DYNAMIC AXIAL AND OBLIQUE CRUSHING OF FOAM-FILLED ALUMINIUM CONICAL TUBES

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DYNAMIC AXIAL AND OBLIQUE CRUSHING OF FOAM-FILLED ALUMINIUM CONICAL TUBES

by

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THESIS DECLARATION

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Fauziah Mat

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LIST OF ABBREVIATIONS

WHO	World Health Organization
DOE	Design of experiments
ANOVA	analysis of variance
RS	Response surface
CCD	Central Composite Design
AR	Arthogonal Array
BBD	Box-Behnken Design
FE	Finite element
RSM	Response Surface Methodology
AA6061-T6	Aluminium Alloy 6061-T6
MIROS	Malaysian Institute of Safety Research
KKR	Ministry of Works Malaysia
ASEAN NCAP	ASEAN New Car Assessment Programme
ROPS	Rollover Protective Structures
VFPS	Vehicle Frontal Protection Systems
CPU	central processing unit
UoL	University of Liverpool
NUS	National University of Singapore
ASTM	American Society for Testing and Materials
LWA	Linear Weighted Average

LIST OF SYMBOLS

SEA	Specific Energy Absorption
D, q	Cowper-Symonds material constant
γ, α_2, β	material constant in yield stress calculations
$D_\circ$	diameter
D_b	bottom diameter
t	thickness of tube
T	time
ΔT	time step
a	semi apical angle
L	length of tube
b	regression coefficient
θ	load angle
η_c	centre point
f	response surface approximation of actual response function
$\check{f}$	actual response function
R^2	coefficient of correlation in least square fitting
R^2_{adj}	adjusted coefficient of correlation in least square fitting
$RMSE$	root mean square error in analysis of variance calculations
SSE	sum of squared error in analysis of variance calculations
SST	sum of total squares in analysis of variance calculations
Φ	yield function

δ	length of deformation
$\delta_{\max}$	effective deformation length
ν^{p}	Poisson's ratio
M	mass
E	Young's Modulus
E_{δ}	absorbed energy
σ_{p}	plateau stress
σ_{m}	mean stress
σ_{e}	effective Von Mises stress
$\sigma_{\circ}^{d}$	dynamic flow stress
σ_{o}	associated flow stress
σ_{y}	yield stress
$\bar{\sigma}$	equivalent stress
ρ_{f}	foam density
ρ_{m}	mesh density
ρ_{f_o}	density of base material
α	shape of yield surface
F_{m}	mean force
F	instantaneous force
ε	engineering strain
$\dot{\varepsilon}$	plastic strain rate
ε_{D}	densification strain
$\bar{\varepsilon}$	equivalent strain

ε_{true}	true strain
σ_{true}	true stress
SEA^{*}	ideal optimum solution of SEA
F^{*}	ideal optimum solution of initial peak force
V	velocity
w	weighting coefficient
L_e	element length
c	speed of sound
e	statistical error
k	number of variables
$c_{\circ}$	side width
m	number of design sampling points
p	number of non-constant

Penghancuran Tiub Kon Aluminium Diisi Busa Terhadap Bebanan Paksi dan Serong Dinamik

ABSTRAK

Kajian ini dijalankan dengan matlamat untuk menyelidiki tindakbalas tiub kon aluminium terhadap bebanan paksi dan serong dinamik. Kesan pengisian busa terhadap penyerapan tenaga untuk perubahan geometri, bahan tiub dan ketumpatan pengisi dinilai dan dibincangkan. Kajian ini menggunakan model unsur terhingga tak lelurus yang telah disahkan dengan data eksperimen. Pola utama yang ditunjukkan oleh keputusan eksperimen telah berjaya diperolehi dalam keputusan unsur terhingga untuk bebanan paksi dan serong dinamik. Walau bagaimanapun, didapati terdapat perbezaan antara keputusan eksperimen dan unsur terhingga terhadap bebanan serong adalah sehingga 35.4 % terutamanya untuk tenaga yang diserap. Perbezaan ini berkemungkinan disebabkan oleh ketebalan yang tidak seragam dan ketidakmampuan untuk mengekang pergerakan tiub pada hujung yang ditetapkan (seperti dalam simulasi) ketika eksperimen. Model yang telah disahkan kemudiannya digunakan untuk menaksir faedah pengisian busa terhadap perubahan geometri, bahan tiub dan ketumpatan pengisi. Pengenalpastian titik efektif kritikal yang mana mewakili jumlah jisim tiub kritikal dan ketumpatan pengisi kritikal di samping pendekatan yang diambil dalam merubah sudut dan mengekalkan diameter bawah dalam keadaan malar terbukti meningkatkan Tenaga Penyerapan Spesifik (*SEA*) tiub diisi busa berbanding tiub kosong. Walau bagaimanapun, pendekatan ini hanya tergunapakai kepada gabungan parameter geometri, bahan tiub dan ketumpatan pengisi yang tertentu sahaja. Manakala, *SEA* tiub ysng diisi didapati telah kehilangan prestasi pada 240 mm diameter bawah. Tambahan pula, *SEA* maksimum tidak semestinya dapat dicapai apabila *SEA* tiub diisi meningkat melebihi tiub kosong. Penemuan ini menegaskan betapa pentingnya pemilihan parameter yang bersesuaian seterusnya menunjukkan bahawa parameter ini dapat dikawal dan membolehkan lesapan yang lebih berkesan oleh penyerap tenaga dan bermanafaat untuk aplikasi hentaman. Dengan tujuan untuk mencapai peningkatan prestasi tiub kon aluminium diisi busa, pengoptimuman berbilang-objektif telah dikaji untuk mencapai fungsi berbilang objektif iaitu *SEA* dan puncak daya mula di bawah pelbagai bebanan. Didapati bahawa tiub aluminium yang lurus dan diisi busa lebih berkemampuan untuk mencapai rekabentuk optimum di bawah bebanan paksi dinamik sementara tiub kon kosong lebih berkelebihan di bawah bebanan serong dinamik. Maklumat yang diperolehi menyediakan asas untuk peningkatan penyerap tenaga aluminium di masa hadapan.

Dynamic Axial and Oblique Crushing of Foam-filled Aluminium Conical Tubes

ABSTRACT

The aim of this study was to investigate the response of conical aluminium tubes subjected to dynamic axial and oblique loading. The effect of foam filling on the energy absorption for variation in geometry, tube material and filler density was evaluated and discussed. This study employs a nonlinear finite element model which was validated against experimental data. Main trends in the experimental results are well captured by the FE results under dynamic axial and oblique loading. Nevertheless, the differences observed under oblique loading between experimental and FE results are as high as 35.4 % particularly for energy absorption. These differences may due to uneven thickness and inability to constraint the movement of the tube at the fixed end (as per simulation) during experiment. The validated model was subsequently used to assess the beneficial of foam filling with respect to the variation of geometry, tube material and filler density. The identification of critical effective point which signifies the critical total tube mass and critical filler density with the approach taken in varying the semi apical angle and by keeping the bottom diameter constant proved to enhance the Specific Energy Absorption (*SEA*) of foam-filled tube over that of empty tube. However, these approaches apply to only particular combination of geometrical parameters. Moreover, *SEA* of foam-filled tubes is found to loss its performance at a bottom diameter of 240 mm. On top of this, the maximum SEA is not necessarily obtained with achieving higher SEA of foam-filled tube over that of empty tube. These findings highlight the importance of appropriate selection of these parameters thus showing that these parameters can be controlled and hence permits an efficient dissipation of energy absorber which is beneficial for impact applications. With the intention of achieving enhanced performance foam-filled conical aluminium tube, multi-objective optimization is explored to search for multiple objective functions namely *SEA* and initial peak force under various loading. It is found that foam-filled straight aluminium tube is favoured in achieving optimum design under dynamic axial loading whilst empty conical tube is preferable under dynamic oblique loading. The information gained serves as a basis for future enhancement of aluminium tube energy absorber.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The growth in population and economy has led to an increase in traffic worldwide. The number of vehicles has continuously increasing from year to year hence increases the number of traffic accidents. In 2010, road accidents are one of the leading causes of death in the world (World Health Organization, 2013).

In Malaysia, according to The Malaysian Institute of Road Safety Research [MIROS] (2014), a total of 462 423 road traffic accidents were reported in 2012, leading to 6 917 fatalities. Projections show that, road traffic death will increase substantially to 8 760 fatalities in 2015 and by 2020, road traffic death is predicted to be 10 716 (MIROS, 2012). Figure 1.1 shows the breakdown of road traffic accidents for road users in 2012 (Ministry of Works Malaysia [KKR], 2013). It is shown that cars account for 30.5 % of the total accidents.

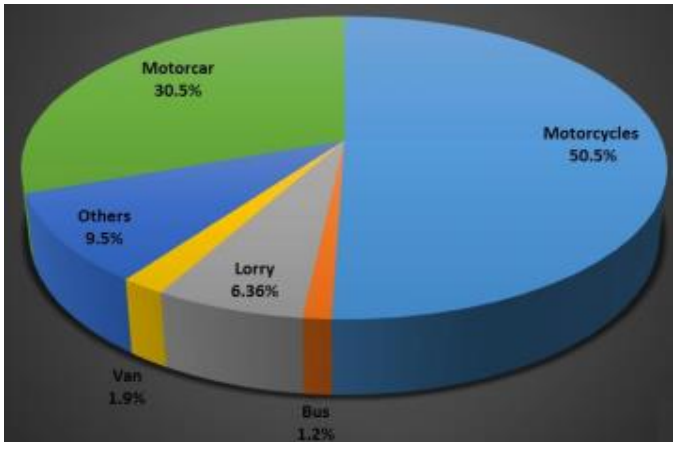

Figure 1.1: Total road traffic accidents in Malaysia for the year of 2012 (*Road Safety Situation In Malaysia*, 2013).

Various factors may contribute to those numbers. Human error, road infrastructures and vehicle conditions are among factors causing road accidents. Despite all these factors, they are preventable. The enhancement of infrastructures and the motor vehicles become the main focus in crashworthiness study nowadays. Crashworthiness refers to the quality of response of a structure during an impact to protect the system under consideration. For motor vehicle, improving crashworthiness may as important as the needs for lighter vehicles as mass reduction allows higher fuel efficiency at minimum cost. However, increasing the safety and achieving mass reduction are two criteria that unquestionably conflict each other. Therefore, extensive research and development in design geometry and applications of new materials seem to be the alternatives to satisfy these constraints.

1.2 Thin-walled tubes and foam as energy absorbers

In vehicle crashworthiness, the enhancement work focuses in several aspects; crash avoidance technology, structural crashworthiness and occupants protection devices. For structural crashworthiness, the application of a collapsible energy absorber allows an undesirable response during an impact to be dissipated in a controlled manner. During impact, the kinetic energy is converted into internal energy or strain energy through plastic deformation whilst at the same time preventing permanent deformations into the rest of the vehicle components. Hence protect the system under consideration. For vehicle, collapsible energy absorber or also known as crash box is connected to the bumpers, located in the front and rear end of the body structure (Reyes, Langseth, & Hopperstad, 2003). However, an energy absorber structure is rarely subjected to pure axial or pure bending loads, but rather a combination of both in

real impact event. In such condition, it will be likely to deform in a combination of axial and global bending modes.

Various structures have been developed and continuously being investigated such as cellular materials, sandwich, lattice structures, composites and thin-walled tubes. Among these structures, thin-walled tubes have been widely used as energy absorber in multidisciplinary fields including automotive and shipping industries due to their impact energy-absorbing capability and manufacturability. The potential of thin-walled tube is further explored by investigating the influence of geometrical and loading parameters on its energy absorption capacity.

Previous studies have shown that tapered and conical tubes would have more stable force-deformation curve under quasi-static and dynamic loading (Mamalis, Manolakos, Ioannidis, & Kostazos, 2005; Nagel & Thambiratnam, 2004; Reid & Reddy, 1986b). Therefore, it is considered preferable than that of straight tube. In addition to that, the introduction of taper and semi apical angle to the straight tubes minimises the chances of collapse by global buckling under oblique loading (Ahmad, Thambiratnam, & Tan, 2010; Nagel & Thambiratnam, 2006). As is seen in Fig. 1.2, conical tube has been applied as an energy absorber by Peugot for 3008 model in 2011 (Peugeot, March 2014). The two conical energy absorbers have been positioned between the car beam and the chassis leg for energy absorption enhancement and in order to achieve deformation in more controlled manner.

In addressing the mass reduction as part of crashworthiness goal, a combination of cellular material and thin-walled tubes seems advantageous to further improve the energy absorption capacity of thin-walled tubes. Foam is an example of cellular material that demonstrates good energy absorption capacity. It exhibits an almost constant stress plateau and a long stroke of deformation (Lu & Yu, 2003). Honeycombs,

polyurethane, polystyrene and metal foams can be suitable as fillers in thin-walled tubes.

Figure 1.2 : Introduction of Boge impact absorber to Peugeot 3008 model (Peugeot, March 2014).

In order to further improving the energy absorption capacity of thin-walled tubes, extensive investigations have been carried out on the response of foam-filled tubes, numerically and experimentally. The energy absorption has notably increased under quasi-static and dynamic loading particularly when filling the tubes with metallic foam (Seitzberger, Rammerstorfer, Gradinger, & Degischer, 2000; Zhang, Feng, & Zhang, 2010). The increase in energy absorption is due to interaction effect which occurs between the filler and the tube wall, and the strength of the filler itself contributes to the stability of the structure. The interaction effect occurs when the impingement of the tube wall into the filler results in additional compression to the filler. Furthermore, the mode of deformation of foam-filled tube shows a greater tendency to shift from diamond to concertina mode (Güden & Kavi, 2006; Yamada, Banno, Xie, & Wen, 2005). For the same length of deformation, foam-filled tubes