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DAMAGE DETECTION AND CHARACTERIZATION IN C-GLASS AND E-GLASS FIBRE-REINFORCED POLYMER DUE TO LOW AND HIGH VELOCITY IMPACT EVENTS

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By

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

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November 2014

Chair: Mohamed Thariq Bin Hameed Sultan, PhD

Faculty: Engineering

This thesis presents low velocity impact testing and high velocity impact testing on fibreglass reinforced polymer. The materials used in this experiment are Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m². The ultimate objective of this research is to conduct an experimental investigation using low velocity impact testing and high velocity impact testing to detect and quantify impact damage for Glass Fibre Reinforced Polymer Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² plate. The purpose of this research is to choose the best material for structural application by comparing the mechanical properties and damage characteristics of GFRP Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m².

The experimental results of low-energy drop-weight impact tests on woven-roving Glass Fibre Reinforced Polymer (GFRP) type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² are presented. The effects of specimen thickness based on the number of plies and impact energy are investigated. Impact damage and response was observed for eight levels of impact energies, 6, 12, 18, 24, 30, 36, 42 and 48 J. From the experimental studies, it can be concluded that for each type of GFRP, the impact energy showed excellent correlation with the impact response. The difference in the number of plies fabricated and the mechanical properties for both types of GFRP do affect the impact response and impact damage of the specimens tested.

The experimental results of the high velocity impact test using a Single Stage Gas Gun (SSGG) show that both types of GFRP exhibit damage in terms of fibre cracking, and fibre pull out after being tested with four different gas gun pressures. Before fibre failure occurs, they undergo matrix cracking and delamination processes first. As the gas gun pressure increases, the initial velocity of the projectile increases, the projectile kinetic energy increases, the maximum force exerted on the specimen increases, and the energy absorbed by the specimen also increases. Most of the impacted specimens show that GFRP type E-glass/Epoxy 800 g/m² experienced a smaller damage area compared to type C-glass/Epoxy 600 g/m². From the test, the effect of the shape of the projectile, the target thickness and the gas gun pressure affected the performance of GFRP.

It can be concluded that GFRP type E-glass/Epoxy 800 g/m² is stronger compared to GFRP type C-glass/Epoxy 600 g/m² since it has more fibre volume since it is higher in density and has good mechanical properties. Therefore, GFRP type E-glass/Epoxy 800 g/m² is recommended to be used in structural applications.

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

PENGESANAN DAN PENCIRIAN KEROSAKAN DALAM POLIMER BERTETULANG GENTIAN KACA C DAN E AKIBAT PERISTIWA KELAJUAN RENDAH DAN TINGGI

Oleh

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Tesis ini membentangkan ujian kesan halaju rendah dan ujian kesan halaju tinggi ke atas gentian kaca polimer bertetulang. Bahan-bahan yang digunakan dalam eksperimen ini adalah Jenis C-kaca/epoksi 600 g/m² dan Jenis E-kaca/epoksi 800 g/m². Objektif utama kajian ini adalah untuk menjalankan siasatan ujikaji menggunakan ujian kesan halaju rendah dan ujian kesan halaju tinggi untuk mengesan dan menentukan kuantiti kerosakan kesan untuk gentian kaca polimer bertetulang Jenis C-kaca/epoksi 600 g/m² dan Jenis E-kaca/epoksi 800 g/m². Tujuan kajian ini adalah untuk memilih bahan terbaik untuk aplikasi struktur dengan membandingkan sifat-sifat dan ciri-ciri mekanikal kerosakan Jenis C-kaca/epoksi 600 g/m² dan Jenis E-kaca/epoksi 800 g/m² .

Bagi ujian halaju kelajuan rendah, keputusan eksperimen menunjukkan kesan ketebalan specimen berdasarkan bilangan helai dan tenaga kesan terhadap Polimer Bertetulang Gentian Kaca (GFRP) jenis C-kaca/epoksi 600 g/m² dan Jenis E-kaca/epoksi 800 g/m² dibentangkan. Lapan tahap tenaga kesan, 6, 12, 18, 24, 30, 36, 42 dan 48 J digunakan untuk melihat tindak balas bahan dan impak kerosakan. Dari kajian eksperimen, ia boleh disimpulkan bahawa bagi setiap jenis GFRP, tenaga kesan menunjukkan korelasi yang baik dengan kesan tindak balas. Perbezaan bilangan helai fabrikasi dan sifat-sifat mekanikal untuk kedua-dua jenis GFRP memberi kesan kepada impak dan kesan kerosakan daripada spesimen yang diuji.

Keputusan eksperimen daripada ujian halaju tinggi menggunakan senapang gas termampat menunjukkan bahawa kedua-dua jenis polimer bertetulang gentian kaca mengalami kerosakan pameran dari segi keretakan serat, dan penarikan serat selepas diuji dengan empat tekanan gas yang berbeza. Sebelum kegagalan serat berlaku, mereka menjalani keretakan matriks dan proses delaminasi terlebih dahulu. Akibat daripada penambahan tekanan gas senapang, halaju awal peluru akan bertambah, tenaga kinetic peluru bertambah, daya maksimum dikenakan ke atas spesimen, dan tenaga yang diserap oleh spesimen juga meningkat. Kebanyakan spesimen menunjukkan bahawa jenis GFRP E-kaca/epoksi 800 g/m² mengalami kerosakan yang lebih kecil berbanding dengan jenis C-kaca/epoksi 600 g/m². Berdasarkan ujian,

kesan bentuk peluru, ketebalan sasaran dan tekanan senapang gas menjejaskan prestasi GFRP.

Ia boleh disimpulkan bahawa jenis GFRP E-kaca/epoksi 800 g/m² lebih kuat berbanding dengan jenis GFRP C-kaca/epoksi 600 g/m² kerana ia mempunyai isipadu yang lebih serat, lebih tinggi kepadatan dan mempunyai sifat mekanik yang lebih baik. Oleh itu, GFRP Jenis E-kaca/epoksi 800 g/m² adalah disyorkan untuk digunakan dalam aplikasi struktur.

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This thesis was submitted to the Senate of Universiti Putra and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

LVI	Low velocity impact
GFRP	Glass Fibre Reinforced Polymer
BSS	Boeing Specification Support
ASTM	American Society for Testing and Materials
ASME	American Society of Mechanical Engineers
IATA	International Air Transport Association
UV	Ultraviolet
VID	Visible impact damage
BVID	Barely visible impact damage
AE	Absorbed energy
E_o	Maximum energy
F	Force
J	Joule
N	Newton
mm	Millimetre
m/s	Metre per second
ms	Millisecond
t	Time
m	Mass
g	Gravitational acceleration

CHAPTER 1

INTRODUCTION

1.1 Overview

A composite material is a combination of two or more materials and it creates a new material with a unique combination of properties. Normally, composite material is formed by reinforcing fibres in a matrix resin as shown in Figure 1. The strength and stiffness of the composites is provided by the reinforcing fibre or fabric, while the rigidity and environmental resistance of the composite is provided by the matrix.

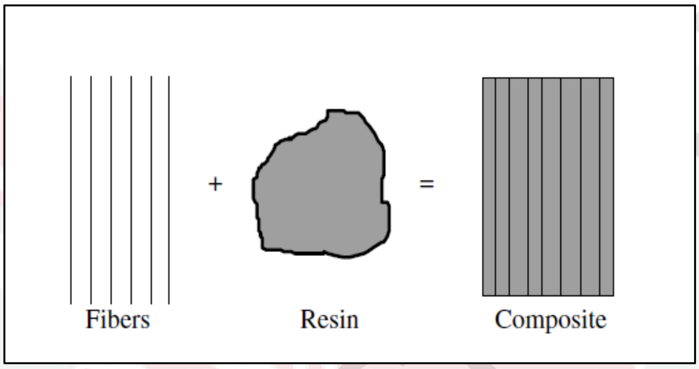

Figure 1: Formation of composite material using fibres and resin (Mazumdar, 2002).

Composites made with a polymer matrix have become more common and are widely used in various industries. In the mid-1960s and early-1970s, composites started to be developed in the aircraft industry. The military were the initial inventors and users of composites where the high performance composites were applied on the empennages of the F-14 and F-15 fighter aircraft. The F-15 fighter aircraft used Boron/epoxy for the horizontal stabilisers, rudders and vertical fins. In the mid-1970s, the fighter aircraft F-15 used carbon/epoxy for the speed brake (Campbell, 2006). In the past few decades, the use of composites in structural applications, especially in the aerospace industry has been increasing as shown in Figure 2.

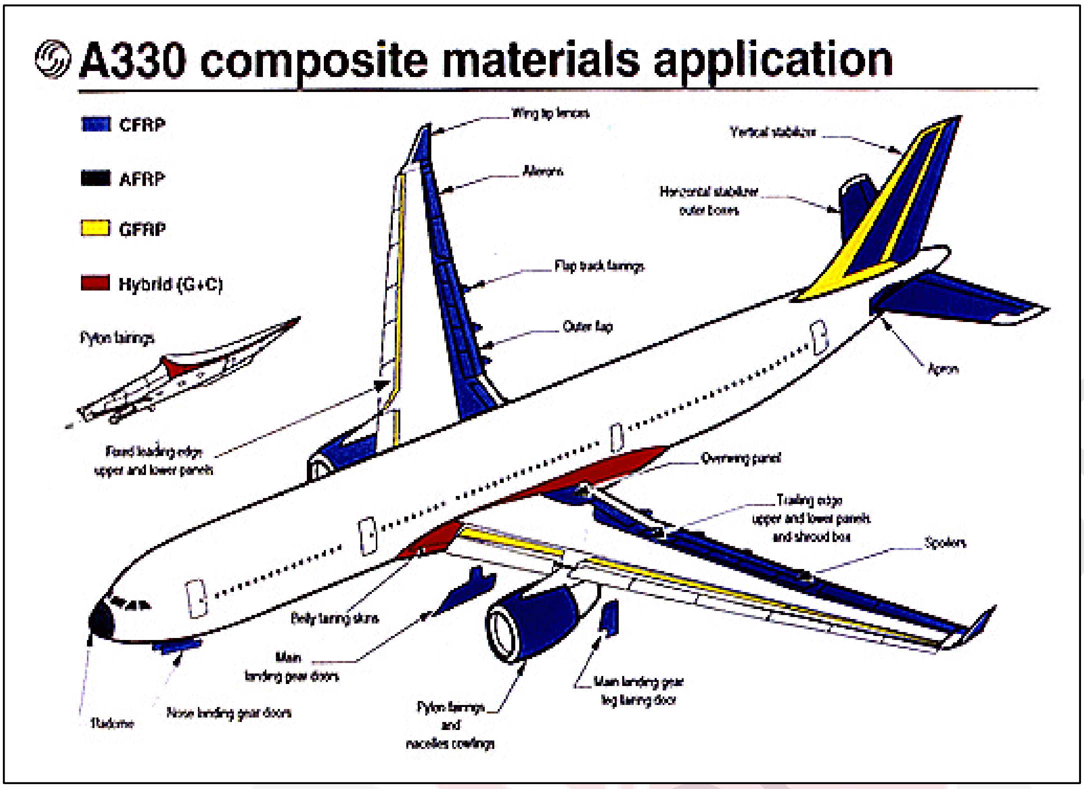

Figure 2: Typical composite structures used in A330 commercial aircraft (Crown, 2003).

The manufacturers have used various techniques to improve the impact resistance and damage tolerance characteristics of fibre composites. The advantages of composite materials are that they can have the best qualities of their original material and often some qualities that neither element possesses. Some of the properties that can be improved by forming a composite material are as shown in Figure 3.

Strength	Weight	Stiffness	Wear resistance
Corrosion resistance	Fatigue life	Thermal conductivity	Acoustical insulation

Figure 3: Properties that can be improved after producing a composite (Jones, 1998)

Composites are used not only for their mechanical properties, which are best for the applications that need good weight to strength ratio, but also for electrical, thermal, tribological and environmental applications (Vijaykumar, 2014). The application of composite materials has become increasingly popular, especially in aerospace structures.

The advantages of using composites in aircraft structures are; weight reduction, high corrosion resistance and high resistance to damage from fatigue. These factors play a role in reducing the operating costs of the aircraft in the long term, further improving its efficiency. Lately composites have been used in beam-type structures under high loading rates, such as the drive shafts in vehicles, the rotor blades of helicopters, the intake fan blades of jet engines and the entire composite wing of a spacecraft (Chatelet, Lornage, & Jacquet-Richardet, 2002).

In structural industry however, corrosion is one of the biggest problems experienced. As an example, in the marine industry, they start to use composites in boats or ships structure since composites do not corrode like metals. This advantage of composites is also chosen for roads and bridges, since roads and bridges are easily corroded. Composites offer a longer life span with less maintenance due to their corrosion resistance (Campbell, 2006). Figure 4 shows the composite designs in infrastructural applications.

Figure 4: Fibres-reinforced composites for infrastructural parts (Park & Seo, 2011).

Glass Fibre Reinforced Polymer (GFRP) is a type of polymer matrix composite (PMC) that has been widely used throughout the structure of large civil aircraft due to its high specific strength, stiffness and good fatigue resistance. It is the most economical choice depending on the cost of the material, the production cost, the life cycle cost, and the material's properties. In recent years, there has been an increasing demand to reduce the weight of the armour structures used in various applications such as tanks and helicopters. This weight reduction results in improved mobility, improved fuel efficiency and the transportability of the armoured vehicle. Glass Fibre Reinforced Polymer (GFRP) is light weight with the ability to resist heavy loads and supply excellent resistance to impact.

However, laminated composite, as example, aircraft components are at risk of impact from runway debris, hail and birds. This research studies the structural integrity of Glass Fibre Reinforced Polymer (GFRP) structures under low and high velocity impacts. Impact damage is an important issue for composites because composites are brittle. Composites only absorb energy in elastic deformation and damage mechanisms. The term damage resistance denotes the sum of the impact damage which is induced in a composite structure (Agrawal, Singh, & Sarkar, 2014).

Impact behaviours and impact damage depend on many parameters such as the projectile/impactor shape, impact velocity and energy, boundary conditions and lay-up sequence (Chib, 2006). Furthermore, laminated fibre reinforced composite materials have various damage modes such as fibre breakage, matrix cracking, and delamination. These various damage modes appear together under the impact loading (Kim, Rim, Lee, & Hwang, 2013).

GFRP has many important properties which make it suitable to be widely used in any structural applications. More on the structural application for GFRP are discussed in chapter 2. Therefore, this research is intended to determine the performance of GFRP under low velocity impact and high velocity impact loading since structures are always at risk of experiencing these events.

1.2 Problem Statements

A question that is naturally raised is how to improve the survivability of structures regarding low and high velocity impacts. Since structural failure is caused primarily by fracture, a fundamental understanding of the mechanisms and mechanics of the material is one of the most important steps needed to solve the problem. In a high velocity impact, fracture often occurs in an impacted zone where compression is dominant. For a low velocity impact, invisible cracks often occur, but they cannot be seen using the naked eye. It is important to understand the deformation and damage mechanisms involved in the impact of targets, for the effective design of composite structures.

There are a lot of Glass Fibre Reinforced Polymer (GFRP) types based on their special characteristics. Glass Fibre Reinforced Polymer (GFRP) type E is mostly used to reinforce composite structures compared to others. Glass Fibre Reinforced Polymer (GFRP) type E and Glass Fibre Reinforced Polymer (GFRP) type C are similar, but each are designed to serve to their advantage in specific end user. However, Glass Fibre Reinforced Polymer (GFRP) type C has high corrosion resistance in acidic environment and type E is useful when strength and high electrical resistivity is needed (Richerson, 1997).

The ultimate objective of this research is to conduct an experimental investigation using low velocity impact testing and high velocity impact testing to detect and quantify impact damage for Glass Fibre Reinforced Polymer Type C-glass/Epoxy 600 g/m^2 and Type E-glass/Epoxy 800 g/m^2 plate. Therefore, the purpose of this research is to choose the best material for structural application by comparing the mechanical properties and damage characteristics of GFRP Type C-glass/Epoxy 600 g/m^2 and Type E-glass/Epoxy 800 g/m^2.

Previous researches have usually involved experiments on the impact parameter effects that may affect the impact test result. Very limited researches have been carried out in comparing these two types of materials. It is important to understand the differences in impact response between Glass Fibre Reinforced Polymer (GFRP) Type C-glass/Epoxy 600 g/m^2 and Type E-glass/Epoxy 800 g/m^2 since both of these materials are rarely used in structural application even though it is the best choice for weight to strength application.

Therefore, this thesis is intended to compare the impact response of Glass Fibre Reinforced Polymer (GFRP) Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² using two different types of impact test, which are low velocity impact testing and high velocity impact testing.

For the high velocity impact test, Glass Fibre Reinforced Polymer Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² plates were tested using a single stage gas gun (SSGG) with varying gas gun pressures, different projectile shapes and different target specimen thicknesses. For the low velocity impact test, Glass Fibre Reinforced Polymer Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² plates were tested using the drop weight impact test, where the impact energy and the specimen thickness are varied. These tests will produce results that will show the impact performance for both materials.

1.3 Research Aim and Objectives

The present research aims to conduct an experimental investigation on two types of Glass Fibre Reinforced Polymer (GFRP) Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² using low velocity impact testing and high velocity impact testing.

The study is divided into three objectives. The objectives in this work are:

i. To fabricate low velocity impact test specimens using a traditional hand lay-up techniques and to manufacture high velocity impact test specimens with the aid of a hot bonder machine and vacuum bagging.

ii. To investigate the effect of the number of layers on the impact characteristics and failure modes of Glass Fibre Reinforced Polymer (GFRP) Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² at different impact energy levels using a drop weight tester and non-destructive testing.

iii. To investigate the effect of specimen's thickness, the type of projectiles and the impact velocity on the impact characteristics and failure modes of Glass Fibre Reinforced Polymer (GFRP) Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m² using a single stage gas gun (SSGG) and non-destructive testing.

1.4 Structure of the Thesis

This thesis consists of six chapters, which can be described as follows:

i. Chapter 1 presents an overview of the whole thesis including the problem statement and the research objectives for the whole research and the contribution from this research.

ii. Chapter 2 presents a critical literature review on composite material, especially Glass Fibre Reinforced Polymer (GFRP), an overview on low velocity impact testing and high velocity impact testing, and damage identification using structural health monitoring.

iii. Chapter 3 describes the procedure for fabricating impact test specimens and the experimental work performed using low velocity and high velocity impact test rigs. This chapter also explains in detail the damage detection method use to examine the failure mode for the impacted test specimen.

iv. Chapter 4 presents and discusses the low velocity impact test results for Glass Fibre Reinforced Polymer (GFRP) Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m². Critical analysis and damage analysis of the impacted specimen is also presented in this chapter.

v. Chapter 5 presents the high velocity impact test results for Glass Fibre Reinforced Polymer (GFRP) Type C-glass/Epoxy 600 g/m² and Type E-glass/Epoxy 800 g/m². This chapter also discusses and analyses impact specimens using the damage detection method.

vi. Chapter 6 presents the research conclusions, summarises the major results, and gives suggestions for future work.

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