APPLICATIONS OF
MODELLING AND SIMULATION
http://arqiipubl.com/ams eISSN 2600-8084 VOL 7, 2023, 85-92

Explicit Dynamic Frontal Crash Analysis of an All-Terrain Vehicle Roll Cage

Ashwani Mittal, Anil C. Mahato*, Mukesh Sharma, Arkadeb Mukhopadhyay and Arun K. Kadian

Department of Mechanical Engineering, Birla Institute of Technology, Mesra, Ranchi, Jharkhand-835215, India

*Corresponding author: anilmahato@bitmesra.ac.in

Submitted 20 May 2023, Revised 11 June 2023, Accepted 30 June 2023, Available online 02 July 2023.

Abstract: This work deals with the explicit dynamic frontal crash analysis of the roll cage of an All-Terrain Vehicle. The crash testing analysis is done to ensure the safety of the driver during an accident in a catastrophic event. A roll cage model of the All-Terrain Vehicle is developed as per the rules laid down by BAJA SAE INDIA for m-BAJA vehicles using SolidWorks. Thereafter, the dynamic frontal crash analysis is performed by making a collision with a rigid wall, keeping a uniform velocity of the roll cage is 40 km/h. The analysis is carried out in HyperWorks software using Radioss solver. The work established the driver safety for the proposed roll cage by analyzing the stress development, and the total deformation after the collision. It is found that Von Mises stresses of the roll cage model except a joint of Side Impact Member is lower than the permissible limit.

Keywords: All-terrain vehicle; Crash analysis; Driver safety; Finite element analysis; Roll cage.

---

1. INTRODUCTION

An All-Terrain vehicle (ATV) is a vehicle that can travel on a variety of terrains including high inclined planes and graveled roads with ease [1]. As the use of ATV is gaining popularity among the youth, there is a tremendous increase in the use of ATV in the past years. In the United States, the number of ATVs in use increased from an estimated 5.6 million in 2001 to about 10.6 million in 2010 [2]. Therefore, the number of accidents related to these multi-purpose vehicles, which are fatal to drivers, has also increased. The data from the Consumer Product Safety Product (CPSC) ranging from 1982 – 2015 reveals that the ATV accidents have resulted in the killing of over 3000 children under the age of 16 years and about a million more required a visit to the emergency department [3]. In 2011, there were 620 deaths reported related to ATV, 513 deaths were reported in 2012 and in the subsequent year, 246 deaths were reported in the US [3]. In [4], it is reported that the rate of youth injury and hospitalization was 30% higher than the adults age (18 to 44 years) in ATV crashes. This survey is based on the pediatric injury severity throughout the nation. Moreover, based on the pediatric trauma population, it was found that children hospitalized rate were seven times more in ATV crashes and almost double as likely as youth in motor vehicle collisions. Outside the United States, most of the research on ATVs has been performed in Canada, the United Kingdom, Australia, and New Zealand. In these countries, the fatal and nonfatal crashes of the victims' children are similar to those in the United States. Due to this reason, it has become very crucial to build an ATV keeping in mind the driver's safety at utmost priority.

To provide a slight experience to undergraduate students of developing an ATV with all safety and measures, each year BAJA SAEINDIA organizes an event in which student teams build their ATV following the rules laid down by BAJA in their SAEINDIA Rulebook [5] and participate with their ATV in various dynamic events organized by BAJA SAEINDIA. According to the rulebook, all the teams must use the Briggs and Stratton engine of model no. 19L232-0054-G1(Vanguard series) to maintain the uniformity of vehicle power. So, the performance of the vehicle solely depends upon its drivetrain efficiency and the weight optimization of its roll cage design without compromising its primary function i.e., to bear static and dynamic forces while keeping the driver safe.

To check whether the roll cage design is safe for the occupant, crash tests are performed on vehicles. Conventional crash tests involve the physical crash of the vehicle to check the crashworthiness of the roll cage design for different impact scenarios. But physical crash tests are laborious, time-consuming, and expensive. It is also difficult in the case of physical crash tests to retrieve data for changes in kinetic energy, internal energy, plastic strain, and so on [6]. Therefore, to avoid unnecessary expenses and to save time, the automobile companies conduct a Finite Element Analysis (FEA) in their initial designing stage. The FEA is a key tool for static, dynamic, thermal analysis of various models, structures, systems etc [7]. Previously, many research used the FEA tool for analyzing initial model of various systems [8-11]. Due to the advancement in the CAE (Computer-Aided Engineering) software and computational power in the last two decades, complex crash simulations can yield accurate results close to the results of physical crash tests [12].

While doing the literature review, various research works about the static analysis of the ATV are found in [1,13,14]. The suspension system and steering mechanism are key components in ATV. In [15], Rajeshkumar *et al*. presented a stability analysis of the ATV by optimizing the geometric design and mass characteristics of the wheel assembly in steering mechanism. Similarly, Verma *et al*. discussed the important aspects of designing and development of the front wheel hub of ATV. The front wheel hub of the ATV was designed by the authors considering that the weight of the front wheel hub should be light and high strength [16]. In [17], analyzed the braking system of the ATV using Ansys and Matlab. A ventilated brake disc rotor, hub etc. are designed and performed static, structural, thermal, computational flow dynamics, vibrational and fatigue analysis. Recently, Singh *et al*. presented the design and FEA analysis of the suspension and the chassis for an SAE BAJA ATV [18]. Also, in [19], an algorithm has been developed for electronic stability control of an ATV. The said algorithm has been applied to a SEA's Robotic Test Driver. It is incorporated into the real time controller and tested its efficacy using two sets of vehicles. However, the static analysis of the ATV roll cage frame is not sufficient to analyze the driver's safety as it acted various dynamical forces during crash of the vehicle. Therefore, for an accurate result, a dynamic crash analysis of the structure is a key operation. Generally, there are three different modes of crash testing: Frontal Impact test, Side way Impact test, and Roll over test. In this regard, very few works are available on explicit dynamic crash analysis of the ATV roll cage designed according to SAE BAJA guidelines. In [20], Safiuddeen *et al*. performed a dynamic crash analysis of the roll cage using finite element method in ANSYS workbench and LS DYNA software. The simulation work is performed using carbon fiber (ePA-CF) and ASTM A36 steel materials. In 2017, Vora *et al*. [21] developed and analyzed an ATV, which runs on electricity. Authors developed a roll cage frame as per SAEINDIA rules and performed FEA analysis for design validation. The roll cage design is modified for three-seater instead of single seater vehicle, and it was tested under static and dynamic loading conditions. Still, various aspects like variation of kinetic energy, internal energy, and the total energy of the ATV during the crash are unknown. This analysis may help the undergraduate and the postgraduate students who are engaged to develop an ATV for various computations, organized by SAEINDIA and others.

This work is an extended work regarding explicit dynamic frontal crash analysis on the ATV roll cage to ensure the driver's safety during an event of crash. A model of the Roll Cage has been designed using SolidWorks 2021, and the crash analysis is performed using Finite Element Methods by HyperWorks 2020.1 software. In addition, the variation of the kinetic energy, internal energy, and the total energy of the ATV during the crash are analyzed.

2. MODELING AND MATERIAL SELECTION OF ROLL CAGE

The modeling of the Roll Cage has been done using SolidWorks 2021 following all the rules and guidelines laid down by BAJA SAE INDIA in their rulebook. While designing the roll cage, a Mannequin of height 5 ft 8 inch was placed inside the roll cage in the driving position as shown in Figures 1(a) and 1(b) to check the roll cage clearances with respect to the driver as suggested in the rulebook. The size of the Roll Cage is 1766 × 846 × 1172 mm in length, width and height, respectively. Tubes of three different cross-sections namely primary, secondary and tertiary have been used to design the roll cage structure to achieve the optimal strength to weight ratio. The dimensions of these tubes have been shown in Table 1. The roll cage has been designed to achieve better stress flow due to dynamic forces during vehicle operation, hence minimizing stress concentration at the joints. The final roll cage design has been achieved after performing a few design iterations and simulating them to check the stress flow and stress concentration in that design.

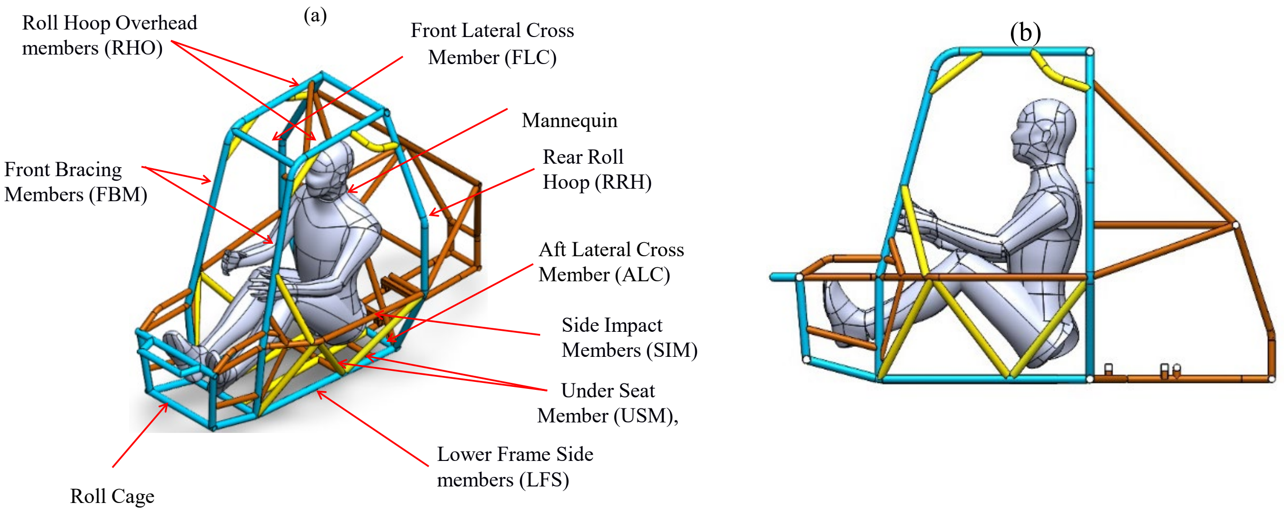


Figure 1. Roll cage with Mannequin (a) Isometric view, (b) Side view

Table 1. Tube dimensions of roll cage

Tube Dimensions	
Primary Tube	29.2 × 1.65 mm
Secondary Tube	25.4 × 1.00 mm
Tertiary Tube	18.0 × 1.00 mm

Table 2. Element quality checks

Parameters	Value	Parameters	Value	Parameters	Value
Min. Length	2.00 mm	Max. Angle Quad	< 135°	Skew	< 45°
Max. Length	10.00 mm	Min. Angle Quad	> 45°	Jacobian	> 0.6
Aspect Ratio	< 5	Max. Angle Tria	< 120°	% of Trias	< 15%
Warpage	< 10°	Min. Angle Tria	> 20°		

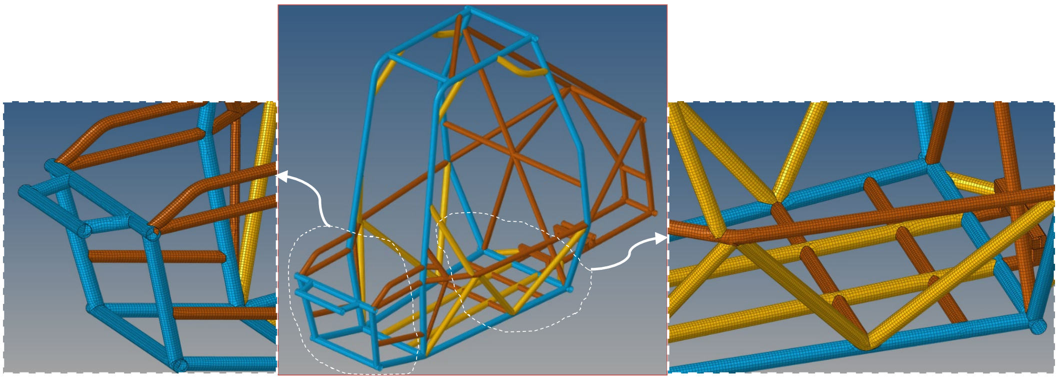


Figure 2. Images of fully meshed roll cage model

According to the requirement, AISI 4130 grade of steel alloy has been selected as the roll cage tube material following the rule that the tube material should contain at least 0.18% carbon content. The optimum ratio of Chromium, Molybdenum, and Carbon provided us the desired combination of strength, toughness, and anti-corrosive nature for our use. Due to the low carbon content present in AISI 4130, it has great weldability. All these factors together made AISI 4130 steel grade the best choice for using it as the roll cage tube material among all other available options. The ATV was developed at the Birla Institute of Technology, Mesra by considering AISI 4130 grade of steel alloy for the Roll Cage. The stated steel tubes were tested in MICROLAB (accredited by NABL), Coimbatore, India.

After creating the model of the roll cage in Solidworks, it was imported to HyperWorks 2020.1 software for pre-processing and simulating explicit dynamic frontal crash analysis by impacting the roll cage with a rigid wall. The steps involved in the pre-processing of the model are described below in detail.

2.1 Mid-Surface and Mesh Creation

For performing FEA, the model should contain the finite number of degrees-of-freedom present in the model as the calculations are done by the solver at finite number of points which are also known as nodes. After that, those results are interpolated to obtain the results for remaining nodes on the entire surface. The process of dividing a model into finite number of elements is known as meshing. From the imported CAD geometry, the mid-surface was extracted for meshing. After mid-surface extraction, the tubes of the roll cage were grouped under three components namely Primary, Secondary and Tertiary according to the dimensions of the tubes. The shell elements were selected for meshing the model of mixed type i.e., both quad and tria elements. The average element size was given as 5 mm, which was ideal because the accuracy of the results and the computational time that the solver took during the analysis were optimum at this element size (refer Figure 2). The quality check parameters used for the shell meshing are provided in Table 2 (Data taken from [22]).

2.2 Material and Property Cards

To simulate the material properties of AISI 4130 steel alloy, material card image M2_PLAS_JOHNS_ZERIL was selected to represent the isotropic elastoplastic material properties using the Johnson-Cook material model (Data taken from [23]). The parameters used for creating the material property card for the roll cage tube material are given in Table 3. Properties to provide the thickness to the shell elements were created using the P1_Shell card image. The roll cage incorporates the tubes of three different cross-sections namely primary tube, secondary tube, and tertiary tube. Therefore, three properties were created for providing respective thicknesses (T) and other parameters as shown in Table 4 (Data taken from [23]).

Table 3: Material card parameters

Parameters	Value	Parameters	Value
Type	PLAS_JOHNS	Iflag	1
Initial Density	7.89 x 10-09 Tonne/mm^3	Yield Stress	800 MPa
Young Modulus	210000 N/mm^2	Ultimate Tensile Stress	1008 MPa
Poisson ratio	0.3		

Table 4: Property card parameters

I_{Shell}	24: QEPH Shell Formulation
N	6
$T_{Primary}$	1.65 mm
$T_{Secondary}$	1.00 mm
$T_{Tertiary}$	1.00 mm

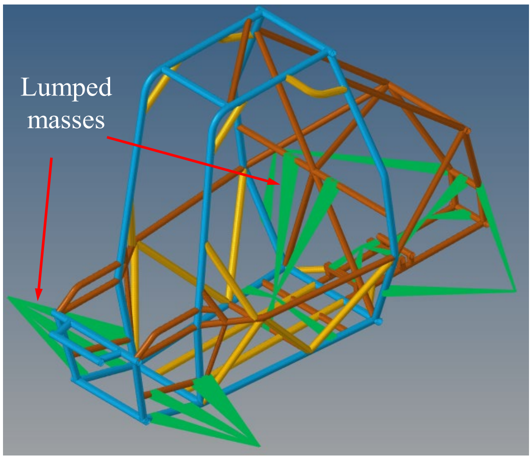


Figure 3. Roll Cage model with lumped masses

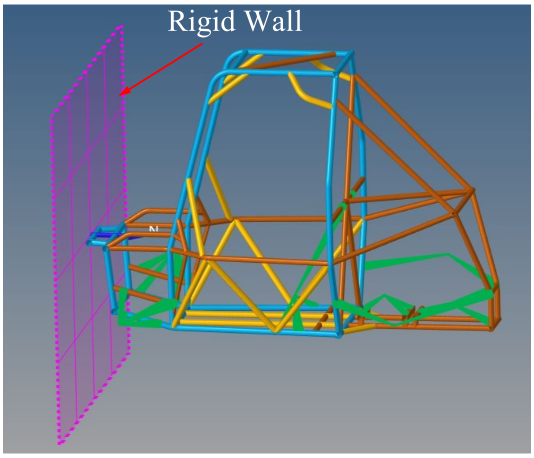


Figure 4. Rigid wall structure for vehicle collision

2.3 Lumped Masses Creation

The mass of the roll cage is about 25.7 kg which constitutes about 12.7% of the total mass of the vehicle including the driver i.e. 201 kg approximately. Therefore, to include the inertial effect of the total mass of the vehicle including the driver during the crash, lump masses of components such as the engine, gearbox, CVT, wheel assemblies, and the driver were created using the 1D rigid elements to constitute the total mass of the vehicle as shown in Figure 3.

2.4 Rigid Wall Creation and Loading Conditions

To simulate the impact of the vehicle with a structure, a rigid wall was created in front of the roll cage model as shown in Figure 4. As no air drag or ground friction has been taken into account, the velocity of the vehicle before the impact would remain constant for the whole time. Therefore, the rigid wall was created at a distance just 5 mm away from the vehicle to save the computational time of solver before the impact.

In the other hand, all the roll cage nodes including the lump masses nodes were given the initial velocity of 40 km/h in the forward direction towards the wall. The velocity given is above the usual velocity of the ATV at the BAJA tracks.

2.5 Contacts

The contact with card image TYPE 7 [24] was also included in the model to simulate the effect of self-interference among the surface of the tubes of the roll cage due to the deformation of the roll cage structure during its collision with the rigid wall. The parameters used while creating the contacts are given in Table 5.

3. RESULTS AND DISCUSSION

After the completion of the simulation, the results are post-processed using Hyperview and Hypergraph 2D applications. It took two iterations in the whole design and analysis work to obtain satisfactory results.

Table 5. Contact card parameters

Parameters	Value/Type
Card Image	TYPE7
Slave Entity IDs (S)	3 Components (Primary, Secondary, Tertiary)
Master Entity IDs (M)	3 Components (Primary, Secondary, Tertiary)
Flag for Stiffness Definition (I_{stf})	4
Gap for Impact Activation (G_{apmin})	1 mm
Flag for Stiffness Deactivation (I_{nacti})	6

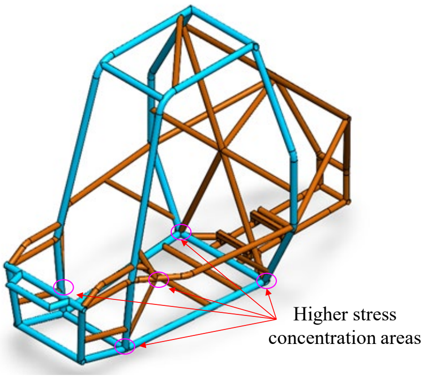


Figure 5. First design iteration of roll cage

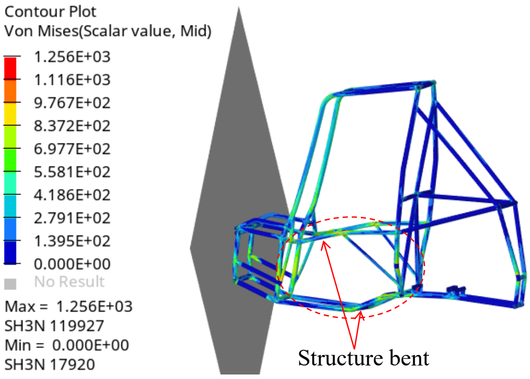
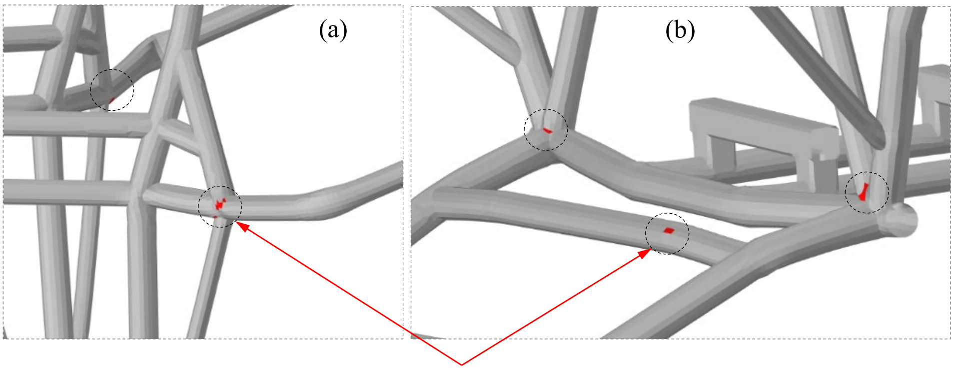


Figure 6. Stress contour plot of first design iteration of roll cage



Higher stress concentration areas

Figure 7. Areas of roll cage where the elements failing (indicated in red colour) due to high stress concentration (a) Failure of joint of SIM and suspension mounting, (b) Failure of under seat member and joints

3.1 First Design Iteration

The maximum von Mises stress developed in the first design iteration of the roll cage (refer Figure 5) was about 1256 MPa, which is higher than the ultimate tensile stress of the roll cage material i.e. 1008 MPa (refer Figure 6). The areas of the roll cage where the stress developed exceeds the ultimate tensile stress are indicated in red colour in Figure 7. These failing regions of the roll cage also include some regions like under seat member (USM) and Aft Lateral Cross Member (ALC) which were very critical for the driver's safety.

The maximum deformation in the vehicle's cockpit between Front Lateral Cross Member (FLC) and ALC was about 202 mm (refer Figure 8). The deformation was almost constant after 0.03 s. Also due to impact, the Lower Frame Side Members (LFS) of the roll cage got bent as shown in Figure 6. Therefore, to bring the stress develop within the limit of the ultimate tensile stress in the critical regions of the roll cage and to reduce the deformation of the roll cage in the region of the vehicle's cockpit, it is required to reduce the travel of the driver's legs during the impact scenario to accommodate the roll cage deformation. Various bracings have been added into the roll cage at various locations. The modified model of the roll cage is shown in Figure 9.

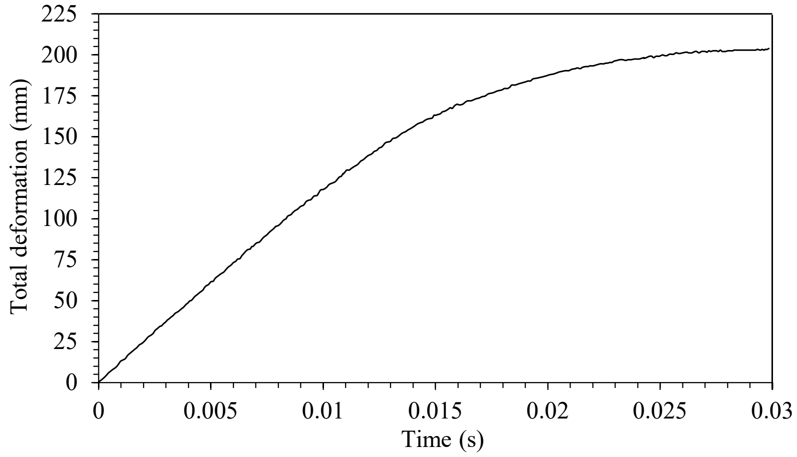


Figure 8. Total deformation vs. time graph (First design iteration)

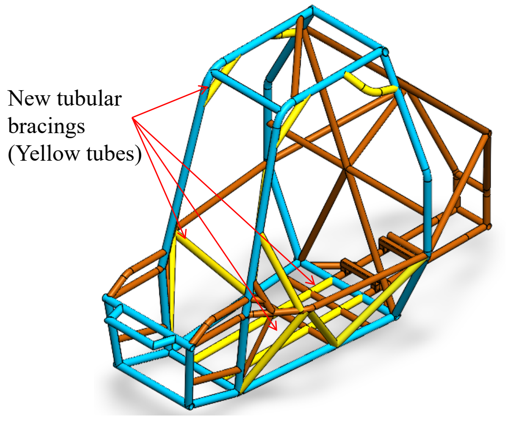


Figure 9. Modified roll cage design for second iteration

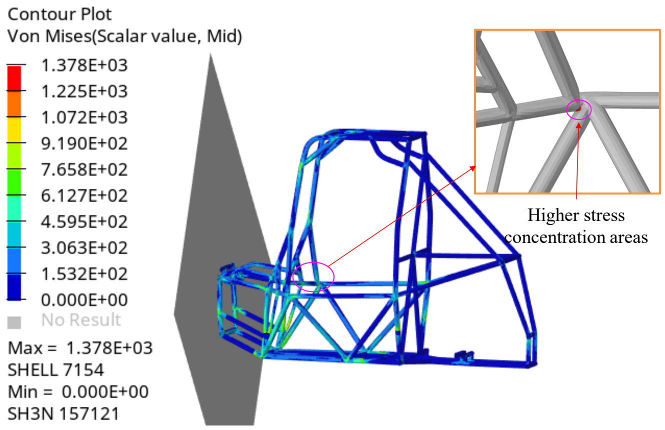


Figure 10. Stress contour plot of the modified roll cage after second iteration

3.2 Second Design Iteration

To make the roll cage design sturdy and robust, various tubular bracings have been introduced in the roll cage structure at the locations where there was a need of reducing stress concentrations and deformation from the point of view of driver's safety. Tubular bracings of the same cross-section that of primary members were incorporated between both the LFS, between Side Impact Members (SIM) and LFS, between Front Bracing Members (FBM) and SIM, between Roll Hoop Overhead members (RHO) and Front Bracing Members (FBM) and also in between RHO and Rear Roll Hoop (RRH) as shown in Figure 9.

On analyzing and post-processing of the modified roll cage structure, it is found that the maximum von Mises stress appeared at a joint of SIM and it is increased slightly to 1378 MPa as shown in Figure 10. However, the von Mises stress is found to be of lower value as comparison to the ultimate tensile stress (UTS) over the entire members of the roll cage except the joint of SIM. Also, the locations where higher stress concentration was observed in the first iteration were now reduced in the second iteration of the modified roll cage. Moreover, the high-stress concentration in the driver's seating area (obtained from first iteration result) was eliminated successfully with the addition of extra bracings and members in the second iteration. Therefore, the driver will remain safe from any kind of injury in the modified roll cage design when the impact occurs.

In the second iteration, the change in roll cage deformation during impact is observed as it was reduced from 202 mm (first design iteration) to 174 mm in the second design iteration as shown in Figure 11. This allows the driver to respond conveniently and with a faster rate to the crash than before as the driver's legs has to travel about 28 mm less to accommodate the deformation.

4. VALIDATION OF ANALYSIS

The roll cage tubes were grouped under three components namely Primary, Secondary and Tertiary according to the dimensions of the tubes. The shell elements were selected for meshing the model of mixed type i.e., both quad and tria elements. The mesh size selection of the roll cage is passed through the mesh sensitivity study and five different sizes of meshes are considered for the convergence and the meshing convergence is shown in Figure 12. It is found that the von Mises stress and the total deformation of the roll cage converged when element size is chosen to 5 mm. This mesh is ideal because the accuracy of the results and the computational time that the solver took during the analysis were optimum at this element size.

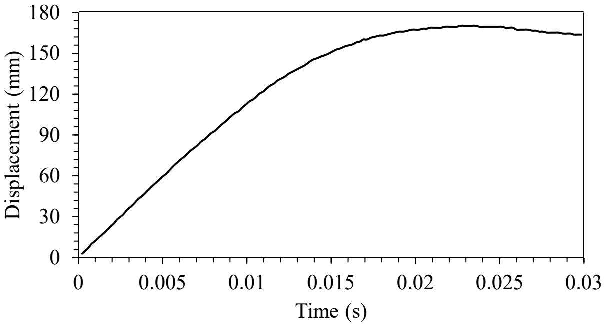


Figure 11. Total deformation of the modified roll cage

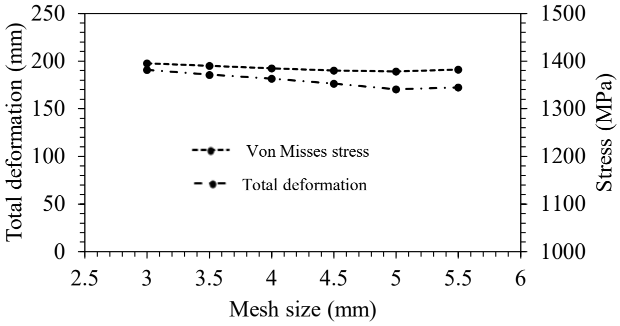


Figure 12. Mesh convergence on the von Mises stress and total deformation of the roll cage

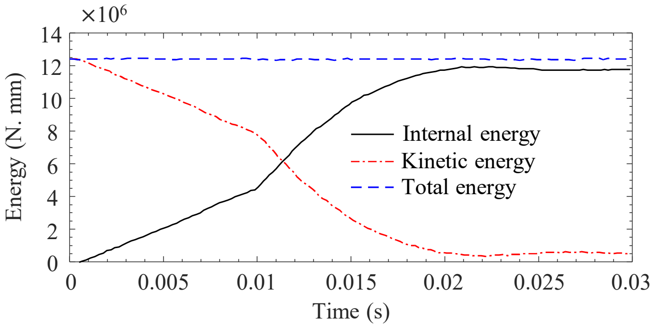


Figure 13. Energy conservation of the modified roll cage model

To validate the explicit dynamic crash analysis of the ATV roll cage model, the energy curves like total energy, kinetic energy and internal energy were plotted during post-processing. It was observed that at the start of the simulation, there was only kinetic energy present. As the simulation proceeds and the crash begins, the kinetic energy gradually decreased, and the internal energy of the model increased in the same proportion till the end of the simulation. The total energy of the model is the sum of its kinetic energy and internal energy, and it is always constant. Therefore, the kinetic energy lost is gained in the form of internal energy of the model. The total energy along with the hourglass energy remains the same during the whole simulation time as shown in Figure 13. Hence, this validates that the model simulation is theoretically correct.

5. CONCLUSIONS

This paper has developed a roll cage design for an ATV in such a way that it keeps the driver safe during the event of a frontal crash of the vehicle. Two iterations of the design and the FEA of the roll cage were performed before obtaining satisfactory results in the second iteration. The necessary design changes done during the second iteration were made after taking feedback from the stress and deformation results of the roll cage design of the first iteration. From the final analysis results of the roll cage design, the following conclusions can be drawn:

- After studying the stress contour plot, obtained after FEA analysis of the modified roll cage design, it can be concluded that the roll cage can effectively protect the driver from any injury during the event of a frontal crash of the vehicle.
- The tubular bracings added in the roll cage during the final design iteration successfully eliminated the structural failure in the seating area of the driver which could be fatal during the crash.
- The added bracings reduced the deformation of the roll cage during the crash thus making it easier for the driver to accommodate the deformation.

ACKNOWLEDGEMENT AND FUNDING

The first author thanks Birla Institute of Technology, Mesra, Ranchi, India for allowing him to carry out research. The authors receive no financial support for the research, authorship, and publication of this article.

DECLARATION OF CONFLICTING INTERESTS

The authors declare no potential conflicts of interest with respect to the research and publication of this article.

REFERENCES

[1] R. Soundararajan, R. Ajith, U. Sabarivasan and J. S. Mourya, A novel approach for design and analysis of an all-terrain vehicle roll cage, *Materials Today: Proceedings*, 45, 2021, 2239-2247.

[2] A. F. Williams, S. L. Oesch, A. T. McCartt, E. R. Teoh and L. B. Sims, On-road all-terrain vehicle (ATV) fatalities in the United States, *Journal of Safety Research*, 50, 2014, 117-123.

[3] J. Topping and S. Garland, *2013 Annual Report of ATV-Related Deaths and Injuries*, Bethesda, Consumer Product Safety Commission, USA, 2015.

[4] C. A. Jennissen, G. M. Denning and M. E. Aitken, A comprehensive report on all-terrain vehicles and youth: continuing challenges for injury prevention, *Pediatrics*, 150(4), 2022, e2022059280.

[5] BAJA SAEINDIA Rulebook, 2022 Collegiate Design Series, Revision A, 16th Aug. 2021.

[6] C. Peshin, M. Walia, P. Madhan and S. Gaikwad, Design and simulation of components of an all-terrain vehicle, *SAE Technical Paper*, 2020-28-0486, 2020.

[7] D. V. Hutton, *Fundamentals of Finite Elements Analysis*, McGraw Hill Education (India) Private Limited, New Delhi, 2005.

[8] O. Prakash and A. C. Mahato, Finite element analysis of the side bolster beam of the wagon tippler, *International Journal of Computer Aided Engineering and Technology*, 15(4), 2021, 553-564.

[9] M. T. Hamisu, U. S. Umar and A. Sa'ad, FEA and modal analysis of a damped flywheel with unbalanced masses, *Applications of Modelling and Simulation*, 4, 2020, 21-30.

[10] L. H. T. That, Free vibration and buckling analyses of functionally graded porous columns by FEM, *Applications of Modelling and Simulation*, 6, 2022, 98-106.

[11] P. Bral, J. P. Tripathi, S. Dewangan and A. C. Mahato, CFD analysis of an exhaust manifold for emission reduction. *Materials Today: Proceedings*, 63, 2022, 354-361.

[12] C. K. Thorbole, M. Aitken, J. Graham, B. Miller and S. H. Mullins, Assessment of the dynamic behavior of a single person ATV in presence of a passenger: outcome on the rider and passenger crash impact kinematics using computational model, In *ASME International Mechanical Engineering Congress and Exposition*, 45271, 2012, 161-171.

[13] U. S. Gupta, S. Chandak and D. Dixit, Design & manufacturing of all terrain vehicle (ATV)-selection, modification, static & dynamic analysis of ATV vehicle, *International Journal of Engineering Trends and Technology*, 20(3), 2015, 131-138.

[14] A. S. Shridhar, A. Tukkar, A. Vernekar, V. Badderu, A. Y. Patil and B. B. Kotturshettar, Modeling and analysis of ATV roll cage, *Advances in Engineering Design and Simulation*, 2020, 281-292.

[15] L. Rajeshkumar, V. Bhuvaneswari, B. Pradeepraj and C. Palanivel, Design and optimization of static characteristics for a steering system in an ATV, *IOP Conference Series: Materials Science and Engineering*, 954(1), 2020, 012009.

[16] H. Verma, S. Kumar, R. S. Bharj and R. Kumar, Design and development of the front wheel hub for all-terrain vehicle (ATV), *Journal of Mechanical Engineering (JMechE)*, 17(1), 2021, 49-62.

[17] S. Kumar and T. Rajagopal, Braking system for ATV (No. 2020-01-1611), *SAE Technical Paper*, 2020.

[18] G. Singh, A. Kumar and S. Menwal, Suspension and chassis design, and steering calculations for SAE BAJA all-terrain vehicle, *International Research Journal of Engineering and Technology (IRJET)*, 10(2), 2023, 283-289.

[19] S. Zagorski and G. Heydinger, Development of an electronic stability control algorithm for all-terrain vehicles, *SAE Technical Paper*, 2023-01-0661, 2023.

[20] 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*, 39, 2021, 183-200.

[21] K. C. Vora, M. R. B. Agrewale, M. M. Desai, H. Mishra and O. Narkar, Development, analysis and testing of an electric all-terrain vehicle. *In 2017 IEEE Transportation Electrification Conference (ITEC-India),* India, 2017, 1-6.

[22] Practical aspects of Finite Element Simulation 2021, ©Altair Engineering, Inc. https://altairuniversity.com/free-ebooks/free-ebook-practical-aspects-of-finite-element-simulation-a-study-guide/

[23] Altair Radioss 2021 Reference Guide, ©Altair Engineering, Inc.

[24] Introduction to Explicit Analysis with Altair Radioss^{TM}, ©Altair Engineering, Inc. https://altairuniversity.com/free-ebooks/free-ebook-crash-analysis-with-radioss-a-study-guide/