UNIVERSITI PUTRA MALAYSIA

DESIGN AND ANALYSIS OF FILAMENT- WOUND COMPRESSED NATURAL GAS CARBON FIBRE - REINFORCED COMPOSITE TANK

NURUL ZUHAIRAH MAHMUD ZUHUDI

DESIGN AND ANALYSIS OF FILAMENT- WOUND COMPRESSED NATURAL GAS CARBON FIBRE - REINFORCED COMPOSITE TANK

NURUL ZUHAIRAH MAHMUD ZUHUDI

MASTER OF SCIENCE
UNIVERSITI PUTRA MALAYSIA

2008

DESIGN AND ANALYSIS OF FILAMENT- WOUND COMPRESSED NATURAL GAS CARBON FIBRE - REINFORCED COMPOSITE TANK

By

NURUL ZUHAIRAH MAHMUD ZUHUDI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Master of Science

May 2008

DEDICATION

Especially to Abah, Hj. Mahmud Zuhudi Tahir and Umi, Hjh. Kamariah Mohd Noor…this is my special gift to both of you. To my beloved husband, Mohd Azan Che Noh, kakak (Nurul Izzati Amali) and abang (Muhammad Ameerul Wajdi), they have been and will be my inspiration…

ABSTRACT

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

DESIGN AND ANALYSIS OF FILAMENT - WOUND COMPRESSED NATURAL GAS CARBON FIBRE - REINFORCED COMPOSITE TANK

By

NURUL ZUHAIRAH MAHMUD ZUHUDI

May 2008

Chairman: Professor Fakhru'l-Razi Ahmadun, PhD

Faculty: Faculty of Engineering

First ply failure (FPF) strengths of laminated composite tank subjected to uniform internal pressure loads are studied via both analytical and finite element analysis approaches. The filament-wound CNG carbon fibre reinforced composite tanks are designed with a T6-6061 aluminium cylinder with elliptical end closures acts as the liner which is over-wrapped with high modulus carbon fibre-reinforced epoxy composite.

The objectives of this study are to optimize the composite layer thickness and to optimize fibre orientation configurations of carbon fibre laminate as to have a lightweight and high performance filament-wound CNG carbon fibre-reinforced composite tanks. In analytical approaches, in order to predict the first-ply failure (FPF) pressure of filament-wound CNG carbon fibre-reinforced composite tanks, the stresses and strains

throughout the laminate were determined using the classical lamination theory which were then used in three most common composite failure theories, that are the maximum stress theory, maximum strain theory, and quadratic or Tsai-Wu failure theory.

Optimal general design of fibre orientations were then used to carry out in lay-up optimization or arrangement of composite layer stage to be used for filament winding process in order to study the effect of fibre orientation angles using an equal thickness of composite layer on the tank performance. The range of helical angles used is in between 0° to 60°, which is based on the traditional theoretical optimal helical angles from classical lamination theory. The ratio of 2:1 hoop to helical angles is used to predict the maximum first-ply failure (FPF) pressure.

The optimization results gave the optimal fibre orientations of the $\left[(30/-30)_{11}/90_{24}\right]$ with b/a = 1.093 for CNG 1, b/a = 1.110 for CNG 2 and b/a = 1.128 for CNG 3 which obtained were then used for stress analysis in finite element analysis using ANSYS version 7.1 software. The accuracy of the theoretical and finite element analysis of first-ply failure (FPF) pressure is verified by a verification study where a similar finite element model from literature have been modelled and analysed using similar method used to design filament wound CNG carbon fibre-reinforced composite tanks in order to verify a valid finite element method used. The results were then being compared literature study.

ABSTRAK

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

REKA BENTUK DAN ANALISIS TANGKI KOMPOSIT FILAMEN BERLILIT BERISI GAS ASLI MAMPAT DENGAN GENTIAN KARBON DIPERKUKUHKAN

Oleh

NURUL ZUHAIRAH MAHMUD ZUHUDI

May 2008

Pengerusi: Professor Fakhru'l-Razi Ahmadun, PhD

Fakulti: Fakulti Kejuruteraan

Kegagalan lapisan pertama (FPF) kekuatan-kekuatan tangki komposit yang berlapis bawah muatan-muatan tekanan dalaman yang seragam adalah dikaji melalui analisis kedua-dua pendekatan iaitu analitikal dan analisis unsur terhingga. Tangki-tangki komposit filamen berlilit gentian karbon CNG yang diperkukuhkan direka bentuk dengan satu silinder aluminium T6-6061 dengan penutupan akhir yang bujur berfungsi sebagai lapisan dalaman yang akan dibungkus besar dengan gentian karbon bermodulus tinggi yang diperkukuhkan dengan rencam epoksi.

Objektif-objektif kajian ini adalah untuk mengoptimumkan ketebalan lapisan komposit dan untuk mengoptimumkan orientasi gentian konfigurasi-konfigurasi lapis gentian karbon sebagai untuk menghasilkan tangki-tangki komposit berfilamen berlilit gentian karbon CNG yang

diperkukuhkan yang ringan dan berprestasi tinggi. Dalam pendekatan-pendekatan analisis, untuk meramalkan tekanan bagi kegagalan lapisan pertama (FPF) tangki-tangki komposit berfilamen gentian karbon CNG yang diperkukuhkan, tekanan dan terikan sepanjang lapis adalah ditentukan menggunakan teori pelapisan klasik yang telah kemudiannya digunakan dalam tiga rencam paling popular dalam teori-teori kegagalan, yang adalah teori tegasan maksimum, teori keterikan maksimum, dan kuadratik atau teori kegagalan Tsai-Wu.

Corak umum optimum orientasi-orientasi gentian adalah kemudian digunakan bagi menjalankan dalam mengumpul pengoptimuman atau susunan peringkat lapisan komposit teratur untuk digunakan dalam proses lilitan filamen bagi mengkaji kesan sudut-sudut orientasi gentian menggunakan ketebalan yang sama rata lapisan tangki komposit. Julat sudut-sudut berlingkar digunakan adalah dalam antara 0° to 60°, yang adalah diasaskan ketradisionalan sudut-sudut yang berlingkar teori dan optimum daripada teori pelapisan klasik. Nisbah 2:1 gelung untuk sudut-sudut berlingkar adalah digunakan untuk meramal maksimum tekanan kegagalan lapisan pertama (FPF).

Hasil-hasil pengoptimuman memberi orientasi-orientasi gentian optimum $\left[(30/-30)_{11}/90_{24}\right]$ dengan b/a = 1.093 untuk CNG 1, b/a = 1.110 untuk CNG 2 dan b/a= 1.128 untuk CNG 3 yang diperolehi adalah kemudiannya digunakan untuk analisis tegasan dalam analisis unsur terhingga menggunakan perisian ANSYS versi 7.1. Ketepatan analisis teori dan analisis unsur terhingga bagi tekanan kegagalan lapisan pertama (FPF) disahkan oleh satu pengesahan kajian di mana satu elemen terhad serupa daripada maklumat kajian bertulis terdahulu telah dijadikan contoh dan dianalisis menggunakan kaedah serupa digunakan untuk mereka tangki-tangki komposit berfilamen berliku gentian karbon CNG yang diperkukuhkan untuk mengesahkan satu kaedah unsur terhingga yang tepat digunakan. Hasilnya adalah kemudian dibandingkan dengan kajian terdahulu.

ACKNOWLEDGEMENTS

One page to acknowledge all those who encouraged, inspired, and hung out with the author during her stay at UPM... my 1st supervisor, Dr. El Sadig Mahdi for his guidance and generous support and also for his solid, logical suggestions for conquering obstacles, instead of his casual, nurturing relationship that allowed some of my rather abstract and often harebrained ideas to mature into interesting scientific questions. Indeed his moral and kind guidance was one in a kind.

The author also extend her gratitude to Prof. Fakhru'l-Razi Ahmadun, her current supervisor, Dr. Mohd Amran and his team (Fuel Storage Team) which she deeply indebted to them for their help in so many aspects of her work and life. The author would like to thank her friends and lab mates, past and present, for their collaboration as colleagues and support as friends.

Finally, and most importantly the author would like to thank her family particularly her parents, for the obvious reasons (i.e., her birth) and for their enthusiastic support. The author's brothers and sisters get credits for they lifted her up when she could not reach. They are the ones who held her up and never let she fall. And last but not least, especially for the author beloved husband, Mohd Azan, her child Izzati Amali and Ameerul Wajdi , they have been and will be her inspiration…………

I certify that an Examination Committee met on 28 May 2008 to conduct the final examination of Nurul Zuhairah Mahmud Zuhudi on her Master Science thesis entitled "Design and Analysis Of Filament-Wound Compressed Natural Gas Carbon Fibre-Reinforced Composite Tank" 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:

Robiah Yunus, Ph.D.
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Sapuan Salit, Ph.D.
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mohamed Tarmizi Ahmad, M.Sc.
Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Che Hassan Che Haron, Ph.D.
Professor
Faculty of Engineering
Universiti Kebangsaan Malaysia
(External Examiner)

HASANAH MOHD. GHAZALI, Ph.D.
Professor and 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 of the requirement for the degree of Master Science. The members of the Supervisory Committee were as follows:

Prof. Fakhru'l-Razi Ahmadun, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Dr. Mohd Amran Mohd Salleh, PhD
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Dr. Mohd Rizal Zahari, PhD
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Dr. El Sadig Mahdi Ahmed Saad, PhD
Faculty of Engineering
International Islamic University Malaysia
(Member)

____

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

Date: 14th August 2008

DECLARATION

I 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 is not concurrently, submitted for any other degree at UPM or other institutions.

NURUL ZUHAIRAH BINTI
MAHMUD ZUHUDI

Date: 10^{th} July 2008

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

υ_{12}	Poisson's ratio	48
G_{12}	Shear Modules	48
R	Tensor strain	51
T	Tensor rotation	51
θ	Fibre orientation angle	47
$\overline{Q}$	The elastic properties of composite at arbitrary angle to the fibres	52
β	Cone vertex angle	74
δ	Transverse deformation	74
FEA	Finite Element Analysis	106

CHAPTER 1

INTRODUCTION

1.1 Introduction

Known pressure vessels that can operate at high pressures include all metallic vessels. An all-metallic vessel which would satisfy the strength requirements for operating at high pressures generally requires high grade steel whose cost makes commercial production of such vessels unfeasible. Filament-wound composite pressure tanks, which utilize a filament winding fabrication technique to form high strength and light weight reinforced plastic parts, are a major type of high pressure vessels and are widely used in commercial and aerospace industries such as fuel tanks, and rocket motor cases as reported by Shen [35].

Due to the rapid development of material science, the composite material industry has been growing at a dramatic pace in order to meet the challenges of the future. The lightweight, high strength and high performance composite structures can offer a significant weight savings over their traditional metal parts studied by Chang [26].

Continuous filament winding has provided opportunities for designers to gain the ultimate strength out of materials and to efficiently place materials where is needed. The successful development of filament-wound pressure tanks with metal liner has provided significant weight savings over the conventional metal pressure tanks. The basic concepts of this design is to use a thin metallic liner designed mainly as permeation barrier with little load carrying capacity capability, while the composite is sized to carry all the pressure loads. Therefore, the weight savings can be derived from the dramatic difference in specific strength between metal and composite. The leaks before burst or rupture characteristics of the filament-wound metal lined pressure vessel further enhance the safety of the overall system.

1.2 Problem Statement

Among present known fuels natural gas is one of the cheapest, the most environmentally friendly and provides the highest safety margin during operation. The most important component of natural gas fuel systems is the compressed natural gas (CNG) storage tank. The high-pressure tank must safely (statically) withstand, without leakage or cracking, the maximum operational pressure and fatigue load cycles resulting from recharging. The problems or issues involved in the design and analysis of a filament-wound composite tank is to optimise composite layer thickness and optimise fibre orientation configuration of composite laminated in order to have high pressure tank.