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 menglibatkan 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 kolum 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 iaitu 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 , ρ)* = (2.0,88.6,0.1) dan (t L,ρ)* =(1.4 , 129.6 , 0.2). Dari segi keselamatan penumpang, kereta yang menglibatkan 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 kolum 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

LIST OF TABLES

LIST OF FIGURES

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
$\in$	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
$\boldsymbol{S}$	Search direction
KT	Kuhn Tucker
$\Delta\boldsymbol{X}$	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 absorbed 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.