

University of Southern Queensland
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Comparison of Injury Criteria for Human Head Impacts

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Abstract

Head injury is a dangerous possible outcome every time the head is decelerated rapidly. The outcome for the victim of the injury can range from mild concussion to permanent coma and in extreme cases death.

In an attempt to better understand how hard an impact must be to cause severe head injury analysis systems called injury criteria have been developed to analyse collisions. To obtain collision data tests are performed in circumstances similar to the environment the is being investigated.

The main goal of this document is to develop a solid understanding to the different criteria and creat a program which will analyse impact data using the injury criteria investigated.

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Prof R Smith

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Chapter 1

Introduction

1.1 Introduction to project

Injuries to the head can lead to symptoms ranging from mild disorientation to permanent coma and in extreme cases death. It is therefore desirable to seek a method of analysing the cause and effect of head injury with the intent of lessening its likelihood.

The brain can be injured by many different causes, including blood poisoning, exposure to dangerous amounts of radiation, exposure to extreme temperatures or mechanical impact.

In the course of this document the head injuries studied are those caused by rapid acceleration or deceleration to the brain. Assuming that the brain, skull and all other contributing factors of a healthy adult human and the other causes of brain injury are not present.

1.2 Importance of impact analysis

Rapid acceleration of the head can be caused by a range of activities, for example vehicle accidents, falls from playground equipment or heavy tackles etc encounter in

contact sport. In situations where there is a high possibility that the head will be dramatically decelerated design measures need to be taken to ensure that damage to the brain is minimised.

To properly account for safety in design it is desirable to be able to analyse the potential lethality of the situation which has caused the collision. This is achieved by using test apparatus with appropriate measuring equipment, performing tests to get suitable collision data and analysing the impact data.

1.2.1 Collision data

Collision data is obtained through experimental procedure using test apparatus appropriate to the situation the test is trying to recreate. The test apparatus consists of a headform and an accelerometer mounted inside the head form.

To perform a test the head form is accelerated to a set speed and allowed to decelerate as though it would in the conditions the test is trying to simulate. Impact data is read from the accelerometer mounted inside the test headform.

1.2.2 Injury Criteria

Once the collision data has been collected it requires analysis to determine the predicted severity of the impact. The systems that are used perform analysis on collision data are called injury criteria. Each injury criterion rates the severity of the impact with a single numerical output, over a certain threshold number indicates a severe collision and under a certain threshold number indicates a non-severe collision.

1.3 Conclusion

Testing the environment that could potentially lead to a head injury can be used to obtain impact data. The impact data can be analysed using injury criterion to give a prediction of whether a collision is severe or not.

The aim of this document is to identify the conditions surrounding a head impact and how they relate to the injury criteria. In addition the injury criteria will be examined with the intention of creating a computer program to apply the injury criteria to a range of collision data.

Chapter 2

Anatomy of head injuries and the collisions which cause them

2.1 Chapter Overview

There are three important physical aspects that play a key role in the exchange of kinetic energy to brain injury: the actual anatomy of the head, the type of collision and the brain injury mechanisms.

2.2 Anatomy of the human head

The human head is a very complex structure. Only the key elements to head injury criterion will be described. Head injury is mainly a function of the interaction between soft tissue and bony structure. The area that is directly contacted in a collision is the top and sides, this section of the head can be described as four layers, the scalp, skull, meninges and brain. Figure 2.1 shows a side on cross section of a human head.



Figure 2.1: Cross Section of a human head, taken using magnetic resonance imaging, (source: www.neurosurgery.ucsd.edu/pediatricneurosurgery/)

2.2.1 Scalp

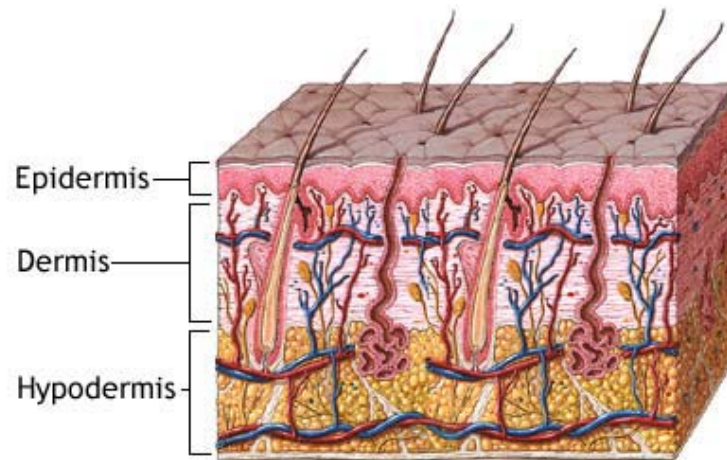
The scalp is five layers outside the skull, generally 5 to 7 mm thick. It is fed by four arteries, occipital artery, superficial temporal artery, supraorbital artery and the supratrochlear artery. Scalp is an acronym of **S**kin, **C**onnective tissue, **A**poneurosis, **L**oose connective tissue, and **P**ericranium.

Skin

Skin has many functions; it covers the majority of the human body and constantly sheds and grows new layers. Skin has three layers, the epidermis, the dermis, the hypodermis.

Connective Tissue

To anchor the skin to the aponeurotic layer there is a dense layer of connective tissue. The veins, arteries and nerves that supply the rest of the scalp are contained in this layer.



ADAM.

Figure 2.2: Anatomical diagram of skin, main layers have been labeled, (source: <http://www.nlm.nih.gov/medlineplus/ency/imagepages/8912.htm>)

Aponeurotic layer

Lumley, Craven and Aitken, (1995) define the aponeurotic layer as the musculo-fibrous layer between the connective tissue and the loose connective tissue, containing the occipitalis muscle at the rear of the head and the frontalis muscle at the front of the head.

Loose Connective tissue

Drake, Vogl, Mitchell, (2005, p.826) state that the "loose connective tissue separates the aponeurotic layer from the pericranium and facilitates the movement of the scalp proper over the calvaria."

Pericranium

The external envelope of fibrous connective tissue that covers the outer surface of the skull.

2.2.2 Skull

The skull is made up of twenty two bones interconnected by sutures forming the cranium. The cranium can be looked at as two sections, calvaria (*upper*) and viscerocranium (*lower*). The upper section encases and protects the brain. It consists of the frontal bone, sphenoid bone, ethmoid bone and occipital bone (**Unpaired**) and the parietal bones and temporal bones (**Paired**). The lower section makes up the facial skeleton, consisting of the vomer (**Unpaired**), and the nasal bones, palatine bones, lacrimal bones, zygomatic bones, maxillae, inferior nasal conchae (**Paired**). The mandible is not part of either section, although it is accepted as one of the bones in the skull.

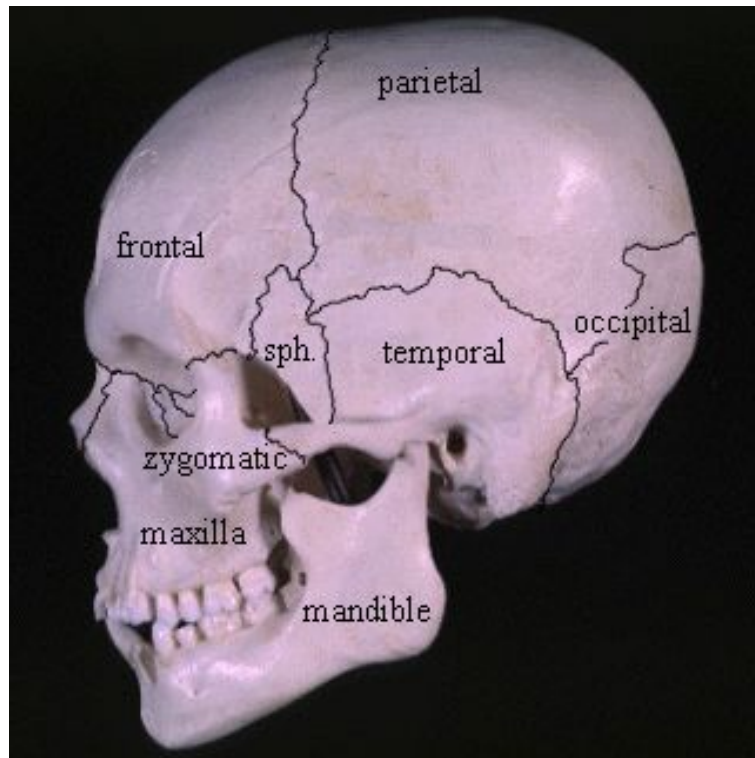


Figure 2.3: Lateral view of human skull, major bones have been labeled, (Source: <http://www.med.mun.ca/anatomyts/head/latskull.htm>)

2.2.3 Meninges

The meninges consists of three layers; the dura mater, the arachnoid mater and the pia mater. The meninges surround both the brain and the spinal chord.

Dura Mater

The dura mater consists of two layers, the periosteal layer and the meningeal layer. The outer layer is the periosteal layer, it is attached directly to the skull itself. The inner layer is the meningeal layer, it is in direct contact with the arachnoid mater.

Arachnoid Mater

The arachnoid mater is a thin membrane which lies between the dura mater and the subarachnoid space. It is not attached to the dura mater and follows the contours of the brain loosely, not entering the grooves of the brain.

Pia Mater

The pia mater is a slim layer which closely follows the contour of the brain. It lies between the brain and the subarachnoid space.

2.2.4 Brain

The most complex organ of the human body, it controls involuntary activities to keep the body alive as well as conscious activities such as thought. The typical adult brain weighs between 1 kg and 1.5 kg.

D. Wilhelmus and A. Brands (2002) states that the brain "consists largely of a network of nerve cells, neurons and supportive cells", which can be functionally arranged into two areas; grey matter and white matter.

One of the things that makes the brain prone to injury is its incompressibility, being susceptible to shearing pressure.

2.3 Anatomy of collisions

There are key aspects to any collision which can greatly affect severity the of the outcome. There are two types of collision, and two factors which make up the anatomy of a collision.

2.3.1 Collision types

There are two main types of collisions; contact and non-contact. There are a few notable points about each type.

Contact collision injuries are the most common, quite simply when the head impacts on another surface at sufficient speed the result is a contact injury. Contact injuries can lead to skull fracture, although this does not have to be the case. The probability of a contact injury causing skull damage is dependant on the relative velocity and the dynamic response of the impact surface, i.e. the rate of deformation/energy attenuation.

Non-contact collision injuries are less common. They are caused when the whole body is shaken and the head is shaken as a result. An example of conditions that would cause this type of injury would be whiplash in a car accident or a heavy tackle where the body is dramatically decelerated. Non-impact injuries cannot cause skull fracture.

2.3.2 Collision factors

The rate of deformation of the impacted masses is an important factor in collision anatomy. For example in the case of a car crash into a tree there is deformation of tree, car (area in contact with tree and contact with head), and the head itself. In cases where the objects involved other than the head absorb large amounts of energy, a high speed collision may cause only minor injury to the victim. The ability of a material to absorb energy is known as its energy attenuation. This has been identified as a very important property of material where there is a higher than usual chance of contact

head collision. An example of this is airbags in cars or the surfaces of playgrounds where falls may occur.

The impacted area is also important as smaller area causes the stress in the skull to become significantly larger than the stress experienced in larger areas of impact. The effect of this is that the probability of skull fracture increases significantly, which can cause a small portion of the bone to be isolated from the rest of the skull and pushed into the brain cavity.

2.4 Head injury mechanisms

The previous section stated that when the head is dramatically decelerated the brain is damaged. There are a number of internal processes which act as injury mechanisms. Head injuries may be either, focal or diffuse.

Focal

Focal injuries are localised in a section of the brain, typically as a result of a direct impact. Focal injuries are the result of converging shock waves moving through the brain. The resulting injury comes from bleeding of the affected blood vessels which cause pressure build-up inside the skull, which in turn puts pressure on the rest of the brain, stopping the flow of blood causing death.

Diffuse

Diffuse injuries are typically less severe but affect a greater area of the brain. They are typically caused by severe acceleration of the brain inside the skull and can be from contact or non-contact collisions. The resulting injury comes from the injured nerves all over the brain leading to depleted brain function. Milder diffuse injuries lead to loss of consciousness, while more severe diffuse injuries lead to permanent coma and death.

2.4.1 Primary mechanisms

Primary mechanisms are the means of collision energy becoming a head injury.

(1) Direct brain contusion from skull deformation at the point of contact; (2) Brain contusion from movements of the brain against rough and irregular interior skull surfaces or from the side opposite the impact; (3) Brain and spinal chord deformation in response to pressure gradients and motions relative to the skull, resulting in stress in the tissues; and (4) subdural haematoma from movement of the brain relative to its dural envelope, resulting in tears of connecting blood vessels (Viano et al. 1989).

From this we can surmise that the actual damage is done to the blood vessels, nerves and skull.

2.4.2 Primary affected aspects

The actual mechanisms of injury lead to two basic types of damage, blood vessel damage and nerve damage. Additionally the skull itself can be injured due to external mechanisms acting on the bone.

Blood Vessel damage

Damage to the blood vessels of the brain and surrounding envelope is caused when the local pressure becomes too great and the blood vessels burst or when the vessels come into contact with rough bone surfaces i.e. fractures or sutures.

Blood vessel damage can also be the cause of secondary injury mechanisms. If local bleeding is bad enough then the excess of blood can cause slow build up of pressure inside the cranium. This can lead to further local damage through restricted blood flow or in severe cases death if the pressure is acting down through the brain stem.

Nerve Damage

Damage to the nerves inside the brain is encountered when the strain on them becomes too large and they tear.

Nerves can also be damaged through secondary impact mechanisms, when brain cells are damaged calcium and potassium ions leak into the interstitial fluid adjacent to the cells. M. Shorten et. al. (2003) point out that "since nerve impulses are transmitted by the flow of these ions across cell membranes, the released ions can disrupt neural function".

Skull Damage

Damage to the skull itself occurs when stress in the bone becomes too large and the bone fractures. A. McLean et. al. (1997) state that "Skull fractures may be grouped into three main categories: penetration fracture at the impact site, comminuted depressed fractures at the impact site, and linear fractures remote from the impact site". Depressed fractures tend to occur when the collision surface is smaller than 7 cm^2 , comminuted depressed fractures occur where the impact is larger than 7 cm^2 and remote linear fractures tend to be caused by blunt impact, for example a continuous surface such as a brick wall.

2.5 Chapter Summary

The brain is the primary concern in a head injury, whether it is affected through direct or indirect injury mechanisms. There are layers of bone and tissue surrounding the brain, that act to prevent and minimise brain injury. If the layers are damaged seriously enough they cause rather than prevent brain injury.

Collisions themselves are a complex part of understanding head injury and the conditions that cause a collision determine the key aspects. If these conditions can be altered then the outcome of a collision can be manipulated to prevent and lessen head injury.

There are defined processes that lead from collision to injury. These brain injury mechanisms have different triggers and outcomes. Analysis of a collision to determine which mechanisms would have occurred can give an indication of the potential severity of an impact.

Chapter 3

Injury Criteria

3.1 Chapter Overview

Injury criteria are the systems used to analyze accelerometer data from tests to determine the outcome of an impact. The different approaches can be broken into four sections; Graphical analysis systems, functional analysis systems, translation head injury models and rotational systems.

3.2 Graphical Analysis Systems

Graphical analysis systems were the first major step in the evolution of the analysis of collision data, the lines of each graph were interpolated purely from experimental data.

The impact duration and acceleration characteristics of a given test were very much dependent on the person performing the analysis. The time increment was chosen from simply looking at the graph to determine which part of the collision data was most important, and the acceleration was then averaged to give the characteristic acceleration. This process is shown in figure 3.1.

For the methods examined in this section above and to the right of the threshold curve

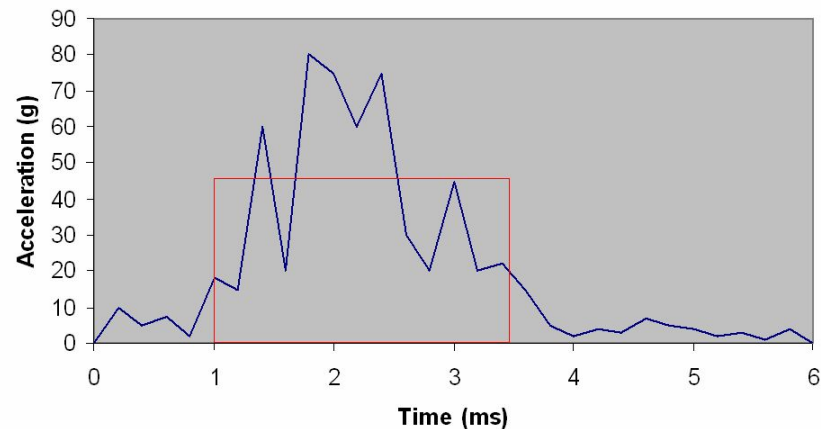


Figure 3.1: Example of method used to find characteristic duration and acceleration level

is indicative of severe head injury.

3.2.1 Wayne State Tolerance Curve

The **Wayne State Tolerance Curve (WSTC)** was the first extensive system to attempt to measure the severity of a head injury, it became the basis for almost every injury criterion to date. It was built from experimental data obtained from experiments using cadavers and animal heads.

Research for the WSTC was carried out from the 1940s to the 1960s at the Wayne State University in Detroit. The most notable contributors in its progress being Gurdjian and Lissner. When the WSTC was first proposed by Lissner, Lebow and Evans in 1960 it was comprised of six points (from 1 ms to 6 ms), each point determined by the average acceleration and total duration to cause a high probability of a critical head injury. Figure 3.2 shows a plot of the WSTC.

In 1943 Gurdjian and Webster began research on the effect of impacts administered in various ways at the Wayne State University in Detroit. In 1955 Gurdjian, Webster and Lissner published "Observations on the mechanism of brain concussion, contusion, and laceration". A. McLean and R. Anderson mention that by applying air pressure directly to the unopened dural sac for various time periods Gurdjian et. al were able

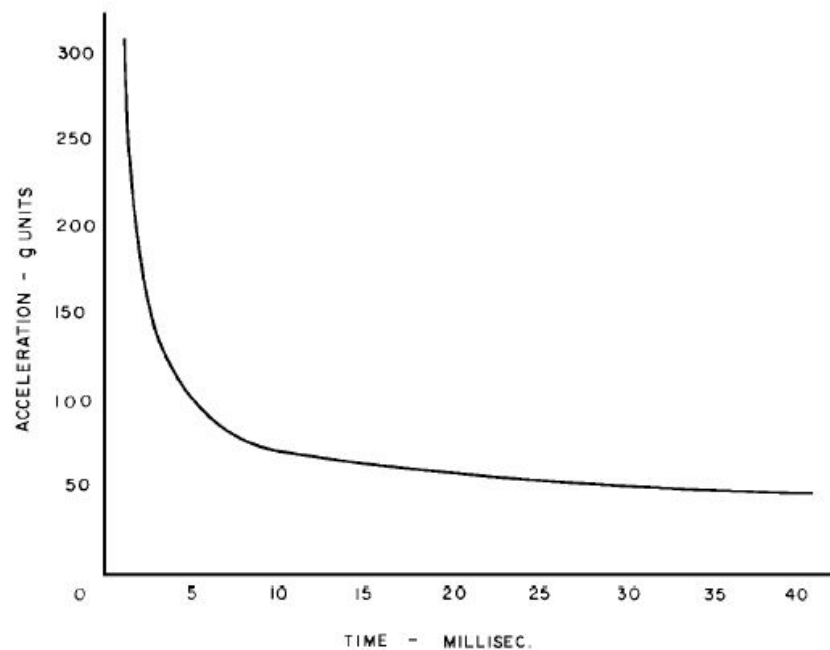


Figure 3.2: Plot of the WSTC, A. McLean et. al. (1997) p.69

to illustrate that "the severity of the concussive effect depended on both the intensity of the pressure pulse and the duration of its application".

The WSTC was revised and extended utilising data from comparative animal and cadaver experiments. R. Hess, K. Weber and J.Melin (1980) report using pressure transducers implanted in the right temporal and left posterior regions of the brain and an accelerometer implanted in the center rear of the skull. R. Hess, K. Weber and J.Melin (1980) then go on to state that the cadavers were dropped onto "automotive instrument panels, damped steel plates, steel anvils, and padded steel anvils".

D. Wilhelmus and A. Brands (2002) stated that the curve was developed "using a combination of linear skull fracture data in (embalmed) cadaver heads (short duration impacts), brain concussion data in animal heads (medium duration impacts) and non injury producing, low acceleration, volunteer data."

3.2.2 JARI Human Head Tolerance Curve

The **JARI Human Head Tolerance Curve (JHTC)** was first suggested by Ono et. al. in 1980, as a result of work done in the **Japan Automobile Research Institute (JARI)**. The JHTC complemented and extended on the data provided by the WSTC. The JHTC assumes that concussion marks the onset of temporary/reversible injury and skull fracture marks the onset of more severe head injuries.

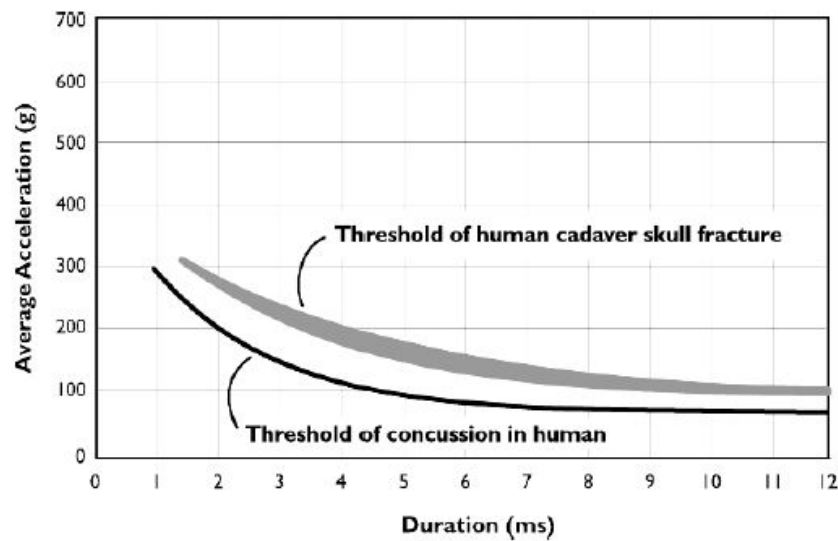


Figure 3.3: Plot of the JHTC (source: A. McLean et. al. (1997), p.71)

The JHTC was produced from experiments on monkeys, with the data scaled to better apply to the human head. A. McLean et. al. (1997) noted that in some of the experiments the initial diagnosis of the experiment was concussion only but later autopsy revealed contusion. A secondary set of experiments using cadavers was the basis for the threshold of skull fracture.

3.3 Function Analysis Systems

Function analysis systems utilise a mathematical formula to derive a number that indicates how severe an impact is by integrating the formula over a given time interval.

3.3.1 Gadd Severity Index

The Gadd Severity Index (**SI**) was developed as a result of Gadd's examination of the WSTC.

In 1961 Gadd proposed that a linear fit could be found for the injury threshold curve if it were plotted on a logarithmic axis. Rough plot of WSTC on log - log axes is shown in figure 3.4. Although the WSTC was modified after his original proposal Gadd felt that the approximation provided was still reasonably accurate due to the fact that the experimental results had a significant spread. In 1966 Gadd presented his ideas at the tenth Stapp Car Crash Conference. He stated that the gradient of the line on the logarithmic axis was approximately -2.5 and from this assumed a power weighting factor of 2.5. J. P. Danforth suggested that the weighting exponent need may not be constant and the log-log plot of the WSTC could be better modeled if the weighting factor could vary as a function of acceleration, R. Hess, K. Weber and J. Melvin (1980). However at the time Gadd's approximation was reasonable given the level of experimental data. The formula derived from this discovery is given in 3.1.

$$SI = \int a^{2.5} dt \quad (3.1)$$

3.3.2 Head Injury Criterion

The head injury criterion was derived from the SI which in turn was based on the WSTC. In 1971 Versace suggested improvements to the SI formula, that the effective acceleration ($\frac{1}{T} \int a^n dt$) should be raised to the power of 2.5 and multiplied by the impact duration. This new formula was named the **Head Injury Criterion (HIC)**. The National Highway Traffic Safety Administration reviewed Versace's idea and found that it better reflected the trend towards low severity at long impacts and high severity at short impacts. The HIC replaced the SI as the standard for predicting head injury severity. The formula for the HIC is shown in figure 3.2. The time interval is modified to give the maximum HIC value, as this allows the time increment to be decided based on mathematical logic rather than intuition.

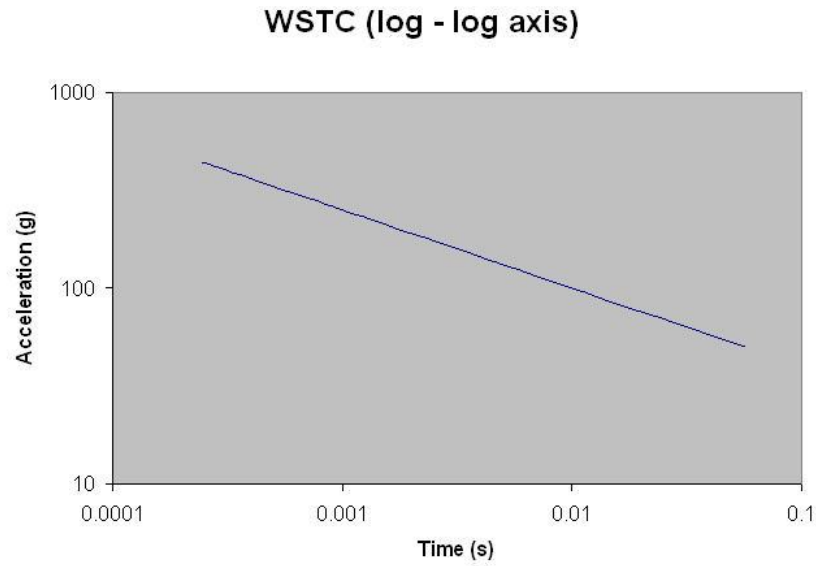


Figure 3.4: WSTC plotted on log - log axis

$$HIC = \left[\frac{1}{t_2 - t_1} \int a \, dt \right]^{2.5} \quad (3.2)$$

In 1985 Prasad and Mertz performed experiments on cadavers to determine the relationship between probability of head injury and HIC value. A. McLean et. al. (1997) states that in order to analyse the cadaver experiment results "Prasad and Mertz used a statistical method called Mertz/Weber method". Expanded Prasad-Mertz curves are shown in figure 3.5.

General Motors was responsible for a large push towards the HIC replacing the SI, due to the fact that SI was found to be weighting brief high acceleration impacts very harshly. The HIC was found to be a much better indication of the level of severity. The key difference between the two systems is that the SI applies the exponent and then averages whereas the HIC averages and then applies the exponent.

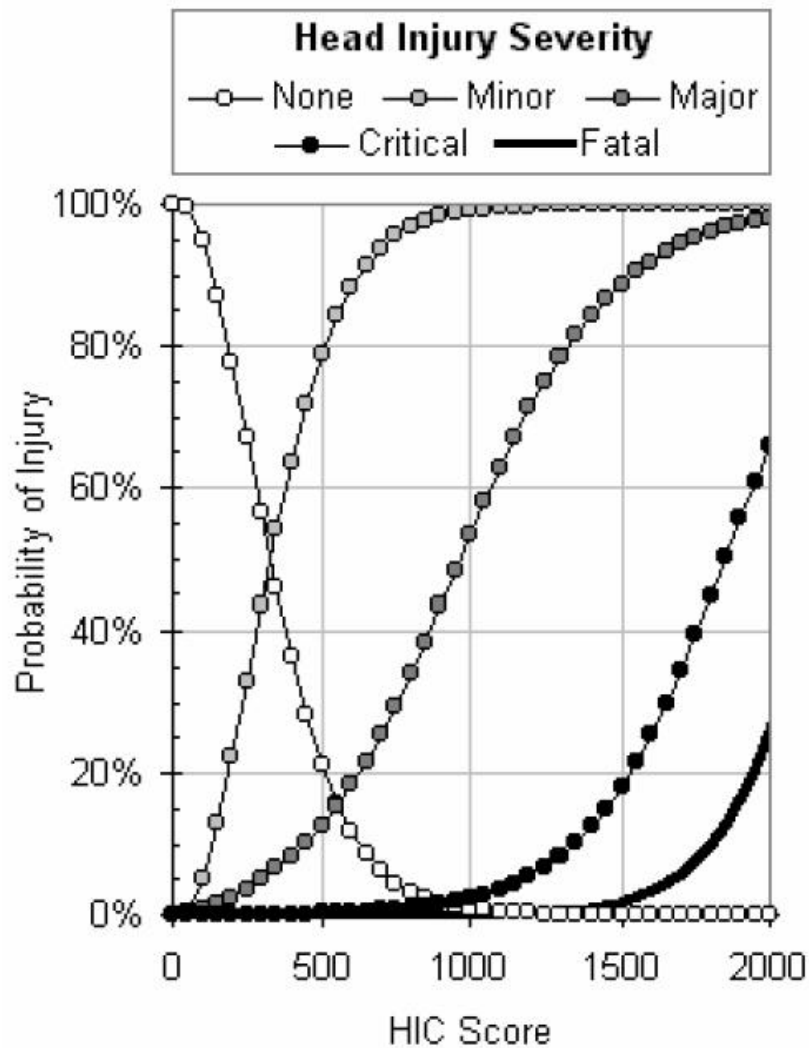


Figure 3.5: Prasad-Mertz curves, M. Shorten and J. Himmelsbach (2003)

3.4 Translational Head Injury Models

Translational **Head Injury Models** (THIMs) are another series of systems developed to determine the severity of an impact. They consist of masses coupled together with springs and dampeners. THIMs attempt to "examine the dynamic response of the head and from this, generate response models which try to predict the injury outcome of an impact" A. McLean et. al. (1997). The basis for the THIMs was experiments carried out on cadavers and animals.

3.4.1 Mean Strain Criterion

The **Mean Strain Criterion (MSC)** was first suggested by Stalnaker in 1971 and modified in 1985 to give better agreement with experimental data. The model which describes the MSC is shown in figure 3.6. Where m_1 is the mass of the tissue at the point of deformation caused by contact, m_2 is the remaining mass of the head, the spring stiffness k_1 is the stiffness of the skull, c_1 is the damping of the cerebrospinal fluid.

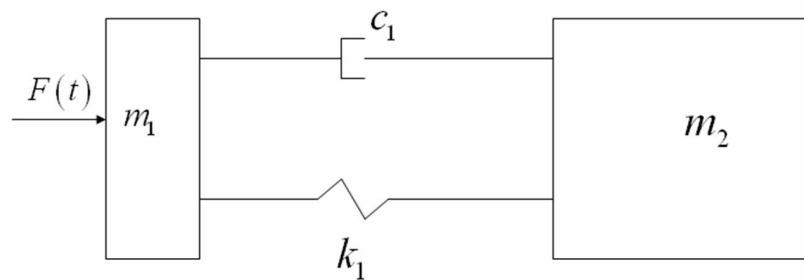


Figure 3.6: Diagram of the MSC

In 1971 using impedance data from animal experiments Stalnaker developed a model that viewed the response of the head as two masses linked by a spring and damper A. McLean et. al. (1997). Experimental data from cadaver and scaled monkey experiments in 1985 was the basis for alteration of the model as the model was tweaked to better fit the impedance data. The experiments performed on the monkey heads needed to be scaled to apply to humans. There has been criticism of the way the data was scaled, however the data was still used as it agreed with other results.

3.4.2 Translational Energy Criterion

The **Translational Energy Criterion (TEC)** is an extension of the MSC. It was first suggested by Stalnaker in 1987. The model which describes the TEC is shown in figure 3.7. Where m_1 is the mass of the tissue at the point of deformation caused by contact, m_2 is the remaining mass of the head, c_1 is the damping provided by deformation of the brain, c_2 is the damping provided through deformation of the skull.

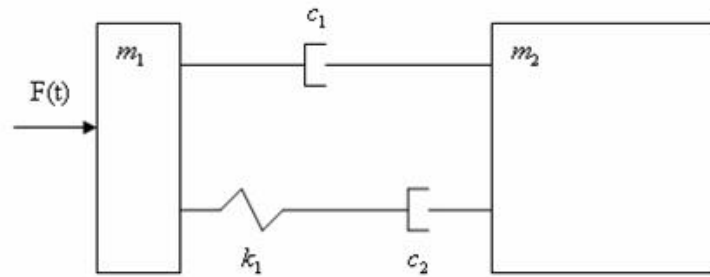


Figure 3.7: Diagram of the TEC

In 1987 the TEC was proposed by Stalnaker as criteria for skull fracture and brain injury, as the TEC was an improved version of the MSC. Due the similarity of the two models the same experiments were applicable. "The original primate experiments that were the basis of the MSC were reanalysed and the force/time histories of these experiments were applied to the model" A. McLean et. al. (1997) (in reference to the TEC).

3.5 Rotational Models

In a collision the brain can move in translation, rotation or a combination of the two. Earlier criterion assumed that the rotational aspect was insignificant and didn't need to be taken into account, however research has shown that the rotational aspect has far more importance in determining the severity of an impact.

3.5.1 Generalised Acceleration Model for Brain Injury Threshold

In 1986 Newman suggested an injury criterion that assessed the severity of a collision based on a combination of translational and rotational acceleration be used, Newman called this system the **Generalised Acceleration Model for Brain Injury Threshold (GAMBIT)**. GAMBIT has the form described in equation 3.3, where $a(t)$ is the translational acceleration and $\alpha(t)$ is the rotational acceleration. a_c is the limiting translational critical value and α_c is the limiting rotational critical value, m , n , and s

are imperial values used to manipulate the formula to get the best fit of experimental data. If the value of G is greater than 1 then the collision will cause a critical head injury.

$$G(t) = \left[\left[\frac{a(t)}{a_c} \right]^m + \left[\frac{\alpha(t)}{a_c} \right]^n \right]^{\frac{1}{5}} \quad (3.3)$$

GAMBIT "follows a classical engineering approach used for modeling strain" T. Gibson et. al. (2001). The validity of GAMBIT was tested against other criteria, and as a result the model itself has remained the same but the variables have been revised to fit experimental data.

T. Horgan (2005) states that tests were performed using cadavers, monkeys and piglets, and the results were graphed. The graph was found to contain an "ellipsoid of influence", showing that GAMBIT provided a good indication of injury threshold.

3.6 Chapter Summary

There are a range of different techniques to analyse collision data, these criteria can be broken down into 4 groups; graphical models, function models, translational models and rotational models.

Graphical systems take average acceleration over a time interval and plot the point representing these two figures and a graph. The collision severity is determined by looking at which side of a predefined curve the point lies.

Functional models utilise mathematical formulae to process the collision data and give a numerical output which is indicative of the potential severity of the collision.

Translational models use a system of masses springs and dampers to predict the dynamic response of the brain. The severity is then calculated by analysing either the average strain in the spring or the energy dissipated by the damper.

Rotational models incorporate both the linear and angular acceleration of the head-form to determine the severity of an injury. Rotational models use formulae to derive indicative values in a similar way to function models.

Chapter 4

Impact Testing

4.1 Chapter Overview

Impact testing is used to get impact data for a collision. In a typical experiment a headform is allowed to hit a designated surface at a certain speed. An accelerometer inside the headform records the acceleration experienced during the collision.

There are many different standards which govern how testing should be done. The key elements are a headform, a system to accelerate the headform, and a surface to impact on the headform once it has the required velocity. The standards examined are BS EN 117:1998, Impact absorbing playground surfacing - Safety requirements and test methods and AS/NZ 4422:1996 Playgroung surfacing - Specifications, requirements and test methods. These two standards were chosen due the simplicity of the test, no expensive equipment was required to accelerate the headform and the procedures described were simple enough to be performed at the University of Southern Queensland labs. There is also a fair amount of overlap between the two standards, which means that they can be examined simultaneously.

4.2 Test Equipment

The two key pieces of equipment are the headform and the apparatus used to accelerate and guide the direction of the headform. Both of these vary greatly depending on which standard they must conform to and the reason for this is the varying environments which need to be examined.

4.2.1 Headform

There is much debate as to the exact geometry of the headform. The head-form needs to be easy to reproduce and manufacture, yet act like human skull as closely as possible. The headform changes to better imitate real life, for example tests to determine the safety of motorcycle helmets require a headform geometry and mass similar to an adult, whereas tests to determine the safety of playground surfacing need to mimic the head of a child.

AS 4422 refers to AS/NZ 2512.1 for the geometry of the head-form. The size J head-form with a mass of $5 \text{ kg} \pm 0.1 \text{ kg}$, plot of J headform is shown in figure 4.1. AS/NZ 2512.1 also states that the head-form material should be "hardwood or metal or other suitable material".

EN 1177:1997 is less particular about the headform, specifying that it should be either an aluminium ball or a hemispherical ended missile of diameter $160\text{mm} \pm 5\text{mm}$ with a mass of $4.6\text{kg} \pm 0.05\text{kg}$.

Accelerometer

An accelerometer device used to measure acceleration, the accelerometer used in impact testing is a small metallic box, similar in size to a matchbox.

The accelerometer is mounted securely inside the head-form. It needs to have a reasonable sampling frequency, and the recommendation for sampling frequency for the HIC is $\geq 8000 \text{ hz}$. Having a high maximum value is also important as some of the tests can

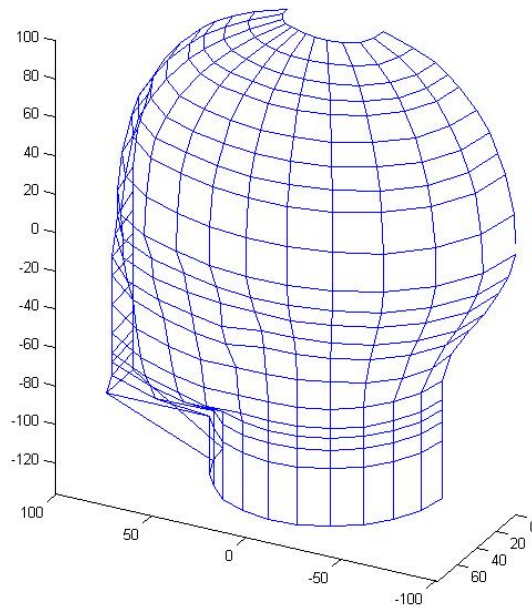


Figure 4.1: Image of the J head-form, generated using MATLAB

exceed 300g.

AS 4422 states that the accelerometer should be mounted;

- (a) In the case of the free falling headform an accelerometer, capable of measuring acceleration triaxially, shall be mounted in the centre of gravity of the headform.
- (b) Where the headform is guided to fall vertically, the accelerometer shall be aligned to measure in the vertical axis, and the velocity of the headform, immediately prior to impact shall be measured.

4.2.2 Headform acceleration apparatus

The apparatus used to accelerate and guide the headform also varies depending on the real-life situation it is intended to mimic. Tests on motorcycle helmets use pneumatics to simulate a high speed impact, while tests on playground surfaces simply use gravity to accelerate the headform.

Both AS 4422 and EN 1177 utilise acceleration due to gravity to accelerate the headform to the required velocity. Both standards specify drop height as the key factor, not speed as other standards dictate. This is to better match real life situations so that the experimental results show at what fall height the surface is unable to keep a person safe.

4.3 Test procedure

There are a number of ways in which the impact tests can be carried out. Different standards call for different procedures and circumstances.

AS/NZ 4422 specifies that the headform be dropped from a range of heights. Each time a test is performed the impacted surface needs to be moved so that the headform hits a different part of the surface.

4.4 Results

The resultant data from a typical impact is shown in figure 4.2. The actual shape of the plot of the collision data varies greatly with physical circumstances. It is important to note that the surface impacted greatly contributes to not only the peak acceleration and duration but the shape of the acceleration profile as well. For example the profile of safety glass used in car windscreens typically has a very large peak as soon as the headform comes into contact with the glass, but once the glass has cracked the acceleration is significantly less as the plastic inside the glass deforms with relative ease compared to the glass.

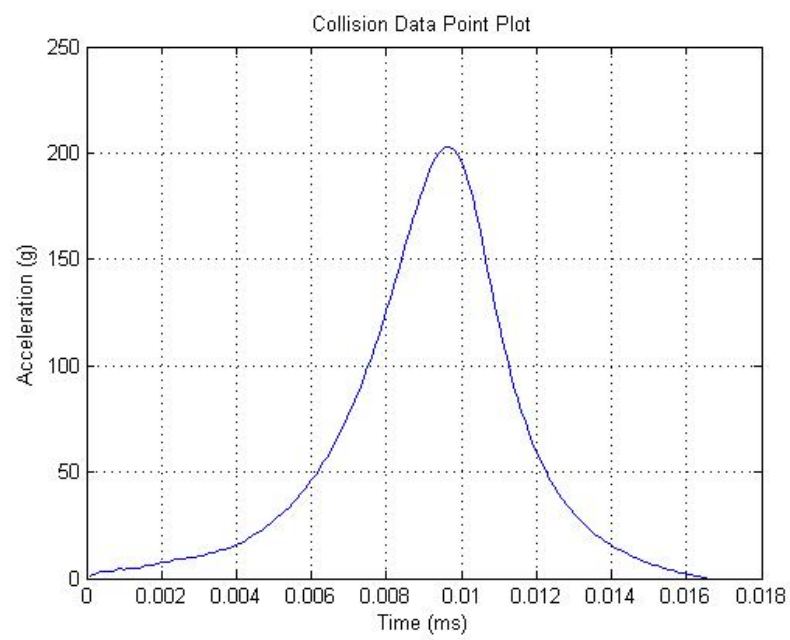


Figure 4.2: Plot of acceleration versus time for a typical impact

4.5 Chapter Summary

Impact testing is a useful tool for obtaining collision data for given circumstances. By changing the apparatus used collision data can be collected for a specific set of circumstances. This flexibility allows impact testing to be used to set safety standards for many different applications.

The apparatus used varies with the intended test circumstances. However there are four vital aspects which are used in all tests. The headform, accelerometer, headform accelerator and impacted surface.

The test procedure itself is also quite simple; the headform is accelerated to a specified speed and allowed to strike the impact surface. Experiments with these procedures have the advantage of being mainly non-destructive the only exception is situations which call for the surface to be replaced.

Chapter 5

Program

5.1 Chapter Overview

The analysis program was written using the formulas and models identified in the earlier section. The programming language chosen was MATLAB, this was due to the advantage of several predefined mathematical function which are crucial to the program.

The analysis program is designed to perform a number of functions. In addition to the analysis program there are modules within the program to build data comparing impacts key characteristics and injury criteria performance. To achieve all the different tasks there are three different types of modules, Builder modules, Analysis modules and Control modules. Source code for each module can be found in appendix.

5.2 Builder Modules

Builder modules are used to build a collision data points matrix from either a collision acceleration log or from user inputs.

For the user specified collision the maximum acceleration and collision duration are

input by the user and the collision form is selected for a range of collision shapes.

5.2.1 Square

For this type of collision the acceleration remains constant over the entire duration. Governed by equation 5.1, where g_{max} is the maximum acceleration and duration refers to total collision duration.

Equation used

For: $t = 0 : 0.1 : \text{Duration}$

$$y = g_{max} \quad (5.1)$$

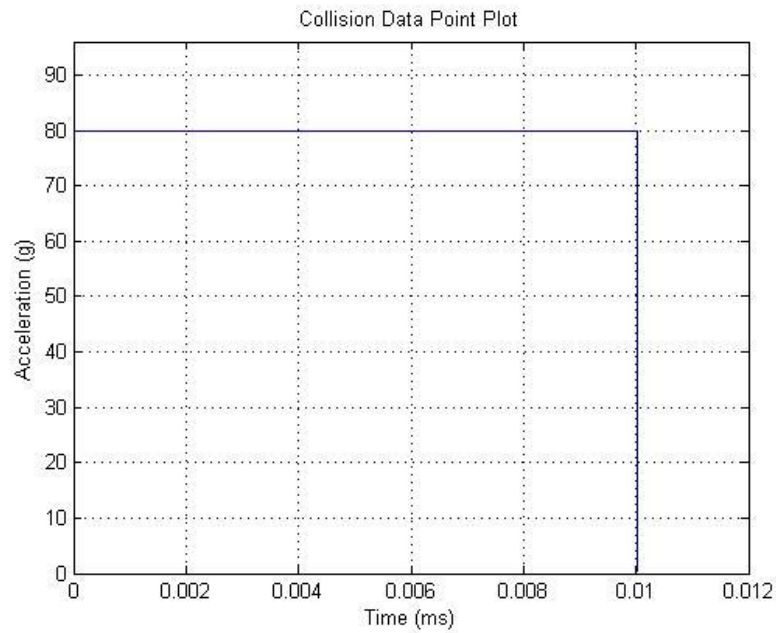


Figure 5.1: Plot of collision data points for square type collision with a duration of 10 ms and a peak acceleration of 80g

Code for module is in section B.1.

5.2.2 Ramp

For this type of collision the acceleration varies from zero to maximum over the duration of the impact in a linear fashion. Governed by equation 5.2, where g_{max} is the maximum acceleration and duration refers to total collision duration.

Equation used

For: $t = 0 : 0.1 : \text{Duration}$

$$y(t) = m \times t \quad (5.2)$$

Where:

$$m = \frac{g_{max}}{\text{Duration}} \quad (5.3)$$

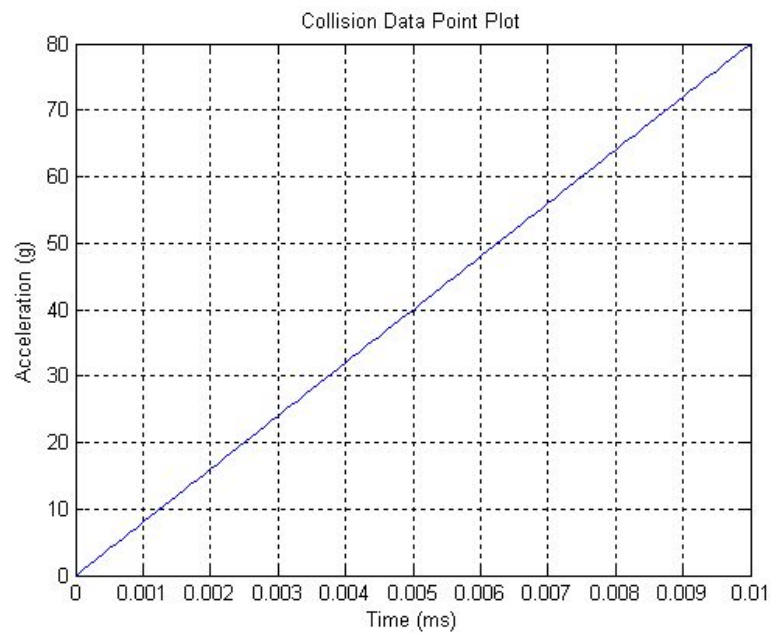


Figure 5.2: Plot of collision data points for ramp type collision with a duration of 10 ms and a peak acceleration of 80g

Code for module is in section B.2.

5.2.3 Half Sine Wave

For this type of collision the acceleration goes from zero to maximum and back to zero, varying in a sinusoidal fashion. Governed by equation 5.4, where g_{max} is the maximum acceleration and duration refers to total collision duration.

Equation used

For: $t = 0 : 0.1 : \text{Duration}$

$$y(t) = g_{max} \times \sin\left(\frac{t \times \pi}{\text{Duration}}\right) \quad (5.4)$$

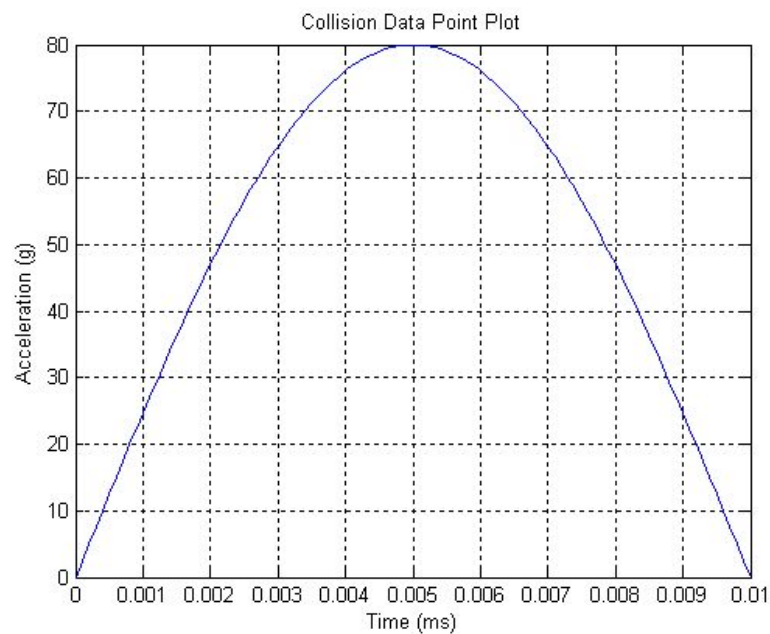


Figure 5.3: Plot of collision data points for half sine wave type collision with a duration of 10 ms and a peak acceleration of 80g

Code for module is in section B.3.

5.2.4 Triangular

For this type of collision the acceleration goes from zero to maximum and back to zero, varying in a linear fashion. Governed by equations 5.5 and 5.6, where g_{max} is the

maximum acceleration and duration refers to total collision duration.

Equation used

For: $t \leq \frac{\text{Duration}}{2}$

$$y = m \times t \quad (5.5)$$

For: $t > \frac{\text{Duration}}{2}$

$$y = -1 \times m \times t \quad (5.6)$$

Where: $m = \frac{g_{max} \times 2}{\text{Duration}}$

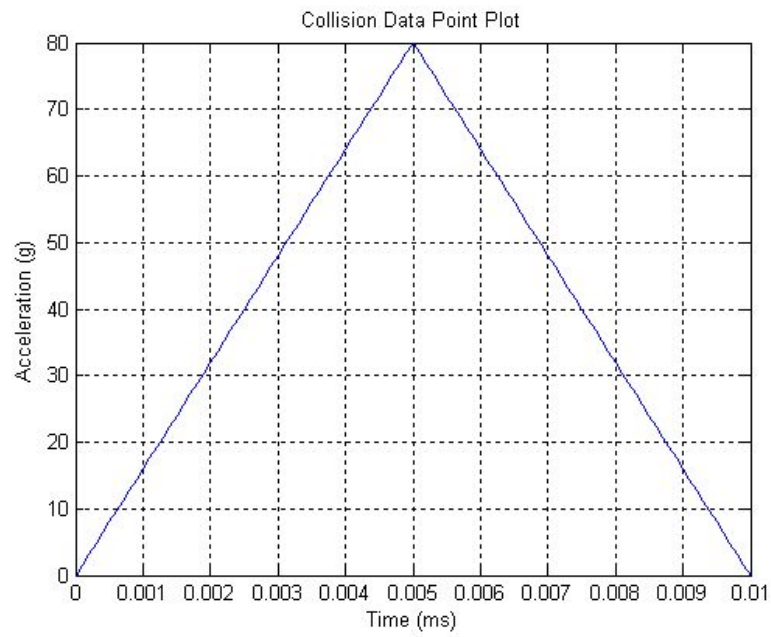


Figure 5.4: Plot of collision data points for triangular type collision with a duration of 10 ms and a peak acceleration of 80g

Code for module is in section B.4.

5.2.5 Trapezoidal

For this type of collision the acceleration goes for zero to maximum in a linear fashion between one quarter duration, stays at maximum duration until three quarters duration and decreases in a linear fashion from maximum to zero between three quarters and full duration with the $-1 \times$ the gradient used in the first quarter. Governed by equations 5.7, 5.8 and 5.9, where g_{max} is the maximum acceleration and duration refers to total collision duration.

Equation used

For: $t \leq \frac{\text{Duration}}{4}$

$$y = m \times t \quad (5.7)$$

For: $\frac{\text{Duration}}{4} < t \leq \frac{3 \times \text{Duration}}{4}$

$$y(t) = g_{max} \quad (5.8)$$

For: $t > \frac{3 \times \text{Duration}}{4}$

$$y = -1 \times m \times t \quad (5.9)$$

Code for module is in section B.5.

5.2.6 Excel File

This module is designed to allow the user to build collision data in excel for use to make a collision data point matrix. This means that if the user requires a shape not available in the previous module then they can make one in excel.

Code for module is in section B.6.

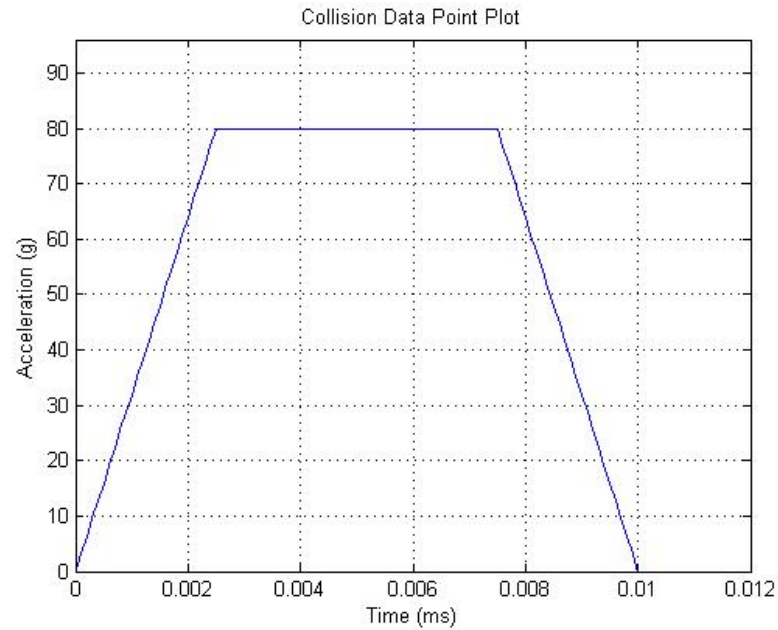


Figure 5.5: Plot of collision data points for trapezoidal type collision with a duration of 10 ms and a peak acceleration of 80g

5.2.7 Experimental Data

The datareader module is used to make the collision data point matrix from experimental data. The module allows the user to specify which lines of the file to use as impact data and which columns contain the time data and which columns contain the acceleration data.

Code for module is in section B.7.

5.3 Analysis Modules

There are four analysis modules, they utilise the Severity Index, the Head Injury Criterion, the Mean Strain Criterion and the Translational Energy Criterion. The only input required for each module is the collision data point matrix

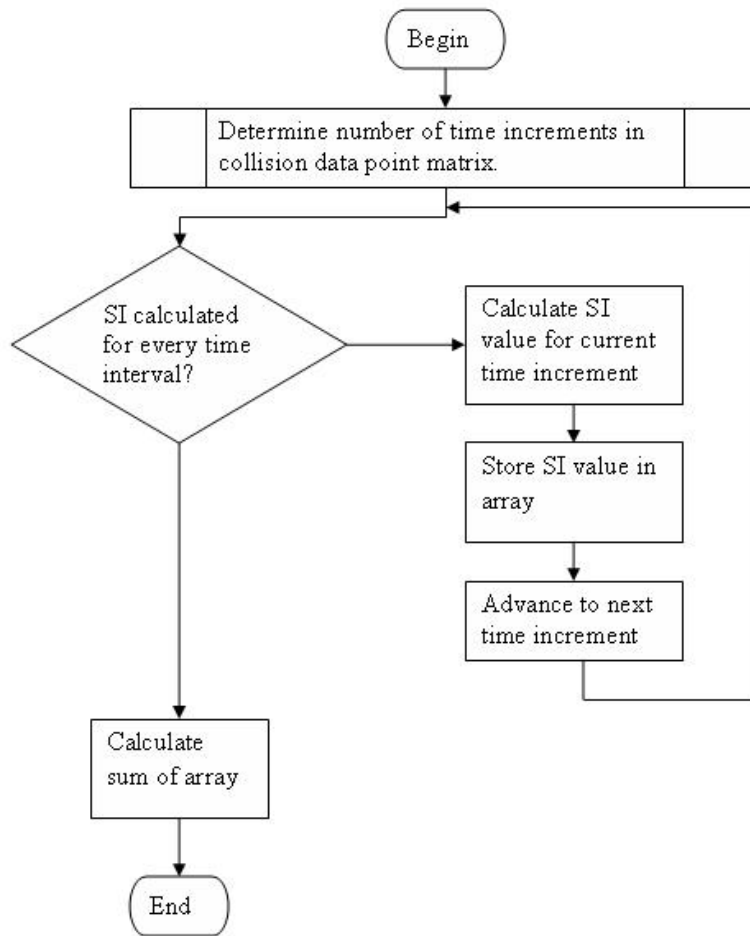


Figure 5.6: Flowchart for severity index module

5.3.1 Severity Index Module

The severity index module calculates the SI values for every time step in the collision data point matrix. The result is then stored in an array and the array summed to find the total SI value. Figure 5.6 shows a flowchart illustrating this process.

Code for module is in section B.8.

5.3.2 Head Injury Criterion Module

The HIC module obeys formula 3.2, also the time increment that gives the maximum HIC value needs to be found. This is done by calculating the HIC value for every possible time increment length and position, storing the values in an array then finding the maximum value. The process is illustrated in figure 5.7

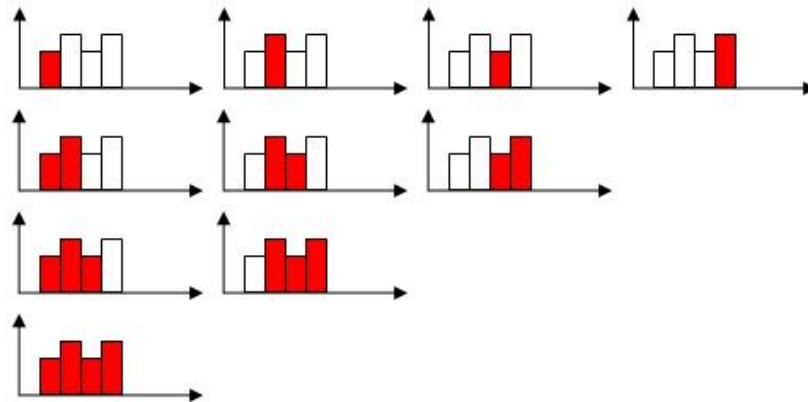


Figure 5.7: Iterations to find HIC value

The first step of the module is a loop. The loop calculates the area of every time increment in the collision data point matrix. The areas are then stored in an array called **chunk**.

The next part of the module is two nested loops. The variable **hcounter** is set to 1, and **hcounter** is used as an index in the two arrays later used. A **for** loop is initiated for chunk length, denoted as **CL**, varying **CL** from 1 to the total number of collision data points. This loop ensures that the HIC value for every chunk size is calculated. Inside this loop there is a **for** loop the chunk position denoted **CP**, the **CP** represents the start position of the chunk. The **CP** is varied from the very start position till the end of the chunk is the end of the total time duration. The two loops combined ensure that the HIC value will be calculated. Within the two loops the chunk end **CE** needs to be calculated. The total area is then calculated, this value is (insert details of where in the formula total area fits in)

Uses left hand sum to calculate the definite integral.

Uses a loop to create an array with the HIC values for each possible time start and end time.

The number of iterations to calculate the values in the array is a triangular number, dependent on the number of collision data points.

A triangular number is the number of points in a triangle of a certain height, for a triangle of height 2 there are 3 points, for a height of 3 there are 6 points etc.

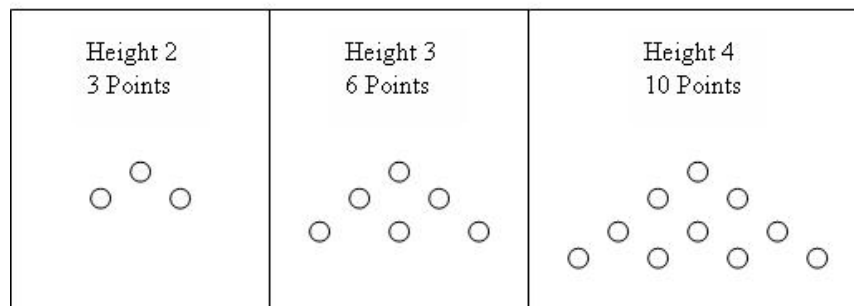


Figure 5.8: Number of points in various triangles, corresponding to triangular number

The number of iterations is given by equation 5.10 or equation 5.11

$$tri = \frac{n \times (n + 1)}{2} \quad (5.10)$$

$$tri = n + (n - 1) + \dots + 3 + 2 + 1 \quad (5.11)$$

Where tri is the triangular number corresponding to number of iterations required, and n is the number of collision data points. For a 10 ms impact we have 100 intervals (if the sampling frequency is 1000 hz), will require 5050 iterations, if the impact is 20 ms then 20100 will be required, if the impact is 100 ms then 500500 iterations are required. As the number of iterations increases the time required to run the module increases, for this reason it is necessary to include a warning message if the number of iterations is large enough to significantly increase the solve time.

Code for module is in section B.9.

5.3.3 Mean Strain Criterion Module

An iterative approach was taken to solve for the MSC, by analysing the FBD of the system the forces can be calculated. The Free Body Diagram is shown in figure 5.9. There are two loops; a loop that calculates the response to acceleration (**Force response loop**) and loop to allow the system vibration to die down (**Decay loop**).

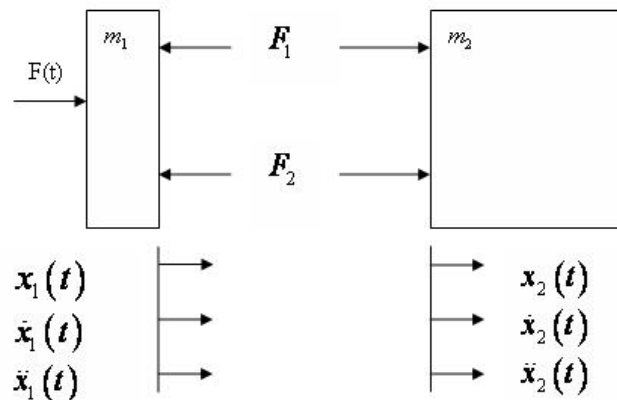


Figure 5.9: Free Body diagram of MSC

There are 4 stages in the MSC. (1) The initial values and constants are set. (2) Force response loop. (3) Decay loop. (4) The final calculation to find the MSC value.

Initial and constant values

The initial values of the acceleration, speed and displacement arrays for each of the two points are set. The constants representing the mass of both points, the damping coefficient and the spring stiffness coefficient are set. These values are shown in table 5.1.

Force response loop

The force response loop predicts the response of the model under acceleration defined in the collision data point matrix.

Table 5.1: Table of constant values used in HIC module

| Constant name | Value of constant |
|------------------------------|-------------------|
| Mass 1 | 0.5 kg |
| Mass 2 | 4.5 kg |
| Coefficient of damping | 1000 |
| Spring stiffness coefficient | 2,500,000 |

The time interval is calculated from the time of the next data point minus the time of the current collision data point.

Acceleration of mass 1 for next time interval is read from the collision data point matrix and stored in the array containing the values of mass 1 acceleration to be used in the next execution of the loop. Acceleration of mass 1 is stored in a1 array.

The reaction force of the damper is calculated using the relative velocities for mass 1 and 2 and the coefficient of damping. Force from damper is stored in fc array.

The reaction force of the spring is calculated using the distance between mass 1 and 2 and the spring stiffness coefficient. Force from spring is stored in the fk array.

The acceleration of mass 2 for next time interval is then calculated from the forces from the spring and damper and the mass of mass 2. Acceleration of mass 2 is stored in a2 array.

Velocity for mass 1 and 2 are then calculated using the acceleration of each mass for the current time step, the interval length and the individual masses. Velocity of mass 1 and 2 are stored in arrays v1 and v2 respectively.

Displacement for mass 1 and 2 are then calculated using the acceleration and speed of the mass at the current time interval, the length of the current time interval and the mass of the individual masses. Displacement 1 and 2 are stored in arrays d1 and d2 respectively.

The distance between the two masses is then calculated and stored in the diff array.

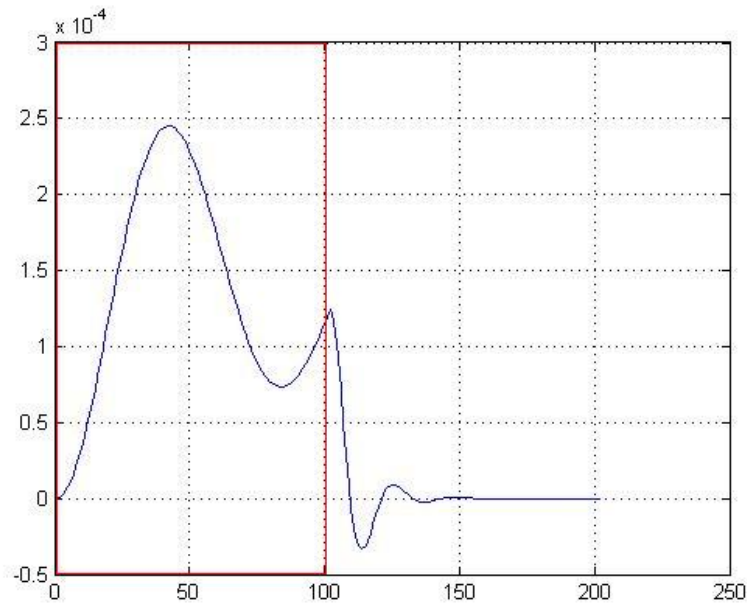


Figure 5.10: Distance between two masses for a 10 ms, 80g square impact response due to force response loop outlined.

Decay loop

The structure of the decay loop is almost identical to the structure of forced response loop but with two major differences; (1) the time interval is calculated as the time interval between the first two collision data points in the collision data point matrix. (2) the acceleration for mass 1 is calculated as using the force from the spring and the damper and the mass of mass 1.

Code for module is in section B.10.

5.3.4 Translational Energy Criterion Module

The TEC module (`translationalenergycriterion.m`) is very similar to the MSC module except there is force from an extra dampener and a very small mass added. The free body diagram is shown in figure 5.12. There are two loops; a loop that calculates the response to acceleration (**Force response loop**) and loop to allow the system vibration to die down (**Decay loop**).

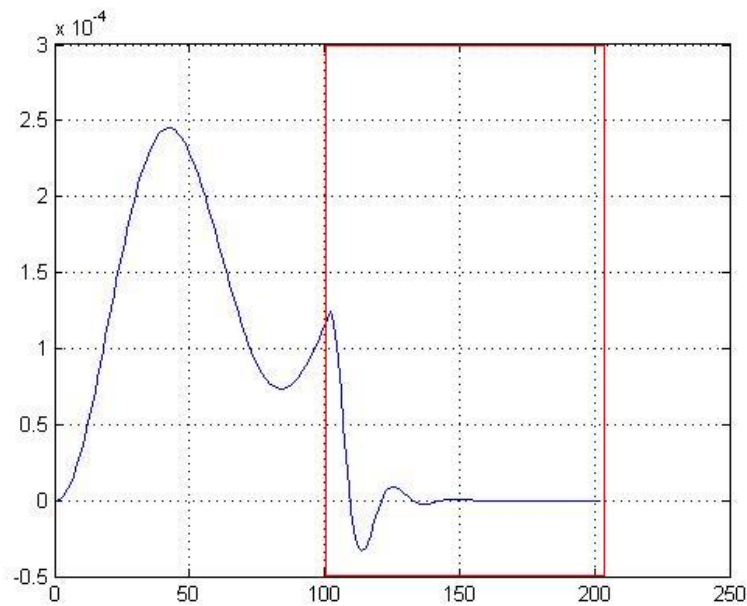


Figure 5.11: Distance between two masses for a 10 ms, 80g square impact response due to decay loop outlined

Initial and constant values

The initial values of the acceleration, speed and displacement arrays for each of the three points are set. The constants representing the mass of all three points, the damping coefficients and the spring stiffness coefficient are set. These values are shown in table 5.1.

Table 5.2: Table of constant values used in HIC module

| Constant name | Value of constant |
|------------------------------|-------------------|
| Mass 1 | 0.5 kg |
| Mass 2 | 4.5 kg |
| Coefficient of damping 1 | 1000 |
| Coefficient of damping 2 | 1000 |
| Spring stiffness coefficient | 2,500,000 |

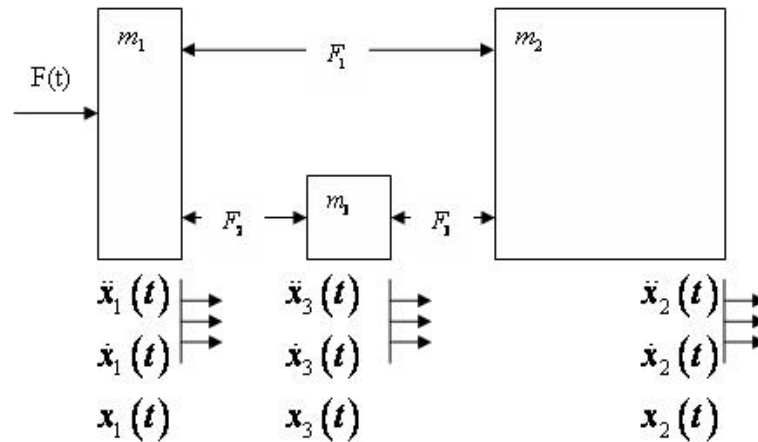


Figure 5.12: Free body diagram for TEC

Force response loop

The force response loop predicts the response of the model under acceleration defined in the collision data point matrix.

The time interval is calculated from the time of the next data point minus the time of the current collision data point.

Acceleration of mass 1 for next time interval is read from the collision data point matrix and stored in the array containing the values of mass 1 acceleration to be used in the next execution of the loop. Acceleration of mass 1 is stored in a1 array.

The reaction force of the damper is calculated using the relative velocities for mass 1 and 2 and the coefficient of damping. Force from damper is stored in f1 array.

The reaction force of the spring is calculated using the distance between mass 1 and 3 and the spring stiffness coefficient. Force from spring is stored in the f2 array.

The acceleration of mass 2 for next time interval is then calculated from the forces from the spring and damper and the mass of mass 2. Acceleration of mass 2 is stored in a2 array.

Velocity for mass 1, 2 and 3 are then calculated using the acceleration of each mass for the current time step, the interval length and the individual masses. Velocity of mass 1, 2 and 3 are stored in arrays v1, v2 and v3 respectively.

Displacement for mass 1 and 2 are then calculated using the acceleration and speed of the mass at the current time interval, the length of the current time interval and the mass of the individual masses. Displacement 1 and 2 are stored in arrays d1tec and d2tec respectively.

Displacement for mass 3 is then calculated using f2 and displacement of mass 2 at the current time interval. Result is stored in d3tec array.

Decay loop

The structure of the decay loop is almost identical to the structure of forced response loop but with two major differences; (1) the time interval is calculated as the time interval between the first two collision data points in the collision data point matrix. (2) the acceleration for mass 1 is calculated as using the force from the spring and the damper and the mass of mass 1.

Code for module is in section B.11.

5.4 Control Modules

Control modules control how the other modules are used to give the required output. They make sure that the collision data point matrix is built to user specification, and that the required analysis modules are executed.

The modules are either designed to provide the user with total control or to build up a database of results into in an excel file.

5.4.1 Main

The main module is designed to give the user maximum control, the user is asked how the data point matrix should be built and what analysis modules should be run. The modules are then executed as required. Figure 5.13 is a flow chart for main.m. The key input screens for main are shown in figure 5.14, which is used to determine how the collision data point matrix should be built and figure 5.15 which is used to determine which criterion will be used to analyse the collision data point matrix.

Code for module is in section B.12.

5.4.2 Collisionsim

The collisionsim module allows the user to select which idealised collision data shape to use and the collision duration and peak acceleration, other control modules call the collisionsim module to build a data point matrix using idealised impact data..

The module displays the shape options available, once the user has selected a shape the user is then asked to input required collision duration and peak acceleration. Then the builder module corresponding to the selection made is run. Code for module is in section B.13.

5.4.3 Buildtest

The buildtest module is used to compare the different impact shapes. The user is given options of: saving results to an excel file, plotting the collision data point matrix in MATLAB, displaying the results in MATLAB and using the area equaliser.

The buildtest module has two aspects, specification and calculation. Figure 5.16 shows the flowchart for the specification aspect, figure 5.17 shows the calculation aspect of the module. The predefined processes "square part", "Ramp part" etc are all nearly identical, figure 5.18 shows the general structure for these parts.

Area Equaliser

The area equaliser uses simple maths to modify the collision duration and peak acceleration so that the change in speed for each collision is the same. The equaliser assumes that the ratio of peak collision acceleration to collision duration and change in speed is constant for each collision type. The area of the plot is equal to the change in speed, from this the standard area can be defined for each collision type.

For a square collision type area is defined by equation 5.12

$$\text{Area} = \text{Peak Acceleration} \times \text{Collision duration} \quad (5.12)$$

For a ramp collision type area is defined by equation 5.13

$$\text{Area} = \frac{\text{Peak Acceleration} \times \text{Collision duration}}{2} \quad (5.13)$$

For a half sine wave collision type area is defined by equation 5.14

$$\text{Area} = \frac{\text{Peak Acceleration} \times \text{Collision duration} \times 2}{\pi} \quad (5.14)$$

For a triangular collision type area is defined by equation 5.15

$$\text{Area} = \frac{\text{Peak Acceleration} \times \text{Collision duration}}{2} \quad (5.15)$$

For a trapezoidal collision type area is defined by equation 5.16

$$\text{Area} = \frac{3 \times \text{Peak Acceleration} \times \text{Collision duration}}{4} \quad (5.16)$$

The user defines the standard collision duration (stdcoldur) and standard collision maximum (stdcolmax), from this the standard ratio (stdrat) and standard area (stdarea) are calculated using formulas 5.17 and 5.18 respectively.

$$stdrat = \frac{stdcolmax}{stdcoldur} \quad (5.17)$$

$$stdarea = stdcolmax \times stdcoldur \quad (5.18)$$

Using these two values the appropriate collision peak acceleration and collision duration can be determined for each impact type.

For a square collision type;

$$coldur = \sqrt{\frac{stdarea}{stdrat}}$$

$$colmax = coldur \times stdrat$$

For a ramp collision type;

$$coldur = \sqrt{\frac{stdarea \times 2}{stdrat}}$$

$$colmax = coldur \times stdrat$$

For a half sine wave collision type;

$$coldur = \sqrt{\frac{stdarea \times \pi}{2 \times stdrat}}$$

$$colmax = coldur \times stdrat$$

For a triangular collision type;

$$coldur = \sqrt{\frac{stdarea \times 2}{stdrat}}$$

$$colmax = coldur \times stdrat$$

For a trapezoidal collision type;

$$coldur = \sqrt{\frac{stdarea \times 4}{stdrat \times 3}}$$

$$colmax = coldur \times stdrat$$

Code for module is in section B.14.

5.4.4 Compare

The compare module is used to compare the results from each analysis module as the peak acceleration is changed. The compare module is comprised of two aspects **define** and **calculate**.

The define aspect gets the user to select; the idealised collision type, collision duration, maximum collision acceleration, name of excel file results should be saved in and the number of increments that are to be used.

The calculate aspect is a loop which compiles a collision data point matrix based on selected characteristics and determines the SI, HIC, MSC and TEC values. The loop executes the once for each iteration, changing the peak acceleration each time. The results of each iteration are saved in a matrix and when the loop has finished executing the matrix is written to the excel file specified by the user.

Code for module is in section B.15.

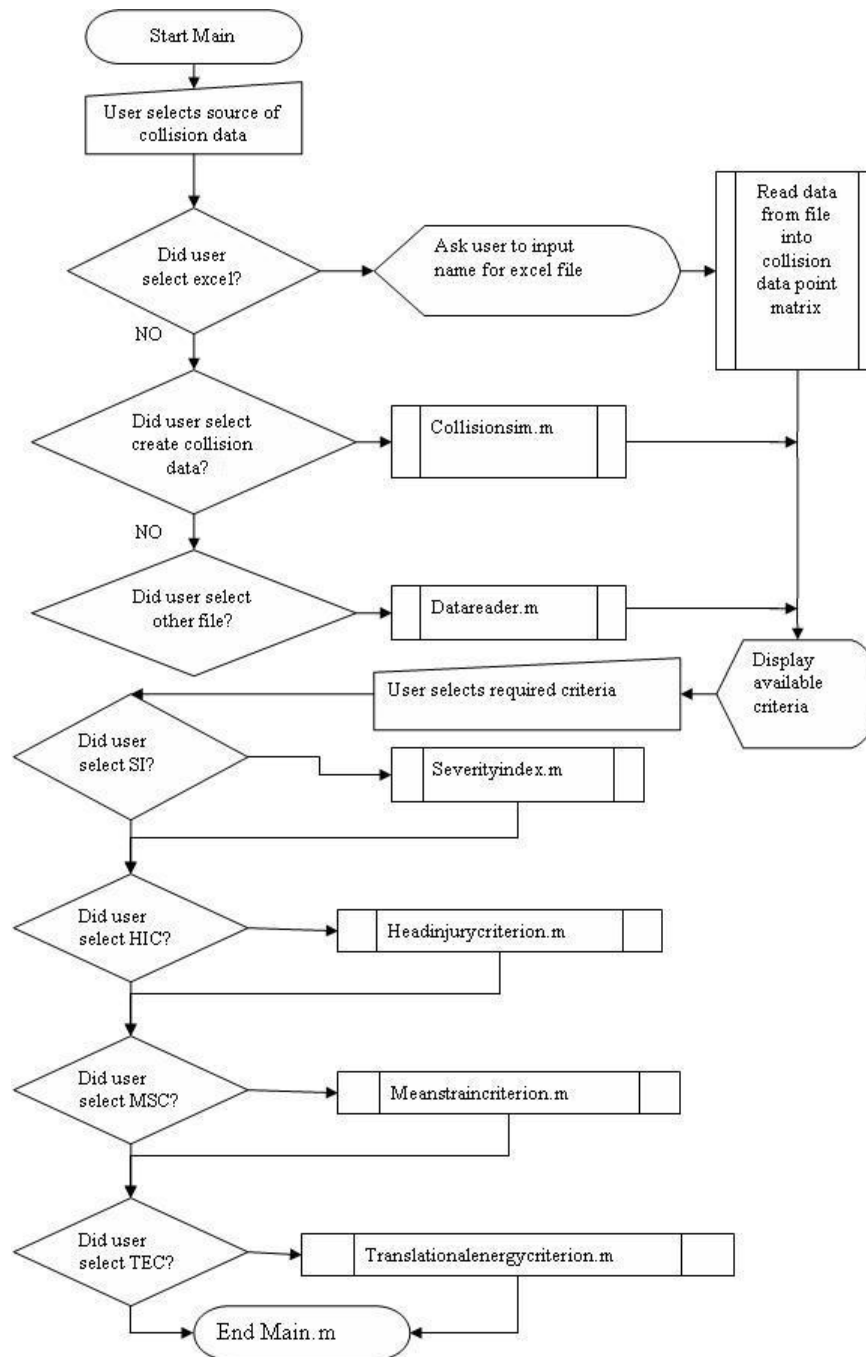


Figure 5.13: Flowchart for main.m

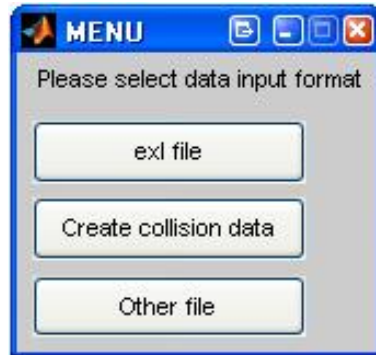


Figure 5.14: First display of main

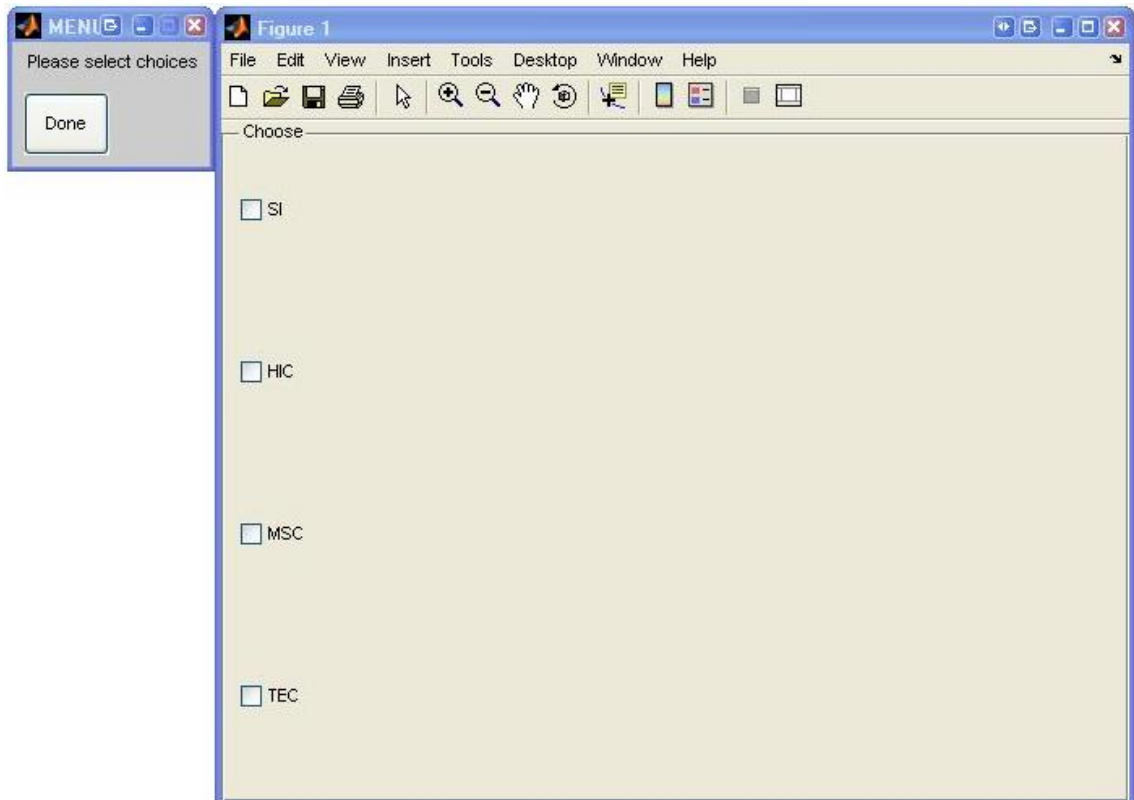


Figure 5.15: Second display of main

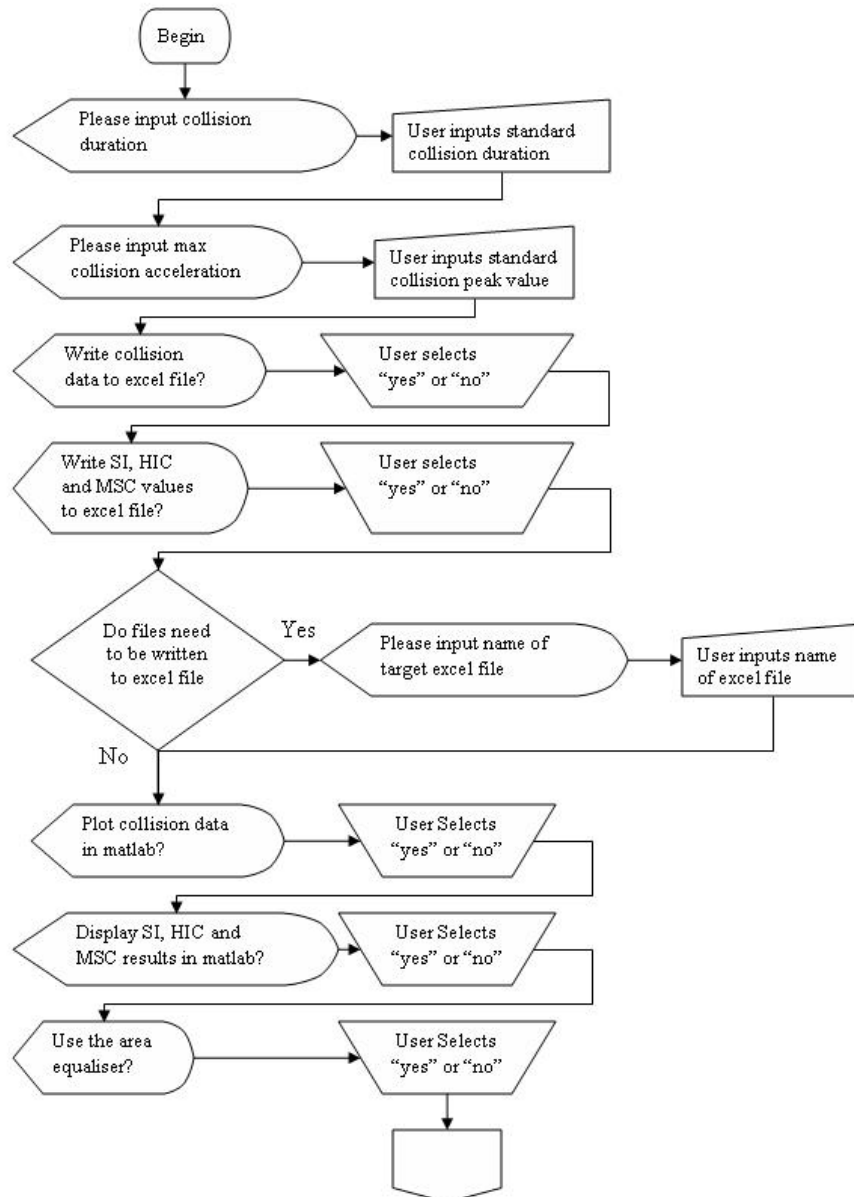


Figure 5.16: Flowchart for the specification aspect of buildtest module

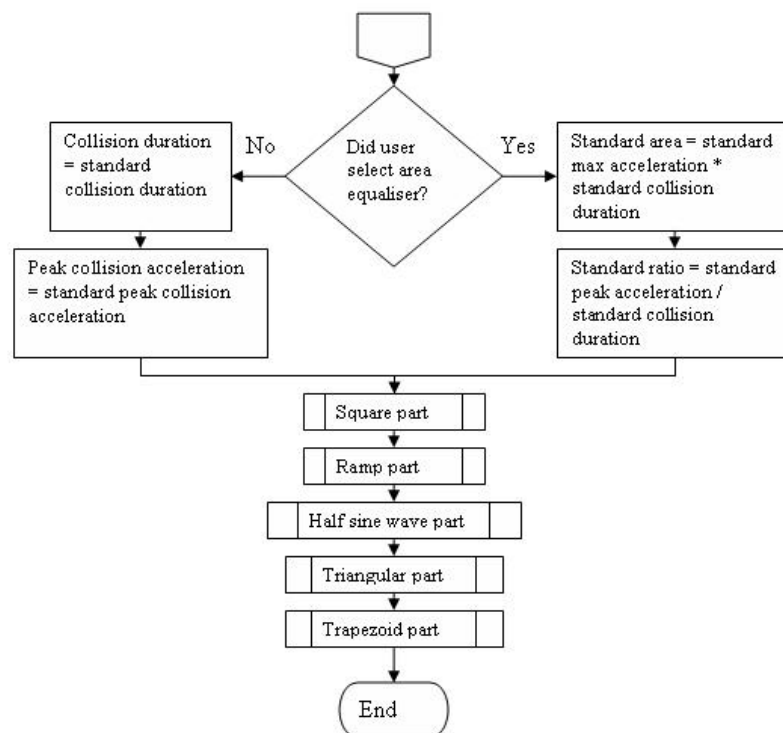


Figure 5.17: Flowchart for the calculation aspect of buildtest module

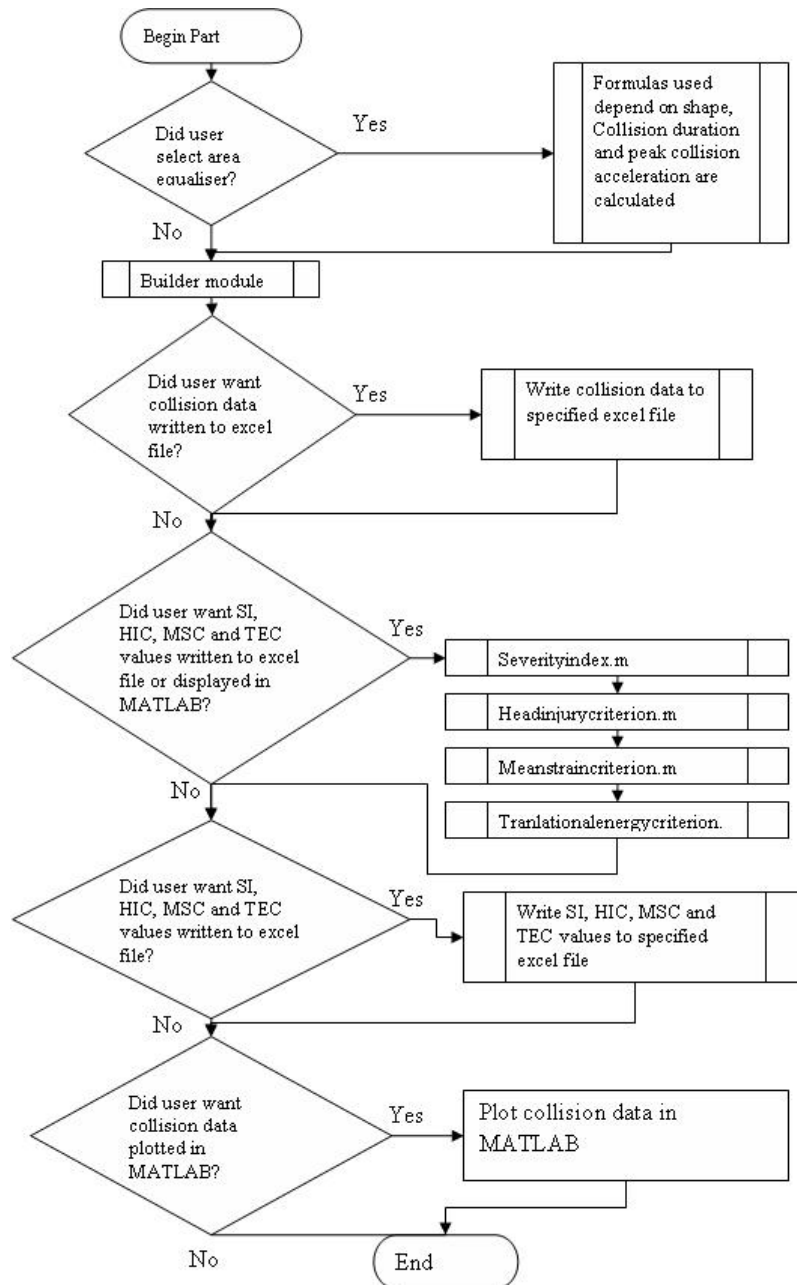


Figure 5.18: Generalised flowchart for each shape part

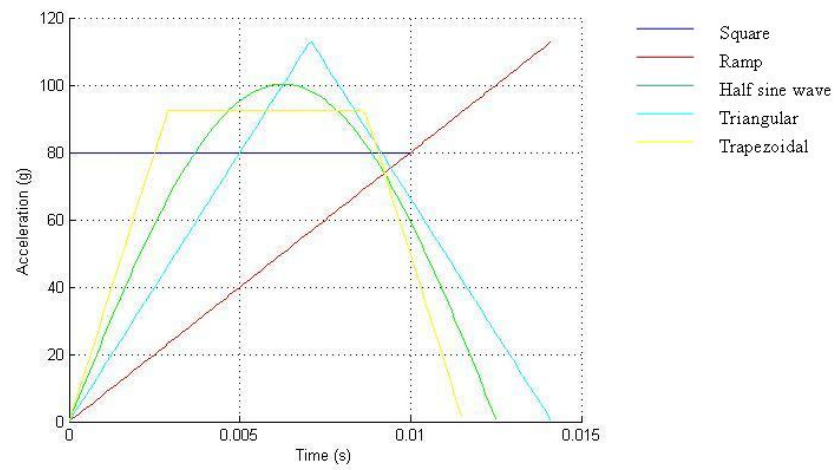


Figure 5.19: Plot of collision data using area equaliser.

5.5 Chapter Summary

The criteria mentioned previously can be utilised by MATLAB code to quickly calculate figures indicative of injury severity. By using the three different module types the roles required in analysing impact data can be broken down. This allows the same modules to be re-arranged to do additional tasks such as demonstrating criteria performance. The module types are; data builder, analysis and control.

The data builder modules create a matrix with the collision data, containing information on acceleration and time. The analysis modules use the matrix created by the data builder modules and the analysis technique described by their corresponding criterion to output the value indicative of collision severity. Control modules simply control which modules are run to do a specific task.

Chapter 6

Program Demonstration

6.1 Chapter Overview

In this chapter the main module will be used to determine the SI, HIC, MSC and TEC values for a range of collisions. The collision data point matrix will be compiled from both idealised and real collision accelerometer data. The results will be shown in a table with the information critical to the collision.

6.2 Idealised Collision Data

The idealised collision data tested will be created using the square, ramp, half sine wave, triangular and trapezoidal modules.

6.2.1 Square

The plot of the collision data point matrix for a 10ms, 80g collision is shown in figure 5.1. The results are show in table 6.1

Table 6.1: Table results and statistics for a 10 ms and 80g maximum acceleration square collision.

| SI | HIC | MSC | TEC | Equivalent impact velocity | Equivalent fall height |
|-------|-------|------------------------|--------|----------------------------|------------------------|
| 572.4 | 572.4 | 1.296×10^{-4} | 0.4708 | 7.848 m/s | 3.139 m |

Table 6.2: Table results and statistics for a 10 ms and 80g maximum acceleration ramp collision.

| SI | HIC | MSC | TEC | Equivalent impact velocity | Equivalent fall height |
|-------|-------|------------------------|--------|----------------------------|------------------------|
| 163.5 | 141.0 | 6.734×10^{-5} | 0.1536 | 3.924 m/s | 0.7848 m |

6.2.2 Ramp

The plot of the collision data point matrix for a 10ms, 80g ramp collision is shown in figure 5.2. The results are show in table 6.2

6.2.3 Half Sine Wave

The plot of the collision data point matrix for a 10ms, 80g half sine wave collision is shown in figure 5.3. The results are show in table 6.3

6.2.4 Triangular

The plot of the collision data point matrix for a 10ms, 80g triangular collision is shown in figure 5.4. The results are show in table 6.4

Table 6.3: Table results and statistics for a 10 ms and 80g maximum acceleration half sine wave collision.

| SI | HIC | MSC | TEC | Equivalent impact velocity | Equivalent fall height |
|-------|--------|-------------------------|--------|----------------------------|------------------------|
| 261.9 | 237.25 | 1.0615×10^{-4} | 0.3393 | 4.996 m/s | 1.272 m |

Table 6.4: Table results and statistics for a 10 ms and 80g maximum acceleration triangular collision.

| SI | HIC | MSC | TEC | Equivalent impact velocity | Equivalent fall height |
|-------|-------|------------------------|--------|----------------------------|------------------------|
| 163.5 | 141.0 | 8.917×10^{-5} | 0.2454 | 3.924 m/s | 0.7848 m |

Table 6.5: Table results and statistics for a 10 ms and 80g maximum acceleration trapezoidal collision.

| SI | HIC | MSC | TEC | Equivalent impact velocity | Equivalent fall height |
|-------|--------|-------------------------|--------|----------------------------|------------------------|
| 367.9 | 346.34 | 1.1689×10^{-4} | 0.4160 | 5.886 m/s | 1.7658 m |

6.2.5 Trapezoidal

The plot of the collision data point matrix for a 10ms, 80g trapezoidal collision is shown in figure 5.5. The results are show in table 6.5

6.3 Real Collision Data

This section looks at the results for the criteria for impact data created by tests. The test were performed by C. Snook in accordance with the guidelines set out in AS4422, at the time C. Snook was doing related research for a separate project. Five different surfaces were tested; Carlile No. 1 crumbed rubber mat, Sorbathane sheet, shredded woodchips and pine peelings. Different test heights were tested for each surface, a c size headform was used in all tests.

6.3.1 Carlile No. 1 Crumbed Rubber Mat

Table 6.6 shows the results for each criterion , figures 6.1, 6.2, 6.3, 6.4 and 6.5 show a plot of the collision data point matrix made from the test results.

Table 6.6: Table of results for test performed on Carlile

| SI | HIC | MSC | TEC | Impact Velocity | Fall Height |
|-------|--------|-------------------------|--------|-----------------|-------------|
| 167.9 | 145.1 | 7.4109×10^{-5} | 0.2052 | 3.132 m/s | 0.5 m |
| 490.5 | 425.5 | 1.2446×10^{-4} | 0.5528 | 4.429 m/s | 1 m |
| 959.5 | 827.39 | 1.692×10^{-4} | 0.9833 | 5.425 m/s | 1.5 m |
| 1823 | 1.544 | 2.206×10^{-4} | 1.6919 | 6.264 m/s | 2 m |
| 2218 | 1914 | 2.5243×10^{-4} | 2.0085 | 7.004 m/s | 2.5 m |

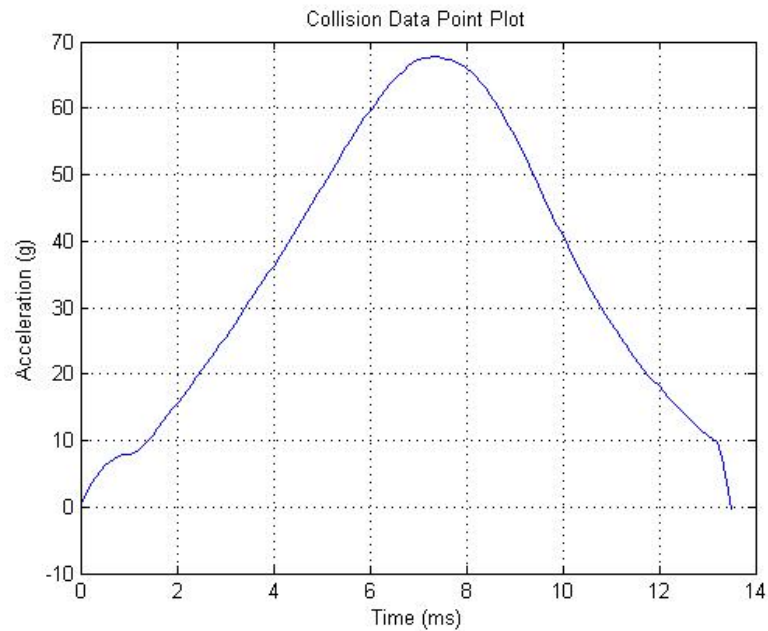


Figure 6.1: Collision data point matrix plot for 0.5m fall onto Carlile No. 1 Crumbed Rubber Mat

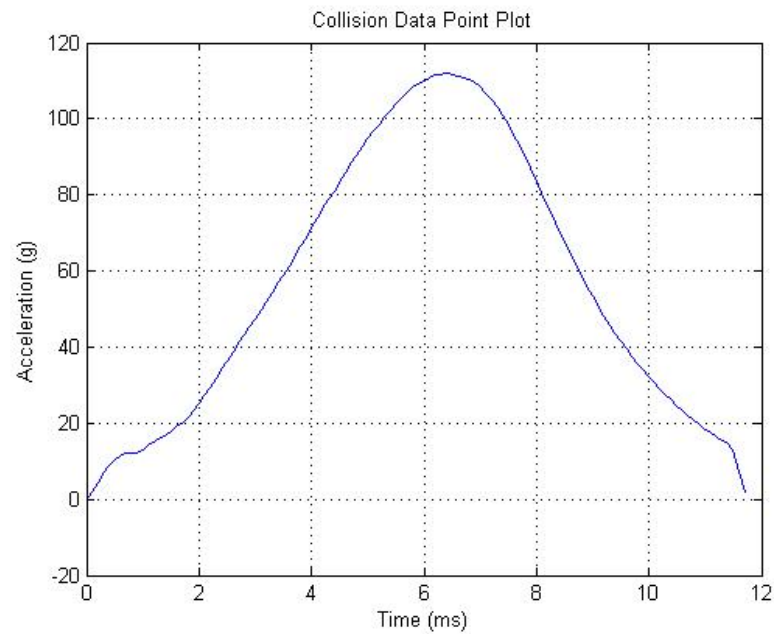


Figure 6.2: Collision data point matrix plot for 1m fall onto Carlile No. 1 Crumbed Rubber Mat

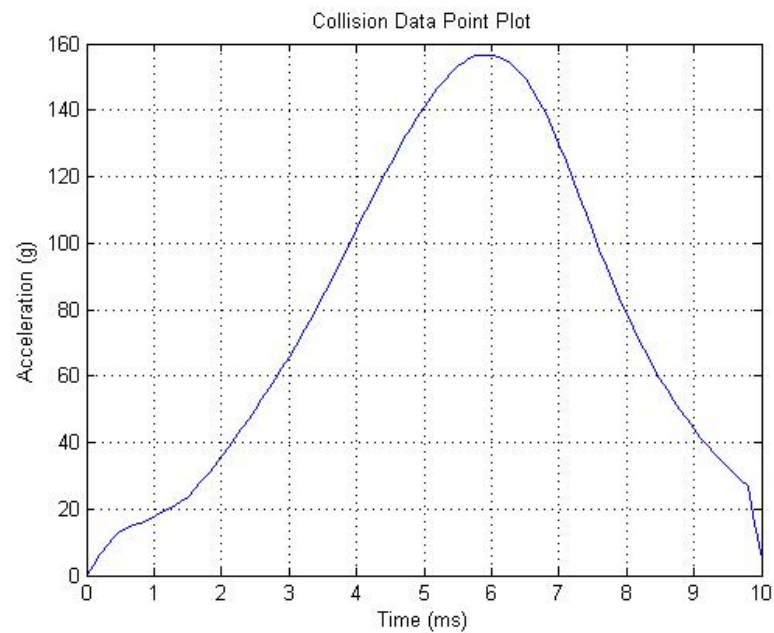


Figure 6.3: Collision data point matrix plot for 1.5m fall onto Carlile No. 1 Crumbed Rubber Mat

Table 6.7:

| SI | HIC | MSC | TEC | Impact Velocity | Fall Height | Sheet thickness |
|------|-------|-------------------------|--------|-----------------|-------------|-----------------|
| 476 | 412.2 | 1.3674×10^{-4} | 0.6053 | 3.132 m/s | 0.5 m | 3mm |
| 1697 | 1459 | 2.2561×10^{-4} | 1.4861 | 4.429 m/s | 1 m | 4mm |

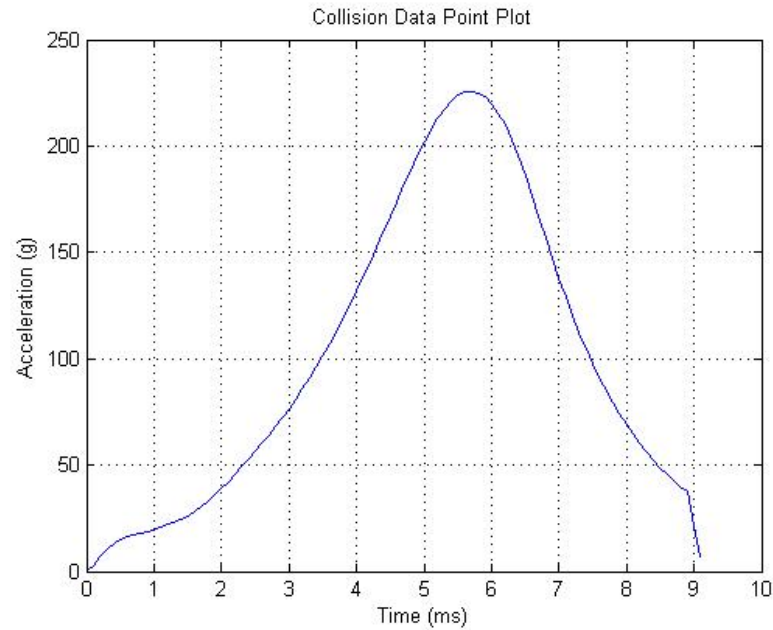


Figure 6.4: Collision data point matrix plot for 2m fall onto Carlile No. 1 Crumbed Rubber Mat

6.3.2 Sorbathane Sheet

Table 6.7 shows the results for each criterion, figures 6.6 and 6.7 show a plot of the collision data point matrix made from the test results.

6.3.3 Synthetic Mat

Table 6.8 shows the results for each criterion, figures 6.8, 6.9, 6.10, 6.11 and 6.12 show a plot of the collision data point matrix made from the test results.

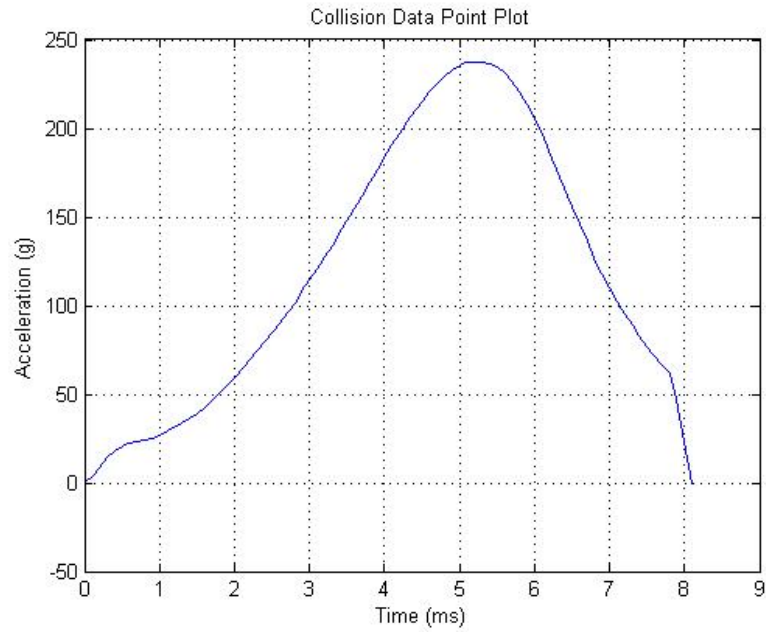


Figure 6.5: Collision data point matrix plot for 2.5m fall onto Carlile No. 1 Crumbed Rubber Mat

6.3.4 Shredded Woodchips

Table 6.9 shows the results for each criterion , figures 6.13, 6.14, 6.15, 6.16, 6.17, 6.18 and 6.19 show a plot of the collision data point matrix made from the test results.

Table 6.8:

| SI | HIC | MSC | TEC | Impact Velocity | Fall Height |
|-------|-------|-------------------------|--------|-----------------|-------------|
| 319 | 276.8 | 9.1767×10^{-5} | 0.4793 | 4.429 m/s | 1 m |
| 382.3 | 339.8 | 1.0353×10^{-4} | 0.4925 | 5.425 m/s | 1.5 m |
| 807.1 | 694.9 | 1.5514×10^{-4} | 1.105 | 6.264 m/s | 2 m |
| 988.8 | 832.7 | 1.4508×10^{-4} | 1.1782 | 7.004 m/s | 2.5 m |
| 1374 | 1189 | 1.7934×10^{-4} | 1.6326 | 7.672 m/s | 3 m |

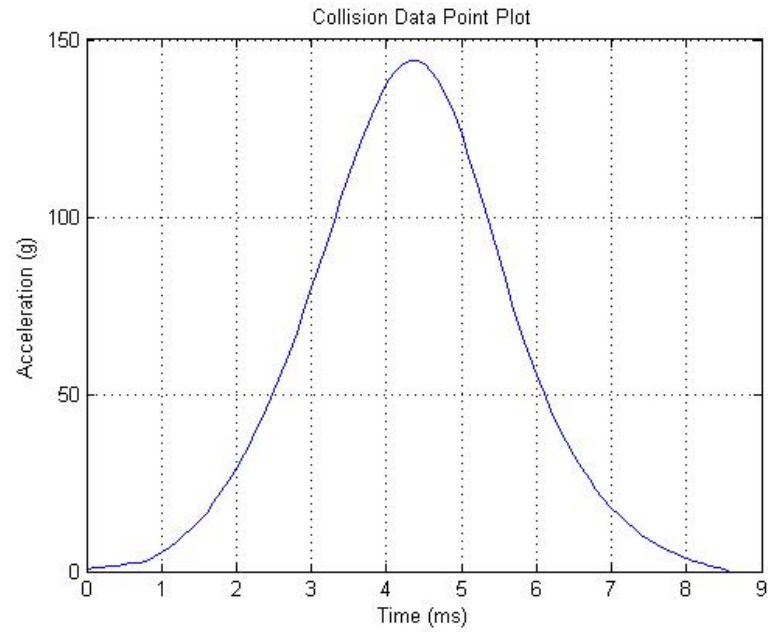


Figure 6.6: Collision data point matrix plot for 0.5m fall onto 3mm thick Sorbathane Sheet

6.3.5 Pine Peelings

Table 6.10 shows the results for each criterion, figures 6.8, 6.9, 6.10, 6.11 and 6.12 show a plot of the collision data point matrix made from the test results.

Table 6.9:

| SI | HIC | MSC | TEC | Impact Velocity | Fall Height |
|-------|-------|-------------------------|--------|-----------------|-------------|
| 78.12 | 67.56 | 4.7588×10^{-5} | 0.1056 | 2.426 m/s | 0.3 m |
| 166.5 | 143.5 | 6.8661×10^{-5} | 0.2154 | 3.132 m/s | 0.5 m |
| 354.4 | 303.5 | 9.7494×10^{-5} | 0.4773 | 3.706 m/s | 0.7 m |
| 665.3 | 567.4 | 7.4163×10^{-5} | 0.8839 | 4.429 m/s | 1 m |
| 1000 | 849.2 | 8.796×10^{-5} | 1.2769 | 4.852 m/s | 1.2 m |
| 1457 | 1223 | 1.0769×10^{-4} | 1.6811 | 5.241 m/s | 1.4 m |
| 1647 | 1384 | 1.1191×10^{-4} | 1.8756 | 5.425 m/s | 1.5 m |

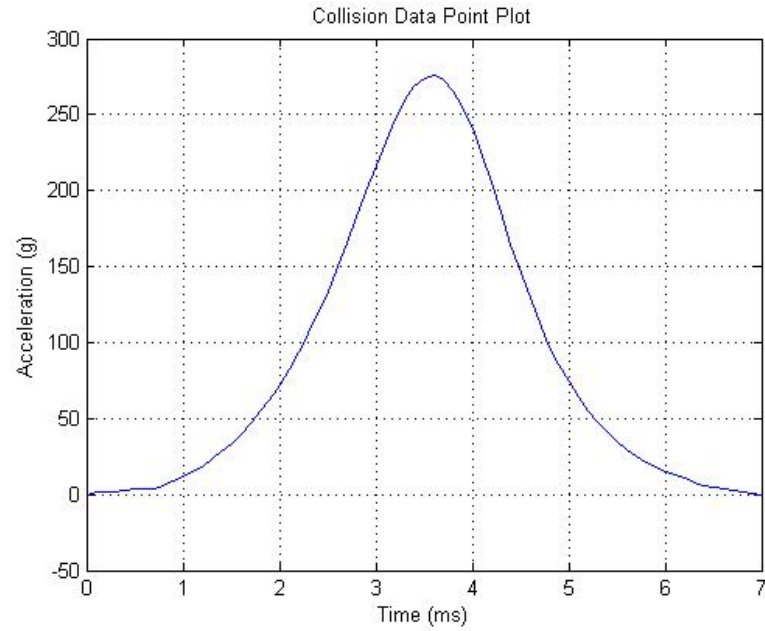


Figure 6.7: Collision data point matrix plot for 1m fall onto 4mm thick Sorbathane Sheet

Table 6.10:

| SI | HIC | MSC | TEC | Impact Velocity | Fall Height |
|-------|-------|-------------------------|--------|-----------------|-------------|
| 60.80 | 52.27 | 2.9226×10^{-5} | 0.0780 | 3.132 m/s | 0.5 m |
| 270.8 | 234.5 | 5.7813×10^{-5} | 0.3030 | 4.429 m/s | 1 m |
| 475.9 | 409.9 | 5.2444×10^{-5} | 0.5246 | 5.425 m/s | 1.5 m |
| 899.6 | 777.9 | 7.0915×10^{-5} | 0.9837 | 6.264 m/s | 2 m |
| 1712 | 1481 | 9.5446×10^{-5} | 1.7075 | 7.004 m/s | 2.5 m |

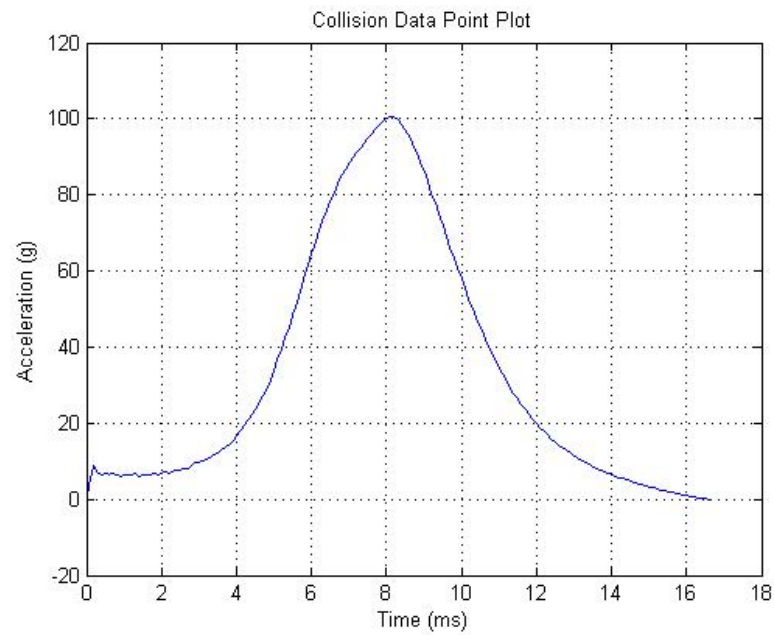


Figure 6.8: Collision data point matrix plot for 1m fall onto Synthetic Mat

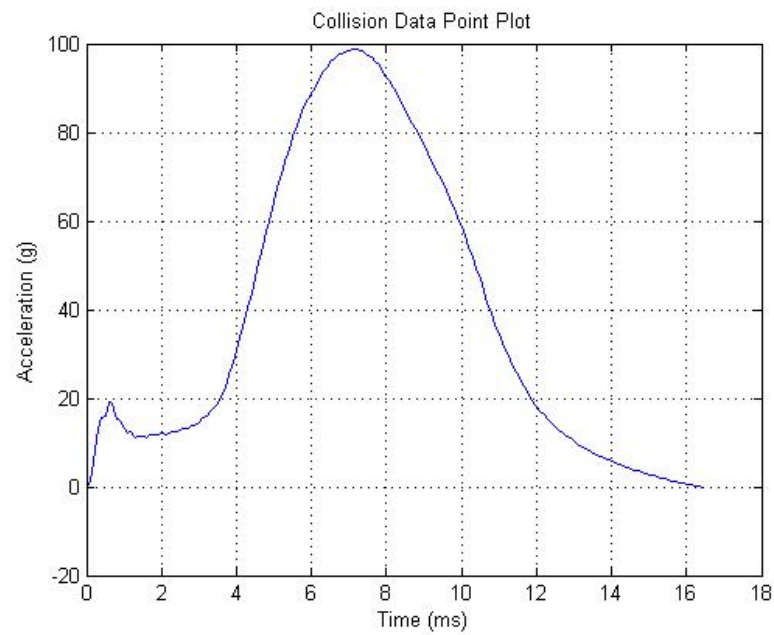


Figure 6.9: Collision data point matrix plot for 1.5m fall onto Synthetic Mat

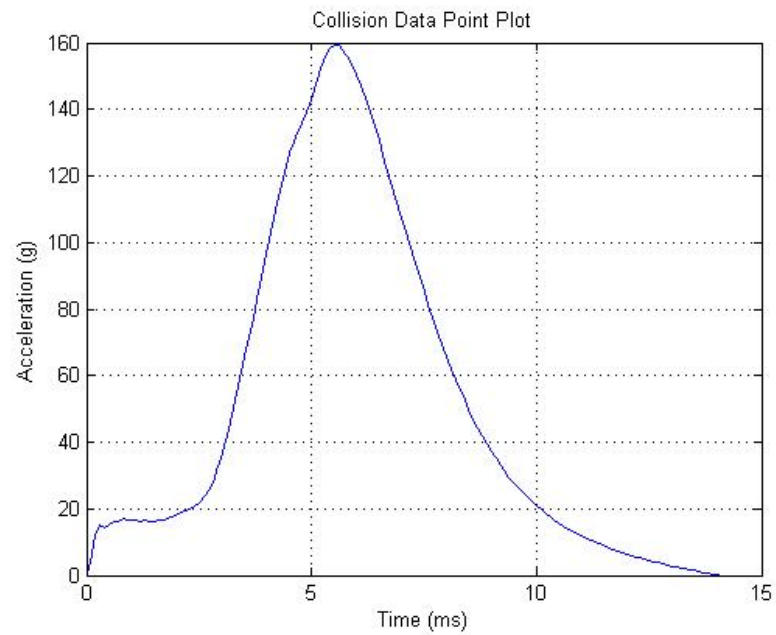


Figure 6.10: Collision data point matrix plot for 2m fall onto Synthetic Mat

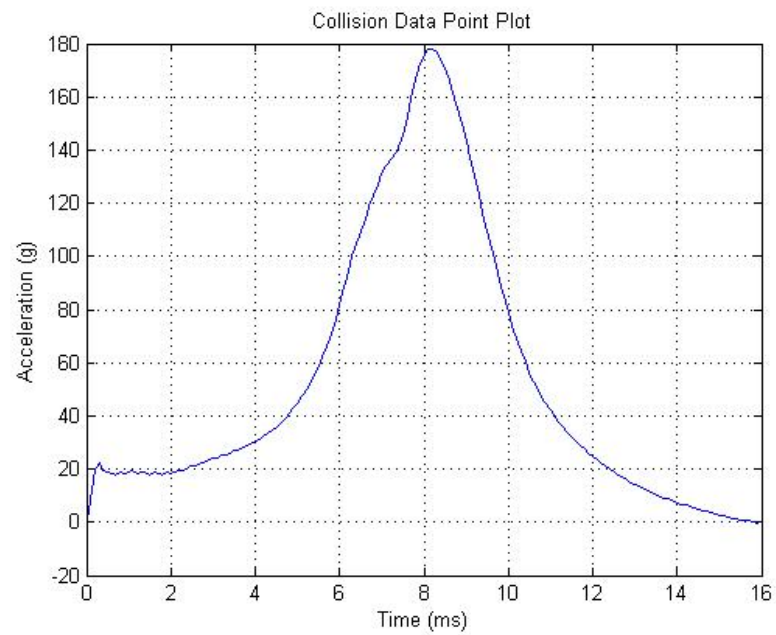


Figure 6.11: Collision data point matrix plot for 2.5m fall onto Synthetic Mat

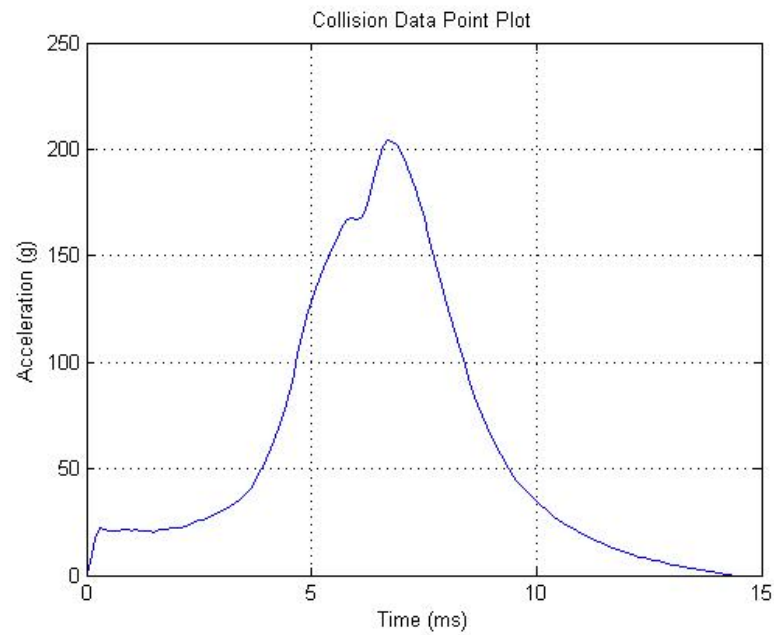


Figure 6.12: Collision data point matrix plot for 3m fall onto Synthetic Mat

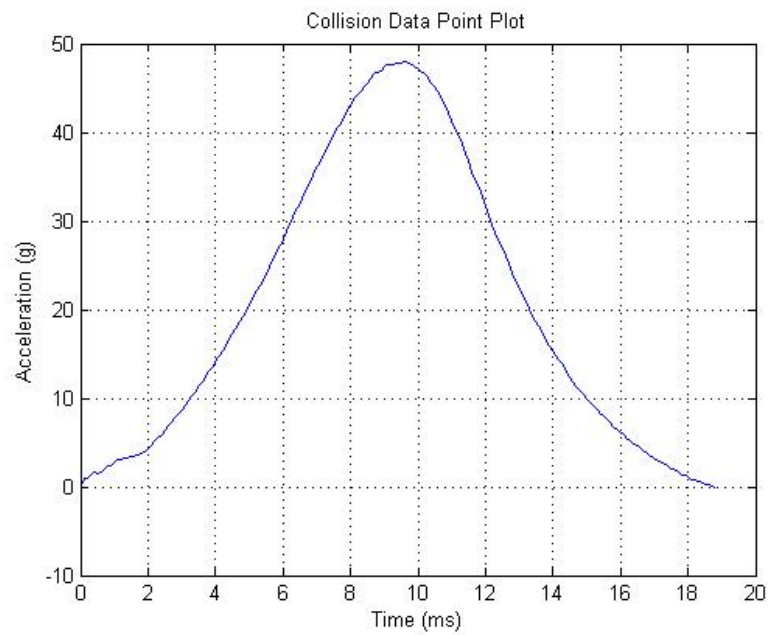


Figure 6.13: Collision data point matrix plot for 0.3m fall onto Shredded Woodchips

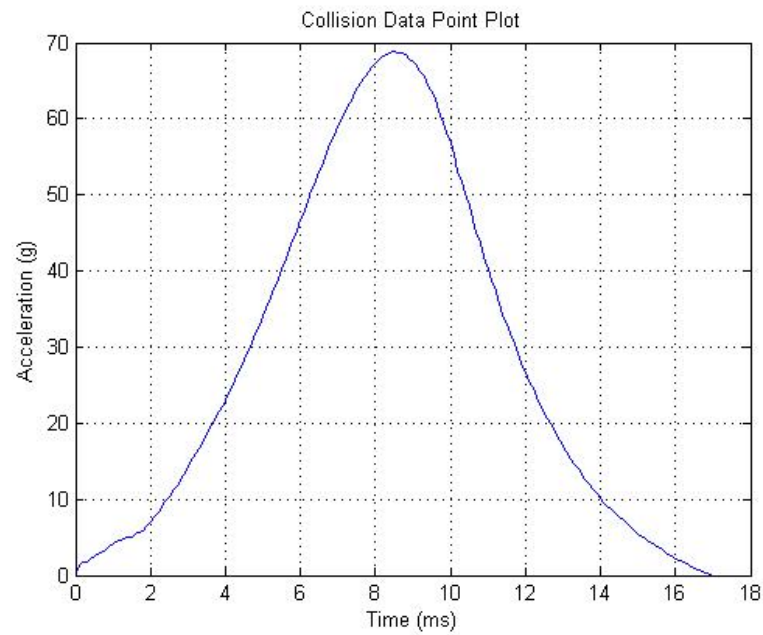


Figure 6.14: Collision data point matrix plot for 0.5m fall onto Shredded Woodchips

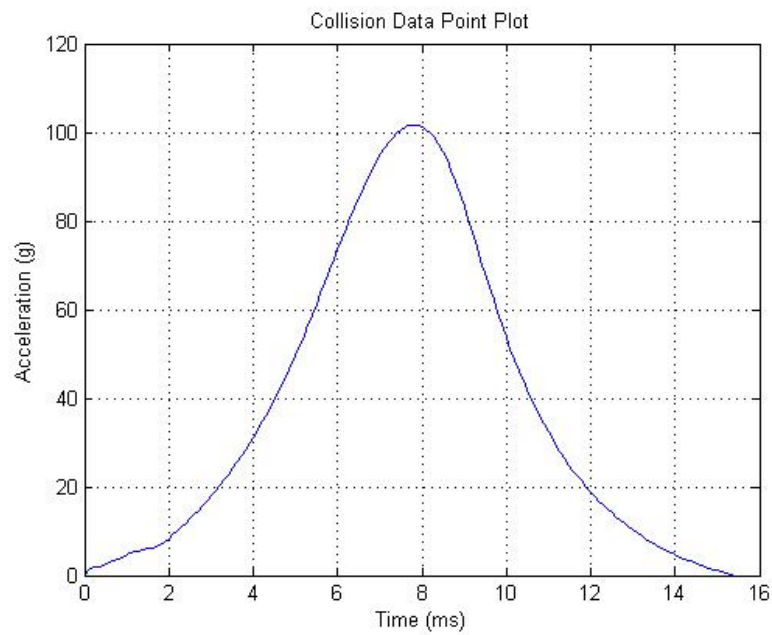


Figure 6.15: Collision data point matrix plot for 0.7m fall onto Shredded Woodchips

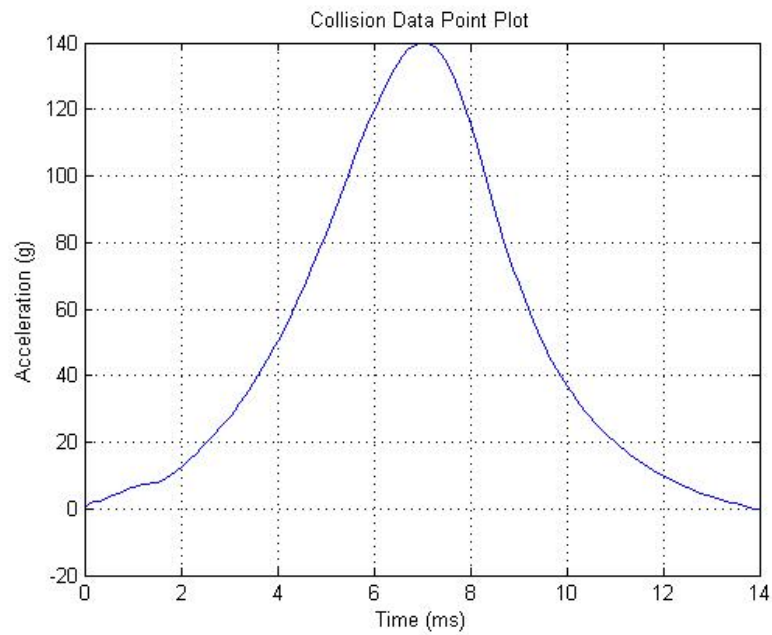


Figure 6.16: Collision data point matrix plot for 1m fall onto Shredded Woodchips

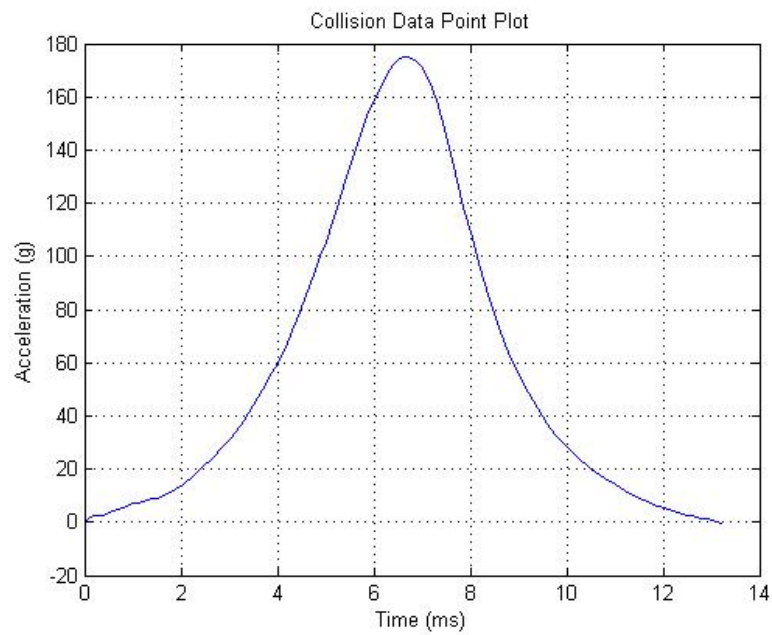


Figure 6.17: Collision data point matrix plot for 1.2m fall onto Shredded Woodchips

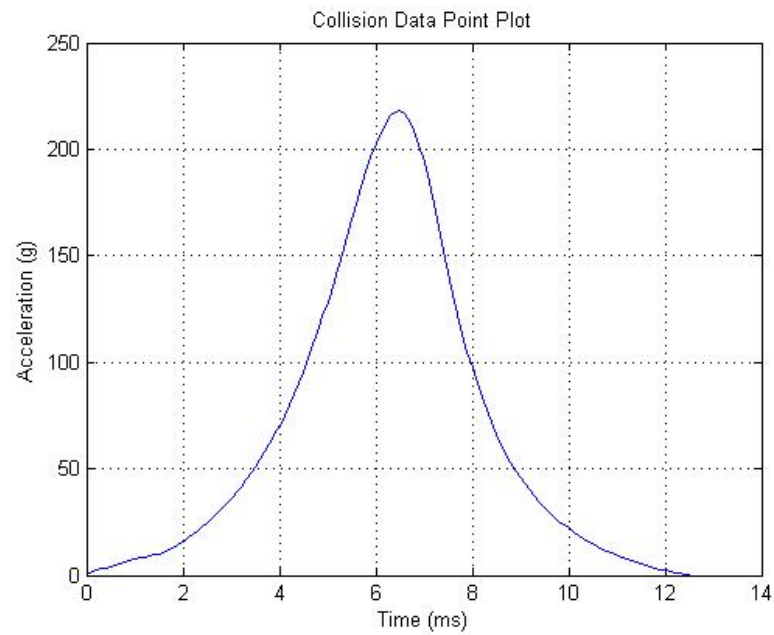


Figure 6.18: Collision data point matrix plot for 1.4m fall onto Shredded Woodchips

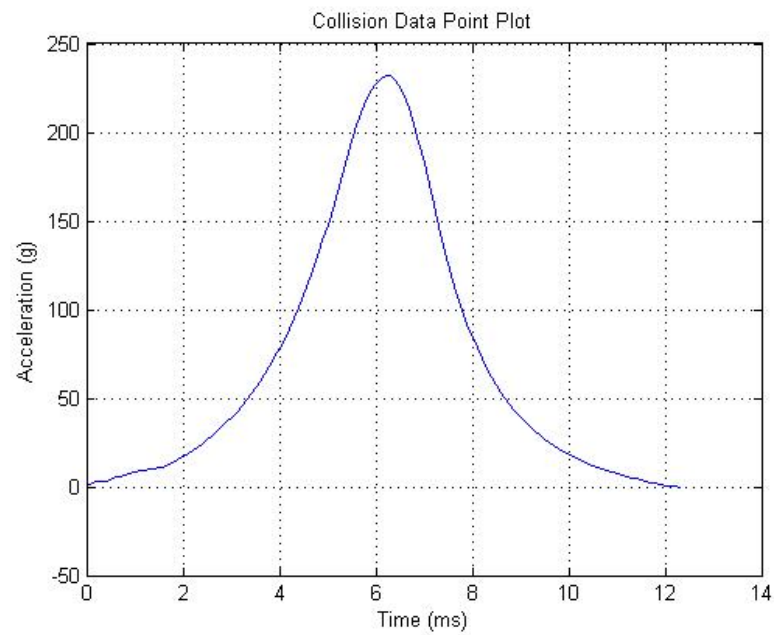


Figure 6.19: Collision data point matrix plot for 1.5m fall onto Shredded Woodchips

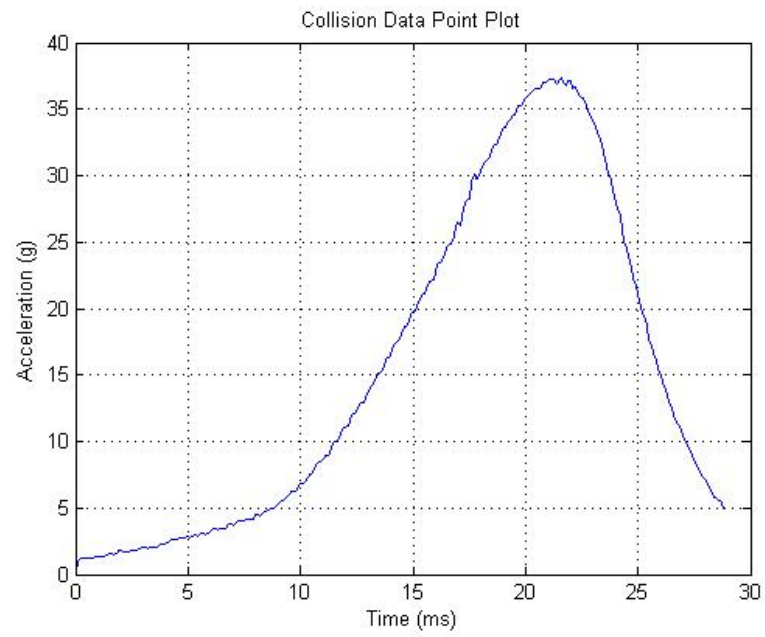


Figure 6.20: Collision data point matrix plot for 0.5m fall onto Pine Peelings

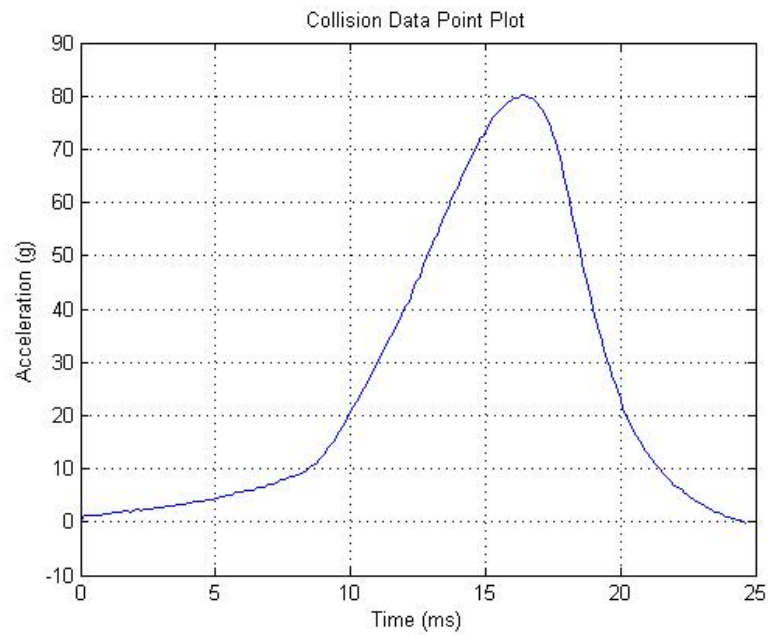


Figure 6.21: Collision data point matrix plot for 1m fall onto Pine Peelings

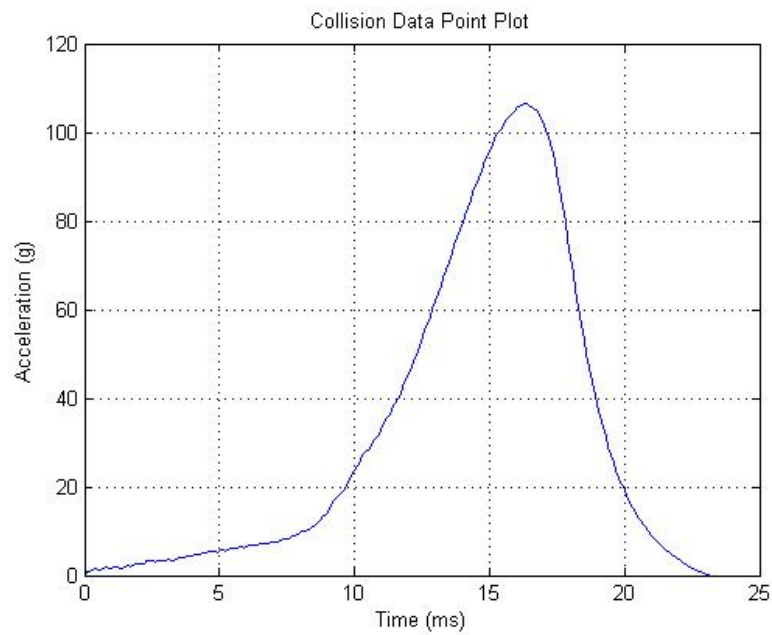


Figure 6.22: Collision data point matrix plot for 1.5m fall onto Pine Peelings

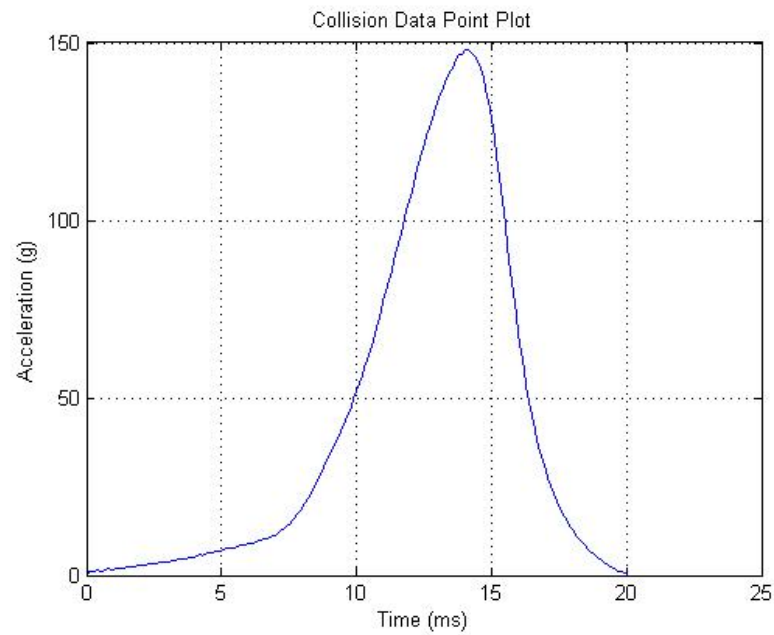


Figure 6.23: Collision data point matrix plot for 2m fall onto Pine Peelings

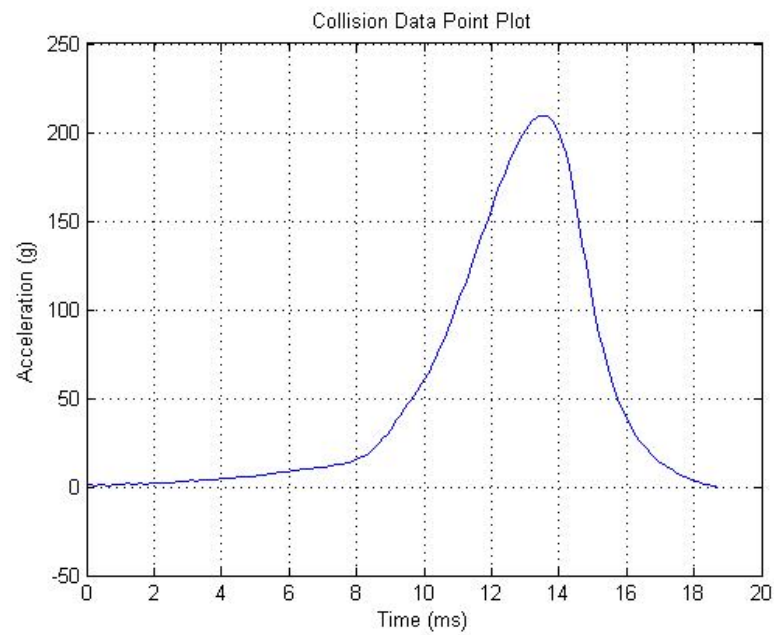


Figure 6.24: Collision data point matrix plot for 2.5m fall onto Pine Peelings

6.4 Chapter Summary

This chapter demonstrates the ability of the analysis program to analyse collision data from both idealised and test collision data. The idealised data was analysed for each available collision type, with the peak acceleration at 80g and the duration at 10ms. The test data analysed was for a range of playground surfaces at differing heights.

The idealised data demonstrates the relationship between the output values for the different criteria. The test data illustrates the safe fall heights for the difference surfaces.

Chapter 7

Review of Injury Criterion

7.1 Chapter Overview

The injury criteria for the human head have been developed over a number of decades, however there is still much debate as to which system is the most suitable and when a system is most suitable.

7.2 WSTC compared to the JHTC

The WSTC was first suggested 20 years before the JHTC, and there are significant differences between how the curves were formulated and the range of data they cover. No analysis modules were developed to use the WSTC or JHTC, as a result no numerical comparison was undertaken.

7.3 SI compared to the HIC

The SI was first suggested 10 years before the HIC. The major difference between the two is the formula. The formula for the SI applies the exponent and then averages compared to the HIC which averages and then applies the exponent. The effect of this

Table 7.1: Table results for SI and HIC for a collision duration of 10 ms and 80g maximum acceleration.

| Collision Type | SI value | HIC value | Reduction (Percentage) |
|----------------|----------|-----------|------------------------|
| Square | 572 | 572 | 0 |
| Ramp | 163 | 141 | 13.76 |
| Half Sine Wave | 262 | 237 | 9.41 |
| Triangular | 164 | 141 | 13.76 |
| Trapezoidal | 368 | 346 | 5.87 |

is that the SI value is much larger for short duration high peak impacts.

7.3.1 Comparison of results from different idealised collision shapes

Different collision shapes give different values for SI and HIC. To give an indication of what factors influence the different values, results were compiled using idealised collision data.

Using the control module `buildtest.m`, the SI and HIC values were calculated for each of the idealised collisions. For 10ms 80g collisions, 10ms 160g and 20ms 80g collisions, results are shown in tables 7.1, 7.2 and 7.3.

General comparison of tables 7.1, 7.2 and 7.3 show that the HIC value is always less than or equal to the SI value for idealised collision data, illustrating the effect of the reversing the averaging and exponent steps in analysis. Additionally comparison between tables 7.1 and 7.2 the reveal that the percentage reduction is not dependent on the maximum acceleration. Comparison of tables 7.1 and 7.3 reveal that the percentage reduction is not dependent on the collision duration.

Using the control module `buildtest.m` the SI and HIC values were calculated for each of the idealised collisions. For 10ms 80g collisions and 10ms 160g collisions using the area equaliser , results are shown in tables 7.4, 7.5 and 7.6.

Comparison of tables 7.4, 7.5 and 7.6 indicate that the percentage difference is inde-

Table 7.2: Table results for SI and HIC for a collision duration of 10 ms and 160g maximum acceleration.

| Collision Type | SI value | HIC value | Reduction (Percentage) |
|----------------|----------|-----------|------------------------|
| Square | 3238 | 3238 | 0 |
| Ramp | 925 | 798 | 13.76 |
| Half Sine Wave | 1481 | 1342 | 9.41 |
| Triangular | 925 | 798 | 13.76 |
| Trapezoidal | 2081 | 1959 | 5.87 |

Table 7.3: Table results for SI and HIC for a collision duration of 20 ms and 80g maximum acceleration.

| Collision Type | SI value | HIC value | Reduction (Percentage) |
|----------------|----------|-----------|------------------------|
| Square | 1145 | 1145 | 0 |
| Ramp | 327 | 282 | 13.76 |
| Half Sine Wave | 524 | 475 | 9.39 |
| Triangular | 327 | 282 | 13.76 |
| Trapezoidal | 736 | 693 | 5.88 |

Table 7.4: Table results for SI and HIC for a collision duration of 10 ms and 80g maximum acceleration using the area equaliser.

| Collision Type | SI value | HIC value | Reduction (Percentage) |
|----------------|----------|-----------|------------------------|
| Square | 572 | 572 | 0 |
| Ramp | 544 | 469 | 13.76 |
| Half Sine Wave | 765 | 523 | 31.6 |
| Triangular | 550 | 474 | 13.76 |
| Trapezoidal | 617 | 572 | 7.22 |

Table 7.5: Table results for SI and HIC for a collision duration of 10 ms and 160g maximum acceleration using the area equaliser.

| Collision Type | SI value | HIC value | Reduction (Percentage) |
|----------------|----------|-----------|------------------------|
| Square | 3238 | 3238 | 0 |
| Ramp | 3080 | 2656 | 13.76 |
| Half Sine Wave | 4325 | 2959 | 31.6 |
| Triangular | 3111 | 2683 | 13.75 |
| Trapezoidal | 3492 | 3240 | 7.22 |

pendent of both peak acceleration and time, the same as the results without the area equaliser.

7.3.2 Comparison of results with and without the area equaliser

The area equaliser is an aspect of the buildtest module that creates idealised collision data for the various shapes with equal change in velocity. Table 7.7 lists the results for a 10ms 80g collision with and without the area equaliser. The table shows that that equaliser increases both the SI and HIC values by approximately the same percentage. Illustrating the fact that the SI and HIC deal with changes in duration and peak acceleration the same way. For the tests without the equaliser the square impact gives the most severe collision. With the equaliser however, the SI values for both the trapezoidal and the half sine wave collisions are larger than the square collision. In comparison the HIC still rates the square collision as the most damaging collision,

Table 7.6: Table results for SI and HIC for a collision duration of 20 ms and 80g maximum acceleration using the area equaliser.

| Collision Type | SI value | HIC value | Reduction (Percentage) |
|----------------|----------|-----------|------------------------|
| Square | 1145 | 1145 | 0 |
| Ramp | 1089 | 939 | 13.76 |
| Half Sine Wave | 1529 | 1046 | 31.6 |
| Triangular | 1100 | 949 | 13.76 |
| Trapezoidal | 1235 | 1146 | 7.22 |

Table 7.7: Comparison of SI and HIC values with and without area equaliser for a 10ms 80g collision

| Collision Type | SI value | SI value (equaliser) | Increase (Percent) | HIC value | HIC value (equaliser) | Increase (Percent) |
|----------------|----------|-------------------------|-----------------------|-----------|--------------------------|-----------------------|
| Square | 572 | 572 | 0 | 572 | 572 | 0 |
| Ramp | 163 | 544 | 233.74 | 141 | 469 | 232.62 |
| Half Sine Wave | 262 | 765 | 191.98 | 237 | 523 | 120.67 |
| Triangular | 164 | 550 | 235.37 | 141 | 474 | 236.17 |
| Trapezoidal | 368 | 617 | 67.66 | 346 | 572 | 65.32 |

equal to the trapezoidal collision.

7.3.3 Comparison of results with increasing peak acceleration

As the peak acceleration is increased both the SI and the HIC values increase. To better understand how both systems responded, the values were recorded for linearly increasing peak acceleration.

Using the control module compare.m, the SI and HIC values were recorded for all collision types, using a collision duration of 10ms and maximum peak acceleration of 200g with values taken at 10g increments.

Figure 7.1 indicates that both the SI and the HIC increase non-linearly as the peak

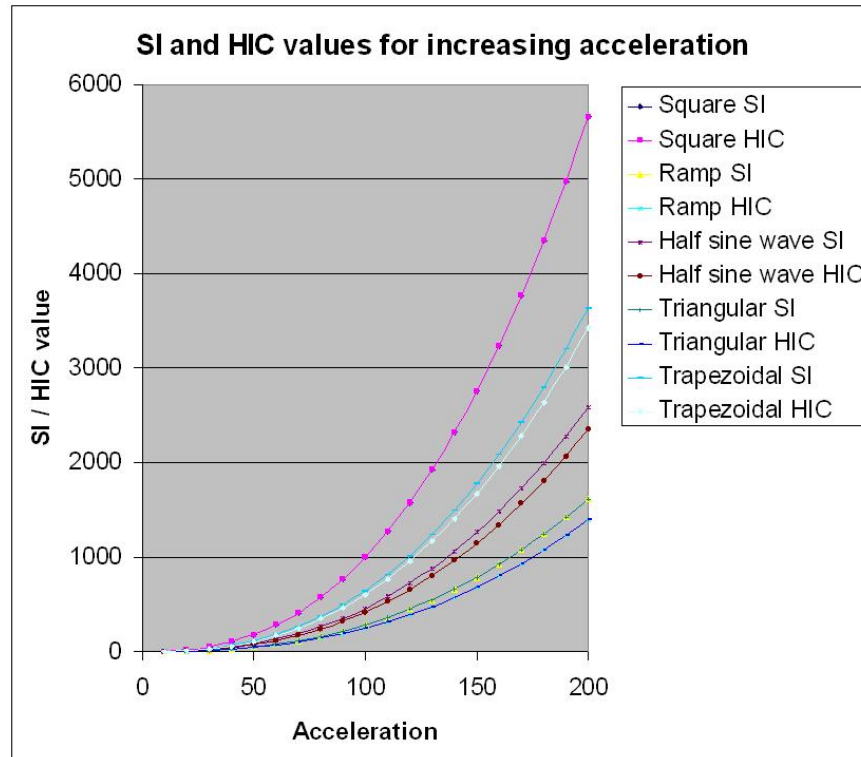


Figure 7.1: SI and HIC values for increasing peak acceleration.

acceleration is increased.

7.4 MSC compared to the TEC

The MSC criterion was first suggested 16 years before the TEC. The most significant change to the model is the role of the skull and the mechanisms used to indicate the severity of the impact.

7.4.1 Comparison of results from different idealised collision shapes

Figures 7.2, 7.3, 7.4, 7.5 and 7.6 shows the plot of the displacement between the two masses of each model. MSC is shown in blue and TEC is shown in red. Note the dramatic change in response at 0.01s. This is because every impact has a length of 10ms, and any response after this initial time is a result of the decay down loop.

Table 7.8: Table results for MSC and TEC for a collision duration of 10 ms and 80g maximum acceleration.

| Collision Type | MSC value (m) | TEC value (J) |
|----------------|-------------------------|---------------|
| Square | 1.2957×10^{-4} | 0.4708 |
| Ramp | 6.7343×10^{-5} | 0.1536 |
| Half Sine Wave | 1.0615×10^{-4} | 0.3393 |
| Triangular | 8.9176×10^{-5} | 0.2454 |
| Trapezoidal | 1.1689×10^{-4} | 0.4160 |

Table 7.8 Shows the results for the MSC and TEC for each collision type.

This table shows an agreement as to which collisions are more severe for the MSC and TEC. The order of magnitude in results is significantly different, making direct comparison difficult. The plot of the responses gives a better indication of how the two criteria respond to the different collisions. One of the most important points to note is that the MSC settles about zero displacement and the TEC settles about a point depending on how large the collision was. The reason for the TEC settling about this point is that it has no spring to restore the displacement between the two masses.

Square collision response

Figure 7.2 is a plot of the response of the two systems when exposed to a 10ms 80g square collision. Both systems reach maximum displacement at approximately 4ms, the TEC reaches a higher peak than the MSC. The plot indicates that the at the 10ms point the MSC is beginning to decay towards a new point of equilibrium, in comparison the TEC has moved closer to the origin and shows minimal signs of damping. When the forcing loop has completed both systems damp down to a constant value, the MSC damps down much quicker than the TEC.

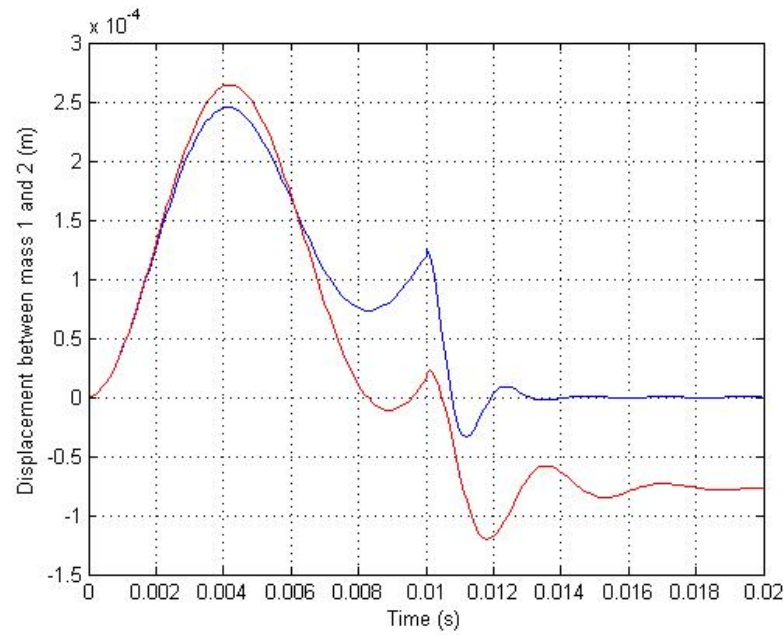


Figure 7.2: Response of MSC and TEC models when exposed to a square 10ms, 80g max impact.

Ramp collision response

Figure 7.3 is a plot of the response of the two systems when exposed to a 10ms 80g ramp collision. For the first 8ms of the collision the MSC and TEC system response is very similar. After 8ms the MSC continues to increase at a steady rate but the TEC stays close to constant value. Once the forcing loop is finished both systems move back towards the start position. The MSC quickly damps down to 0, the TEC shows significantly more overshoot and takes longer to damp down.

Table 7.9: Table results for MSC and TEC for a square collision with duration of 10 ms and 80g maximum acceleration.

| Point | MSC | TEC |
|--------------|-----------|---------|
| Max (s) | 4.1ms | 4.2ms |
| Max (mm) | 0.245mm | 0.264mm |
| Min (s) | 11.2ms | 11.8ms |
| Min (mm) | -0.0335mm | -0.1mm |
| Settle point | 0 | -0.77mm |

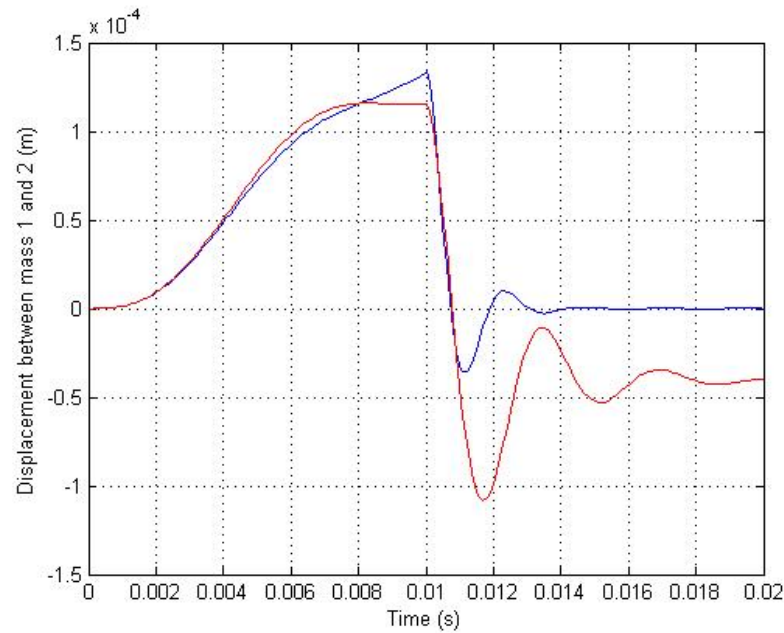


Figure 7.3: Response of MSC and TEC models when exposed to a ramp 10ms, 80g max impact.

Half sine wave collision response

Figure 7.4 is a plot of the response of the two systems when exposed to a 10ms 80g half sine wave collision. The response of both systems to this impact is smooth and similar with both experiencing a maximum peak at 6ms and a minimum peak at 10.5ms shortly after the damp down loop has begun. The TEC model experiences greater peaks and takes longer to damp down. The reason that the curve is so smooth between the two loops is that the collision ends with zero acceleration.

Table 7.10: Table results for MSC and TEC for a ramp collision with duration of 10 ms and 80g maximum acceleration.

| Point | MSC | TEC |
|--------------|------------|----------|
| Max (s) | 10ms | 8.3ms |
| Max (mm) | 0.134mm | 0.116mm |
| Min (s) | 11.2ms | 11.7ms |
| Min (mm) | -0.03576mm | -0.108mm |
| Settle point | 0 | 0.0395mm |

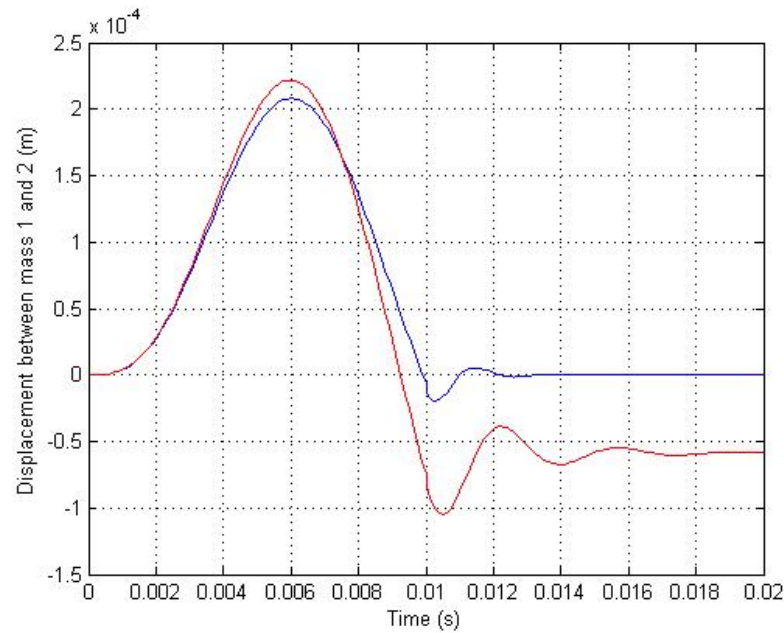


Figure 7.4: Response of MSC and TEC models when exposed to a half sine wave 10ms, 80g max impact.

Triangular collision response

Figure 7.5 is a plot of the response of the two systems when exposed to a 10ms 80g triangular collision. Both systems experience a maximum at 6.5ms and a minimum at 10.5ms, but note once again the TEC experiences greater maximums and lower minimums and took longer to die down. This response indicates that the TEC model experiences greater relative velocity than the MSC with the response between 4ms to 6ms and 8ms to 10ms, this has the affect that the TEC also experiences slightly more

Table 7.11: Table results for MSC and TEC for a half sine wave collision with duration of 10 ms and 80g maximum acceleration.

| Point | MSC | TEC |
|--------------|---------|-----------|
| Max (s) | 6ms | 6ms |
| Max (mm) | 0.208mm | 0.22mm |
| Min (s) | 10.3ms | 10.5ms |
| Min (mm) | -0.02mm | -0.1044mm |
| Settle point | 0 | -0.0585mm |

Table 7.12: Table results for MSC and TEC for a triangular collision with duration of 10 ms and 80g maximum acceleration.

| Point | MSC | TEC |
|--------------|----------|-----------|
| Max (s) | 6.4ms | 6.4ms |
| Max (mm) | 0.1845mm | 0.1953mm |
| Min (s) | 10.2ms | 10.4ms |
| Min (mm) | -.0352mm | -0.1029mm |
| Settle point | 0 | -0.048mm |

inertial affect.

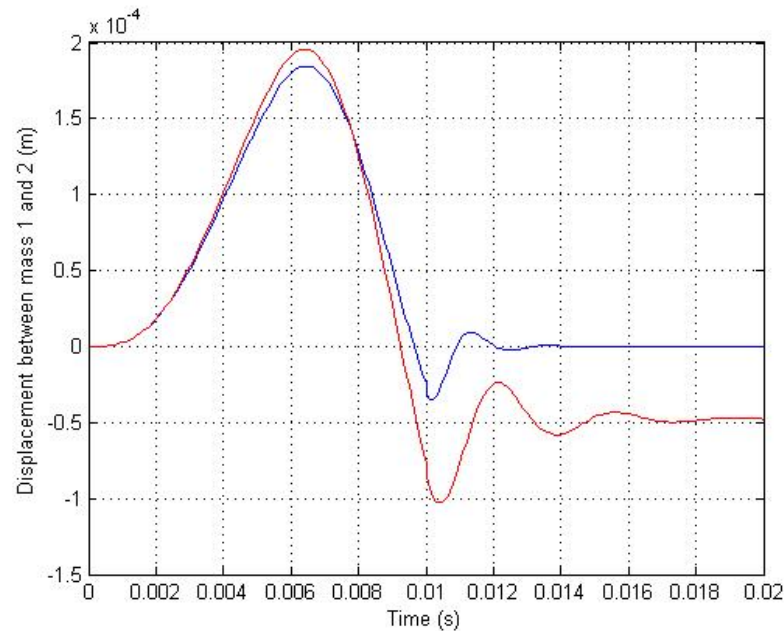


Figure 7.5: Response of MSC and TEC models when exposed to a triangular 10ms, 80g max impact.

Trapezoidal collision response

Figure 7.6 is a plot of the response of the two systems when exposed to a 10ms 80g triangular collision. Both systems experience maximum at relative displacement at 5.5ms and minimum at 10.5ms, the TEC experienced greater maximum and minimum values and took longer to damp down.

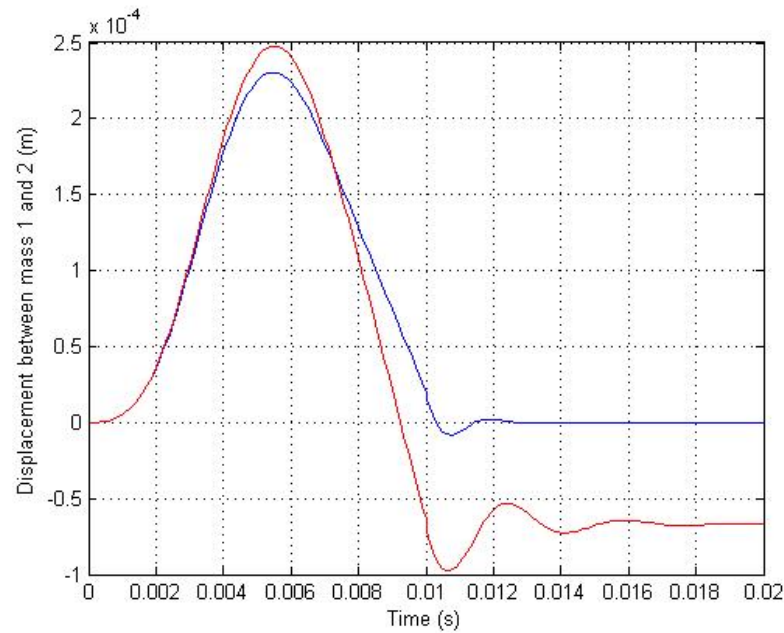


Figure 7.6: Response of MSC and TEC models when exposed to a trapezoidal 10ms, 80g max impact.

7.4.2 Comparison of results with and without the area equaliser

The area equaliser is an aspect of the buildtest module that creates idealised collision data for the various shapes with equal change in velocity. Table 7.15 lists the results for a 10ms 80g collision with and without the area equaliser. The MSC values from the equaliser data indicate that the square collision is always the most severe collision, in comparison the TEC indicates that the trapezoidal collision is the most severe collision. Table ??etter demonstrates this phenomom.

Table 7.13: Table results for MSC and TEC for a trapezoidal collision with duration of 10 ms and 80g maximum acceleration.

| Point | MSC | TEC |
|--------------|----------|-----------|
| Max (s) | 5.5ms | 5.5ms |
| Max (mm) | 0.2305mm | 0.2477mm |
| Min (s) | 10.7ms | 10.7ms |
| Min (mm) | -0.008mm | -0.0977mm |
| Settle point | 0 | -0.0665mm |

Table 7.14: Comparison of MSC and TEC values with and without area equaliser for a 10ms 80g collision

| Collision Type | MSC value | MSC value (equaliser) | TEC value | TEC value (equaliser) |
|----------------|-------------------------|--------------------------|-----------|--------------------------|
| Square | 1.2957×10^{-4} | 1.2957×10^{-4} | 0.4708 | 0.4718 |
| Ramp | 6.734×10^{-5} | 9.698×10^{-5} | 0.1536 | 0.33937 |
| Half Sine Wave | 1.0615×10^{-4} | 1.219×10^{-4} | 0.3393 | 0.5346 |
| Triangular | 8.92×10^{-5} | 1.176×10^{-4} | 0.2454 | 0.5086 |
| Trapezoidal | 1.1689×10^{-4} | 1.262×10^{-4} | 0.4159 | 0.5569 |

Table 7.15: Comparison of MSC and TEC values with the area equaliser in relation to collision shape

| Collision Type | MSC value | Collision Type | TEC value |
|----------------|-------------------------|----------------|-----------|
| Square | 1.2957×10^{-4} | Trapezoidal | 0.5569 |
| Difference | 3.370×10^{-6} | Difference | 0.0223 |
| Trapezoidal | 1.262×10^{-4} | Half Sine Wave | 0.5346 |
| Difference | 4.3×10^{-6} | Difference | 0.026 |
| Half Sine Wave | 1.219×10^{-4} | Triangular | 0.5086 |
| Difference | 4.3×10^{-6} | Difference | 0.0368 |
| Triangular | 1.176×10^{-4} | Square | 0.4718 |
| Difference | 2.062×10^{-5} | Difference | 0.1328 |
| Ramp | 9.698×10^{-5} | Ramp | 0.339 |

7.4.3 Comparison of results with increasing peak acceleration

As the peak acceleration is increased both the MSC and the TEC values increase. To better understand how both systems responded, the values were recorded for linearly increasing peak acceleration.

Using the control module compare.m, the MSC and TEC values were recorded for all collision types, using a collision duration of 10ms and maximum peak acceleration of 200g with values taken at 10g increments.

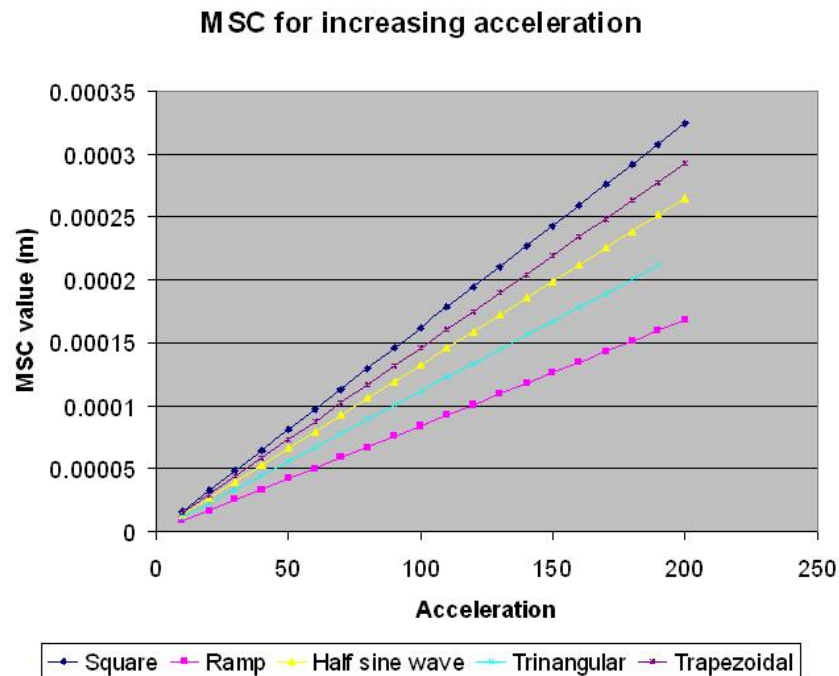


Figure 7.7: MSC value for increasing peak acceleration.

These two figure clearly indicate that the MSC value increases linearly as the peak acceleration increases whereas the TEC value increases non-linearly.

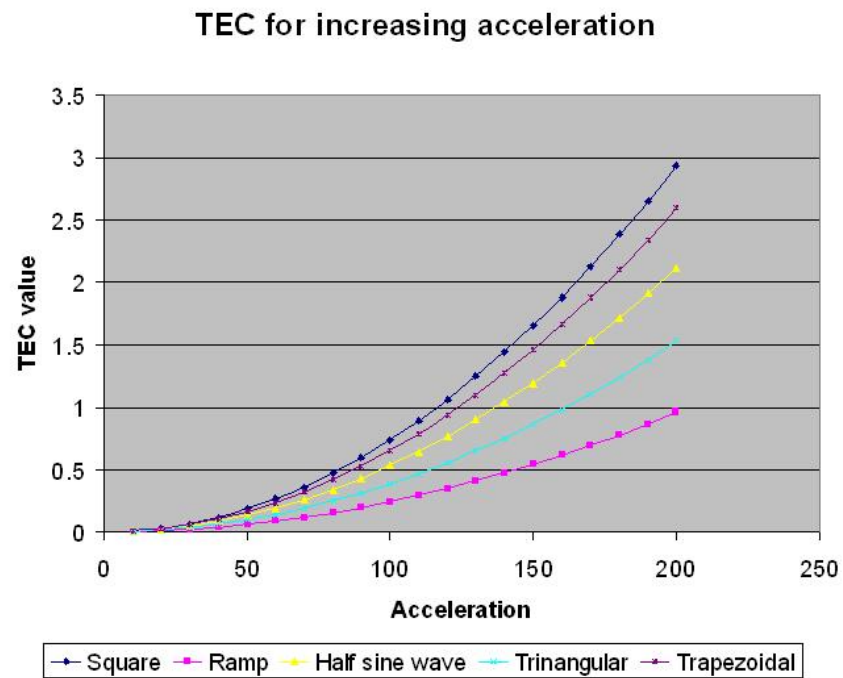


Figure 7.8: MSC value for increasing peak acceleration.

7.5 Chapter Summary

By analysing collision results for a range of circumstances using the different criterion the program provided results which could be further analysed to examine the performance of the criteria.

The HIC value proved to be consistently less than the SI value for all collision types with the exception of the square which was always equal. Generally the performance of the HIC was shown to be significantly better than that of the SI due to its ability to find the most suitable collision duration.

The TEC was shown to be less affected by shape variation than the MSC, due to the different technique of indication severity. The plots of displacement successfully demonstrated how the MSC and TEC differed in terms of dynamic response.

Chapter 8

Conclusions and Further Work

Head injury criteria can be applied to any situation which allows testing. Testing can be performed quite simply and easily, standards both in Australia and overseas utilise testing and injury criteria.

The varying criteria developed to date all have differences, for this reason it is important to apply more than one criterion to test data.

8.1 Achievement of Project Objectives

The following objectives have been addressed:

- Examine Australian and overseas standards concerning impact assessment
- Examine literature relevant to impact assessment
- Review of current injury criteria
- Review of biomechanical understanding of head injury impact
- Develop software to evaluate and process impact data
- Develop software to apply injury criteria to impact data
- Apply developed software to typical head impact study

8.2 Further Work

Due to constraints on time and equipment no testing was performed, additional data could be used to properly examine how test environment effects both the impact data and the SI, HIC, MSC and TEC values. Additionally test data needs to be collected to indicate the level of angular acceleration in test collisions.

To better understand the strengths and weaknesses of each criterion physical testing is required. That is testing on cadavers, monkeys or other real life heads. The reason for this is that further experiments can further improve on existing criteria.

The criteria used in the program are the most common criteria used to date, however further work should include more injury criteria. In short the more injury criteria available the more detailed the analysis.

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A viscoelastic fluid model for brain injuries

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Biodynamic Response of the Human Body in Vehicular Frontal Impact

Narayan Yoganandan (Medical College of Wisconsin), Frank A. Pintar (Department of Veterans Affairs Medical Center)

Source: <http://civil-ws2.wpi.edu/Documents/Roadsafe/KTH/Biblio/Docs/Biodynamic%20response%20in%20frontal%20impact.pdf#search=%22%22revised%20brain%20model%22%22>

Last accessed: 11/10/06

Reducing Head Injuries In Soccer

February 2003

Source: <http://www.full90.com/pdf/White%20Paper%201st%20Edition%20-%20Feb%202003.pdf>

Last accessed: 16/10/06

REDUCTION OF BLAST INDUCED HEAD ACCELERATION IN THE FIELD OF

ANTI-PERSONNEL MINE CLEARANCE

A. Makris, J. Nerenberg, J.P. Dionne, Med-Eng Systems Inc.

C. R. Bass, Automotive Safety Laboratory, University of Virginia

C. Chichester, United States Army, CECOM, RDEC, NVESD

Source: <http://www.humanitariandemining.org/demining/pubs/protection/headacceleration.pdf>

Last accessed: 16/10/06

Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems

Michael Kleinberger, Emily Sun, and Rolf Eppinger

National Highway Traffic Safety Administration

National Transportation Biomechanics Research Center (NTBRC)

September 1998

Source: <http://www-nrd.nhtsa.dot.gov/pdf/nrd-11/airbags/criteria.pdf>

Last accessed: 16/10/06

The effectiveness of lap straps as seat restraints on tractors in the event of overturning

TRL Limited

Source: http://www.hse.gov.uk/research/crr_pdf/2000/crr00310.pdf

Last accessed: 16/10/06

Appendix A

Project Specification

PROJECT SPECIFICATION

For: Daniel Treverrow
Submission: November 2006

Topic: Comparison of Injury Criteria for human head impacts

Supervisors: Chris Snook

Objective: To investigate techniques for estimating the severity of a head injury and create a computer program to utilise these techniques under applicable circumstances.

Programme:

1. Search for existing impact-testing devices and procedures and assess their effectiveness;
2. Examine Australian and overseas standards and other literature relevant to impact assessment.
3. Review current injury criteria and biomechanical understanding of head impact injury.
4. Develop software to evaluate impact data and if necessary process impact data.
5. Develop software to apply the injury criteria and processed impact data to calculate theoretical implications of impact on a human head.
6. Apply the developed criteria to data from a typical head impact study.

Chris Snook 28/3/06

D. Treverrow

D. Treverrow

10/4/06

Appendix B

Source Code

B.1 The square.m MATLAB Function

The square module uses user inputs to create a collision data point matrix with a square shape.

Listing B.1: Code for the square module.

```
%square
: colmax, coldur
: cdpts
scounter=1; %initiate square counter values
for time = 0:0.1:coldur
    cdpts(scounter,1)= time; %fills the time column of the cdpts matrix
    cdpts(scounter,2)=colmax; %fills the acl column of the cdpts matrix
    scounter=scounter+1;
end

%to put time interval into seconds from milli seconds
cdpts(:,1)=cdpts(:,1)*0.001;
```

B.2 The ramp.m MATLAB Function

The square module uses user inputs to create a collision data point matrix with a ramp shape.

Listing B.2: Code for the square module.

```
%ramp
%input: colmax, coldur
%output: cdpts
rcounter=1; %initiate ramp counter values
%plot the points using the formula y=m*x+b
rgrad=colmax/coldur; %gradient of ramp slope
for time = 0:0.1:coldur
    cdpts(rcounter,1)= time; %fills the time column of the cdpts matrix
    cdpts(rcounter,2)=rgrad*cdpts(rcounter,1); %fills the acl column of th
    rcounter=rcounter+1;
end

%numpts=length(cdpts(:,1)); %number of collision datapoints

%to put time interval into second
cdpts(:,1)=cdpts(:,1)*0.001;
```

B.3 The halvesinewave.m MATLAB Function

The square module uses user inputs to create a collision data point matrix with a half sine wave shape.

Listing B.3: Code for the square module.

```
%halfsinewave
: colmax, coldur
: cdpts
hcounter=1; %initiate ramp counter values
for time=0:0.1:coldur
    cdpts(hcounter,1)=time; %fills the time column of the cdpts matrix
    cdpts(hcounter,2)=colmax*sin(cdpts(hcounter,1)*pi/coldur); %plot poin
    hcounter=hcounter+1;
end
%to put time interval into second
cdpts(:,1)=cdpts(:,1)*0.001;
```

B.4 The triangular.m MATLAB Function

The square module uses user inputs to create a collision data point matrix with a triangular shape.

Listing B.4: Code for the square module.

```
%triangular
: colmax, coldur
%output: cdpts
tcounter=1; %initiate ramp counter values
%plot the points using either y=mx or y=-m(x-x1)+y1
tgrad=colmax*2/coldur;
for time=0:0.1:coldur
    cdpts(tcounter,1)=time; %fills the time column of the cdpts matrix
    if time<+coldur/2
        cdpts(tcounter,2)=tgrad*cdpts(tcounter,1);
    else
        cdpts(tcounter,2)=-tgrad*(cdpts(tcounter,1)-coldur/2)+colmax; %fi
    end
    tcounter=tcounter+1;
end
%to put time interval into second
cdpts(:,1)=cdpts(:,1)*0.001;
```

B.5 The trapezoidal.m MATLAB Function

The square module uses user inputs to create a collision data point matrix with a trapezoidal shape.

Listing B.5: Code for the square module.

```
%Parrallelogram
: colmax, coldur
: cdpts
pcounter=1; %initiate ramp counter values
 $\%plot$  the points using either  $y=m1*x$ ,  $y=colmax$  or  $y=m2(x-x1)+y1$ 
colpt1=coldur*0.25; %time at beginning of plateau
colpt2=coldur*0.75; %time at end of plateau
pgrad=colmax/coldur*4;
for time=0:0.1:coldur
    cdpts(pcounter,1)=time;
    if time <=colpt1
        cdpts(pcounter,2)=pgrad*cdpts(pcounter,1);
    elseif time <=colpt2
        cdpts(pcounter,2)=colmax;
    else
        cdpts(pcounter,2)=colmax-pgrad*(cdpts(pcounter,1)-colpt2);
    end
    pcounter=pcounter+1;
end
 $\%to$  put time interval into second
cdpts(:,1)=cdpts(:,1)*0.001;
```

B.6 The excelread.m MATLAB Function

Uses a excel file to create a collision data point matrix.

Listing B.6: Code for the square module.

```
%excelread  
%exlname=input('Please enter exl file name ','s')  
%cdpts=xlsread(exlname);  
  
[filename , datadir]=uigetfile('*.xls')  
cdpts = xlsread([datadir filename]);
```


B.7 The datareader.m MATLAB Function

Uses a any file to create a collision data point matrix.

Listing B.7: Code for the square module.

```
%datareader

%filename=input('What is the FULL name of the file containing the data? '
%datadir = uigetdir
[filename , datadir]=uigetfile('*.*)
inputmatrix = importdata([datadir filename]); %( 'D:\! Daniels work\proj\S
disp(inputmatrix.data)

%to shave the bottom line/s off
modstart=0;%input('How many lines need to be removed from start of matrix
datastartpt=modstart+1;
modend=1;%input('How many lines need to be removed from end of matrix ');
dataendpt=length(inputmatrix.data(:,1))-modend;
datamatrix=inputmatrix.data(datastartpt:dataendpt,:);
%%%%%%%%%

%work out which columns do what
%time column
timecol=1;%input('Which column contains the time data ');
cdpts=datamatrix(:,timecol);
%acceleration (in g's) column
accelcol=2;%input('Which column contains the time data ');
cdpts(:,2)=datamatrix(:,accelcol);
%display plot for user to see
plot(cdpts(:,1),cdpts(:,2))
hold on

xlabel('Time_(ms)')
ylabel('Acceleration_(g)')
title('Collision_Data_Point_Plot')

grid on

menu('does_this_plot_look_correct?', 'Yes');

%plot subcritical line
%%subcrit=max(cdpts(:,2))*0.1;% finds 10% of maximum value of acceleration
%%critln=[0, subcrit; (max(cdpts(:,1))), subcrit];% critln is the line 10%
%%plot(critln(:,1),critln(:,2),'r')%plots the critical line on the plot o
%%title('Please select start point')
%%t1=ginput(1);%time where user wants to begin to evaluate data
%%title('Please select end point')
%%t2=ginput(1);%time where user wants to stop evaluating data
t1=roundn(t1,-1); %only necessary if time interval is 0.1 ms
t2=roundn(t2,-1); %only necessary if time interval is 0.1 ms
%%close
%the following lines work only for a time interval of 0.1 ms
tstart=find(cdpts(:,1)==t1(1));
tend=find(cdpts(:,1)==t2(1));
cdpts=cdpts(tstart:tend,:);
plot(cdpts(:,1),cdpts(:,2));
%%%%%%%%%
```

```
%the following lines are intended to work for any time interval
%to get the start of the required data
%%stime(:,1)=cdpts(:,1)-t1(1,1);%stime = start time
%%[aa, stpos]=min(abs(stime));%stpos = start position
%to get the end of the required data
%%etime(:,1)=cdpts(:,1)-t2(1,1);%etime = end time
%%[bb, endpos]=min(abs(etime));%endpos = start position

%%cdpts=cdpts(stpos:endpos,:);%re-defines the collision data points

%%plot(cdpts(:,1), cdpts(:,2)); %plots re-difined data
grid on
%to put time interval into second
cdpts(:,1)=cdpts(:,1)/1000;
```

B.8 The severityindex.m MATLAB Function

Analyses collision data point matrix using SI.

Listing B.8: Code for the square module.

```
%severityindex
%input: cdpts
%output: SI
numpts=length(cdpts(:,1)); %number of collision points
%uses inputs to calculate average height, width and SI value of each chunk
for chunk=1:numpts-1 %looks at each chunk in within the given bounds
    chnkht=(cdpts(chunk,2)+cdpts(chunk+1,2))/2; %average height of chunk,
    chnkwidth=(cdpts(chunk+1,1)-cdpts(chunk,1)); %Width of chunk
    SIarray(chunk)=(chnkht^2.5)*chnkwidth; %calculate SI value for chunk g
end
SI=sum(SIarray) %sums up every chunk in the SI array to get a total SI va
disp('end_of_SI')
```

B.9 The headinjurycriterion.m MATLAB Function

Analyses collision data point matrix using the HIC.

Listing B.9: Code for the square module.

```
%headinjurycriterion
%input: cdpts
%output: HIC
numpts=length(cdpts(:,1));
%uses inputs to calculate average height, width and area of each chunk.
for area=1:numpts-1 %creates and area value for each chunk
    chnkht(area)=(cdpts(area,2)+cdpts(area+1,2))/2; %average height of chunk
    chnkwdth(area)=(cdpts(area+1,1)-cdpts(area,1)); %Width of chunk
    chunk(area)=chnkht(area)*chnkwdth(area); %calculates the area of each chunk
end
hcounter=1; %initiat hic counter
for CL=1:numpts %CL = Chunk length, this line ensures that the number even
    for CP=1:numpts-CL %CP = chunk position, this line uses the given com
        CE=CP+CL-1; %CE = chunk end
        chnkbt(hcounter)=sum(chunk(CP:CE)); %total area of combined chunks
        chnkdur=sum(chnkwdth(CP:CE)); %total time of combined chunks
        HICarray(hcounter)=(chnkbt(hcounter)/chnkdur)^2.5*chnkdur; %creat
        hcounter=hcounter+1;
    end
end
HIC=max(HICarray) %finds the largest value in the HIC array
disp('end_of_hic')
```

B.10 The meanstraincriterion.m MATLAB Function

Analyses collision data point matrix using the MSC.

Listing B.10: Code for the square module.

```

%meansraincriterion
%input: cdpts
%output: MSC
numpts=length(cdpts(:,1));
%%% Define starting values %%%
a1(1)=cdpts(1,2);
a2(1)=0;
v1(1)=0;
v2(1)=0;
d1(1)=0;
d2(1)=0;

m1=0.5;
m2=4.5;

c=1000;%dampening coef
k=2.5*1000^2;%stiffnes coef

for mcounter=1:numpts-1
    %%%Get deltat and a1,m%%
    deltat(mcounter)=cdpts(mcounter+1,1)-cdpts(mcounter,1);%deltat for cu
    a1(mcounter+1)=cdpts(mcounter+1,2);%acceleration1 for next timestep b
    %%%get the forces exerted on m2%%
    fc(mcounter)=(v1(mcounter)-v2(mcounter))*c;%dampening force
    fk(mcounter)=(d1(mcounter)-d2(mcounter))*k;%stiffness or spring force
    %%%use foreced to calc. a2%%
    a2(mcounter+1)=(fc(mcounter)+fk(mcounter))/m2;
    %%%Use deltat, a1 and a1, v1 and v2 to get v1 and v2 for next time ste
    v1(mcounter+1)=a1(mcounter)*deltat(mcounter)+v1(mcounter);
    v2(mcounter+1)=a2(mcounter)*deltat(mcounter)+v2(mcounter);
    %%%Use deltat, a1 and a1, v1 and v2, d1 and d2 to get d1 and d2 for n
    d1(mcounter+1)=a1(mcounter)*deltat(mcounter)^2+v1(mcounter)*deltat(mc
    d2(mcounter+1)=a2(mcounter)*deltat(mcounter)^2+v2(mcounter)*deltat(mc
    %%%Find difference between two masses%%
    diff(mcounter)=d1(mcounter)-d2(mcounter);
end

for mcounter=numpts:numpts*2
    %%%Get deltat%%
    deltat(mcounter)=cdpts(2,1)-cdpts(1,1);%deltat for current timestep

    %%%get the forces exerted on m2%%
    fc(mcounter)=(v1(mcounter)-v2(mcounter))*c;%dampening force
    fk(mcounter)=(d1(mcounter)-d2(mcounter))*k;%stiffness or spring force
    %%%use foreced to calc. a1 and a2%%
    a1(mcounter+1)=-1*(fc(mcounter)+fk(mcounter))/m1;%acceleration1 for n
    a2(mcounter+1)=(fc(mcounter)+fk(mcounter))/m2;%acceleration1 for next
    %%%Use deltat, a1 and a1, v1 and v2 to get v1 and v2 for next time ste
    v1(mcounter+1)=a1(mcounter)*deltat(mcounter)+v1(mcounter);
    v2(mcounter+1)=a2(mcounter)*deltat(mcounter)+v2(mcounter);
    %%%Use deltat, a1 and a1, v1 and v2, d1 and d2 to get d1 and d2 for n
    d1(mcounter+1)=a1(mcounter)*deltat(mcounter)^2+v1(mcounter)*deltat(mc
    d2(mcounter+1)=a2(mcounter)*deltat(mcounter)^2+v2(mcounter)*deltat(mc

```

```
    %%Find difference between two masses%%
    diff(mcounter)=d1(mcounter)-d2(mcounter);
end
%plot(diff)
%grid on

%a little code to calculate what values should be used to obtain average
lastsig=numpts*2;
for mcounter2=1:round(numpts*2)
    if diff(mcounter2) > 0.1*max(diff)
        lastsig=mcounter2; %last sig is last significant value
    end
end

MSC=mean(diff(1:lastsig))
%hold on
%plot(a1, 'r')
%plot(a2, 'g')
%plot(nrg/250, 'r')

disp('end_of_msc')
```

B.11 The translationalenergycriterion.m MATLAB Function

Analyses collision data point matrix using the TEC.

Listing B.11: Code for the square module.

```
%translational energy Criterion Module

: cdpts
output: MSC
numpts=length(cdpts(:,1));
%%% Define starting values %%%
a1(1)=cdpts(1,2);
a2(1)=0;
v1(1)=0;
v2(1)=0;
d1tec(1)=0;
d2tec(1)=0;

v3(1)=0;
d3tec(1)=0;

m1=1;
m2=5;
m3=0.001;

c1=1000;%dampening coef
c2=1000;
k=2.5*1000^2;%stiffnes coef

for mcounter=1:numpts-1
    %%%Get deltat and a1,m%%
    deltat(mcounter)=cdpts(mcounter+1,1)-cdpts(mcounter,1);%deltat for cu
    a1(mcounter+1)=cdpts(mcounter+1,2);%acceleration1 for next timestep b
    %%%get the forces exerted on m2%%
    f1(mcounter)=(v1(mcounter)-v2(mcounter))*c1;%damping force
    f2(mcounter)=(d1tec(mcounter)-d3tec(mcounter))*k+(v3(mcounter)-v2(mco
    %%%use foreces to calc. a2%%
    a2(mcounter+1)=(f1(mcounter)+f2(mcounter))/m2;

    %a3(mcounter+1)=((d1(mcounter)-d3(mcounter))*k+(v3(mcounter)-v2(mcoun
    %%%Use deltat, a1 and a1, v1 and v2 to get v1 and v2 for next time ste
    v1(mcounter+1)=a1(mcounter)*deltat(mcounter)+v1(mcounter);
    v2(mcounter+1)=a2(mcounter)*deltat(mcounter)+v2(mcounter);

    v3(mcounter+1)=f2(mcounter)/(2*c2)+v2(mcounter);%a3(mcounter)*deltat(1
    %%%Use deltat, a1 and a1, v1 and v2, d1 and d2 to get d1 and d2 for n
    d1tec(mcounter+1)=a1(mcounter)*deltat(mcounter)^2+v1(mcounter)*deltat(
    d2tec(mcounter+1)=a2(mcounter)*deltat(mcounter)^2+v2(mcounter)*deltat(
    d3tec(mcounter+1)=f2(mcounter)/(2*k)+d2tec(mcounter);%a3(mcounter)*de
    %%%Find difference between two masses%%
    difftec(mcounter)=d1tec(mcounter)-d2tec(mcounter);
    tec(mcounter)=c2*deltat(mcounter)*(v2(mcounter)-v3(mcounter))^2;
    %%%calculate energy in system%%
```

```

    %nrg(mcounter)=0.5*m1*(v1(mcounter)-v2(mcounter))^2+0.5*m2*(v1(mcount
end
for mcounter=numpts:numpts*2
    %%%Get deltat%%
    deltat(mcounter)=cdpts(2,1)-cdpts(1,1);%deltat for current timestep

    %%%get the forces exerted on m2%%
    f1(mcounter)=(v1(mcounter)-v2(mcounter))*c1;%damping force
    f2(mcounter)=(d1tec(mcounter)-d3tec(mcounter))*k+(v3(mcounter)-v2(mco
    %%%use forced to calc. a1 and a2%%
    a1(mcounter+1)=-1*(f1(mcounter)+f2(mcounter))/m1;%acceleration1 for n
    a2(mcounter+1)=(f1(mcounter)+f2(mcounter))/m2;%acceleration1 for next
    a3(mcounter+1)=((d1tec(mcounter)-d3tec(mcounter))*k+(v3(mcounter)-v2(m
    %%%Use deltat, a1 and a1, v1 and v2 to get v1 and v2 for next time st
    v1(mcounter+1)=a1(mcounter)*deltat(mcounter)+v1(mcounter);
    v2(mcounter+1)=a2(mcounter)*deltat(mcounter)+v2(mcounter);

    v3(mcounter+1)=f2(mcounter)/(2*c2)+v2(mcounter);

    %%%Use deltat, a1 and a1, v1 and v2, d1 and d2 to get d1 and d2 for n
    d1tec(mcounter+1)=a1(mcounter)*deltat(mcounter)^2+v1(mcounter)*deltat
    d2tec(mcounter+1)=a2(mcounter)*deltat(mcounter)^2+v2(mcounter)*deltat
    d3tec(mcounter+1)=f2(mcounter)/(2*k)+d2tec(mcounter);

    %%%Find difference between two masses%%
    difftec(mcounter)=d1tec(mcounter)-d2tec(mcounter);
    tec(mcounter)=c2*deltat(mcounter)*(v2(mcounter)-v3(mcounter))^2;
    %%%calculate energy in system%%
    %nrg(mcounter)=0.5*m1*(v1(mcounter)-v2(mcounter))^2+0.5*m2*(v1(mcount
end
TEC=sum(tec)

disp('end_of_TEC')
```


B.12 The main.m MATLAB Function

The main module allows the user to specify source of collision data point matrix and which injury criteria to apply.

Listing B.12: Code for the square module.

```
%main
clear
clc

inputtype=menu('Please_select_data_input_format','exl_file','Create_collis

if inputtype == 1
    excelread
elseif inputtype == 2
    collisionsim
elseif inputtype == 3
    datareader
end

h = uibuttongroup('visible','off','Position',[0 0 1 1],'Title','Choose');
%run si
u0 = uicontrol('Style','checkbox','String','SI',...
    'pos',[10 350 100 30],'parent',h,'HandleVisibility','off');
%run HIC
u1 = uicontrol('Style','checkbox','String','HIC',...
    'pos',[10 250 100 30],'parent',h,'HandleVisibility','off');
%run msc
u2 = uicontrol('Style','checkbox','String','MSC',...
    'pos',[10 150 100 30],'parent',h,'HandleVisibility','off');
%run tec
u3 = uicontrol('Style','checkbox','String','TEC',...
    'pos',[10 50 100 30],'parent',h,'HandleVisibility','off');
set(h,'Visible','on');

k=menu('Please_select_choices','Done');
if k == 1
    eval(1)=get(u0,'value');
    eval(2)=get(u1,'value');
    eval(3)=get(u2,'value');
    eval(4)=get(u3,'value');
    close
end

if eval(1)==1
    severityindex
end

if eval(2)==1
    headinjurycriterion
end

if eval(3)==1
    meanstraincriterion
    plot([cdpts(:,1);cdpts(:,1)+cdpts(numpts,1)],diff)
    hold on
    xlabel('Time_(s)')
    ylabel('Displacement_between_mass_1_and_2_(m)')
```

```
end
if eval(4)==1
    translationalenergycriterion
    plot([cdpts(:,1);cdpts(:,1)+cdpts(numpts,1)],difftec,'r')
    xlabel('Time_(s)')
    ylabel('Displacement_between_mass_1_and_2_(m)')
end
grid on
```

B.13 The collisionsim.m MATLAB Function

The collisionsim module is a small module to utilise the build modules which create idealised data.

Listing B.13: Code for the square module.

```
%collisionsim
coltype=menu('Select collision type', 'Square', 'Ramp', 'Half_sine_wave', 'Triangular', 'Trapezoidal')
if coltype == 1
    coldur=input('Please input collision length in ms'); %collision duration
    colmax=input('Please input maximum collision value'); %max collision value
    square
elseif coltype == 2
    coldur=input('Please input collision length in ms'); %collision duration
    colmax=input('Please input maximum collision value'); %end collision value
    ramp
elseif coltype == 3
    coldur=input('Please input collision length in ms'); %collision duration
    colmax=input('Please input maximum collision value'); %maximum collision value
    halvesinewave
elseif coltype == 4
    coldur=input('Please input collision length in ms'); %collision duration
    colmax=input('Please input maximum collision value'); %maximum collision value
    triangular
elseif coltype == 5
    coldur=input('Please input collision length in ms'); %collision duration
    colmax=input('Please input maximum collision value'); %maximum collision value
    Trapezoidal
end

x=cdpts(:,1);
y=cdpts(:,2);
plot(x,y)
xlabel('Time_(ms)')
ylabel('Acceleration_(g)')
title('Collision_Data_Point_Plot')
axis([0 coldur*1.2/1000 0 colmax*1.2])
grid on

menu('does this plot look correct?', 'Yes');
```

B.14 The buildtest.m MATLAB Function

The buildtest module creates results using each analysis module and every idealised collision shape.

Listing B.14: Code for the square module.

```
%buildtest
clear
clc
stdcoldur=input('Please input collision duration ');
stdcolmax=input('Please input max collision acceleration ');

usexls1=menu('write collision data to excel file?', 'Yes', 'No');
usexls2=menu('write SI, HIC, MSC and TEC values to excel file?', 'Yes', 'No')
if usexls1==1 | usexls2==1
    xlstarget=input('Please input name of target excel file', 's')
end
useplot1=menu('Plot collision data in matlab?', 'Yes', 'No');
useplot2=menu('Display SI, HIC, MSC and TEC results in matlab?', 'Yes', 'No')

useconstarea=menu('Use the area equaliser?', 'Yes', 'No');
if useconstarea==1
    stdarea=stdcolmax*stdcoldur;
    stdrat=stdcolmax/stdcoldur;
else
    coldur=stdcoldur;
    colmax=stdcolmax;
end

hold on
grid on
%%%%%%%%
if useconstarea==1
    coldur=sqrt(stdarea/stdrat);
    colmax=coldur*stdrat;
end
square
if usexls1==1
    xlswrite(xlstarget, cdpts, 'square')
end
if usexls2==1 | useplot2==1
    severityindex
    headinjurycriterion
    meanstraincriterion
    translationalenergycriterion
end
if usexls2==1
    results=[SI;HIC;MSC;TEC];
    xlswrite(xlstarget, results, 'square', 'c1')
end
if useplot1==1
    plot(cdpts(:,1), cdpts(:,2), 'b')
end
clear cdpts
%%%%%%%%
if useconstarea==1
    coldur=sqrt(stdarea*2/stdrat);
    colmax=coldur*stdrat;
```

```

end
ramp
if usexls1==1
    xlswrite(xlstarget, cdpts, 'ramp')
end
if usexls2==1 | useplot2==1
    severityindex
    headinjurycriterion
    meanstraincriterion
    translationalenergycriterion
end
if usexls2==1
    results=[SI;HIC;MSC;TEC];
    xlswrite(xlstarget, results, 'ramp', 'c1')
end
if useplot1==1
    plot(cdpts(:,1), cdpts(:,2), 'r')
end
clear cdpts
%%%%
if useconstarea==1
    coldur=sqrt(stdarea*pi)/(2*stdrat);
    colmax=coldur*stdrat;
end
halfsinewave
if usexls1==1
    xlswrite(xlstarget, cdpts, 'halfsinewave')
end
if usexls2==1 | useplot2==1
    severityindex
    headinjurycriterion
    meanstraincriterion
    translationalenergycriterion
end
if usexls2==1
    results=[SI;HIC;MSC;TEC];
    xlswrite(xlstarget, results, 'halfsinewave', 'c1')
end
if useplot1==1
    plot(cdpts(:,1), cdpts(:,2), 'g')
end
clear cdpts
%%%%
if useconstarea==1
    coldur=sqrt(stdarea*2/stdrat);
    colmax=coldur*stdrat;
end
triangular
if usexls1==1
    xlswrite(xlstarget, cdpts, 'triangular')
end
if usexls2==1 | useplot2==1
    severityindex
    headinjurycriterion
    meanstraincriterion
    translationalenergycriterion
end
if usexls2==1
    results=[SI;HIC;MSC;TEC];
    xlswrite(xlstarget, results, 'triangular', 'c1')
end

```

```
if useplot1==1
    plot(cdpts(:,1),cdpts(:,2),'c')
end
%%%
clear cdpts
if useconstarea==1
    coldur=sqrt(stdarea*4/(stdrat*3));
    colmax=coldur*stdrat;
end
Trapezoidal
if usexls1==1
    xlswrite(xlstarget,cdpts,'Parrallelogram')
end
if usexls2==1 | useplot2==1
    severityindex
    headinjurycriterion
    meanstraincriterion
    translationalenergycriterion
end
if usexls2==1
    results=[SI;HIC;MSC;TEC];
    xlswrite(xlstarget,results,'Parrallelogram','c1')
end
if useplot1==1
    plot(cdpts(:,1),cdpts(:,2),'y')
end

xlabel('Time_(s)')
ylabel('Acceleration_(g)')

disp('Finished')
```

B.15 The compare.m MATLAB Function

The compare module is designed to compare the results from each analysis module by changing the peak acceleration of idealised collision data.

Listing B.15: Code for the square module.

```

clear
clc
%%m file to build results from different systems
coltype=menu('Select_collision_type','Square','Ramp','Half_sine_wave','Triangular');
stdcoldur=input('Please_input_collision_duration');
stdcolmax=input('Please_input_max_collision_acceleration');
xlstarget=input('Please_input_name_of_target_xls_file','s');
iters=input('Please_input_number_of_iterations_required');
iter=1;
for colmax=stdcolmax/iters:stdcolmax/iters:stdcolmax
    coldur=stdcoldur;
    iter=iter+1;
    if coltype == 1
        square
        typetitle=('Square')
    elseif coltype == 2
        ramp
        typetitle=('Ramp')
    elseif coltype == 3
        halvesinewave
        typetitle=('Half_Sine_Wave')
    elseif coltype == 4
        triangular
        typetitle=('Triangular')
    elseif coltype == 5
        Trapezoidal
        typetitle=('Trapezoidal')
    end
    severityindex
    headinjurycriterion
    meanstraincriterion
    translationalenergycriterion
    results=[SI,HIC,MSC,TEC];
    xlswrite(xlstarget,results,'Datacomparison',strcat('A',num2str(iter)))
end
stats={typetitle, stdcoldur, stdcolmax};
xlswrite(xlstarget,stats,'Datacomparison','A1')
%xlswrite(xlstarget, stdcoldur, 'Datacomparison', 'B1')
%xlswrite(xlstarget, stdcolmax, 'Datacomparison', 'C1')

```

Analyses collision data point matrix using HIC formula.