MADYMO MODELING OF THE IHRA PEDESTRIAN HEAD-FORM IMPACTOR

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ABSTRACT

The International Harmonization Research Activities Pedestrian Safety Working Group (IHRA PSWG) has specified requirements for two head-form designs for vehicle hood (bonnet) impact testing. The main objectives of this thesis were to develop MADYMO models representing the response characteristics of the IHRA adult and child head-forms, validate the models using laboratory drop tests, and conduct a parameter sensitivity analysis of the head-forms to assess the effect of IHRA geometric and mass constraints on their responses. In the MADYMO head-form model, the aluminum core and the accelerometer mount were represented by a multibody sphere and the vinyl skin was modeled with finite elements.

The most important part in developing the MADYMO head-form model was to determine the material properties of the vinyl skin and incorporate them into MADYMO using a suitable material model. Three material models (linear isotropic, viscoelastic, hyperelastic) were examined. It was determined that the vinyl material behaved as a hyperelastic material by comparing the MADYMO simulation results with the laboratory certification test results.

The MADYMO model of the IHRA adult head-form was validated with laboratory head-form drop tests of four different drop heights. The model’s peak
resultant acceleration was less than 9% lower than laboratory drop tests for the four different drop heights and the HIC was less than 10% greater than the laboratory drop tests for three out of the four drop heights.

Parameter sensitivity analysis was conducted by varying the head-form parameters within their respective tolerances. Because of physical limitations for locating accelerometers near the head-form center of gravity, this analysis was much more easily accomplished using a MADYMO model. It was found that the peak acceleration was well within the IHRA–specified range for both the adult and child head-forms when the mass and geometric parameters were varied within the IHRA tolerances.
TO MY FAMILY AND FRIENDS
ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

1.1. Pedestrian problem definition

Pedestrians killed by motor vehicles represent one of the largest health hazards in the world. In the United States in the 1970’s and early 1980’s approximately 150,000 pedestrian collisions occurred and 8,000 pedestrians were killed every year in traffic accidents [4]. On average a pedestrian is killed in a traffic crash every 108 minutes [23]. According to the International Harmonization Research Activities (IHRA), on average, 7,000 pedestrians are killed in a road accident every year in Europe [12]. The number of pedestrians killed on French roads was 3,202 in 1970 and 1,027 in 1995, representing 21 % and 12 % of all traffic fatalities respectively [2]. In Japan approximately 3,000 pedestrians die in traffic accidents every year, which is roughly 30 % of all motor vehicle-related fatalities [17]. Pedestrians often represent an even larger portion of motor vehicle-related fatalities in developing countries of the world. For example, in Ethiopia and Zambia, pedestrian deaths outnumber occupant deaths [35].
Although long-term trends show a decline in pedestrian fatalities, they still account for over 11% of all fatalities from motor vehicle crashes in most countries.

Pedestrian collisions often result in the death or serious injury to the pedestrian. In many cases where the victim survives, the person will have to adapt physically, mentally and financially to loss of mobility or disability in everyday life. These serious injuries resulting from pedestrian accidents diminish one’s ability, both physically and mentally. Studies have shown that in low- and middle-income countries, the injury situation, including transport-related injuries, will grow rapidly in comparison to high-income countries because they have poorly developed health information systems including little or no data regarding morbidity, causes of death, or economical costs [28].

1.2. Pedestrian injury distributions

In a typical pedestrian/vehicle collision, the bumper hits the pedestrian’s lower extremities, resulting in the impact of the upper body parts (head, torso, arms) with the hood (bonnet) or windshield (windscreen) of the automobile. When an automobile strikes a pedestrian, different body regions are injured with different levels of injury. The major injury sustaining body regions of pedestrians are the lower extremities (pelvis and legs), head, chest, upper extremities (arms), abdomen and neck [6, 11, 12]. The major injury inflicting areas of passenger cars are the front bumper, hood (bonnet), windshield (windscreen) glass, windshield
(windscreen) frame/A-pillars, wheels/tires and other front components [6, 12].

Most of the severe injuries are due to the impact with the vehicle and not with the road. Table 1.1 lists the distribution of pedestrian injuries by body region and country, based on a total of 1,605 pedestrian accident cases collected from the United States, Germany, Japan and Australia [12]. There were 3,305 AIS 2-6 (Abbreviated Injury Scale) injuries as listed in the Table 1.1. Table 1.1 shows that the head and legs are the most frequently injured body regions.
<table>
<thead>
<tr>
<th>Body region</th>
<th>USA</th>
<th>Germany</th>
<th>Japan</th>
<th>Australia</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>32.7 %</td>
<td>29.9 %</td>
<td>28.9 %</td>
<td>39.3 %</td>
<td>31.4 %</td>
</tr>
<tr>
<td>Face</td>
<td>3.7 %</td>
<td>5.2 %</td>
<td>2.2 %</td>
<td>3.7 %</td>
<td>4.2 %</td>
</tr>
<tr>
<td>Neck</td>
<td>0.0 %</td>
<td>1.7 %</td>
<td>4.7 %</td>
<td>3.1 %</td>
<td>1.4 %</td>
</tr>
<tr>
<td>Chest</td>
<td>9.4 %</td>
<td>11.7 %</td>
<td>8.6 %</td>
<td>10.4 %</td>
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<tr>
<td>Abdomen</td>
<td>7.7 %</td>
<td>3.4 %</td>
<td>4.7 %</td>
<td>4.9 %</td>
<td>5.4 %</td>
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<tr>
<td>Pelvis</td>
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<td>Arms</td>
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<td>Legs</td>
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<td>37.2 %</td>
<td>25.8 %</td>
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<td>Unknown</td>
<td>0.0 %</td>
<td>0.4 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Total</td>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
<td>100 %</td>
</tr>
</tbody>
</table>

Table 1.1  Distributions of pedestrian injuries by body region and country

1.3.  Head injury

The head is a very delicate part of the human body. Several studies [6, 11, 12, 21] have shown that head injury is commonly the most fatal and most severe of all pedestrian injuries (Figure 1.1). Severe head injury is often indicative of brain damage. In addition to causing death, head injury often results in severe and long-lasting functional impairment in survivors [9]. Head injury is of prime importance in the study of pedestrian safety.
Figure 1.1 Distribution of AIS 4-6 Injuries in IHRA Database [12]

In pedestrians struck by a passenger car, the head can be subjected to high levels of acceleration as the lower part of the body is almost instantly accelerated to the speed of the striking car, and consequently the upper part of the body is accelerated forward and downward relative to the vehicle front end. The head is accelerated by a force acting through the neck and impacts the vehicle at high velocities [12]. The location of the head impact on the striking car depends largely on the size, shape and speed of the car and the height of the pedestrian [16]. The leading sources of head injury to pedestrians in passenger cars are hood (bonnet), windshield (windscreen) glass and A-pillars [12].
1.4. Pedestrian protection

There are three possible ways to approach pedestrian protection. They are

1. Designing roadways and pedestrian pathways to be independent of one another.

2. Educating adults and children about the potential dangers that pedestrians encounter when crossing roadways.

3. Minimizing vehicle aggressiveness towards pedestrians.

Even with better roadway design and public education, pedestrian accidents still occur [5]. Improving pedestrian protection through vehicle design has been researched extensively, and it has been shown that relatively minor changes to the front ends of vehicles can significantly reduce the potential for death and severe injury to pedestrians [25]. To minimize injuries the pedestrian must be decelerated as slowly as possible when being struck by the front of the car [7]. Further research has led and can lead to the development of pedestrian friendly car fronts with soft and energy absorbing structures. Europe and Japan have standards to test vehicle fronts to reduce head injury [7]. The IHRA Pedestrian Safety Working Group (PSWG) is conducting research aimed at establishing harmonized test procedures to improve pedestrian safety afforded by vehicles in the event of a collision.
1.5. **Subsystem test methods**

Simulation of pedestrian accidents can provide insight into understanding the dynamics of these accidents and methods of prevention. Several methods have been developed to simulate pedestrian/vehicle collisions. These techniques have involved cadavers, anthropomorphic test devices (crash dummies), body segment modeling, and mathematical simulations. Staged pedestrian impacts with these modeling techniques can provide a qualitative and sometimes quantitative measure of injury by reconstructing real world accidents in the laboratory [5]. Stammen et al. showed that an actual pedestrian/vehicle collision could be successfully replicated using a computer model simulation and laboratory experiment [25]. To study pedestrian head impact, test procedures using a pedestrian dummy were initially considered, but some significant disadvantages such as fabricating cost, dummy repair, test repeatability and set-up time became apparent. Subsystem component tests are less complex and less costly to perform. The component can be aimed accurately at selected vehicle impact points and requires less testing space as the car remains stationary. The test requirements are simpler to design and model mathematically and are not entirely dependent on full body simulation model biofidelity. Hence, subsystem test methods are being used to study pedestrian head impacts. Two types of head-forms, an adult-sized head-form and a child-sized head-form are being used. The head-forms have accelerometers mounted inside near the center of gravity, which record the linear acceleration time histories in the X, Y, and Z-axes during an impact event.
1.6. **Head injury criteria (HIC)**

An injury criterion can be defined as a biomechanical index of exposure severity that indicates the potential for impact-induced injury by its magnitude [30]. The Head Injury Criterion (HIC), which is derived from the resultant acceleration history at the center of the gravity of the head, is the most widely used criterion for head injury assessment. HIC was defined based on a comparison of the Wayne State Tolerance Curve (WSTC) and Gadd Severity Index (GSI). The WSTC was developed from experimental data obtained by dropping human cadaver and animal heads. The accepted form of the WSTC is shown in Figure 1.2. The ordinate represents the effective or average acceleration (measured at the rear of the head) and the abscissa represents the time duration of this acceleration [30].

![Figure 1.2 Wayne State Tolerance Curve](image)
HIC is given by,

$$
HIC = \max_{t_1, t_2} \left\{ \left( t_2 - t_1 \right) \frac{1}{(t_2 - t_1)^2} \int_{t_1}^{t_2} a(t) dt \right\}^{2.5}
$$

(1.1)

where $a(t)$ is the resultant acceleration history and $t_1$ and $t_2$ are two points in time which would maximize the HIC value and $(t_2 - t_1)$ is the maximum time interval. Limitations of the HIC are:

- HIC only includes linear acceleration, while biomechanical response of the head also includes angular motion which is believed to cause brain deformation relative to the skull and subsequent injury,
- HIC is only valid for a hard contact, thus limiting the time duration of impact,
- HIC is based on the WSTC, which is derived from subjects loaded in the anterior-posterior direction only [30].

Despite its limitations, HIC has been shown to be an effective indicator of head injury and has been used almost universally in crash injury research and prevention since its introduction [12]. The relationship between probability of skull fracture and HIC is shown in Appendix A.

1.7. **Head impact testing**

In a head impact test, the head-form is fired at a given speed and approach angle in free flight at a vehicle area of interest. The area of interest might vary
from a rigid part of a windshield frame to a soft portion of the hood (bonnet). This 
section will briefly discuss three head impactors and the impact test procedures in 
which they are used.

a) EEVC procedure

The European Enhanced Vehicle-Safety Commission (EEVC) consists of 
representatives from several European Nations, initiating research work in a 
number of automotive working areas. The pedestrian safety Working Group 10 of 
the EEVC specified a free flight impactor with a mass of 4.8 kg for the adult 
head-form. The spherical diameter is to be 165 mm, including a 7.5 mm thick 
rubber skin covering. The center of gravity of the head-form is required to be 
within 10 mm of the geometric center of the sphere. The EEVC head-form must 
be checked at specified intervals using a certification test. The resultant 
acceleration must be between 225 and 275 g when the head-form is dropped from 
a height of 376 mm onto a rigid steel plate. The EEVC procedure specifies the 
velocity of the impactor at the time of impact in the test of a vehicle to be 11.1 
m/s at an angle of 65 degrees from a plane parallel to the ground [25].

b) ISO procedure

The International Standards Organization (ISO) consists of 146 member 
countries with 188 Technical Committees (TC). The road vehicles committee 
(TC22) has 26 Sub Committees (SC) and 80 Working Groups (WG). The 
ISO/TC22/SC10/WG2 formulates pedestrian impact test procedures. The 
spherical adult head-form specified in the ISO procedure has a mass of 4.5 kg and 
must be 165 mm in diameter with the accelerometer and center of gravity within
10 mm of the geometric center of the sphere. The head-form should meet the certification procedure described above for the EEVC head-form. The ISO procedure specifies an angle of 53 degrees from a plane parallel to the ground. The ISO procedure does not specify a velocity, as it is not intended as a regulation [25].

c) IHRA procedure

The International Harmonization Research Activities (IHRA) was established at the 15th International Technical Conference on Enhanced Safety of Vehicles (ESV) in Melbourne, Australia. The Pedestrian Safety Working Group (PSWG) was one of the six working groups initiated. The membership of the IHRA Pedestrian Safety Working Group (IHRA-PS-WG) is comprised of experts selected by the governments of Australia, Europe (EC/EEVC), Japan and the U.S., experts from industry selected by the industrial organization of Organisation Internationale des Constructeurs d'Automobiles (OICA), and a chairperson selected by Japan [20]. One of the primary tasks assigned to the PSWG was to establish harmonized test procedures that would reflect the accident conditions in IHRA member countries and would induce vehicle structures to be improved for the reduction of fatalities and alleviation of severe injuries in pedestrian vs. passenger car crashes [12]. Two head-forms were proposed for use in subsystem testing. The adult head-form represents the head of a 50th percentile adult and the child head-form that of a 6 year old child [20]. Table 1.2 shows the characteristics of the two head-forms. The test methods proposed by the IHRA are explained in detail in the next section.
<table>
<thead>
<tr>
<th>Requirement description</th>
<th>Adult head-form</th>
<th>Child head-form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>4.5 +/- 0.1</td>
<td>3.5 +/- 0.1</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>165 +/- 1</td>
<td>165 +/- 1</td>
</tr>
<tr>
<td>Maximum distance from head CG to center of sphere (mm)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Maximum seismic mass distance from center of sphere (mm)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Head drop acceleration (g)</td>
<td>225 - 275</td>
<td>245 - 300</td>
</tr>
</tbody>
</table>

Table 1.2  IHRA Head-form Characteristics

1.8.  IHRA head-form

The head-form consists of a solid aluminum core, a vinyl skin, an accelerometer mount and an accelerometer mounted within a radius of 10mm from the center of the sphere.

- Certification test

The head-form is dropped from a height of 376 mm. The peak resultant acceleration measured by one triaxial (or three uniaxial) accelerometer(s) in the head-form impactor shall meet the requirements for acceleration response shown.
in Table 1.2. The head-form impactor shall be suspended from a drop rig as shown in Figure 1.3. The head-form impactor shall be dropped from the specified height onto a rigidly supported flat horizontal steel plate, 50 mm thick and 600 mm square which has a clean dry surface and a surface finish of between 0.2 and 2.0 micrometers [12].

– Passenger vehicles – Pedestrian protection – Impact test method for adult pedestrian head

This test method simulates the head impact of an adult pedestrian to the front structure of a passenger vehicle. The vehicle is stationary and the head-form is propelled on to the required vehicle surface. The head-form shall be in free flight at the moment of impact. The impact velocity, direction and angle of impact and impact points are in accordance with the IHRA specifications. The acceleration time histories, velocity of head-form impactor at some point during free flight and the first point of contact are recorded [12].
1.9. Modeling the IHRA head-forms

The IHRA head-forms have specified parameters such as mass, diameter, center of gravity location and accelerometer position. The values for these parameters and their respective tolerances are given in Table 1.2. Varying these parameters within their respective tolerances might cause a considerable variation in the acceleration time histories measured during testing. This is one of the unexplored areas with regard to the IHRA head-forms. For example, if the accelerometer is placed at a distance of 10 mm from the center of gravity of the head-form, the peak acceleration and HIC values obtained in a certification might
change considerably. Similarly, change in the mass, diameter and center of gravity of the head-form could cause a considerable variation in the results. It should be noted that all the variations in the parameters discussed herein are within the respective tolerances. To study these effects, a number of head-forms covering the entire range of mass, diameter, center of gravity and location of the accelerometer would be needed. It would be impractical to change the position of center of gravity or accelerometer seismic mass within a 10 mm range. Studying the effect of varying these parameters using a mathematical model would be logical, cost effective and less time consuming.

1.10. Objective

The objectives of this research are to

1. Develop MADYMO models simulating the response characteristics of the IHRA pedestrian head-form impacts
2. Validate the MADYMO head-form models using laboratory drop tests
3. Conduct a parameter sensitivity analysis. i.e. study the change in head-form acceleration and HIC by varying the head-form parameters within their respective limits of tolerances.

1.11. Related work

Various methods and techniques have been used over the years to study head injuries using mathematical head models. Ruan et al. [22] developed a 3-D human
head finite element model and validated it against cadaveric test data in frontal impact. The validated model was used to conduct a parametric study of intracranial pressure, maximum shear stress in the brain, and von Mises stress in the skull. Willinger et al. [33] developed a 3D finite element human head model with a realistic geometry integrating a skull fracture simulation capability. The skull mesh was obtained by digitalizing the external and internal surface of a human skull and skull properties were based on established bone mechanical properties. The model was validated and could be a powerful tool to predict the aggressiveness level of a head impact. Takhounts et al. (16) developed a mathematical surrogate of the human head called SIMon FEHM solving approximately 30,000 equations every millisecond. This model was designed to best replicate all available experimental data and is not meant to simulate the proper response of every region of the head. Kleiven et al. [13] developed a parameterized finite element (FE) model of the human head and validated it against cadaver experiment data. In the parameterized model, the geometry could be adjusted to fit a particular specimen, which would reduce some of the concerns associated with scaling. Zhang et al. [34] developed a new version of the 3-D finite element model of the Wayne State Brain Injury Model (WSUBIM). This model featured detailed anatomical characteristics of the human head including an anatomically realistic facial model and was validated against published cadaver test data. This model is capable of simulating impacts with very high rotational acceleration.
Although a lot of work had been done on modeling the human head, limited research has been done on head-form modeling. Konosu et al. [14] developed a computer simulation model of the EEVC pedestrian subsystem models, which included the adult and child head-forms. The model was intended to promote the development of pedestrian friendly cars by simulating head-form drop tests on cars. Though the models showed good agreement with the values obtained from subsystem tests, some improvements would be needed to apply it to simulate subsystem tests on cars. Deb et al. [8] developed a nonlinear lumped mass model for simulating head-form impact with rotation on a stiff target with countermeasures for HIC reduction. Results from the model were verified against an equivalent finite element based model using LS-DYNA package. The model could be used as a good tool for head impact safety evaluation in the preliminary design phase of vehicles. The model also gave some idea about how head-form rotation could reduce HIC. Sulzer, J. [26] developed a head-form model using multibody elements in MADYMO. The input stiffness characteristics for the head-form were derived from the acceleration time history obtained from a drop test. The head-form model was validated using experimental data from drop tests.
CHAPTER 2

MATERIALS AND METHODS

2.1. MADYMO

MADYMO (MAthematical DYnamic MOdel) is a computer program that simulates the dynamic behavior of physical systems emphasizing the analysis of vehicle collisions and assessing the sustained injuries [30]. It has finite element capabilities incorporated in it along with multibody elements. MADYMO is an explicit FE code that uses a Lagrangian description. The head-form model used in this research was developed using MADYMO.

MADYMO has two types of solid elements, an eight-node hexahedral element and a four-node tetrahedral element. MADYMO writes the tetrahedral elements as hexahedral elements in the output (kn3) file. When MADYMO writes these modified tetrahedral elements, some post processors such as ALTAIR Hyperview cannot visualize it. Early attempts to use tetrahedral elements showed that to rectify this problem, the output (kn3) file has to be modified. The fifth column in the output (kn3) file would have to be replaced by the sixth column in order to view the mesh with post processors such as ALTAIR Hyperview. This problem does not occur with the hexahedral elements. In the hexahedral elements, each
node has three translational degrees of freedom. The mass of this element is lumped and equally distributed over the eight nodes [30]. The current model uses the hexahedral elements to circumvent this deficiency.

Contact is an important entity in solving realistic problems. There are two types of contact force models for a contact between two finite element surfaces: 1) penalty based contact and 2) elastic characteristic based contact [29]. The contact force of an elastic characteristic based contact is defined by a specified characteristic function such as a force vs. penetration or a stress vs. strain characteristic. In the penalty based contact, the contact force is based on a penalty function and is limited to

\[ F_c = \frac{K}{V_o} A^2 \zeta \min(d, \eta t_e) \]  

(2.1)

where,

- \( F_c \) – the contact force
- \( K \) – bulk modulus
- \( V_o \) – volume
- \( A \) – surface area
- \( d \) – penetration
- \( t_e \) – thickness of the penetrated element
- \( \zeta \) – the penalty factor and
- \( \eta \) – the contact force limitation
2.2. Head-form model

The model of the IHRA head-form is characterized by its geometry as well as its inertial and material properties. The mass, center of gravity, and the mass moments of inertia of the head-form were obtained from the manufacturer. The significance and contribution of each of the primary components of the IHRA head-form was considered in MADYMO modeling. When the head-form is propelled onto a surface, the vinyl skin undergoes elastic deformation during impact. The aluminum core and the accelerometer mount are rigid and they mainly contribute to the inertial properties. In MADYMO, the aluminum core and accelerometer mount were represented by a multibody sphere to make the model simple. The vinyl skin was modeled using finite elements. The geometry and finite element mesh for the vinyl skin were implemented using ABAQUS and imported into MADYMO. The vinyl skin was modeled as a hollow hemisphere with eight node hexahedral (brick) elements. Figure 2.1 shows the FE vinyl skin, which consisted of 600 elements and 963 nodes. The average length for each element was assigned as 12 mm. In employing finite elements in a model, increasing the number of elements would increase the accuracy of the model and at the same time increase the computation time. Another model with three layers of elements across the thickness was compared with the present model (Figure 2.1) in the simulation of a drop test. No difference was noticed between the results obtained from these two models. Based on this finding the simpler model was deemed to be sufficient.
The mass, diameter, center of gravity and moment of inertia of both the adult and child head-forms were measured and are listed in Table 2.1. These values were used in the simulation. The accelerometer was assumed to be positioned at the center of the sphere in the simulation.
<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Adult Head-form</th>
<th>Child Head-form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>4.44</td>
<td>3.49</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>Location of Head CG from Center of Sphere (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>4.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Y</td>
<td>-0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Z</td>
<td>0.55</td>
<td>-2.5</td>
</tr>
<tr>
<td>Moment of Inertia (kg.m²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I_{XX}</td>
<td>0.0116</td>
<td>0.00873</td>
</tr>
<tr>
<td>I_{YY}</td>
<td>0.0116</td>
<td>0.00872</td>
</tr>
<tr>
<td>I_{ZZ}</td>
<td>0.0126</td>
<td>0.0114</td>
</tr>
</tbody>
</table>

Table 2.1 IHRA Head-form characteristics

2.2.1. Simulation of the certification test

The certification test of the head-form was simulated in MADYMO to validate the head-form model. The steel plate used in the certification is modeled as a rigid plane using four node quadrilateral elements. The finite element plane consisted of 289 elements and 324 nodes. Although the drop height in the physical test is 376 mm, the drop height in the simulation was selected as 5 mm. The initial velocity of the head-form in the simulation was then adjusted to compensate for this reduced drop height such that the final velocity during impact is unaltered. This is done to reduce the large number of data points due to high
sampling rate and also to reduce the simulation time. The gravity field, which is a field based contact, is applied to the head-form. The contact between the head-form model and the plate was defined using the penalty-based contact shown by equation 2.1. The HIC algorithm in MADYMO is based on the algorithm developed by Mentzer [30]. In MADYMO, the maximum time interval, which is the maximum interval between the calculation points ($t_2 - t_1$) was set to 36 ms. Figure 2.2 shows the head-form and plane used in the certification test simulation in MADYMO.

![MADYMO Simulation of the certification test](image)

Figure 2.2 MADYMO Simulation of the certification test

2.3. Material model

To formulate a determinate problem in continuum mechanics, it is usually necessary to specify the material to determine the deformation or motion of a body subject to a given loading. Such a specification is stated by constitutive equations that relate the stress tensor to the motion [31]. Physically, the
constitutive equations define various idealized materials, which serve as models for the behavior of real materials [18]. Certain idealizations and assumptions are needed for the mathematical model because of the non-linearity of the material. Hence, it might not be easy for the mathematical model to exactly replicate the response of the physical system. Of all the idealized material models available in MADYMO, three material models are relevant to this application. They are linear isotropic elastic, viscoelastic and hyperelastic material models.

2.4. **Linear isotropic elastic model**

Initially, the material was assumed to be a linear isotropic elastic model. Hooke’s law gives the constitutive equation for this material. The material is specified by a relationship between stresses and strains. The relationship can be written in matrix notation as

\[
\sigma = S \varepsilon
\]

(2.2)

where, \(S\) is the stiffness matrix with elasticity coefficients and \(\sigma\) and \(\varepsilon\) are stress and strain column matrices respectively.

The vinyl skin was compressed uniaxially at two different strain rates to determine the stress-strain relation as shown in Figure 2.3. Notice the energy loss present between the loading and unloading curves. This indicates that the material is not purely elastic and has viscous properties.
Figure 2.3 Stress-strain relation from uniaxial compression of the vinyl skin of the IHRA head-form

In MADYMO this material model requires data for density, damping and loading and unloading functions. Density was given by the manufacturer and loading and unloading functions were obtained from the uniaxial compression test. Since only low strain rates were possible with this material testing machine, the phase between the input and output response could not be characterized. Since phase is directly related to damping, the calculation of a damping coefficient $C$ was a problem. Moreover, damping could not be assumed, as it is a function of velocity rather than a constant. One of the main drawbacks of this model is that it does not take into account the strain rate. The acceleration time history of the MADYMO simulation did not correlate well with that of the experimental results.
The peak acceleration and HIC value of the MADYMO simulation was smaller than that of the experimental data. The results are discussed in detail in Chapter 3.

2.5. Viscoelastic material model

Engineering materials that exhibit both elastic and viscous properties at varying levels during loading/unloading are termed viscoelastic materials. Viscoelastic materials simultaneously store (elastic) and dissipate (viscous) energy when subjected to applied forces [18]. The output response of this material model depends on the applied strain rate. In MADYMO, a linear viscoelastic material is represented by a multi-mode Maxwell model. The multi-mode Maxwell model [2] consists of a spring and three Maxwell models in parallel as shown in Figure 2.4.

Figure 2.4 Multi-mode Maxwell model
The multi-mode Maxwell model has shear moduli and relaxation times for each mode, which form a part of the data required in MADYMO to incorporate this material model. The shear moduli and relaxation times could be obtained using an oscillatory experiment.

2.5.1. Oscillatory experiment

Brands et al. [1] conducted oscillatory shear experiments to find out the characteristics of viscoelastic materials. In these experiments, samples of the material under study were placed between two flat parallel plates. A prescribed rotation was applied on one plate, while the torque $T$, was measured on the other fixed plate. The samples were fixed to the plates using appropriate adhesives. Then, the shear modulus was derived from the measured torque and applied strain.

The vinyl skin has characteristics similar to rubber. Such types of materials are assumed to be incompressible, i.e. there is no volume change in shear or compression mode [15]. Hence the vinyl skin was subjected to an oscillatory compressive experiment. A compressive rather than a rotational or shear experiment was done to simplify the experimental set up and to overcome some disadvantages such as finding a suitable adhesive to fix the sample in shear or torsion mode. The experimental set up is shown in Figure 2.5.
A cylindrical sample of the vinyl was placed between two parallel plates. A sinusoidal strain of known frequency and amplitude was applied to one plate, while the force was measured on the other fixed plate. The sinusoidal strain was measured by double-integrating the acceleration from an accelerometer and dividing by the initial height of the sample.
The sinusoidal strain ($\gamma(t)$) would be of the form,

$$\gamma(t) = \gamma_0 \sin(\omega t)$$  \hspace{1cm} (2.3)

When steady state is reached and strain amplitude, $\gamma_0$, is sufficiently small, the stress $\sigma$ will also be sinusoidal, but with a phase shift, $\delta$, due to the viscous behavior,

$$\sigma(t) = G_d \gamma_0 \sin(\omega t + \delta)$$ \hspace{1cm} (2.4)

$$= \gamma_0 [G'(\omega) \sin(\omega t) + G''(\omega) \cos(\omega t)]$$ \hspace{1cm} (2.5)

$$G'(\omega) = G_d \cos \delta$$ \hspace{1cm} (2.6)

$$G''(\omega) = G_d \sin \delta$$ \hspace{1cm} (2.7)

Where, $G_d$ is the dynamic modulus, $\omega$ is the frequency and $G'$ and $G''$ are storage modulus and loss modulus respectively.

### 2.5.2. Results of the oscillatory experiment

For an input strain ($\gamma_0$) of 20 %, the frequency, measured force, calculated stress, dynamic modulus and phase shift are given in Table 2.2. The phase shift $\delta$ was determined by comparing the sinusoidal waveform time histories of the output force and input displacement. Figure 2.5 shows the variation in dynamic modulus with frequency.
<table>
<thead>
<tr>
<th>Frequency ((\omega)) (rad)</th>
<th>Force (N)</th>
<th>Stress (Pa)</th>
<th>Dynamic Modulus ((G_d)) (Pa)</th>
<th>Phase ((\delta)) (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.227</td>
<td>24.40</td>
<td>1.43E+06</td>
<td>7.14E+06</td>
<td>0.368</td>
</tr>
<tr>
<td>0.332</td>
<td>23.52</td>
<td>1.41E+06</td>
<td>7.07E+06</td>
<td>0.158</td>
</tr>
<tr>
<td>0.436</td>
<td>25.20</td>
<td>1.62E+06</td>
<td>8.10E+06</td>
<td>0.178</td>
</tr>
<tr>
<td>0.541</td>
<td>26.51</td>
<td>1.68E+06</td>
<td>8.42E+06</td>
<td>-0.222</td>
</tr>
<tr>
<td>0.663</td>
<td>27.08</td>
<td>1.72E+06</td>
<td>8.62E+06</td>
<td>0.018</td>
</tr>
<tr>
<td>0.873</td>
<td>27.67</td>
<td>1.65E+06</td>
<td>8.24E+06</td>
<td>0.438</td>
</tr>
<tr>
<td>1.100</td>
<td>23.98</td>
<td>1.48E+06</td>
<td>7.42E+06</td>
<td>0.055</td>
</tr>
</tbody>
</table>

Table 2.2 Test Matrix for the oscillatory experiment of the vinyl skin

![Dynamic modulus, phase shift vs. frequency of the material of the vinyl skin](image-url)

Figure 2.6 Dynamic modulus, phase shift vs. frequency of the material of the vinyl skin
In order to check whether the natural frequency of the system had any influence on the peak value of dynamic modulus, the natural frequency of the system was derived. The mass of the moving element of the shaker was 0.454 kg and the stiffness of the vinyl skin obtained from the compression test was 190,916 N/m. The calculated natural frequency of 103 Hz exceeded the experimental frequency range; therefore, resonance did not distort the response.

The Maxwell model can be presented in terms of storage modulus \( G' \) and loss modulus \( G'' \) [3],

\[
G' = G_o + \sum_{i=1}^{n} G_i \frac{\lambda_i \omega^2}{1 + \lambda_i^2 \omega^2} \quad (2.8)
\]

\[
G'' = \sum_{i=1}^{n} G_i \frac{\lambda_i \omega}{1 + \lambda_i^2 \omega^2} \quad (2.9)
\]

Where, \( n \) is the number of modes, \( \omega \) is the frequency \( \lambda_i \) and \( G_i \) are relaxation times and shear moduli of the \( i^{th} \) mode respectively.

Combining equations 2.6 and 2.8

\[
G_o + \sum_{i=1}^{n} G_i \frac{\lambda_i \omega^2}{1 + \lambda_i^2 \omega^2} = G_d \cos \delta \quad (2.10)
\]

Combining equations 2.7 and 2.9

\[
\sum_{i=1}^{n} G_i \frac{\lambda_i \omega}{1 + \lambda_i^2 \omega^2} = G_d \sin \delta \quad (2.11)
\]

Substituting the values for \( G_d \), \( \omega \) and \( \delta \) in (2.10) and (2.11) rendered ‘n’ unknowns and ‘(n-1)’ unsolvable equations. The data from Table 2.1 could not be
fitted with equations (2.10) and (2.11) using a least squares fit method. Hence this data could not be used effectively to incorporate the viscoelastic material model.

2.5.3. MADYMO model employing viscoelastic material

In MADYMO, the viscoelastic material model requires data for density, bulk modulus, shear modulus at infinitesimal deformation rate and shear moduli and relaxation times of each mode.

The bulk modulus (K) is given by the following equation, (24)

\[
K = C_p^2 \rho \\
(2.12)
\]

Where, \(C_p\) is the velocity of sound in the material (the vinyl) and \(\rho\) is the density of the material (the vinyl). The value for the velocity of sound in vinyl obtained from literature is from 730 m/s to 1830 m/s [24]. For a value of 1600 m/s for the velocity of sound, the Bulk modulus would be 2.56 GPa. The shear modulus at infinitesimal deformation rate (G) is given by,

\[
G = \frac{3K(1-2\nu)}{2(1+\nu)} \\
(2.13)
\]

where, \(\nu\) is the Poisson’s ratio. As the vinyl skin was assumed to be incompressible, the value for \(\nu\) would be close to 0.5 [15]. When the data given in Table 2.3 is used to plot \(\nu\) versus G, it can be shown that G increases significantly as \(\nu\) reaches its physical limit of 0.5. Hence, choosing the value for the Poisson’s ratio is crucial for this material model.
Table 2.3  Variation of shear modulus with Poisson’s ratio

<table>
<thead>
<tr>
<th>ν</th>
<th>G (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49</td>
<td>5.15E+07</td>
</tr>
<tr>
<td>0.499</td>
<td>5.12E+06</td>
</tr>
<tr>
<td>0.4999</td>
<td>5.12E+05</td>
</tr>
<tr>
<td>0.49999</td>
<td>5.12E+04</td>
</tr>
</tbody>
</table>

Brands et al. [3] determined relaxation times and shear moduli of each mode for brain tissue. Using those values as base parameters and varying these values within the acceptable range in MADYMO, the simulation was run for this material model. The acceleration time history of the MADYMO simulation did not correlate with experimental results, as will be discussed in more detail in Chapter 3. The peak acceleration and HIC values obtained using these values were higher than that of the experiments.

2.6. Hyperelastic material model

In certain types of rubber materials that remain elastic even under high loads, the elastic behavior is sometimes defined on the basis of the existence of a strain energy function. When the work done in elastic deformation is stored as internal energy, so that the stresses are derivable from a stored-energy function as a potential, the material is deemed hyperelastic [31].
The strain energy density, $W$ (strain energy per unit volume) \[18\] is given by

$$W = A(J_1-3) + B(J_2-3) + C(J_3-2-3) + D(J_3-1)^2 \quad (2.14)$$

where, $J_1$, $J_2$ and $J_3$ are the invariants of the right Cauchy-Green strain tensor $e$.

$$J_1 = \text{trace}(e) \quad (2.15)$$

$$J_2 = \frac{1}{2} \{\text{trace}^2(e) - \text{trace}(e^2)\} \quad (2.16)$$

$$J_3 = \det(e) \quad (2.17)$$

and material parameters $C$ and $D$ are functions of the coefficients $A$ and $B$

$$C = \frac{1}{2} A + B \quad (2.18)$$

$$D = \frac{A(5-2\nu) + B(11\nu - 5)}{2(1-2\nu)} \quad (2.19)$$

Where, $\nu$ is the Poisson’s ratio

The right Cauchy-Green strain tensor $e$ is given by

$$e = F^T F \quad (2.20)$$

where, $F$ is the deformation tensor

For a uni-axial compression test,

$$F = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \quad (2.21)$$

where, $\lambda_1$, $\lambda_2$ and $\lambda_3$ are the stretch in $x$, $y$ and $z$ directions respectively.

The stretch $\lambda$ is defined by,
\[ \lambda = \frac{h_o}{h_c} \quad (2.22) \]

\( h_c \) - instantaneous length

\( h_o \) - initial length

and for a cylindrical specimen, \( \lambda_2 = \lambda_3 \) \quad (2.23)

from (2.20), (2.21) & (2.23)

\[ \varepsilon = \begin{bmatrix} \lambda_1^2 & 0 & 0 \\ 0 & \lambda_2^2 & 0 \\ 0 & 0 & \lambda_2^2 \end{bmatrix} \quad (2.24) \]

\[ \text{trace} (\varepsilon) = \lambda_1^2 + 2\lambda_2^2 \quad (2.25) \]

\[ J_1 = \lambda_1^2 + 2\lambda_2^2 \quad (2.26) \]

\[ J_2 = 2\lambda_1^2\lambda_2^2 + \lambda_2^4 \quad (2.27) \]

\[ J_3 = \lambda_1^2\lambda_2^4 \quad (2.28) \]

Accounting for the incompressibility of the material, i.e., assuming \( v = 0.5 \)

\[ J_3 = \lambda_1^2\lambda_2^4 = 1 \quad (2.29) \]

The 2\textsuperscript{nd} Piola-Kirchoff stress tensor is obtained by differentiating the strain energy function \( W \) with respect to the right Cauchy-Green strain tensor \( \varepsilon \) [32]

\[ \sigma_1 = \lambda_1 \frac{\partial W}{\partial \lambda_1} - \lambda_2 \frac{\partial W}{\partial \lambda_2} \quad (2.30) \]

\[ \sigma_1 = 2A\lambda_1^2 - \frac{2A}{\lambda_1} + 2B \lambda_1 - \frac{2A}{\lambda_1^2} \quad (2.31) \]

\[ \sigma = \frac{\text{Force}}{A_c} \quad (2.32) \]
\[ A_c h_c = A_o h_o \]  \hspace{1cm} (2.33)

where, \( A_c \) – instantaneous area
\( A_o \) – initial area

\[ A_c = \frac{A_o}{\lambda_1} \]  \hspace{1cm} (2.34)

Thus, selecting appropriate values for \( A \) and \( B \) can define the hyperelastic material model.

### 2.6.1. Material parameters \( A \) and \( B \)

The hyperelastic parameters \( A \) and \( B \) of the vinyl material were found using compression tests. \( A \) and \( B \) were obtained by fitting the experimental data with equation (2.26) using a least squares fit. Figure 2.7 shows the compression test results of the vinyl head skin. The diameter the cylindrical specimen was 5.92 mm and the length was 7.11 mm. The specimen was compressed to a maximum compression of 3 mm. In Figure 2.7, the frequencies 2 Hz, 4 Hz, 6 Hz, 8 Hz and 10 Hz correspond to compression speeds of 12 mm/s, 24 mm/s, 36 mm/s, 48 mm/s and 60 mm/s. The figure shows that with increasing strain rates the curves approach a limiting condition or asymptote. This indicates that for this material, true stress is not dependent on strain rate at high strain rates.

The true stress \( \sigma \) was obtained using the following equations,

\[ \sigma = \frac{\text{Force}}{A_c} \]  \hspace{1cm} (2.35)

\[ A_c h_c = A_o h_o \]  \hspace{1cm} (2.36)
$A_c$ – instantaneous area

$A_0$ – initial area

$$A_c = \frac{A_0}{\lambda_1} \quad (2.37)$$

Figure 2.7 Compression test results of the vinyl skin

In a least squares fit, the best fitting curve to a given set of points is obtained by minimizing the sum of the squares of the offsets ("the residuals") of the points from the curve [36]. Applying this to the true stress vs. stretch data of the vinyl skin;

$$R^2 = \sum [\sigma - \sigma_i]^2 \quad (2.38)$$
where, $\sigma_c$ is the calculated value of true stress

$$R^2 = \sum \left[ \sigma - \left( 2A\lambda_1^2 - \frac{2A}{\lambda_1} - \frac{2B}{\lambda_1^2} + 2B\lambda_1 \right) \right]^2$$  \hspace{1cm} (2.39)$$

Minimizing the sum of the residuals,

$$\frac{\partial R^2}{\partial A} = 0$$  \hspace{1cm} (2.40)$$

$$A\sum [(-2\lambda_1^2 + \frac{2}{\lambda_1^2})(\lambda_1^2 + \frac{1}{\lambda_1^2})] + B\sum [(\frac{2}{\lambda_1^2} - 2\lambda_1)(-\lambda_1^2 + \frac{1}{\lambda_1^2})] = -\sum \sigma(-\lambda_1^2 + \frac{1}{\lambda_1^2})$$  \hspace{1cm} (2.41)$$

$$\frac{\partial R^2}{\partial B} = 0$$  \hspace{1cm} (2.42)$$

$$A\sum [(-2\lambda_1^2 + \frac{2}{\lambda_1^2})(\frac{1}{\lambda_1^2} - \lambda_1)] + B\sum [(\frac{2}{\lambda_1^2} - 2\lambda_1)(\frac{1}{\lambda_1^2} - \lambda_1)] = -\sum \sigma(\frac{1}{\lambda_1^2} - \lambda_1)$$  \hspace{1cm} (2.43)$$

A and B were obtained by solving equations (2.41) and (2.43) simultaneously.

Figure 2.8 shows the least squares fit for the 2 Hz curve. Table 2.4 lists the values for A and B obtained using a least squares fit for the entire test data. As observed from the compression test results, it can be seen from Table 2.4 that the values of A and B close in at higher frequency. Extrapolating to this limit it was decided to use the following values for A and B.

$$A = -1.1e6 \text{ N/m}^2, \quad B = 1.1e6 \text{ N/m}^2$$
Figure 2.8 Fitting the data obtained from compressive test using least square fit

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>A (N/m²)</th>
<th>B (N/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-1.89E+06</td>
<td>1.83E+06</td>
</tr>
<tr>
<td>4</td>
<td>-1.58E+06</td>
<td>1.54E+06</td>
</tr>
<tr>
<td>6</td>
<td>-1.33E+06</td>
<td>1.31E+06</td>
</tr>
<tr>
<td>8</td>
<td>-1.07E+06</td>
<td>1.09E+06</td>
</tr>
<tr>
<td>10</td>
<td>-1.12E+06</td>
<td>1.09E+06</td>
</tr>
</tbody>
</table>

Table 2.4 Hyperelastic parameters A and B of the vinyl skin of the IHRA head-form
A limitation of MADYMO is that neither A nor B can be negative and hence
the derived values for A and B could not be used in MADYMO. This restriction
prevents the accurate representation of certain materials such as the vinyl being
modeled here. Although this limitation will be lifted in the future versions of
MADYMO, such limitations remained for the current research. Given the
restriction of only positive values for A and B, the asymptotic values of A and B
derived above were adjusted to give a reasonable fit to the data as shown in
Figure 2.9 with both A and B as positive numbers, i.e., $A = 6e4 \text{ N/m}^2$ and $B = 5e5 \text{ N/m}^2$.

Figure 2.9 Positive hyperelastic parameters A and B for the vinyl skin in
MADYMO model of the IHRA head-form
2.7. Friction

The coefficient of friction (coulomb) between the steel plate and the head-form was measured to define the kinematic contact characteristics of the hyperelastic model with the plate. It adds external damping afforded by the plate to the simulation. Figure 2.10 shows the apparatus used to measure the coefficient of friction.

The mass of the head-form was 4.5 kg, and the normal force \( N \) was \( 4.5 \text{ kg} \times 9.81 \text{ m/s}^2 = 44.15 \text{ N} \). The friction force \( F \) required to move the head-form on the steel plate was found experimentally to be between 17 N to 20 N. The coefficient of friction was calculated to be in the range of 0.38 to 0.44 using the equation

\[
\mu = \frac{F}{N} \tag{2.44}
\]
Figure 2.10  Measurement of friction between the vinyl skin and steel plate
3.1. Certification test results

The IHRA adult head-form was dropped in a laboratory certification test nine different times to assess the repeatability of its response. Table 3.1 shows the peak acceleration, HIC value and the HIC duration of the resultant acceleration time history obtained from these certification tests. Figure 3.1 shows the X, Y & Z components of acceleration acquired by three uniaxial accelerometers near the center of gravity and the resultant acceleration \( r^2 = x^2 + y^2 + z^2 \) obtained from one of the certification tests. The resultant acceleration from the MADYMO simulations were compared with the acceleration time history obtained from the certification drop tests.
Figure 3.1 IHRA adult head-form certification test result, drop 01
<table>
<thead>
<tr>
<th>Test No.</th>
<th>Peak acceleration (G)</th>
<th>HIC 36</th>
<th>Hic Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DROP_01</td>
<td>253</td>
<td>856.8</td>
<td>45.86 - 47.34</td>
</tr>
<tr>
<td>DROP_02</td>
<td>259</td>
<td>885.9</td>
<td>42.04 - 43.50</td>
</tr>
<tr>
<td>DROP_03</td>
<td>265</td>
<td>918.9</td>
<td>45.86 - 47.28</td>
</tr>
<tr>
<td>DROP_04</td>
<td>247</td>
<td>828.4</td>
<td>54.88 - 56.38</td>
</tr>
<tr>
<td>DROP_05</td>
<td>250</td>
<td>844.9</td>
<td>48.02 - 49.52</td>
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<tr>
<td>DROP_06</td>
<td>259</td>
<td>914.3</td>
<td>49.1 - 50.58</td>
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<tr>
<td>DROP_07</td>
<td>248</td>
<td>823.4</td>
<td>43.04 - 44.54</td>
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<tr>
<td>DROP_08</td>
<td>253</td>
<td>871.4</td>
<td>45.78 - 47.28</td>
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<tr>
<td>DROP_09</td>
<td>261</td>
<td>934.5</td>
<td>46.24 - 47.74</td>
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<tr>
<td>Average</td>
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<td></td>
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<tr>
<td>Standard Deviation</td>
<td>6.3</td>
<td>40.6</td>
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</tr>
</tbody>
</table>

Table 3.1  IHRA adult head-form certification test results

3.2. Linear isotropic elastic model results

Figure 3.2 shows the result obtained by employing the linear isotropic elastic material model in MADYMO. This is shown in comparison with one of the certification test result. It can be seen from Figure 3.2 that the acceleration time history of the MADYMO simulation employing the linear isotropic elastic model does not correlate well with that of the experimental results. The peak resultant acceleration obtained from the MADYMO simulation was 50 % less than that of the laboratory certification test results.
3.3. **Viscoelastic material model results**

Figure 3.3 shows the result obtained by employing the viscoelastic material model in MADYMO. This result is one among the many simulations conducted by varying the relaxation times and shear moduli of the viscoelastic vinyl material. All the other results had higher values for peak acceleration and HIC than this one. The certification test result is also given for comparison. In the Figure 3.3 it is observed that the acceleration of the MADYMO simulation
abruptly rises at 47.5 ms. This was due to one or two elements of the vinyl sticking to the impact surface while the head-form was on rebound. Although this did not happen when the bulk modulus of the vinyl material was reduced in the MADYMO simulation, the peak acceleration did not decrease much with a lower bulk modulus. The peak resultant acceleration obtained from the MADYMO simulation was 68% greater than that of the laboratory certification test results.

---

Figure 3.3 Comparison of the certification test result with the MADYMO simulation employing viscoelastic material model
3.4. Hyperelastic material model results

Figure 3.4 shows the result obtained by employing the hyperelastic material model in MADYMO along with the certification test result for comparison. The peak resultant acceleration obtained from the MADYMO simulation was 8% less than the laboratory certification test results.

Figure 3.4 Comparison of the certification test result with the MADYMO simulation employing Hyperelastic material model
3.5. Validation of the IHRA head-form model

To verify that the hyperelastic vinyl material model adequately replicated the IHRA adult head-form model’s response, the IHRA adult head-form was dropped from heights higher than 376 mm and compared with the corresponding MADYMO simulations. The IHRA adult head-form was dropped from heights of 500 mm, 880 mm and 950 mm. Figure 3.6 shows the comparison between results of the physical head-form drop and the corresponding MADYMO simulation for a drop height of 500 mm. Two drop tests were performed at this drop height. In the first drop test, the head-form was oriented such that the Z – axis was perpendicular to the steel plate. No rotation occurred during this impact, and the X and Y components of acceleration were close to zero compared to the Z component of acceleration. The peak resultant acceleration for this drop test was 282 G. In the second drop test, the head-form was oriented such that the Z – axis was at an angle with respect to the steel plate and thus the head-form rotated during impact. Figure 3.5 shows the orientation of the head-form during impact for the two cases. In the second drop test, the gravitational pull acting along the center of gravity of the head-form does not coincide with the point of impact on a radius through the geometric center of the head-form sphere. Thus, there is a moment arm between the center of gravity and the point of impact, causing the head-form to rotate. The peak resultant acceleration for this drop test was 320 G. It can be seen from Figure 3.8 that there was considerable acceleration in the X and Y directions for this second drop test, compared to the first drop as shown in Figure 3.7. Thus, the resultant acceleration is greater by 14 % for the second drop.
when compared to the first drop. For the 500 mm drop, the peak acceleration and
HIC were taken as the average of these two drops for comparison with the
simulation results.

Figure 3.5 Comparison of the two laboratory drop tests of the 500 mm
height drop
Figure 3.6 Comparison of MADYMO simulation results with physical head-form drop results for a drop height of 500 mm
Drop_1, Drop height = 500 mm

![Graph showing acceleration over time for the first drop.](image)

Figure 3.7 First drop of the IHRA adult head-form from a drop height of 500 mm

Drop_2, Drop height = 500 mm

![Graph showing acceleration over time for the second drop.](image)

Figure 3.8 Second drop of the IHRA adult head-form from a drop height of 500 mm
Figure 3.9 shows the comparison between the physical head-form drop and the MADYMO simulation for a drop height of 880 mm. Figure 3.10 shows the comparison between the physical head-form drop and the MADYMO simulation for a drop height of 950 mm. Table 3.2 shows the impact velocities and velocities at a height of 5 mm from the impact surface of the head-form for the different drop heights. Table 3.3 shows the results comparing the physical drop tests with the MADYMO simulation for the four drop heights.

<table>
<thead>
<tr>
<th>Drop height m (h)</th>
<th>Impact velocity m/s ((v = \sqrt{2gh}))</th>
<th>Velocity at a height of 5 mm from the impact surface m/s ((v = \sqrt{2g(h-0.005)}))</th>
</tr>
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<tbody>
<tr>
<td>0.376</td>
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<td>2.698</td>
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<td>0.950</td>
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<td>4.306</td>
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</table>

Table 3.2  Impact velocities and velocity from a height of 5 mm from the impact surface for the four drop heights
Figure 3.9 Comparison of MADYMO simulation results with physical head-form drop results for a drop height of 880 mm
Figure 3.10  Comparison of MADYMO simulation results with physical head-form drop results for a drop height of 950 mm

<table>
<thead>
<tr>
<th>Drop height (mm)</th>
<th>Peak Acceleration (G)</th>
<th>HIC</th>
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<td>950</td>
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</table>

Table 3.3  Comparison of results from physical drops and MADYMO simulation of the IHRA adult head-form for different drop heights
3.6. IHRA child head-form

The MADYMO model of the IHRA child head-form differs from the IHRA adult head-form only in mass, center of gravity and moment of inertia. The diameter and skin properties are identical. The values for these parameters are given in Table 2.1. Figure 3.11 shows the resultant acceleration time history from the certification test of the IHRA child head-form using MADYMO.

Figure 3.11 Resultant acceleration time history of the certification test of the IHRA child head-form using MADYMO
3.7. Parameter sensitivity analysis

Table 3.4 shows the test matrix for the parameter sensitivity analysis of the
IHRA adult head-form using MADYMO. Table 3.5 shows the test matrix for the
parameter sensitivity analysis of the IHRA child head-form using MADYMO.
With respect to the parameters, the adult and child head-forms are different only
in mass and moment of inertia. The values and tolerances of the diameter, center
of gravity and location of accelerometer are the same for both the head-forms.
Test numbers 1 – 5 in Table 3.4 and Table 3.5 show the mass test matrix for the
IHRA adult and child head-forms respectively. Test numbers 6 – 10 in Table 3.4
and Table 3.5 show the diameter test matrix for the IHRA adult and child head-
forms respectively. Test numbers 11 – 22 in Table 3.4 and Table 3.5 show the test
matrix for the location of the center of gravity with respect to the center of the
sphere for the IHRA adult and child head-forms respectively. Test numbers 23 –
34 in Table 3.4 and Table 3.5 show the test matrix for location of the
accelerometer with respect to the center of the sphere for the IHRA adult and
child head-forms respectively. Table 3.6, Table 3.7, Table 3.8, and Table 3.9
show the results of the parameter sensitivity analysis for both the adult and child
head-forms.
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<th>Test No.</th>
<th>Mass (kg)</th>
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Table 3.4  Test matrix for the parameter sensitivity analysis of the IHRA adult head-form MADYMO model
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<th>Mass (kg)</th>
<th>Diameter (mm)</th>
<th>Center of gravity location with respect to the center of the sphere (mm)</th>
<th>Accelerometer location with respect to the center of the sphere (mm)</th>
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Table 3.5 Test matrix for the parameter sensitivity analysis of the IHRA child head-form MADYMO model
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<th>S.No.</th>
<th>Mass (kg)</th>
<th>Peak acceleration (G)</th>
<th>HIC</th>
<th>Mass (kg)</th>
<th>Peak acceleration (G)</th>
<th>HIC</th>
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</thead>
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<td>909.9</td>
<td>3.45</td>
<td>258</td>
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</tr>
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<td>4.5</td>
<td>232.1</td>
<td>904.8</td>
<td>3.5</td>
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<td>1025.1</td>
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<tr>
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<td>4.55</td>
<td>231.1</td>
<td>899.8</td>
<td>3.55</td>
<td>255.1</td>
<td>1018</td>
</tr>
<tr>
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<td>4.6</td>
<td>230.1</td>
<td>894.9</td>
<td>3.6</td>
<td>253.7</td>
<td>1011</td>
</tr>
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</table>

Table 3.6  Results of varying the mass within the limits of mass tolerance in the IHRA head-forms using MADYMO

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Diameter (mm)</th>
<th>Adult head-form</th>
<th>Child head-form</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Peak Acceleration (G)</td>
<td>HIC</td>
</tr>
<tr>
<td>1</td>
<td>164</td>
<td>239.5</td>
<td>949.5</td>
</tr>
<tr>
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<td>164.5</td>
<td>235.9</td>
<td>927.7</td>
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<td>165</td>
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</tr>
<tr>
<td>4</td>
<td>165.5</td>
<td>229.1</td>
<td>887.4</td>
</tr>
<tr>
<td>5</td>
<td>166</td>
<td>225.9</td>
<td>869.1</td>
</tr>
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</table>

Table 3.7  Results of varying the diameter within the limits of diameter tolerance in the IHRA head-forms using MADYMO
<table>
<thead>
<tr>
<th>S.No.</th>
<th>Location of COG w.r.t center of sphere (mm)</th>
<th>Adult head-form</th>
<th>Child head-form</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
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<td>0</td>
</tr>
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<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
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<td>-5</td>
</tr>
<tr>
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<td>0</td>
<td>-10</td>
</tr>
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<tr>
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Table 3.8  Results of varying the location of the center of gravity within the limits of center of gravity tolerance in the IHRA head-forms using MADYMO
<table>
<thead>
<tr>
<th>S.No.</th>
<th>Location of accelerometer w.r.t center of sphere (mm)</th>
<th>Adult head-form</th>
<th>Child head-form</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
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<td>0</td>
<td>5</td>
</tr>
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<td>3</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>-5</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>-10</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
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<td>11</td>
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</tr>
<tr>
<td>13</td>
<td>-10</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.9  Results of varying the location of accelerometer within the limits of accelerometer location tolerance in the IHRA head-forms using MADYMO
CHAPTER 4

DISCUSSION

4.1. Material model for the vinyl skin

The most significant part in modeling the MADYMO head-form model was to determine a suitable material model for the vinyl skin. The first approximation for a material model was for a linear, isotropic material. This choice was based on the belief that the vinyl skin is isotropic and because it is the simplest material model. After examining the linear isotropic material model results as shown in Figure 3.2, it was concluded that this material model does not suit the vinyl material. The main drawback of this material model was its inability to address the issue of strain rate. Had it been possible to measure the force-penetration characteristic at higher levels of strain rates, damping could have been determined and incorporated into the model’s response. Instead, damping coefficients had to be estimated by iteratively selecting a value and matching the response of the material model with a laboratory test. Although different values of the damping coefficient were tried in the MADYMO simulation, an adequate replication of the laboratory test response was not obtained. This result suggests that the damping is not linearly related to velocity and cannot be approximated as a constant value over all velocities.
The viscoelastic material model was considered next to address the issue of strain rate. The bulk modulus and Poisson’s ratio were obtained from the literature as discussed before in Chapter 2. The data from the oscillatory compression tests could not be used, as the resulting equations were not solvable. The values for shear moduli and relaxation time for brain tissue from Brands et al. [3] gave an indication of appropriate values for these viscoelastic parameters. Since it was not possible to determine exact values for shear moduli and relaxation time analytically, an iterative-fitting method was used to determine values for these properties by selecting values near those recommended by Brands et al. [3] and then adjusting them and determining the agreement of the response of the model with the response of the head-form measured in drop tests. The best agreement was obtained with the simulation resultant acceleration being 168% higher than the expected result as shown in Figure 3.3. This unacceptable match with actual data showed that the viscoelastic model did not adequately model the vinyl material.

As explained in Chapter 2, in the hyperelastic material model, true stress is not dependent on strain rate at higher strain rates. Because of the incompressibility of the vinyl material, the Poisson’s ratio for this material was assumed to be 0.499 (close to 0.5) and is also the maximum possible value for this material in MADYMO. It should be noted that hyperelasticity accounts for the stiffness characteristics of the vinyl but does not adequately account for the damping characteristics, although external friction is added at the contact between the vinyl and the impact surface. Hence, without adding proper damping to the
material model, the results were still not close to the laboratory drop results. Although the error in peak acceleration was 3 %, HIC error was as high as 46 %. To address this deficiency, various general damping coefficients were used to minimize the error between the simulation response and the laboratory test response. It was found that a value of 30,000 Ns/m for the damping coefficient produced a result that was comparable with the laboratory drop for the certification test as shown in Figure 3.4. This shows that the vinyl skin material is complex with properties of stiffness, hysteresis, relaxation, and damping which must be taken into consideration. In addition these properties are rate dependent.

It should be noted that the hyperelastic material model had a limitation, in which negative values could not be used for the material parameters A & B. The material parameters A and B used in the MADYMO simulation were approximated values of the actual material parameters A & B measured from the compression testing of the vinyl skin. Had it been possible to use the actual values for the material parameters A and B in MADYMO, the response would have more accurately replicated the laboratory drop test response.

4.2. Validation results of the head-form model

The MADYMO model of the adult head-form with the hyperelastic material model for vinyl seemed to most closely reproduce the laboratory drop test results. The model was validated with laboratory test drops at different heights. Although the comparison between the simulation results and laboratory drop test results as shown in Figure 3.4, Figure 3.6, Figure 3.9 and Figure 3.10 are consistent in peak
acceleration, there is considerable error in the HIC values as shown in Table 3.3. As given in equation 1.1, in the calculation of HIC, the area under the resultant acceleration curve is raised to the power of 2.5 and thus any deviation in the acceleration curve from the laboratory drop test response would be more pronounced in the HIC calculation. In Table 3.3 the peak acceleration error is positive whereas the HIC error is negative for all the four drop heights when the true value is the laboratory value of the IHRA head-form. The MADYMO simulation HIC is greater than the laboratory drop HIC because of shorter duration and a smaller difference in amplitude illustrated by the difference in the curve shapes.

Comparing the acceleration traces of the MADYMO simulation and laboratory drop for the 880 mm drop. Based on equation 1.1, HIC could be written as,

\[
\text{HIC}_{\text{MADYMO}} = A_1 \times B_1
\]
\[
\text{HIC}_{\text{DROP}} = A_2 \times B_2
\]

where,

\[
A_1 = \left(\frac{1}{(4.3 - 1.0)}\right)^{1.5}
\]
\[
= 0.125
\]
\[
B_1 = \left(\int_{-0}^{4.3} a(t)dt\right)^{2.5}
\]
\[
= 20760
\]

Comparing the acceleration traces of the MADYMO simulation and laboratory drop for the 880 mm drop. Based on equation 1.1, HIC could be written as,
\[ A2 = \left[ \frac{1}{(4.1 - 0.1)} \right]^{1.5} \]
\[ = 0.167 \]
\[ B2 = \left[ \int_{0.1}^{4.1} a(t)dt \right]^{2.5} \]
\[ = 18579 \]

now,
\[ A1/A2 = 1.334 \]
\[ B2/B1 = 0.895 \]

From equations 4.11 and 4.12, \( A1/A2 > B2/B1 \) hence, HIC value of MADYMO simulation is greater than HIC value of the laboratory drop.

Again as mentioned before, had the actual values for the material parameters A and B been used in the simulation, the response would have matched the laboratory drop test response more closely.

In Figure 3.4, after the rebound of the head-form from the impact surface there is a small bump in the acceleration of the laboratory head-form drop after 48 ms. The trend of acceleration of the MADYMO simulation is similar to that of the acceleration of the laboratory drop test except for this slight deviation. This difference is due to the X-component of the acceleration of the laboratory drop test as can be seen from Figure 3.1. During the laboratory drop test, the test set up (Figure 1.3) used for dropping the head-form that included the string support mechanism had a constraint that limited the maximum height of the head-form drop to 500 mm. In this test set up (Figure 1.3), the head-form is held at the
desired height before the drop with the help of strings. The string is detached from
the top to initiate the drop. The string is used to precisely maintain the desired
drop height and to avoid the rotation of the head-form, which might be caused
while dropping the head-form using hands. For the 880 mm and 950 mm drop
heights, this set up could not be used and the head-form was released by the hand
onto a steel plate placed on the ground. Hence the prospect of maintaining the
desired height accurately and avoiding rotation of the head-form during the drop
became intricate. An error of approximately +/- 20 mm was possible in the
measurement of the height for the 880 mm and 950 mm drops. From Table 3.2 it
could be seen that the errors for peak acceleration and HIC for the four drops are
within 10 % except for the HIC error of the 880 mm drop. It is possible that the
measured drop height for the 880 mm laboratory drop test was greater than the
actual drop. With a decreased drop height, the peak acceleration and HIC would
decrease accordingly, thereby decreasing the error in HIC value for this drop. For
instance, the error in HIC dropped to -15 % and the peak acceleration error
increased to only 3 % while dropping the head-form from 860 mm instead of 880
mm in the MADYMO simulation. For the 880 mm and 950 mm drops, there was
considerable acceleration in the X – direction due to rotation of the head-form
during impact as could be seen from Figure 4.1 and Figure 4.2.
Figure 4.1 Acceleration time history of the IHRA adult head-form from a drop height of 880 mm

Figure 4.2 Acceleration time history of the IHRA adult head-form from a drop height of 950 mm
4.3. Parameter sensitivity analysis

MADYMO simulations of IHRA adult and child head-form certification drop tests were conducted to study the sensitivity of head-form parameters to impact mode. While varying one parameter, the other parameters were fixed. For example when the mass was varied, the diameter was fixed as 165 mm and the center of gravity of the head-form and the location of the accelerometers were fixed at the center of the sphere. The mass was fixed as 4.5 kg when the other parameters were varied.

The results of varying the mass within the limits of mass tolerance are given in Table 3.6. With increase in mass, the peak acceleration and HIC values decrease. Assuming the head-form to be a simple spring mass system, the relationship between the contact force and displacement is given by,

$$ma = Kx$$  \hspace{1cm} (4.13)

where,

$m$ – Mass of the head-form

$a$ – acceleration of the head-form

$K$ – Stiffness of the spring

$x$ – deflection of the spring

With increase in mass, the acceleration will decrease. This also explains why the peak acceleration range (Table 1.2) for the child head-form is greater than that of the adult head-form as both the head-forms have the same vinyl skin. The peak acceleration values for both the head-forms were well within the given acceleration range for the different masses within the limits of mass tolerance.
Figure 4.3 and Figure 4.4 show the variation of peak acceleration and HIC respectively obtained by varying the mass of the head-forms within the limits of mass tolerances.

![Graph showing variation of peak acceleration and HIC](image)

Figure 4.3 Variation of peak acceleration obtained by varying the mass within the limits of mass tolerance
For varying the head-form diameter within the limits of diameter tolerance, the inner diameter of the vinyl skin was maintained as a constant and the outer diameter was changed which resulted in the thickness change of the vinyl skin. With increase in the thickness of the vinyl skin, there is more room for deformation and hence the deceleration decreases as listed in Table 3.7. The peak acceleration values for both the head-forms were well within the acceleration range for the different diameters. Figure 4.5 and Figure 4.6 show the variation of peak acceleration and HIC respectively obtained by varying the diameter of the head-forms within the limits of diameter tolerance.
Figure 4.5 Variation of peak acceleration obtained by varying the diameter within the limits of diameter tolerance

Figure 4.6 Variation of HIC obtained by varying the diameter within the limits of diameter tolerance
As the head-form is dropped along the Z – axis, changing the position of the center of gravity along this axis did not change the results as shown in Table 3.8. Both the head-form models were symmetrical about the Z – axis in MADYMO; hence, the result was the same in the positive and negative directions of the X and Y-axes. The results were well within the given acceleration range for both the head-forms. Figure 4.7 and Figure 4.8 show the variation of peak acceleration and HIC respectively obtained by varying the location of the center of gravity from the center of the sphere, along the X and Y-axes within the limits of center of gravity location tolerance.

![Graph showing variation of peak acceleration](image URL)

Figure 4.7 Variation of peak acceleration obtained by varying the location of the center of gravity from the center of the sphere along the X and Y-axes
In the case of varying the location of the accelerometer for both the head-forms, the center of gravity was maintained as the actual center of gravity as given in Table 2.1. As the head-form is dropped along the Z-axis without any rotation, varying the accelerometer position while maintaining the center of gravity of the head-form at the center of the sphere did not change the results considerably. Using the actual center of gravity in the MADYMO model resulted in the rotation of the head-form during impact, thereby allowing the study of variation of the accelerometer position. Along the Z-axis, the results did not change because it is the axis along which the head-form is dropped. The results were well within the given acceleration range for both the head-forms. Figure 4.9 and Figure 4.10 show the variation of peak acceleration and HIC respectively obtained by varying the location of the accelerometer from the center of the sphere along the X and Y-axes.
sphere, along the X - axis within the limits of accelerometer location tolerance. Figure 4.11 and Figure 4.12 show the variation of peak acceleration and HIC respectively obtained by varying the location of the accelerometer from the center of the sphere, along the Y - axis within the limits of accelerometer location tolerance.

\[
y = -0.26x + 265.2 \\
R^2 = 1
\]

\[
y = -0.29x + 232.92 \\
R^2 = 0.9996
\]

Figure 4.9 Variation of peak acceleration obtained by varying the location of the accelerometer from the center of the sphere along the X – axis
Figure 4.10  Variation of HIC obtained by varying the location of the accelerometer from the center of the sphere along the X – axis

Figure 4.11  Variation of peak acceleration obtained by varying the location of the accelerometer from the center of the sphere along the Y – axis
Figure 4.12 Variation of HIC obtained by varying the location of the accelerometer from the center of the sphere along the Y-axis.

<table>
<thead>
<tr>
<th>Mass</th>
<th>Adult head-form</th>
<th>Child head-form</th>
</tr>
</thead>
<tbody>
<tr>
<td>For 0.1 kg increase</td>
<td>&lt; 1 %</td>
<td>&lt; 2 %</td>
</tr>
<tr>
<td>For 1 mm increase</td>
<td>&lt; 4 %</td>
<td>&lt; 5 %</td>
</tr>
<tr>
<td>Center of gravity</td>
<td>For 10 mm in X</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>For 10 mm in Y</td>
<td>&lt; 1 %</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>For 10 mm in Z</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Accelerometer seismic mass location</td>
<td>For 10 mm in X</td>
<td>&lt; 2 %</td>
</tr>
<tr>
<td>For 10 mm in Y</td>
<td>&lt; 2 %</td>
<td>&lt; 4 %</td>
</tr>
<tr>
<td>For 10 mm in Z</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 4.1 Summary of results of parameter sensitivity analysis
Table 4.1 shows the summary of results of the parameter sensitivity analysis of both the adult and child head-forms. The change in the diameter within the tolerances produces considerable change in the peak acceleration and HIC values. There is no change in the results for varying the center of gravity or the accelerometer seismic mass location along the Z – axis within the given tolerance of 10 mm as this the direction along which the head-form is dropped.

In summary, a hyperelastic material model for the vinyl skin was found to best represent the response of the IHRA head-forms. The MADYMO model of the IHRA adult head-form was validated at several drop velocities to assess its versatility. Finally, the MADYMO head-form model was used to evaluate the effect of mass and geometric parameters on its response.
5.1. Conclusion

Pedestrian collisions are one of the leading causes of death and injury around the world. Head injury is the leading cause of death and injury in pedestrian collisions and thus gathers prime importance in the study of pedestrian safety. Minimizing vehicle aggressiveness towards pedestrians is one of the major possible ways to approach pedestrian protection. It has been shown that relatively minor changes to the front ends of vehicles can significantly reduce the potential for death and severe injury to pedestrians [25]. Simulation of pedestrian collisions can provide insight into understanding the dynamics of the collision and methods of prevention. Subsystem component tests are less complex, less costly and less time consuming when compared to the pedestrian dummy testing. The International Harmonization Research Activities Pedestrian Safety Working Group (IHRA PSWG) is conducting research aimed at establishing harmonized test procedures to improve pedestrian safety afforded by vehicles in the event of a collision. The IHRA PSWG has developed two head-form designs for vehicle hood (bonnet) impact testing.
The main objectives of this research were to develop MADYMO models of the IHRA adult and child head-forms, validate the models using laboratory drop tests, and conduct parameter sensitivity analysis of the head-forms. In the MADYMO model of the head-form, the aluminum core and the accelerometer mount were represented by a multibody sphere whereas the vinyl skin was modeled with finite elements using ABAQUS and imported into MADYMO. The most significant part in modeling the MADYMO head-form model was to determine a suitable material model for the vinyl skin. After examining the linear isotropic material model results as shown in Figure 3.2, it was concluded that this material model was not appropriate for the vinyl material. The main drawbacks of this material model were its inability to address the issue of strain rate and the subsequent unavailability of damping data for the vinyl material. The viscoelastic material model was considered to address the issue of strain rate but the data from the oscillatory compression tests could not be used, as the resulting equations were not solvable. From the MADYMO simulation results as shown in Figure 3.3 it was concluded that this material model was also not appropriate for the vinyl material.

The hyperelastic material parameters A and B were determined by curve fitting the data obtained from the uniaxial compression test of the vinyl skin. Due to the limitations in MADYMO, negative values of A were not permitted and instead positive asymptotic values of A and B were derived and adjusted to give a reasonable fit. With inclusion of a suitable value for damping coefficient, the
hyperelastic material model for the vinyl skin produced the results that were close to the laboratory drop test results. The vinyl material was thus discovered to behave as a hyperelastic material.

The MADYMO model of the IHRA adult head-form was validated with laboratory head-form drop tests of different drop heights. The MADYMO model closely replicated the laboratory drop test response with slight deviations, which can be attributed to the use of approximate values for the hyperelastic material parameters A and B. The peak acceleration was well within 9% error for the four different drop heights and the HIC error was within -10% for three out of the four drop heights.

Parameter sensitivity analysis was conducted by varying the head-form parameters within their respective limits of tolerances and it was found that the peak acceleration was well within the given range for both the adult and child head-forms. For the adult head-form, with 1 kg increase in mass, the peak acceleration decreased by less than 1% and the HIC decreased by less than 2%. For the child head-form, with 1 kg increase in mass, both the peak acceleration and HIC decreased by less than 2%. With 1 mm increase in diameter, the peak acceleration decreased by less than 4% and the HIC decreased by less than 5% for both the adult and child head-forms. Varying the center of gravity along the Z-axis neither changed the peak acceleration nor the HIC. Positioning the center of gravity within a distance of 10 mm from the center of the sphere in either X or Y-axes increased the peak acceleration and HIC by less than 1% for both the adult
and child head-forms. Positioning the accelerometer within a distance of 10 mm from the center of the sphere changed the peak acceleration by less than 2% and HIC by less than 4% for both the adult and child head-forms.

5.2. Recommendations

During the finite element modeling of the vinyl skin using four-node tetrahedral elements, it was found that there were compatibility issues between MADYMO and some postprocessors like ALTAIR Hyperview. Although this problem was bypassed by using eight-node hexahedral elements for the current model, this could not be done for models with complex shapes. This problem was reported and is expected to be rectified in the future versions of MADYMO. Similarly, the limitation of MADYMO, i.e., allowing only positive values for the hyperelastic parameters A and B should be rectified. This would greatly improve the accuracy of the MADYMO head-form models in the future.

One suggestion for improving the head-form model would include the measurement of a damping coefficient for the vinyl skin. The correct damping coefficient for the vinyl skin along with actual values for hyperelastic parameters A and B are expected to improve the accuracy of the model. The model should also be validated by conducting laboratory drop tests of the head-forms at different angles. Finally, the rotation of the head-form during impact could be incorporated into the MADYMO model by knowing the exact orientation of the head-form before the impact, i.e., knowing the location and orientation of the coordinate axes of the center of gravity.
BIBLIOGRAPHY


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35. http://www.factbook.net/EGRF_Regional_analyses_Africa.htm

APPENDIX A

Figure A.1 shows the relationship between probability of skull fracture and HIC [19].

Figure A.1 Probability of skull fracture vs. HIC
APPENDIX B

0 shows the various subsystem components used by the European Enhanced Vehicle-Safety Commission (EEVC) and the intended impact surface for the subsystem components in the car front [12].

Figure B.1 EEVC pedestrian protection subsystem tests