

**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**

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**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” CENGERANG “CORRUGATED”  
BERKOMPOSIT**

Oleh

**ALI MOHAMED ALI ELGALAI**

**Februari 2006**

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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 inovatif, 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 inovatif dan mesin “filament winwing” telah direkabentuk dan dibina. Tiub komposit “corrugated” yang telah diambil kira 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 diambil kira. 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 penyerapan 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 sensitif terhadap perubahan jarak tiub, sudut “corrugation” , jenis gentian dan bilangan mod runtuh 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 runtuh 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 penyerapan 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 didapati iaitu berada pada julat 0.259 (CL4-10) hingga 0.998 (GL4-40).



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I certify that an Examination Committee has met on 7<sup>th</sup> 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:

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## **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.

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**ALI MOHAMED ALI ELGALAI**

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