



UNIVERSITI PUTRA MALAYSIA

**FINITE ELEMENT SIMULATION AND EXPERIMENTAL
EVALUATION OF MOTORCYCLE BASKET
FOR CRASHWORTHINESS ANALYSIS**

HOW CHEE KEONG

FK 1999 18

**FINITE ELEMENT SIMULATION AND EXPERIMENTAL
EVALUATION OF MOTORCYCLE BASKET
FOR CRASHWORTHINESS ANALYSIS**

By

HOW CHEE KEONG

**Thesis Submitted in Fulfilment of the Requirement for the
Degree of Master of Science in the Faculty of Engineering,
Universiti Putra Malaysia**

July 1999



~ ♥ ~

**To my parents, How Hock Seng and Tan Chah Boh;
my best friend and wife, Lim Tan Chin;
and my brother and sisters,
Siew Cheng, Chee Hua and Siew Hoon.**

~ ♥ ~



ACKNOWLEDGEMENTS

It is indeed a great pleasure, upon the completion of a research of this nature, to acknowledge the contribution of those who assisted me in the evolution of the text. First and foremost, I would like to express my most sincere thanks and appreciation to the Chairperson of Supervisory Committee, Dr. Megat Mohamad Hamdan Megat Ahmad, Head of the Department of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, for his guidance, encouragement and constructive suggestions throughout the course of study. I also wish to extend my gratitude to Assoc. Prof. Ir. Dr. Radin Umar Radin Sohadi and Dr. Abdel Magid Salem Hamouda for their support, constructive criticisms and valuable comments in making this study a success.

I would like to express my deep appreciation to Universiti Putra Malaysia (UPM), UPM library and her staff, particularly Puan Nor Hajar Abu Bakar, Puan Azizah Zainal Abidin and Puan Fatimah, for their help and support.

I am indebted to the Faculty of Engineering and her staff, particularly Mr. Ratnasamy Muniandy, Mr. Hussain Hamid, Puan Fadhilah Omar, Puan Khatijah Hassan, Puan Nor Maziah Abd. Manaf, Haji Razali Mohd. Amin, Mr. Zainuddin Ismail and Mr. Mohd. Jan Mohd. Daud for their help, assistance and co-operation throughout my study in Road Safety Research Centre (RSRC).

I would also like to thank the Ministry of Transport, Malaysia and RSRC for the research fund of Motorcycle Safety Programme. This enabled me to complete the study without encountering any financial difficulties.



I am especially grateful to my brother, Chee Hua and a friend of mine, Tan Saw Chin for their assistance in searching and collecting many related journal and conference papers, as well as other types of publication from UK during the early part of my research.

Thanks also to Mr. Loo Lean Tin and Helen Loo of Kah Motor Co. Sdn. Bhd. for providing me the information about the materials and general dimensions of a typical motorcycle basket. I would like to acknowledge the assistance from Haji Ghazali Said of the Structure Laboratory who helped me in doing the material coupon tests using the Instron machine. I am deeply indebted to the lecturer in-charge, Mr. Mustafa Yusof, the laboratory assistants, Mr. Abdul Malik Husin and Mr. Suhaimi Ishak of the Department of Mechanical Engineering, Universiti Teknologi Malaysia, for allowing and assisting me to carry out the drop hammer tests in the Solid Mechanics Laboratory. Their thoughtful suggestions and guidance made the tests measurably better and my relationship with them has been pleasurable.

I owe a great deal to a few valued friends who took time and generously made several suggestions and effort that greatly improved the modelling and simulations of the finite element basket model. They are Mr. James M. Kennedy, the president of KBS2 Inc., Mr. Goman Ho and Dr. Chew Guan Gae of Ove Arup and Partners, Mr. Benjamin Goba of Altair Computing and Dr. David J. Byrne.

I am particularly thankful to Assoc. Prof. Ir. Dr. Barkawi Sahari of the Department of Mechanical Engineering, Faculty of Engineering, UPM and Dr. Scott Liu De-Shin of the Mechanical Engineering Department, National Chung Cheng University for their willingness in sharing their opinions and knowledge.



Numerous thanks also to Mr. Suleiman Abdul Aziz for his teachings and advice in using the video camera, recording techniques and capturing the video images from the display.

Special thanks to Law Teik Hua who has made countless valuable comments and shared his valuable time entertaining lengthy discussions about my research right from the beginning. I will always be grateful to him. I am also deeply indebted to the other postgraduate students in the research centre, particularly Pang Toh Yen, Tang Eng Loong, Kulanthayan Subramaniam, Mohtady Ali Musa, Abdullahi Ali, Mr. Mohd. Faudzi Mohd. Yusoff, Ng Boon Cheen and Ong Wei Yang, who have been a friend and helpful in many aspects.

I owe special thanks to Cheong Keng Leng, Chai Choong Heng, Mr. Jamaluddin Md. Bakir, Teng Wan Tien, Chan Kah Lon and many others for all their help and care in one way or another in thought, words and deeds. Besides, I am particularly grateful to my housemates, Michael Lim Yung Hui, Foo Siew Mei, Leong Khai Hwei, Ng Phek Lan, Wong Mun Wai, Yap Wai Ling, Goh Lai Wan and Aileen Chong Hui Ching, for their understanding and support. Together, we have made our time in UPM an enjoyable and memorable one.

To my beloved parents, brother and sisters, thank you for being understanding and supportive during my entire study in UPM. Thanks also for always having faith in me. Your patience allows me to find my own path. Lastly, and most importantly, I would like to thank my wonderful wife, Tan Chin, who always gives me the unending love and encouragement, and has never wavered in her support of my ventures.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iii
LIST OF TABLES	viii
LIST OF FIGURES	x
LIST OF PLATES	xiii
LIST OF ABBREVIATIONS	xix
ABSTRACT	xv
ABSTRAK	xvii
 CHAPTER	
I	
INTRODUCTION	1
Background of the Study	1
Numerical Crashworthiness Analysis	6
Problem Statement	9
Objective	11
Importance of Study	11
Scope of Study	13
Assumptions	14
Limitations	15
Definition of Terms	16
II	
LITERATURE REVIEW	20
Injury Risk for Motorcyclists in Malaysia	20
Injury Distribution of Motorcyclist Casualties	22
Collision Characteristics of Motorcycle Impacts	24
Collision Contact Locations	24
Speed Analysis	26
Injury Mechanisms in Motorcyclist Casualties	28
Mechanism of Lower Extremities Injuries	29
Background of LS-DYNA	32
Computational Aspects	33
The Finite Element Method (FEM)	34
Finite Element (FE) Formulation	35
Numerical Integration	40
Time-step Size and Stability	43
Material Models	44
Rigid Bodies	46
Contact	47
III	
METHODS AND MATERIALS	49
Overview of the Study Design	49



	Description of the Computer Software and Hardware	53
	Development of Finite Element (FE) Basket Model	53
	Material Coupon Tests	54
	Tensile Tests	55
	Material Types and Their Parameters	57
	Description of Finite Element (FE) Basket Model	59
	Model Information	62
	Material Model	64
	Types of Contact Surface	66
	Impact Scenario	67
	Model Validation	69
	Drop Hammer Test	69
IV	RESULTS	74
	Comparison of Test and Simulation	74
	Simulation Output	75
	Crash Deformation Profile	82
	Time History Records of a Tracking Node	82
V	DISCUSSION	93
	Comparison of Test and Simulation Results	93
	Further Simulations for Other Impact Speeds	94
	z-axis Displacement	95
	Application Toward Lower Extremity Modelling	96
	Biological Material Characterisation	97
	Model Description and Simulations Performed	98
	Impact Response of a Human Lower Extremity Model	100
	Acceleration History Criterion	104
	Energy History Criterion	105
	Contact Time	109
	Limitations	114
VI	CONCLUSIONS AND RECOMMENDATIONS	119
	Summary	119
	Future Research	120
	BIBLIOGRAPHY	123
	APPENDIX	
	A Additional Tables	131
	B Standard Police Crashes Information Form POL27 (Pin 1/91)	133
	C Additional Figures	138
	VITA	142

LIST OF TABLES

Table		Page
1	Injury Risk for Occupants of Motorised Vehicles Involved in Fatal and Hospitalised Motorcycle Crashes in 1997	21
2	Injury Casualties for Fatal and Hospitalised Motorcycle Riders by Their Body Region from 1992 to 1997	23
3	Injury Casualties for Fatal and Hospitalised Motorcycle Riders Involved in Frontal Damage by Their Body Region from 1992 to 1997	26
4	LS-DYNA Material Parameters for Modelling the Basket ...	60
5	Model and Element Information of the FE Model	61
6	LS-DYNA Basket Components (or Parts) Used	63
7	LS-DYNA Material Models Used	64
8	Rigid Material Model	65
9	Material Model of Mild Steel JIS G3101-73 SS41	65
10	Material Model of Mild Steel SA36	65
11	Description of Drop Test	70
12	Summary of the Results Database for Each Impact Speed ...	81
13	Summary of the Figures Used to Illustrate the Deformation Profile	83
14	Impact Duration of Node 18878 Corresponding to Different Impact Speeds	95
15	Material and Mass Properties of Lower Extremity Model	98
16	Comparison of Assembly Masses and External Dimensions for Dummies	99
17	Impact Sequence Descriptions of the Offset Frontal Configuration	111



18	General Road Crash Data in Malaysia	131
19	Crashes and Casualties Involving Motorcycle Riders and Their Pillions	132



LIST OF FIGURES

Figure		Page
1	Fatality Model and Safety Target in Malaysia (Radin Umar, 1997)	3
2	Frequency of Motorcycle Damage Locations for Fatal and Hospitalised Crashes	25
3	Collision Speeds of the Two-wheeler and Object when the First Contact is in the Area of the Lower Extremities of the Rider (Spomer <i>et al.</i> , 1989)	27
4	Speed Limits of the Crashes between Motorcycle (under 250 cc) and Other Vehicles that Caused Frontal Damage and Casualties to the Riders	28
5(a)	Isometric View of the FE Model of a Motorcycle Basket	51
5(b)	Front View of the FE Model of a Motorcycle Basket ..	51
5(c)	Bottom View of the FE Model of a Motorcycle Basket	52
5(d)	Side View of the FE Model of a Motorcycle Basket ...	52
6b	Bottom View of Simulation for Rigid Wall into Basket at Impact Speed 10-km/hr	76
6d	Diagonal View of Simulation for Rigid Wall into Basket at Impact Speed 10-km/hr	78
7	Simulation Plot at Time 40 ms of Impact Speed at 10-km/hr	80
8b	Bottom View of Simulation for Rigid Wall into Basket at Impact Speed 35-km/hr	84
8d	Isometric View of Simulation for Rigid Wall into Basket at Impact Speed 35-km/hr	85
9b	Bottom View of Simulation for Rigid Wall into Basket at Impact Speed 50-km/hr	86



9d	Isometric View of Simulation for Rigid Wall into Basket at Impact Speed 50-km/hr	87
10b	Bottom View of Simulation for Rigid Wall into Basket at Impact Speed 70-km/hr	88
10d	Isometric View of Simulation for Rigid Wall into Basket at Impact Speed 70-km/hr	89
11b	Bottom View of Simulation for Rigid Wall into Basket at Impact Speed 90-km/hr	90
11d	Isometric View of Simulation for Rigid Wall into Basket at Impact Speed 90-km/hr	91
12	Comparison of Node 18878 of a Rigid Wall Impacting a Basket	92
13b	Bottom View of Simulation for Elastic Material into Basket at Impact Speed 50-km/hr	101
13d	Isometric View of Simulation for Elastic Material into Basket at Impact Speed 50-km/hr	102
13s	Side View of Simulation for Elastic Material into Basket at Impact Speed 50-km/hr	103
14	Comparison of Impact Barrier Acceleration Pulses from 50-km/hr Basket-Barrier Impact Simulation	104
15(a)	Energies Time History of the Leg Striking a Basket at 50-km/hr	107
15(b)	Energies Time History of the Rigid Wall Striking a Basket at 50-km/hr	107
16	Motorcycle and Opposing Vehicle Contact for Offset Frontal Configuration (Rogers and Zellner, 1996)	110
17	Impact Force Time History of the Composite and Cadaver Lower Leg Dynamic Impact Tests (Zellner <i>et al.</i> , 1996)	113
18(a)	Load versus Elongation Plot for Net Components	138
18(b)	Load versus Elongation Plot for Wire Components	139



19(a)	Energies Time History of the Rigid Wall Striking a Basket at 10-km/hr	140
19(b)	Energies Time History of the Rigid Wall Striking a Basket at 35-km/hr	140
19(c)	Energies Time History of the Rigid Wall Striking a Basket at 70-km/hr	141
19(d)	Energies Time History of the Rigid Wall Striking a Basket at 90-km/hr	141



LIST OF PLATES

Plate		Page
1(a)	Side View of a Typical Basket of Honda Motorcycle ..	5
1(b)	Back View of Motorcycle Basket	5
2(a)	Diagonal View of a Basket	50
2(b)	Front View of a Basket	50
2(c)	Bottom View of a Basket	50
2(d)	Side View of a Basket	50
3	Test Coupon of the Net Component	56
4(a)	Instron Testing Instrument	57
4(b)	Grips and Their Holders	57
5(a)	Drop Hammer Testing Instrument in UTM	71
5(b)	Close-up View of the 50-kg Hammer	71
6	Set-up of a Drop Hammer Test	71
7(a)	Location of the Video Cameras from Side Angle	72
7(b)	Location of the Video Cameras from the Other Side Angle	72
8	A Damaged Basket by Hammer at 10-km/hr	73
9b	Bottom View of Test for Rigid Wall into Basket at Impact Speed 10-km/hr	77
9d	Diagonal View of Test for Rigid Wall into Basket at Impact Speed 10-km/hr	79
10	Drop Test Picture at Sequence (vii) of Impact Speed at 10-km/hr	80



LIST OF ABBREVIATIONS

AIS	Abbreviated Injury Scale
ASTC	Applied Safety Technologies Corporation
ATD	anthropomorphic test device
EDO	Extended Data Output
FE	finite element
FEM	finite element method
FEMB	Finite Element Model Builder
FTSS	First Technology Safety Systems Inc.
GDP	Gross Domestic Product
LLNL	Lawrence Livermore National Laboratory
MAAP	Microcomputer Accident Analysis Package
MODENAS	Motorsikal Dan Enjin Nasional Sdn. Bhd.
MPP	Massively Parallel Processor
ms	millisecond(s)
PC	personal computer
PDRM	Royal Malaysia Police
RSRC	Road Safety Research Centre
SAE	Society of Automotive Engineers
SMP	Symmetric Multi-Processor
TRL	Transport Research Laboratory
UPM	Universiti Putra Malaysia
UTM	Universiti Teknologi Malaysia



Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science.

**FINITE ELEMENT SIMULATION AND EXPERIMENTAL EVALUATION
OF MOTORCYCLE BASKET FOR CRASHWORTHINESS ANALYSIS**

By

HOW CHEE KEONG

July 1999

Chairman: Megat Mohamad Hamdan Megat Ahmad, Ph.D.

Faculty: Engineering

In this study, a detailed finite element model of a motorcycle basket used in Malaysia was developed. The model was developed specifically to address motorcycle safety issues, which had reached an alarming rate of casualties in road traffic crash. The finite element method was employed to investigate large deformation of basket at different impact speeds.

The study described the simulation results of a full rigid wall impacting a basket using a non-linear finite element code, LS-DYNA. Drop tests were conducted to validate and compare with the simulation results. The comparisons were made at the impact speed of 10-km/hr. Evaluation between experimental and simulation results in terms of overall impact deformation of the basket were presented. The results clearly indicate that the model correlated well with the test. Additional simulations for higher impact speeds were performed and discussed. Furthermore, simulation of a finite element model of human lower extremity striking a basket at 50-km/hr were also



addressed. The results suggest that a significant amount of energy was transformed by the leg to the basket and consequently caused the basket to deform extensively. As a result, the injury risk of the motorcyclist was minimised through absorbing most of the energy by the basket. However, further study needs to be done to improve the leg-basket model and to incorporate the model with other motorcycle structures.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains.

**SIMULASI UNSUR TERHINGGA DAN PENILAIAN SECARA
EKSPERIMEN TERHADAP RAGA MOTOSIKAL UNTUK ANALISIS
KETAHANAN PELANGGARAN**

Oleh

HOW CHEE KEONG

Julai 1999

Pengerusi: Megat Mohamad Hamdan Megat Ahmad, Ph.D.

Fakulti: Kejuruteraan

Dalam kajian ini, satu model unsur terhingga yang terperinci untuk raga motosikal yang biasa digunakan di Malaysia telah dibina. Model ini dibina khas bagi menangani isu keselamatan motosikal memandangkan kadar kecelakaan jalan raya yang melibatkan motosikal agak membimbangkan. Kaedah unsur terhingga telah diguna untuk mengkaji perubahan bentuk raga yang ketara pada kelajuan hentaman yang berbeza.

Kajian ini menunjukkan keputusan simulasi untuk hentaman dinding tegar penuh terhadap raga dengan menggunakan suatu kod unsur terhingga tak linier, LS-DYNA. Ujian hentaman untuk mengesahkan serta membandingkan dengan keputusan simulasi telah dilaksanakan. Perbandingan telah dilakukan pada kelajuan hentaman 10-km/j. Penilaian di antara ujikaji dan simulasi dari segi perubahan bentuk hentaman secara menyeluruh terhadap raga telah ditunjukkan. Keputusan ini jelas menunjukkan kesepadanan di antara model dan ujian. Simulasi tambahan untuk kelajuan hentaman

yang lebih tinggi telah dilakukan dan dibincangkan. Selain daripada itu, simulasi model unsur terhingga yang melibatkan hentaman bahagian kaki manusia terhadap raga pada 50-km/j juga dilakukan. Keputusan ini menunjukkan sejumlah tenaga yang jelas telah dipindah daripada bahagian kaki kepada raga dan seterusnya menyebabkan perubahan bentuk raga secara ketara. Lantaran itu, risiko kecederaan penunggang motosikal dapat dikurangkan hasil daripada lebih banyak tenaga yang diserapi raga. Walau bagaimanapun, kajian selanjutnya untuk model raga-kaki perlu diperbaiki dan disesuaikan dengan struktur motosikal yang lain.



CHAPTER I

INTRODUCTION

Background of the Study

With reference to Economic Report 1998/99 (Ministry of Finance, 1998), Malaysia's population of 21.666 million¹ in 1997 has increased 27.9% over the last decade. At the same period of time, the country's average annual Gross Domestic Product (GDP) has been growing at a rapid rate of 8.7% from 1988 to 1997. As a result of the tremendous economic boom, there is a resultant growth in the number of registered vehicles in Malaysia. This number has increased from 3,674,482 in 1987 to 8,550,469 in 1997 (PDRM, 1997), which is 132.7% within 11 years (See Table 17 in Appendix A for general road crash data). This of course has put the country's road network under great stress. Consequently, there is a relatively high increase rate in national road traffic crashes (formerly known as accidents), with an annual increase in fatalities by 5.6% on average between 1987 and 1997 (PDRM, 1997). Injuries are reported to be one of the leading causes of death and disability in Malaysia. Road injuries, therefore, form a significant proportion of them (Ho, 1994).

Apart from Malaysia, other countries in the Asia Pacific region such as India, Pakistan, Bangladesh and South Korea are also undergoing uninhibited motorisation and thus are in a rapid transition process (Krishnan, 1996). Since increases in the capacity of public transportation systems have failed to match transportation needs,

¹ Forecast result.



private ownership of vehicles, especially motorcycles in rapidly motorising country has soared. In Malaysia, the single largest group of registered vehicles on the road and consequently recorded the highest proportion for casualties in traffic crashes (62.8%) is motorcycle (PDRM, 1997). The majority of motorcyclists, especially in the rural areas today, are commuters who have adopted the motorcycle as a convenient, fast and cheap mode of personalised transport (Radin Umar, 1996a). The PDRM statistical report of road crash (1997) states that the number of registered motorcycles in Malaysia in 1997 is 4,328,997 (Table 18, in Appendix A). Due to the increasing number of motorcycle on the road, on average, there was an annual increase of 10.7% in crashes involving motorcycle between 1987 and 1997. In addition, the rate of motorcycle crashes has increased from 9.66 reported crashes per 1,000 motorcycles in 1987 to 18.50 per 1,000 motorcycles in 1997 (Table 18).

This situation has taken a disproportionately higher toll on the road in the last ten years. The average annual increase in motorcycle deaths, which includes motorcyclists and their pillions, was 8.2% between 1987 and 1997 (PDRM, 1997). Therefore, it is not surprising that motorcyclist and the pillion constituted 58.9%, an alarmingly high percentage of death in road traffic crash in 1997.

Owing to the highest fatalities in motorcycle crashes, a Cabinet Committee on Road Safety, with the Prime Minister as the Chairman was formed in 1990. The committee has set a target of reducing fatalities by 30% by the year 2000 based on a forecast linear model by Aminuddin (1991). However the forecast result is far less than the real situation because of rapid growth in traffic exposures following the economy recovery since late 1980s. In addition, gauging from the trends, Krishnan (1996) reports that the incidence of road injuries can be expected to increase further.

Due to motorisation policies of the government, private ownership of vehicles will increase until public transportation is widely available and acceptable. In line with this, the motorcycle will continue to remain the main mode of transport for lower to middle income families. Therefore, a more realistic target was justified and reviewed by the Road Safety Research Centre (RSRC), Universiti Putra Malaysia (UPM, formerly known as Universiti Pertanian Malaysia). The outcome of the research is illustrated by the following statistical model which predicted that 9,127 road users will be killed in road crashes in the year 2000 if traffic exposures continue to increase at projected rate (Figure 1). Among the total deaths, about 5,200 (57%) will be motorcyclists and their pillions. Besides, for every death case, there will be at least 3 permanent disabilities and 10 more other injuries (Radin Umar, 1996b and Radin Umar, 1997).

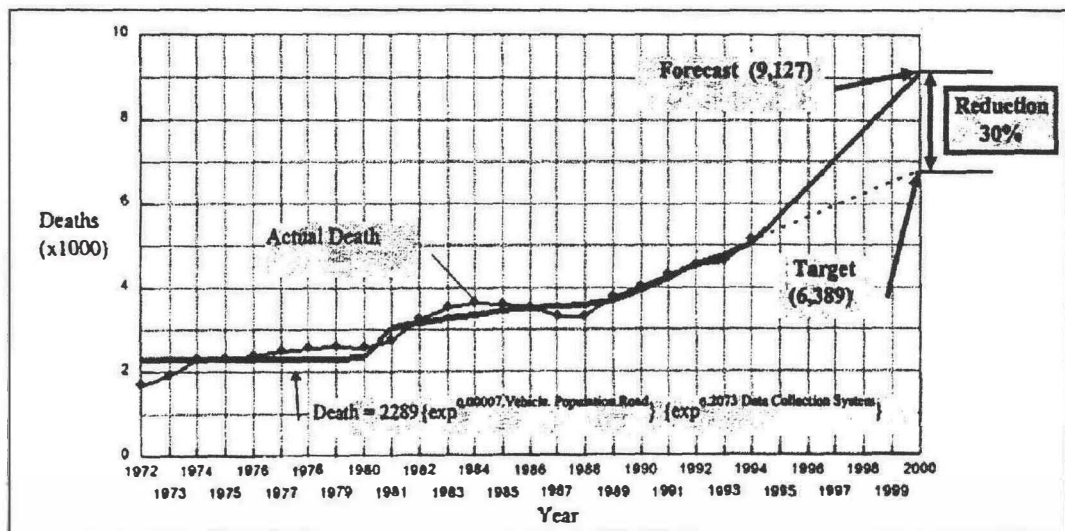


Figure 1: Fatality Model and Safety Target in Malaysia (Radin Umar, 1997)

Furthermore, motorcycle casualties disproportionately affect the young and the economically disadvantaged. In Malaysia, it is estimated that one in about three

thousand males between the ages of 13 and 45 or one in about two thousand male motorcyclist dies of motorcycle injuries each year. This does not include those with severe, minor and unreported injuries (Krishnan, 1993). A significant proportion of those injured on the road suffers from injuries to the lower extremities. They become permanently and temporary disabled. In 1997, it is reported that leg injuries constituted the highest proportion for serious injuries. There were 43.1% (3,511 out of 8,144) of the motorcycle riders and 53.8% (733 out of 1,363) of their pillions involved in serious leg injuries (PDRM, 1997). Apparently, injuries to the lower extremities are an important cause of loss of productivity years of life.

Prevention is always better than cure. Since road crashes are unfortunately inevitable, prevention is of course the ideal way of reducing casualties. Owing to this, research to protect the motorcyclists and their pillions ought to be directed at investigating the most frequent serious injuries, which are leg injuries. Likewise, most of the local light-powered motorcycles are attached with a basket as shown in Plates 1(a) and 1(b). The location of the basket has a very close and immediate contact with the lower extremities of the rider. Thus, injuries to the lower extremities caused by secondary impact with the basket is very much possible. To have a better understanding on this problem, research on basket is carried out to investigate its crash behaviour under different impact speeds.

Local light-powered motorcycles, with engine displacement not more than 120 cm³ (cc), dominate more than 80% of the motorcycles in Malaysia. In view of this, it is important either to keep the motorcyclists and their pillions out of trouble in the first place, or to minimise injury should a crash occur. Apart from anti-lock braking system (Cart and Pickenhahn, 1991; Hikichi *et al.*, 1991; Präckel *et al.*, 1996),



Plate 1(a): Side View of a Typical Basket of Honda Motorcycle



Plate 1(b): Back View of Motorcycle Basket

motorcycle airbags (Hirsch and Bothwell, 1973; Danner *et al.*, 1985; Happian-Smith and Chinn, 1990) and leg protectors (Chinn *et al.*, 1989; Chinn, 1991; Yettram *et al.*, 1994), research on other motorcycle structures or components is still very few. Hence, the possible effects and crash behaviour of basket should be evaluated and discussed. By understanding the problem better, it is hoped that the chances of reducing the injury risk are the greatest in case of frontal collisions.

Numerical Crashworthiness Analysis

Engineering structures are designed to withstand loads below a certain level. If excessive loads are applied to it, the structure is likely to fail. During crashes, a structure may be exposed to excessive loads, which are far beyond the capacity of the structure. It experiences non-linear geometric and material deformations. Consequently, the structure may be destroyed within a fraction of a second.

As occasional road crashes such as car and motorcycle crashes cannot be avoided, it is highly desirable that a structure under crash loads should behave in such a way that harm to occupants, riders and economic loss is minimised. The term 'crashworthiness' is used to denote the ability of a structure to sustain a crash in such a way that the part of the structure holding occupants or payloads does not suffer excessive distortion or deceleration (Zhong, 1993).

In earlier stages, experimental approaches and/or analytical approaches were exclusively used due to the lack of other available choices. However, with the parallel development of the finite element method (FEM) and computational mechanics, and modern computer techniques; it is possible to perform crashworthiness analyses numerically. The computer system used to perform these analyses must have enough