ENERGY ABSORPTION PERFORMANCE OF BRAIDED BASALT
REINFORCED COMPOSITE TUBES UNDER AXIAL LOADS

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Specially dedicated to both of *Ayah*, *Mama*, and *Emak*, as well as beloved wife, and children for supporting my entire PhD study

May Allah bless all of you

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ABSTRACT

The thin-walled composite tube is recognised as a potential replacement for thin-walled metal tubes in light-weight structures. In higher load-bearing structures, thick-walled composite tubes have more advantages compared to thin-walled composite tubes. However, thick-walled composite tubes use more material, thus resulting in additional weight to the structure. Therefore, a decent design of fibre reinforced sandwich composite tube with polymer foam-core could have a higher potential to provide both demands of high energy absorption capacity as well as light-weighting structure. Due to the recent environmental awareness, natural basalt fibre has been getting more demand and interest from preform manufacturers. Hence, the aim of this research is devoted to the investigation of energy absorption performance of novel and eco-friendly braided basalt composite tubes associated with axial crushing loadings. A series of thin-walled and sandwich composite tubes were fabricated using braided basalt/epoxy composite and expanded polyurethane foam. The axial crushing tests of these tubes under quasi-static and impact loads were carried out. A numerical model of sandwich tube with the highest energy absorption capability obtained experimentally was developed and validated with the experimental result. The main finding shows that sandwich tubes have better crushing control than thin-walled tubes under a dynamic impact loading. The result implies that there is an approximately 30% drop in value of crush force efficiency of thin-walled tubes under quasi-static compared to dynamic crushing, while sandwich tubes have sustained values. The experimental result also reveals that the basalt composite tube with a ±45º braid angle has the highest crushing performance compared to other braid orientations. The numerical model of sandwich tube (±45º/core/±45º) was validated with experimental result in accordance to the scopes and parameters used in this study.

ABSTRAK

Tiub komposit berdinding nipis merupakan salah satu struktur ringan yang berpotensi tinggi bagi menggantikan struktur tiub logam berdinding nipis. Manakala, struktur tiub komposit berdinding tebal mempunyai kelebihan yang lebih banyak dalam menahan bebanan yang besar berbanding tiub komposit berdinding nipis. Namun, tiub komposit berdinding tebal menggunakan bahan yang lebih banyak menyebabkan pertambahan berat kepada struktur binaan tersebut. Oleh itu, reka bentuk komposit susunan serat diperkuatkan dengan teras busa polimer berbentuk sandwic mempunyai kedua-dua potensi menyerap tenaga yang tinggi dan struktur yang ringan. Kesedaran tentang alam sekitar masa kini menyebabkan serat semulajadi basalt mendapat permintaan yang tinggi dalam kalangan pengeluar bahan prabentuk. Maka, tujuan kajian ini dijalankan adalah untuk menyelidiki prestasi penyerapan tenaga melalui pembebanan penghancuran berpaksi terhadap tiub komposit yang diperbuat daripada jalinan basalt yang mesra alam. Satu siri tiub berdinding nipis dari komposit sandwic telah dihasilkan menggunakan teknik campuran jalinan tiub komposit basalt/epoksi bersama busa polyurethane terkembang. Model berangka tiub sandwic dengan keupayaan penyerapan tenaga tertinggi diperolehi secara eksperimen telah dibangunkan dan ditentusahkan dengan hasil eksperimen. Hasil penemuan utama menunjukkan bahawa tiub sandwic mempunyai kawalan penghancuran yang lebih baik berbanding dengan tiub berdinding nipis di bawah beban impak dinamik. Hasilnya menunjukkan bahawa terdapat kira-kira 30% penurunan nilai kecekapan daya penghancuran tiub berdinding nipis di bawah ujian kuasi-statik berbanding dengan ujian dinamik. Manakala, tiub sandwic mengekalkan nilainya dalam kedua-dua ujian tersebut. Keputusan ujian juga membuktikan bahawa tiub komposit basalt dengan sudut jalinan sebesar ±45º memperoleh prestasi penghancuran tertinggi berbanding sudut jalinan bagi tiub yang lain. Model berangka tiub sandwic (±45º/core/±45º) telah ditentusahkan dengan keputusan eksperimen selaras dengan skop dan parameter yang digunakan dalam kajian ini.

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LIST OF ABBREVIATION

ASTM	- American Society for Testing and Materials
CDM	- Continuous damage mechanics
CFE	- Crush force efficiency
EPU	- Expanded polyurethane
FE	- Finite element
FRP	- Fibre reinforced polymer
F_{avg}	- Average load
F_{max}	- Peak load
GFRP	- Glass fibre reinforced polymer
PE	- Polypropylene
PP	- Polyethylene
PU	- Polyurethane
PVC	- Polyvinylchloride
PFM	- Progressive failure model
SEA	- Specific energy absorption
3D	- 3-dimensional

LIST OF SYMBOLS

A	- Area
D	- Diameter
E	- Modulus of elasticity
F	- Load
h	- Height
m	- Mass
R	- Radius
t	- Thickness
V	- Volume
w	- Weight
θ	- Braid angle
ρ	- Density
σ	- Strength, stress
τ	- Shear strength
ε	- Strain
υ	- Poisson ratio

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CHAPTER 1

INTRODUCTION

1.1 Background and Motivations

Major changes of structural materials have been implemented in the high technology development of future vehicles. One of the reasons is the demand for a light-weighting vehicle that might consume less fuel and faster movement. As an example, in the automotive industry, Lotus started composite cars longer than any other car manufacturer, with Lotus Elite in 1957. Meanwhile, Aston Martin launched its carbon fibre body named Vanquish V12, which weighed not more than 2 tonnes. A report claimed that the assembly's weight is only 22.5 kg yet it can absorb a maximum of 140 kJ of energy in a 16 ms^{-1} impact [1]. On the other hand, a recent event by Composites UK has set out the new composite material to their rail industry, High Speed 2. The automotive pioneer industries, Voith [2] launched their new energy absorber that used glass fibre reinforced plastic (GFRP) composite in their new Galea vehicle on the head-front of the crash energy systems, as illustrated in Figure 1.1.

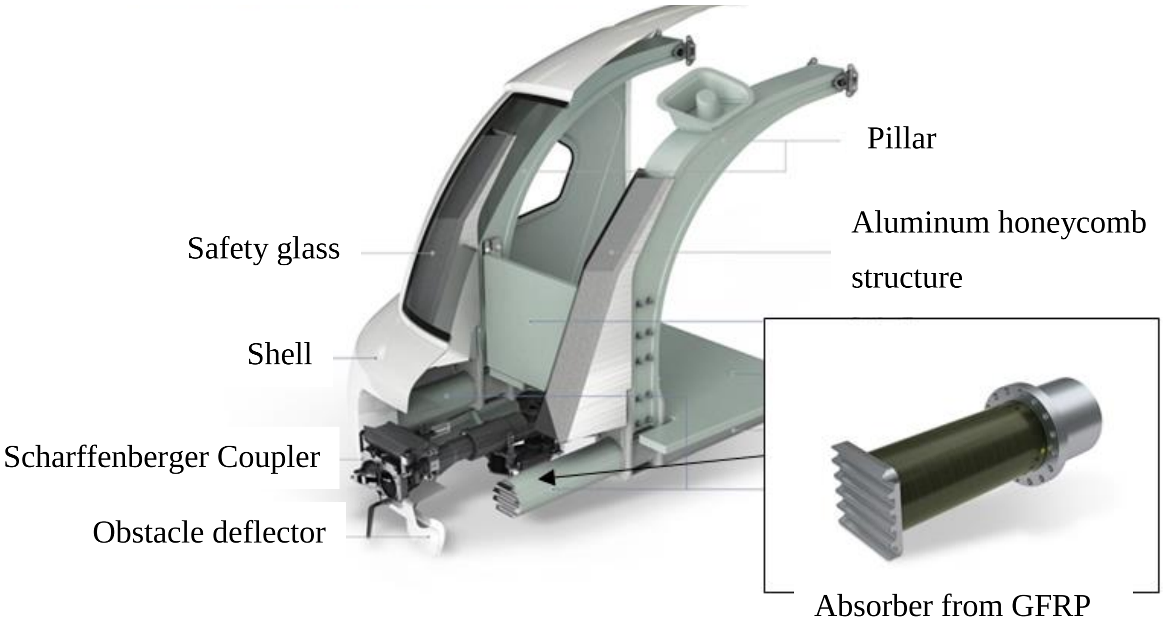

Figure 1.1: Voith Turbo's in new Galea vehicle head and front end systems [2]

With an increase in public and personal transportation, more safety concerns have been highlighted by vehicle manufacturers. As there are trends toward the use of composite materials in vehicle components, manufacturers must ensure that composite structures are capable of absorbing impact during an accident. Vehicle collisions can be classified into frontal, side, rear, and rollover crashes. The frontal crash is the most unsafe impact situation, and the front structure is the most exposed to absorb the crash kinetic energy and prevent intrusion into the occupant compartment. Therefore, it is crucial for the design of the frontal structure of vehicles to have a stable and controllable energy dissipation [3].

The most important goal in designing light-weighting crashworthy structures is to absorb maximum energy with minimum mass. Thin-walled tubes are being widely explored and used as energy-absorbing members in many fields due to their high strength-to-weight ratio, good energy absorption performance, and capability of controlling crush progression. Thus, the thin-walled cylindrical structure has been extensively studied by numerous researchers [4–6]. An energy-absorbing structure under crush demonstrated various interaction effects, for example nonlinearity of geometry, strain-hardening influences, and rate sensitivity effect are tangled with each other and associated to plastic deformation and failure mechanism in crushing history [7–10]. The ductility of metals can absorb the impact energy by buckling and deforming. However, most of the composites are brittle, reinforced by relatively strong fibres surrounded with a weaker matrix and some of them are relatively infused with ductile matrix. A fibre reinforced polymer (FRP) composite absorbs impact crash energy principally by debonding or delaminating at the fibre-matrix interface, crushing into fragments and creating large amounts of new surface area. Thus, a successful composite design can accomplish impact energy absorptions much greater than metals.

Practically, due to the higher load bearing and impact resistance applications, thin-walled tubular structures filled with polymer foams have garnered attention among researchers and high-end industries such as automotive and aircraft. Compared to thin-walled composite tubes, the foam-filled thin-walled tube offers higher local flexural stiffness and impact energy absorption efficiency. However, without proper design, the foam-filled composite tube encounters a low specific energy absorption problem. For many years, sandwich structures have recognised applications in the aerospace and automotive industries. A sandwich panel typically consists of two thin skins, stiff FRP composite facings detached by a light-weight polymer foam-core. The structure is proven to provide extremely efficient light-weighting structures. Many studies conducted in collapsible sandwich structure through the years were subjected to wide range loadings such as those associated with quasi-static [11–15], impact [5,16,17], and blast loadings [18,19]. Only a few of those works reported that FRP composite plays an important role as skins in a sandwich structure for a crashing performance [14,15,19]. A good design of a sandwich structure probably could improve the specific energy absorption capacity better than having a thin-walled structure.

Continuous improvement from the production technology has improved the fibre tailoring process in composite tube manufacturing. Several of the textiles preform techniques, for example filament winding, unidirectional and braiding, are often adopted in orienting the fibrous yarn for the cylindrical composite fabrications. From those techniques, braiding is the most cost effective and well-performance among them [20–22]. Braided composite particularly offers many advantages such as excellent impact resistance and high interlaminar shear strength due to their locking mechanism and continuously oriented to any kind of shape. Owing to their good impact resistance and interlaminar shear properties, braided composites have been continuously explored by researchers around the world as one of the good potential candidates for energy absorber devices. Previous studies [23–27] indicated that the crushing performance of energy absorber made with braided composite significantly depends on its fibre/matrix material properties, fabrication conditions, braid angle and dimensions of the structural components.

To date, considerable interest in environmental issues has encouraged the amount of literature focusing on the use of natural fibres in composite reinforcing polymer [28,29]. Most kinds of plant fibres such as flax, sisal and kenaf have been studied and used. Unfortunately, those fibres are very delicate to thermal and hygroscopic load. Moreover, it shows imperfect mechanical properties due to the fibre removal system, the difficulty in fibre placement, low interfacial strength and the non-homogenous fibre dimensional. Fortunately, one type of mineral natural fibre known as basalt has been successfully made with continuous filament yarn type which is available in the market nowadays. The basalt fibre has many advantages such as high modulus and strength, high temperature resistance, good chemical resistance, non-toxic, eco-friendly and inexpensive. The density of the basalt fibre is the same as that of the glass fibre, but the specific modulus and strength of the basalt fibre are higher than general glass fibre.

Several important views and advantages had been addressed on the usage of thin-walled FRP composite associated with crashing performance. Even though the sandwich tube structure is highly potential in a high load-bearing capacity, the quantification studies of the usage of natural FRP composite as sandwich skins are less in numbers. There is a shortfall on a well-established composite of basalt material which is important to be known for critical applications as an alternative material to synthetic glass fibre. Therefore, the motivation of the current research is to establish a novel braided basalt reinforced polymer sandwich composite tube with expanded polyurethane (EPU) foam-core for energy-absorbing applications throughout the axial crushing experiments and simulation.

1.2 Problem Statements

In the past reports, thin-walled metal tubes have been highlighted for its crushing performance [30,31]. However, the new era of transportation technology is demanding light-weighting body parts, and new material with comparable or higher strength is needed. Thus, new material fibre reinforced polymer (FRP) composite had been extensively studied for their capabilities. The energy-absorbing structures are expected to absorb the maximum crash energy with minimum unit of weight. A few research groups claimed the energy absorption of a well-designed thin-walled FRP composite achieved better than metals [8–10]. The ideal phenomena would be the composite structure being fragmented into small pieces where the crush happens, yet everything else is still intact [32]. Consequently, some researchers attempted to increase the energy absorption capacity by increasing the thickness of the tube wall [32,33]. As a result, a thick-walled tube consumes higher local stiffness but gives significant additional weight to the structure. Meanwhile, cellular materials such as polymer foams exhibited superior performance for absorbing impact energy as they can withstand large deformation at nearly a constant load. However, the strength of polymer foam itself is low, thus the quantity of energy absorption is very restricted. Although polymer foams are not recommended to use unaided for an energy-absorbing unit, they can be taken as a filler material in thin-walled structures.

By introducing either a thick-walled, or thin-walled with foam filler in a composite tube, the energy absorption capacity is eventually increased. However, the specific weight unit of the energy absorption response is unknown but important to be discovered. Palanivelu *et al.* [34] has reported that the usage of polyurethane foam increased thin-walled tube strengthening and steadiness for progressive crushing; but the usage of foams has reduced the specific energy absorption capacity. A report claimed that foams with higher density has higher compression strength, contrarily the range of the plateau relative density is reduced [35]. Thus, the choice of suitable foam parameters and thin-walled tube walls are vital for energy-absorbing structure.

Besides that, the capability of a braided composite as an energy absorber unit is significantly dependent on their materials and properties, fabrication conditions, and geometry and dimensions of the structural components [23,26,27]. Each of the fibre materials have different strain sensitivity rates at higher impact energy. Even with the same fibre tow direction, early prediction on their energy-absorbing behaviour could be misled. Therefore, the role of a braided FRP composite tube as the backbone of a sandwich skin structure is still much unknown and yet to be discovered especially on the usage of natural fibre reinforcement. Hence, the braided parametric studies on sandwich skins structure is crucial to the new contribution of knowledge.

Subsequently, due to the life cycle of a synthetic fibre reflecting to the ecological issues, in the last couple of decades natural fibres have come into consideration in reducing the dependency of synthetic fibres for high-end composite applications. Natural fibres have been grouped in three which are plant, animal, and mineral. Natural plant fibres such as flax, kenaf, coir, or sisal have lighter weight as compared to natural mineral fibres. However, plant fibres are susceptible to thermal and hygroscopic load, besides showing limited mechanical properties with different fibre dimension and have uneven interface strength [36]. So, plant fibres are not feasible to be used in fibre placement and fibre extraction system. Thus, manmade glass fibre was continuously leading the low-cost fibre reinforcement as compared with natural plant fibres. However, one of limitation of glass fibre is low on chemical resistance, as result limited to be part of certain application [37]. As an alternative, natural and eco-friendly fibre called basalt had paid attention as the best choice in replacing glass fibre due to their comparative performance and good in chemical resistance. The capability of basalt fibre reinforcement in energy absorption performance is still unknown yet to be discovered. Hence, the combination of braided basalt reinforcement in sandwich composite study is another new exploration of knowledge.

1.3 Research Objectives

The aim of this research is to investigate the energy absorption performance and deformation mechanism of thin-walled and sandwich tube of braided basalt reinforced polymer composite subjected to axial crushing loadings. To achieve this aim, the research objectives are set as follows:

1. To evaluate the mechanical properties of thin-walled composite tube, expanded polyurethane foam, and in-plane shear properties of sandwich tube of basalt reinforced composite tube.
2. To identify the effect of different braid angle and braided materials of thin-walled, and sandwich composite tube subjected to quasi-static and dynamic crushing experiments.
3. To examine the energy absorption performance of different foam thickness on sandwich basalt composite tubes under quasi-static crushing experiment.
4. To develop the finite element models to represent the optimised braided basalt of thin-walled and sandwich composite tube, and validate these models with experimental results.

1.4 Research Scope and Limitations

The research scope and limitations of this study are listed as follows:

- All tested tube specimens were consisting of two types geometries; thin-walled tube, and sandwich composite tube. The thin-walled composite tubes consist of braided basalt and glass reinforcement materials, and epoxy as a matrix. Meanwhile, the sandwich composite tubes consist of thin-walled basalt composite tube as skins and expanded polyurethane foam (EPU) as foam-core.

- Thin walled composite tubes are fabricated using hand-layup and thermal shrink method with three layers, and three types of braid angle, θ; ±30º, ±45º, and ±60º. Consequently, sandwich composite tubes are fabricated using

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