CRUSHING BEHAVIOUR OF GLASS FIBRE/EPOXY COMPOSITE PIPES: THE EFFECTS OF WINDING ANGLES, AGEING, AND TEMPERATURES

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Crushing Behaviour of Glass Fibre/Epoxy Composite Pipes: The Effects of Winding Angles, Ageing, and Temperatures

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GRE	Glass fibre reinforced epoxy
UTM	Universal Testing Machine
SEM	Scanning Electron Microscopy
CNC	Computer numerical control
PIC	Peripheral interface controller

LIST OF SYMBOLS

V_g	Volume fraction of glass fibre
V_e	Volume fraction of epoxy
W_g	Weight fraction of glass fibre
W_e	Weight fraction of epoxy
ρ_g	Density of glass fibre
ρ_e	Density of epoxy
E_1	Modulus of elasticity for longitudinal direction
E_e	Mmodulus of elasticity for epoxy
v_e	Poisson ration for epoxy
E_g	Modulus of elasticity for glass fibre
v_g	Poisson ratio for glass fibre
E_2	Modulus of elasticity for transverse direction
v_{12}	Poisson ratio for 1-2 plane
v_{21}	Poisson ratio for 2-1 plane
G_{12}	Shear modulus of 1-2 plane
G_e	Shear modulus of epoxy
G_g	Shear modulus of glass fibre
σ	Stress
θ	Angle
$[\bar{Q}]$	Transformed stiffness matrix
$\nu_{hp/ax}$	Poisson ratio at hoop to axial plane
$\nu_{ax/hp}$	Poisson ratio at axial to hoop plane
E_{ax}	Modulus of elasticity at axial

E_{hp}	Modulus of elasticity at hoop
G_{xy}	Shear modulus
T_g	Glass transition temperature
M_t	Percent moisture at time
m_t	Original weight of the specimen prior to ageing
m_i	Weight of the specimen after ageing
$M_{\%}$	Percent moisture at time
M_{∞}	Percent moisture saturation
D	Diffusion coefficient
H	Specimen thickness
$M_2 - M_1$	Slope of the plot of moisture absorption rate during initial ageing
$\sqrt{t}_{2-}\sqrt{t}_1$	Linear portion of the curve
D_o	Outer diameter of GRE pipe
D_i	Inner diameter of GRE pipe
L_o	Original length of GRE pipe
τ_y	Shear yield stress
τ_{ult}	Shear ultimate stress
γ	Shear strain
G_{12}^e	Shear elastic in-plane modulus
G_{12}^p	Shear plastic in-plane modulus
σ_y	Yield stress
σ_{ult}	Ultimate stress
ε	Strain
E_{12}^e	Elastic in-plane modulus
E_{12}^p	Plastic in-plane modulus

Tingkah Laku Pemampatan Paip Gentian Kaca/ Epoksi: Kesan-kesan Sudut Belitan, Penuaan, dan Suhu

ABSTRAK

Kesan penuaan hidroterma ke atas tingkah laku proses pemampatan paip gentian kaca diperkukuhkan dengan epoksi (GRE) telah dibincangkan. Paip dengan tiga sudut belitan berbeza (±45 °, ±55 °, ±63 °) telah dihasilkan dengan menggunakan proses belitan filamen. Sebelum ujian mampatan, paip telah direndam untuk tujuan penuaan dalam air paip pada suhu malar 80 °C untuk tempoh 500, 1000, dan 1500 jam. Ujian kemampatan dijalankan ke atas sampel asal dan yang telah melalui penuaan menggunakan mesin ujian universal (UTM, Shimadzu) mengikut ASTM D695-10. Ujian juga dilakukan pada suhu antara suhu bilik (RT) hingga 45 °C, 65 °C, dan 95 °C untuk mengkaji tindak balas paip pada suhu tinggi. Suhu dipilih berdasarkan keputusan pengimbasan pembezaan kalorimeter (DSC) ujian, di mana nilai suhu peralihan kaca (T_g) didapati bernilai 66.39 °C. Imej imbasan mikroskop elektron (SEM) telah ditangkap dan hubungan antara tempoh penuaan dan kekuatan paip GRE ditentukan. Keputusan menunjukkan bahawa kekuatan paip GRE ketara berkurangan dengan peningkatan suhu di mana paip dimampatkan pada RT menghasilkan kekuatan tertinggi manakala yang terendah adalah pada 95 °C. Perkara yang sama boleh diperhatikan untuk tempoh penuaan di mana paip dara menunjukkan kekuatan mampatan yang paling tinggi dan kekuatan menurun apabila tempoh penuaan telah dilanjutkan. Kekuatan paip GRE meningkat apabila sudut belitan berkurangan. Sudut belitan ±45 ° mempunyai kekuatan tertinggi diikuti oleh ±55 °, dan akhir sekali ±63 °. Keputusan eksperimen juga dibandingkan dengan analisis teori yang diperolehi berdasarkan model Berbinau dan nilai eksperimen didapati berkorelasi dengan baik dengan nilai-nilai yang diramalkan.

Crushing Behaviour of Glass Fibre/Epoxy Composite Pipes: The Effects of Winding Angles, Ageing, and Temperatures

ABSTRACT

The effects of hydrothermal ageing on the crushing behaviour of glass fibre-reinforced epoxy (GRE) pipes are discussed. Pipes with three different winding angles (±45 °, ±55 °, ±63 °) were manufactured using the filament winding process. Prior to the compression tests, the pipes were hydrothermally aged in tap water at a constant temperature of 80 °C for periods of 500, 1000, and 1500 hours. Uniaxial compressive tests were conducted on the virgin and aged samples using a universal testing machine (UTM, Shimadzu) in accordance with ASTM D695-10. The tests were also performed at temperatures ranging from room temperature (RT) to 45 °C, 65 °C, and 95 °C to study the response of the pipes at elevated temperatures. The temperatures were selected based on the results of differential scanning calorimetry (DSC) tests, where the value of the glass transition temperature (T_g) was determined to be 66.39 °C. Scanning electron microscopy (SEM) images were captured and the relationship between the ageing period and strength of the GRE pipes was determined. The results indicate that the strength of the GRE pipes significantly decreases with increase in the temperature where pipes compressed at RT produced the highest strength while the lowest is at 95 °C. The same could be observed for ageing periods where virgin pipes shows the highest compressive strength and the strength degrades as the ageing period was extended. The strength of GRE pipes increases as the winding angles decrease. ±45 ° winding angle has the highest strength followed by ±55 °, and lastly ±63 °. The experimental results were also compared with theoretical analysis obtained from Berbinau's based model and the experimental values are found to correlate well with the predicted values.

CHAPTER 1

INTRODUCTION

1.1 Overview

This study was carried out to determine the effect of winding angles, different temperatures, and ageing on the crushing behaviour of glass fibre reinforced epoxy (GRE) pipes. The GRE pipes were manufactured through wet filament winding process for different angles of ±45 °, ±55 °, and ±63 °. The different winding angles were used to determine the effect of winding angles on the compressive behaviour of the pipes during uniaxial compression. Prior to compressions, the pipes also undergo accelerated ageing for a period of 500, 1000, and 1500 hours. An initial measurement of the weight, height, and diameter of the pipes were taken for further assessments. The pipes were immersed into tap water which was heated up to a constant temperature of 80 °C to test the ageing effect on the properties of the specimens.

Differential scanning calorimetry (DSC) tests were carried out to obtain the value of T_g, which is glass transition temperature to determine the range of temperatures that would be selected when compressing the pipes at different temperatures. T_g is the point where the material change from a rigid state to a more rubbery state. The value of T_g obtained was 66.39 °C and so the range of elevated temperatures chosen was from room temperature (RT) to 45 °C, 65 °C, and 95 °C where all of the temperatures were to be below T_g, at T_g, and above T_g respectively.

After ageing, the moisture absorption behaviour of the pipes were determined by weighing the pipes after each ageing periods and later applying Fickian's method. The GRE pipes then were compressed using Shimadzu universal testing machine (UTM) at a maximum load of 250 kN. Starting from RT, virgin pipes were compressed followed by pipes aged at 500, 1000, and 1500 hours. After the compression for specimens at RT had been achieved, a thermostatic chamber was installed into the UTM. The temperature was set to 45 °C and specimens from virgin to 1500 hours aged pipes were compressed and the process was repeated up to 95 °C.

Microscopic analysis of the crushed specimens were later determined using Scanning Electron Microscope (SEM). The effects of ageing and compressions were determine through analysis of the figures obtained through SEM. The study shows that higher winding angle exhibits a lower strength. For different temperatures and ageing periods, an increase in values of such parameters will cause the strength of the GRE pipes to degrade as a result of weakened fibre-matrix bond. Lastly, a mathematical model using Berbinau's based model equation was applied to determine the theoretical value of compressive strength of pipes under uniaxial compression. The theoretical values and experimental values were compared and the results showed that experimental values were higher compared to theoretical values but with an overall variation below than 25 %.

1.2 Problem Statements

Filament wound glass fibre reinforced epoxy (GRE) pipes are being increasingly used in a wide range of applications, especially in high pressure containers and long distance piping for oil and gas industries. Their proliferation used in the petrochemical and oil industries is due to their superior corrosion resistance and high strength to weight ratio. The use of GRE composite pipes has supplanted that of steel casings in many cases due to the former's relatively low cost. This has encouraged researchers to develop and carry out experimental and theoretical investigations in order to understand their mechanical and failure behaviour under a variety of load and under severe environmental conditions. One of the recent interest in study is the behaviour of such pipes under high compression loading in order to further understand the crushing failure. However, crushing failure of these cylinders is inherently complex. At present, there was a large uncertainty of understanding effect of end reinforcing layer and winding angle on crushing failure behaviour of these cylinders. There also have been little investigations looking at the compressive behaviour of the GRE pipes with respect to elevated temperature and moisture.

1.3 Research Objectives

(1) To investigate the crushing failure of glass fiber reinforced epoxy (GRE) composite pipes of various winding angles.

(2) To investigate the effects of elevated temperature and ageing on the crushing behaviour of GRE composite pipes.

(3) To model of compressive behaviour of GRE pipes and comparison with experimental findings.

1.4 Research Scope

(1) The GRE composites were fabricated using filament winding process.

(2) The GRE pipes used consist of three different winding angles (±45 °, ±55 °, ±63 °).

(3) The GRE pipes undergo accelerated ageing (500, 1000, 1500 hours) at a constant temperature of 80 °C.

(4) Different temperatures were used during uniaxial compression tests (RT, 45 °C, 65 °C, 95 °C).

(5) Microscopic analyses were conducted using SEM.

(6) Mathematical model is developed to describe the crushing behaviour.

1.5 Thesis Organization

Chapter 1 discussed the overview of the whole thesis. It also included the problem statement which explains the purpose of conducting this study. Next are the objectives where as a whole there are three objectives to be fulfilled and the scope explains the parameters and processes involved in this experiment.

Chapter 2 is mainly about previous studies done by published researches which are related in this study. The literature review provides a platform to further understand and guide to carry out the experiments and to analyze the data and findings.

Chapter 3 includes the methodology used in this study. A flowchart acts as a guideline for the study and an elaborate explanation on the processes involved in this study is further discussed in this chapter.

Chapter 4 is on results and discussions. The results obtained from the study were clearly presented and explained followed by the discussions of the results which includes the validation of the results from other past researches.

Lastly, in Chapter 5, the conclusion of the whole study was stated and further work that can be done in the future on the findings of the study was also discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Composites have been a subject of research for a variety of studies which involves both numerical modelling and also experimental observations (Mercier et al., 2008, Kara et al., 2013, Mortas et al., 2014 & Liang et al., 2015). The overall material properties such as elastic modulus, hygrothermal expansion coefficients, and diffusion coefficients are affected by the result of mechanical damage and chemical changes (Lundgren & Gudmundson, 1999). Composite materials are found to be able to absorb high energy, despite rather than plastic deformation, the failure mechanism was fracture at the surface (Mahdi et al., 2003). In the early stages of loading, the first form of damage in composite laminates is usually matrix cracks, which are intra-laminar cracks that transverse the thickness of the ply and run parallel to the fibers in that ply. Shearing stresses at the free edges which are the sites of stress concentration generally is what initiated delamination (Wharmby & Ellyin, 2002). When tensile load is applied in a different direction from fiber direction, this is when matrix cracking will happen (Sadeghi et al., 2014). Damage growth in composite laminates involve interaction between various damage modes on both microscopic and macroscopic scales which is proved to be a complex process. How the failure modes interact with each other is difficult to be determined when it involves variances in the geometry of the laminate plies (Wharmby & Ellyin, 2002).

2.2 Glass Fibre Reinforced Epoxy (GRE) Composite Pipe

Recently, glass fibre-reinforced epoxy (GRE) composite pipes have been extensively used in oil and gas industries for the underground transportation of fluid material, such as highly corrosive liquids, oil, water, and natural gas. GRE composite pipes are considered a cheaper alternative to steel pipes because they exhibit fewer problems due to corrosion (Rodriguez et al., 2013). They also show fatigue resistance, high specific strength and stiffness (Deniz & Karakuzu, 2012). In this current study, GRE pipes are used. The GRE pipes are fabricated by filament winding process where resin impregnation is caused by passing the fiber through a resin bath. The wet fiber is then applied to the wooden mandrel to form the filament wounded laminate (FWL) composite shells. After curing process and let to dry, the composite shells are then extracted from the wooden mandrel. The process is as illustrated in Figure 2.1 below.

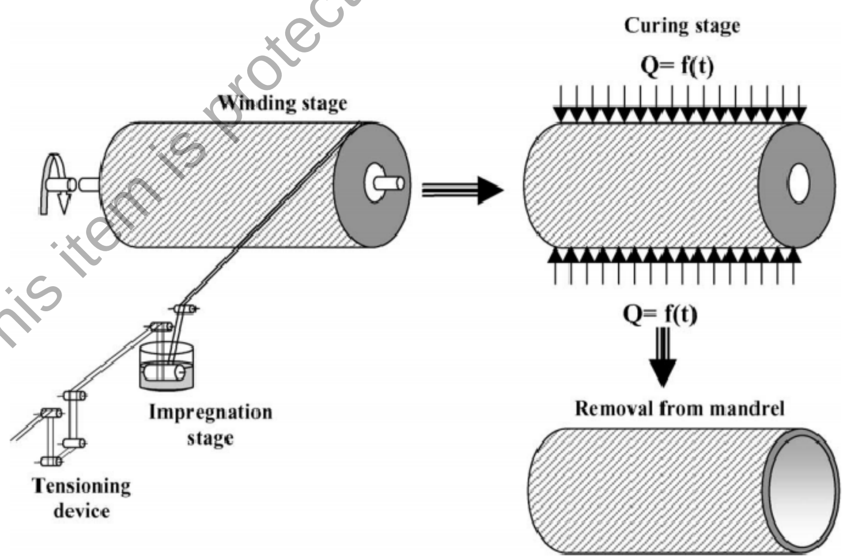

Figure 2.1: Schematic diagram for filament winding process (Mahdi, 1999).

2.3 Studies on Load Application on Composites

There are many methods used by researchers to study the behaviour of composites. Composites had been a topic of interest for their ability to substitute metal. One of the studies involving transverse cracking on GRE pipes was conducted by Hoover et al. (1997) which discussed the transverse cracking of symmetric and unsymmetric glass fiber/epoxy-resin laminates which was investigated experimentally. During a fixed-stress hold-time period when load-controlled tests were carried out, transverse crack initiated but correlated well with measured strain. By increasing the duration of the fixed-strain hold-time period, the number of transverse cracks was not reduced as showed by the displacement-controlled tests.

Three stages of stiffness reduction were observed in three stages which are initial, intermediate, and final. As observed in accordance to the stages, in the initial stage, stiffness losses were observed prior to transverse cracking. While the stiffness reduction was linear with respect to the number of transverse crack in the intermediate range and finally a reduction in stiffness due to delamination and fiber breakage was observed in the final stage. When the laminate was subjected to a fixed load, the cracks will accumulate over time and the strain will also increase as shown by the load controlled tests.

Xia et al. (2000) conducted a study to predict the overall mechanical behaviour and damage mechanisms in fiber-reinforced polimer laminates of a $[0, 90_3, 0]_T$ glass-fiber/epoxy laminate by developing a three-dimensional multi-cell meso/micro-mechanical finite-element model. A damage criterion which includes these types of failure modes which are matrix cracking, fiber-matrix interface debonding, delamination, and fiber rupture was introduced into the finite element model. Since the matrix has the lowest stress to failure of all the composite constituents, the first damage process to take place is usually matrix cracking. Matrix cracks between plies that appear near the final failure stage in certain types of laminates are called delamination. But as observed, the onset of delamination is higher than matrix cracking so the dominant mode is the matrix transverse cracking for this laminate structure. In the study, it can be observed that the maximum local principal strain in the epoxy matric has almost reached 3 % which is the failure threshold value when the applied global strain is about 0.6 % which means that the matrix will crack if there is further increase in loading.

Another study was carried out by Mahdi et al. (2003) on how hybridization affects the energy absorption, crushing behaviour, and failure mechanism and mode for composite cylinders. Five types of composites were tested which are carbon fiber/epoxy, glass fiber/epoxy, carbon-glass-glass (CGG)/epoxy, glass-carbon-glass (GCG)/epoxy, glass-glass-carbon (GGC)/epoxy. The failure modes observed are highly affected by hybridization. The test was done using an Instron 8500 digital-testing machine with a full-scale load range of 250 kN.

From the study, the load-displacement curve shows that up to the initial failure stage, the curve shows a linear relationship. The load then falls sharply after that, where at the two end parts of the cylinders, a micro-fragmentation was observed. The load fluctuates constantly with sharp peaks and troughs increasing with displacement after the first reduction of load. Material condensation process takes place after that and the load rises sharply to the final crushed stage. The load displacement curve is illustrated as in Figure 2.2.

Interlaminar cracks propagating between the layers in the crushed zone forming lamina bundles dominated the crushing process of filament winding of glass/carbon hybrid composite circular-cylindrical shell. When the volume of the lamina bundles reaches a critical value, the lamina bundles resists the applied loads and fall down. The transverse crack causes the load to drop sharply because the failure zone acts as a low modulus zone. As a result of the study, compared to other types of cylinders tested, GCG displays a higher compressive load as the interface of this reinforcement sequence is more adequate as in Figure 2.2.

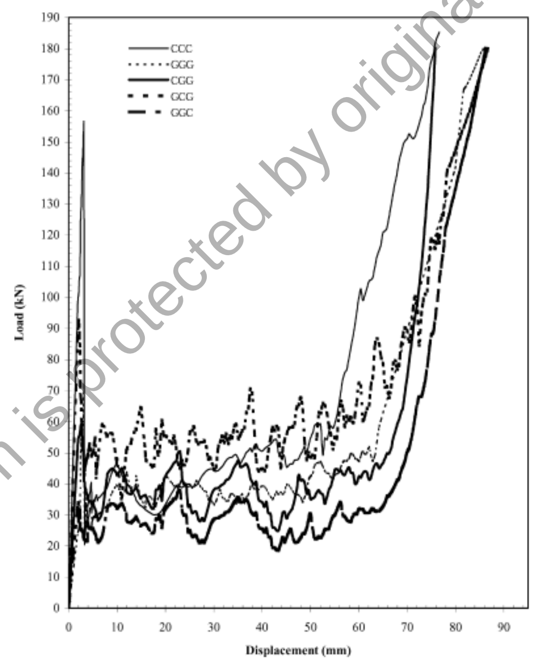

Figure 2.2: Load-displacement curve for the FWL carbon/glass hybrid circular-cylinder shell (Mahdi, 2003).

Abdewi et al. (2008) investigated how the corrugation geometry affects the woven roving glass fiber/epoxy laminated composite tube in terms of failure mode, energy absorption, failure mechanism, and also the crushing behaviour. From their