Finite element dynamic simulation of whole rallying car structure: Towards better understanding of structural dynamics during side impacts

E. Nassiopoulos and J. Njuguna*
School of Applied Sciences, Cranfield University, Bedfordshire MK43 0AL, UK

Abstract

Side impact accidents against a tree or pole remain the most dangerous accident scenarios in rally cars. Statistical data shows that 52% of the fatalities between 2004 and 2009 concern crashes against a rigid pole by the track sides, whilst among those more than 60% were side impacts. Despite the present scientific efforts, rallying cars side impacts are still among the least understood primarily due to limited space between the occupant and door sill, evolving safety regulations and vehicle dynamics.

In this study, finite element dynamic characteristics of the whole car were studied. The finite element model consisted of the whole car structure and 241 parts including the engines, tyres and the suspension members with 4 different element types and 7 material models. All structural parts were modelled as low-carbon steel with the piecewise-linear-plasticity material model (mat 24). The tyres were modelled with the Blatz-Ko rubber material (mat 07) whilst also rigid and other materials (mat 020, 01, 09, S01 and S02) were used to represent different parts of the model, as the suspension members, suspension links and the engine. A rollcage and two racing seats were modelled with four-node shell elements and the use of piecewise-linear-plasticity and composite-damage materials respectively. A semi-cylindrical pole of 200mm diameter was also designed and modelled as a rigid body. The model was used to first investigate the dynamics of the crash, and later run a wide range of simulations and parametric studies in the cage, the car's floor and the seats.

The important findings from the study are presented, conclusions drawn and scope for further development outlined.

Keywords: Side impact protection, World rally championship (WRC), Rollcage, Energy Absorption, Finite Element analysis, LS-DYNA

* Corresponding author. j.njuguna@cranfield.ac.uk, Tel. +44 1234 754186, Fax: +44 1234 752473 (J. Njuguna).
E. Nassiopoulos: Email contact: e.nassiopoulos@cranfield.ac.uk

1 Introduction

In the last two decades safety in rally cars has improved significantly due to successful efforts in new innovative and crashworthy materials [1; 2], improvements of the seats [3] and the rollcage design [4]. However the car side remains the most vulnerable area since there is very small distance (approximately 200mm) between the outer skin of the car (door-skin) and the occupants. The open space required for the quick extraction of the occupants in case of an accident, minimizes further the space available for protection and for dissipation of the energy. Even worse are crashes against trees as the small contact area results in load concentration and excessive deformations of the structure. Unfortunately, protection against side impacts is one of the least researched areas in rally cars despite being found largely ineffective in preventing injuries in case of side crashes against trees or posts [5].

Statistical data [5; 6] show that side impacts against a tree or post are nowadays among the most dangerous accident scenarios in rally cars with a high number of casualties every year underlying the necessity for research and improvements in this area. Between 2004 and 2009 52% of occupant fatalities were due to crashes against a tree whilst among them more than 60% considered side impacts. Fatalities due to rollover represented the 10% of the cases and another 10% was due to wall crashes. The foundation of the FIA institute in 2004 and the new side safety upgrade in 2008 had a positive influence in the safety of the sport but there is still the necessity for further measures.

On the road cars, much research has focused on the development of countermeasures including the vehicle side structure energy absorption and human response in side impact events [3; 7-9]. New composite materials and structure optimization [10] have been widely used and some advanced methods have been developed to protect the occupants during a side impact. For road vehicles, tests and simulations are performed to evaluate a vehicle's side impact safety. Various side impact test methods exist [5; 9; 11], and the moving deformable barrier together with pole side impact test are being used as the standard certified test on a car for side impact safety analysis.

However, racing cars are very different from road cars and some of these systems are either not allowed in the rallying cars (e.g. airbags) or would need a careful re-thinking for practical implementation in a racing car. Several studies focused already on the problem of side impacts in racing vehicles [12-14]. Though very few of these studies are on rallying cars [4; 9].

Side impacts are nowadays among the major concerns of the racing regulation boards, the racing teams and the participants themselves with a number of running research programs [15]. However the significant number of incidents, with some recent examples [6; 16] underline the necessity for systematic research and improvements on the cars, the safety features and the tracks.

FEA dynamic simulations can help the assessment of the current structure and potential improvements. The LS-DYNA explicit finite element code was used to analyze a detailed model of a rally car rollcage and simulate its response under a side-pole-impact, using a 200mm cylindrical indenter. Simulations were conducted to understand the real sequence of events during a side impact against a pole. Three main studies on the rollcage, the seats, and the floor were run to assess their contribution into the side impact safety of WRC cars.

The model used consisted of an assembly of three individual models as shown in Figure 1, a full

car model including an engine, a fuel tank, tyres and the whole suspension setup, two racing seats and a standard FIA rollcage. All three are described individually below and have been validated with different methods as discussed later. For the mesh generation and set-up of the models ANSA 13.0.2 was whilst each model was then imported in the non-linear FE code LS-DYNA.

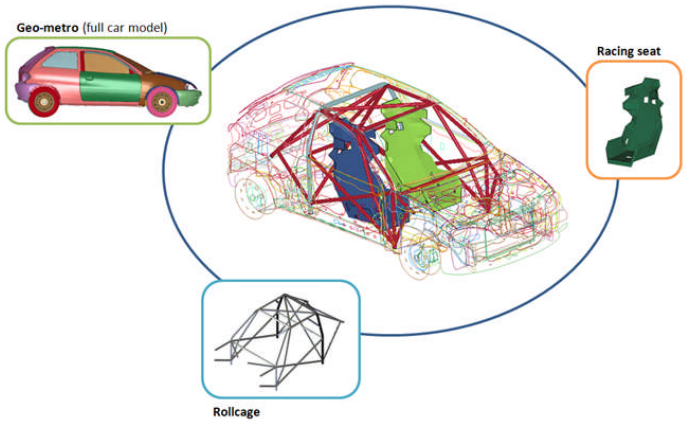


Figure 1: The model assembly

2 Model assembly and validation

2.1 Chassis model

In this study a Geo metro was used for the simulations and was analyzed in side impacts against a rigid post. The Geo Metro was a marketing and manufacturing variation of the Suzuki Cultus available in North America from 1989 through 2001 as a joint effort of GM and Suzuki. The full model of this vehicle was developed and released by NCAC (National Crash Analysis Centre), a successful collaborative effort among the Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration (NHTSA) and The George Washington University (GWU).

Although the model represents the commercial edition of the vehicle, the overall dimensional and weight properties fit nicely with the properties of a recent rally car and was therefore chose for these studies. The overall length of the car/model was 3755mm, its width 1560mm, and the height 1420mm from the ground. The centre of gravity was at around 500mm from the ground and located in 1750mm from the front end of the car giving a distribution of around 55/45. The overall weight was 1300 kg and so later together with the seats and cage the weight raised to 1400kg which was the target value.

The full-vehicle model, consisting of 193200 elements and 200348 nodes was used. The model consists of 241 parts including the engines, tyres and the suspension members, 4 different element types, and 7 material models.

The structural parts are modelled as low-carbon steel with different mechanical properties representing different steel grades. All steel parts were modelled with the piecewise-linear-

plasticity material model (mat 24). The tyres were modelled with the Blatz-Ko rubber material (mat 07) whilst also rigid material (mat 020) and materials 01, 09, S01 and S02 were used to represent different parts of the model as the suspension members, suspension links and the engine.

Four-node shell elements were mainly used while three-node elements (trias) were unavoidably required in complicated regions of the model. Constant stress solid elements were also used for some engine brackets and the accelerometers as well as beam and discrete elements for the suspension members.

Since experimental data was unavailable to validate the car model a EuroNCAP pole test was simulated and photographic evidence was used from a real EuroNCAP tests of a Renault Megane of 1999 which has same mass and dimensional values. In a EuroNCAP side pole test, the car travels with a velocity of 29 km/h into a rigid pole of 254mm diameter. The model was set with the exact same values.

The results from the simulation and comparison with the EuroNCAP test are depicted below. It can be seen that our full car model has realistic deformations and the response match closely with the EuroNCAP test. These results give confidence about the model which can be trusted for further research and simulations. Data from accelerations and forces during the crash were not available hence the need of precise validation is underlined for future research.

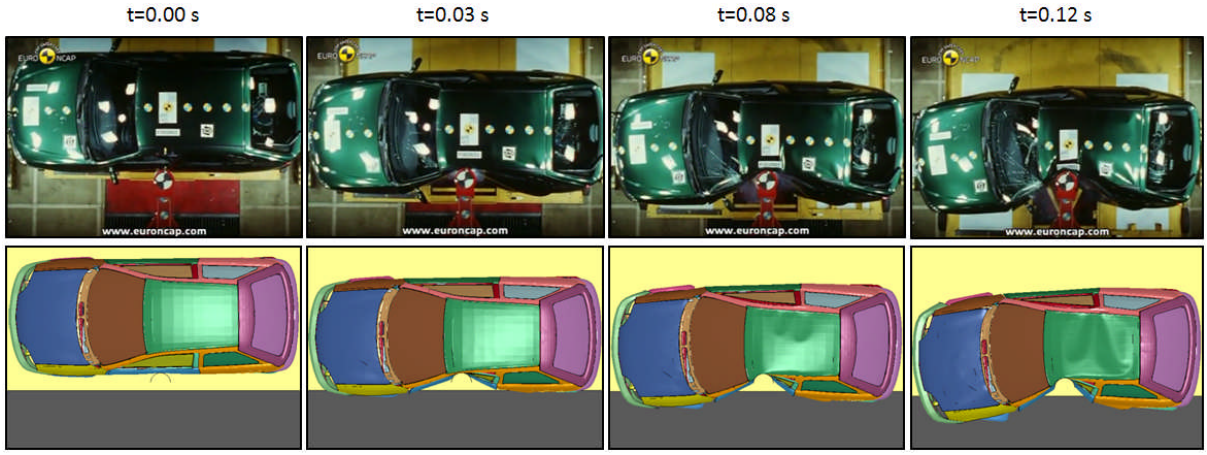


Figure 2: Validation of the car model using photographic evidence from a EuroNCAP test

2.2 Rollcage

A 3D model of a typical WRC rollcage was introduced into the model. The rollcage was carefully designed to follow and comply with the 2009 rally season (group N, A, B, SP) FIA regulations [17]. The material used was low-carbon steel with mass density, ρ= 7.83g/cm^3, Young's modulus E = 210GPa, yield stress, σ= 690MPa and Poisson's ratio, ν= 0.3. These properties represent T45 tubes (carbon-manganese cold drawn seamless tubes) which are widely used by the WRC teams and several cage manufacturers for the construction of the rollcage [17]. The material was modelled with the piecewise-linear-plasticity material model (mat 24). For the stress-strain behaviour a curve of effective stress vs. effective strain was defined. Failure was also added as a plastic strain limit, above which elements were deleted from the calculation.

Two sections were used for the cage tubes as described in the FIA regulations. For the main hoop tubes with a 50mm diameter were used with a thickness of 2mm, while for the rest of the cage members 40mm diameter tubes with 2mm thickness. Between the different dimensional options allowed into the regulations these two were chosen due to their small advantage in the weight. The cage tubes were modelled with 2D-shell elements created on the circumference of their mean diameter. A Belytschko-Tsay [18-19] formulation was again chosen with three through-the-thickness integration points. Again four-node shell elements were mainly used while three-node elements (trias) were unavoidably required in complicated regions of the model like the intersection of two tubes. Thus 106600 tetras (quads) and 2230 trias shell elements were generated, sufficient for accurate representation of the deformations expected and computational time efficiency.

The cage model was fitted into the Geo-metro full car model and was attach in the four bases, the rear backstays and the front suspension members. For the attachment spot-weld connections were utilized as in a real rally car but the strength and failure of the welding was not considered. The effect of the welding between the tubes was also excluded from the simulations.

2.3 Racing seats

The seats that conform to the latest FIA regulations (FIA 8862-2009) were modelled with 2D-shell elements. A Belytschko-Tsay [19] formulation was again chosen with eight through-the-thickness integration points to represent the carbon-composite layers. The model consisted of 2764 four-node shell elements with 2897 nodes.

As the seat originally consisted of composite materials, the material model “composite damage” (mat 22) was used. Experimental results from a side pad test conducted for the specific seat were readily available although material data details were withheld due to confidentiality issues.

To validate the seat model, a side pad simulation was reproduced as required WRC regulations. Two cylindrical pads of 300mm diameter, compress the seats from both sides and on the seat side-shoulder positions. Forces and deformations are then measured. To simulate the test, the cylindrical pads were modelled as rigid bodies and a prescribed motion was applied on both. The force was measured with the help of two spring elements introduced in the pad ends. The deformations were calculated comparing the initial position of the pads with the resulting displacement for each time step.

Figure 3 depicts the results for both the experiment and the simulation. The results from the simulation are in very good agreement with those from the experiments and confirm that the model properties match closely with the experimental ones.

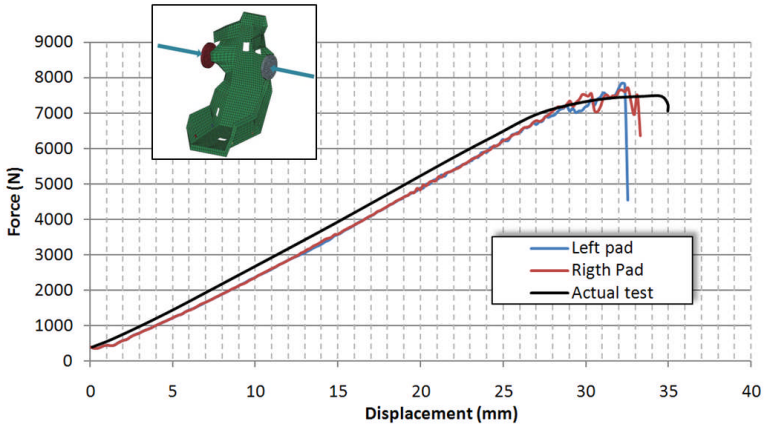
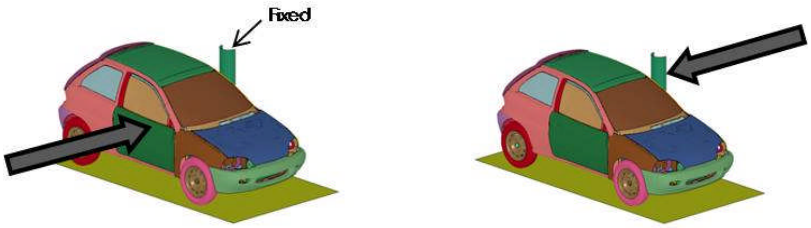


Figure 3: Side pad test of the seat model; comparison of the simulation and the test results

2.4 Crash dynamics

Previous studies [1; 4] looking into the topic of side impacts against a tree or pole in rally cars have conducted simulations having the car or the cage constrained while the tree was moving against it having initially the total energy of the crash. This assumption resulted in efficient models with a small simulation time. Additionally the same procedure is often used by testing authorities for crash-test studies. The car is standing while a rigid pole is thrown into its side having the same energy as the moving car would have travelling sideways with 16.6 m/s.

To understand the differences between the two different situations simulations were carried (figure 4). In the first, the car was given the initial velocity of 16.6m/s and was displaced sideways to impact with the tree. No kinematic constrains were applied on the car, apart from the physical constrain of the road represented by a flat rigid wall. The tree was rigidly constrained and an automatic surface to surface contact was set between the two. An accelerometer on the door (on the contact area) and another one on the top of the gearbox were placed to measure the velocities and forces of the crash. The placement of the accelerometers was chosen so as to help the measurement of the velocities during the crash in a position into the cockpit close to the occupants.



(a) (b)

Figure 4: The two different kinematic approaches. (a): The car runs into the tree (b) The tree intrudes the stationery car

In the second simulation, the tree was given the velocity to go into the car that was now standing. A mass of 1350 kg and a velocity of 16.6 m/s were added to give the tree the same kinetic energy. The car was stationery on the road level defined by a flat rigid wall without any other kinematic constraints. The same positioning for the accelerometers was used.

The results shown below depict a significant difference between the two cases. When the tree hits the car in the second simulation it first deforms the side of the car (as the inertia forces of the car are initially big), which however slowly obtains the velocity of the tree. Being free to move the car will after some moments move in a direction away from the tree. This ability of the car to move freely after the impact has an influence on the accelerations and the forces measured.

Clearly the practical case where the car runs into a rigid tree is more severe. The accelerations as well as the deformations are higher, and during an impact are more likely to cause severe injuries and damage to the occupants. This method was therefore used in these studies.

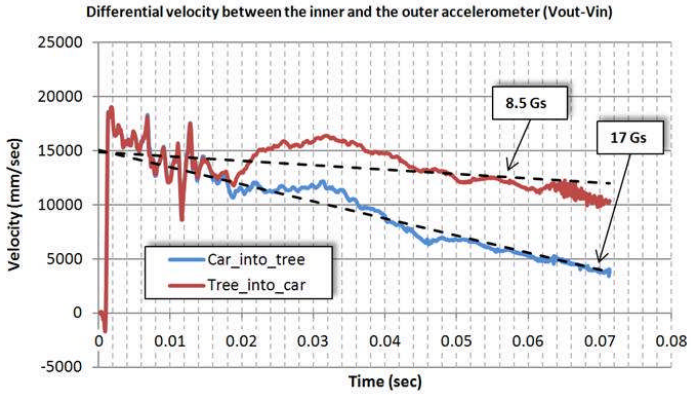


Figure 5: Differential velocity between the inner and the outer accelerometer for both tests

3 Results and Discussion

Three parametric studies on the cage, seats and floor were conducted. These areas where chosen so as to give an overall view of the sequence of events during a side impact and lead to realistic conclusion on which area of the car should be more investigated and improved.

3.1 Cage studies

Two simulations were first run, with and without rollcage. Their comparison gives the magnitude of the contribution that a standard FIA cage has in the side impact protection of the WRC cars. The tube thickness was then increased from 2 to 4 mm. The tube thickness was selected as it is the parameter that controls the bending stiffness and strength of the tubes and as a consequence of the whole cage.

The results can be seen and compared in the figure 6. The case without cage is as expected the weakest with almost a d=748 mm deformation of the side of the car, resulting in a remaining space in the cockpit of R=722mm. In figure 6 the excessive deformations of the car's structure can

be observed. The inside door fully disappeared after the crash whilst the front and rear end of the car came in contact. The outside door was also deformed and opened as the seat pushed it to the outside. Interesting is also the final position of the seat that ended almost out of the car, and could in a real situation cause extremely severe injury to the occupant seated. The negative values in figured 7 can be explained as elastic rebound of the car after the whole kinetic energy is absorbed.

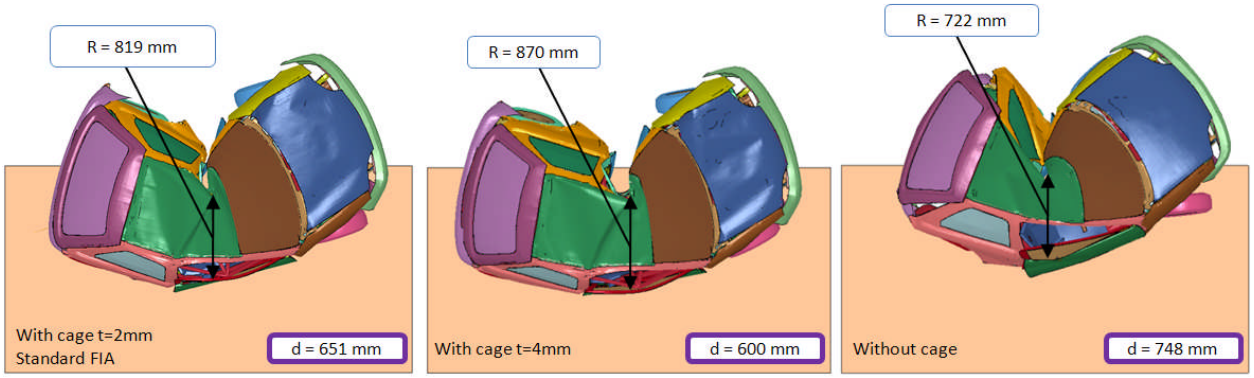


Figure 6: Deformation results of the three simulations conducted

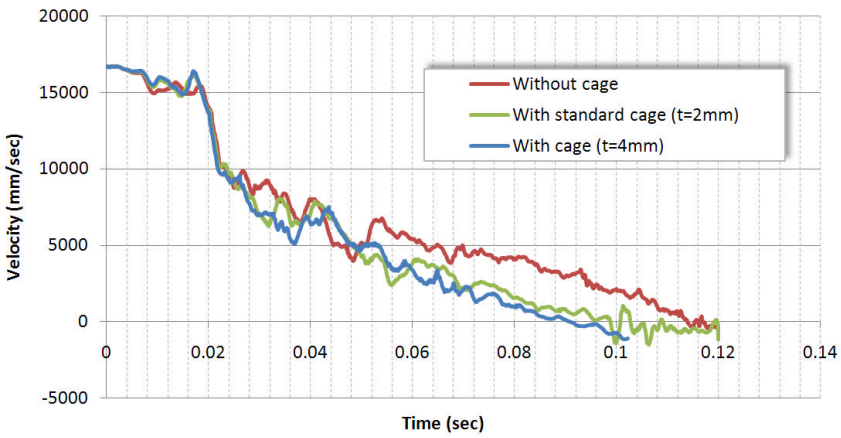


Figure 7: Velocity profiles

The results obtained above show that the rollcage structure has an effect on the energy absorption as it reinforces the chassis and reduces the deformations. This effect is associated primarily with the members on the outer side (opposite side of the impact) that are loaded under tension, in comparison with the member on the impact side which due to the contact, collapse instantly. Large deformation and failure can be observed on the doorbars on the same side.

The standard rollcage reduces the deformation 97mm improving safety by almost 13.5%. The 4mm-thickness cage reduces them by 148mm, a further improvement of 6.2%. However the weight penalty for the further improvement doubles from 55 to 110kg.

3.2 Seat studies

From the observation of the first simulation results, the seats have proven to be a big load path. During a crash the tree intrudes the side of the car and contacts the interior seat. Under the load the seat deforms and starts moving towards the exterior and the second seat. The contact between the two seats signifies after some instants the stop of the intrusion, even though the deformation of the car's structure continues for some more milliseconds.

Looking closer at the seats, deformation and failure of the interior seat can be observed due to the contact with the intruding tree and the high energy of the impact. Failure can also be observed in both seats in the mountings, as these points work as stress concentrators when the seats are both pushed to move towards the exterior. In the contact area no severe deformation can be observed, however the loading results in a relative rotation between the seats.

A simulation without the seats was first run, and the results (figure 8) show excessive deformations of the car structure. The intrusion was 805mm ending in a 665mm remaining cockpit width. The rear and front ends are in contact, and the exterior side of the car is also heavily distorted. Compared to the results presented above, this case proves that the seats reduce up to 25% the deformations and underlines the importance of the seats in the side impact protection of the occupants.

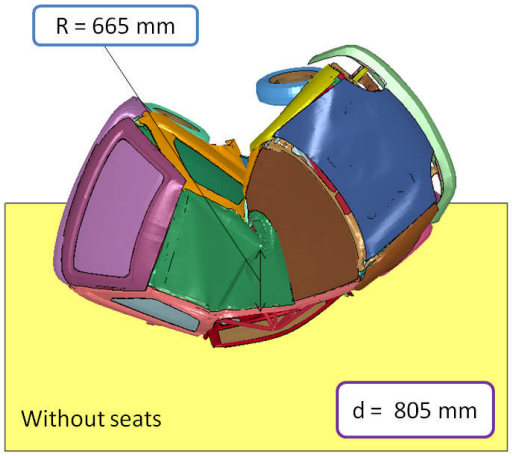


Figure 8: Resultant deformations of car the car structure without seats

Two more simulations were conducted. This was to better understand the benefit that attaching the seats would bring in the case of an accident and assess the potential of such an attachment. In the first, the seats are rigidly attached using rigid beam elements as shown in figure 9 whilst in the second simulation two steel beams of 10mm are introduced between the seats so as to control the deformation and absorb energy before the contact of the seats (figure 10).

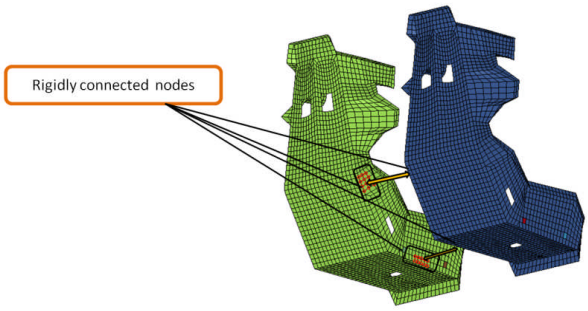


Figure 9: Rigidly attached seats

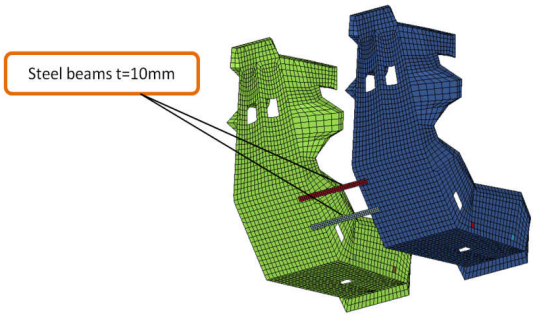


Figure 10: Seat attached via two steel beams

Figures 11 to 13 present the results for both simulations including photos and curves for the comparison of the solutions. It was expected that attaching rigidly the seats would have a significant effect on the energy absorption and the reduction of the deformations. However the results show that intrusion is 567mm and the remaining width 903mm, just 84mm less than the initial case and the standard vehicle. This result can be associated with the response of the interior seat as can be depicted in figure 11. The stiffness of the structure due to the attachment ends in high deformations of the seat that is totally destroyed. The forces and the energy of the impact were absorbed not any more from the displacement of the seat and its mountings, but from the deformation of the head and pelvis protecting pads and the multiple failures of the seat's body. Extended deformations and failure can now also be observed in the exterior seat as the later was crashed with high energy in the car's interior and the cage. This result shows that a rigid attachment can be crucial in the case of a crash, as it can result in high distortion of the seat and thus suppression of the human body.

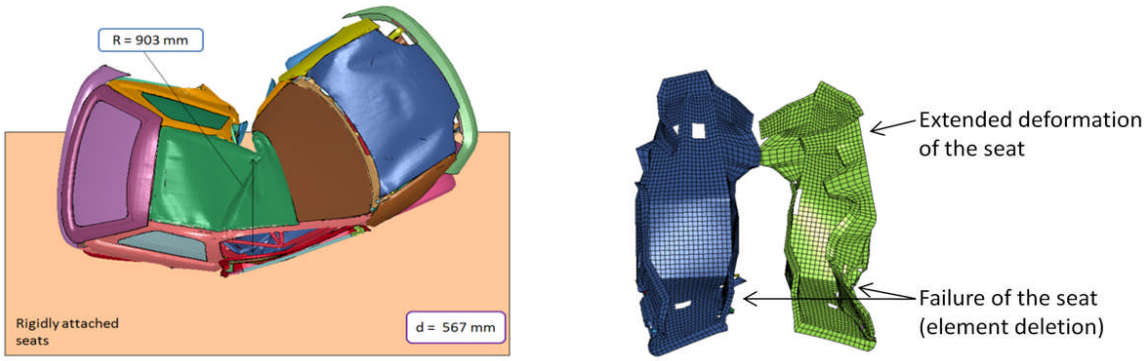


Figure 11: Resultant deformations of the structure and the seats after the simulation with rigidly attached rigidly

Similar conclusions with less encouraging results can be made for the second solution/simulation. The remaining width is 810mm, 9mm less than the standard vehicle! High deformation can again be seen in the internal seat and failure in the mounting points. Further the crash energy together with the rigidity of the seat close to the pelvis area deflects abruptly the lower beam while the upper still resist. This phenomenon ends in high rotation of the seat as can be seen in figure 12 and can result in unfavorable situations for the occupants.

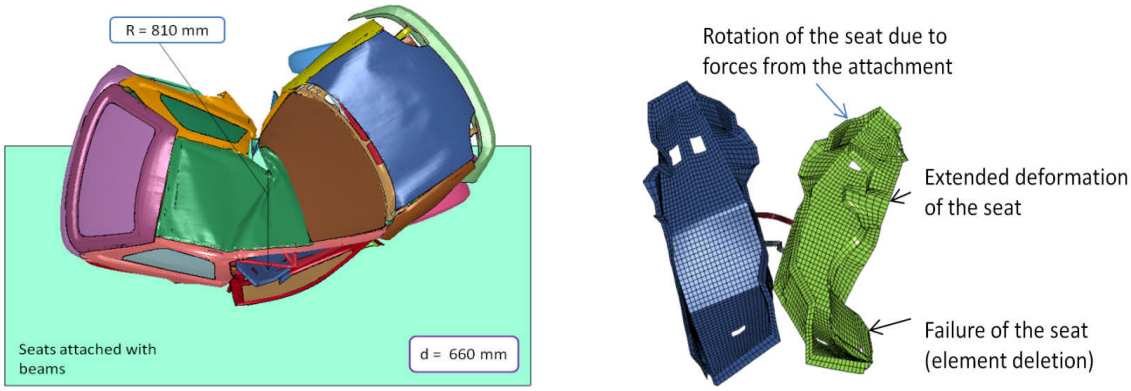


Figure 12: deformations of the structure and the seats after the simulation with steel beam attachment

In the graph below, the velocity profile for both cases and, for comparison reasons the initial simulation of the standard vehicle, are presented. As it can be seen the car in the case of the rigidly attached seats has a linear deceleration of 19.3 Gs (comparing to 17.1 of the initial run) and stops after 85ms. In the second case the car stops after 97ms as in the initial run. However differences in the profile and the instant decelerations can be pointed, as for instance around 20ms where for both simulations the abrupt drop of the velocity observed in the initial run is missing.

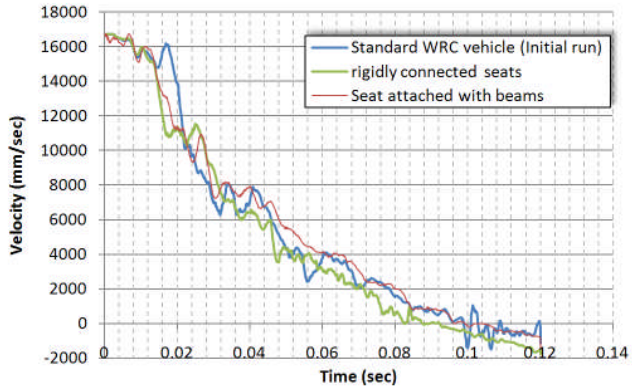


Figure 13: Velocity profiles and comparison

3.3 Floor reinforcement studies

Looking at a transverse section of the car in the contact position, the floor is among the first to participate into the crashing sequence. After only 7ms the floor starts to deform comparing to the cage and seats that start after 13 and 15 ms respectively.

Two simulations were therefore conducted to assess the potential of reinforcement of the floor structure. In the first, the thickness of the floorboard was doubled from 0.76mm initially to 1.5mm. In the second simulation a composite tube was introduced into the model as a transversal

reinforcement of the structure (Figure 14).

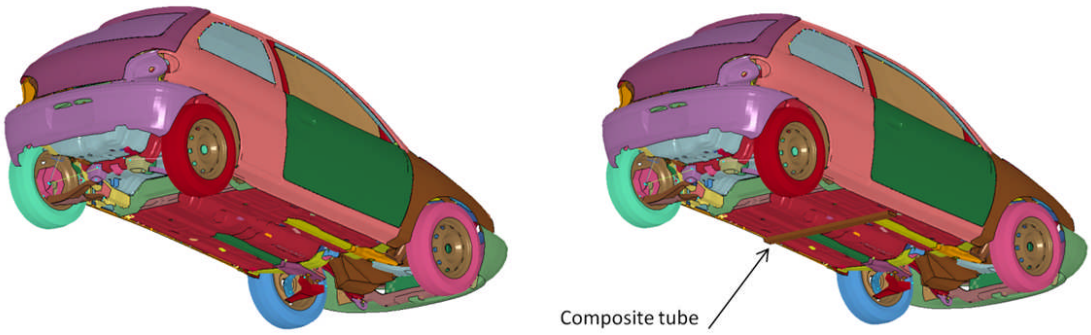


Figure 14: Floor of the Geo Metro model and floor reinforcement

For both simulations the results are depicted in figure 16. With the thickness increase, an advantage in terms of energy absorption can be seen as the stops after 90ms and the reduction of the cars width was 830mm. The fact that the transmission (gearbox) was missing from the simulations resulted in a weak point into the floor and high deformations. The floorboard resisted as its stiffness was higher, but on the contrary the transmission tube collapsed earlier. However the idea of stiffening the floor proved to be promising.

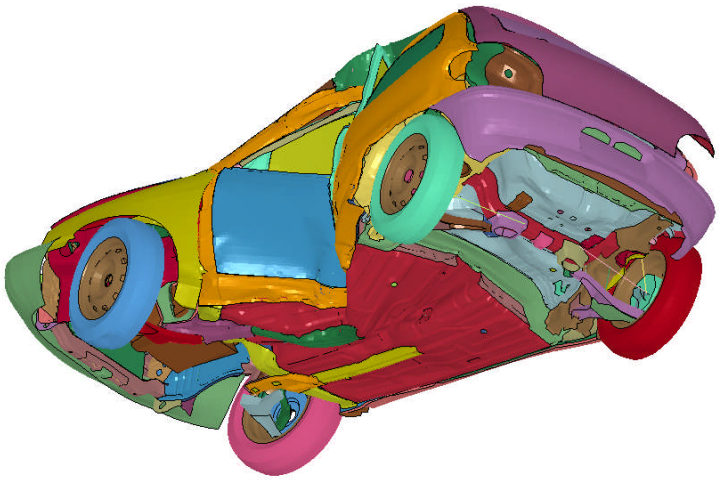


Figure 15: Instant from the deformations of the floor during the impact (floor: t=1.5mm)

A step further was then taken introducing a composite tube in the transverse direction so as to reinforce the floorboard. For the modelling of the tube the composite material model was again used and the walls of the tube were simulated as 2D shell elements.

During the crash the tubes fails progressively absorbing a significant amount of energy. However the sudden crash at the beginning of the impact, combined with the stiffened structure, provokes a small rotation of the car, ending in loss of the contact between the tube and the intruding tree. Even though, the reinforced structure due to the tube that embraces now the transmission tube as well, gives a high improvement of the car's safety. As can be seen from the velocity profile in

Figure 16, the car stops after 78 ms whilst the reduction of space for the occupants is 870mm, which is an improvement of 6% compared to the initial run and a standard WRC car.

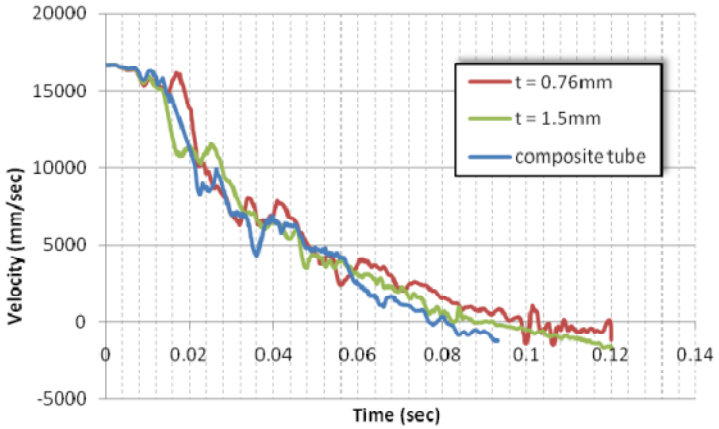


Figure 16: Floor studies results; velocity profiles

4 Summary and conclusions

Studies have been successfully carried out on the safety of WRC cars in the accident scenario of side impacts against trees using the LS-DYNA explicit numerical method. A full car model was used for the simulations including a rollcage and two racing seats. The most important findings can be summarized in the following.

First the different testing and simulation approaches reported in several studies were questioned. Our findings show significantly higher deformations and decelerations in the case when the car travels against the tree than in the opposite case. The ability of the car to move freely after the impact is unrealistic and leads to underestimated values and results. Surprisingly, the FIA and the testing authorities are currently doing actual testing on the cars following the second methodology [15] and our studies aim to ring a bell for reconsideration of the methods used.

Three different studies on the cage, seats and floor were then conducted. A standard cage has a significant contribution in safety reducing the deformations around 13.5%. However this number is unlikely to be improved as that would require a high and unreasonable increase of the weight.

The seats form a significant load path. Their rigidity and the rigidity of their mounts control the sequence of events during a crash whilst their contact signifies the end of the intrusion. Using the available space to fit a structure that would absorb energy during the impact is a reasonable idea that can prove to be beneficial. However, using such a structure can easily lead to excessive concentration of the deformations and dangerous displacement of the seats that can lead to serious injury or death. Careful research and application are thus required.

A great potential for improvements can be seen on the floor of the car. The floor starts to deform very early in the crash, and can be used to absorb energy and prevent deformations. Increasing the floor thickness results in significant reduction of the deformations. Reinforcing the structure of the floor with transverse tubes can improve further the results while also keeping the weight minimum.

Our studies proved that the side impact safety of rally cars is far from being solved. However the results of all these studies can only be 'quantitative' and used for comparisons between different solutions as the lack of validation testing is underlined throughout this work. Further investigation, simulations and experiments of the whole car chassis including the rollcage are needed with most important being first to validate the models with real experimental data, including force plots, accelerations, velocities and photographic evidence.

5 Acknowledgments

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Nassiopoulos, Elias; Njuguna, James A. K.

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