA

Streszczenie: Praca przedstawia badania dotyczące ustalenia rozległości obrażeń (Siła normalna oraz tnąca w odcinku szyjnym kręgosłupa oraz ugięcie klatki piersiowej) kierowcy samochodu wyposażonego w klatkę bezpieczeństwa podczas dachowania. Do symulacji został użyty model dyskretny 50 centylowego manekina Hybrid III. Test dachowania pojazdu (1996 Dodge Neon) został przeprowadzony przy użyciu Metody Elementów Skończonych w programie LS-DYNA.