Development of Pedestrian Headform Finite Element (FE) Model using LS-DYNA® and its validation as per AIS 100/GTR 9

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1 Abstract

Thousands of pedestrians die due to road accidents in the world every year. Head injury is more life threatening and most common cause of pedestrian deaths in pedestrian to vehicle collision. To reduce rate of pedestrian death, international safety committees have developed test in which headform impactors are impacted upon car vehicle front structure (bonnet) and approval is given based on headform acceleration within specified range.

In the development stage of vehicle, when vehicle prototype is not available and to make the design compliant to pedestrian safety standard, use of computer simulation is very essential. In order to predict performance of vehicle structure in simulation, it is necessary to develop validated Finite Element (FE) model of headform. This paper investigates development of FE model of pedestrian headform using LS-DYNA® as per Automotive Industry Standard (AIS) 100 standard with experimental validation. The development activity was carried out along with Livermore Software Technology Corporation (LSTC) USA.

In the development, 3D Scanning of physical headform of adult and child impactors was performed to prepare 3D CAD models. Suitable Finite Element Analysis (FEA) parameters such as material model, characteristic length of element, element formulation, and contacts were selected by iterative process. The developed headform FE model was validated against physical properties of headform and the calibration tests as per AIS 100.

This validated headform was used for assessment of a passenger vehicle. The simulation results obtained from LS-DYNA®, correlated very well with testing. This developed FE Headform can be used for assessment of vehicle structure in the development stage.

2 Introduction

Based on the recent statistics presented by the World Health Organization, road traffic injuries are the eighth leading cause of death for people of all ages. Although the rate of deaths per number of vehicles on the road has somewhat decreased, it is not fast enough to compensate for rapid population growth and increased road lengths across the world. There has been no reduction in the number of road traffic deaths in middle and low-income countries since 2013. More than half of all road traffic deaths are among vulnerable road users like pedestrians, cyclists and motorcyclists. The main cause for the same is wide implementation of vehicle standards developed for vehicle occupants globally, while ignoring pedestrian safety, especially in middle and low-income countries [1]

The 2018 study by Ministry of Road Transport and Highways (MoRTH), nodal authority under Government of India, indicated that pedestrians comprised of 11% of deaths in road accidents recorded the previous year, second only to motorcyclists (33%). Accident severity (deaths per 100 accidents) in pedestrian collision cases was at an all-time high of 25%, on account of increase in population, while not maintaining proper infrastructure for such vulnerable road users [2]

3 Safety Scenario in India

Indian government has mandated front and side crash regulations consistent with UN standards from 2017 for new cars and 2019 for all cars. Similarly, the pedestrian protection regulation came into force recently in October 2018 for new vehicle models and extended to 2020 for all vehicle models.

Currently in India, Automotive Indian Standard (AIS) 100, Amendment 1 is used to evaluate performance of vehicle against pedestrian safety. This standard has been harmonized from the international evaluation standard Global Technical Regulation No. 9 (GTR 9), whose purpose is to bring about an improvement in the construction of the fronts of vehicles and, in particular, those areas which have been most frequently identified as causing injury when in collision with a pedestrian or other vulnerable road user. The tests required are focused on those elements of the child and adult body most frequently identified as sustaining injury, i.e. the adult head and leg and the child head. To achieve the required improvements in construction of vehicles, the tests are designed in such a way that they will represent rear world accedent scenario.[3]

Figure 3:1 below summarizes the different tests applicable as per the AIS 100 standard.

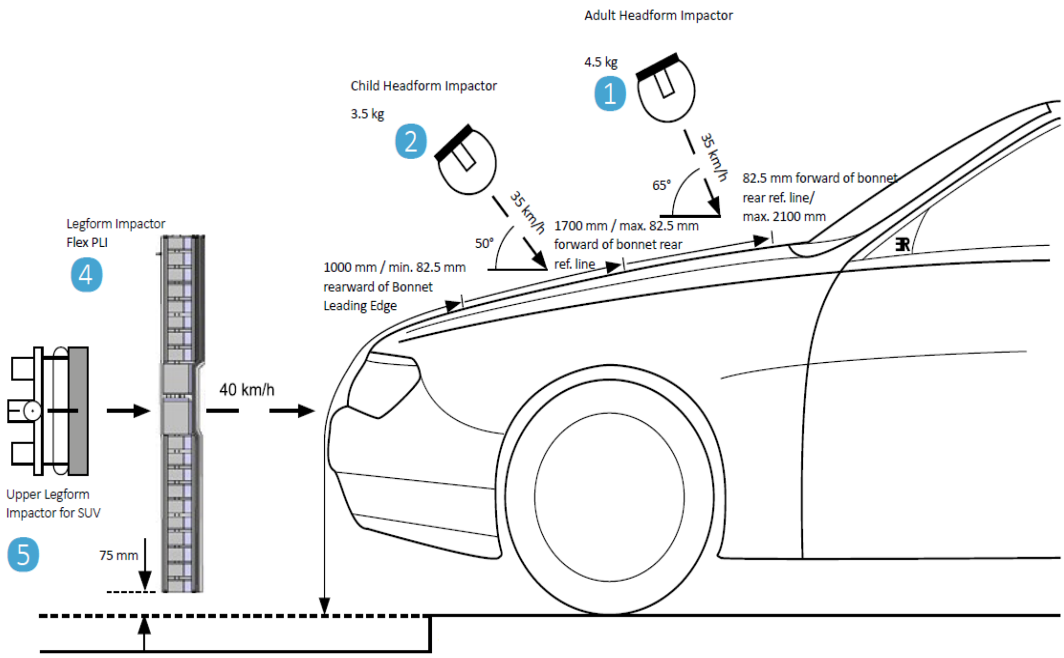

Figure 3:1 Pedestrian Protection Test Procedures as per AIS 100 / GTR 9 [4]

The different impactors used in predicting the perfromance against pedestrian safety are the lower legform and upper legform impactors (representative of the adult leg) and the adult and child headform impactors (representative of the adult head and child head). Head injury is more life threatening and most common cause of pedestrian deaths in pedestrian to vehicle collison;it was decided to focus on these impactors and test procedures as a part of this study.

The child headform impactor is made of aluminium and is of a spherical shape of 165 mm overall diameter. This sphere is covered with a 14 mm thick synthetic rubber skin, covering more than half of the front face, while having provision for instrumentation at the flat rear face. The total mass of the impactor is 3.5 kg, with the centre of gravity (CG) located at the geometric centre of the sphere. A triaxial accelerometer is mounted in the sphere recess, used for measuring the total acceleration of the impactor during impact and subsequently the Head Injury Criterion (HIC) value. [3]

The adult headform impactor is almost similar to the child headform impactor in terms of size and shape. However, it is heavier than the former, with a total mass of 4.5 kg. The aluminium sphere is covered by the synthetic rubber skin and also has a triaxial accelerometer mounted in its recess, similar to the child headform impactor.

Figure 3:2 below shows the cross sectional geometry of both impactors

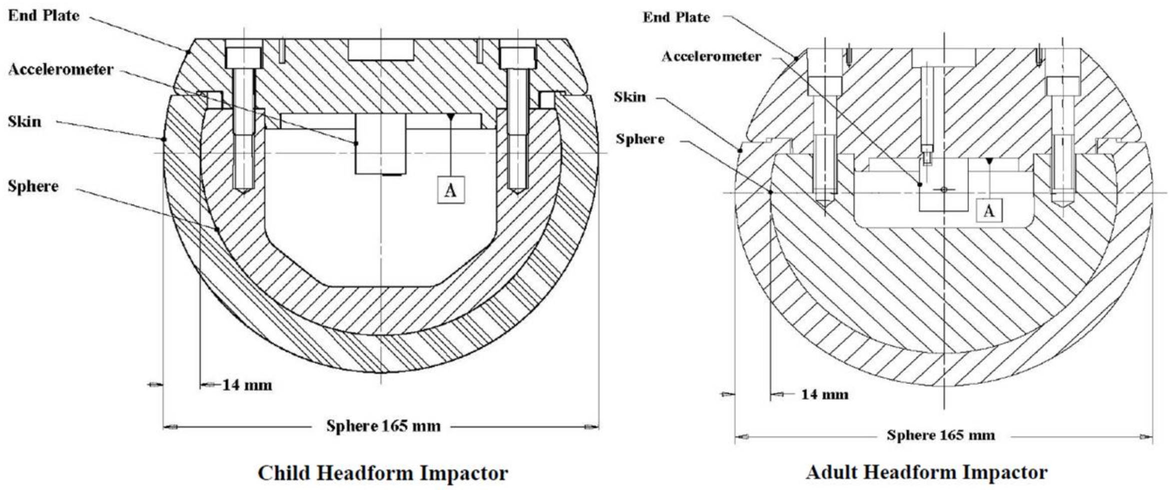

Figure 3:2 Child and Adult Headform Impactor Components & Geometry [3]

As a homologation body, Automotive Research Association of India (ARAI) has been entrusted with evaluation of vehicle models as per Indian standards (AIS 100). One of the requirements of AIS 100 is marking of impact zones on the vehicle front hood and bumper based on its impact with either the pedestrian head or leg. The evaluation criteria of each zone is dependent on the type of impact. Another requirement of AIS 100 is also to identify hard points (critical points with higher HIC values) in the given headform impact zone (Figure 3:3), so as to evaluate the vehicle performance with minimum number of physical homologation tests. For child area, half of total area should be below HIC 1000 and two third of combined child and adult area should be below HIC 1000. For remaining area HIC should be below 1700; is the accepance criteria as per AIS 100. This identification process would become very efficient through different simulation iterations using Finite Element (FE) impactor models.

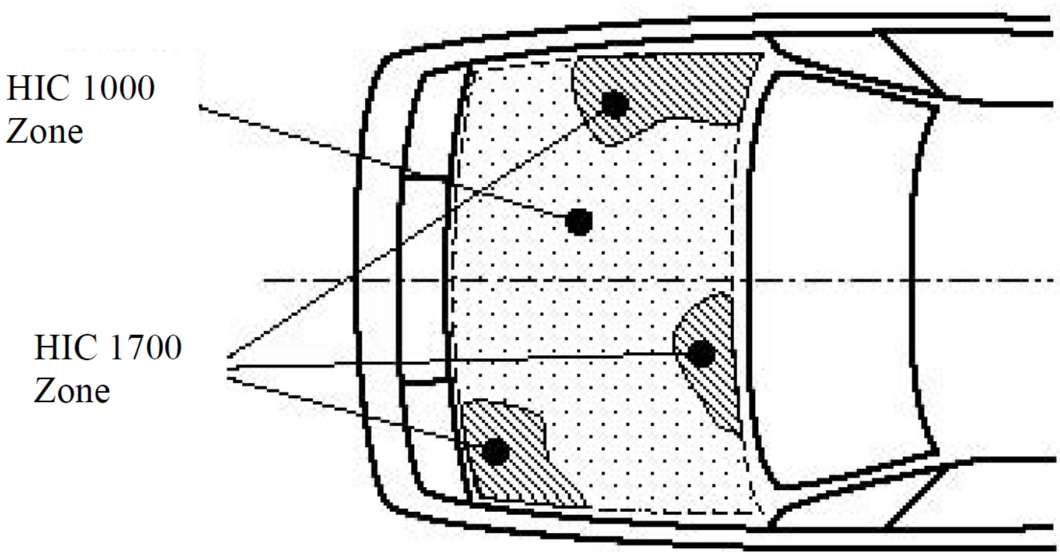

Figure 3:3 Marking of Head Impact Zones as per maximum HIC requirements [3]

Over the years, many vehicle manufacturers have developed their own headform impactor models for vehicle development programs. Such models were claimed to be validated to their physical counterparts. Being proprietary data, these models were never shared on a public platform for use. Any models available to the interested general public are currently leased through a paid contract for commercial use. This would add to existing product development cost which would be unacceptable to some vehicle manufacturing startups.

This challange led to a common thought process between LSTC, and ARAI to create open source FE impactor models to help promote research and development in the field of pedestrian safety. The scope was currently limited to creation of Child and Adult Headform Impactors in LSDYNA® solver and its validation through calibration and representative vehicle impact tests and simulation.

4 Development of Pedestrian Headform Finite Element (FE) Model

In this research FE model development methodology was set in four phases as below

- **3D Scanning of Physical Headform to generate CAD**
- **Generation of FE model form 3D CAD Data**
- **Material Characterization**
- **Material Card Development for each FE Model Component**

This methodology was used for both headform. Being a homologation body, ARAI had direct access to physical headform impactors which are used for AIS 100 evaluation.

3D Scanning of physical headforms was conducted using the blue light scanning facility at ARAI. This phase was important from acquiring accurate geometry of the headforms . Each of headform component was scanned separately and the entire assembly was scanned subsequently to understand contact and interfacing of different components to each other. Figure 4:1below shows the 3D scanning process, converting physical headform to 3D CAD

Figure 4:1 Comparison between Physical Headform Impactor and its 3D CAD Model

Using CAE tools, each component of Headform was converted in to corresponding FE Model of solid Hexahedral Element (**`*ELEMENT_SOLID`**). Care was taken to achieve node matching at component contact locations, while ensuring that the overall mesh parameters lie within suitable crash analysis criteria. Geometry cleanup was performed based as per requirement, while mesh size was different at different locations based on impact direction and subsequent load transfer and contact. The final Child Headform FE Model was generated with 25658 nodes and 20028 elements, while the Adult Headform FE Model was generated with 33424 nodes and 27647 elements.

Figure 4:2 indicates the conversion of different child headform components to FE mesh models. Triaxial accelerometer element was placed on the rear plate inside the inner sphere recess at the same location as its counterpart in the physical headform. **`*CONSTRAINED_EXTRA_NODES_SET`** was used to assign contact between outer skin and inner sphere of headform. **`*CONSTRAINED_RIGID_BODIES`** was used between back plate and Sphere and acceletometer block.

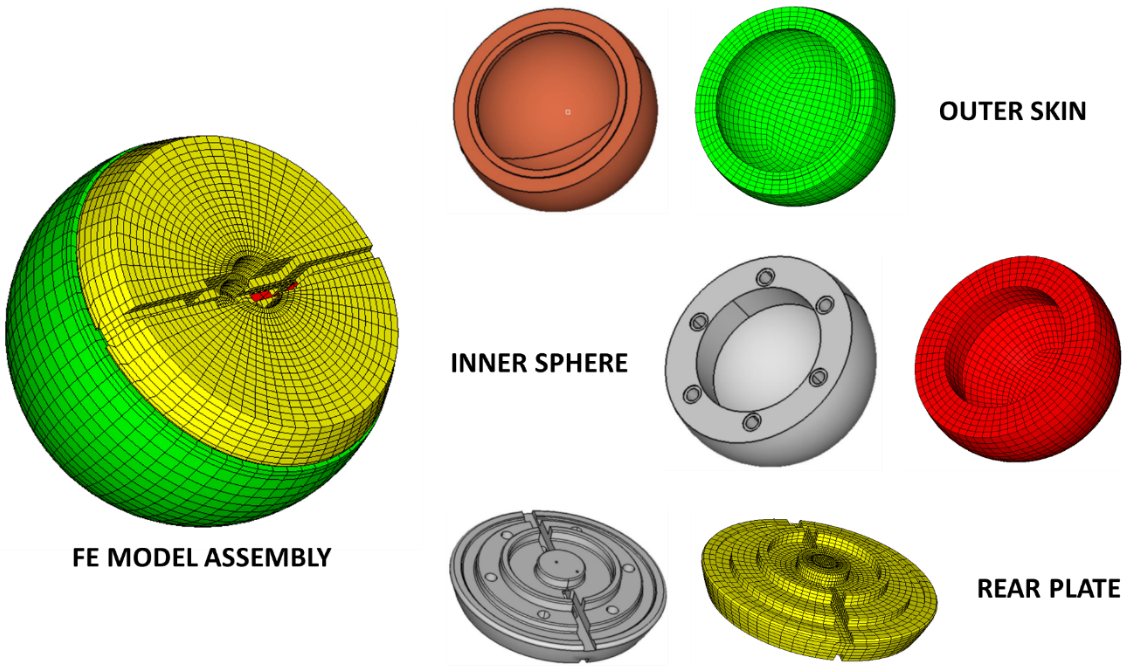

Figure 4:2 .Child Headform FE Model of Individual Components and Assembly

`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID` was used to assign contact between outer skin and inner sphere. **`*ELEMENT_SEATBELT_ACCELEROMETER`** was used to define accelerometer. Local coordinate system were assigned wherever required as per calibration load case and representative passenger vehicle impact load case

Each component of the physical headform and the complete assembly were weighed to obtain their masses. Density values of each component were adjusted based on the geometry scanned and total mass weighed.

The density values of each component of FE headform were assigned so as to match the physical properties like mass, C.G. Mass moment of inertia etc with that of actual headfrom. The final FE child and adult headform model masses were 3.51 kg and 4.52 kg respectively. These were within the allowable tolerance as per AIS 100 (+/- 0.07 kg for Child Headform and +/- 0.10 kg for Adult Headform).

The important material in physical headform were aluminium and synthetic rubber, which were used for material characterization. Different properties like Young's Modulus, Poisson's Ratio, Visco-Elastic Curve, etc. were obtained during material characterization through iterative process, which were incorporated into FE model material cards. This activity of iteration for Outer skin material was carried out along with Livermore Software Technology Corporation (LSTC) USA.

Since the entire headform is not deformable, except for the outer skin, FE model material properties were adjusted accordingly. **`*MAT_OGDEN_RUBBER_TITLE`** was used for outer skin of headforms. Doing so, the FE models of both headforms were completed, and Calibration test for FE validation was carried out with validation on representative passanger vehicle subsequently.

5 Validation of FE Headform Models using Calibration Test

As per AIS 100, the impactors used to perform the homologation tests are required to comply with certain performance requirements. These requirements are the basis of ‘calibration’ of the impactors and need to be assessed periodically in order to ensure that the impactors are in perfect condition to perform the vehicle homologation.[3] For the child and adult headforms, the performance is assessed through a drop test, setup of which is shown in Figure 5:1 below

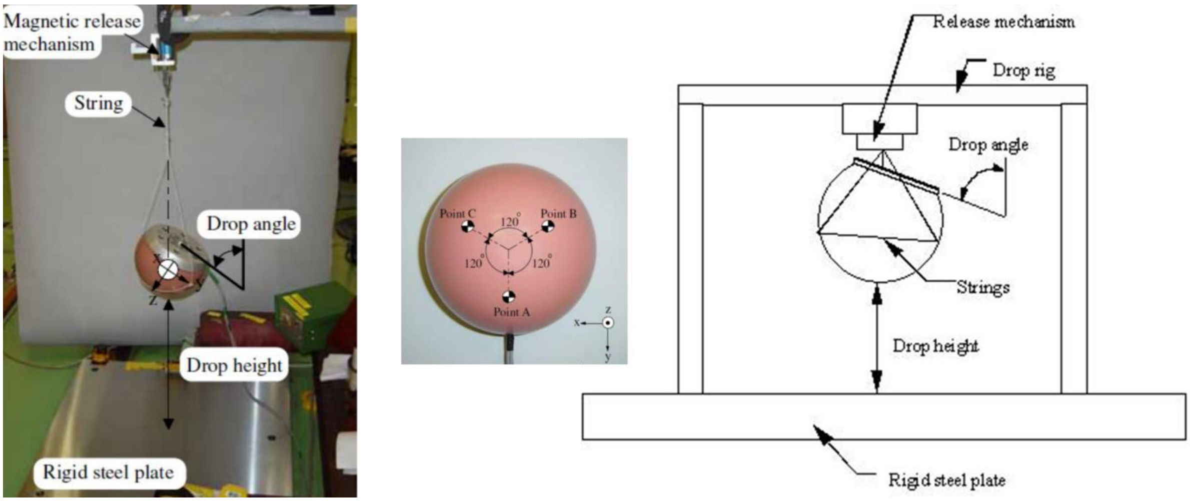

Figure 5:1 Drop Test Setup for Headform Impactors [3]

The headforms are to be dropped from a height of 376 mm, wherein the peak resultant acceleration is measured. Table 2 below shows the calibration performance requirements for both headforms.

Table 5-1 Headform Impactor Performance Requirements in Calibration Test [3]

Sr. No.	Test Particulars	Child Headform (kg)	Adult Headform (kg)
1	Drop Height	376 mm	
2	Headform Orientation	0^0, 120^0, 240^0 with reference plane	
3	Drop Angle	50^0	65^0
4	Min. Acceleration (g)	245	225
5	Max. Acceleration (g)	300	275

Set of three drop tests were conducted as per AIS 100 for the physical child and adult headforms, each at different orientations as required. Similarly, set of three FE model drop simulations were performed each for the FE child and adult headforms. The FE model was setup to impact a rigid wall vertically, with input velocity at impact calculated from the drop height. Figure 5:2 below shows different time plots at 0^0 headform orientation FE headform drop simulation.

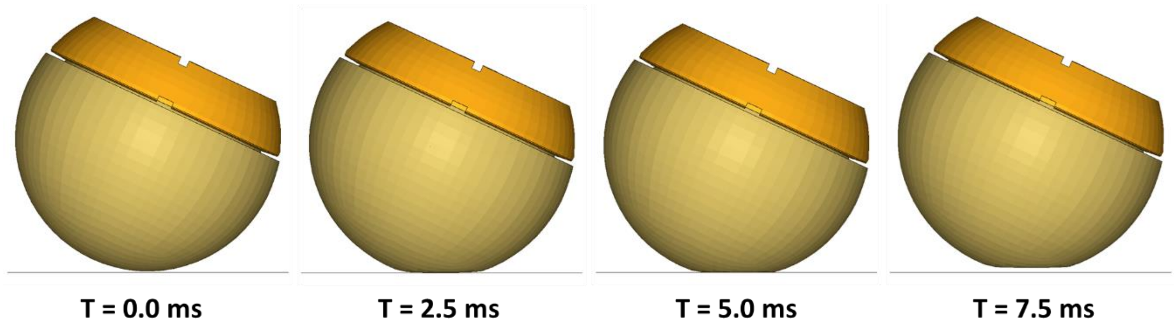

Figure 5:2 Time plots showing FE Headform Drop Simulation

Figures 5:3 and 5:4 below shows comparison between one set of physical test and CAE simulation results obtained each for the child headform and adult headform. For the child headform, it can be seen that the maximum resultant acceleration obtained in CAE simulation was 280 g as against 284 g obtained in the physical test. The trend of both acceleration curves were very similar in nature, while both values were within the 245 g to 300 g range as required by AIS 100. This validated the FE child headform for the calibration loadcase

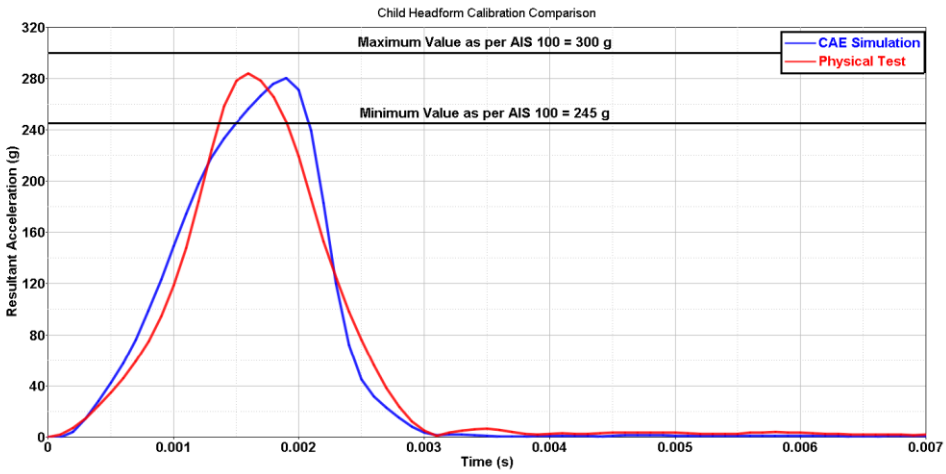

Figure 5:3 Comparison of Simulation and Test Results for Child Headform Calibration for one set

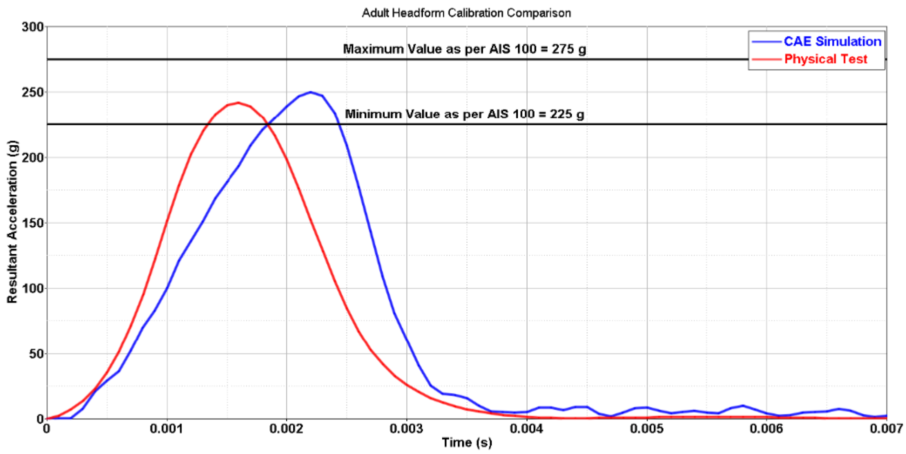

Figure 5:4 Comparison of Simulation and Test Results for adult Headform Calibration for one set

For the adult headform, it can be seen that the maximum resultant acceleration obtained in CAE simulation was 250 g as against 242 g obtained in the physical test. The trend of both acceleration curves were very similar in nature, while both values were within the 225 g to 275 g range as required by AIS 100. This validated the FE adult headform for the calibration loadcase.

6 Validation of FE Headform Models through Impact on Representative Passenger Vehicle

In order to check accuracy of FE models for AIS 100 homologation loadcases, a physical headform impact test was performed on a representative passenger vehicle. Figure 11 below shows the test setup as per AIS 100. The release angle was 50^0 for the child headform and 65^0 for the adult headform. The headform velocity at impact was 9.7 m/s (35 km/h) for both headforms. Impact point on the vehicle (A) was marked on the physical vehicle. [3]

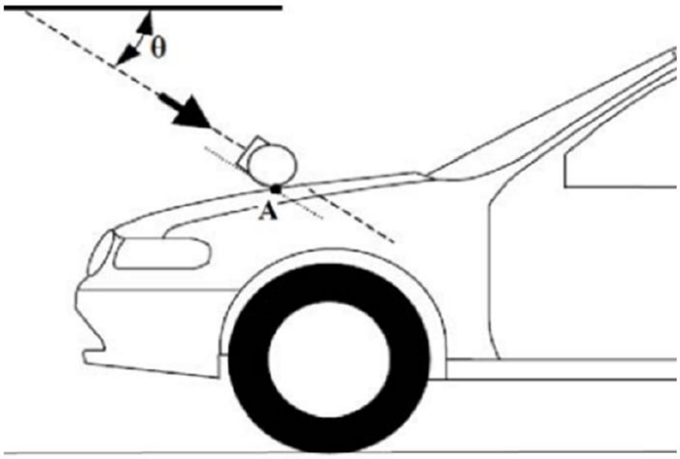

Figure 6:1 Test Setup for Headform Impact on Vehicle [3]

Headform resultant acceleration was measured and displacement is calculated through double integration approach. Based on the resultant acceleration vs time curve, Head Injury Criterion for 15 ms (HIC-15) value was calculated as per formula below–

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2 - t_1) \qquad \dots (1)$$

Where a is resultant acceleration (measured in g)
t_1 and t_2, = two time instants (measured in seconds) during the impact, defining an interval between the beginning and the end of the recording period for which the value of HIC is maximum.
In this case, $t_2 - t_1$ = 15 ms. [3]

The accepance criteria for Head impactors are as below.
For complete child area(WAD1700 mm) half of area (1/2) should be below HIC 1000 and for Combined adult and child area, two third (2/3) area should be below HIC 1000. In the remaining area HIC should be below 1700

In order to predict the performance under pedestrian impact, FE vehicle preparation (area marking) as per AIS 100 (GTR 9) should be same as that of Physical test. Thus area markup script in representative FE vehicle was carried out and The FE model of representative vehicle and FE headform was positioned

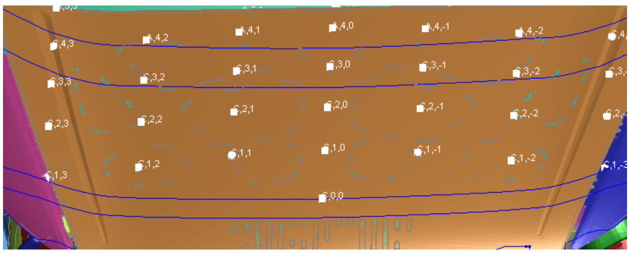

Figure 6:2 Pedestrian impact area markup

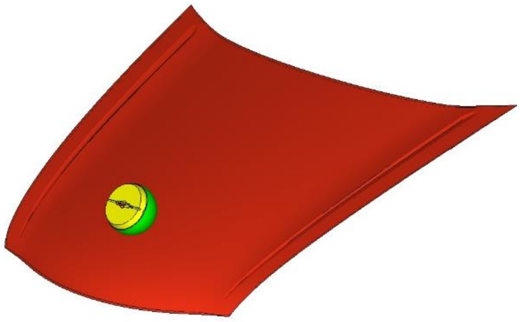

Figure 6:3 FE setup for Child impact on Bonnet

The area for Child headform was marked. By knowing the excact point of impact on actual vehicle ; FE Script marking point was used for analysis.To position the headform at exact location **`*DEFINE_TRANSFORMATION`** cards were used in the setup.(Figure 6:2 and 6:3) **`*CONTACT_AUTOMATIC_SINGLE_SURFACE`** contact was used in BIW except headform.The contact between FE headform and Reference FE vehicle was defined by using **`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID.`** Friction coefficient between the headform and vehicle plays important role in resultant head acceleration and HIC. Generally, higher friction coefficient between headform and bonnet result in higher resultant forces, accleleration and HIC. Thus suitable friction coefficient of friction was used for the analysis.[6]. The acceleration output at headform was obtained by useing **`*DATABASE_HISTORY_NODE_ID`** at accelerometer location in FE headform. For the stability of solution **`*CONTROL_BULK_VISCOSITY and *CONTROL_CONTACT`** cards were used. Input velocity vector in the direction of impact was set and the simulation by using **`*INITIAL_VELOCITY_GENERATION`** [7] at required direction.This complete FE setup was solved in LS-DYNA®. The simulation was run until the headform bounced back after impacting vehicle hood. Figure 6:4 below shows different time plots of FE headform impact simulation.

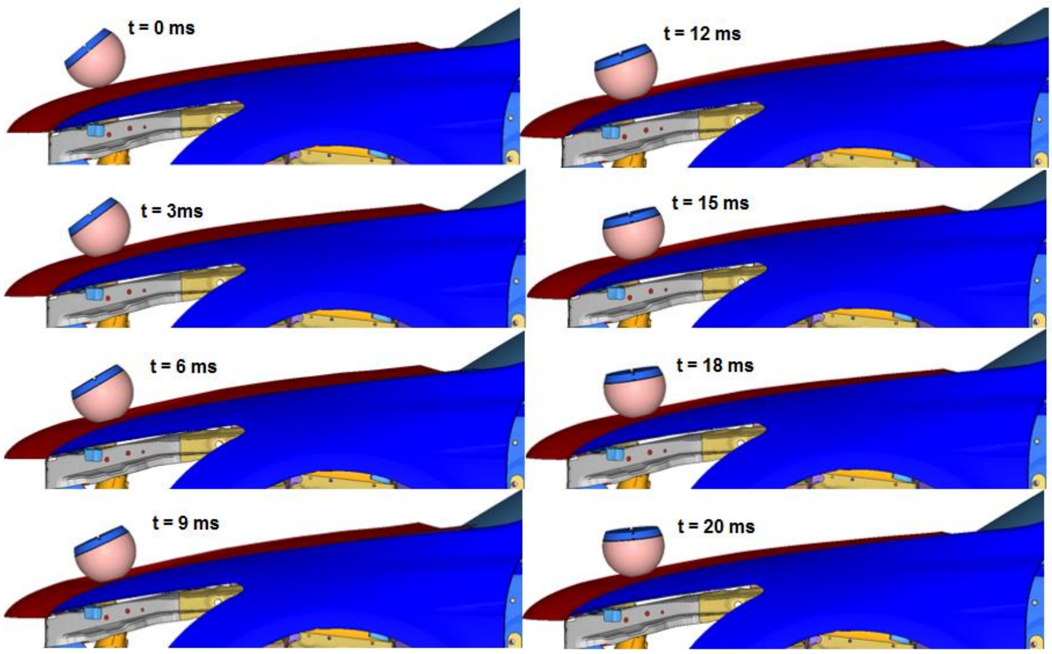

Figure 6:4 Time plots showing FE Headform Impact on Passenger Vehicle

Similar to physical test, resultant acceleration data was captured at the headform accelerometer location and HIC-15 value was calculated. Headform displacement was subsequently calculated through double integration approach. Figure 6:5 shows comparison of resultant acceleration values of CAE simulation with physical test results.

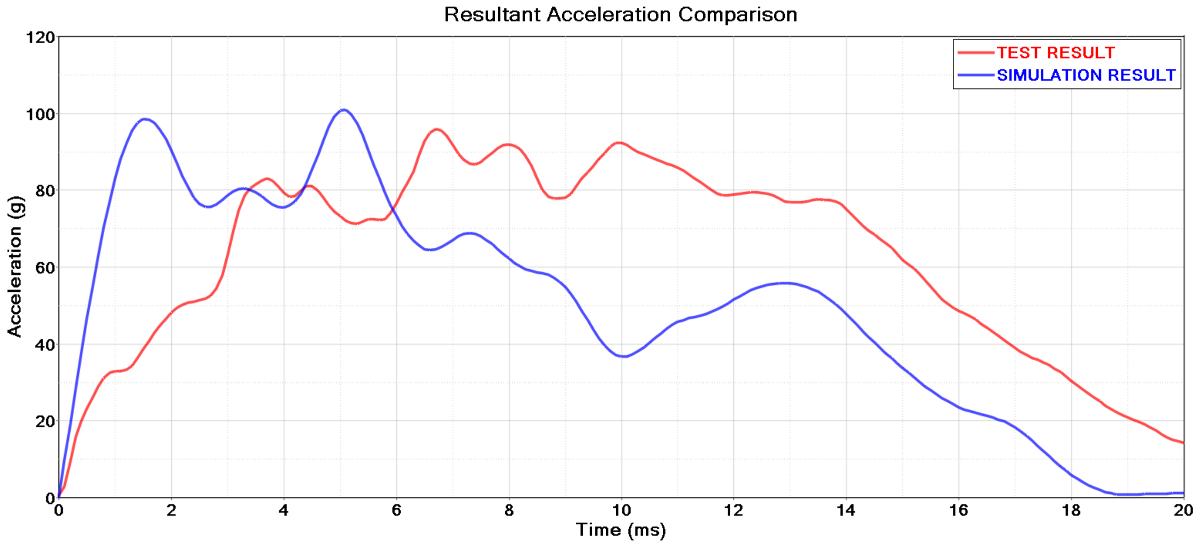

Figure 6:5 Resultant Acceleration Comparison of Simulation and Test Results for Headform during Impact on Vehicle

The CAE simulation acceleration curve deviated a little from the physical test on account of some geometry differences in the representative passenger vehicle hood. Maximum resultant acceleration obtained in the CAE simulation was 101 g as against 95 g obtained through the physical test. However, HIC-15 values for both results were similar with 724 and 732 for CAE simulation and physical test respectively. These were well within the 1000 HIC-15 Limit, since the impact occurred in the HIC 1000 Zone (as per Figure 3:3).
Maximum forward displacement of the headform into the vehicle hood i.e. intrusion was 82 mm for both, the CAE simulation and physical test. Hence, the CAE simulation acceleration vs intrusion curve was similar to that of the physical test.
Figure 6:6 shows the deformation pattern similarity between physical vehicle and FE vehicle model, post headform impact.

Figure 6:6 Comparison of Post-Impact Vehicle Hood Deformation in Simulation and Test

7 Summary

The FE child and adult headform models generated through 3D scanning were validated for the calibration loadcase first. Further, the same were validated to AIS 100 homologation loadcases by using actual vehicle physical test data. Hence, these FE models can be used for different future vehicle development programs.
As is the case with all FE models, higher degree of model accuracy can be achieved through continuous correlation and results validation process. The future roadmap for these headform models would be to fine-tune material properties and input boundary conditions, so that the models will provide simulation results with higher accuracy when compared with test results of different vehicles. Based on the same simulation methodology, FE models in other solvers can also be created.
This FE headform development study was an earnest attempt to provide a platform to use CAE simulation as a part of the vehicle design process. Using these validated FE models available in the open domain would help automotive startups focus on pedestrian safety as an important aspect of vehicle design.

8 Acknowledgement

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9 Literature

References should be given in the last paragraph of your manuscript. Please use following scheme:

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