UNIVERSITI PUTRA MALAYSIA

OPTIMIZATION OF MATERIAL SELECTION AND THICKNESS FOR CRASHWORTHINESS OF SIDE DOORS OF CARS

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

OPTIMIZATION OF MATERIAL SELECTION AND THICKNESS FOR CRASHWORTHINESS OF SIDE DOORS OF CARS

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August 2016

Chairman : Faieza Binti Abdul Aziz, PhD
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Prediction of a conceptual car's crashworthiness and testing its safety, as well as testing the effect of variables on the safety, has not proved practical to date. While a vehicle is still at the design stage and has not yet been manufactured, it is not possible to conduct a crash test. Nevertheless, as manufacturing of one individual component of the car requires up to five sets of dies, in order to find the best material and thickness for the car body, a new set of dies will be required for each change, which is both expensive and time consuming.

The aim of this research is to develop a method for determining the star rating of a Malaysian car using a computer and also to study the effect of variables on car crashworthiness. The first objective is to determine crashworthiness for side doors and the B-pillar of a conceptual vehicle body in Euro-NCAP side and pole side impact tests. The second objective of this research is to determine the effect of material and thickness on crashworthiness of side doors and B-pillars in Euro-NCAP side impact test and pole side impact test. The third objective will focus on developing a mathematical modelling of HIC to predict and calculate it in side and pole side impact tests by assigning various materials and thicknesses to the side doors and B-pillar. The fourth objective of this research is to develop a mathematical model of internal energy to predict and calculate it in side and pole side impact tests by assigning various materials and thicknesses to the side doors and B-pillar. The main goal of this research is to analyse crash criteria and multi-objective optimisation to propose a proper material and thickness for each side door and B-pillar in order to achieve maximum absorbed energy, minimum weight and thus a higher star rated car.

The methodology of this study was to conduct simulation tests of the conceptual vehicle. A model of the vehicle, a Moving Deformable Barrier

(MDB) and a rigid pole were designed, and this was followed by assigning all initial conditions defined in Euro-NCAP. Car crash simulation using LS-DYNA was conducted to determine the crashworthiness of side doors and B-pillars for side impact tests and then for pole side impact tests, to address objective number one. Four materials including Steel AISI 1006, Aluminum Alloy 5182, Magnesium AZ31B and High Strength Steel 204M with five distinct thicknesses including 0.65, 0.75, 1.0, 1.2 and 1.4mm were assigned to the side doors and B-pillar to investigate the effect of material and thickness on crashworthiness and crash simulations were conducted for both side impact and pole side impact to achieve objective number two. For each conducted simulation, Head Injury Criteria (HIC) and Internal Energy of the side doors and B-pillar were determined from LS-DYNA post processing and then two equations were generated for HIC and Internal Energy as a function of the effective variables. Data analysis and multi-objective optimisation, considering all pertinent variables, was carried out to propose a material and a thickness for the highest absorbed energy with the lowest HIC to achieve objective number three. Several materials and thicknesses, in addition to those tested, were assigned to the formula of HIC and Internal Energy to predict those that are best and safest for the vehicle body to achieve objective number four.

Results of side impact tests when the thickness remains original, 0.75mm, show that the highest absorbed energy is when the material is High Strength Steel 204M, where absorbed energy by rear door is 1e+6j, 1.8e+6j for the front door and 1.5e+6j for the B-pillar. In pole impact tests where the material was original and unchanged, the B-pillar with a thickness of 0.75mm absorbed 25e+3j of energy, the front door with a thickness of 1.4mm absorbed 0.14e+6j of energy and the maximum energy absorbed by the rear door was 0.13e+6j for all various thicknesses.

Based on the HIC multi-objective crashworthiness determination assigning various thicknesses and materials to the side doors and B-pillar in side impact tests as well as pole side impact tests, it was clearly demonstrated that to have the lowest HIC, the optimised thickness was 1.1mm while the material was Carbon Fibre Reinforced. The Internal Energy multi-objective crashworthiness determination showed that the very best thickness and material for the vehicle body in side impact tests as well as pole side impact tests is Titanium with the thickness of 1.4 mm.

In conclusion, as this research was conducted on the side doors and B-pillars only and each material or thickness was assigned to all these three components together, it can be concluded that Carbon Fibre Reinforced with a thickness of 1.1mm is the best option for the safest and highest star rated car for this specific Malaysian local car. Titanium is not a viable option as it is expensive and there are also issues in relation to manufacturing the car body, especially when the thickness is 1.4mm.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGOPTIMUMAN PEMILIHAN BAHAN DAN KETEBALAN UNTUK KEBOLEHTAHANAN PERLANGGARAN PINTU SISI KERETA

Oleh

ALI HASSANZADEH LILEHKOOHI

Ogos 2016

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Ramalan kebolehtahanan pelanggaran sesebuah konsep kereta dan ujian ke atas keselamatannya, serta pengujian ke atas kesan pembolehubah terhadap keselamatan masih belum terbukti praktikal sehingga kini. Bagi sesebuah kenderaan yang masih di dalam peringkat reka cipta dan belum dikilangkan, ia tidak memungkinkan untuk ujian impak dijalankan. Walau bagaimanapun , memandangkan pembuatan setiap satu komponen sesebuah kereta memerlukan sehingga lima set acuan yang bertujuan untuk mengenal pasti bahan dan ketebalan terbaik untuk badan kereta, setiap satu set acuan baharu adalah diperlukan untuk setiap perubahan, yang mana ianya mahal dan memakan masa.

Tujuan penyelidikan ini adalah untuk membangunkan satu kaedah bagi menentukan penarafan bintang sesebuah kereta di Malaysia dengan aplikasi komputer di samping untuk mengkaji kesan pembolehubah-pembolehubah ke atas kebolehtahanan pelanggaran kereta. Objektif pertama adalah untuk menentukan kebolehtahanan pelanggaran pintu sisi dan tiang-B dalam ujian impak sisi dan ujian impak sisi tiang berdasarkan Euro-NCAP. Objektif kedua kajian ini pula adalah untuk mengkaji kesan pengaruh bahan dan ketebalan ke atas kebolehtahanan pelanggaran pintu sisi dan tiang-B dalam ujian impak sisi dan ujian impak sisi tiang Euro-NCAP. Objektif ketiga kajian ini akan memfokuskan kepada analisis secara matematik ke atas ujian impak sisi dan ujian impak sisi tiang dengan menggunakan pelbagai bahan dan ketebalan kepada pintu sisi dan tiang-B. Objektif keempat kajian ini adalah untuk menganalisis kriteria pelanggaran dan pengoptimuman pelbagai objektif dengan mencadangkan satu bahan dan ketebalan yang sesuai untuk setiap pintu sisi dan tiang-B bagi mencapai tenaga serapan yang maksimum, berat minimum dan memperolehi pengiktirafan kenderaan berbintang tinggi.

Kaedah kajian ini adalah untuk menjalankan ujian simulasi ke atas konsep kenderaan. Sebuah model kenderaan, sebuah penghadang boleh ubah bentuk serta mudah alih (MDB) dan sebatang tiang tegar telah direka bentuk , dan ini telah diikuti dengan menentukan semua syarat awal yang telah dijelaskan dalam Euro NCAP. Untuk mencapai objektif pertama, simulasi perlanggaran kereta menggunakan LS-DYNA telah dijalankan untuk ujian-ujian impak sisi dan ujian-ujian impak sisi tiang. Bagi mencapai objektif kedua, empat bahan dengan, Steel AISI 1006, Aluminum Alloy 5182, Magnesium AZ31B dan High Strength Steel 204M lima ketebalan 0.65, 0.75, 1.0, 1.2 and 1.4mm yang berbeza telah diuji ke atas pintu sisi dan tiang-B bagi menyiasat kesan bahan dan ketebalan untuk kebolehtahanan pelanggaran di samping beberapa simulasi pelanggaran telah dijalankan untuk kedua-dua impak sisi dan impak sisi tiang. Untuk setiap simulasi yang dijalankan, kriteria kecederaan piawai pada kepala (HIC) and tenaga dalaman pintu sisi dan tiang-B telah ditentukan dari pasca pemprosesan LS-DYNA dan kemudiannya, dua persamaan telah dihasilkan untuk kriteria kecederaan piawai pada kepala dan tenaga dalaman sebagai satu fungsi pembolehubah berkesan. Analisis data dan pengoptimuman kepelbagai objektif dengan mempertimbangkan semua pembolehubah berkaitan, telah dijalankan bagi mengusulkan satu bahan dan ketebalan untuk tenaga serapan tertinggi dengan kriteria kecederaan piawai pada kepala yang terendah bagi mencapai objektif ke tiga. Beberapa jenis bahan dan ketebalan, selain daripada ujian yang telah dijalankan, turut digunakan di dalam formula kriteria kecederaan piawai pada kepala dan tenaga dalaman bagi meramalkan hasil yang terbaik dan yang paling selamat untuk badan kenderaan bagi mencapai objektif keempat.

Keputusan ke atas ujian impak sisi pada ketebalan asal, 0.75mm, menunjukkan bahawa tenaga serapan tertinggi adalah apabila bahan ialah dari jenis keluli berkekuatan tinggi 204M (High Strength Steel 204M), di mana tenaga serapan oleh pintu belakang ialah 1e+6j, 1.8e+6j untuk pintu hadapan dan 1.5e+6j untuk tiang-B. Untuk ujian hentaman tiang di mana bahannya asal dan tidak berubah, tiang-B dengan ketebalan 0.75mm menyerap 25e+3j tenaga, pintu hadapan dengan ketebalan 1.4mm menyerap 0.14e+6j tenaga dan tenaga serapan maksimum bagi pintu belakang ialah 0.13e+6j untuk semua jenis ketebalan.

Berdasarkan kepada kepelbagaian objektif kebolehtahanan pelanggaran ke atas kriteria kecederaan piawai pada kepala, dalam menentukan pelbagai ketebalan dan bahan kepada pintu sisi dan tiang-B ke atas ujian impak sisi serta ujian impak sisi tiang, ia dengan jelas menunjukkan bahawa untuk mempunyai bacaan kriteria kecederaan piawai pada kepala yang terendah, ketebalan yang dioptimumkan ialah 1.1mm dengan bahan yang digunakan adalah gentian karbon yang ditambah baik (Carbon Fibre Reinforced). Kepelbagaian objektif kebolehtahanan pelanggaran ke atas tenaga dalaman menunjukkan bahawa ketebalan dan bahan terbaik untuk badan kenderaan dalam ujian impak sisi serta ujian impak sisi tiang ialah Titanium dengan ketebalan 1.4 mm.

Kesimpulannya, memandangkan penyelidikan ini hanya dijalankan ke atas pintu sisi dan tiang-B, dan setiap bahan atau ketebalan ditetapkan kepada kesemua tiga komponen ini secara serentak, ia boleh disimpulkan bahawa bahan gentian karbon yang ditambah baik (Carbon Fibre Reinforced) dengan ketebalan 1.1mm adalah pilihan terbaik untuk kereta tempatan Malaysia yang paling selamat dan dinilai sebagai bintang bertaraf tinggi. Titanium bukanlah satu pilihan berdaya maju kerana ianya mahal dan terdapat beberapa isu berkaitan dengan pembuatan badan kereta, terutamanya apabila ketebalan adalah 1.4mm.

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I certify that aThesis Examination Committee has met on 19 August 16 to conduct the final examination of Ali Hassanzadeh Lilehkoohi on his thesis entitled "Optimization of Material Selection and Thickness for Crashworthiness of Side Doors of Cars" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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Declaration by graduate student

I hereby confirm that:

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LIST OF ABBREVIATIONS

AR	Acceleration
ANN	Artificial Neural Network
ANCAP	Australian New Car Assessment Program
d	Ductility
ECE R95	Economic Commission for Europe Regulation No. 95
FMVSS	Federal Motor Vehicle Safety Standards
GRP	Glass Reinforced Plastic
HIC	Head Injury Criteria
ISS	Injury Severity Score
JNCAP	JNCAP:japanese New Car Assessment Program
MDB	Moveable Deformable Barrier
NHTSA	National Highway Traffic Safety Administration
NCAP	New Car Assessment Program
NCF	Non Crimped Fabrics
v	Poisson Ratio
RTM	Resin Transfer Moulding
TWB	Tailor Welded Blank
k	Stiffness
UTS	Ultimate Tensile Strength
S_y	Yield Strength
E	Young's Modulus

CHAPTER 1

INTRODUCTION

Investigation of the effects of the vehicle body's variables using a real car side impact test is economically unsound due to expensive costs of body die and car manufacturing. Alternatively, the easier and more reliable method to perform car crash test is through computer simulation based on European New Car Assessment Program (Euro-NCAP), using a solver such as LS-DYNA. In this method changing the variables such as body's thickness and material will not incur any cost; hence, investigation on their effects on crashworthiness is practical and repeatable.

1.1 Introduction to car assessment program

Adult Occupant Protection with a weight factor of 50%, is one out of three parameters which needs to be calculated to assess a car under the Euro New Car Assessment Program (Euro-NCAP); while the other parameters which are the Child Occupant Protection and Pedestrian Occupant Protection have a weight factor of 20%. The Side Impact Test and the Pole Side Impact Test, as well as Front Impact, are required for calculating the Adult Occupant Protection. For adult protection testing, three tests are required to be performed: 1- side impact, 2- pole impact 3- front impact. In the side impact test, the dummy's head, chest, shoulder, thorax, ribs, abdomen, pelvis, and femur must be studied to evaluate the rating score. Crashworthiness of a car during side impact can describe the score rated for that car. The overall score of safety rating of a car has been described by Euro NCAP as adult protection, child protection, pedestrian protection and safety assist. In particular, for children protection assessment there are two tests required to be performed, which are the front and side impact tests.

Weight factors of these safety protections have been allocated by Euro-NCAP, which are shown in Table 1.1. Total points applied to star values, based on weighting, have been described by Euro NCAP, as shown in Table 1.2. As it can be seen, side impact test is the second most important crash configuration and has more effect on car safety and car star rating than other tests. Nonetheless, major cause of car accident injuries are from side crashes. In Japanese NCAP, for side impact the test speed is 55 km/h and no child dummies are prescribed, while Australian NCAP is similar to Euro NCAP for side impact tests where no child dummies are tested in the rear seat. In Latin NCAP there is no side impact test. The National Highway Traffic Safety Administration (NHTSA) side impact test procedure is analogous to the FMVSS 214 protocol. The impact velocity is 62 km/h and direction is described as in Figure 1.1.

Table 1.1: Weighting factors

Year	2009	2010	2011	2012
Adult Occupant Protection	50%	50%	50%	50%
Child Occupant Protection	20%	20%	20%	20%
Pedestrian Protection	20%	20%	20%	20%
Safety Assist	10%	10%	10%	10%

Adapted from Assessment Protocol, Overall Rating, Version 5.1 (2011)

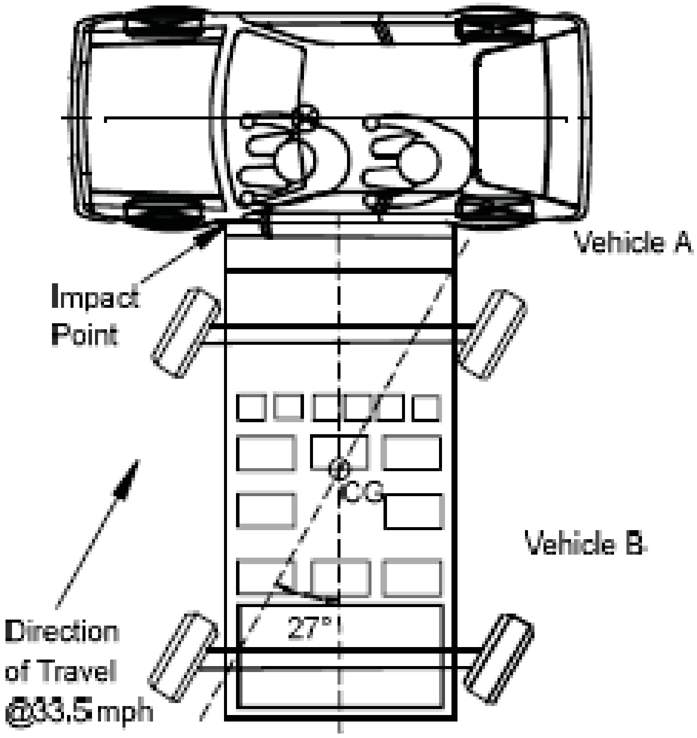

Figure 1.1: Impact configuration adopted from FMVSS 214

Table 1.2: Total points applied to star values, based on weighting

Year	2009	2010	2011	2012
For five star, at least:	70%	75%	75%	80%
For five star, at least:	55%	60%	60%	70%
For five star, at least:	45%	50%	50%	60%
For five star, at least:	35%	35%	35%	55%
For five star, at least:	20%	25%	25%	45%

Adapted from Assessment Protocol, Overall Rating, Version 5.1 (2011)

The Euro-NCAP describes the side impact test by having a Mobile Deformable Barrier (MDB), according to ECE R95 impact to driver's door at 50 km/h at an angle of 90°. The configuration is described in Figure 1.2. “The barrier weighs 950 kg and has a width of 1500 mm. The deformable element has a ground clearance of 300 mm. The centre line of the MDB should match with the X position of the hip point of the 95-percentile dummy (R-point). A Euro SID dummy is positioned in the driver’s seat” Assessment Protocol, Overall Rating, Version 5.1 (2011).

One out of the three sorts of crash tests in Euro NCAP standard is the side impact test. Passengers are highly in danger in car side crash, because of the distance between passenger’s head and vehicle body. In side impact test, front and rear doors and B-pillar are most absorbent parts among vehicle body parts. Therefore, it is very important to conduct a study on side doors and B-pillar as well as their behaviour during and after collision to achieve maximum absorbed energy in order to increase passenger’s safety.

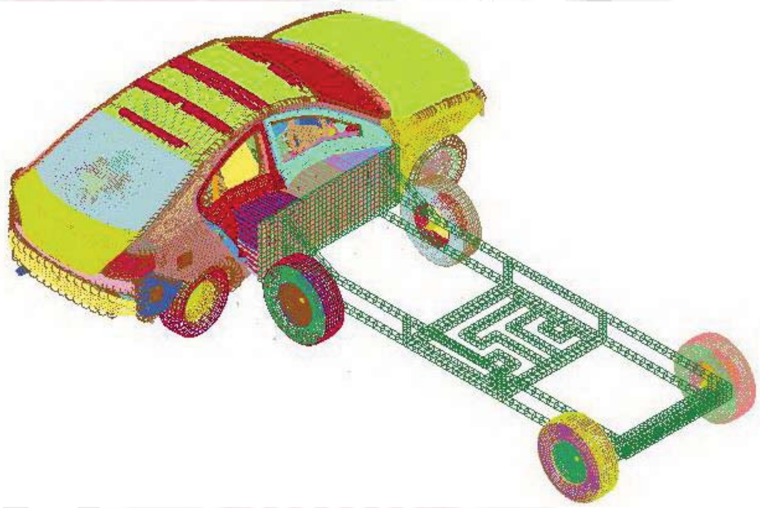

Figure 1.2: Schematic of Euro NCAP side impact test

The Pole Impact Test is one out of three Impact Tests, aside from Side and Front Impact Tests, described by Euro New Car Assessment Program (Euro NCAP) in order to assess Adult Occupant Protection. In conducting this test, Head, Chest, Abdomen and Pelvis are the criteria to be assessed and each of them will be marked between 0 and 4. The point score in each area of assessment will be calculated by those marks. Four areas of assessment are Adult Occupant Protection, Child Occupant Protection, Pedestrian and Safety Assist. The weight factors reflect the relative importance of the four areas of assessment in the final score and the overall rating will be composed of it. The Weight Factor for Adult Occupant Protection, Child Occupant Protection, Pedestrian and Safety Assist are 50%, 20%, 20% and 10% respectively. Figure 1.3 shows the schematic of the pole side impact test. In this test, the velocity of 29km/h must be assigned to the vehicle which is placed on top of a cart, while the pole has been assigned as a rigid static object based on Euro NCAP requirements.

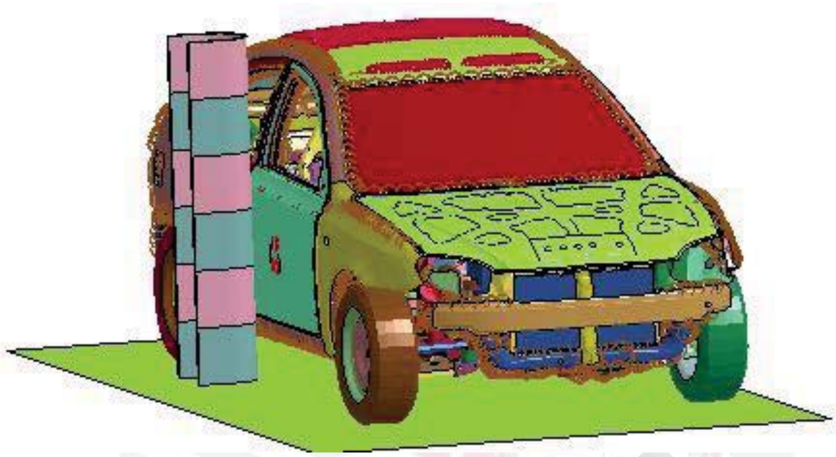

Figure 1.3: Pole side impact in perspective view

The side crash of a vehicle may cause severe injury to adult and child occupants, especially to their heads and necks. Injuries to occupants will be assessed according to Euro New Car Assessment Program (Euro-NCAP) in order to provide a star rating to the vehicle. Pole side impact is one of the tests described in Euro-NCAP Pole Side Impact Testing Protocol, Version 5.1 (June 2011). To improve crashworthiness of a vehicle, it is essential to find a way to increase the absorbed energy by the vehicle body. Basically, variables include material, thickness and geometry of a vehicle body. Changing the geometry of the vehicle body is not an objective of this study. The goals of this research are to study the effects of material and thickness of side doors and B-pillar on crashworthiness and absorbed energy during Side Impact Test and Pole Side Impact Test and to select a proper material and an optimized thickness for these three parts in order to approach a five star car concept.

Production of industrial dies of vehicle body is very complicated, expensive and time consuming. In order to create one individual part, it could require four or five dies. If researchers want to investigate the effect of material of a vehicle body on crashworthiness, they must design and produce a new set of dies. This approach is considered to be impractical for a research study due to financial and time constrains.

Investigating the effects of the variables of the vehicle body on side impact test based on European New Car Assessment Program (Euro-NCAP) standard is economically unsound; due to expensive manufacturing cost of the car and of the body dies. It is apparently easier and more practical to change the variables and investigate their effects on crashworthiness by using a computer and a solver such as LS-DYNA.

In order to study the effects of the material and thickness of the side doors and the B-pillar on the absorbed energy by a vehicle, preparation need to be made. The preparation of the vehicle which requires several different initial conditions, such as body shape, thickness and material of body, is a time consuming and expensive process. Investigation of the effects of vehicle body's material on crashworthiness by simulation methods helps researches to overcome the practical problems of crash test such as die making, long period of test preparation and financial issues.

Crash simulation is an affordable method in investigating the effects of material selection on crashworthiness virtually without spending money and time. The only thing researchers need is a computer, model of vehicle, as shown in Figure 1.3, and software. This enables researchers to carry out crash tests multiple times and investigate the effect of any changes assigned to the vehicle. Additionally, this will allow researchers to find a material and thickness which absorbs maximum energy and minimise head injuries during a car crash, and eventually it can be proposed to vehicle manufacturers to produce a car with higher star rating.

Computers and developed solvers, such as LS-DYNA, could realize the researcher's ambitious dreams when they study the influences of variables on absorbed energy by a conceptual vehicle. LS-DYNA software is the best software for the impact test purposes. It was previously impossible to manufacture and prepare a real vehicle for a crash test because of its duration and costs. Selecting different thicknesses and assigning them to each part of the vehicle body in the virtual world merely requires the cost of a solver. Data validation can be done through comparing the results with actual results of crash tests or by mathematical modelling.

1.2 Introduction to vehicle body manufacturing

Production of industrial dies of a vehicle body is a very complicated and expensive process and usually requires a long period of time. At some instance, it would requires several dies just to produce one individual part, hence, if researchers plan to investigate the effect of the variables of a vehicle body on crashworthiness, they have to design and produce a new set of dies. In other words, in order to conduct a simple change in one individual component of a vehicle body, like material or thickness, a new set of dies which consists of five to six dies are required to be manufactured and prepared in order to manufacture that single component. This is economically unsound and indeed it is impractical to carry out such a research because of the costs and time constrains.

1.3 Problem statement

The increasing cases of car accident death and injuries in Malaysia since 1997 is very drastic and alarming, hence, designing a safer car is necessary to reduce the amount of injuries and to prevent fatal car accident. Table 1.3 below shows the statistics of car accidents and serious injuries as well as slight injuries in Malaysia between 1997 and 2014 (Rahman 2014). It can be seen in Table 1.3 that road crashes had increased from 1997 to 2014. A constant death has increasingly been reported from 6302 in 1997 to 6674 in 2014 due to road accidents while serious and slight injuries remarkably decreased from 14105 and 36167 to 4432 and 8598 respectively from 1997 to 2014. Potential deaths due to car crashes could be avoided by using safer cars with five-star rated in Euro-NCAP standard. Due to that reason, in achieving a safer car, the study on injuries and affecting parameters on crashworthiness is essentially necessary.

Table 1.3: General road accident data in Malaysia (1997 – 2014)

Year	Registered Vehicles	Population	Road Crashes	Road Deaths	Serious Injury	Slight Injury
1997	8,550,469	21,665,600	215,632	6,302	14,105	36,167
1998	9,141,357	22,179,500	211,037	5,740	12,068	37,896
1999	9,929,951	22,711,900	223,166	5,794	10,366	36,777
2000	10,598,804	23,263,600	250,429	6,035	9,790	34,375
2001	11,302,545	23,795,300	265,175	5,849	8,680	35,944
2002	12,068,144	24,526,500	279,711	5,891	8,425	35,236
2003	12,819,248	25,048,300	298,653	6,286	9,040	37,415
2004	13,828,889	25,580,000	326,815	6,228	9,218	38,645
2005	15,026,660	26,130,000	328,264	6,200	9,395	31,417
2006	15,790,732	26,640,000	341,252	6,287	9,253	19,885
2007	16,813,943	27,170,000	363,319	6,282	9,273	18,444
2008	17,971,901	27,730,000	373,071	6,527	8,868	16,879
2009	19,016,782	28,310,000	397,330	6,745	8,849	15,823
2010	20,188,565	28,910,000	414,421	6,872	7,781	13,616
2011	21,401,269	29,000,000	449,040	6,877	6,328	12,365
2012	22,702,221	29,300,000	462,423	6,917	5,868	11,654
2013	23,819,256	29,947,600	477,204	6,915	4,597	8,388
2014	25,101,192	30,300,000	476,196	6,674	4,432	8,598

Adopted from (Rahman 2014)

Car crash test by Euro-NCAP is expensive, time consuming and requires a ready manufactured car, not only a conceptual one. It is necessary to find a way to investigate the effective parameters on crashworthiness of a car and also optimise the effective parameters to maximise the car's safety. Manufacturing and preparing a vehicle for a crash test is a long and expensive process, so studying the effect of material and thickness on crashworthiness is unsound economically. In other hand, a full set of dies will be required in case of any changes in a single component. In case of changing material or thickness of the vehicle body, a new set of dies is required to manufacture that individual component. So repeating the real crash test for various ranges of material and thicknesses is very expensive and a kind of impossible. At the same time, there is no way to predict the effects of non-tested material or thickness on crashworthiness, HIC (Head Injury Criteria) and internal energy. Effective parameters on crashworthiness and absorbed energy are not formulated in real crash test. There is no way to predict the crashworthiness of a car right after designing.

The solution is using computer simulation for crashworthiness determination. Studying the effect of affecting parameters on crashworthiness on a conceptual car was not previously possible even for a single component of a vehicle but with the help of computer and software; there is now a solution to determine crashworthiness and to investigate the effect of material type and thickness on crashworthiness. Developed solvers, such as LS-DYNA, and computers make the researcher's ambitious dream of studying the influences of variables on absorbed energy for a conceptual vehicle come true. Selecting different values for the variables and assigning them to each part of the vehicle body in the virtual world merely requires the cost of solver. Also, it is possible to repeat a test for several times with no cost.

1.4 Objectives

As the goal of this research is to find methods to improve car safety based on Euro-NCAP, the overall objective can be described by optimization of material or optimization of body thickness to achieve a five star car. In this way, it is necessary for the crashworthiness of the car to be determined first and then the effect of material or thickness on crashworthiness be investigated. In order to validate and verify the results, those of mathematical modelling of HIC and also the results of mathematical modelling of internal energy must be checked against the results of crashworthiness.

The objectives of this research are as follows:

1- To determine crashworthiness for side doors and B-pillar of a conceptual vehicle body in Euro-NCAP side and pole side impact tests.
2- To determine the effects of material and thickness on crashworthiness of side doors and B-pillar in Euro-NCAP side impact test and pole side impact test.
3- To develop mathematical model of HIC to predict and calculate it in side and pole side impact tests by assigning various material and thicknesses to the side doors and B-pillar.
4- To develop mathematical model of internal energy to predict side and pole side impact tests by assigning various material and thicknesses to the side doors and B-pillar

The aim of this research is to develop a method for determining the star rating of a Malaysian car using a computer and also to study the effect of variables on car crashworthiness. The main goal of this research is to analyse crash criteria and multi-objective optimisation to propose a proper material and thickness for each side door and B-pillar in order to achieve maximum absorbed energy, minimum weight and thus a higher star rated car.

1.5 Scope of research

Basically, occupant safety is the main concern of this research. Crashworthiness determination of Proton Persona body in Side Impact and Pole Side Impact using simulation techniques is the first scope of this research. Secondly, it is to study the effect of material and thickness on crashworthiness in Side Impact and Pole Side Impact. Mathematical modeling and multi-objective optimization is the next scope of the research to develop an equation for HIC as a function of mechanical and physical properties of the vehicle body. The fourth scope of this study is mathematical modeling and multi-objective optimization to develop an equation for internal energy as a function of mechanical and physical properties of the vehicle body in order to propose a material with a certain thickness to absorb maximum energy in side impact and pole side impact test. This will achieve a safer car with a higher star rated in Euro-NCAP crash test. Crash simulation is a method and technique to investigate the effect of variables of the vehicle parts on crashworthiness virtually without spending a great deal of money and time. The only thing researchers need is a computer, a model of vehicle, as shown in Figure 1.4, and a solver, and then extensive research can be carried out on crash tests several times and investigate the effect of any changes assigned to the vehicle.

Figure 1.4: Vehicle model designed using CATIA

Side crash of a vehicle may cause severe injury to adult and child occupants especially to their head and neck. Injuries to occupants will be assessed by

Euro-NCAP in order to provide a star rating to the vehicle. To improve crashworthiness of a vehicle, in order to get a higher star rating, finding a way to increase energy absorbed by the vehicle body is essential. Basically, variables include material, thickness and geometry of a vehicle body. Changing the geometry of the vehicle body is not an objective of this research. The goals of this research are to study the effect of material and thickness of side doors and B-pillar on crashworthiness as well as measuring the absorbed energy by them during Pole Side and Side Impact Tests and to select a proper material and an optimized thickness for these three parts in order to approach a five star car.

The overall score of safety rating of a car has been described by Euro-NCAP as Adult Occupant Protection, Child Occupant Protection, Pedestrian Protection and Safety Assist. There are three kinds of impact described by Euro-NCAP: Front Impact, Side Impact and Pole Impact all of which must be performed for adult protection assessment. For children protection assessment front and side impact tests are required to be performed. Weighting factors of these safety protections have been described in Table 1.1.

One out of three sorts of crash tests in Euro-NCAP standard is the side impact test, as mentioned above. This kind of crash may have adverse injury to passenger. Mostly, a big percentage of absorbed energy belongs to the side doors and B-pillar. Therefore, it is very important to study on side doors and B-pillar and its circumstances to achieve maximum absorbed energy in order to increase passenger safety. It means if a material or thickness could be found leading to maximum absorbed energy and minimum head injury during side crash, so it can be proposed to vehicle manufacturers to produce a car with a higher star rating. Total points applied to star values, based on weighting factors, have been described in Table 1.2. The overall weighted score is used to generate the overall star rating by applying the score against the percentage score required for each star. There will be a minimum score required in each box to validate a star rating (Assessment Protocol, Overall Rating, Version 5 (2011)).

As it can be seen, side impact test is the second most important crash configuration and has more effect on car safety and car star rating than other tests. However, a major amount of car accident injuries are caused by side crashes.

In order to perform the crash simulation, there were several limitations. First of all, the conceptual model of Proton GEN2 was available and the whole research group members, who were working on this project, were supposed to focus on Proton GEN2 only. Secondly, Crashworthiness and Euro-NCAP crash test results were not available. Thirdly, the only available solver and its certificate at research center was LS-DYNA, which was the most powerful software for crash simulations but was not practical for meshing and modelling.

Hypermesh was used for meshing and Catia for all other drawings and modellings. Fourthly, the focus of this research was on side door's outer parts and to change its material and thickness, because studying on all car components was not practical as a matter of time. Finally, thickness selection was limited between 0.65 to 1.4 mm due to technical matters.

1.6 Thesis layout

After chapter one, which is introduction, chapter two has gone through to a deep review of literatures related to crash simulation and modeling as well as triple crash test. In chapter two, literatures on crash simulation with finite element method has been reviewed, followed by benefits of crash simulation. Developed models of occupant's body and simulation software's are the next sub-titles of the chapter two and at the end; some of recent researches on crash simulation have been reviewed.

In chapter three, methodology of this research has been explained including Euro-NCAP description, Flowchart, and simulation of side/pole impact tests and data analysis are briefed.

Chapter four consists of four sub-headings tailed to the research objectives. Firstly, results of simulation of side and pole impact tests and its crashworthiness using LS-DYNA are discussed as objective one. Secondly, results of side impact and pole side impact test simulation and study the effect of material and thickness on crashworthiness are discussed as objective number two. Thirdly, mathematical modeling, multi-objective optimization and data analysis of HIC value, extracted from simulation of side impact and pole side impact test, is discussed as objective number three in order to develop an equation for HIC as a function of mechanical and physical properties of the vehicle body. Fourthly, mathematical modeling, multi-objective optimization and data analysis of internal energy value extracted from simulation of side impact and pole side impact test is discussed as objective four in order to develop an equation for HIC as a function of mechanical and physical properties of the vehicle body. Finally, all achievements are collected and discussed in summary and further discussions session.

Chapter five is conclusion and recommendations for future research.

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