DYNAMICS CHARACTERISTICS AND ENERGY ABSORPTION OF FIBRE-METAL-LAMINATE (FML) THIN-WALLED TUBES

ZAILI BIN MOHD BAHARI

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

JUNE 2015

To my parents, wife and children.

ACKNOWLEDGEMENT

I would like to place my deepest respect and profound gratitude to my supervisor Dr. Zaini bin Ahmad for his valuable guidance, assistance, advice, and cordial dealings throughout the project period.

A hearty thanks to Mr. Aidid bin Hussin, Mr. Sazali bin Ngadiman, Mrs. Siti Norbiha bte Abd Aziz, Mrs. Nurzaidatul Akmal bte Mohd Yassin, Mr Muhammad Zharif bin Muhamed and Mr. Mohd Zakaria bin Awang of the Mechanical Engineering Faculty and the UTM Composite Centre for their invaluable assistance and the knowledge they had shared during the fabrication of the test samples and the execution of experiment.

ABSTRACT

Fibre-metal-laminate (FML) hybrid material has an enormous potential to replace metallic materials in vehicle structural applications. In this study the dynamic response and energy absorption capability of FML thin-walled tube were investigated via parametric study using finite element models. The models were validated by comparing their numerical analysis results with experimental results. The FML tubes were configured as a 2/1 alternating layer(s) of aluminium alloy and glass-fibre-reinforced epoxy (GFRE) composite. The results of the parametric study suggest that increasing the aluminium thickness has more profound effect on the energy absorption performance of the FML tube under axial compression compared to increasing the composite thickness. Another important finding is that sandwiching the composite layer with metal layers prevents catastrophic failure of the composite tube while promoting progressive collapse of the FML tube. These findings show the prospect of the FML tube as impact energy absorber for land transport vehicles.

ABSTRACT

Bahan hibrid lamina gentian-logam (FML) mempunyai potensi yang besar untuk menggantikan bahan-bahan logam di dalam aplikasi struktur kenderaan. Dalam kajian ini tindakbalas dan tenaga keupayaan penyerapan dinamik tiub FML berdinding nipis disiasat melalui kajian parametrik menggunakan model unsur terlansung. Model telah disahkan dengan membandingkan keputusan analisis berangka mereka dengan keputusan eksperimen. Tiub FML telah dikonfigurasikan sebagai lapisan selang- seli 2/1 aloi aluminium dan komposit epoksi kaca-bertetulang gentian (GFRE). Keputusan kajian parametrik menunjukan bahawa peningkatan ketebalan aluminium mempunyai kesan yang lebih mendalam kepada prestasi penyerapan tenaga tiub FML di bawah mampatan paksi berbanding meningkatkan ketebalan komposit. Satu lagi penemuan penting ialah ‘mensandwichkan’ lapisan komposit dengan lapisan logam menghalang kegagalan teruk tiub komposit di samping menggalakkan keruntuhan progresif tiub FML itu. Penemuan ini menunjukkan prospek tiub FML sebagai penyerap tenaga hentakan untuk kenderaan pengangkutan darat.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AA - Aluminium alloy
CFE - Crush force efficiency
EA - Absorbed energy
FE - Finite element
FML - Fibre metal laminate
FRP - Fibre reinforced polymer
g - Gram
GFRE - Glass fibre reinforced polymer
kJ/kg - KiloJoule/Kilogram
kN - KiloNewton
OD - Outsite diameter
PAS - Polyarilsulfone
PEEK - Polyetheretherketone
PEI - Polyetherimide
PI - Polyimide
PVC - Polyvinyl chloride
SE - Stroke efficiency
SEA - Specific Energy absorption
SRS - Supplemental Restraint System
UTM - Universal testing machine
WHO - World health organization

LIST OF SYMBOLS

D - average diameter

F - axial crush load

F_c - constant load

F_{mean} - average axial load

F_{peak} - maximum axial load for first peak

g - acceleration due to gravity

H - half-wavelength of fold

L - length

M_o - full plastic bending moment of tube wall per unit length

m - geometric eccentricity factor

N - number of circumferential lobes

OD - outside diameter

R - average radius

t - wall thickness of tube

t_A - wall thickness of aluminium alloy layer

t_c - wall thickness of GFRE layer

δ_e - effective crushing distance

σ_0 - flow stress

CHAPTER 1

INTRODUCTION

1.1 Research Background

For the last several years, the global spending on the treatment and recovery of an estimated 50 million road accident victims exceeds USD 100 billion annually (WHO, 2013). The huge figure, compounded with 1.2 million road fatalities every year, justifies the need for a continuous improvement on vehicle structural crashworthiness. Structural crashworthiness is the single most important passive mechanism to protect vehicle occupants from the devastating effect of crash energy.

Structural crashworthiness can be defined as "*the vehicle's structural ability to plastically deform and yet maintain a sufficient survival space for its occupants in crashes involving reasonable deceleration loads* (Chang, 2008)". As such, constructing an optimised vehicle structure capable of absorbing crash energy through controlled deformations to protect the passenger cell has always been the ultimate goal of vehicle structural engineering (American Iron and Steel Institute, 2004). Ideally the optimized vehicles structure should possess superior energy absorption capability while being lightweight at the same time.

Basically, a vehicle body is one big energy absorber by itself because it deforms upon impact to absorb some of the kinetic energy but not in efficient manner. In order to mitigate high speed impact energy, devoted energy absorbing components are required to effectively accomplish the purpose. In land transport vehicles such as a passenger car or a bullet train, these energy absorbing components can be found at strategic locations of the vehicle body.

For a passenger car, the front section has the most energy absorbing components since frontal crash, both straight and oblique, is the most common and one of deadliest type of crash (Payne-James *et al*., 2003). The energy absorbing structural components located at the front section are the S-frame or lower rail, the upper rail, the crush box and the bumper beam, as shown in Figure 1.1. These structural components are conventionally made from metals such as aluminium, mild steel and high strength steel.

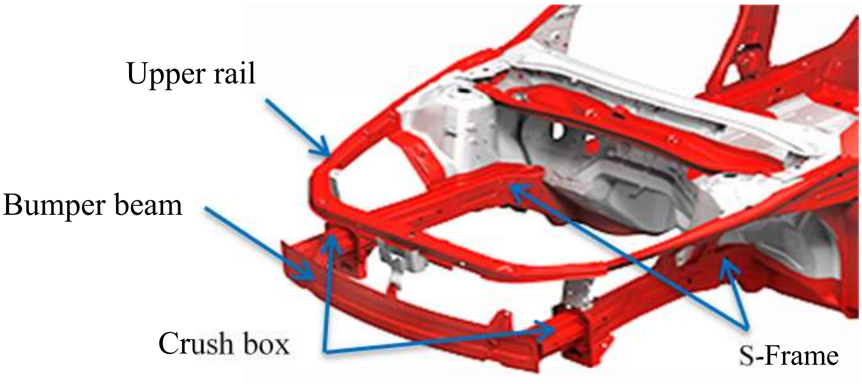

Figure 1.1 Energy absorption elements of a passenger vehicle
Source: http://blog.twwhiteandsons.co.uk

The crush box which is attached to the bumper beam and the S-frame is a dedicated impact energy absorber that would be permanently deformed in the event of a collision. The crush box, constructed in a tubular form, is a superb and efficient energy absorber under axial loading. Upon axial impact, it would collapse progressively from front to back, resulting in a controlled dissipation of the energy. The 'before and after' impact shape of the crush box is shown in Figure 1.2.

Since the crush box receives impact energy prior to the S-frame, enhancing the energy absorption performance of the crush box would definitely lessen the transmitted energy to the S-frame. One of the possible approaches to realize the enhancement of the crush box performance is by constructing the crush box from alternative materials with superior energy absorption property than that of the existing materials.

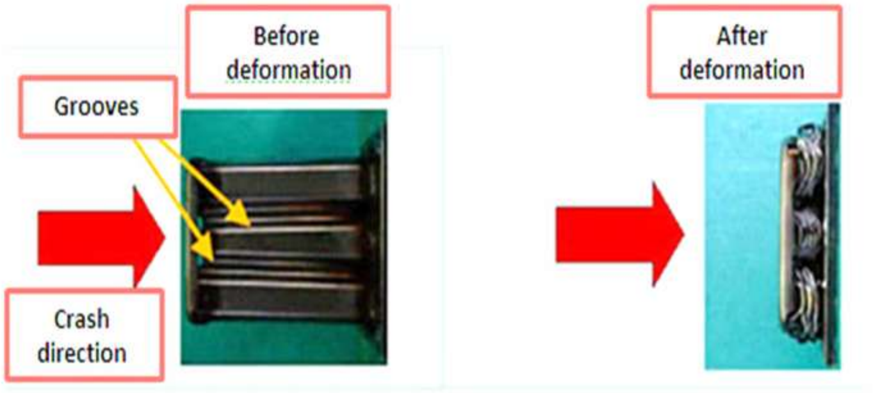

Figure 1.2 Progressive folding of a crush box with groove design.
Source: http://www.nssmc.com

Since crush box is designed as a non-repairable component, it is viable to construct the box from composite materials which are known to have high strength to weight ratio. One distinct advantage offered by composite materials is that composite structures can be constructed using different types of reinforcement materials, matrix materials and reinforcement schemes to tailor to the desired mechanical properties for specific application (Kutz, 2006). Among the many composite material candidates that fit the criteria as energy absorber, the one that has been outstanding in structural application, specifically as aerospace structure is fibre-metal-laminate (FML).

1.2 Background of Fibre-metal-laminate (FML)

Fibre-metal-laminate is a hybrid structure based on thin sheets of metal alloys bonded with plies of composite materials such as fibre reinforced polymer (FRP). It was developed at the Faculty of Aerospace Engineering of the Delft University of Technology, Netherlands in the 1970s from a research on new lightweight materials capable of replacing aluminium alloys as aerospace structure.

The goal of the research team was to develop materials with high strength, low density and high elasticity modulus compounded with improved toughness, corrosion resistance and fatigue resistance. The first variant of FML structure was

ARALL which is the acronym of Aramid Fibre Reinforced Aluminium Laminate. ARALL, as shown in Figure 1.3, consists of alternating thin aluminium alloy layers and aramid fibre prepregs. This layer arrangement grants ARALL the combined advantages of metallic material and aramid fibre reinforced epoxy.

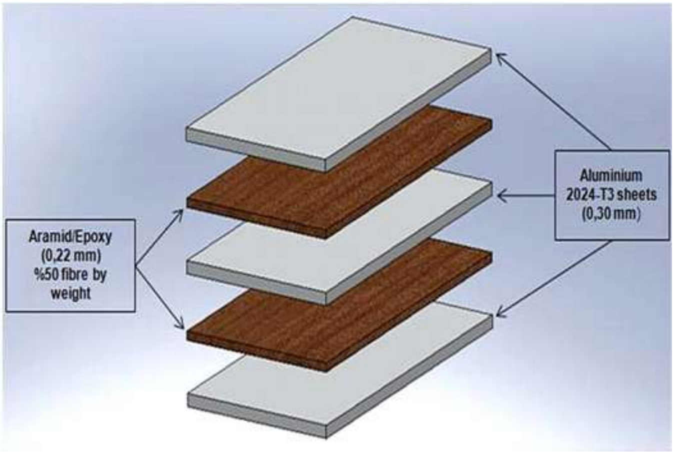

Figure 1.3 The layer arrangement of ARALL (Sinmazçelik *et al.,* 2011).

The next variant which is much stiffer uses carbon fibres for the composite layer(s) and thus codenamed CARALL. After extensive testing, CARALL was found to be less suitable for aerospace applications. It exhibited poor performance during fatigue tests at elevated stress levels and was plagued with galvanic corrosion problem between ply materials (Sinmazçelik *et al.,* 2011). Continuous development was able to produce another variant named GLARE. GLARE, as schematically shown in Figure 1.4, stands for GLASS LAMINATE ALUMINIUM REINFORCE EPOXY. To date GLARE is the most successful variant of the FML composite since it was commercialised in 1991. GLARE has been extensively used as aerospace structure to replace aluminium particularly on the fuselage of Airbus's A380 airliner. The success is contributed by the favourable properties of GLARE as listed in Table 1.1 which was extracted from the review work by Sinmazçelik *et.al* (2011). These properties boost the potential of GLARE as structural material for other type of vehicles such as land and sea transport vehicles.

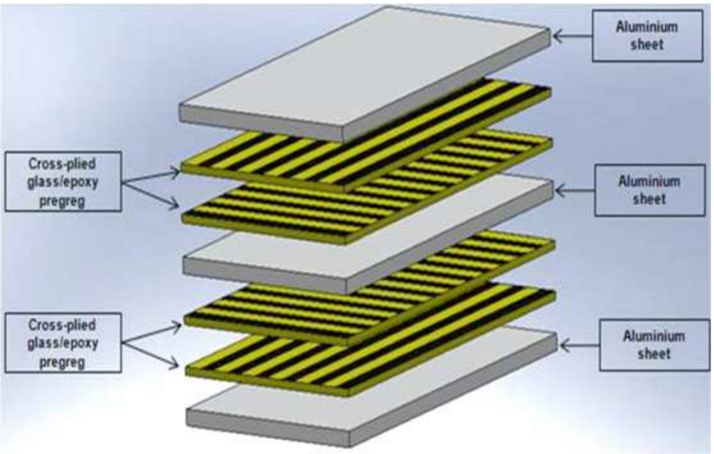

Figure 1.4 A cross-ply GLARE laminates (Sinmazçelik *et al*., 2011).

Table 1.1 : General properties of FML

Subject	Trait
Material behaviour	High strength High fracture toughness High fatigue and impact resistance High energy absorbing capacity
Physical properties	Low density
Durability	Excellent moisture and corrosion resistance Lower material degradation
Safety	Fire resistance

1.3 Research Problem

There had many investigations on the energy absorption and crush response of tubular composite structures such as fibre-reinforced polymer (FRP) tubes, filled metallic tubes, externally-reinforced composite tubes, etc. The general finding from these investigations is that the energy absorption performance of composite tubes is superior in comparison to the performance of monolithic metal tubes, under axial compressive loading. These finding were reported among others by Babbage and Mallick (2005), Ahmad and Thambiratnam (2009) and Li *et al.* (2012). For FRP composite tubes, Farley (1983) and Shin *et al.* (2002) reported the same finding on their performance.

In contrast to their desirable energy absorption performance, the crush response of these composite tubes is not that consistent. A distinctive collapse characteristic of the non-filled composite tubes, specifically the FRP composite tubes, is that they do not exhibit the ductile failure mechanism commonly displayed by metal tubes. Instead, three main crush modes were observed when they deform under axial compressive load; (1) progressive tube crushing with micro-fragmentation of the composite materials, (2) brittle fracture of the composite tube and (3) mixed mode of collapse. (Mamalis *et al.*, 1990).

Mode 1 is associated with considerable amounts of crush energy absorbed. Mode 2 on the other hand is rather unpredictable because it can cause catastrophic tube failure resulting in minimal crush energy absorbed. Mode 3 is the combination of Mode 1 and Mode 2. These crush characteristics which can be associated to the brittleness and the anisotropic property of FRP composite materials are not the desired compressive failure mechanisms as far as the energy absorption application is concerned (Ma *et al.*, 2015).

The drawback on crush characteristic of the FRP composite tube provides a sound motive to investigate the crush response and energy absorption of fibre-metal-laminate (FML) tube. As previously mentioned, FML inherits the properties of both metal and FRP composite. Therefore there is a high probability that FML tube under axial compression would exhibit the combined energy absorption characteristics of its parent elements as well.

Having discussed the reasoning, it is also worthy to mention that the study on energy absorption capability of FML tube has been very sparse indeed. As such, the knowledge on the capability of the FML tube as energy absorber is still very much limited. The findings of this study hopefully could provide a glimpse on the potential of FML tube in impact energy mitigating applications.

1.4 Objective

The objectives of the project are as follows

1. To fabricate seamless fibre-metal-laminate (FML) thin-walled tube from aluminium alloy (AA) circular tube and glass-fibre-reinforced epoxy (GFRE).

2. To investigate the dynamic response and energy absorption performance of AA-GFRE FML circular tubes under axial compressive loading.

1.5 Scope of Project

The scopes of the project are as follows

1. Laboratory fabricated seamless thin-walled FML and bare aluminium circular tubes as the test specimens.

2. Testing of specimens under quasi-static axial compressive load on universal testing machine (UTM).

3. The development of detailed FE model for simulating progressive crushing of FML thin-walled tubes.

4. Validation of FE models by using the experimental results.

5. Parametric study using the validated models to determine the dynamic response and energy absorption capability of FML tubes.

1.6 Contribution of Study

The outcomes of study should be able to provide a preliminary knowledge on the dynamic behaviours and energy absorption capability of FML thin-walled tubes when subjected to impact loading. The knowledge could be used to develop a more robust FML structure through further investigations on the factors that influence the behaviours and energy absorption performance of FML tubes. With the superior properties and performance, FML tubes can become good alternatives to metal tubular structure in energy absorbing management.

REFERENCES

Abramowicz, W. and Jones, N. (1984). Dynamic axial crushing of circular tubes. *International Journal of Impact Engineering*. 2(3).

Abramowicz, W. and Jones, N. (1986). Dynamic progressive buckling of circular And square tubes. *International Journal of Impact Engineering*. 4.

Ahmad, Z and Thambiratnam, D.P. (2009). Crushing response of foam-filled conical tubes under quasi-static axial loading. *Materials & Design*. 30(7), 2393-2403

Alexander, J.M. (1960) An approximate analysis of collapse of thin cylindrical Shells under axial loading. *Quarterly Journal of Mechanics and Applied Mathematics*.13.

Al Galib, D and Limam, A. (2004). Experimental and numerical investigation of static and dynamic axial crushing of circular aluminum tubes. *Thin-Walled Structures*. 42, 1103–1137

Babbage, J.M and Mallick, P.K. (2005). Static axial crush performance of unfilled and foam-filled aluminum–composite hybrid tubes. *Composite Structures*. 70 (2), 177–184

Prasad, P. and Belwafa, J.E. (2004). *Vehicle crashworthiness and occupant protection*. Southfield, Michigan: American Iron and Steel Institute

Chang, Q. (2008). *A Magic Cube Approach for Crashworthiness and Blast Protection Designs of structural and material systems*. Ann Arbor MI: ProQuest LLC.

Courteau, M.,A. (2011). Investigating the crashworthiness characteristics of carbon fiber/epoxy tubes. Master of Science. The University of Utah,Utah.

Farley, G. L. (1983). Energy Absorption of Composite Materials. *Journal of Composite Materials.*17

Farley, G. L. and Jones. R.M. (1992). Crushing characteristics of continuous fiber-reinforced composite tubes, *Journal of Composite Materials*.

Guillow, S.R., Lu, G. and Grzebieta, R.H. (2001). Quasi-static axial compression of thin-walled circular aluminium tubes. *International Journal of Mechanical Science.* 43,2103–2123.

Hanefi, E.H. and T. Wierzbicki, T.(1996). Axial resistance and energy absorption of externally reinforced metal tubes. *Composites Part B: Engineering*. 27B.

Kutz, M. (2006) *Mechanical Engineers' Handbook: Materials and Mechanical Design Volume 1*, (3rd ed.). New Jersey: John Wiley & Sons, Inc.

Li, Z., Yu, J., Guo,.L. (2012). Deformation and energy absorption of aluminium foam- filled tubes subjected to oblique loading. *International Journal of Mechanical Sciences*. 54, 48–56

Ma, Y., Suguhara, T., Yang, Y., Hamada, H. (2015). A study on the energy absorption properties of carbon/aramid fiber filament winding composite tube. *Composite Structures*. 123, 301–311

Mamalis, A.G. Manolakos, D.E., Viegelahn, G.L. (1990). Crashworthy Behaviour of Thin-Walled Tubes of Fibreglass Composite Materials Subjected to Axial Loading. *Journal of Composite Materials.* 24, 72

Mamalis, A.G. Manolakos, D.E. Demosthenous, G.A. and Johnson, W. (1991) Axial plastic collapse of thin bi-material tubes as energy dissipating systems. *International Journal of Impact Engineering.* 11(2), 185–196.

Nagel,G. (2005). Impact and Energy Absorption of Straight and Tapered Rectangular Tubes. Doctor of Philosophy. Queensland University of Technology, Queensland

Naik, N.K. and Nemani, B. (2001). Initiation of damage in composite plates under transverse central static loading. *Composite Structure*.52, 167-172

Payne-James, J., Busuttil, A., Smock, W.(2003). *Forensic Medicine: Clinical and Pathological Aspects.* London: Greenwich Medical Media Ltd:

Ramakrishna, S., Hamada, H., Maekawa, Z and Sato, H. (1995) Energy absorption behavior of carbon-fiber-reinforce thermoplastic composite tubes. *Journal of Thermoplastic Composite Materials*. 8, 323-344

Singace A.A., Elsobky H. Further experimental investigation on the eccentricity Factor in the progressive crushing of tubes. *International Journal of Solids and Structures*. 33, 3517–3538.

Singace, A,A. (1999) Axial crushing analysis of tubes deforming in the multi-lobe mode. *International Journal of Mechanical Sciences*. 41, 865–90.

Sinmazçelik ,T., Avcu, E., Bora and, M.O., Çoban, O. (2011). A review: Fibre metal laminates, background, bonding types and applied test methods. *Materials and Design.* 32, 3671–3685

Shin, K. C., Lee, J.J, Kim, H. K., Song, M. C and Huh, J.S. (2002). Axial crush and bending collapse of an aluminum/GFRP hybrid square tube and its energy absorption capability. *Composite Structures.* 57, 279–287

Thornton. P.H. and Edward, P. J. (1982). Energy absorption in composite structures. *Journal of Composite Materials.* 16, 522-544

Wierzbicki, T. Bhat, S.U. W. Abramowicz, and Brodkin, D. (1992). Alexander revisited – a two folding elements model of progressive crushing of tubes. *International Journal of Solids and Structures*. 29, 3269-3287.

World Health Organization (2013). *Global status report on road safety 2013: supporting a decade of action*. Geneva.