MODELING AND EVALUATION OF CHILD SAFETY SEAT AND RESTRAINT SYSTEM FOR AEROSPACE APPLICATION

A Thesis By

Ashutosh A. Patil

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Visveswaraiah Technological University, 2003

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MODELING AND EVALUATION OF CHILD SAFETY SEAT AND RESTRAINT SYSTEM FOR AEROSPACE APPLICATION

I have examined the final copy of this Thesis for the form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering

________________________________________
Hamid Lankarani, Committee Chair

We have read this Thesis and Recommend its acceptance:

________________________________________
Bob Minaie, Committee Member

________________________________________
Bayram Yildirim, Committee Member
DEDICATION

To my parents for their unconditional support guidance and encouragement
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ABSTRACT

The increasing trend of carrying babies in aircraft raises the question of their safety. The National Transportation Safety Board (NTSB) states that all occupants should be restrained during takeoff, landing, and turbulent conditions and that all infants and small children should be restrained in an approved child restraint system appropriate to their height and weight. The present child seats are primarily developed for automotive applications and not tested for aerospace applications; therefore, there is a need to test these child restraint systems for aerospace test conditions. Also, the cost of actual testing and the secrecy maintained by manufacturers make research process difficult and increase the importance of computer simulations. The need for validated computer models is imperative. The 12-month-old and 3-year-old child seats used in this research have been approved for use in automobiles but not in aircraft. This research attempts to develop and validate a child restraint seat model for aerospace application. Two types of child restraint seat models - 12-month-old and 3-year-old child seat models were developed and validated using the computational tool MADYMO.

The surface models of these two types of seat were exported in IGS format and meshed using Hypermesh. The meshed model was then defined as a facet in MADYMO. These models were validated for the type II dynamic test condition specified according to FAA regulations.

Validation was carried out by comparing the kinematics in the simulations and the actual sled tests. To ensure validity, a comparison of various acceleration profiles and force/moments experienced by the occupant under test conditions were compared. Furthermore, the injury levels sustained by the occupant in the actual sled tests and the simulations were compared. Thus, the seat models were validated for their practical applications. These simulated models can help in future research on child safety and to generate guidelines for child restraint use in aircraft.
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CHAPTER 1
INTRODUCTION

1.1 Motivation

The increasing trend toward fractional aircraft ownership has seen a rise in the number of babies and children being transported on corporate and private airplanes. Occupant protection policies for children younger than two years on aircraft are inconsistent with all other national policies relative to safe transportation. Children younger than two years are not required to be restrained or secured on aircraft during takeoff, landing, and conditions of turbulence. In the National Transportation Safety Board (NTSB) 2005-2006 Most Wanted Transportation Safety Improvements, NTSB states that all occupants should be restrained during takeoff, landing, and turbulent conditions and that all infants and small children should be restrained in an approved child restraint system appropriate to their height and weight.

A child restraint system (CRS) provides specialized protection for small occupants whose body structures are still immature and growing. Child restraint designs vary with the size of the child, the direction the child faces, the type of internal restraining system, and the method of installation. All CRSs, however, work on the principle of coupling the child as tightly as possible to the vehicle. Historically in North America, the CRS has been attached to the vehicle with existing seatbelts, sometimes supplemented by an additional top tether strap. The child is then secured to the CRS with a separate harness and/or other restraining surface (shield). This results in two links between the vehicle and the occupant, rather than only one. Therefore, it is critical that both the seatbelt and the harness, for instance, be as tight as possible to allow the child to ride down the crash with the vehicle. When this system has been properly used and secured, child restraints have been estimated to reduce the risk of death and serious injury by
approximately 70 percent. By comparison, estimates of fatality reduction in adults with lap/shoulder belts for the same time period averaged about 50 percent [11].

Current FAA recommendations for child restraints are based on Federal Motor Vehicle Safety Standards (FMVSS) and typically involve the use of child safety seats restrained by aircraft lap belts. Newer automotive restraint standards use the structure of the vehicle to restrain the child safety seat. These standards differ between North America (lower anchors and tethers for children or LATCH system) and the rest of the world (international organization for standardization FIX or ISOFIX system). Development and testing is needed to determine the optimum means of child restraint and a solution that works in both North America and the rest of the world.

1.2 Objective

FMVSS 213 defines performance standards for child seats sold in the United States. Because of the differences between car seat and airplane seat structures, the methods and fixtures used to certify child seats may not produce the same results when evaluating the performance of airplane seats. Public awareness of the benefits provided by using child restraint systems has grown in the past decade. National highway traffic safety administration (NHTSA) estimates that more than 4.5 million child restrains are sold every year. Both the increased awareness and use of approved child restraints by the public may encourage the use of child restraints in commercial air transportation.

The objective of this research was to develop mathematical models for infant seat (for children’s up to 12 months old), convertible seat (for children up to 3 years old) and 6 year old child without child restraints. So they could be used to perform simulations to study different scenarios.
1.3 Background

Performance standards for child restraint systems (CRS) in the United States are defined by FMVSS 213, which requires that any marketed child seat for use in a vehicle should be designed to restrain and protect children in the event of a crash. Performance criteria include protection from serious injury to head, chest, and legs.

In 1982, the first FAA policy that allowed a child restraint device (CRD) on airplanes was issued in Technical Standard Order (TSO) C100. TSO C100 defined two performance standards for CRD’s in airplanes. The first was FMVSS 213, and the second was defined in the TSO, which specifies an 18 g, 22 ft/sec dynamic test with the CRD installed on a representative airplane seat fixture.

In September 1994, the FAA issued a report entitled “The Performance of Child Restraint Devices in Transport Airplane Passenger Seas” [1]. This study was done by the Civil Aero Medical Institute (CAMI) and involved dynamic impact tests with a variety of CRSs installed in transport category aircraft passenger seats. Some of the tests were configured to represent a typical multi-row seat installation and included testing the effects of an adult occupant impact against the back of a seat in which a CRS’ was installed. The tests also investigated other aspects of CRSs used in aircraft, including whether they fit within an aircraft passenger seat and their ease of installation.

The CAMI study made the following findings:

1. Rear-facing CRSs for children under 20 pounds performed well, protected the child, and could be adequately restrained with existing aircraft seat belts.
2. All eight forward-facing CRSs that were tested for children from 20 to 40 pounds, when restrained with aircraft seat belts and subjected to the 16 g longitudinal aircraft deceleration failed to prevent the head from impacting the forward seatback. Routing the aircraft seat belt through a forward-facing CRS and buckling, adjusting proper tension, and unbuckling it were difficult, leading to the conclusion that some CRSs might not be easily and adequately secured to aircraft seats.

3. Normal lap belts for children who weighed 33 pounds provided adjustable tight fit, a belt path over the pelvic bone, and no indication of submaring or rollout during dynamic tests. However, because lap belts are not designed to inhibit upper torso flail, head impacts against the seat structure that were severe enough to cause head injury occurred during testing. These impacts were substantially higher than those exhibited in the forward CRS tests.

4. The child anthropomorphic test dummy (ATD) moved forward and over the front edge of the seat cushion, and proceeded to submari to the floor during dynamic testing of harness restraints. Elasticity in the webbing of the harness and seat belts then pulled the ATD rearward. These restraints consisted of a torso harness for the child ATD placed in its own seat, with the airplane seat belt routed through a loop of webbing attached to the back of the harness.

1.4 Child Seat Classification

The physiology of a child differs with age, and therefore, recommended restraints also differ. Some of the restraints used are described as follows [2]:

...
1.4.1 Infant Seats

Figure 1.1 shows the different types of infant seats. Infants from birth to at least one year of age, and at least 20 pounds should ride in the back seat in a rear-facing safety seat. Harness straps should be at or below the infant’s shoulders. Harness straps should fit snugly. The straps should lie in a relatively straight line without sagging. The harness chest clip should be placed at the infant’s armpit level. This keeps the harness straps positioned properly. Infants weighing 20 pounds or more before one year should ride in a convertible child safety seat rated for heavier infants (most convertible seats are rated up to 30 to 35 pounds rear-facing).

![Figure 1.1. Infant seats.](image)

1.4.2 Convertible Seats

Figure 1.2 shows the convertible seats. Children over one year of age and at least 20 pounds may ride in a forward-facing child safety seat in the back seat. Children should ride in a safety seat with full harness until they weigh about 40 pounds. Harness straps should be at or above the child’s shoulders, and threaded through the top slots, in most cases. The harness should be snug. Straps should lie in a relatively straight line without sagging. The harness chest clip should be at the child’s armpit level, and helps keep the harness straps positioned properly on the child’s shoulders.
1.4.3 **Booster Seats**

Figure 1.3 shows the belt-positioning booster seat. All children who have outgrown child safety seats should be properly restrained in booster seats until they are at least eight years old, unless they are four feet nine inches tall. Belt-positioning boosters can only be used with both the lap and shoulder belts across the child. The shoulder belt should be snug against the child’s chest, resting across the collar bone. The lap belt should lay low across the child’s upper thigh area. Boosters should be used as “in between” safety restraints for children over 40 pounds who have outgrown a forward-facing child seat and are not yet ready for the adult safety belt.
Figure 1.4 shows the high back booster seat. High back booster seats with a five-point harness are recommended for children between 20 and 40 pounds. Built-in harness straps should be used with proper precautions.

![Figure 1.4. High back booster with five-point harness](image)

Figure 1.4. High back booster with five-point harness

Figure 1.5 shows the high back belt-positioning booster. High Back belt-positioning seats position the child for proper use of the lap-shoulder belts and also give support to the head. These seats should always be used with lap-shoulder belts and not with just one of the belts.

![Figure 1.5. High back belt-positioning booster.](image)
1.5 Child Seat Dimensions

Typical child seat dimensions, are listed in Table 1.1, are actual measurements taken before sled testing. The reason for taking these measurements was to see whether these seats were able to fit in a typical aircraft seat or whether adjustments had to be made. Fortunately all the child seats were able to fit in the aircraft seat but with very limited space between them and the armrest.

TABLE 1.1
CHILD SEAT DIMENSIONS

<table>
<thead>
<tr>
<th>Type</th>
<th>Height (Inches)</th>
<th>Width (Inches)</th>
<th>Depth (Inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convertible – 1</td>
<td>26.8</td>
<td>17.7</td>
<td>16.3</td>
</tr>
<tr>
<td>Convertible – 2</td>
<td>24.2</td>
<td>18.9</td>
<td>17.7</td>
</tr>
<tr>
<td>Booster</td>
<td>26.4</td>
<td>16.5</td>
<td>13</td>
</tr>
<tr>
<td>Infant</td>
<td>18.1</td>
<td>10.2</td>
<td>21.3</td>
</tr>
</tbody>
</table>

1.5.1 Infant Seat Generic Dimensions

Figures 1.6 and 1.7 show the dimensions for an infant seat. This kind of seat is used to restrain a 12 month–old child and should be rear-facing. Figure 1.6 shows the baby carrier that was placed on the base shown in Figure 1.7.

Figure 1.6. Rear-facing infant seat I.
1.5.2 Convertible Seat Generic Dimensions

Convertible seats are used to restrain a 3 year-old child. This restraint system should be placed in the forward-facing position. It has a four-point harness belt system to keep the child in place, and can be used with both the ISOFIX and LATCH systems depending on the attachment method on the aircraft seat.
1.6 Typical Aircraft Seat Dimensions

It is necessary to measure the different aircraft seat dimensions to ensure that all child restraint seats are able to fit. Figure 1.9 shows a typical aircraft seat, and the various seat dimensions are listed in Table 1.2.

![Figure 1.9. Typical seat geometry.](image)

**TABLE 1.2**

TYPICAL SEAT DIMENSIONS

<table>
<thead>
<tr>
<th>Seat configuration</th>
<th>One-arm rest configuration</th>
<th>Two-arm rest configuration</th>
<th>Width between arm rests (Inches)</th>
<th>Seat cushion width (Inches)</th>
<th>Seat cushion depth (Inches)</th>
<th>Seat-back angle (Inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Y</td>
<td></td>
<td>17.5</td>
<td>19.5</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td></td>
<td>18.5</td>
<td>20.5</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>Y</td>
<td>18.5</td>
<td>20.5</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td></td>
<td>16.5</td>
<td>20.5</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>18</td>
<td>22</td>
<td>21</td>
<td>10</td>
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<td></td>
<td>19.5</td>
<td>19</td>
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</tbody>
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### TABLE 1.2 (continued)
**TYPICAL SEAT DIMENSIONS**

<table>
<thead>
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<th></th>
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<td>22.6</td>
</tr>
<tr>
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<td>20</td>
<td>22</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>AVG</th>
<th></th>
<th>20.5</th>
<th>10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVG</td>
<td>17.9</td>
<td>19.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIN</td>
<td>16.5</td>
<td>18.5</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>MAX</td>
<td>18.5</td>
<td>22</td>
<td>22.6</td>
<td>10</td>
</tr>
</tbody>
</table>

### 1.7 Attachment Methods

The attachment method is the way in which the child restraint system is fixed on any automobile or aircraft seat. There are several ways to attach a child restraint to seats. In an automobile adult seat belts typically are used to attach the child restraint. But now, two attachment methods LATCH and ISOFIX are most effective and widely used to attach the child restraint to seats.

#### 1.7.1 LATCH

National Highway Traffic Safety Administration administrator, Dr. Jeffrey W. Runge has explained that "LATCH is an important innovation in child restraint and vehicle design. Used properly, the system is expected to save up to 50 lives a year and prevent close to 3,000 injuries in a crash. This new technology will help us move forward in our quest to further reduce death and injury among our youngest passengers."
According to NHTSA, at least 80 percent of child safety seats are incorrectly installed. LATCH resolves two of the most common safety seat misuses: the safety seat is not tightly fitted into the vehicle seat, and the seat belt is not properly locked in place.

NHTSA sites the following as some other common mistakes that can cause serious injury or death in the event of a crash:

- Child safety seat harness straps are too loose.
- The safety seat is facing the wrong direction in the vehicle.
- The child is not the appropriate height, weight and/or age for the safety seat.
- The infant seat is in the path of an air bag.
- Children who should ride in a booster seat are moved prematurely to an adult seat belt system.
- The safety seat has been recalled or has been involved in a crash.

The Lower Anchors and Tethers for Children system is designed to make installation of child safety seats easier by requiring child safety seats to be installed without using the vehicle’s seat belt system. As of September, 1999, all new forward-facing child safety seats (not including booster seats) must meet stricter head protection requirements, which, in most cases, call for a top tether strap. This adjustable strap is attached to the back of a child safety seat. It has a hook for securing the seat to a tether anchor found either on the rear shelf area of the vehicle or, in the case of mini-vans and station wagons, on the rear floor or on the back of the rear seat of the vehicle. As of September, 2000, most new cars, minivans, and light trucks have this tether anchor.

As of September 1, 2002, two rear-seating positions of all cars, minivans and light trucks must be equipped with lower child safety seat anchorage points located between a vehicle’s seat
cushion and seat back. Also as of this same date, all child safety seats must have two attachments that connect to the vehicle’s lower anchorage attachment points. Together, the lower anchors and upper tethers make up the LATCH system.

LATCH is designed to make car seat installation easier. It eliminates the need to use the vehicle's seat belt system, which is a common source of misuse. It uses anchors found between the vehicle's back seat cushions, and buckles or hooks on child safety seats. The two parts snap together to secure the child safety seat to the vehicle seat. In addition, all new vehicles have top anchor points that connect to a child safety seat's top tether strap. Together, these components are intended to make safety seat installation easier for parents.

![LATCH attachment](image)

Figure 1.10. LATCH attachment.

### 1.7.2 ISOFIX

The International Organization for Standardization FIX involves two fixed points on the vehicle seat. ISOFIX is a system of attaching child restraint to the vehicle seat. The child restraint system is attached to two rigid vehicle anchors by means of two rigid attachments at the bottom of the CRS in order to limit the pitch rotation of the child restraint system. It has a top tether, which prohibits the restraint system to rotate [3]. Figure 1.11 and 1.12 shows the ISOFIX lower attachments for ISOFIX child restraint fixture.
This system provides the more rigid coupling of CRS to the vehicle, offering the best performance in side-impact crashes.

Figure 1.11. Lower attachments for ISOFIX child restraint fixture.

Figure 1.12. ISOFIX child restraint fixture.
1.8 General Injury Mechanisms in Crash Scenarios

Three types of collision forces can cause injuries. The primary force is the direct impact due to the collision of the vehicle with another object. The second is due to the impact between the interior and the passenger body. The third result from the violent collision of body organs within the body frame. The last two forces increase the importance of consistent use of safety.

1.8.1 Head Injury

Head Injuries are divided into three types: skull injuries, brain injuries and scalp injuries. Scalp injuries are most common injuries in accidents, but they are considered to be of minor importance [8].

1.8.2 Skull Injuries

Skull fracture can take place with or without damage to the brain but is itself not an significant cause of neurological fatality or disability. Skull fractures can be classified in several ways. They are considered open fractures if the durra is torn, or closed fractures if the durra is not torn. Injuries to the neural substance of the brain are the first and foremost cause of neurological dysfunction and can readily be divided into two categories – local and neural.

1.8.3 Focal Brain Injuries

Focal brain injuries are those in which a lesion large enough to be visualized with the naked eye has occurred and has resulted in contusion, subdural hematoma, epidural hematoma, and/or intracerebral hematoma. These injuries comprise approximately 50 percent of all head injury patients admitted to the hospital and are responsible for two-thirds of head injury deaths.

1.8.4 Diffuse Brain Injuries

Diffuse brain injuries are associated with more widespread or global disruption of neurological function and usually not associated with a macroscopically visible brain lesion. To a
certain extent they cause widespread disruption of either the function or structure of the brain. Since diffuse brain injuries, for the most part, are not associated with visible microscopic lesions, they have historically been lumped together to mean all injuries not associated with focal lesions.

1.9 Injury Criterion

An injury criterion can be defined as a biomechanical index of exposure severity, which indicates the potential for impact-induced injury by its magnitude [8].

There are several reasons why injury criteria have been developed. The search for a valid criterion improves the understanding of injury mechanisms and situations in which they occur. An injury criterion also relates loading conditions during impacts on human bodies to certain levels of injury scales as the AIS scale. Another practical reason is that experiments with cadavers, animals, and mechanical surrogates (dummies) of occupants provide only measurements of forces, displacements, velocities, and accelerations but not injuries. The injury criteria, based on data of these experiments or mathematical simulations, can be used for an efficient analysis of car safety design and optimization [8].

Most injury criteria are based on accelerations, relative velocities or displacements, or joint constraint forces. These quantities must be requested with standard output options. Most injury criteria need some mathematical evaluation of a time history signal [8].

1.9.1 Head Injury Criterion

The head injury criterion (HIC) was used to assess head injury. Values greater than 1000 indicate that there is likelihood of serious head injury. HIC is calculated when the head of the occupant comes in hard contact with another rigid object during a frontal (contact) impact. It is evaluated as
Whereas,

\[ HIC = \max \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} (t_2 - t_1) \]

\[ t_1, t_2 = \text{arbitrary instants of time when head experiences acceleration or deceleration.} \]

\[ a(t) = \text{resultant linear acceleration at the center of gravity of the head} \ [9]. \]

1.9.2 Neck Injury Criterion

Neck injury occurs due to excessive compressive or tensile forces along the neck axis or excessive shear forces acting perpendicular to the neck axis. The duration of the load acting on the neck also affects the level of injury. Neck injury criteria formulated by Mertz and Patrick was used [8].

The criteria for compressive loading was as follows:

\[ F > 900 - 20t \quad t < 30 \text{ ms} \]
\[ F > 250 \text{ lb (f)} \quad t > 30 \text{ ms} \]

The criteria for tensile loading was as follows:

\[ F > 740 - 2.6 t \quad t < 34 \text{ ms} \]
\[ F > 1888 - 36.4 t \quad 34 \text{ ms} < t > 45 \text{ ms} \]
\[ F > 250 \text{ lb (f)} \quad t > 45 \text{ ms} \]

Neck injuries can also occur due to excessive moments. A limiting value of 504 in-lb and 1,680 in-lb was set for moments in extension and flexion respectively (the SI equivalent of 1 lb-f is 4.484 N and in 1 in-lbf is 0.1130 N-m).

1.9.3 Thoracic Trauma Index (TTI)

Thorax consists of vital organs like the heart, and lungs that are vulnerable to rapid changes in the acceleration pulse. It has been seen for the cadaver tests that peak lateral
acceleration on the struck side of the rib and lower thoracic spine greatly influences the injury to the thorax [9]. The TTI for the side impact has been defined as

$$TTI (d) = 0.5 \times (RIBg + T12g)$$

Whereas,

RIBg = peak acceleration of the 4th and the 8th rib

T12 g = peak absolute value of the 12th thoracic vertebrae in lateral direction (G)

TTI (d) = thoracic trauma index for the side impact dummy

1.9.4 Viscous Injury Response Criteria (VC)

Vital organs of the chest, heart, and blood vessels are built of soft tissues. Therefore, an understanding of the mechanism of soft tissue is critical for safety of the occupant. Experiments show that soft tissue injury is induced by rate sensitive deformation of the chest. In a few cases, pulmonary and cardiac injuries occurred during high-impact velocities with very little chest deflection. This is also supported by injuries caused by impacts that are fatal [8].

The viscous criterion (VC) is the maximum value of a time function and calculated by the product of the velocity of deformation (V) and the instantaneous compression function (C). It is represented by

$$V \times C = \max \left[ \frac{dD(t)}{dt} \times \frac{D(t)}{T_0} \right]$$

Whereas,

D(t) = deflection of the chest

T0 = initial torso thickness
A value of 1.5 m/s was used as a reference value for the human tolerance for the chest and a value of 2 m/s for the abdomen of side impact dummy in a lateral collision.

1.10 Child Versus Adult

Restraint of infants and children traveling in an airplane is of interest because of the large number of deaths and injuries sustained by young occupants, and because there are special considerations in protecting children in crashes. The standard safety devices used in any airplane, like the lap/shoulder belts, are designed to protect an average adult occupant. The belt routing over the occupant body decides the kinematics of the occupant. Restraining forces exerted by the belt on the occupant also are applied to specific regions on the body depending on the belt path.

Tolerance limits of the human body to resist these forces are different for different body parts and change with age. Belt forces generated in the event of a crash, if inappropriately applied on an occupant’s body, may result in fatal injuries.

1.11 Child Physiology and Injury Mechanisms

The child anatomy itself is unlike that of an adult. The properties of human tissues also diverge with age. Therefore injury mechanisms and tolerance limits for children are very dissimilar than those in adults [10].

1.11.1 Head

The relative size and mass of the head with respect to the body changes with age. An infant’s head contributes 30 percent of body weight whereas an adults head contributes 7 percent. The head shape, structure and, strength of the skull of children are also different from adults. The head shape is also different as compared to that of adults. Figure 2.1 shows the developmental stages of the head with age [10].
1.11.2 Neck Vertebrae

A newborn baby has neck vertebrae consisting of three different bones joined by cartilage. These bones grow up simultaneously up to the age of three, but they are not fully joined until the age of six. They are fully developed by 25 years of age.

1.11.3 Spinal Cord

A child’s vertebrae are more flexible and it can displace more without fracture, and allow the spinal cord to stretch. This can lead to spinal cord fractures even though the vertebrae are intact. This kind of spinal cord stretch injury is specifically found in children. Another difference between children and adults is the position at which the most cervical spine fracture occurs. Most fractures in children occur at C1 or C2. This is because the natural pivot point for the neck in children is different from that of adults. This point is normally at C2 or C3 in children whereas near C6 for adults.

1.11.4 Center of Gravity

Since a child’s body structure is different from that of an adult, the center of gravity is higher. This also changes the interaction of the body with the restraint systems. The child is more likely to bend over a lap belt or around a shoulder belt during a crash.
1.11.5 Iliac Crests

The iliac crest of the pelvis helps in positioning the lap belt over the occupant. The iliac crest, however, does not develop until the age of 10. This makes it difficult to properly position the lap belt.

1.11.6 Strength and Structure

A child’s ribs generally are more flexible than those of adults, thus having two effects: a lower probability of rib fracture, but a higher probability of thoracic organ damage from compression. A child’s abdomen protrudes more than an adult’s, and the liver and spleen are not as protected by the rib cage as they are in case of adults. Therefore children are more likely to suffer higher chances of multiple organ injury because kinetic energy is dissipated into a smaller mass.

1.11.7 Biomechanical Properties and Age

The mechanical properties of biological tissue such as modulus of elasticity, ultimate strength, and percentage of elongation change with age. These properties lead to changes in impact responses and the injury mechanism. These properties also play an important role in deciding the tolerance levels against sustaining injuries.

These differences in anatomy result in deviations in the kinematics and the injury mechanisms in children in case of a crash scenario:

1. Children have a disproportionately large head size, high center of gravity, poor head support, and soft bone structure of the skull that are less protective of the intracranial contents.
2. The abdominal organs – liver, spleen and kidneys - are less protected by the rib cage, and the bladder is less protected by the bony pelvis, thereby making these organs susceptible to injury in crash.

3. The ratio of sitting height to total height decreases with growth. The curvature of the vertebral spine and the tilt of the pelvis result in children not sitting upright, so adult seat belts that are designed for upright posture do not fit well.

![Figure 1.14. Child posture in adult seat [10].](image)

4. Behavioral characteristics of the child, such as inability to sit still and perfectly erect for a sustained period of time, often results in a child maneuvering out of the system or altering the fit.

5. Adult seat belts tend to ride up over the abdomen of a child and place the load directly on the abdomen.

6. The child is at a risk for flexing over the belt in a crash and for the pelvis to submarine under the belt.

7. The seat belt syndrome, a spinal cord fracture associated with an internal abdominal injury, is related to compression of internal abdominal organs and hyperflexion of the spine over the belt system.

8. Cervical seat belt syndrome fractures or fractures of the proximal cervical spine with or without head injuries may result from hyperflexion of the neck over the secured torso.
9. The buckle of the lap/shoulder belt may sit high against the child’s abdomen and slide up during a collision, thereby increasing the chances of submarining under the belt.

10. The shoulder portion of the seat belt does not sit on the child’s shoulder; rather often lies against the child’s neck, and frequently is placed behind the child or under the arm, disrupting the optimal function of the integral restraint system. The shoulder belt routing differences with and without a booster seat are shown in Figure 1.15.

Figure 1.15. Shoulder belt positioning over a child dummy [10].

Thus, child restraint systems must be designed to distribute forces over a large portion of the body, protect those organs not well protected by the bony skeleton, and account for both the sitting posture of the child and the inability of the iliac crest to serve as anchor points for the belt system. The design also should help to avoid ejection of the child from the seat and protect the child from the interior.
CHAPTER 2
TESTING PROCEDURES AND STANDARDS

This chapter discusses about the available standards for child restraint systems. There are several standards available all over the world, but only North American and European standards are discussed here since most of the research on child safety is being done on these two continents. The standards discussed here are North American standard FMVSS 213 for child restraints used in automobiles and airplanes, North American standard FMVSS 225 for strength requirement for anchorages, and the European standard ECE R 44 for child restraint systems use in automobiles. All three standards are summarized below.

2.1 FMVSS Standard 213

This standard specifies requirements for child restraint systems used in motor vehicles and aircraft. The purpose of this standard is to reduce the number of children killed or injured in motor vehicle crashes and in aircraft. It applies to passenger cars, multipurpose passenger vehicles, trucks and buses [4].

2.1.1 Terms and Definitions

FMVSS standards specifies some technical terms and their definitions, as follows:

1. Add-on child restraint system - any portable child restraint system.

2. Backless child restraint system - child restraint system, other than belt-positioning seat, that consists of a seating platform that does not extend to support the child’s back or head and has a structural element designed to restrain the forward motion of the child’s torso on impact.
3. Belt positioning seat - Child restraint system that positions a child on a vehicle seat to improve the fit of vehicle TYPE II belt systems and lacks any structural component to restrict the forward motion of the child’s torso in a forward impact.

4. Booster seat - either a backless child restraint system or belt positioning seat.

5. Built in child restraint system - a child restraint system that is designed to be an integral part and permanently installed in a motor vehicle.

6. Car bed - a restraint system designed to restrain or position a child on a continuous flat surface.

7. Child restraint system - Any device except TYPE I or TYPE II seat belts designed for use in a motor vehicle or aircraft to restrain, seat or position children who weigh 50 pounds or less.

8. Contactable surface - any child restraint system surface (except the belt hardware) that may contact any part of the head or torso of the appropriate test dummy specified in section 7 when the system is tested in accordance with section 6.1 of FMVSS standard 213.

9. Harness - combination of a pelvic and upper torso child restraint system that consists primarily of flexible material and does not include a rigid seating structure for the child.

10. Rear-facing child restraint system - child restraint system, except a car bed that positions a child to face in the direction opposite to the normal direction of travel of the motor vehicle.

11. Child restraint anchorage system - a vehicle system that is designed for attaching the child restraint system to a vehicle at a particular designated seating position.
12. Torso - the portion of the body of a seated anthropomorphic test dummy, excluding the thighs that lie between the top of the child restraint system seating surface and the top of the shoulders of the test dummy.

13. Specific vehicle shell - means the actual vehicle model part into which the built-in child restraint system is or intended to be fabricated, including the complete surroundings of the built-in child restraint system.

14. Factory-installed child restraint system – built-in child restraint system that has been or will be installed permanently in a motor vehicle before that vehicle is certified as a completed or altered vehicle in accordance with part 567.

2.1.2 Test Devices

1. Add-on restraint system - The test device for add-on restraint systems is a standard seat assembly consisting of a simulated vehicle bench seat with three seating positions which are described in drawing package SAS-100-1000 with addendum A. The assembly is mounted on a dynamic test platform so the SORL is parallel to the direction of the movement of the platform, and the movement between the base and the platform is avoided.

2. Built-in child restraint system - the specific vehicle shell or the specific vehicle is used for testing the built-in child restraint systems.

2.1.3 Dynamic Test Conditions

The tests are frontal barrier impact simulations of the test platform or frontal barrier crashes of the specific vehicles as specified in S5.1 of section 571.208 for the following two test configurations I and II.
a) Test Configuration I

This test is set at a velocity change of 48 km/h (30 miles/h) with the acceleration of the test platform entirely within the curve shown in Figure 2.1 (for child restraints manufactured before August 1, 2005) or in Figure 2.2 (for child restraints manufactured after August 1, 2005) for the specific vehicle test with the deceleration produced in a 48 km/h (30 miles/h) frontal barrier crash.

![Acceleration Function for 30mph](image1)

**Figure 2.1.** Acceleration function for test configuration I.

![Upper and Lower Bound for Acceleration Function](image2)

**Figure 2.2.** Acceleration function for test configuration I (upper and lower bounds).
b) Test Configuration II

This test is set at a velocity change of 32 km/h (20 miles/h) with the acceleration of the test platform entirely within the curve shown in Figure 2.3, or for the specific vehicle test, with the deceleration produced in a 32 km/h (20 miles/h) frontal barrier crash.

![Acceleration Function for 20mpg](image)

Figure 2.3, Acceleration function for test configuration II.

### 2.1.4 Dynamic Test Procedure

a) Test Configuration I

- Child restraint other than belt-positioning seats- attach the child restraint system in the center seating position in accordance with the manufacturer’s instructions and as specified in this standard.

- Belt-positioning seats – a belt positioning seat attached to the outboard seating position of the standard seat assembly in accordance with the manufacturer’s instructions provided with the system using only the standard vehicle lap and shoulder belt and no tether (or any other supplementary device).
• For each built-in child restraint system, activate the restraint system in the specific vehicle, in accordance with the manufacturer’s instructions.

b) Test Configuration II

• In the case of each child restraint system that is equipped with a fixed or movable surface, or a backless child restraint system at the center seating position of the 26 standard seat assembly use only the standard seat lap belt to secure the system to the standard seat.

• In the case of each built-in child restraint system that is equipped with a fixed or movable surface, or a built-in booster seat with a top anchorage strap, activate the system in the specific vehicle shell or the specific vehicle in accordance with the manufacturer’s instructions.

  • Select dummy according to standards specified in section 7 of FMVSS 213. The dummy is assembled, clothed and prepared as specified in S7 and S9 and part 572.

  • Place the dummy in the child restraint, and attach the child restraint belts as specified.

c) Inversion Test for Use of Child Restraint

• Position and adjust a standard seat assembly consisting of a representative aircraft passenger seat so that its horizontal and vertical orientations and its seat back angle are the same as shown in Figure 2.4 a simulated aircraft seat.
• Attach the child restraint system to the representative aircraft passenger seat using, at
the manufacturer’s option, any Federal Aviation Administration - approved aircraft
safety belt, according to the restraint manufacturer’s instructions for attaching the
restraint to an aircraft seat. Do not attach supplementary anchorage belts or tether
straps; however, use FAA - approved safety belt extensions.

• Rotate a combination of representative aircraft passenger seat, child restraint, and test
dummy forward around a horizontal axis that is contained in the median transverse
vertical plane of the seating surface portion of the aircraft seat located 25 mm below
the bottom of the seat frame, at a speed of 35 to 45 degrees per second, to an angle of
180 degrees. Stop rotation when it reaches that angle, and hold the seat in this
position for three seconds. Do not allow the child restraint to fall out of the aircraft
safety belt or the test dummy fall out of the child restraint at any time during the
rotation or the three-second period. Attain the specified rate of rotation in not less
than one half second and not more than one second, and bring the rotating
combination to a stop in not less than one half second and not more than one second.

• Rotate a combination of the representative aircraft passenger seat, child restraint, and
test dummy sideways around a horizontal axis that is contained in the median
longitudinal vertical plane of the seating surface portion of the aircraft seat and is
located 25 mm below the bottom of the seat frame, at a speed of 35 to 45 degrees per
second, to an angle of 180 degrees. Stop the rotation when it reaches that angle, and
hold the seat in this position for three seconds. Do not allow the child restraint to fall
out of the aircraft safety belt or the test dummy fall out of the child restraint at any
time during the rotation or the three-second period. Attain the specified rate of
rotation in not less than one half second and not more than one second, and bring the rotating combination to a stop in not less than one half second and not more than one second.

2.1.5 Simulated Aircraft Passenger Seat

A simulated aircraft seat is shown in Figure 2.4 and constructed as follows:

- A two to three inch thick polyurethane foam pad, with density of 1.5 to 2.0 pounds per cubic feet, over a 0.020-inch-thick aluminum pad covered by 12 to 14 ounces of marine canvas.

- The aluminum sheet pan is 20 inches wide and supported by rigid structures on each side.

- The seat back is a rectangular frame covered with an aluminum sheet weighing between 14 and 15 pounds with centre of mass 13 to 16 inches above the seat pivot axis.

- The mass moment of inertia of the seat back is 195 to 220 ounce-inch – second² about the seat pivot axis.

- The passenger safety belt anchor points are spaced 21 to 22 inches apart and located in line with the seat pivot axis.
2.1.6 Injury Criteria and Occupant Excursion Limits

- HIC36 (Head Injury Criteria) should be less than 1,000.

- Resultant chest acceleration limit is 60 g’s, regardless of whether the child restraints are equipped with a top tether.

- The head excursion limit is 720 mm (28.34 inches) maximum, or 813 mm (32 inches) without a tether.

- The knee excursion limit is 915 mm (36 inches) maximum.

- The seat back angle shall not exceed 70 degrees.
2.2  FMVSS Standard 225

This standard specifies requirements for child restraint anchorage systems to ensure their proper location and strength for effective securing of child restraints, to reduce the likelihood of the anchorage systems failure, and to increase the likelihood that child restraints are properly secured and thus fully achieve their effectiveness in motor vehicles. This standard applies to passenger vehicles and trucks with a gross weight rating (GWVR) of 8,500 pounds or less and to busses with a GWVR of 10,000 pounds or less [5].

2.2.1  Terms and Definitions

- **Child restraint anchorage** – any vehicle component other that Type I or Type II seat belts that is involved in transferring loads generated by a child restraint system to the vehicle structure.

- **Child restraint anchorage system** – a vehicle system that is designed for attaching a child restraint system to a vehicle at a particular designated seating position consisting of two lower anchorages and a tether anchorage.

- **Child restraint fixture** – the fixture that simulates the dimensions of a child restraint system, and that is used to determine the space required by the child restraint system and the location and accessibility of the lower anchorage.

- **Seat bight** – the area close to and including the intersection of the surfaces of the vehicle seat cushion and seat back.

2.2.2  Lower Anchorage Specifications

- Two bars of diameter 6mm (0.23 inches).
• The bars should be straight, horizontal, and transverse, and the axes collinear.

• The bars should be not less than 25mm (0.98 inches) and not more than 60mm (2.36 inches) in length.

• The centre distance between the two bars should be 280mm (11.08 inches).

• The bars should be permanent and an integral part of the vehicle.

• The bars shall not deform more than 5mm (0.2 inches) under the application of load of 100N in any direction.

2.2.3 Lower Anchorage Location

Figure 2.5 shows the location of lower anchors and the specifications are as follows:

• Not more than 70mm (2.75 inches) behind point Z.

• Not less than 120mm (4.72 inches) behind the vehicle seating reference point measured along the vertical-longitudinal plane.

![Figure 2.5 Lower Anchorage Location](image)

2.2.4 Strength Requirements of Lower Anchorages

When tested in accordance with test requirements for lower anchorages, do not allow point X on SFAD 2 to be displaced more than 125 mm (5 inches) when the following occur:
• A force of 11,000 N (2,472 lbf) is applied in a forward direction in the vertical longitudinal plane parallel to the vertical longitudinal centerline.

• A force of 5,000 N (1,124 lbf) is applied in lateral direction 75±5 degrees to either side of the vertical longitudinal plane parallel to the vertical longitudinal centerline.

2.2.5 Test Requirements for Lower Anchorages

The vehicle shall meet the strength requirements with following test requirements

• Vehicle seat position should be at their full rearward and full downward position and seat back in its upright position.

• Place SFAD 2 in the vehicle seating position, and attach the lower anchorages of the CRS with a no-tether anchorage and do the test with two types of loading directions

(a) Forward force direction: Apply a preload force of 500 N (112 lbf) at point X. Increase the force to 11,000 N (2472 lbf) within 30 seconds, with an onset rate not exceeding 135,000 N (30350 lbf) per second, and maintain the 11,000 N (2472 lbf) load for 10 seconds.

(d) Lateral force direction: Apply a preload force of 500 N (112 lbf) at point X. Increase the force to 5,000 N (1124 lbf) within 30 seconds, with an onset rate not exceeding 135,000 N (30350 lbf) per second, and maintain the 5,000 N (1124 lbf) load for 10 seconds.
2.3 **ECE Regulation 44**

2.3.1 **Child Restraints for Five Mass Groups**

- Group 0 for children of mass less than 10kg (22 lb) [6].

- Group 0+ for children of mass less than 13kg (28 lb).

- Group I for children of mass from 9kg (20 lb) to 18kg (40 lb).

- Group II for children of mass from 15kg (33 lb) to 25kg (55 lb).

- Group III for children of mass from 22kg (48.5 lb) to 36kg (79 lb).
2.3.2 Dynamic Test Requirements

2.3.2.1 Chest acceleration 3ms

- The chest acceleration shall not exceed 55g except during periods whose sum does not exceed 3 ms.
- The vertical component of the acceleration from the abdomen towards the head shall not exceed 30g except during period whose sum does not exceed 3 ms.
- The above limits do not apply for newborn manikin.

2.3.2.2 Manikin Displacement

1. Forward-Facing Child Restraints

   The head of the manikin shall not pass beyond planes BA and DA as shown in Figure 2.7.

![Figure 2.7. Arrangement for testing forward-facing device.](image)

2. Rear-Facing Child Restraints

   a) CRS supported by dashboard

   The head of the manikin shall not pass beyond the planes AD, DCr, as shown in Figure 2.8.
b) CRS in Group 0 not supported by dashboard, carrycots

The head of the manikin shall not pass the planes AB, AD, and DE, as shown in Figure 2.9.

Figure 2.9. Arrangement for testing child restraint devices in group 0, not supported by the dashboard.
c) CRS other than group 0 not supported by the dashboard.

The head of the manikin shall not pass the planes FD, FG, and DE, as shown in Figure 2.10. In the case involving contact of such a child restraint with the 100 mm diameter bar and all performance criteria are met, there shall be one further dynamic test (front impact) with the heaviest dummy intended for such a child restraint and without the 100 mm diameter bar. The requirements for this test are that all criteria other than forward displacement, shall be met.

Figure 2.10 Arrangement for testing rearward-facing devices, except group 0, not supported by the dashboard

2.3.3 Conditions for Dynamic Test

Dynamic tests are for both frontal and rear impact conditions. These apply to a trolley with a test seat, rearward facing front and rear seats, a vehicle body on a trolley and a whole vehicle barrier test. These conditions are summarized in Table 2.1.
TABLE 2.1
DYNAMIC TEST CONDITIONS

<table>
<thead>
<tr>
<th>Test</th>
<th>Restraint</th>
<th>Frontal Impact</th>
<th>Rear Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed (km/h)</td>
<td>Test Pulse</td>
<td>Stopping Distance During Test (mm)</td>
</tr>
<tr>
<td>Trolley with test seat</td>
<td>50+0 -2</td>
<td>1</td>
<td>650±50</td>
</tr>
<tr>
<td>Rearward facing front and rear facing seats</td>
<td>50+0 -2</td>
<td>1</td>
<td>650±50</td>
</tr>
<tr>
<td>Vehicle body on trolley</td>
<td>50+0 -2</td>
<td>1</td>
<td>650±50</td>
</tr>
<tr>
<td>Whole vehicle barrier test</td>
<td>50+0 -2</td>
<td>1</td>
<td>Not specified</td>
</tr>
</tbody>
</table>

NOTE: All restraint systems for Groups 0 and 0+ shall be tested according to rearward facing conditions in frontal and rearward impacts.

Test Pulse 1

![Deceleration Function for Front Impact](image)

Figure 2.11. Deceleration function for front impact.
Test Pulse 2

![Deceleration Function for Rear Impact](image)

Figure 2.12. Deceleration function for rear impact.

2.4 Overview of Emergency Landing Dynamic Conditions

The following sections describe two different dynamic test conditions per FAA regulations part 23 and part 25.

2.4.1 Section 23.562

1. For the first test, the change in velocity may not be less than 31 feet per second. The seat/restraint system must be oriented in its nominal position with respect to the airplane and with the horizontal plane of the airplane pitched up 60 degrees, with no yaw, relative to the impact vector. For seat/restraint systems to be installed in the first row of the airplane, peak deceleration must occur in not more than 0.05 second after impact and must reach a minimum of 19g. For all other seat/restraint systems, peak deceleration must occur in not more than 0.06 second after impact and must reach a minimum of 15g.

2. For the second test, the change in velocity may not be less than 42 feet per second. The seat/restraint system must be oriented in its nominal position with respect to the airplane and with the vertical plane of the airplane yawed 10 degrees, with no pitch, relative to the impact vector in a direction that results in the greatest load on the shoulder harness. For seat/restraint systems to be installed in the first row of the airplane, peak deceleration
must occur in not more than 0.05 second after impact and must reach a minimum of 26g. For all other seat/restraint systems, peak deceleration must occur in not more than 0.06 second after impact and must reach a minimum of 21g.

2.4.2 Section 25.562

1. For the first test, the change in downward vertical velocity may not be less than 35 feet per second, with the airplane’s longitudinal axis canted downward 30 degrees with respect to the horizontal plane and with the wings level. Peak floor deceleration must occur in not more than 0.08 second after impact and must reach a minimum of 14g.

2. For the second test, the change in forward longitudinal velocity may not be less than 44 feet per second, with the airplane’s longitudinal axis horizontal and yawed 10 degrees either right or left, whichever could cause the greatest likelihood of the upper torso restraint system (where installed) moving off the occupant’s shoulder, and with the wings level. Peak floor deceleration must occur in not more than 0.09 second after impact and must reach a minimum of 16g. Where floor rails or floor fittings are used to attach the seating devices the test fixture, the rails or fittings must be misaligned with respect to the adjacent set of rails or fittings by at least 10 degrees vertically (i.e., out of parallel), with one rolled 10 degrees.

2.4.3 Static Test Specifications

2.4.3.1 FAR 23.561 Emergency Landing Conditions

1. The occupant experiences static inertia loads corresponding to the following ultimate load factors:
   - Upward, 3.0g for normal, utility, and commuter category airplanes, or 4.5g for acrobatic category airplanes: 853 N (18 kg 4 YOLD + 11 kg seat) (192 lbf)
• Forward, 9.0g: 2560 N (18 kg 4 YOLD + 11 kg seat) (575 lbf)
• Sideward, 1.5g: 427 N (18 kg 4 YOLD + 11 kg seat) (96 lbf)
• Downward, 6.0g, when certification to the emergency exit provisions of Sec. 23.807(d)(4) is requested: No load requirement since child seats will not be placed at these positions.

2. The items of mass within the cabin that could injure an occupant, experience the static inertia loads corresponding to the following ultimate load factors

• Upward, 3.0g: 853 N (18 kg 4 YOLD + 11 kg seat) (192 lbf)
• Forward, 18.0g: 5115 N (18 kg 4 YOLD + 11 kg seat) (1150 lbf)
• Sideward, 4.5g: 1278 N (18 kg 4 YOLD + 11 kg seat) (287 lbf)

2.4.3.2 FAR 23.785 (a) Seats, Berths, Litters, Safety Belts, and Shoulder Harnesses

In addition, these loads must be multiplied by a factor of 1.33 in determining the strength of all fittings and the attachment of each seat to the structure and of each safety belt and shoulder harness to the seat or structure.

2.5 Differences Between Automotive and Airplane Seat Structure

FMVSS 213 test fixtures are designed to represent an automobile seat with lap belts and shoulder strap anchored geometrically at locations typical in an automobile. There are some significant differences between the FMVSS 213 test fixture and a transport airplane passenger seat. These differences can affect overall performance of child restraint seats. Some of these differences are listed below.

• The location of lap belts on a vehicle seat is different than on a typical airplane seat.

The inboard and outboard belt anchor points on an automotive seat are at different
heights. The lap belt anchor points on an airplane seat are at the same height and located near the line passing through the cushion reference point.

- The seat back of a vehicle seat does not rotate forward like an airplane passenger seat during impact. The combined effects of break over seat back and aft occupant impact forces transferred through the seat back are not evaluated in FMVSS 213.

- The tension on seat belts in an automobile is automatically adjusted by the retractor mechanism in the inertia reel. Airplane seat belts are manually adjusted, and the range of adjustment is limited.

- The buckle mechanism of an automobile seatbelt is smaller and has a push button release. Airplane buckles are as wide as the two-inch webbing of the belts and have a lift–latch type release.

- The available space for installation of a CRS on an airplane seat is restricted to 16.5 to 17.5 inches, which is the distance between two arm rests for economy class.

- The foreign standard for child restraint differs from FMVSS 213. The requirement of a top tether strap prohibits the installation of a CRS on an airplane, unless it has been approved for airplane use without the top tether.

### 2.6 Test ATDs Specifications

#### 2.6.1 CRABI 12-Month-Old Child Dummy 921022-000

The CRABI 12-month-old child dummy was developed by First Technology Safety Systems, Inc. to evaluate small-child restraint systems in automotive crash environments, in all directions of impact, with and without air bag interaction. The basic anthropometry for this important new test device was taken from the University of Michigan Transportation Research
The Society of Automotive Engineers (SAE) Infant Dummy Task Group approved weight distribution and scaling methods for the infant [8].

The 12-month-old child dummy weighs 10.0kg and has a 747mm standing or 480mm sitting height. The Hybrid III-like neck and lumbar spine are laterally notched to reduce lateral stiffness. The shoulders have ample support for durability and human-like performance in areas where seatbelt webbing may be placed. In addition, rubber elements are used in each joint to improve biofidelity and to give the CRABI infant-like range of motion.

The FTSS design meets all requirements of the SAE Infant Dummy Task Group for anthropometry, biomechanics and instrumentation. The instrumentation design incorporates six load cells to provide load measurements at the occipital condyles, cervical vertebrae-7, and lumbar vertebrae-S, shoulders, and pubic locations. Accelerometers are used to measure head, chest, and pelvic acceleration and head angular acceleration. All instrumentation is easily accessed.

Test dummy measurement capabilities include the following:

- Head Triaxial Acceleration
- Head Angular Acceleration (1 channel)
• Upper Neck Forces and Moments (8 channels)
• Lower Neck Forces and Moments (6 channels)
• Shoulder Forces (2 channels each)
• Chest Triaxial Acceleration Lumbar Spine Forces and Moments (6 channels)
• Pelvic Triaxial Acceleration Pelvic (Pubic) Forces (2 channels)

2.6.2 Hybrid III 3 Year Old Child Dummy 210-0000

The Hybrid III 3-year-old child crash test dummy was developed by First Technology Safety Systems in cooperation with the SAE Biomechanics Committees and the National Highway Transport Safety Administration. Originally developed in 1992, the dummy went through a complete upgrade in 1997 to enable it to evaluate airbag aggressiveness when a child is close to a deploying airbag. The "Out of Position" (OOP) test procedures require the dummy to accurately measure neck loading, chest compression, and the viscous criterion, while being durable and repeatable in these severe test conditions. The dummy can be positioned standing or sitting, and can evaluate the safety performance of many types of child restraint systems. The FTSS Hybrid III 3-year-old dummy is dynamically tested and passes to the latest test conditions. The anthropometry of the dummy is derived from University of Michigan Transport Research Institute (UMTRI) studies and scaled data from the current Hybrid III 50th dummy [8].

Figure 2.14. FTSS 3-year-old child dummy.
Test dummy measurement capabilities include the following:

- **Head And Neck**: Fiberglass skull and cap with vinyl skin certified to a head drop impact test. It has a tri-axial accelerometer pack for HIC calculation and one accelerometer for measurement of head rotation. The neck is a segmented, flexible, molded butyl rubber construction with a center cable to limit elongation. It is certified to biofidelic flexion and extension moment/rotation corridors. Optional upper and lower six axis neck load cells are available.

- **Upper Torso**: Ballasted steel spine box supporting three high-strength steel ribs bonded with polymer-based damping material. A urethane bib and aluminum sternum carries accelerometers for measurement of viscous criterion in frontal impact. Rib vertical motion is limited by upper and lower rib guides, and sternum bump stops limit total chest deflection. The upper torso is certified to thorax pendulum impact and lumbar flexion tests. Shoulder pivot joints and elastomeric links provide biofidelic ranges of motion, and bi-axial shoulder load cells are available.

- **Lower Torso**: Cylindrical rubber lumbar spine with cable mounts on an optional six axis lumbar load cell. The pelvic bone is a welded-aluminum construction with optional biaxial load cells on each ilium at the ASIS, a biaxial pubic load cell, and left and right acetabulum uniaxial load cells. A triaxial accelerometer pack mounts in the rear of the pelvis. Limbs are urethane and Ensolite™ foam molded over a welded-steel skeleton.

### 2.6.3 Hybrid III 6 Year Old Child Dummy 127-0000

The Hybrid III 6-year-old child crash test dummy from First Technology Safety Systems was developed in cooperation with the SAE Biomechanics Committees and NHTSA. Originally
designed in 1993, the dummy went through a complete upgrade in 1997 to enable it to evaluate airbag aggressiveness when a child is close to a deploying airbag. The "Out of Position" (OOP) test procedures require a dummy to accurately measure neck loading, chest compression, and viscous criterion while being durable and repeatable in these severe test conditions. The FTSS Hybrid III 6-year-old dummy is dynamically tested and proven to withstand the latest frontal crash environments. The anthropometry of the dummy is derived from NHTSA research studies, and the biomechanical corridors are derived from scaling of adult dummies [7].

Test dummy measurement capabilities include the following:

- **Head and Neck:** The skull is a two-piece aluminum casting with a removable vinyl skin certified to a head drop impact test. It has a tri-axial accelerometer pack for calculation of HIC. The neck is a flexible, molded butyl rubber construction with a center cable to limit elongation. Nodding blocks are located at the occipital condyle pivot. It is certified to biofidelic flexion and extension moment/rotation corridors. Optional six-axis upper and lower neck load cells are available.

- **Upper Torso:** Ballasted steel spine box supporting six high-strength steel ribs bonded to polymer based damping material. A urethane bib and aluminum/nylon sternum
carries accelerometers for measurement of viscous criterion in OOP airbag testing. Rib vertical motion is controlled by upper and lower rib guides, and sternum bump stops limit total chest deflection. The upper torso is certified to thorax pendulum impact and lumbar flexion tests. A two-piece aluminum clavicle and clavicle link assemblies have cast integral scapulae to interface with shoulder belts. Limbs are vinyl skin over urethane foam over a welded-steel skeleton.

- Lower Torso: Cylindrical rubber lumbar spine with center cable mounts on an optional six-axis lumbar load cell. The pelvis assembly is vinyl skin over urethane foam construction, molded in the seated position. The pelvic bone is a welded-aluminum construction with optional biaxial load cells on each ilium. A tri-axial accelerometer pack mounts in the rear of the pelvis. An abdominal insert controls lumbar flexion. Legs are vinyl skin over urethane foam molded over a welded-steel skeleton.

All instrumentation is optional except for the chest deflection potentiometer. The standard dummy is delivered with structural replacements for the load cells.
CHAPTER 3
COMPUTATIONAL TOOLS

3.1 MADYMO Occupant Simulation Tool

MADYMO (MAtematical DYnamical MOdels) is a general-purpose software package, which is used to simulate the dynamic behavior of mechanical systems. Although initially developed to study passive safety, MADYMO is now progressively more used for vigorous safety and wide-ranging biomechanics studies. MADYMO combines in one simulation program the capabilities offered by a multi-body.

![Diagram of MADYMO 3D structures]

The multi-body algorithm in MADYMO yields second-time derivatives of the degrees of freedom in explicit form. A number of different kinematic joint types are available with dynamic restraints to account for joint stiffness, damping, and friction. Joints can be (un)locked or removed based on a user-defined criterion.

The finite element module is also available in MADYMO. The finite element method divides the actual continuum into finite volumes, surfaces, or line segments. The continuum is
then analyzed as a complex system, composed of quite simple elements where continuity should be ensured along the interface between elements. These elements are connected at a discrete number of points, or nodes. The initial nodal positions and velocities, the nodes corresponding to each element, the connectivity, as well as the element properties, e.g., the material behavior, must be specified at the start of the simulation. A variety of material models is available for metals, fabrics, foams, composites, rubbers, and honeycomb.

The way the interaction between bodies and finite elements is modeled allows the use of different time-integration methods for the equations of motion of the finite element part and the multi-body part. All integration methods used are conditionally stable and therefore put limitations on the time-step that can be used. To increase the efficiency of the entire analysis, the finite element module is being sub-cycled with respect to the multi-body module using a different constant time-step for each module.

To create a MADYMO input data file, the user first selects the number of multi-body systems and finite element structures to be included in the simulation model. For instance, a simulation model can consist of one multi-body system for a dummy, one for a deformable steering column, and one for a child restraint system, and finite element structures for the driver-passenger side airbag and the knee-bolster. For crash dummies, standard databases are available. Next, for each multi-body system, the number of bodies and their configurations and for each structure, the finite element mesh, the element types, and the material properties must be specified.

An input data file is then set up to specify the configuration, the mass distribution, and the general properties of the multi-body systems (joint characteristics) and the finite element structures.
The acceleration field model calculates the forces at the centers of gravity of bodies or finite elements due to a homogeneous acceleration field. This model is particularly useful for the simulation of acceleration forces on a vehicle occupant during impact. It is not necessary to apply an acceleration field to all bodies. Three types of mass less spring-damper elements are available. The Kelvin element is a uniaxial element, which simulates a spring parallel with a damper. The Maxwell element is a uniaxial element, which simulates a spring and damper in series. Non-linear spring characteristics as well as velocity dependent damping can be defined. The point-restraint can be considered a combination of three spring-damper elements, each parallel to one of the axes of an orthogonal coordinate system.

Planes, ellipsoids, cylinders, and facet surfaces can be attached to a body to represent its shape. These surfaces are also used to model contact with other bodies or with finite elements. The contact surfaces are of major importance in the description of the interaction of the occupant with the interior. The elastic contact forces, including hysteresis, are a function of the penetration of the contact surfaces. In addition to elastic contact forces, damping and friction can be specified.

The belt model accounts for initial belt slack or pre-tension and rupture of belt segments. Elastic characteristics can be specified separately for each belt segment, and slip of belt material from one segment to another is taken into consideration. A special belt segment is available for fuse belts. Slip rings, retractors, and pretensioners with webbing grabber can be applied.

The final section of the input file deals with the output required from the simulation. The output generated by MADYMO is specified through a set of output control parameters. A large number of standard output parameters are available, such as accelerations, forces, torques, and kinematic data. In addition to standard output quantities, MADYMO offers the possibility to
calculate injury parameters like femur and tibia loads, Head Injury Criterion (HIC), Gadd Severity Index (GSI), Thoracic Trauma Index (TTI) and Viscous Injury Response (VC). Special output can be obtained through user-defined output routines. Results of the simulation are stored in a number of output files, which are accessible by post-processing programs.

Once a given crash situation has been modeled with the MADYMO package, it is relatively straightforward for users to determine how the scale of potential injuries can be reduced by introducing special safety features or by changing certain design parameters. This makes the MADYMO package an extremely useful tool for enhancing vehicle safety.

3.2 Systems in MADYMO

3.2.1 Reference / Inertial Space

A coordinate system (X, Y, Z) is connected to the reference space, as shown in Figure 3.2. The origin and orientation of this reference space coordinate system can be selected arbitrarily. Usually the positive Z-axis is chosen pointing upwards, opposite to the direction of gravity. The motion of all systems is described relative to this coordinate system. Contact surfaces such as planes and ellipsoids, restraint systems, spring-damper elements as well as nodes of finite element structures in MADYMO can be attached to the reference space.

Figure 3.2. Reference space.
3.2.2 Multi-body Systems

A multi-body system is a system of bodies. A kinematic joint can interconnect any pair of bodies of the same system; however kinematic joints cannot connect bodies of different systems. The MADYMO multi-body formalism for generating the equations of motion is suited for multiple systems of bodies with a tree structure, as shown in Figure 4.4 and systems with closed chains. Systems with closed chains must be reduced to systems with a tree structure by removing every chain in a kinematic joint. Removed joints are subsequently taken into account by a closing joint. For each (reduced) system, one body can be connected to the inertial space by a kinematic joint, or the motion relative to the inertial space of one body can be prescribed as a function of time.

![Diagram of multi-body systems with tree structure](image)

Figure 3.3. Examples of single and multi-body systems with tree structure.

A kinematic joint restricts the relative motion of the two bodies it connects. In MADYMO, twelve types of joints are available such as spherical joints, translational joints, revolute joints, cylindrical joints, planar joints and universal joints. Figure 3.4 shows the different types of joints. The way a specific type of kinematic joint constrains the relative motion of two bodies is characteristic for that type of joint. The relative motion allowed by a joint is
described by quantities called joint degrees of freedom. Their number depends on the type of joint.

![Different types of joints.](image)

Kinematic joints interconnect the bodies in a system, the type of kinematic joints, the geometry (i.e., locations of the centers of gravity of the bodies and the kinematic joints), the mass distribution of bodies, and initial conditions. In addition, the shape of bodies may be needed for contact calculations or post-processing purposes.

Applied loads on bodies can be modeled with the force models described in subsequent chapters.

A kinematic joint can connect a pair of bodies. A kinematic joint constrains the relative motion of this pair of bodies, e.g., a translational joint allows only relative translation. A kinematic joint is referred to by the number of the child body of the two bodies connected by the joint. The constraints imposed by a kinematic joint cause a load on the pair of interconnected
bodies, or the constraint load. Due to this load the relative motion of the pair of bodies is restricted to a motion that does not violate the constraints imposed by the kinematic joint. The constraint loads on the separate bodies are equal but opposite. Figure 4.6 shows the constraint load in a spherical joint. Constraint loads can be used to assess the strength of the joint.

Figure 3.5. Constraint load in a spherical joint.

3.3 Numerical Integration Methods in MADYMO

The equations of motions are solved numerically. In MADYMO, three methods are available:

- Modified Euler method with a fixed time step.
- Runge-Kutta method with fixed time step.
- Runge-Kutta Merson method with variable time step.

These one-step explicit methods mean that the solution at a time point $t_n+1$ can be written explicitly in terms of the solution at the preceding time point $t_n$. The Runge-Kutta Merson method cannot be used for applications with finite element models because they do not allow the repeated time integration over the same time interval, which occurs when the step size is reduced. For a given time-step, the modified Euler method is less accurate than the Runge-Kutta method. In order to obtain the same accuracy, the time-step in the modified Euler method should be $1/8$ of the Runge-Kutta method and $1/16$ of the Runge-Kutta Merson method. When stability
determines the step size, the modified Euler method is more stable than the Runge-Kutta method. When the finite element model is supported on a rigid body, the Runge-Kutta method may become unstable.

### 3.4 Finite Element Modeling in MADYMO

MADYMO features full Finite element (FE) capabilities for structural impact analysis. In the FE module, truss, beam, membrane, shell, and brick elements are implemented. Several material models such as elastic, elasto-plastic, Mooney-Rivlin, and hysteresis can be used. Several finite element models can be used within one simulation. A MADYMO model can consist of only a multi-body system, only finite element models, or both.

The interaction between the multi-body model and the finite element model is shown in figure 3.6. Two kinds of interactions, supports and contacts, generate forces between finite element models and multi-body systems.

![Figure 3.6 Interaction between Multi-body and Finite Element Models](image)

For a MADYMO analysis with a finite element model, the fourth-order Runge-Kutta or Euler method must be used for the time integration of the equations of motion of the multi-body module. The central difference method is used for the time integration of the equations of motion of the finite element models. Actual positions and velocities at each time step of the central difference method determine the support and contact forces. The forces acting on the multi-body system are accounted for in each main time point of the fourth-order Runge-Kutta and each time-step of the Euler method.
A smaller time-step is needed for the finite element models compared to the multi-body models. To increase the cycle efficiency of the entire analysis, the FE analysis is sub-cycled with respect to the multi-body analysis using a different constant time step for each finite element model. If contacts between different finite element models are specified, the time step is identical for all the finite element models that are in contact. MADYMO automatically selects the smallest time step used in any of the FE models defined.

### 3.5 Acceleration Field Model

This model calculates the forces at the centers of gravity in bodies with an uniform acceleration field \( a(t) \) as shown in Figure 3.7. The acceleration field is defined as a function of time. The components of acceleration must be expressed relative to the reference space coordinate system (X, Y, Z). An acceleration field does not need to be applied to all bodies or all systems.

![Figure 3.7. A system of bodies in uniform acceleration field.](image)

### 3.6 MADYMO Dummy Database

Biodynamic simulations are done using well-validated ATD databases. MADYMO 6.0 and above databases have three types of dummy models:
• Ellipsoid dummy models.
• Facet dummy models.
• Finite Element dummy models.

The main difference between the model types lies in the modeling techniques applied to represent the geometry and the mechanical properties of the dummy components. Ellipsoid models are the most CPU time-efficient type of models. Therefore, they are particularly suitable for concept, optimization, and extensive parameter sensitivity studies. Their time efficiency has the most benefit in a multi-body environment that is modeled similarly by ellipsoids, planes, and cylinders. Facet models are more realistic and detailed than ellipsoid models but are still very CPU time-efficient compared to FE models. They include a number of degrees of freedom that is comparable to that of the ellipsoid models. The limited increase in the CPU cost is mainly due to the additional evaluations performed in the contact algorithm. FE models incorporate a vast amount of degrees of freedom and require a small time-step. As a result, they are much less CPU time-efficient than the ellipsoid and facet models. FE models are recommended for use in the most detailed studies, where local effects of contact interactions and local material deformations are of interest.

A wide range of MADYMO ATD models are available. The standard models of the adult and child Hybrid III dummies are the 5th percentile female, the 50th percentile male, the 95th percentile male, 6-year-old child, 3-year-old child Hybrid III dummy, and CRABI 12-month-old dummy models. The size and weight of the American adult male is represented by the Hybrid III 50th percentile male ATD. In order to cover the extremes of the American adult population, two other versions of the Hybrid III have been developed, the 5th percentile small female and the 95th percentile large male.
3.7 **Injury Parameters**

The field of injury biomechanics deals with the effect of mechanical loads, in particular impact loads on the human body. Due to a mechanical load, a body region will experience mechanical or physiological changes. These changes are called biomechanical responses. An injury will occur if the biomechanical response is of such a nature that the biological system deforms beyond a recoverable limit, resulting in damage to anatomical structures and alteration in normal function. The mechanism involved is called the injury mechanism, and the severity of the resulting injury is called as the injury severity. An injury criterion is a physical parameter or a function of several physical parameters, which correlates with the injury severity of the body region under consideration. There are many proposals for ranking and quantifying injuries. Anatomical scales describe the injury in terms of its anatomical location, the type of injury, and its relative severity. The mostly accepted anatomical scale worldwide is the Abbreviated Injury Scale (AIS), which distinguishes the following levels of injury:

- 0 - No injury,
- 1 - Minor,
- 2 - Moderate
- 3 - Serious
- 4 - Severe
- 5 - Critical
- 6 - Maximum injury (cannot be survived)
- 9 - Unknown

The AIS is a so-called “threat to life” ranking. The numerical values have no significance other than to designate order. Many injury criteria’s are based on acceleration forces,
displacements, and velocities. These quantities can be obtained with the standard features offered by MADYMO. Some injury criteria need some mathematical evaluation of a time history signal. MADYMO offers the possibility to perform some of these injury parameter calculations.

Injury biomechanics deals with the effect of mechanical loads, in particular impact loads on the human body. Due to a mechanical load a body region will experience mechanical and physiological changes, the so-called biomechanical response. Injury will take place if the biomechanical response is of such a nature that the biological system deforms beyond a recoverable limit, resulting in damage to anatomical structures and alteration in normal function. The mechanism involved is called the injury mechanism, and the severity of the resulting injury is indicated by the expression “injury severity”.

An injury parameter is a physical parameter or a function of several physical parameters, which correlates well with the injury severity of the body region under consideration. Many schemes have been proposed for ranking and quantifying injuries. Anatomical scales describe the injury in terms of its anatomical location, the type of injury and its relative severity. These scales rate the injuries rather than the consequences of the injuries. The most well-known anatomical scale is the Abbreviated Injury Scale (AIS). Although originally intended for impact injuries in motor vehicle accidents, updates of the AIS now allow its application for other injuries like burns and penetrating injuries.

Most injury criteria are based on accelerations, relative velocities or displacements, or joint constraint forces. These qualities must be requested with standard output options. Most injury criteria need some mathematical evaluation of a time history signal. MADYMO performs these injury parameter calculations, the following of which are available:

Gadd Severity Index (GSI)
Head Injury Criterion (HIC)

Neck Injury Criteria (FNIC)

3 ms Criterion (3MS)

Thoracic Trauma Index (TTI)

The injury parameter calculations for HIC, GSI, and 3MS are carried out on the linear acceleration signal of a selected body. The TTI calculation is carried out on linear acceleration signals of two selected bodies. These linear acceleration signals must have been defined under the LINACC keyword.

3.8 *HyperMesh*

Altair HyperMesh is a high-performance finite element pre- and post-processor compatible with most widely used finite element solvers. HyperMesh’s user-interface is easy to learn and supports many CAD geometry and finite element model files, thus increasing interoperability and efficiency. Advanced functionality allows users to efficiently mesh highly complicated models. It allows user-defined quality criteria and controls, morphing technology to update existing meshes to new design proposals, and automatic mid-surface generation for complex designs with of varying wall thicknesses. Automated tetra-meshing and hexa-meshing minimizes meshing time, while batch meshing enables large-scale meshing of parts with no model clean up and minimal user input.

HyperMesh incorporates a variety of tools for seamless integration into any existing engineering process. It allows customizing the layout of HyperMesh's menu system through an easy-to-use interface according to the user’s convenience. Users can take advantage of the power within the Tcl/Tk toolkit to build custom applications fully integrated with HyperMesh. One can create macros that automate a process or series of steps. Export templates and input translator’s
increase flexibility, making Hypermesh compatible with many solvers. The export templates allow the HyperMesh database to be written out to formats to non-supported solvers. The input translators support the addition of the user’s own input translators for reading different analysis data decks.

HyperMesh provides direct access to a variety of industry-leading CAD data formats for generating finite element models. It also provides robust tools to clean imported geometry containing surfaces with gaps, overlaps, and misalignments, which prevents auto-meshing and high quality mesh generation. By eliminating misalignments, and holes, and suppressing the boundaries between adjacent surfaces, users can mesh across larger, more logical regions of the model while improving overall meshing speed and quality. Boundary conditions can be applied to these surfaces for future mapping to underlying element data.

HyperMesh includes a sophisticated suite of easy-to-use tools to build and edit models. For 2D and 3D model creation, users have access to a variety of mesh-generation panels in addition to HyperMesh's powerful auto-meshing module. Automatic mid-surface generation, a comprehensive laminate modeler and morpher capable of stretching existing FE meshes to new design geometries), creating surfaces from the existing mesh, offer new levels of model manipulation.

The surface auto-meshing module in HyperMesh is a robust tool for mesh generation that provides users the ability to interactively adjust a variety of mesh parameters for each surface or surface edge. These parameters include element density, element biasing, mesh algorithm and more. This gives a very high user control over the meshing process, enabling meshing of even highly complicated surfaces with desired quality.
HyperMesh supports a host of different solver formats for both import and export. Along with fully-supported solvers, HyperMesh also provides the flexibility to support additional solvers via a complete export template language and C libraries for development of input translators, such as those that follows [10]:

- OptiStruct
- ABAQUS
- NASTRAN
- ANSYS
- MOLDFLOW/C-MOLD
- LS-DYNA
- RADIOSS
- PAMCRASH
- MADYMO
- MARC

### 3.8.1 Geometry Terminology

Commonly used terminologies and features of MADYMO are explained below [10]:

- **Face**: The smallest entity created by a mathematical model.

- **Surface**: A collection of one or more adjacent faces whose common edges are suppressed. Different surfaces are related to their adjacent surfaces depending on the type of the edge shared by the two adjacent surfaces.

- **Free edge**: An edge belonging to one surface only. Free edges that appear between two adjacent surfaces indicate the existence of a gap between two surfaces.
• Shared edge: An edge is shared by two adjacent surfaces. When the edges between two adjacent surfaces are shared, they are considered to be geometrically continuous. While meshing such surfaces, the auto-mesher creates a continuous mesh without any gap along the edge, but it will not create any elements such that they cross over the shared edge.

• Suppressed edge: An edge is shared by two adjacent surfaces but completely ignored while meshing. This indicates geometric continuity between two adjacent surfaces; however while meshing, the mesh seed is not laid on this edge and the elements formed can cross over the edge. By suppressing undesirable edges, two surfaces are combined into a single large surface.

• Non-manifold edge: An edge owned by three or more surfaces. The auto-mesher always places seed nodes along the length of these edges and will produce a continuous mesh without gaps. Elements are not allowed to cross over a non-manifold edge. These edges cannot be suppressed.

• Fixed point: A point associated with a surface and a finite element node that is created at each fixed point on the surfaces being meshed. A fixed point that is placed at the junction of three or more edges (non-suppressed) is called a vertex (or vertex point). Such vertices cannot be suppressed (removed).

• Free point: A point in space not associated with a surface.
CHAPTER 4
METHODOLOGY

4.1 Need for Simulations

Laboratory sled testing has been the traditional approach for automobile and airplane safety research. However, such testing is limited to standard crash types, whereas in real life, crash types tend to be much more complex.

Simulations prove to be a useful tool in conjunction with traditional testing methods, for both industrial and research purposes. In industry, the main purpose of the simulation is to check designs for crashworthiness before they are actually tested. Thus simulations help in reducing the number of tests as well as the number of prototypes and designs to be manufactured and tested. In research they help in analyzing existing or hypothetical scenarios or designs. Therefore, simulations help in reducing the cost as well as time in the product development cycle and are also a valuable research tool.

The use of finite element models in the field of crashworthiness is a recent research area that enables advancement in transportation safety. However to obtain the maximum benefits from research in child restraint systems using various computational techniques with tools such as MADYMO, LS-DYNA requires a detailed model of a CRS. The use of a geometrically well-defined CRS in the overall simulation model provides a more realistic interaction of it with the child anthropomorphic test devices (ATD) and also gives a better and more realistic visualization and understanding. Therefore, it is important to develop such models for all categories of CRS. These well-defined models will assist safety engineers in developing mathematical models that not only enhance the understanding of the kinematics of children in a CRS but also help in designing a better CRS to increase the safety of the children in automobiles and airplanes.
4.2 CAD Geometry

CAD geometry, provided by a children’s seat manufacturer, was created in different parts of 12-month-old and 3-year-old child seats using Pro/E. Some part were created using solid modeling and some of them were only surfaces. The different parts of the model were assembled in Pro/E and then exported in Initial Graphics Exchange Specification (IGES) format.

Before transferring CAD data into the HyperMesh preprocessor, it was converted into IGES format, which was developed to address the incompatibility issue with various CAD/CAM systems. This standard allows efficient and accurate exchange of product definition data across all CAD/CAM systems. All Pro/E files of bus geometry were converted into IGES format to facilitate easy transfer of solid bus geometry data to HyperMesh.

4.3 Mesh Development

Meshing can be defined as the process of breaking up one large component into small elements in order to facilitate the carrying out of numerical solutions. Normally, surface domains are subdivided into triangle or quadrilateral shapes, and volume may be divided into tetrahedral or hexahedra shapes. HyperMesh, a high-performance FE preprocessor, was selected because of its wide range of features and tools. Shell meshing is the process of generating a 2D triangle or quadrilateral element by dividing a big surface. Full model meshing is done using shell meshing. Most of the shell elements are quadrilateral in shape because of their superior performance over triangular and tetrahedral-shaped elements when comparing an equivalent number of degrees of freedom.

Procedure used to mesh a child seat is as follows:

- IGES format geometry data was imported in to HyperMesh.
• The IGES file imported in HyperMesh consisted of several individual components having original names provided in the Pro/E file.

• The IGES geometry was imported into HyperMesh, as shown in Figure 4.1.

![Figure 4.1. Imported IGES file in HyperMesh](image)

• Using the automesh option in the 2D section, a mesh seed was created with element size of 5 mm. Element density was varied until a satisfactory mesh was obtained.

• Mesh was created from the mesh seed, and care was taken to keep the shape of all elements quadrilateral. In the case of complex surfaces, which includes curves and holes, all quadrilateral shape elements were not possible so meshing was done with both quadrilateral and triangular shaped elements. The FE mesh generated is shown in Figure 4.2.
• The equivalence of nodes, deleting duplicate elements, and checking the shell normal direction was done.

• Quality of the mesh was not checked because the meshed model used as facet model in MADYMO.

4.4 MADYMO Model Development

4.4.1 Modeling of Facet Model

For studying the kinematics of a child seat, the meshed model was imported into MADYMO. In MADYMO, the meshed model was defined as a facet model. To create facets in MADYMO, the quad and triad elements were separated in two different parts but retaining their connectivity. This was done because MADYMO defines two separate properties for quad and triad elements. A revolute joint was defined between the child seat and the rigid seat at the same location as in the sled test.

Figure 4.3 shows the facet model of a forward-facing child seat, which is used to restrain a 3-year-old child. Also, the facet model for an infant seat used to restrain 12-month-old child is shown in Figure 4.4
Figure 4.3. Forward-facing convertible child seat.

Figure 4.4. Rear-facing child seat.
4.4.2 Modeling of Rigid Seat

The seat back and seat pan of rigid seat were modeled in MADYMO using planes with same dimensions. The rigid seat pan and back were modeled in the reference space system of MADYMO, and the properties were specified by giving the suitable force deflection characteristics obtained from earlier studies and references to obtain a validated response of the setup. Figure 4.5 shows the CAD model used for the sled test and the MADYMO model of the rigid seat used for simulation.

![Rigid seat](image)

Figure 4.5. Rigid seat.

4.4.3 Dummy Selection

The MADYMO dummy database is provided with validated dummy models to represent their counterparts used in full-scale or sled testing. These dummy models, as described earlier are available as multi body, facet and human models. Six-year-old Hybrid III, three-year-old Hybrid III, and CRABI 12-month-old child dummies were selected from the MADYMO database to suitably represent the respective dummies used in the test configuration.
4.4.4 Simulation Setup

The rigid seat modeling was done as is and the anchor points were at the same locations as they are in an actual seat. The 12-month-old rear-facing baby carrier and 3-year-old forward facing convertible child seat were used for testing. Both seats were attached to the rigid seat using an ISOFIX attachment. In simulation, the ISOFIX joint is defined using element JOINT.REVO, the joint parent body is a rigid seat, and the child body is the child seat. For all three simulations, an FE belt system was used since it gives better representation of the actual belt. Respective child dummies were then positioned on the child seat according to the sled test setup. The child seats were then restrained along with the child dummy to the sled bench. Figure 4.6 shows the tests and simulation setup for all three models.

Figure 4.6 Test Setup
4.4.5 Property Selection for MADYMO

The main influential factors for simulation are the contacts between the sled and child seat, child seat and dummy, and dummy and seat belt. The contacts in MADYMO are calculated according to the user input force deflection characteristics. The two governing factors in the calculations are the contact characteristics and the friction coefficients. Since these properties were not available, the standard set of values was used to obtain the best validation.

4.4.6 Contact Properties for Facet Model

Facet surfaces normally represent the outer surfaces of thick or solid structures. In actual cases where the structures have a compliant surface, this compliance is modeled by one or more contact characteristics defined for a facet surface. Facet surface contact characteristics are best defined by using the contact model stress so that the contact surface is taken into account for contact force calculations. It also provides the independence to give variable contact characteristics according to the structure by varying the element thickness. The local contact area is used for the force calculations.

4.4.7 Belt Properties

An FE belt model was used to represent the belts. A 5.17 percentage elongation belt property was used for all belts. The belt property was provided by BRITEX and it was given in the form of force versus deflection curve. The force deflection curve was then converted to a stress versus strain curve. The stress versus strain curve property of the FE belt is shown in Figure 4.7.
Figure 4.7. Belt material properties.
CHAPTER 5
VALIDATION

5.1 Introduction

In mathematical model development, the creation of a simulation model is just the first step. The most time-consuming phase is validation of the developed model with the real test. Generally, analysts compare the simulation and test kinematics with visual aids. To get a clear idea of the comparison of simulation and test results, validation methods utilized are discussed in this chapter.

5.2 Validation of Dummy Kinematics

The dummy response in the test is most important since it provides a visualization of occupant response in crash scenarios. Such responses, despite the fact that they do not include the reactions of the occupants, which would vary among for individuals, provide us with a reasonable idea of occupant motion and interaction with the surroundings.

The dummy kinematics in the test and simulations were visually compared to confirm similarity in both the cases. The videos obtained from testing were used to compare the dummy kinematics with the simulation.

5.3 Validation of Profile

For validation of the profile, peak values were compared. Most injury criteria are based on peak values. The time window in which the peak is achieved is also important for injury value. A square box is considered around the peak. If the simulation values lie inside the square, the model is considered valid. Also head, chest, and pelvic accelerations from the test and simulation were compared, and see that the curve follows the same profile.
5.4 Injury Parameters

Injury parameters are the main responses obtained from crash testing. These responses are used to predict the severity and type of injuries that the occupant may suffer in each crash scenario under consideration. These injury criteria are also utilized as the basis for certification by government agencies.

Injury levels obtained from testing and simulation were used to validate the simulation model. Values from the simulation must be within the tolerance range of those from the test values. Comparisons of some of the injury parameters are listed in the results and discussion section.

Injury parameters of dummies obtained from the test were compared with those obtained from the simulation. Those injury parameters compared are listed below:

- Head Injury Criteria (HIC)
- Chest 3 ms
- Pelvic 3 ms
- Neck Forces and Moments
CHAPTER 6
RESULTS AND DISCUSSION

6.1 Comparison of Kinematics

The kinematics of the dummy for all three models in the simulation were compared to the dummy kinematics in an actual sled test. The comparison for different models is shown in Figures 6.1 and 6.2, Figure 6.3 and 6.4, and Figures 6.5 and 6.6 for a 12-month-old child seat, a 3-year-old child seat and a 6-year-old child, respectively.

For a 12-month-old child seat, there was very little displacement. The dummy was totally covered inside the seat and not visible from the side view. The dummy remained inside the seat and did not come out of the seat for simulation, but in the actual test, the head was partially visible at 300 ms. The child seat remained at its place for both the test and simulation, and showed similar kinematics.

In the case of the forward-facing convertible seat, the forward head movement for both the test and simulation was exactly same, but the return movement was not the same. In the actual test, the head came back faster than during the simulation.

The 6-year-old child was tested without any child restraint; the only restraint used was a lap belt. During the simulation the dummy kinematics were the same, but there was some time delay between the simulation and the test.
Figure 6.1. Kinematics of 12-month-old child seat I.
Figure 6.2. Kinematics of 12-month-old child seat II.
Figure 6.3. Kinematics of 3-year-old child seat I.
Figure 6.4. Kinematics of 3-year-old child seat II.
Figure 6.5. Kinematics of 6-year-old child I.
Figure 6.6. Kinematics of 6-year-old child II.
6.2 Comparison of Profile

Profiles of the head in the test and the simulation followed the same path for all three models. The peak values were close, but there was some time delay in reaching that peak in the simulation compared to the test. The chest and pelvic profiles also followed the same path. The seat pan forces predicted in simulation showed a similar profile as obtained from the sled test. Detailed comparisons of the profiles are found in Appendices A, B, and C for a 12-month-old child seat, 3-year-old child seat, and 6-year-old child respectively.

6.3 Comparison of Injury Criterion

The injury criterion is used to check the chances and level of injury that the occupant may sustain during the crash condition under consideration. In the first chapter the various injury criterion are described. For child safety, the excursion also is of importance, since more excursion tends to increase the chances of child getting in contact with surrounding interior parts.

The different injury levels obtained from the sled test were used as a reference to validate those obtained from the simulations.

6.3.1 Head

Maximum head accelerations, HIC, and head excursion were used as parameters for validation. Head injury levels showed that the head acceleration obtained from the simulation was well within the acceptable limits of validation and only the HIC in simulation for 6-year-old child model was high. The head excursions for a 3-year-old child were within the range of validation.
### TABLE 6.1
COMPARISON OF HEAD INJURIES INVOLVING A 12-MONTH-OLD CHILD SEAT

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Test</th>
<th>Simulation</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>FMVSS 213</td>
</tr>
<tr>
<td>Maximum Head Acceleration (g’s)</td>
<td>47</td>
<td>42</td>
<td>N/A</td>
</tr>
<tr>
<td>HIC (36 ms)</td>
<td>233</td>
<td>69</td>
<td>1000</td>
</tr>
</tbody>
</table>

### TABLE 6.2
COMPARISON OF HEAD INJURIES INVOLVING A 3-YEAR-OLD CHILD SEAT

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Test</th>
<th>Simulation</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>FMVSS 213</td>
</tr>
<tr>
<td>Maximum Head Acceleration (g’s)</td>
<td>61</td>
<td>59</td>
<td>N/A</td>
</tr>
<tr>
<td>HIC (36 ms)</td>
<td>221</td>
<td>174</td>
<td>1000</td>
</tr>
<tr>
<td>Maximum Head Excursion (in)</td>
<td>10.75</td>
<td>10.90</td>
<td>28.34</td>
</tr>
</tbody>
</table>

### TABLE 6.3
COMPARISON OF HEAD INJURIES INVOLVING A 6 YEAR OLD CHILD

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Test</th>
<th>Simulation</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>FMVSS 213</td>
</tr>
<tr>
<td>Maximum Head Acceleration (g’s)</td>
<td>241</td>
<td>291</td>
<td>N/A</td>
</tr>
<tr>
<td>HIC (36 ms)</td>
<td>1370</td>
<td>2341</td>
<td>1000</td>
</tr>
<tr>
<td>Maximum Head Excursion (in)</td>
<td>10.75</td>
<td>10.90</td>
<td>N/A</td>
</tr>
</tbody>
</table>
6.3.2 Chest

The chest 3 ms value gives the maximum accelerations experienced by the occupant over a range of 3 ms. The maximum acceleration of 60 g over a time interval of 3 ms is the suggested tolerance level for the human body. Table 6.4 shows a comparison of values obtained from the simulations and the sled tests. The values for a 12-month-old and 6-year-old child are closer to the actual sled test.

<table>
<thead>
<tr>
<th></th>
<th>Chest 3 ms (g)</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Simulation</td>
</tr>
<tr>
<td>12-month-old Child</td>
<td>34</td>
<td>37</td>
</tr>
<tr>
<td>3-year-old child</td>
<td>32</td>
<td>15</td>
</tr>
<tr>
<td>6-year-old child</td>
<td>30</td>
<td>28</td>
</tr>
</tbody>
</table>

6.3.3 Neck

The neck forces and moments are shown in the table 6.5. For a 12-month-old child, the neck moments are within the limit of validation but the neck forces are much higher than the actual test. The 3 year old and 6 year old child neck tension and flexion are within the validation limit, but the compression and extension values are not validated. The biofidelity of the neck is an ongoing research topic. Some new proposed dummy models have a better defined neck model with more joints and better validity.
<table>
<thead>
<tr>
<th>Age Group</th>
<th>Tension (N)</th>
<th>Compression (N)</th>
<th>Flexion (N-m)</th>
<th>Extension (N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test</td>
<td>Simulation</td>
<td>Test</td>
<td>Simulation</td>
</tr>
<tr>
<td>12-month-old child</td>
<td>9</td>
<td>182</td>
<td>-5</td>
<td>-16</td>
</tr>
<tr>
<td>3-year-old child</td>
<td>261</td>
<td>326</td>
<td>-23</td>
<td>-61</td>
</tr>
<tr>
<td>6-year-old child</td>
<td>455</td>
<td>469</td>
<td>-7</td>
<td>-78</td>
</tr>
</tbody>
</table>
CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Referring to the objectives the mathematical model for a 12-month-old child seat, 3-year-old child seat, and 6-year-old child were successfully developed. The validation of these mathematical models was also done successfully.

From the validation process it can be concluded that the method of using facets to represent the actual seat gave a better geometry of the seat. The results obtained from the sled test and simulations were similar. The head, chest, and pelvic acceleration peaks are considerably within the range of comparison. Therefore, it can be said that all three models were successfully validated and could be used in the future to study the implementation of a CRS in aircraft. The kinematics observed in the validation runs confirms the importance of the use of child restraint seats. It can be seen that the child restraint seat helps in maintaining desired positions of the dummy.

For the 12-month-old and 3-year-old child seat the ISOFIX joint forces were within the FMVSS 213 requirements, therefore, these seats could be used in aircraft. The head and chest accelerations for 12-month-old and 3-year-old child were below the FMVSS 213 and ECE R 44 regulations; therefore, this restraint system is safe to use in aircraft under the described conditions. The 6-year-old child without any child restraint system is not safe in an aircraft. The use of a two-point restraint system by a 6-year-old does not offer the level specified in FAR 23.562 (HIC below 1,000). Therefore, it is necessary to do more research on a 6-year-old child using a child restraint system and, if that gives better performance, then define some regulations for a 6-year-old child.
7.2 Recommendations

Material properties for contact definition and belt properties could be obtained from component testing. Use of these properties will help in achieving better and more reliable validations without any trial-and-error methods. The validation for 12-month-old and 3-year-old child restraints used in this research was done with ISOFIX; similarly, this could be done with LATCH system to compare both models. Also, similar work could be done for 6-year-old child restraint systems using ISOFIX and LATCH. It would be interesting to see the difference between the ISOFIX and LATCH system for all kinds of child restraint systems.

Along with type II test, if validations could be done for a type I test, the model could be used to simulate a wider range of scenarios with better reliability.
REFERENCES


APPENDIX A

COMPARISON OF PROFILES FOR 12 MONTH CHILD SEAT

Figure A.1. Accelerations.
Figure A.2. Upper neck forces and moments.

Figure A.3. Seat pan forces.

Figure A.4. ISOFIX joint forces.
APPENDIX B

COMPARISON OF PROFILES FOR 3 YEAR OLD CHILD SEAT

Figure B.1. Accelerations.
Figure B.2. Upper neck forces and moments.

Figure B.3. Seat pan forces.

Figure B.4. Seat back forces.
Figure B.5. ISOFIX joint forces.

Figure B.6. Head and knee path.
Figure C.1. Accelerations.
Figure C.2. Upper neck forces and moments.

Figure C.3. Head path.