



**COMPUTATIONAL CRASHWORTHY OPTIMIZATION
OF PARTIALLY FILLED ALUMINIUM FOAM
FOR AUTOMOTIVE SIDE MEMBER**

By

SALWANI BINTI MOHD SALLEH

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

June 2013

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

**COMPUTATIONAL CRASHWORTHY OPTIMIZATION
OF PARTIALLY FILLED ALUMINUM FOAM
FOR AUTOMOTIVE SIDE MEMBER**

By

SALWANI BINTI MOHD SALLEH

June 2013

Chairman : Professor Ir. Barkawi bin Sahari, PhD

Faculty : Engineering

Lightweight design with good crashworthy characteristic is highly desirable in automotive industry. Frontal crashes is identified as the most often occurrence. Frontal collision occurred at an angle up to 30 degree, so called oblique, as prescribed in Federal Motor Vehicle Safety Standard is used in this study. Geometry changes and material replacement is approaches used to improve the crash performances. Simulation is carried out using Ls-dyna software and optimization is done by using Sequential Quadratic Programming that is run in Matlab.

The structure in this study is using aluminum and aluminum foam. The structure is partially filled to reduce the additional weight cause by the foam. Furthermore, the column thickness, foam length and foam density is varied to achieve the target. From the analysis of partially filled column, it was found that crush force efficiency (CFE) is highly affected by the loading angle unlike specific energy absorption (SEA). The

initial response is however ruled by thin-walled aluminum deformation behavior. Introduction of partially filled column promotes improvement in SEA and CFE. SEA of the new design and empty column is 1237.76 J/kg and 907.28 J/kg with CFE of 0.7 and 0.5, respectively. A surrogate based optimization program developed by employing the Sequential Quadratic Programming method yield an optimum design of $(t, L)^* = (2.3, 151.7)$ and $(t, L)^* = (1.1, 199)$, for SEA and CFE, respectively. In three variables optimization, the optimum design for maximum SEA and CFE are $(t, L, \rho)^* = (2.0, 88.6, 0.1)$ and $(t, L, \rho)^* = (1.4, 129.6, 0.2)$. In term of occupant safety, car associated with partially filled side member exhibit lowest index in occupant injury criteria, 496.6, 694 and 850 for HIC15, HIC36 and CSI, respectively.

The results show that the crashworthiness performance of the structure can be improved through introduction of partially filled column. Using the developed programming for optimization, vehicle structures design can be practically optimized.

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

**KOMPUTASI KEREMUKAN BAGI BAHAGIAN KENDERAAN YANG
SEPARA DI ISI DENGAN FOM ALUMINIUM**

Oleh

SALWANI BINTI MOHD SALLEH

Jun 2013

Pengerusi : Professor Ir. Dr. Barkawi bin Sahari, PhD

Fakulti : Kejuruteraan

Rekabentuk ringan dan mempunyai ciri-ciri perlanggaran yang baik adalah sangat berguna kepada automotif industri. Perlanggaran dari hadapan di kenal pasti sebagai yang paling kerap berlaku. Perlanggaran hadapan yang melibatkan posisi sehingga sudut 30 darjah, juga dipanggil oblik, seperti yang ditetapkan oleh Federal Motor Vehicle Safety Standard telah digunakan untuk kajian ini. Perubahan geometri dan bahan adalah pendekatan yang digunakan untuk menambah baik prestasi perlanggaran. Simulasi di jalankan dengan menggunakan perisian Ls-dyna manakala optimisasi adalah menggunakan Matlab.

Di dalam kajian ini, struktur menggunakan aluminium dan aluminium foam. Hanya sebahagian daripada struktur telah di isi bagi mengurangkan penambahan berat. Ketebalan kolum, panjang foam dan isipadu foam telah dimanipulasi bagi mencapai target. Daripada kajian, didapati CFE sangat dipengaruhi oleh sudut bebanan tidak seperti SEA. Tindak balas awal bagaimanapun menyerupai kolum kosong. Penggunaan kolum separa penuh meningkatkan prestasi struktur. SEA bagi kolum

separa penuh dan kolom kosong adalah masing-masing 1237.76 J/kg dan 907.28 J/kg dengan nilai CFE 0.7 dan 0.5. Program optimisasi menggunakan polinomial model menggunakan Sequential Quadratic Programming menghasilkan rekabentuk optimum yaitu masing-masing $(t, L)^* = (2.3, 151.7)$ dan $(t, L)^* = (1.1, 199)$, bagi SEA and CFE. Bagi optimisasi melibatkan tiga pemboleh-ubah, rekabentuk optimum untuk maksimum SEA dan CFE masing-masing adalah $(t, L, \rho)^* = (2.0, 88.6, 0.1)$ dan $(t, L, \rho)^* = (1.4, 129.6, 0.2)$. Dari segi keselamatan penumpang, kereta yang melibatkan penggunaan side member separa penuh menunjukkan indek terendah bagi kriteria kecederaan iaitu, 496.6, 694 dan 850 untuk HIC15, HIC36 dan CSI.

Keputusan kajian menunjukkan bahawa prestasi perlanggaran bagi sesuatu struktur boleh diperbaiki dengan penggunaan kolom separa penuh. Menggunakan program optimisasi yang telah dibina, rekabentuk struktur kereta boleh di optimumkan.

I certify that a Thesis Examination Committee has met on 14 June 2013 to conduct the final examination of Salwani binti Mohd Salleh on her thesis entitled "Computational Crashworthy Optimization of Partially Filled Aluminium Foam for Automotive Side Member" 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.

Members of the Thesis Examination Committee were as follows:

Shamsuddin bin Sulaiman, PhD

Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Khairol Anuar bin Mohd Ariffin, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Faizal bin Mustafa, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

J.N. Reddy, PhD

Professor
Texas A & M University
United States
(External Examiner)



NORITAH OMAR, PhD
Assoc. Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 2 August 2013

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Barkawi bin Sahari, PhD

Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Aidy Ali, PhD

Professor
Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Member)

Nuraini binti Abdul Aziz, PhD

Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD

Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

TABLE OF CONTENTS

	Page
ABSTRACT	i
ABSTRAK	iii
ACKNOWLEDGEMENTS	v
APPROVAL	vi
DECLARATION	viii
LIST OF TABLES	xii
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS	xix
LIST OF SYMBOLS	xx
CHAPTER	
1 INTRODUCTION	
1.1 Background	1
1.2 Research objectives	2
1.3 Problem statement	3
1.4 Significance of the study	4
1.5 Scope of study	4
1.6 Thesis outline	5
2 LITERATURE REVIEW	
2.1 Introduction	6
2.2 Lightweight design	
2.2.1 Lightweight materials	7
2.2.2 Component design	10
2.2.3 Limitation	15
2.3 Crash	
2.3.1 NHTSA standard	17
2.3.2 Crashworthiness parameter	21
2.3.3 Frontal energy absorber	24
2.3.4 Crash test dummy	26
2.3.5 Human injury tolerance criteria	32
2.4 Collapse mode under crush load	
2.4.1 Axial loading	37
2.4.2 Bending loading	46
2.4.3 Oblique loading	51
2.5 Optimization	
2.5.1 Optimization methodology	54
2.5.2 Optimization in crashworthiness	59
2.6 Summary	63
3 METHODOLOGY	
3.1 Introduction	64
3.2 Geometrical design	
3.2.1 Design of square column	66
3.2.2 Design of Gen-2 side member	67

3.3	Material properties	
3.3.1	Aluminum alloy	68
3.3.2	Aluminum foam	69
3.4	Nonlinear finite element modeling	
3.4.1	Elements	71
3.4.2	Material models	71
3.4.3	Crash simulation	71
3.4.4	Occupant simulation	73
3.5	Model validation	
3.5.1	Experimental work by Reyes et.al	76
3.5.2	Simulation model	77
3.5.3	Experimental and simulation results comparison	78
3.6	Design of Experiments (DOE)	82
3.7	Single objective optimization	
3.7.1	Problem formulation	84
3.7.2	Surrogate model	86
3.7.3	Sequential Quadratic Programming (SQP)	89
3.8	Multi-objective optimization	91
3.9	Summary	92
4	CRASH PERFORMANCE OF COLUMN	
4.1	Introduction	93
4.2	Crash performance of empty aluminum column	
4.2.1	Axial loading	94
4.2.2	Oblique loading	98
4.3	Theoretical aspects	101
4.4	Crash performance of partially-filled column	
4.4.1	The effect of loading angle on crashworthiness	106
4.4.2	The effect of column thickness, foam length and foam density on crashworthiness	114
4.5	Optimization	
4.5.1	Two variables model	119
4.5.2	Three variables model	124
4.5.3	Optimum design comparisons	130
4.6	Summary	132
5	CRASH PERFORMANCE OF AUTOMOTIVE SIDE MEMBER	
5.1	Introduction	134
5.2	Optimization	134
5.3	Crash performances of partially-filled side member	
5.3.1	Occupant injury	137
5.3.2	Energy absorption of partially-filled side member	141
5.3.3	Oblique versus full frontal crash	144
5.4	Conclusion	151
6	SUMMARY, CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH	
6.1	Summary	152
6.2	General conclusions	153

6.3 Recommendations	155
REFERENCES	156
APPENDIX A – Matlab code	166
BIODATA OF STUDENT	176
LIST OF PUBLICATIONS	177

LIST OF TABLES

Table		Page
2.1	Weight saving by the alternative materials	8
2.2	AIS designations and injury examples	33
2.3	Head Injury Criterion for various dummy sizes	34
2.4	Nij values limit for various dummy sizes	35
2.5	Chest Injury Criterion for various dummy sizes	36
3.1	Mechanical properties of AA6060 T4	69
3.2	Stress-strain relationship for arbitrary foam density	70
3.3	Maximum and mean force comparison	79
3.4	Maximum and mean force comparison	80
3.5	Design levels for column simulation	83
3.6	Design levels for automotive side member simulation	83
3.7	Three types of polynomial models used	86
4.1	Collapse behavior of partially filled column subjected to 5 degree loading angle	112
4.2	Collapse behavior of partially filled column subjected to 10 degree loading angle	112
4.3	Collapse behavior of partially filled column subjected to 15 degree loading angle	113
4.4	Collapse behavior of partially filled column subjected to 20 degree loading angle	113
4.5	Collapse behavior of partially filled column subjected to 25 degree loading angle	114
4.6	Collapse behavior corresponding to force-displacement curve in Figure 4.2	114

4.7	Three variables simulation results	116
4.8	Two variables model accuracy	119
4.9	Three variables model accuracy	125
5.1	Two variables simulation results	136
5.2	Design optimization	136

LIST OF FIGURES

Figure		Page
2.1	Lightweight design requirement	7
2.2	Some of the automotive components made of magnesium alloy	9
2.3	Lightweight design concept of automotive body	11
2.4	Effect of ribbing on stiffness	12
2.5	Three types of beads (a) vertical male bead (b) round beads (c) round and vertical male beads	12
2.6	Tailor-welded blank applied in automotive structure	13
2.7	Consolidation of parts by TWB introduction	14
2.8	Weight spiral	16
2.9	Energy consumption during life cycle	17
2.10	Frontal impact configuration in real world accidents	18
2.11	Fixed barrier test (a) full frontal (b) oblique frontal	19
2.12	Deformable barrier test (a) full frontal (b) frontal offset (c) oblique moving	20
2.13	Frequency of the impact directions referring to the car front	21
2.14	Typical load-displacement curve for axial loading	22
2.15	Energy absorber for frontal crash	24
2.16	FE model of the hybrid III (a) 50th and (b) 5th percentile dummy	27
2.17	Dummy modeling method	28
2.18	Dummy kinematic comparison	30
2.19	Test and simulation response for (a) Head resultant acceleration and (b) Chest resultant acceleration	31
2.22	Mechanical response of aluminum foam	41

2.23	Interaction effect of foam-filled columns	42
2.24	Deformation pattern of foam-filled and non-filled column	43
2.25	Three characteristic regions in the crushed foam-filler	44
2.26	(a) SEA versus displacement (b) CFE versus displacement	45
2.27	Experimental setup for the deep bending test	46
2.28	Experimental and numerical crash pattern and crash load-displacement curves of (a) empty and (b) foam-filled tubes	48
2.29	Cut-through view of empty and foam-filled column	49
2.30	Experimental and numerical results of force-displacement curves of (a) foam-filled single column and (b) foam-filled double column	50
2.31	Global bending and formation of plastic hinges during global collapse for (a) empty tube (b) foam-filled tube	53
3.1	Flow chart of research methodology	65
3.2	Mesh of square column and direction of load during impact	66
3.3	Car and component model	67
3.4	Engineering stress-strain curve for AA6060	68
3.5	Typical stress-strain curve of metallic foam materials	69
3.6	Oblique impact layout of a car	72
3.7	Hybrid III 50th percentile FE model	74
3.8	Accelerometer node ID	75
3.9	Oblique test equipment	76
3.10	Foam-filled column	77
3.11	Force-displacement curve comparison between experimental and simulation	79
3.12	Deformation of empty column subjected to 5 degrees loading angle (a) experimental and (b) simulation	80
3.13	Force-displacement curve comparison between experimental and simulation	81

3.14	Deformation of foam filled column subjected to 15 degrees loading angle (a) experimental and (b) simulation	82
3.15	Flowchart of the optimization process	84
4.1	Force versus displacement curve of 1.1 mm thick empty column (axially loaded)	95
4.2	Force versus displacement curve of 1.4 mm thick empty column (axially loaded)	96
4.3	Force versus displacement curve of 1.7 mm thick empty column (axially loaded)	96
4.4	Force versus displacement curve of 2.0 mm thick empty column (axially loaded)	97
4.5	Force versus displacement curve of 2.3 mm thick empty column (axially loaded)	97
4.6	Force versus displacement curve of 1.1 mm thick empty column (obliquely loaded)	98
4.7	Force versus displacement curve of 1.4 mm thick empty column (obliquely loaded)	99
4.8	Force versus displacement curve of 1.7 mm thick empty column (obliquely loaded)	99
4.9	Force versus displacement curve of 2.0 mm thick empty column (obliquely loaded)	100
4.10	Force versus displacement curve of 2.3 mm thick empty column (obliquely loaded)	100
4.11	Correlation between results obtained from numerical and theoretical	103
4.12	Slopes of various loading angles	104
4.13	Correlation between results obtained from numerical and theoretical	105
4.14	Column cross-sections of different foam length, L, (a) L= 40 mm (b) L= 80 mm (c) L= 120 mm and (d) L= 160 mm	106
4.15	Force vs displacement curve for 40 mm foam length	108
4.16	Force vs displacement curve for 80 mm foam length	108

4.17	Force vs displacement curve for 120 mm foam length	109
4.18	Force vs displacement curve for 160 mm foam length	109
4.19	SEA of partially filled column under various loading angle	110
4.20	CFE of partially filled column under various loading angle	111
4.21	Response surface for (a) SEA and (b) CFE	115
4.22	Contour plot for SEA	121
4.23	Contour plot for CFE	122
4.24	Iteration history for SEA optimization involving side constraints	123
4.25	Iteration history for CFE optimization involving side constraints	124
4.26	Iteration history for SEA optimization involving side constraints	127
4.27	Iteration history for CFE optimization involving side constraints	128
4.28	Iteration history for SEA optimization involving side, mass and CFE constraints	129
4.29	Iteration history for CFE optimization involving side, mass and SEA constraints	130
4.30	Comparison of mass, SEA and CFE for two variable (2V) and three variables (3V) optimization	131
4.31	Comparison of mass, SEA and CFE for optimization involving only side constraints (Approach 1) and additional mass and SEA or CFE constraint (Approach 2)	132
5.1	HIC 15 of empty, fully filled and partially filled side member	138
5.2	HIC 36 of empty, fully filled and partially filled side member	139
5.3	CSI of empty, fully filled and partially filled side member	140
5.4	Comparison between the optimal partially filled (Pf) side member to the empty (E) and fully filled (Ff) side member of the same column thickness	141
5.5	Part internal energy for empty aluminum side member	142
5.6	Part internal energy for fully filled aluminum side member	143

5.7	Part internal energy for partially filled aluminum side member	144
5.8	Parts absorbing the energy transferred	145
5.9	Stress distribution at 1 ms (a) oblique and (b) full frontal crash	146
5.10	Stress distribution at 2ms (a) oblique and (b) full frontal crash	146
5.11	Stress distribution at 6ms (a) oblique and (b) full frontal crash	147
5.12	Stress distribution at 20ms (a) oblique and (b) full frontal crash	148
5.13	Stress distribution at 60ms (a) oblique and (b) full frontal crash	148
5.14	Stress distribution at 120ms (a) oblique and (b) full frontal crash	149
5.15	Acceleration curve for HIC in full frontal crash	150
5.16	Acceleration curve for CSI in full frontal crash	150
5.17	Performance comparison between oblique and full frontal crash	151

LIST OF ABBREVIATIONS

SEA	Specific Energy Absorption
CFE	Crush Force Efficiency
FMVSS	Federal Motor Vehicle Safety Standard
NHTSA	National Highway Traffic Safety Administration
TWB	Tailor-welded blank
DOE	Design of Experiment
SQP	Sequential Quadratic Programming
RSM	Response surface method
FE	Finite element
CAD	Computer Aided Design
HIC	Head Injury Criterion
CSI	Chest Severity Index
RMSE	Root Mean Squared Error

LIST OF SYMBOLS

P_{\max}	Maximum crush load
P_m	Mean crush load
E_a	Energy absorbed
δ	Displacement
P	Crush load
α	Coefficient
t	Thickness
σ_y	Yield stress
\hat{y}	Approximation of output response
y	True response
ϵ	Error
σ_p	Plateau stress
ρ_f	Foam density
ρ_b	Foam base material density
C_{pow}	Material constant
m	Mass
E	Young Modulus
$V(t)$	Velocity
d_{\max}	Final displacement
T	Total duration
$a(t)$	Linear acceleration
t	Column thickness

L	Foam length
ρ	Foam density
R^2	Coefficient of determination
ε	Convergence criteria
α^*	Step size
S	Search direction
KT	Kuhn Tucker
ΔX	Changes in variable
r	Constant
C	Constant
Lc	Column length
E	Empty column
Ff	Fully-filled column
Pf	Partially-filled column
sm	Side member

CHAPTER 1

INTRODUCTION

1.1 Background

The recent trend in automobile design is aimed at improving fuel efficiency, crash safety and environmental-friendliness. For the crash safety, energy absorbing members have to absorb sufficient collision energy, whereas for the environment, the automobile structure must be lightweight in order to improve fuel efficiency and reduce tail gas emission. According to Zhang et al. (X. Zhang et al., 2008) 10% reduction of weight was estimated to give 3-7% fuel saving. Therefore, the weight of the automobile must be minimized while ensuring safety against crash.

Automotive structures are designed to sustain impact loading in diverse crash directions such as frontal, lateral and rear impact. Above all crash events, frontal collision was identified as the most common accidents on the road and gives rise to high portion of death (S Kokkula et al., 2006). Thus, it is vital to have an efficient energy absorbing structure on the front side of an automobile. The main energy absorber on the front side of automotive body is the bumper system and the automotive side member (H.-S. Kim, 2001; S Kokkula et al., 2006; Shin et al., 2002; X. Zhang et al., 2008). Bumper system is designed to absorb energy in low speed

crash, whereas the automotive side member is intended for high speed impact. Hence, this study will be focusing on the performance of automotive side member. In the light of lightweight design, partially filled aluminum side member is applied to the automobile body instead of the heavier conventional steel.

The threat to passenger safety arise the need for the crash test. In accordance with the safety requirement, Federal Motor Vehicle Safety Standard (FMVSS) No. 208 has set a procedure for a frontal rigid barrier test of up to 48 kmph, at angles from the perpendicular (90 degrees) to the line of travel of up to 30 degrees (Hollowell et al., 1999). It has been a current practice to initiate crash testing with simulation to avoid expensive investment on repeated physical testing. Thus, this research will manipulate the design and examine alternative materials for an improvement in crashworthiness by using Finite element crash commercial software named Ls-Dyna971. Optimization code is developed in Matlab to optimize the structure design. Crashworthiness performance of the structure subjected to oblique loading is analyzed under the FMVSS No.208 crash test requirement.

1.2 Problem statement

Improvement on safety of automobile is causing an increase in the weight (Carle and Blount, 1999). Thus, automotive industry is facing a big challenge in improving the crash performance without putting on additional weight. Previous studies show that the use of foam filled structure improves the energy absorption, EA (Miranda et.al., 2010; Zhang and Saigal, 2007; Song et. al., 2005). This fully filled structure however

reduces the energy absorption per unit mass, known as specific energy absorption (SEA) by adding too much weight. This research work will analyze the partially filled structure performance as an attempt to alleviate the problem.

Current studies on the partially filled structure are involving either the axial or bending load (Santosa et.al., 2000; 2001; Chen, 2001; Toksoy and Guden, 2004) and insufficient information can be found on the oblique loading. This study will analyze the crash performance of partially filled structure in terms of specific energy absorbed (SEA), crush force efficiency (CFE) and its effect on occupant safety. Optimization will be carried out to improve crash performance by manipulation of design variables.

1.3 Research objectives

This research is aimed to improve crashworthiness performance of the automotive side member. The detailed objectives are:

- i. To identify the parameters affecting the crashworthiness.
- ii. To propose a theoretical equation of mean force for a column subjected to oblique loading.
- iii. To develop a surrogate model based optimization code to optimize crash performances of the column.
- iv. To analyze the effect of an optimum partially filled automotive side member on automobile crash performance.

1.4 Significance of the study

Lightweight component with high energy absorbing capability improves the automobile performance. The use of materials alternative to steel such as aluminium and aluminum foam offering an option for a better weight-specific energy absorption properties than conventional mild steel. In a frontal collision, the impact load is transmitted first through the bumper, then through the side members and many other surrounding parts, before finally goes to the passenger compartment. So, it is desirable to absorb kinetic energy as much as possible before it is passed to the passengers. Thorough numerical analysis of automotive side member gives a crucial understanding in managing energy transferred during collision under predicted oblique loading. Optimization of the components design can also provide guidelines in improving structure crashworthiness while take hold of lightweight opportunity.

1.5 Scope of study

This research covers or limited to the following areas:

- i. Analysis of column and automotive side member
- ii. Crash test simulation conducted according to FMVSS No. 208 frontal crash test specification
- iii. Materials used for crashworthiness improvement are AA6060 T4 and aluminum foam.