THE DEVELOPMENT OF FINITE ELEMENT MODEL FOR MALAYSIAN FEMALE ANTHROPOMETRIC DUMMY

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For my beloved mother,

thank you for your prayer for me whole this time.

I love you very much.

Acknowledgment

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Lina Tam
Parit Raja

Abstract

In recent years, dummy development for crash test have grown rapidly to decrease the fatalities during crash. These dummies are generated based on anthropometric database consisting of several percentile. Anthropometric data is very important in terms of ergonomics to specify the physical dimensions for product design and dynamic behavior for user safety. The development of dummy models starts from rigid body models to deformable models which is then adopted into finite element models for more accurate and detailed results in doing analysis. Using the numerical method (FEM) to evaluate crash test has increase the cost saving and accuracy in crash analysis. An average anthropometric of 100 Malaysian females with 59 anthropometric data is modeled using Solidworks 2010. The parameters of boundary conditions for the model are conducted in the preprocessor called GiD, before the input file from GiD is run using an explicit finite element program suite called Impact. The dummy model is set in sitting position and crushed with a chair at velocity $15.3ms^{-1}$ from behind. The deformation which includes as displacements, velocity and acceleration are presented in this research. The results show that the head experienced the bounce and highest displacement. This model can be further complemented for the family of Malaysian Anthropometric Test Dummy in computational test dummies to improve safety for local passengers.

Abstrak

Pada tahun-tahun kebelakangan ini, perkembangan model untuk ujian pelanggaran telah berkembang dengan pesat untuk mengurangkan kematian semasa kemalangan. Model-model ini dihasilkan berdasarkan pangkalan data antropometri yang terdiri daripada beberapa persentil. Data anthropometri adalah sangat penting dari segi ergonomik untuk menentukan dimensi fizikal rekabentuk produk dan tingkah laku dinamik untuk keselamatan pengguna. Pembangunan model bermula dari model badan tegar kepada model boleh ubah dan kemudiannya diadaptasi ke dalam model unsur terhingga untuk mendapatkan keputusan yang lebih tepat dan terperinci dalam melakukan analisis. Dengan menggunakan kaedah unsur berangka (FEM) untuk menilai ujian pelanggaran telah meningkatkan penjimatan kos dan ketepatan dalam analisis pelanggaran. Purata antropometri 100 wanita Malaysia dengan 59 antropometri data dimodelkan menggunakan Solidworks 2010. Parameter keadaan sempadan untuk model dilakukan di dalam prapemproses yang dipanggil GiD, dan kemudiannya fail input dari GiD dijalankan menggunakan program suit eksplisit unsur terhigga yang dipanggil Impact. Model diletakkan dalam keadaan duduk dan dihempap dengan kerusi dengan kelajuan halaju $15.3ms^{-1}$ dari belakang. Perubahan seperti anjakan, halaju dan pecutan dibentangkan dalam penyelidikan ini. Keputusan menunjukkan bahawa kepala mengalami lantunan dan anjakan yang paling tinggi. Model ini boleh dilengkapkan lagi untuk model keluarga ATD Malaysia dalam ujian berkomputer untuk meningkatkan keselamatan penumpang tempatan.

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List of Nomenclatures

FEM	Finite Element Method
FMVSS	Federal Motor Vehicle Safety Standard and Regulations
HIC	Head Injury Criterion
LSTC	Livermore Software Technology Corporation
MADYMO	Mathematical Dynamic Models
MFA	Malaysian Female Anthropometri
MIROS	Malaysian Institute of Road Safety Research
NHTSA	The National Highway Traffic Safety Administration
SID	Side Impact Dummies
THUMS	Total HUman Model for Safety
UTHM	University Tun Hussein Onn Malaysia

Chapter 1

Introduction

The car industry in Malaysia started in 1985 with its first national car, the Proton Saga (PROTON, 2013). The industry has then expanded and produced various models through two local automobile manufacturers, Proton and Perodua (Wikipedia-Foundation, 2013; PERODUA, 2014). Table 1.1 shows the models produced by both companies. Since then, the number of registered cars and drivers has steadily increased every year.

Table 1.1: Produced cars by Proton and Perodua. (PERODUA, 2014; PROTON, 2013; Wikipedia-Foundation, 2013)

Proton		Perodua	
Model	Year	Model	Year
Proton Saga	1985	Perodua Kancil	1994
Proton Iswara	1992	Perodua Rusa	1996
Proton Wira	1993	Perodua Kembara	1998
Proton Perdana	1995	Perodua Kenari	2000
Proton Satria	1995	Perodua Kelisa	2001
Proton Putra	1995	Perodua MyVi	2005
Proton Tiara	1996	Perodua Viva	2007
Proton Waja	2000	Perodua Nautica	2008
Proton Juara	2001	Perodua Alza	2009
Proton Arena	2002	Perodua Axia	2014
Proton Gen-2	2004		
Proton Savvy	2005		
Proton Persona	2007		
Proton Exora	2009		
Proton Inspira	2010		
Proton Preve	2012		

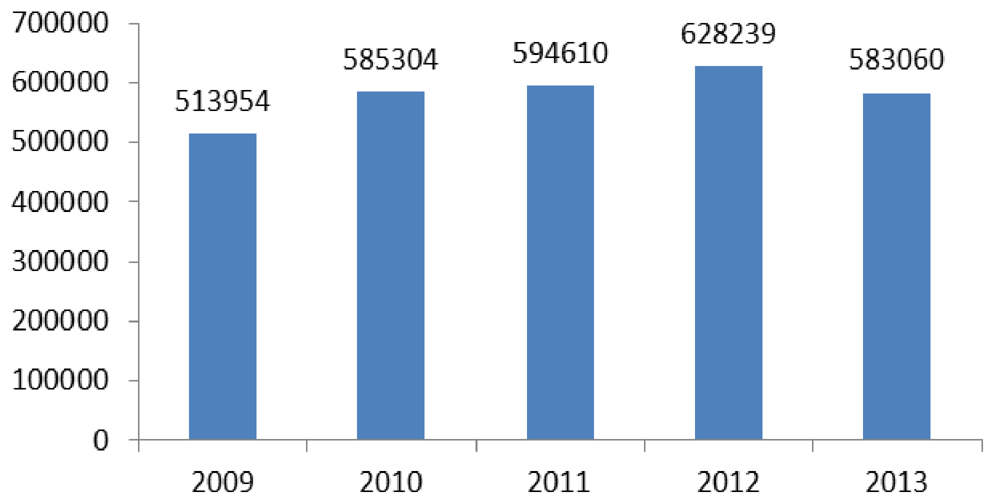

Figure 1.1: Registered Motorcar from 2009 to 2013(JPJ, 2014b).

Figure 1.1 shows the record of registered motorcars in five years since 2009 to 2013 (JPJ, 2014b). From the chart, the number of registered cars have increased every year except in 2013 where it decreased 7.75% from 628239 in 2012 to 583060 in 2013. Within the 5 years, records shows that the percentage has increased to 13.44% from 2009 to 2013.

A type D driving license can be applied by eligible adults aged 17 and above. Records from the Road Transport Department (JPJ) (JPJ, 2014a) showed that the number of registered drivers has been increasing proportionally as shown in Figure 1.2 below. The amount increased by 18.50% within the five years period.

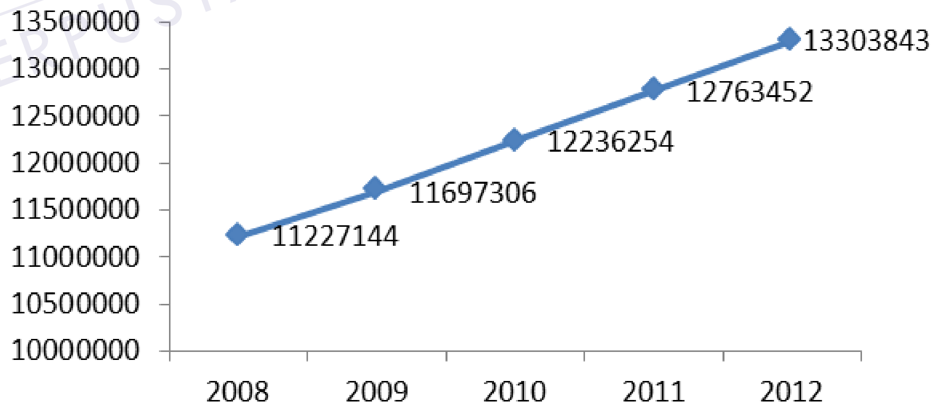

Figure 1.2: Registered driver from 2008 to 2012 (JPJ, 2014a).

According to the statistics of road accidents issued by the Royal Malaysian Police (Police, 2013) in Table 1.2, the number of fatal accidents have increased by 9.4% from 2007 to 2010. This number decreased significantly by 60% in 2011. The number of severe accidents has also decreased from 2007 to 2010 by 18.7%, significantly dropping by 72.5% in 2011. For minor accidents, 3,979 cases were reported in 2007 with the and the number increasing to more than 10,000 cases from 2008 to 2010. However this number dropped to 4,121 cases in 2011.

Table 1.2: Statistic Road Accident for 2007-2011 (Police, 2013).

Year		2007	2008	2009	2010	2011	2012
Type of accident injury	Fatal accident	5,672	5,952	6,218	6,260	2,500	NA
	Severe accident	7,384	7,020	6,978	6,002	2,029	NA
	Minor accident	3,979	12,893	12,072	10,408	4,121	NA
Total of accident with injury		27,035	25,865	25,268	22,670	8,650	NA
Total of accident with no injury (Damage only)		336,284	347,182	372062	391751	170048	NA
	Total accident	363,319	372,990	397,330	414,421	178,698	462,463
Type of injury	Dead	6,282	6,527	6,745	6,872	2,671	6,917
	Seriously injured	9,273	8,866	8,849	7,781	2,581	5,868
	Minor injuries	18,444	16,901	15,823	13,616	5,314	11,654
Total injury		33,999	32,294	31,417	28,269	10,566	24,439
Road death index	Per 100 thousand population	23.10	23.60	23.80	24.20	23.74	23.57
	Per 10 thousand registered vehicle	3.73	3.63	3.55	3.40	3.21	3.05
	Every 1 Billion VKT	17.6	17.2	17.28	16.21	14.68	13.35

As for the total accidents with injury, 2007 showed the highest record with 21,035 cases. This figure showed a decrease of 16% from 2007 to 2010. In 2011 this figure dropped by 61.8% with 8,650 cases. Meanwhile, statistics of accidents with no injury showed an increase of 14% from 2007 to 2010, with a significant decrease of 56.6% in 2011 with 170,048 cases. Overall, the total accidents increased by 14% from 2007 to 2010; and decreased significantly by 56% in 2011. However in 2012 the total accidents increased 158.79% with 462,463 cases and it was the highest record in 6 years.

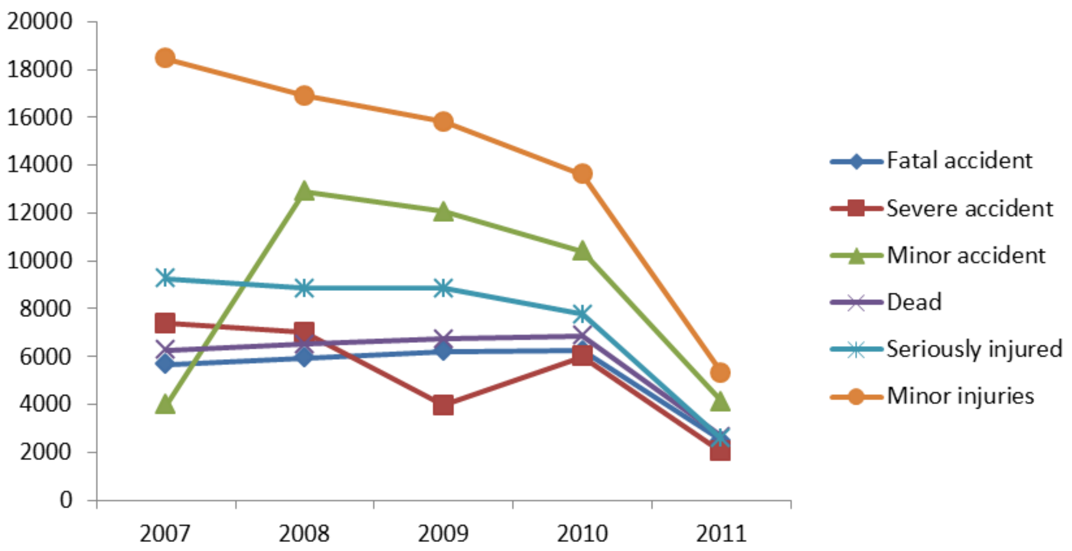

Figure 1.3: Statistic of accidents and injuries for 2007-2011 (Police, 2013).

From Figure 1.3, it can be concluded that the number of accidents and injuries showed a huge improvement with a significant reduction of accidents and injuries compared with the previous years.

The International Transport Forum Paris (2010) study indicated that Malaysia showed the most prominent rate of death on road from 2000 to 2009. It was reported that based on 23.8 deaths per 100,000 people, the rate of the accidental deaths in Malaysia was 6.3 times higher than United Kingdom, Sweden and Netherlands. Furthermore, it costs the government RM 9 million in terms of human life and injuries.

From the 6,640 road accidents in 2009, an estimated 18.2 deaths occurred per day which means that a Malaysian was killed on the road every 80 minutes (Malaysia, 2010). Thus, this research is important in order to provide a model that using Malaysian population anthropometric database that can be used for crash test.

1.1 Problem Statement

Most study for anthropometric in Malaysia are about sitting ergonomic and anthropometric difference in term of age, gender and ethnicity. There is no dummy or model that represent Malaysian has been created for crash test purpose. First Malaysian crash test has been conducted by Malaysian Institute of Road Safety Research (MIROS) in year 2010, loaded with 2 adults and 2 children crash test dummies.

The command dummy used for the crash test is Hybrid III Dummy in frontal crash and automotive safety restrain testing which represents the average adult male worldwide (Solutions, 2012b). Therefore, the available real dummy and computational standard dummy models do not meet with the postures of Malaysian passengers. In order to simulate Malaysian drivers/passengers, the computational dummy model must statistically represent Malaysians to improve the safety standard for the Malaysian car crash test.

To satisfy the safety standards and regulations, the safety protection system of a car model must be tested and assessed. A real crash test of a new car product or an existing car model with a new safety protection system must be conducted. The real car with passenger/driver dummies on board must be impacted as if in a real crash accident and the safety parameters are measured from a test dummy with measurement sensors attached.

The passenger dummy should represent the average passenger which normally depends on the country. Europeans and Americans, generally have bigger postures compared to passengers in Asian countries. To reduce the cost of real crash test, computational crash test simulation can be performed to examine passengers on crash.

1.2 Objective

The research embarks on the following objectives:

1. To propose a computational Malaysian Female Anthropometric (MFA) test dummy that represents the Malaysian female passenger.

2. To evaluate the MFA deformation behavior in frontal crash test for unbelt passenger.

1.3 Scope

The scopes of the research are as follows:

1. Verifying the Impact software to ensure the simulation results meet the input requirement.

2. Collecting 100 Malaysian female anthropometric data to define a computational (finite element) female anthropometric test device.

3. Developing an analytical MFA model following standard finite element format.

4. Computationally testing and benchmarking the kinematic behavior and the Head Injury Criterion (HIC) with other available standard dummy results.

5. Proposing the computational Malaysian female anthropometric test device as the first generation of Malaysian anthropometric test device families.

1.4 Contributions

The developed computational model is the first generation of Malaysian Female Anthropometric (MFA) test dummy and can be further complemented for the family of Malaysian anthropometric test device from baby to male and female elder computational test dummies. Furthermore this research can support automotive industries to improve the safety protection for local passengers.The research outcomes are the following:

1. Providing the first version of the MFA test device finite element model that can be used by automotive industries and vehicles safety researchers to improve the safety protection systems.

2. Publishing the development of the Malaysian female anthropometric test device and its dynamic behaviors on impact in International refereed journals.

3. The product can be used as a basis of further developments of Malaysian dummy families and improving accuracies.

Chapter 2

Literature Review

Dummies have multiple usage and have been developed in several fields according to their needs such as medical dummies, rescue training dummies, space program dummies and automotive crash dummies . In additional, dummies are also used to evaluate clothing and bomb blast testing. Besides the human look alike dummy, there are also animal dummies created for medication, space, radiation and crash testing (Garneau & Parkinson, 2011; Petrone *et al.*, 2010; Parsons, 1995).

2.1 Dummy

The invention of the first automobile began in the early 1769 (Eckermann, 2001) with no safety regulation in place. Due to the continuous development in the automobile industry, the safety of passengers and pedestrians have been taken into account to reduce the fatality rate and injuries in the 1930s (Transport, 2012). Crash test dummies were created to represent humans for testing and producing safer vehicles (D'Elia *et al.*, 2013). The first dummy was created in 1949 for aerospace purposes. It was conventional, had limited utilities and many deficiencies. Continuous research and studies were carried out to develop dummies with improved bio-fidelity and capability to measure greater capacity (Fressmann *et al.*, 2007). The history of crash test dummy development is shown in Table 2.1 (Solutions, 2012a).

Table 2.1: History of dummy evolution (Solutions, 2012a).

Year	Model/Size	Developer	Function
1949	Sierra Sam 95th percentile	Sierra Engineering Co	For evaluation of aircraft ejection seats on rocket sled tests.
1949	OSCAR	Aviation Research	For decompression test in aircraft, rocket sleds and atomic bomb tests.
1952	Mark 1 95th percentile	Alderson Research Laboratories	Use by U.S and European Air Force for general purpose
1952	Wooden Dummy	Tokyo Institute of Technology	Used for testing stability of running motorcycle.
1956	F, B & P 3rd to 98th percentile	Alderson Research Laboratories	Modular series used for variety applications in automotive and aircraft programs
1960	Gard Dummy 3rd to 98th percentile	Alderson Research Dummy	Used for aircraft seat ejection
1966	VIP Series	Automotive Application	Used for testing pilot escape systems
1967	Sierra Stan (M) 50th percentile	Sierra Engineering Co	Used for automotive application.
1968	VIP-50A	Sierra Engineering Co	First standard automotive crash test dummies.
1970	HYBRID I	Alderson Research Laboratories and NHTSA	Refinements dummy
1970	-VIP95 & VIPF5 50th percentile -Sierra Susie (F) 5th percentile -Sierra Sammy (6yrs old) -Sierra Toddler (3yrs old)	Sierra Engineering Co	Used for automotive application
1971	VIP 3C & VIP 6C 50th percentile	Alderson Research Laboratories	Crash test dummy for 3 and 6 years old children.
1972	HYBRID II 50th percentile	Alderson Research Laboratories	Used for compliance testing of cars equipped with passive restraints.
1972	Dynamic Dan	Wyle Laboratories/Payne Division & Aerospace Medical Research Laboratories/USAF	Used for testing aircraft ejection seat systems to simulate the response of the seated human body to vertical acceleration.
1972	Supermorphic Dummy 3rd and 98th percentile	Alderson Research Dummy & Vector an Aydin Co.	Used for testing The Yankee Escape System for the Navy EA6B Program
1972	OPAT Dummy50th percentile 50th percentile	David Ogle Ltd	Used for evaluate lap-shoulder belt systems

1973	Repeatable Pete 10 50th percentile	The Highway Safety Research Instituted	Used to obtained impact response characteristic for a prescribed set of frontal impact condition.
1976	HYBRID III 50th percentile	General Motors & NHTSA	Used for compliance testing cars
1983	Limb Restraint Evaluator	System Research Laboratories	Used to provide a capability that can be used to evaluate the effectiveness of various limb restrain devices to prevent limb flail injured during emergency ejection from military aircraft
1986	ADAM	System Research Laboratories & AAMRL	Used for testing the U.S Air Force Advanced Development Ejection Seat Program, Crew Escape Technologies (CREST), parachute test and helicopter seat crash worthiness test.
1987	Small Female Hybrid III and Large Male Hybrid III	General Motors	Used for frontal crash test.

Crash test dummies were developed based on the anthropometric database according to body postures in various countries (Mohamad *et al.*, 2010b; Lin *et al.*, 2004). Thus, anthropometric data is very important in terms of ergonomics to specify the physical dimensions for product design and dynamic behavior analysis for safety factors (Deros *et al.*, 2009; Mohamad *et al.*, 2010a; Parsons, 1995).

The development of dummies showed an evolution from the rigid body models to deformable models before adopting into finite element models for more accurate and detailed results in doing analysis (Mohan *et al.*, 2007). Developed countries such as United States, Canada, Germany, Japan and Korea developed their own standard family dummies for further crash test in order to increase the safety feature requirement (Seidl, 1997).

2.2 Dummy Modeling

Nowadays, highly advanced and detailed dummy models are used for the crash tests. Instead of physical testing, virtual testing for crash safety has been accepted in the automotive industry (Kan *et al.*, 2003; Noureddine *et al.*, 2002). Both testing results are valuable for validation to predict the behavior of a dummy (Naravane & Deb, 2005; Petrone *et al.*, 2011). The demand for different aspects of crash safety has increased and caused the developed dummy to become more and more complex (Fressmann *et al.*, 2007; Kapoor *et al.*, 2011). Table 2.2 below shows the available dummy models in the market used for different crash test. The dummies are produced by Humanetics Corporation and DYNAmore Corporation.

Table 2.2: Available Dummy Models. (Inc & GmbH, 2014)

	Current Version	Release Date	Modeled by
Front impact dummies			
HYBRID II 50%	V2.0.1	06.09.2012	Humanetics
HYBRID III 5%	V7.0.4	10.08.2012	Humanetics
HYBRID III 50%	V8.0.1	14.01.2013	Humanetics
HYBRID III 95%	V3.0.2	03.08.2012	Humanetics
Side impact dummies			
ES2/ES2re	V5.0.3	30.11.2012	DYNAmore
World SID 50%	V3.0	28.02.2014	DYNAmore
SID-IIs-Build Level C	V3.1a	31.07.2009	Humanetics
SID-IIs-Build Level D	V3.3.3	07.12.2012	Humanetics
US-SID	V5.0	23.10.2006	DYNAmore
Rear Impact Dummies			
BioRID-II	V3.1.1	15.09.2013	DYNAmore
Child Dummies			
P-1.5	V0.2	11.04.2011	DYNAmore
P-3.0	V1.0.1	03.02.2011	DYNAmore
Q-1	V1.0	07.01.2010	Humanetics
Q-1.5	V1.0.1	19.03.2013	Humanetics
Q-3.0	V1.3	15.08.2013	Humanetics
Q-3.0s	V1.1	20.11.2012	Humanetics
Q-6.0	V.1.0.1	27.03.2013	Humanetics
Q-10	V1.2.1	12.09.2013	Humanetics
HYBRID III 3-yr-old	V4.0.2	17.10.2011	Humanetics
HYBRID III 6-yr-old	V3.2	02.12.2009	Humanetics
HYBRID III 10-yr-old	V1.1.1	22.07.2009	Humanetics
Impactor Models			
FLEX-PLI-GTR Legform	V2.0	31.01.2012	Humanetics

2.2.1 Physical modeling

Earlier crash tests are done using real dummies developed based on the average adult male with all parts in rigid body or multibody system (Denton, 2006). Testing is done to determine the dynamic behavior or translation and rotational displacements of interconnected rigid bodies (Teng *et al.*, 2008). Ploen *et al.* (2004) and Kapoor *et al.* (2011) found that the kinematic behavior of the rigid body can be measured and simulated by using equations representing the motion.

Figure 2.1: Family dummy models.(Inc & GmbH, 2014)

Humanetics is the largest development and manufacturing of anthropomorphic test devices (ATDs) followed by DYNAmore which is in cooperation with Livermore Software Technology Corporation (LSTC). The details of produced dummy models are shown in Table 2.2 with the latest version and various models for different crash test. Figure 2.1 shows the example of the real dummy used in crash test from various ages.

2.2.2 Numerical modeling

Computational modeling is a mathematical modeling which was developed using numerical method in a computer program (Moss *et al.*, 2000). The usage of computational method promised accuracy and detailed information to study the behavior of a complex system (Golman *et al.*, 2014). The behavior of the system was simulated in a computer programme which represents the running of the system's model.

The special advantage in finite element approach is it enables stand alone part by part simulation of human body other than full body simulation. Present studies conducted by Fressmann *et al.* (2007) on the development of human modeling in this approach shows that in the future finite element model will come with the creation of skeleton and will be able to define the right material properties to be used in dummy models. Furthermore, it provides more detailed and accurate deformation of the human body in terms of injuries during crash.

Nowadays, usages of numerical modeling are very popular in finite element models (FEM) especially for mass vehicle production in the vehicle industry . Recently numerical models for available dummies are available in RAMSIS (Ltd, 2014), LS-DYNA codes (Inc, 2014), PAM-CRASH (GROUP, 2014), ABAQUS (Systemes, 2014), RADIOSS (HyperWorks, 2014) and MADYMO modeling software (International, 2014a). However, there are few open resource software such as FEBio (Laboratories, 2014), GiD (for Numerical Methods in Engineering, 2014), Salome and Code Aster (Linux, 2014) that also can be used to develop numerical models. Figure 2.2 shows the example of dummies in computational modeling used for different crash (Solutions, 2014).

(a) Frontal Impact Dummies (b) Side Impact Dummies

(c) Rear Impact Dummies (d) Child Dummies

Figure 2.2: Example of dummy models for different crash test. (Inc & GmbH, 2014)

MADYMO (Mathematical Dynamic Models) is one of the software packages that offers the most broad database of world-class dummy models. MADYMO provides dummy models from 6 weeks old infant to the average adult size. All the dummies have been thoroughly validated to fulfill the requirements of crash test. MADYMO models are also renowned for their computational speed, robustness and accuracy abilities. The combination of rigid body and finite element method allows for the improvement of bio fidelity in crash safety and optimally combines the efficiency and accuracy. For crash test, MADYMO also provides automotive occupant safety design for frontal impact, rear impact, side impact, pedestrian impact, rollover and out-of-position applications (International, 2014b).

2.3 Crash Test

Crash test is a destructive testing used to measure the crash worthiness and crash compatibility of new vehicles (Xiang, 2012). An anthropometric test dummy (ATD) is used and represents the human body to determine the injury and fatality in the crash test (Chang *et al.*, 2010). This test can be performed either experimentally using the real car with dummy or via numerical simulations (Croft & Philippens, 2007; Beeman *et al.*, 2012). There are a few types of crash test conducted to simulate vehicle damage and specify occupant injuries. These are described as follows:

i. Frontal-impact test

- This test was simulated as one car having a frontal impact with another car of a similar mass at a specified speed. Mostly this test is conducted to determine the car structure (Naravane & Deb, 2005).

ii. Offset test

- This test is quite similar to the frontal test but with the frontal car impacted with a barrier. Mainly this test is used to determine the absorption and dissipation of crash energy and effect to the driver's side. It is also used to ensure the integrity of the passenger compartment maintains its shape during crash test (Mizuno *et al.*, 2003).

iii. Side-impact test

- Side impact test involves two vehicles which simulates car to car side impact. These tests focus on side occupants especially at the driver position. This type of crash test mostly cause fatality to the occupant because there is no crumple zone to absorb the impact forces. Therefore, side airbags are created to decrease the fatality of side impact crash (Yoganandan & Pintar, 2005).

iv. Roll-over test

- Rollover is a dangerous crash that can cause fatality. This test simulates a car lateral slide or curb trip which causes a rollover. The main purpose of this test is to test the pillars holding of the car roof in a dynamic impact. More recently, dynamic rollover tests have been proposed as opposed to static crush testing (Herbst *et al.*, 1998).

v. Old versus new

- This test was simulated by crashing two vehicles of the same model but different size and generation to test the advancements in crash worthiness (Walton *et al.*, 2013).

vi. Computer model

- Due to the cost of full-scale crash tests, engineers often run many simulated crash tests using computer models to refine their vehicle or barrier designs before conducting live tests (Noureddine *et al.*, 2002).

2.4 Dynamic and Kinematic Response

Each of the crash test gives a simulated human response of the impact, deflection, forces, displacement, velocity, accelerations and moments generated during the crash (Bartsch *et al.*, 2006; Mertz, 1993). The dummy also used to examine the dynamic and kinematic response (Han *et al.*, 2012; Linder, 2000) and displacements of interconnected rigid bodies of occupants during the collision event. It is very important as the kinematical and dynamical predictions of a dummy model or a human model should be extensively verified under various crash scenarios before to be used in the vehicle design process (Untaroiu *et al.*, 2013).

Study conducted by Dehner *et al.* (2008) has shown that the anthropometric difference influenced the kinematics of the cervical spine and the risk of injury in which individuals with small head circumference, long neck, tall body height and high body weight potentially to had high risk of injury. Moreover, the obese occupants experienced greater maximum forward displacement before their motion was arrested by the restraint during the frontal car crash (Kent *et al.*, 2010). Sled test done by Beeman *et al.* (2013) also shows that the forward excursions of anatomical regions increased with increasing acceleration severity.

Recent anthropomorphic test devices used for crash test enables the measurement of the human injury potential according to the type of collision (Golman *et al.*, 2014; Svensson *et al.*, 2000; Beeman *et al.*, 2012). In dummies, the most critical injuries focuses on the occupant's head, chest and pelvic regions (Acierno *et al.*, 2004).

The usage of real multibody system and rigid body model to determine the kinematic behavior are comparable with numerical method. Studies by Teng *et al.* (2008) have shown that the usage of multibody for frontal crash met the dynamic results in simulating the motion of body part during collision. The dynamic behavior also can be measured and simulated using equations representing the motion. Detailed analysis of injuries were obtained using computational methods (Haug *et al.*, 2004).

2.5 Injuries and Fatalities

Each type of collision in crash tests causes different types and part of injuries to the occupants. In the last few years, whiplash injury has been recognized a common public health issue that results from the neck or cervical injury during vehicle crash (Svensson *et al.*, 2000). The most critical part of the human body that can cause death is injury at the head, neck, pelvis and chest (Acierno *et al.*, 2004).

In Epidemiological studies, it has been found that women suffer more of whiplash injury than men (Dehner *et al.*, 2008). Heavy crash test in frontal impact, rear impact and side impact were studied to analyze the injuries that occur in the human body (Stahlschmidt *et al.*, 2006; Fressmann *et al.*, 2007). Some of the injuries may result in either short or long term consequences to the crash victims (Krafft *et al.*, 2000). Another study on frontal impact crash was focused on hip fractures associated with force applied for motor vehicles (Rupp *et al.*, 2010).

Research conducted by Teng *et al.* (2008) showed that the frontal impact test caused the head to move violently towards the steering wheel and rotate downwards when the body backs into the seat because of the lap and shoulder belt. Without the belt, the driver's head and chest hits the steering wheel and pulls back into the seat which results in a double impact that causes more serious injuries. Higher acceleration of the neck deformation may cause neck fail and cause the occupant death instantly.

For side impact test using side impact dummies (SID, BioSID, es-2 and World SIDp), the most critical injured part found was on the thorax, abdomen and pelvis under all impacting conditions (Acierno *et al.*, 2004; D'Elia *et al.*, 2013). Impacting forces in the pelvic and thoracic regions were higher than the abdominal or extremity regions in all surrogates. Most side impact crashes will result in critical injuries or fatalities especially to the side impacted occupant (Yoganandan *et al.*, 2007).

The most critical injury that might caused death or disability occurred at the head. The risk of the head injury can be measured using the Head Injury Criterion (HIC) formula (Gao & Wampler, 2009). Therefore, HIC model been created to measure the quantitatively the head injury risk in crash situation. The equation used to calculate the HIC is shown in Eq. (2.1).

$$\left\{\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2 - t_1)\right\} \tag{2.1}$$

or also can be expressed as

$$A^{2.5} \times d \tag{2.2}$$

where a is a resultant head acceleration, A is the acceleration average, $d = (\frac{t_2 - t_1}{1000})$ is the time different of the interval and t_2, t_1 is the selected so as to maximize HIC (McHenry, 2004).

2.6 Federal Motor Vehicle Safety Standard and Regulations (FMVSS)

Federal Motor Vehicle Safety Standard and Regulations is a federal regulations from U.S that specifying the construction, design, performance and durability requirements for motor vehicles. FMVSS has been issued by The National Highway Traffic Safety Administration (NHTSA) with a legislative mandate under Title 49 of the United State Code, Chapter 301, Motor Vehicle Safety. The standards are regulations written in terms of minimum safety performance requirements for motor vehicles or items of motor vehicle equipment.

The Federal standards consists of 3 main standard namely Crash Avoidance, Crashworthiness and Post Crash Standard. These 3 main standard has sub safety standard that been issued to FMVSS. All of the new standards and amendments to existing standards are published in the Federal Register (Hollowell *et al.*, 1999).

2.7 Effects of Age and Gender on the Risk of Car Crashes

A study conducted by Lardelli-Claret *et al.* (2011) showed that youngest from 18 to 20 years old and oldest drivers aged 60 to 64 years old has higher risk of involvement in a crash. The study also revealed that women had an enhancement risk of crash rate from age 25-29 years onward compared to men with the same age.

Other than risk of involvement in a crash, age and gender also influence the severity of the injuries. Latest study on motor-vehicle crashes conducted by Carter *et al.* (2014) have proved that females have more serious injuries in head, thorax and extremity compared to males. Other than that, comparisons between older females and older males showed that older females are more likely to have thorax and upper extremity injuries.

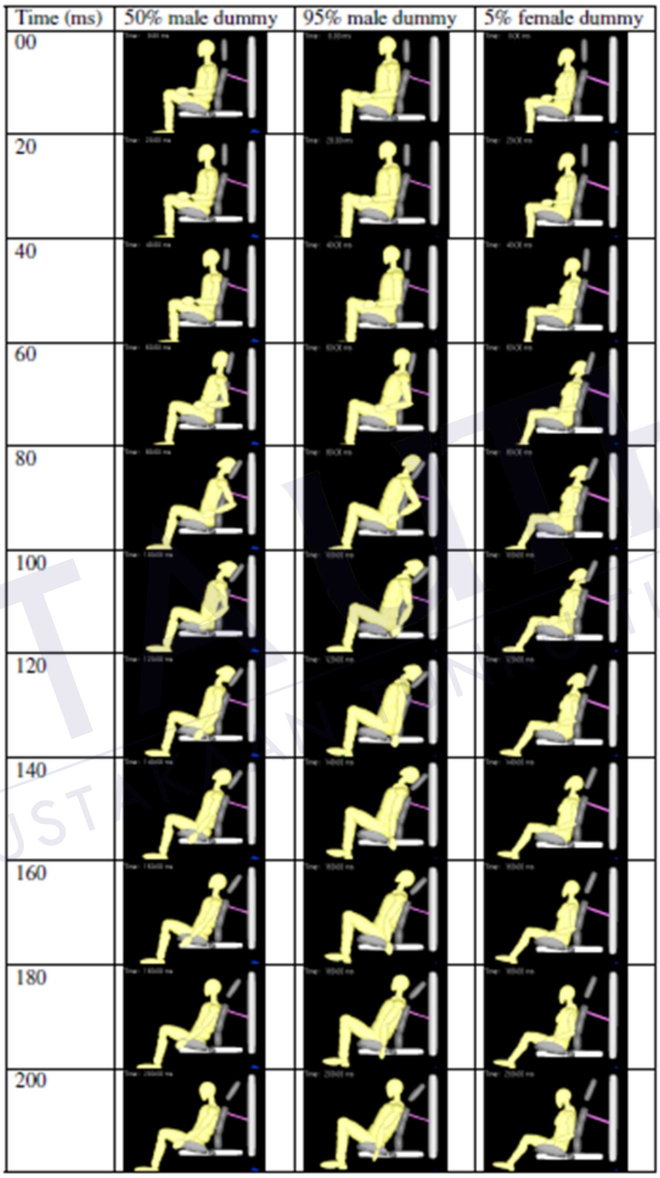

Figure 2.3: Dummy kinematics during impact. (Zou & Grzebieta, 2005)

Zou & Grzebieta (2005) made comparisons of rear seated occupant in frontal impacts for 50th % male, 95th% male and 5th% female using MADYMO models. The result shows that 5th% female occupant resulted in higher head acceleration, chest acceleration and head injury criterion (HIC). Details of dummy deformation can be seen at Figure 2.3 for every dummy from 0ms to 200ms.

Furthermore, research by Obeng (2011) on injury severity risks in crashes between both gender also shows that females injury severity risks resulted larger enhancement in the marginal effects of driver characteristics compare to males. In additional, severe crashes with front and side airbags also indicate that women sustained higher severe injuries than males.

From the stated facts, it can be concluded that the risk of car crashes are more likely involves the beginner drivers (18-20 years) whom are new on the road and also older drivers (60-64 years) which might be caused by lack of focus and sight due to age. Meanwhile in term of gender, females were found to have higher injuries severity compared to males which shows that more study is needed to improve the vehicle safety for female users.

2.8 Percentile Human

Anthropometric data varies considerably between regional populations, for example Scandinavian populations tend to be taller while Asian and Italian population tend to be shorter. Moreover, anthropometric dimensions for each population are ranked by size and described as percentiles. Thus, it is necessary to study about the percentile humans because there are enormous variation in body size between individuals, the gender, ethnic and age (Openshaw & Taylor, 2006).

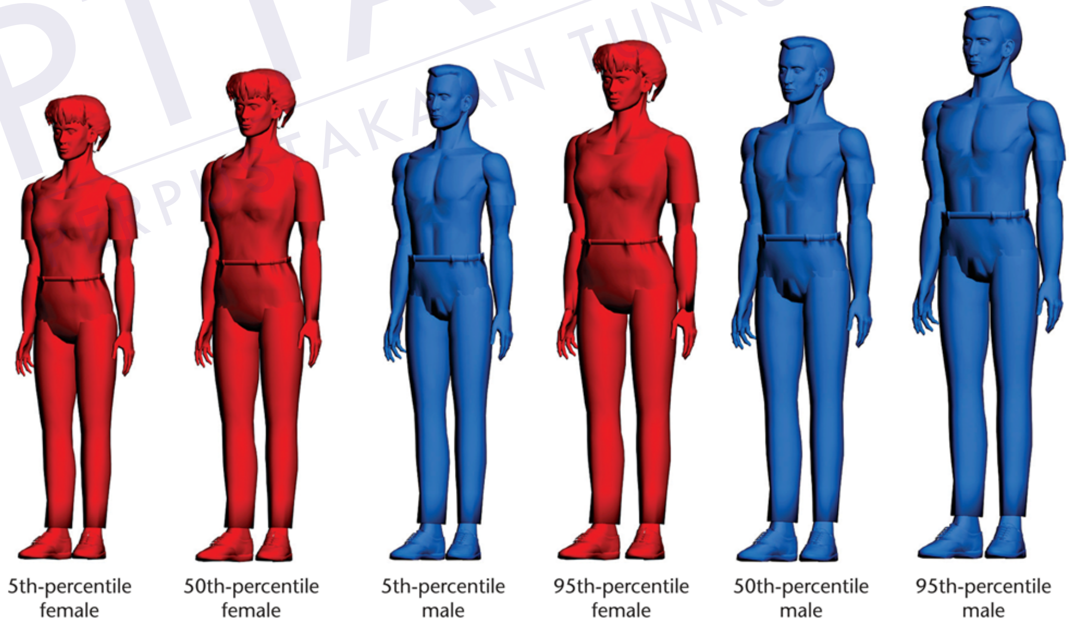

Figure 2.4: Human percentile. (Michalski & Grobelny, 2014)

Figure 2.4 show the example of the human percentile from 5*th* percentile female to 95*th* percentile male. The common practice in designing is from 5*th* percentile (5*th*%) female to the 95*th* percentile (95*th*%) male, with the 5*th* female value is for a particular dimension which usually represents the smallest measurement for design in population. On the contrary a 95th% male value may represent the largest dimensions for which one is designing.

However, in the manufacturing plants in Malaysia, Lin (2005) has figure out that most of Malaysia female faced a problem with the machinery or equipment that imported directly from the western world. These equipment, tools and general plant layouts were designed for the average American male (50th%) with 175cm height. Yet, the tallest 95th% female in Malaysia is at 166cm which definitely falls short of the average American. The average Malaysian female (50th%) at 156cm in height which similar with the small (5th%) female American at 160cm in height.

2.9 Development of Numerical Anthropomorphic Test Devices

Over the last decade, several numerical models of crash test dummies have been developed. From time to time, the models been updated ranging from rigid body to deformable crash dummy. There are three type of human percentile mainly focused for research within numerical models which are 5th%, 50th%, and 95th% for both male and female. A summary of current development for numerical model and their characteristics is illustrated in Table 2.3.

Table 2.3: Development of numerical ATD.

First Author (Year)	Dummy Model	Features	Advantage / Disadvantage
Noureddine *et al.* (2002)	Hybrid III 50th%	Model is made of 53 parts connected together with 13000 elements. Element types are solid and shell while the jointed dummy using a combination of joint definition and torsion springs.	The dummy model is developed special for the airplane cabin passengers only. Used to measure the chest acceleration, chest center line deflection, head acceleration and neck moments.
Kan *et al.* (2003)	Hybrid III 50th%	Model consist of 152 parts connected together with 38521 nodes, 39974 elements, 21880 shell elements, 16453 solid elements, 68 beam elements and 17 joints .	The dummy is used for frontal crash test. Used to measure the head and neck acceleration, chest acceleration, chest deflection and femur load.

Spit & van Hoof (2006)	MADYMO	MADYMO dummy database has 400 dummy component and sled test data. Have 3 different type of models: ellipsoid, facet and finite elements models.	All MADYMO dummy models can be used in other structural codes using the coupling functionality. They also extensively validated to ensure that they accurately represent the hardware dummies.
Mohan *et al.* (2007)	Hybrid III $50th\%$	Model is made of 176 parts with233541 nodes and 280482 elements	The component and the sub-system of the model is still not yet validated. Once the parameters required for the material models are optimized for the sub-system validation, the dummy model will be validated against full scale sled test.
Fressmann *et al.* (2007)	THUMS model	THUMS family consist of $50th\%$ American male (AM50), $5th\%$ American female (AM05) and 6 year old child (6YO). THUMS for pedestrian and occupant model included a very detailed skeletal structure, spinal and muscular system and internal organs.	Currently the model only focus on American citizen. The models consider the muscle activities but the inclusion into one holistic model and the corresponding model validation however hasn't been done yet.
Mohan *et al.* (2010)	Hybrid III $50th\%$ male and $5th\%$ female	The dummy models have 6 main assemblies, head neck, torso, pelvis, arms, and legs. Hybrid III $50th\%$ consist of 255000 elements while $5th\%$ consist of 200000 elements.	Developed dummy was used for frontal crash test. The sled tests were conducted with belted occupant without the seat foam, knee-bolsters and airbags.
Ohnishi *et al.* (2011)	Hybrid III Adult Female $5th\%$	The dummy was modeled using shell and solid elements. The FE model consisted of 336 parts and 253000 elements.	The developed detail FE model showed reasonable correlation for head drop, neck extension and flexion, thorax impact and torso flexion test. The model was effective for analyzing the internal deformation and load transfer during the frontal crash test.

2.10 Summary

This chapter has presented the literature reviews on the dummies development, the dynamic and kinematic responses, injuries and fatalities occurred and how size and gender influenced the crash test. FE model of the dummies are still under heavy development and still require an intensive validation. From time to time, the existing dummy models been updated whenever new and reliable results been found.

Current related researches done in Malaysia more for the ergonomics improvement for equipments and tools used by Malaysian people (Daruis *et al.*, 2007; Deros *et al.*, 2009). Meanwhile for the crash test, it is still a new implementation that been practiced by local automotive industry and they are using the available dummies which is Hybrid III dummy (Jawi *et al.*, 2013). There is no dummy or model base on local anthropometric database been proposed or created to represent local Malaysian for crash test.

Chapter 3

Methodology

This research is focused on developing a computational anthropometric test dummy which represents a Malaysian female passenger for crash test simulation. The simulation was conducted to study the kinematic behavior of the dummy. In this simulation, the damage or deformation on the model parts are neglected because the limitation for this project is only to study on the deformation behavior of the female passenger with shell thickness of 1 mm.

Firstly, research started by gathering all the important information, parameters and the standards which will be used for the simulation. The anthropometric data of Malaysian female are collected to get the average value to develop the anthropometric test dummy. After that, the geometric model of the dummy are developed using Solidworks 2010 and export in IGES file before it can be imported in GiD pre-processor. All body parts are assembled together in sitting position for frontal crash test. In GiD, all the constraint, boundary condition and the material properties are assigned into the female model.

In this research the simulation is conducted using the parallel processor computing method. The simulation test is run using Impact software to obtain the results. After the simulation is done, the data will be analyzed to determine the displacement, velocity and acceleration behavior of the dummy. The simulation result of Malaysian female passenger dummy will be compared with the Hybrid III $5th\%$ adult female.

3.1 Research Flow

This research is carried out according to the flow chart as shown in Figure 3.1. The anthropometric data of Malaysian females were first collected and measured to obtain the dimension of body parts. Then the model is developed using SolidWorks software part by part and saved as .iges file. Then, the parts are imported and assembled in pre and postprocessor called GiD. All meshing, materials properties and condition parameters are set in GiD and exported in .in file. Then the .in file is run using Impact preprocessor before being analyzed using GiD postprocessor. The model was simulated without restraint system to determined the kinematic behavior of the model.

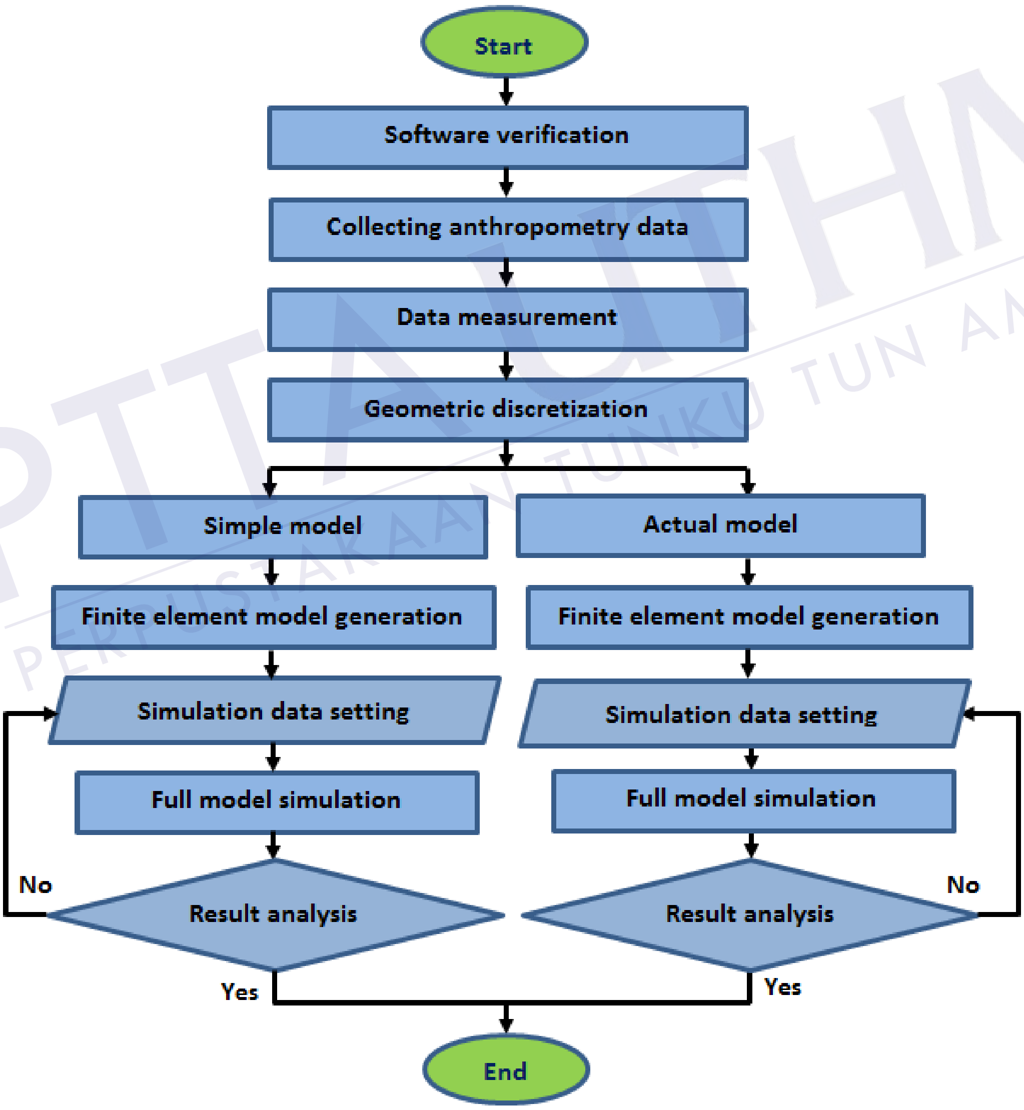

Figure 3.1: Overall flow chart for the research.

3.2 Software Verification

First of all, software verification need to be validated to ensure the simulation results meet the specified requirement for the computer simulation. Verification should be done before doing the simulation to ensure the software quality and data obtained meet the input requirements. For this research, the IMPACT software has been compared with LS-DYNA software.

The software verification is made by doing the visual comparison of a simple model of a rectangular hollow bar which has been done by Jensen *et al.* (2004). The similar hollow bar is created in GiD software with the same dimension as shown in Figure 3.2 where D is dimension and R is radius in millimeter units. The thickness of the hollow bar is 2.5 mm with 80 mm width, 700 mm length and 3 mm outer radius.

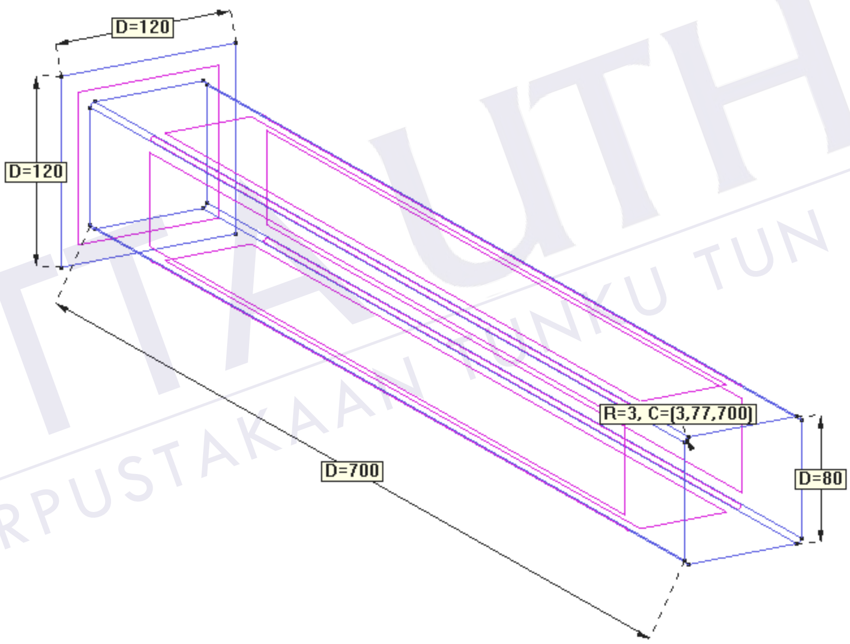

Figure 3.2: Simple model of rectangular hollow tube.

The model is meshed using structural quadrilateral element while the impact is used the the structural triangle element. Total of meshed is 2224 elements for both objects. The material used for the rectangular hollow tube is eleastoplastic and details properties is shown in Table 3.1 while the material for impactor is contact element with default value in GiD. The impactor is set to moved under a velocity of 20 ms^{-1} in negative y direction while the end of the rectangular tube is fix with the length of 100 mm.

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