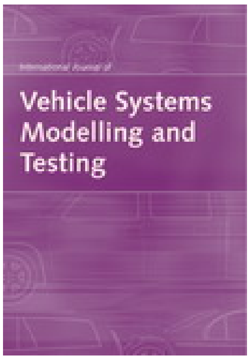

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Finite element modelling and simulation of car bonnet's crashworthiness parameters for pedestrian safety

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Abstract: Pedestrians face heightened vulnerability in car accidents, often experiencing head injuries with severe consequences. The car bonnet emerges as a critical point of contact in these incidents, necessitating the development of assessment parameters like the head injury criterion (HIC), energy absorption, and total deformation to gauge head injury risk. Material selection for automobile closures considers factors like cost, weight, and structural performance. Complying with pedestrian safety standards, evaluated through child and adult headform impactors, is imperative for vehicle bonnets. This study introduces a novel finite element model replicating head impact events between headform impactors and car bonnets. Analysing three identical bonnets made of steel and aluminium alloys (AA 5252 and AA 6061) using this model reveals that while the AA 5252 bonnet exhibits lower energy absorption, it offers greater protection with significantly fewer HICs compared to steel and AA 6061. The findings underscore the weight-protection performance trade-off in different material bonnets.

Keywords: crashworthiness; finite element modelling; energy absorption; deformation; HIC; head injury criteria.

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1 Introduction

Crashworthiness refers to a vehicle's ability to safeguard its occupants during a crash. It is a measure of a vehicle's structural ability to deform plastically while providing sufficient survival space for its occupants in crashes with appropriate deceleration loads. India with 1% of the world's car population and the third-largest road network in the world today, is responsible for 6% of all traffic accidents (Bharat New Vehicle Safety Assessment Program-BNVSAP, 2019). Vehicle dynamics, collision velocity, and all other relevant variables are monitored, assessed, and rectified using crash analysis to ensure the safety of passengers while the vehicle is in motion (Lee et al., 2003). Crashworthiness is the measure of how well a vehicle will protect its occupants in the event of a collision or accident. Structures must have the capacity to withstand energy to prevent severe harm to people or cargo during collisions (Tarlochan, 2021; Nimir et al., 2014). Crash analysis is the method of simulation of the level of protection provided to an automobile and passengers inside it by simulating a real-world collision (Atahan, 2010; Berzi et al., 2018). The crashworthiness of vehicles is practically examined by utilising computer-aided design (CAD), a component of computer-aided engineering (CAE), which is employed by automakers (Yadav and Pradhan, 2014). Automobiles, trains, cars, aeroplane, and helicopter designs now include structural crashworthiness as a fundamental criterion. The crashworthy structure is designed to absorb impact energy in a regulated manner during a crash, preventing the energy from entering the passenger compartment (Sun et al., 2009; Horgan and Gilchrist, 2003). Finite Element FEM is used to model car components, and the design data is then imported into FEM software for crash simulation. Some of the FEM software are LS-DYNA, RADIOSS, ABAQUS and ANSYS EXPLICIT DYNAMICS. A crashworthiness test is performed to ensure that the vehicle meets safe design standards. A variety of experimental and analytical techniques are used to determine crashworthiness. From individual components to full-scale vehicles, crashworthiness should be evaluated in laboratory tests. However, testing takes a lot of time and money. Simulation is now a crucial and helpful tool in the design stage because of the quick evolution of digital technology and CAE methodology (Lim, 2017; Du Bois et al., 2004).

Simulation of vehicle crashworthiness is increasingly used by various institutes to study the outcome of structural stability of the vehicle in various situations under different conditions. Crashworthiness is a structure's capacity to protect its occupants during a collision. Vehicle-to-pedestrian collision is one of those sorts of accidents that can result in permanent injury or death. Every year, almost 1.2 million pedestrians die in road traffic accidents throughout the world, making pedestrians the most susceptible road users who face a significant risk of vehicle crashes in traffic. In a car-pedestrian collision, the pedestrian's lower leg is struck by the bumper first, followed by contact between the upper thigh and the leading edge of the car's bonnet, and lastly, the head and upper torso are barely impacted by the rigid car bonnet's top surface. The bonnet, with which pedestrians frequently come in contact, has been recognised as one of the key contact sites for pedestrian head injuries (Yao et al., 2019; Abdel-Nasser, 2013).

The European Enhanced Vehicle Safety Committee's Working Group 17 (WG17) has suggested component test methods employing specific impacts to carry out vehicle pedestrian protection verification testing. According to a set of standards established by the European Union, pedestrians are less likely to suffer serious injuries from the effects of speeds up to 40 km/h (EURO NCAP, 2017). The process of harm is intricate, though. The head injury criterion (HIC), calculated by the impactor using a simulation of a child's and adult's head, provides an estimate of the likelihood that a head injury may occur as a result of an impact (Peng et al., 2012). It was created by Versace (1971). This concentrates the elapsed period of integration on the region of impulse that does the most harm. By specifying t_1 and t_2 as the moments when equal amounts of acceleration take place on either side of a maximum acceleration instant. Several variables including price, weight, and structural performance, affect the material choice for automotive closures. Steel and aluminium were the two most frequently employed materials in the manufacture of engine hoods (Chen et al., 2021; Teng et al., 2018).

According to EEVC/WG17 specifications, the impactors for the adult and child headforms must be rigid spheres covered in vinyl. For the adult and child headform impactors, respectively, the total impactor masses should be 4.8 ± 0.1 kg and 3.5 ± 0.05 kg. The centre should have a triaxial accelerometer placed so that it can measure the acceleration of both the adult and child headforms as a whole (Masoumi et al., 2011). The headform impactors should be at an angle between 25° and 90^{o} degrees from the horizontal. Between the provided ranges, pick three distinct angles.

The novelty of the present study is to develop a Finite Element Model that simulates frontal impacts between automobiles and pedestrians. This model adheres to EURO-NCAP standards and enables accurate analysis of car bonnet performance in terms of pedestrian safety. This research work focuses on evaluating the effectiveness of hood protection systems in reducing head injuries for adult and child pedestrians. By quantifying the likelihood of head injuries, the study provides valuable insights for enhancing pedestrian safety in car-to-pedestrian accidents. The performance of different bonnet materials, specifically aluminium and steel, in terms of HIC values, energy absorption, and deformation. The findings highlight the advantages of using aluminium, specifically AA 5252, over steel in terms of pedestrian safety. The study examines three impact positions on the car bonnet and evaluates the key parameters of HIC value, energy absorption, and deformation at each position. This comprehensive analysis provides a detailed understanding of the bonnet's performance under various impact scenarios. This work aligns with European Enhanced Vehicle-safety Committee (EEVC) standards and European regulatory requirements. By adhering to these standards, the study ensures its relevance and applicability to the European automotive industry which offers practical implications for car manufacturers by suggesting that the use of specific bonnet materials, such as AA 5252 aluminium alloy, can improve pedestrian safety. This insight can guide future design and manufacturing decisions, leading to the development of safer vehicles.

The HIC value, energy absorption, and deformation for evaluating pedestrian friendliness possess broader implications such as

i *Comprehensive safety assessment*: Each parameter provides valuable information about different aspects of pedestrian safety. A comprehensive evaluation using multiple parameters allows a more accurate and thorough assessment of how a vehicle or structure interacts with pedestrians during an impact.

ii *Material and design optimisation*: These parameters help guide material selection and design optimisation to improve pedestrian protection. By analysing HIC values, energy absorption capabilities, and deformation characteristics, engineers can identify materials and structural configurations that offer better pedestrian friendliness.

iii *Regulatory compliance*: Many regions have established safety standards and regulations to ensure pedestrian-friendly vehicles. HIC, energy absorption, and deformation are often considered in such standards, making them important criteria for manufacturers to meet legal requirements.

iv *Safety innovation*: The use of these parameters encourages the automotive industry to continually innovate and develop safer vehicle designs that prioritise pedestrian protection. As vehicles become more pedestrian-friendly, the overall safety of vulnerable road users improves.

v *Public perception and marketing*: Safety ratings and test results, often influenced by these parameters, can significantly impact the public's perception of a vehicle's safety features. Positive safety ratings can be a marketing advantage for automakers.

The present work includes the modelling of Maruthi Suzuki Swift (2014) bonnet using Solidworks. The bonnet model was meshed in Hypermesh and analysis was carried out by importing the model in LS-DYNA software. The HIC value, energy absorption and deformation of the bonnet are assessed numerically and validated.

2 Finite element modelling

Analysis can be performed using one of the three methods: analytical, experimental or finite element. The experimental method is usually expensive and only used for verification, whereas the closed-form analytical method is confined to simple geometry (Ahmed, 2020; Dagang et al., 2021). Hence, the finite element approach provides viable alternatives. There are three major stages in finite element simulation. Firstly, the pre-processing stage, in which a finite element mesh is created by the analyst and the subject geometry is divided into smaller parts for analysis. In the second stage, called the solution, the program solves for the primary quantities after deriving the governing matrix equations from the model. The final stage is post-processing; where the accuracy of the results such as specialised stresses is verified. The finite element method (FEM), which has undergone extensive development, is recognised by the automotive industry as a useful tool during the initial design phase. Numerous studies employing the FEM have been conducted on structural strength and crashworthiness since the 1990s. Explicit nonlinear finite element technology is rapidly becoming a valuable tool in the automotive industry for crashworthiness design and analysis.

Vehicle collision analysis using the finite element technique comprises many steps. The components that must be included in the crash model, including suitable geometric representation and finite element mesh, must be identified.

2.1 Bonnet modelling

Metallic bonnets typically consist of two parts: an upper and an inner body, with the inner body providing structural support and the upper body almost entirely serving to achieve uniform styling and preserve the aerodynamics of the vehicle body. The upper body of the bonnet is the initial point of contact for pedestrians, thus even though it is less significant in terms of strength, it is extremely crucial for pedestrian bonnet friendliness. Therefore, its strength, shape, curvature, and geometric features have an impact on the head's acceleration during an impact (Schulz and Kalay, 2016).

The upper body of the car bonnet being modelled is of Maruthi Suzuki Swift (2014). Technical drawings and photographs of the car bonnet were gathered. These references helped me understand the shape, dimensions, and details of the bonnet. The bonnet was modelled using Solidworks. In the first 2D sketch of the car, the bonnet was created using the tools such as lines, curves, arcs and splines that are available in the software to accurately draw the profile of the bonnet.

Once the 2D sketch was completed, it was extruded to a thickness of 2 mm converting it into a 3D object. Additional tools such as fillets, chamfers, and splines were used to refine the shape of the bonnet to adjust the dimensions and smooth out the curves. Finally, the model was reviewed checking for any imperfections, gaps, or inconsistencies and necessary adjustments were made to ensure that the model is ready for further use. Figure 1 show the bonnet modelled in Solidworks by considering all the above-mentioned references.

The bonnet model was validated using a reverse engineering process. The process involved the 3D scanning of the part and the creation of the model using obtained dimensions. These models were compared and validated by superimposing them with each other. The similarity index is depicted in Figure 2.

The shape of the bonnet was successfully validated through a comparison between the modelled bonnet and the generated scan. By superimposing the two models, colour contours were utilised to assess the accuracy of the modelled part. In this representation, the green-coloured area indicates a perfect match between the modelled and scanned bonnet surfaces, highlighting their alignment and precision. During the analysis, it was observed that the blue area displayed a slight inward bend in the modelled bonnet surface. Conversely, the orange/red region indicated a deviation of the modelled surface, as it projected slightly outward compared to the scanned model.

Figure 1 3D model of the bonnet (see online version for colours)

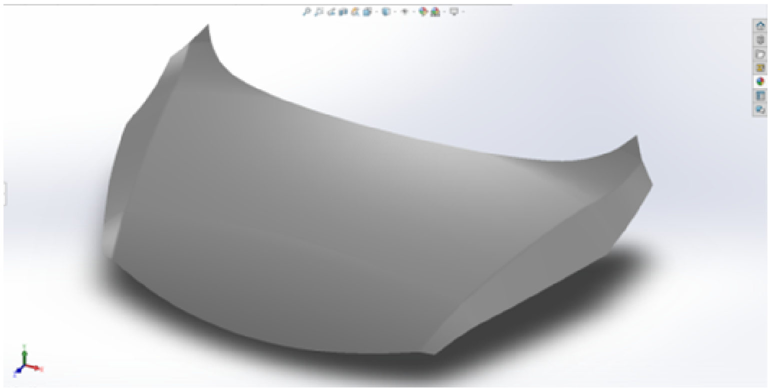
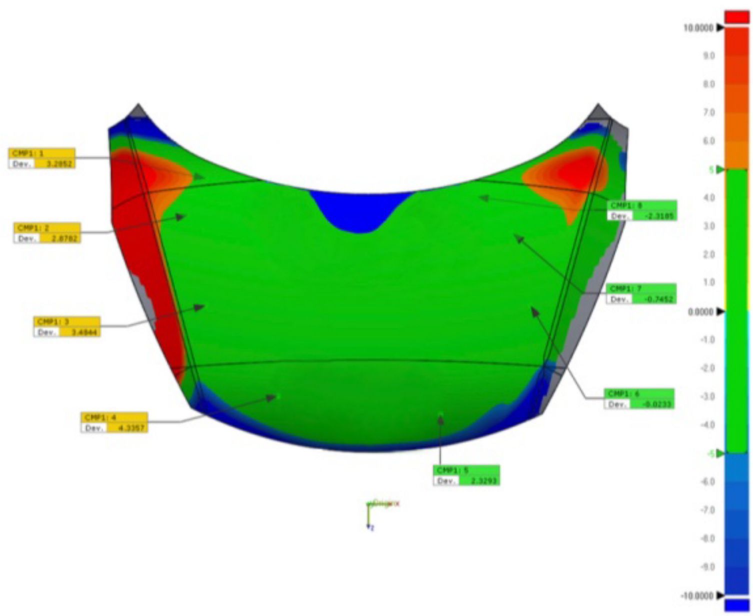


Figure 2 Validation of bonnet (see online version for colours)

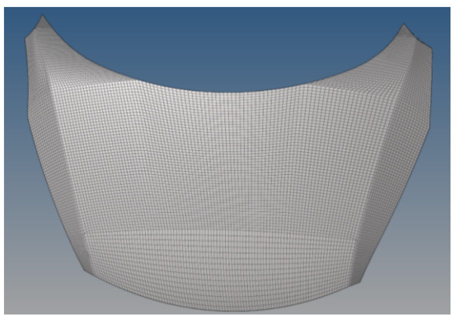


However, the primary focus of the evaluation was on the centre of the bonnet, as the maximum head impacts occur, where the modelled data and the scanned data exhibited an excellent level of congruence. This central area demonstrated a high degree of accuracy, confirming the successful replication of the bonnet's shape in the model. The colour contour visualisation provided valuable insights into the consistency and reliability of the modelled bonnet, with the green area affirming the fidelity of the model and the deviations in the blue and orange/red regions highlighting areas that may require further refinement.

2.2 Meshing of bonnet

Bonnet meshing was carried out using ‘Altair Hypermesh’ software. Firstly, the bonnet part modelled in Solidworks was imported into Hypermesh. There were a few surface irregularities found after importing. They were trimmed and new surfaces were created using the ‘Create surface’ command. Then, the bonnet surface was divided into rectangular sections with the bonnet edges and curves as the boundary. Each part was meshed by giving the number of elements on the sides of the rectangle as the input and this number was equal for the opposite sides as it is a rectangle. The mesh elements formed were 10 mm in size and the majority of them were “Quadratic elements”. The final meshed bonnet part was obtained as shown in Figure 3. It is also found that the value of HIC, energy absorption and deformation of the car bonnet will not be impacted with the confirmed number of elements getting refined further.

Figure 3 Meshed bonnet (see online version for colours)



The bonnet model contains 10,997 elements in total, out of which 10,973 (99.782%) were quad elements and 24 (0.218%) were triangular elements.

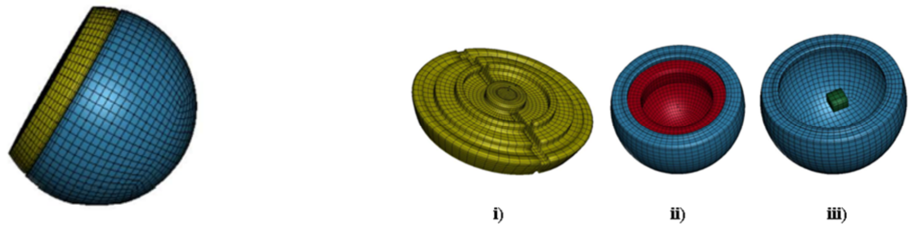
3 Headform modelling

The risk of head damage from collisions with cars is even higher because the head sustains the most severe injuries in numerous crashes, particularly pedestrian-automobile collisions (Horgan and Gilchrist, 2003). International Safety Committee has suggested subsystem tests where head form impactors are hit against the automobile hood to lessen the severity of such injuries. The various impactors considered to determine performance in terms of pedestrian safety are adult and child head form impactors as well as the lower leg and upper leg impactors (representing the adult leg and child’s leg, respectively). Since head injuries are more dangerous and the most frequent cause of pedestrian fatalities in collisions with vehicles, it was decided to concentrate on these impactors and test procedures for this study.

3.1 Headform model

The head-form models are imported from LS-DYNA and consist of a rear plate, an inner sphere, an outer skin and an accelerometer placed on the rear plate inside the inner sphere as shown in Figure 4.

Figure 4 Head-form parts: (i) rear plate; (ii) inner sphere and outer skin and (iii) accelerometer at the sphere centre (see online version for colours)



It is recommended that the adult and child head-form impactors be rigid spheres covered in vinyl, with respective total masses of 4.8 ± 0.1 kg and 3.5 ± 0.05 kg. The acceleration of both adult and child head form impactors is read using a tri-axial accelerometer mounted at the centre.

The adult head form model contains 27,647 hexagonal elements with an effective mass of 4.579 kg. Similarly, the child headform contains 20,027 hexagonal elements with a mass of 3.467 kg. The properties of individual parts of these headforms are specified in Tables 1 and 2.

Table 1 Adult headform properties

Adult headform properties								
S. no.	*Type*	*Part keyword*	*Part name*	*Material type name*	*Density*	*Young's modulus*	*Mass (kg)*	*Number of elements*
1	Solid	PART	Skull	020 RIGID	2.91E-06	207	2.03999	14,800
2	Solid	PART	Skin	077_O OGDEN_ RUBBER	1.09E-06	0	0.759149	3712
3	Solid	PART	Accel Block	020 RIGID	3.15E-06	207	0.013879	27
4	Solid	PART	Back Plate	020 RIGID	3.15E-06	207	1.76609	9108
						Total	4.579108	27,647

Table 2 Child headform properties

Child headform properties								
S. no.	*Type*	*Part keyword*	*Part name*	*Material type name*	*Density*	*Youngs modulus*	*Mass (kg)*	*Number of Elements*
1	Solid	PART	Skull	020 RIGID	2.91E-06	207	1.43593	3968
2	Solid	PART	Skin	077_O OGDEN_ RUBBER	1.09E-06	0	0.714027	4032
3	Solid	PART	Accel Block	020 RIGID	3.15E-06	207	0.013819	27
4	Solid	PART	Back Plate	020 RIGID	3.15E-06	207	1.30362	12,000
						Total	3.467396	20,027

4 Simulation

The simulations were performed for three different impact points axially on the car bonnet with three different kinds of material resulting in a total of nine trials. The pedestrian head impact simulation was carried out in LS-DYNA. The impact points for headformon the bonnet are decided according to the wrap around distance (WAD), which must be within 1000 mm for the child headform and between 1000–1500 mm for that of the adult headform from the leading edge of the bonnet. Here, the headform impact to the bonnet was at 40 kmph with an inclination angle of 55° about the horizontal plane, for all tests. The mentioned conditions are according to the EEVC WG17 regulations. LS-DYNA uses a multi-physics solver for performing the simulations. To simulate pedestrian safety in LS-DYNA the following parameters and conditions are to be considered:

i *Pedestrian model*: The selection of the pedestrian model depends on the level of detail required for the analysis.

ii *Bonnet model*: The bonnet model is essential for pedestrian safety simulations involving vehicle-pedestrian collisions. The bonnet model can vary in complexity, from simple rigid bodies to detailed finite element models of the bonnet's structure.

iii *Material properties*: Proper material modelling is crucial for accurate simulation results. This includes defining the material properties for both the headform and bonnet components involved in the simulation.

iv *Contact interfaces*: LS-DYNA allows users to define contact interfaces between pedestrian parts and bonnet parts. Proper contact definitions are essential to simulate interactions accurately during a collision.

v *Boundary conditions*: Appropriate boundary conditions need to be applied to the model to simulate real-world scenarios.

vi *Impact velocity and angle*: The initial conditions of the simulation may include the impact velocity and angle between the pedestrian and the vehicle. These values play a significant role in determining the outcome of the simulation.

vii *Impact surfaces*: The surfaces of the vehicle and pedestrians that come into contact during the collision need to be accurately defined to ensure realistic interactions.

viii *Time step and solver settings*: The choice of time step and other solver settings can influence the accuracy and stability of the simulation. Smaller time steps are often used in critical impact regions to capture rapid changes in contact behaviour.

ix *Pre and post-processing*: LS-DYNA requires appropriate pre-processing to set up the model correctly, and define contacts, materials, and boundary conditions. Post-processing is essential to interpret and visualise the simulation results.

The input for the LS-Dyna is given as the cards, and here are the following lists of Control Cards used for the simulation.

SECTION_SHELL Card: It defines the section properties for the Shell Elements. Here the shell thickness at nodes is given as 2 mm as the bonnet outer panel thickness is 2 mm.

MAT_PIECEWISE_LINEAR_PLASTICITY: It is possible to define an elastoplastic material with arbitrary stress v/s strain curve and strain rate dependency.

CONTACT_SURFACE_TO_SURFACE: This contact option offers a way to represent components that are initially pre-stressed because they are shrink-fit together. This option disables the nodal interpenetration checks at the beginning of the simulation, allowing the contact forces to build up and remove the interpenetrations without changing the geometry by moving the nodes. Between bonnet and the headform, with bonnet acting as the slave and the headform as the master, a SURFACE TO SURFACE contact has been defined. Because the headform contains five components, the slave node-set type and hood as the master segment type are both assigned Part Set IDs. Here two contacts are given and those are:

1 contact between skin and the skull

2 contact between skin and the bonnet.

INITIAL_VELOCITY: Here the initial velocity is 40 kmph, which equals 11.11 mm/ms. which is a resultant velocity and so resolves the velocity component in *Y* (mag. 6.732) and negative Z-axis (mag. 9.1). In this case, the head is tilted at an angle of 55 Degrees and the values inputted in accordance with the EEVC WG17 Standards.

BOUNDARY_SPC: The Boundary SPC is specified for the Bonnet to limit every degree of freedom for the collection of nodes (NSID) along the hood's boundaries.

CONTROL_TERMINATION: Control_Termination specifies when the simulation stops or the simulation's end time. It has a 25 ms setting.

DATABASE_CREATION:

- **'BINARY_D3PLOT',** which is set to 0.5 ms, specifies the frequency at which the animation file is to be produced.
- **'DATABASE_HISTORY_NODE' –** A node was established on the head's acceleration block to measure acceleration and calculate the HIC value.
- **'DATABASE_EXTEND_BINARY' –** when STRFLG is set to one, this uploads the strain tensor to d3plot.

Tables 1–3 provide a comprehensive overview of the properties associated with the adult headform, child headform, and the different material properties employed for simulation purposes.

Table 3 Material properties of the materials

S. no.	*Material*	*Density* (kg/mm^3)	*Young's modulus* (GPa)	*Poisson's ratio*	*Yield stress* (GPa)	*Ultimate stress* (GPa)	*Tangent modulus* (GPa)
1	AA 6061 T6	2.713E-06	69	0.33	0.26	0.31	0.5065
2	Structural steel	7.85E-06	200	0.3	0.25	0.46	2.1201
3	AA 5252	2.77E-06	71	0.33	0.28	0.31	0.3048

Figures 5–7 represent the initial simulation setup obtained from LS-Dyna software for child and adult headform impact at different positions.

Figure 5 Initial simulation setup for child headform impact at position 1 (see online version for colours)

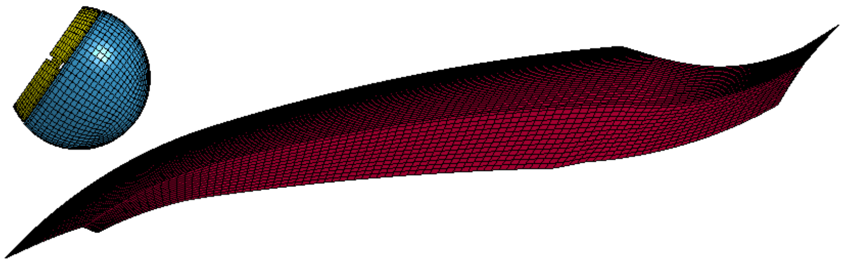


Figure 6 Initial simulation setup for adult headform impact at position 2 (see online version for colours)

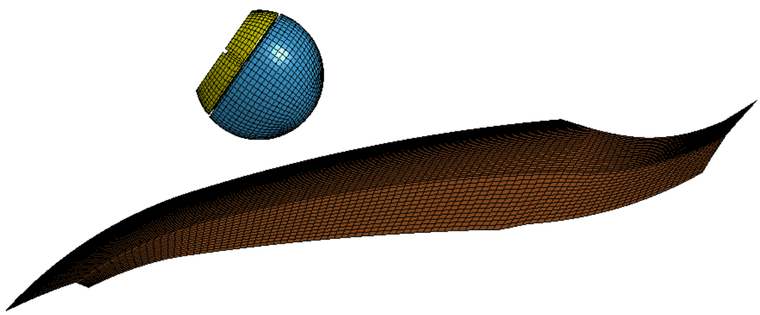
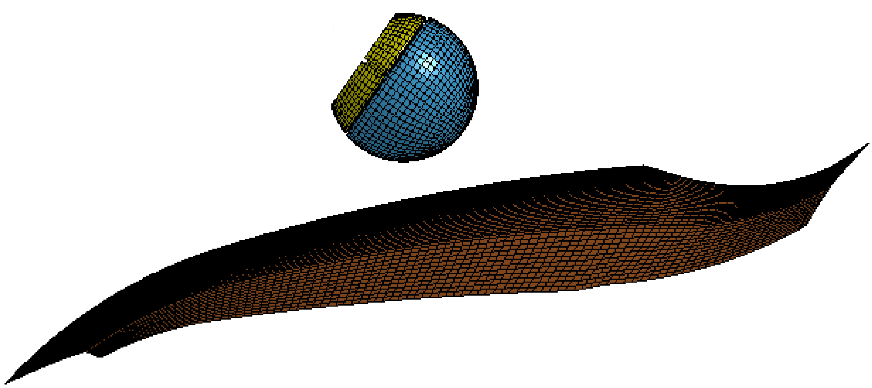


Figure 7 Initial simulation setup for adult headform impact at position 3 (see online version for colours)



5 Results and discussion

Table 4 presents the results of impact testing for three different materials (AA 6061 T6, Structural Steel, and AA 5252) under various headform positions (Position 1, Position 2, and Position 3) using parameters such as HIC, Energy Absorption (Joules), and Deformation (mm). The data allows us to compare the performance of the three materials under different impact conditions. Lower HIC values, higher energy absorption values, and lower deformation values generally indicate better performance in terms of pedestrian safety during an impact.

Table 4 Simulation results for prescribed conditions

Materials	*Parameters*	*Child headform* *Position 1*	*Adult headform* *Position 2*	*Adult headform* *Position 3*
AA 6061 T6	HIC	530.2	1142	1681
	Energy absorption (J)	173.9	246.49	255.2
	Deformation (mm)	94.14	75.865	64.708
Structural Steel	HIC	1004	1479	1711
	Energy absorption (J)	197.89	244.99	246.86
	Deformation (mm)	61.329	47.754	40.367
AA 5252	HIC	523.6	1124	1488
	Energy absorption (J)	174.13	246.08	248.65
	Deformation (mm)	93.383	75.256	62.771

5.1 Head injury criteria (HIC)

The value of HIC is calculated by using the formula mentioned below:

$$\text{HIC} = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,\mathrm{d}t\right]^{2.5}\left(t_2 - t_1\right)$$

where: HIC is the head injury criterion, t_1 and t_2 are the initial and final times within the specified interval respectively, a(t) represents the resultant head acceleration at a given time during the impact, $\int_{t_1}^{t_2} a\,\mathrm{d}t$ denotes the integration of the acceleration over the specified time interval (Yadav and Pradhan, 2014).

The comparison of HIC values for the three bonnet materials is shown in Figure 8. Three impact locations were considered. AA 5252 was shown to have the lowest HIC values for impact at all three locations, while structural steel had the highest values. Other than the aluminium variants at position 1, the values were greater than 1000. Furthermore, regardless of the material, position 1's values were lower than those for the other two positions. For all three materials, position 3 displayed the highest results.

5.2 Energy absorption

An important consideration when designing the hood to prevent and reduce head injury is the absorbed energy of the car bonnet modelling. As seen in Figures 9–11, the energy absorbed by steel is greatest at position 1 but least at positions 2 and 3. For aluminium, it is different. Aluminium absorbs more energy than steel for impact at positions 2 and 3, but less at position 1. The amount of energy absorbed is greatly influenced by the position of impact. It is observed that energy absorption is more for impact at position 3 than that for positions 1 and 2, irrespective of the material (EURO NCAP, 2017; Peng et al., 2012).

Figure 8 Comparison of HIC values (see online version for colours)

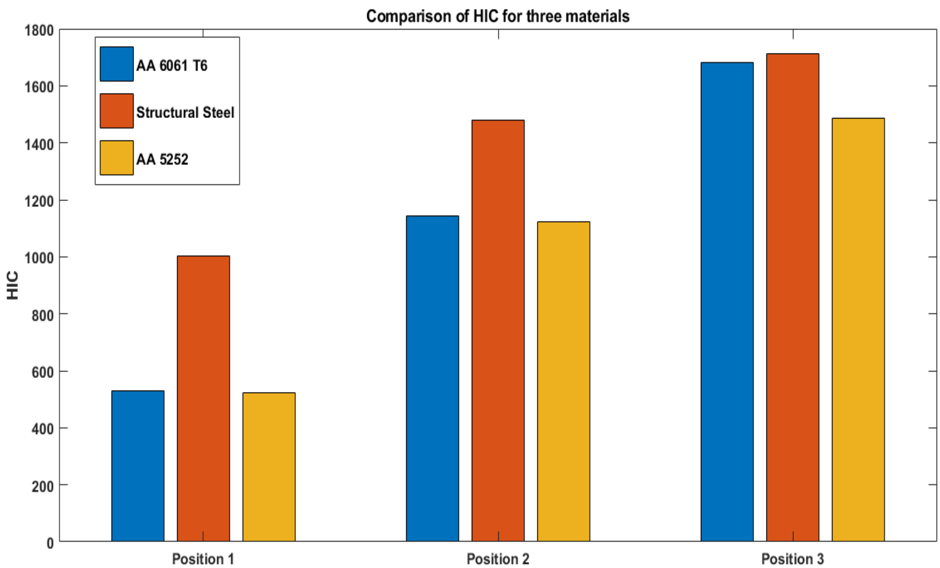


Figure 9 Variation of internal energy for position 1 (see online version for colours)

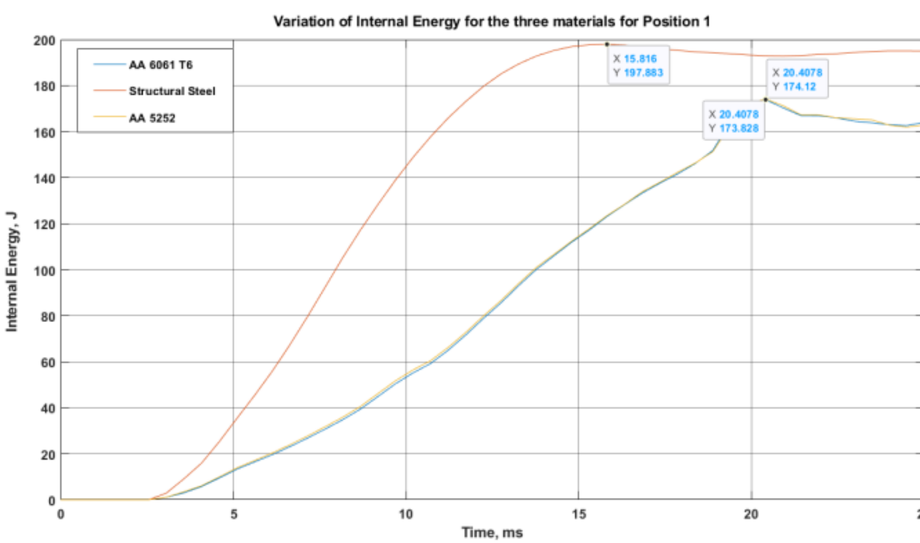


Figure 10 Variation of internal energy for position 2 (see online version for colours)

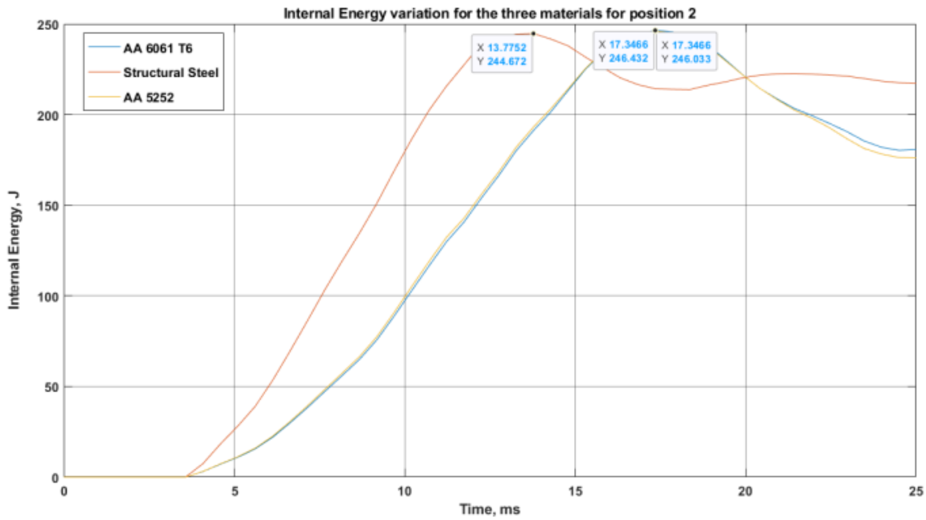
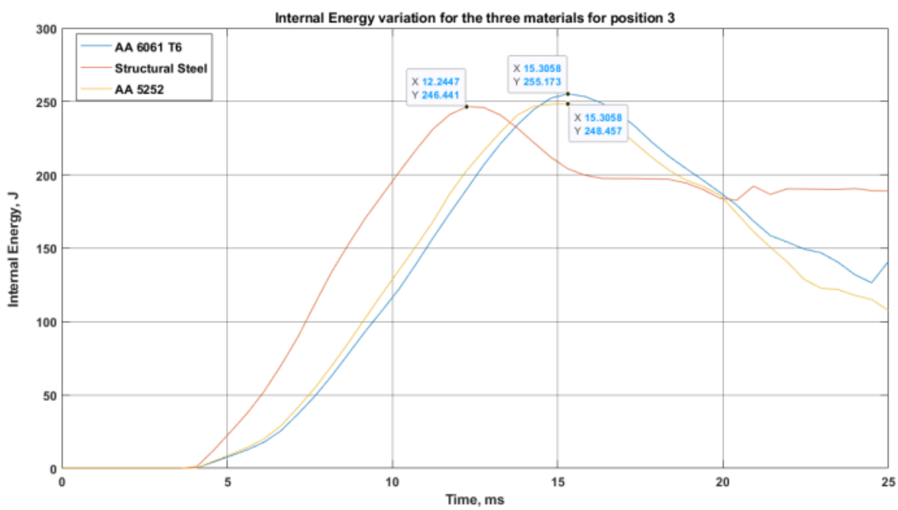


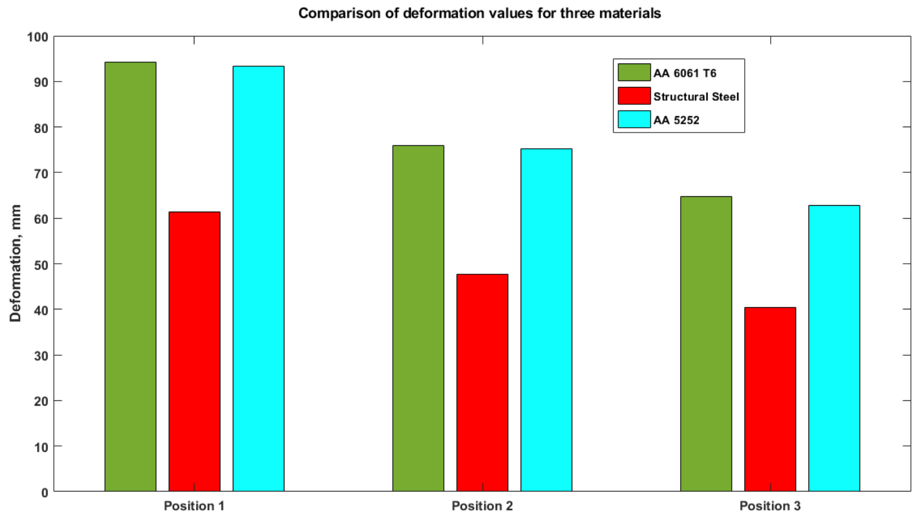
Figure 11 Variation of internal energy for position 3 (see online version for colours)



5.3 *Deformation*

The deformation of the car bonnet after the impact of head-form is summarised and presented in Figure 12 for all three materials and three impact locations. The obtained results follow a similar trend as reported in the previous research work (Ahmed, 2020; Schulz and Kalay, 2016). The bonnet material should be such that it absorbs the maximum amount of impact energy as this would reduce impact on the head. It can be observed that deformation is highest for Al-6061 at position 1, followed by AA 5252 and Structural Steel. This trend follows for the other two positions. A higher deformation value corresponds to a lower HIC value which ensures more pedestrian safety.

Figure 12 Comparison of deformation values (see online version for colours)



The following factors mainly influence to changes in the HIC value, energy absorption, and deformation at different locations on a car bonnet.

i *Impact force distribution*: The distribution of impact forces can vary across different locations on the car bonnet. Certain areas may experience more concentrated or localised forces, resulting in higher HIC values and deformation. Factors such as the shape of the bonnet, impact angle, and pedestrian's point of contact can influence force distribution.

ii *Bonnet design and structure*: The design and structure of the car bonnet can affect its ability to absorb energy and deform upon impact. Variations in the bonnet's thickness, curvature, material properties, reinforcement elements, or the presence of energy-absorbing structures can lead to differences in energy absorption and deformation at various locations.

iii *Material properties*: Different materials used in the construction of the car bonnet can exhibit varying energy absorption characteristics and deformation behaviours. Materials with higher ductility or better energy-absorbing capabilities may perform differently when subjected to impact forces, resulting in variations in HIC values and deformation at different locations.

iv *Stiffness and flexibility*: The stiffness and flexibility of the car bonnet can impact the distribution of impact forces and subsequent energy absorption and deformation. Stiffer areas may transfer more force to the pedestrian, leading to higher HIC values, while more flexible areas may deform more easily, resulting in lower HIC values and higher deformation.

v *Pedestrian anatomy and posture*: Variations in pedestrian anatomy and posture can cause differences in the contact points with the car bonnet. The location and orientation of the impact can influence the HIC value, energy absorption, and deformation, as different parts of the head and body may be more or less susceptible to injury.

vi *Manufacturing considerations*: Variations in the manufacturing process or assembly of the car bonnet can affect its structural integrity and performance. Inconsistent material thickness, bonding techniques, or quality control issues may result in differences in energy absorption and deformation at different locations.

6 Conclusion

This study aimed to assess the likelihood of head injuries in car-to-pedestrian accidents and evaluate the effectiveness of hood protection. A new finite element model, complying with EURO-NCAP standards, was developed to simulate frontal impacts between automobiles and pedestrians. Specifically, the analysis focused on the Swift 2014 car bonnet.

The car bonnet was accurately modelled using Solidworks software, and Hypermesh software was used for meshing. LS-DYNA software facilitated the simulations. The simulations were conducted based on the EEVC standards, using adult and child head-form models and considering three different impact positions on the bonnet. To assess the pedestrian friendliness of the bonnet, three key parameters were considered: the HIC value, energy absorption, and deformation. The simulation results for each material and impact position were compared based on these parameters.

The findings of this study are as follows:

- Aluminium, as compared to steel, demonstrated a lower HIC value and met the requirements of the EEVC WG 17 standards for all three impact positions.
- While steel exhibited better energy absorption at position 1, aluminium showed superior energy absorption at the other impact positions.
- Aluminium displayed higher deformation values at all impact positions compared to steel. Increased deformation leads to lower HIC values, thereby enhancing pedestrian safety.
- Among the two aluminium alloys analysed, namely AA 6061 T6 and AA 5252, the latter demonstrated more favourable characteristics in terms of material cost and composition. Furthermore, AA 5252 exhibited reduced HIC values and increased deformation when compared to AA 6061. Based on these factors, AA 5252 is considered the most suitable bonnet material for pedestrian safety.

The present work includes some limitations such as

i *Simplified representation*: While HIC, energy absorption, and deformation provide valuable information, they represent a simplified model of real-world impact scenarios. Pedestrian accidents can involve complex interactions between vehicles and individuals, which may not be fully captured by these metrics alone.

ii *Specific impact conditions*: HIC, energy absorption, and deformation values are highly dependent on specific impact conditions. Different headform positions, impact angles, and speeds can yield varying results. Therefore, it’s essential to consider a range of impact scenarios for a comprehensive evaluation.

iii *Human variability*: Pedestrian safety assessments often use standardised headforms or dummy models, which may not fully represent the variability in human body sizes, postures, and movements. Real-world pedestrian populations are diverse, and the results may not fully capture all potential scenarios.

iv *Sensitivity to test setup*: These parameters can be sensitive to test setup and boundary conditions. Differences in testing equipment, headform shapes, and boundary constraints can lead to variations in results.

v *Single impact measure*: While each parameter provides valuable insights, no single parameter can fully encompass the complexities of pedestrian safety. It's crucial to consider a combination of metrics, along with real-world crash data and simulations, for a more comprehensive assessment.

Future studies should explore the potential benefits resulting from adjustments in the inner structure of the bonnet, as this may lead to reduced displacement, lower HIC values, and decreased headform displacement. Additionally, investigating different impact angles and placements is a crucial area of interest for further research.

In conclusion, this study provides a valuable method for evaluating hood protection effectiveness and estimating the likelihood of head injuries in car-to-pedestrian accidents. The findings highlight the advantages of using aluminium as a bonnet material, particularly AA 5252, due to its lower HIC values, improved energy absorption, and higher deformation. These insights contribute to enhancing pedestrian safety and can inform future design and manufacturing considerations in the automotive industry.

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