CRASHWORTHINESS OF CORRUGATED COMPOSITE SHELLS

By

ALI MOHAMED ALI ELGALAI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

February 2006

DEDICATION

To whom their true are behind my success love and support my daughters, wife and parents.

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

CRASHWORTHINESS OF CORRUGATED COMPOSITE SHELLS

By

ALI MOHAMED ALI ELGALAI

February 2006

Chairman : Professor, Abdel Magid S. Hamouda, PhD

Institute : Advanced Technology

The increase of number of vehicles on the road has led to an increase in the traffic accidents. Consequently, there is also an increase of deaths and serious injuries. The desire to improve the crashworthiness of automobiles cannot be overestimated. It has been estimated that the annual financial loss from traffic accidents is equal to 2% of the GNP of the USA. Together with a range of environmental concerns and social pressure backed by legislation have led and continue to lead to highly innovative designs, involving lighter materials such as composite materials. During the last decades, researchers' interest have been directed towards the use of composite structures for enhancing crashworthiness due to their superior properties, in particular, strength and stiffness to weight ratios and their ability to be tailored in composition and shape.

Of particular interest of this study is the use of corrugated composite shells in the automobile industry as a crush energy absorber device. Extensive experimental and computational programs have been conducted in order to investigate the crushing

behaviour of corrugated and non-corrugated composite tubes. In the experimental program, innovative mandrels and filament winding machine were designed and fabricated. The investigated corrugated composite tubes consist of a number of similar circular cones connected together by circular tubes in the order: cone-cylinder-cone-cylinder and so on. The outer diameter of each tube is fixed at 100 mm and the number of layers is maintained 6 layers. Two material types, namely, filament wound carbon/epoxy and woven roving glass/epoxy were investigated.

A comprehensive quasi-static crushing test program was performed to examine the influence of the tube length and the corrugation angle on the energy absorption capabilities. The load-displacement curves and typical load paths together with deformation histories were presented and discussed. The specific energy absorption, energy absorption per unit length, crushing force efficiency and stroke efficiency were calculated, analyzed and discussed. Comparisons in terms of specific energy absorption and/or energy absorption per unit length capabilities between corrugated composite and non-corrugated tubes were also presented and discussed. Macroscopic photos were taken during the tests to help understanding the failure modes and the failure mechanisms were analyzed microscopically.

The crushing load-displacement behaviour, energy absorption, and the observed mechanisms and failure modes were found to be sensitive to the change in the corrugation angle, the tube length and the fibre type, and distinct collapse modes were observed. The most dominant observed failure modes are: catastrophic and brittle fracture modes in filament wound carbon/epoxy tubes, progressive folding mode (in the corrugated tubes) and splaying modes (in the non-corrugated tubes) of

woven roving glass/epoxy tubes. Also splitting mode was observed in both filament wound carbon/epoxy and woven roving glass/epoxy tubes. The results have shown that corrugated composite tubes are efficient impact energy absorbers. Based on tube length, GL3-0 and GL1-20 tubes experienced the highest energy absorption per unit length (19.85, 18.89 kJ/m, respectively). Based on material type, filament wound carbon/epoxy tubes exhibited higher specific energy than the corresponding woven roving glass/epoxy tubes where 15.7 kJ/kg was absorbed by CL4-40 tube. Over all, GL1-20 tubes could be recorded as the best choice for crashworthiness applications (moderate load carrying capacity, high absorption energy, high CFE and high SE).

Concurrent with the experimental work, numerical analyses was carried out using commercially available Finite Element Software (LUSAS). Three-dimensional Linear buckling Finite Element was conducted for the corrugated and non-corrugated composite tubes to predict the critical failure load, the deformation at the critical load, and the stress concentration contours. Both the experimental and numerical results were presented for different reinforcements, different corrugation angles, and different tube lengths. Relatively, a reasonable agreement between the experimental initial failure load and the computational critical load was obtained, specially for corrugation angles = 30 and 40 degrees. Knockdown factor is used to compare the results and found to be varying in the range from 0.259 (CL4-10) to 0.998 (GL4-40).

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

"CRASHWORTHINESS" CENGKERANG "CORRUGATED" BERKOMPOSIT

Oleh

ALI MOHAMED ALI ELGALAI

Februari 2006

Pengerusi : Profesor Abdel Magid S. Hamouda, PhD

Institut : Teknologi Maju

Dengan kenaikan produk kenderaan di jalan raya telah menyebabkan pertambahan kemalangan trafik . Oleh sedemikian, kadar kecederaan dan kematian juga meningkat. Kemahuan untuk meningkatkan "crashworthiness" otomobil tidak dapat diabaikan lagi. Ia telah dianggarkan bahawa kerugian kewangan tahunan daripada kemalangan trafik adalah sama dengan 2% daripada GNP sepertimana di Amerika Syarikat. Bersama dengan keprihatinan terhadap isu alam semulajadi dan tekanan social yang disokong oleh perundangan telah menerajui kemajuan ke arah rekabentuk yang innovatif, melibatkan bahan yang lebih ringan seperti komposit. Dekad yang lalu , minat para penyelidik telah terarah kepada struktur komposit untuk menguatkan "crashworthiness" disebabkan oleh cir-ciri kekuatan tinggi, terutama pada nisbah nilai kekuatan dan tegasan terhadap berat bahan tersebut, dan keupayaan untuk diolah mengikut komposisi dan bentuk.

Oleh itu, kegunaan bentuk 'corrugated' juga suatu tarikan untuk diselidiki dalam industri otomobil sebagai alat penyerapan tenaga. Dalam kerja penyelidikan secara mendalam ini, kerja-kerja ujikaji dan program permodelan berangka yang

menyeluruh telah dijalankan untuk menyiasat sifat remukan tiub komposit ‘‘corrugated” dan bukan “corrugated’’. Di dalam program penyelidikan ini, mandrel innovatif dan mesin “filament winwing” telah direkabentuk dan dibina. Tiub komposit “corrugated” yang telah diambilkira mengandungi beberapa kon bulat yang sama dan bercantum dengan tiub silinder dalam satu urutan: kon-silinder-kon ‘frusta’-silinder dan seterusnya (tiub kon-silinder pelbagaian). Bilangan tiub kon dan silinder bergantung kepada jarak tiub. Diameter luaran telah dikekalkan sebagai konstan 100mm. Bilangan lapisan ialah 6. Untuk kajian ini, dua jenis bahan iaitu balutan filament karbon/epoksi dan sulaman “roving” kaca/epoksi telah diambilkira. Didalam ujikaji eksperimental, satu program remukan secara quasi-statik yang komprehensif telah dilakukan untuk mengkaji pengaruh parameter rekabentuk terhadap keupayaan tenaga penyerapan. Kesan terhadap jarak tiub yang berbeza dan sudut “corrugation” telah dikaji. Dariapada keputusan ujikaji, cerun beban-anjakan dan laluan beban tipikal bersama-sama dengan sejarah kecacatan telah ditunjukkan dan dibincang. Perbandingan dalam terma tenaga penyerapan per unit jarak dan/atau tenaga penyerapan spesifik diantara tiub komposit “corrugated” dan bukan “corrugated” telah ditunjukkan dan dibincangkan. Tenaga penyerapan spesifik,tenaga pernyerapan per unit jarak,daya remukan efisien dan efisiensi strok telah dikira dan bincangkan. Gambar makroskopik telah diambil semasa ujikaji untuk menyiasat mod kegagalan. Mekanisma kegagalan juga telah dianalisa secara mikroskopik.

Sifat beban-anjakan remukan,tenaga penyerapan dan mekanisma yang telah diperhatikan dan mod kegagalan telah didapati sentitif terhadap perubahan jarak tiub,sudut “corrugation” , jenis gentian dan bilangan mod runtuhan juga telah diperhatikan. Mod kegagalan yang paling dominant ialah; mod retakan “catastrophic” dan rapuh pada tiub balutan filament karbon/epoksi iaitu mod lipatan

progresif (untuk tiub “corrugated”) dan mod “splaying” (dalam tiub bukan “corrugated”) pada tiub sulaman “roving” kaca/epoksi.Juga mod pisahan diperhatikan pada kedua-dua tiub tersebut. Mod runtuhan ini juga dapat dianggarkan dan dikawal dan dengan ini tenaga penyerapan dapat ditingkatkan. Keputusan telah menunjukkan bahawa tiub komposit “corrugated” sepertimana dengan tiub komposit bercengkerang nipis adalah penyerap tenaga impak yang efisien. Berdasarkan jarak tiub, GL3-0 dan GL1-20 mengalami tenaga penyerapan tertinggi per unit jarak (19.85, 18.89 kJ/m). Berdasarkan kepada jenis bahan, tiub balutan filament karbon/epoksi menunjukkan tenaga spesifik yang tinggi berbanding dengan tiub sulaman “roving” kaca/epoksi dimana tenaga spesifik yang maksimum yang diserap oleh tiub CL4-40 ialah 15.7 kJ/kg. Pada keseluruhannya, tiub GL1-20 boleh direkodkan sebagai aplikasi “crashworthiness” yang terbaik (kapasiti bawaan bebanan yang sederhana,tenaga peryerapan tinggi,CFE dan SE yang tinggi).

Bersamaan dengan kerja tersebut, analisis permodelan telah dijalankan dengan menggunakan perisian kaedah berangka tidak terhingga (LUSAS). Alogritma tiga dimensi element tidak terhingga telah dibangunkan untuk tiub komposit ‘corrugated” dan bukan “corrugated’. Analisis lenturan linear telah dijalankan untuk menganggarkan beban kegagalan lenturan,kecacatan pada beban kritikal dan kontor penyebaran tegasan. Kedua-dua keputusan ujikaji dan permodelan telah ditunjukkan untuk penguatan,sudut “corrugation” dan jarak tiub yang berbeza. Secara relatif, suatu persetujuan telah dicapai diantara kegagalan mula secara eksperimental dan bebanan kritikal secara komputan, terutamanya untuk sudut “corrugation” = 30 dan 40 darjah. Walau bagaimanapun factor “knockdown” telah digunakan untuk membandingkan keputusan yang didapatiiaitu berada pada julat 0.259 (CL4-10) hingga 0.998 (GL4-40).

ACKNOWLEDGEMENTS

First of all, great thanks to the Most Gracious and Most Merciful ALLAH (S.W.T) without his wish and help this work would not have been possible. I also would like to express the most sincere appreciation to those who made this work possible: Advisory members, Friends and Family.

I would like to thank Prof. Dr. Abdel Magid S. Hamouda for providing me with the opportunity to complete my Ph. D. studies under his valuable guidance, for the many useful advice and discussions, for his constant encouragement and guidance, and for co-authoring and reviewing some of my publications, where his practical experience and technical knowledge made this research and those publications more interesting and relevant. Also special thanks extend to the supervisory committee members; Prof. Dr. Barkawi Bin Sahari and Dr. Elsadig Mahdi Ahmed. I am grateful for their willingness to serve on my supervisory committee, constant encouragement, helpful advice and many fruitful discussions.

I would like to thank all my colleagues in Numerical Spatial Modelling Laboratory, in special, brother Risby. Very special thanks extend to the science officer of this laboratory, sister Normalina, for her kindness, support and for providing help whenever needed. Thanks to engineer Wong for his help in fabricating and designing the filament-winding machine. Special thanks extend to the technicians in the Mechanical Engineering and Aerospace Laboratories, in special brother Muhammed Wildan Ilayas. I would like to express my appreciation and thanks to all who have tought me during my life, in special, my main supervisor during my master Degree Prof. Dr. Ro Seng Tack (Souel National University, South Korea).

Ministry of higher education of Great Socialist People's Libyan Arab Jamahiriya is gratefully acknowledged for providing the financial support.

Thanks and acknowledgements are meaningless if not extended to my parents who deserve my deepest appreciation. I am grateful for the countless sacrifices they made to ensure that I could pursue my dreams and for always being there for me. Real and deepest thanks to them (May ALLAH bless and protect them and may live long and healthy). All praise and thanks words said to them will not be enough.

Lastly but not least, very very special thanks to my wife, my daughters and my son, confidante and true love. Their love, support and encouragement are behind my success.

I certify that an Examination Committee has met on 7th February 2006 to conduct the final examination of Ali Mohamed Ali Elgalai on his Doctor of Philosophy thesis entitled "Crashworthiness of Corrugated Composite Shells" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

Ir. Ing. RENUGANTH A/L VARATHARAJOO, PhD
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Ir. SHAHNOR BASRI, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Ir. MOHAMMED SAPUAN SALIT, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

M. S. J. HASHMI, PhD
Professor
Faculty of Engineering
Dublin City University, Ireland
(External Examiner)

_____
HASANAH MOHD GHAZALI, PhD
Professor/ Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment on the requirement for the degree of Doctor of Philosophy. The members of the supervisory committee are as follows:

ABDELMAGID S. HAMOUDA, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

BARKAWI BIN SAHARI, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ELSADIG MAHDI AHMED, PhD
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

_____
AINI IDERIS, PhD
Professor/ Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

_____

ALI MOHAMED ALI ELGALAI

Date:

TABLE OF CONTENTS