UNIVERSITI PUTRA MALAYSIA

EFFECT OF BIAXIAL FABRIC PRESTRESSING ON THE MECHANICAL PROPERTIES OF PLAIN–WEAVE E–GLASS/POLYESTER COMPOSITES

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By

NAWRAS HAIDAR MOSTAFA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

May 2017

DEDICATION

This thesis is dedicated to my parents and my wife for their love and support. Without them, none of this would have been possible.

Nawras H. Mostafa
May 2017

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Chairman : Associate Professor Nur Ismarrubie Bt Zahari, PhD
Faculty : Engineering

It is of interest whether induced residual stresses would affect the mechanical properties of fibre–reinforced composites. One of the methods that can be used for altering the induced residual stresses within the matrix is the method of fibre prestressing. Although this method was previously used for developing the mechanical properties of unidirectional composites, its application to the woven composites was very rare. There are many applications of composite materials where woven fabric has been used instead of unidirectional fibre such as for helmets, armours, boats, and the automotive components. The mechanical properties of woven composite may be improved without increasing its volume and/or weight. Therefore, this study emphasizes on improving the mechanical properties and fatigue behaviour of the plain–weave composite by applying biaxial fabric prestressing.

Firstly, the induced residual stresses within the composite's constituents due to fibre prestress was calculated theoretically by developing the macro-mechanics theory. Secondly, numerical modelling of the prestressed composites was implemented using ANSYS® software for validating the theoretical results and estimating the full distribution of the residual stresses within the composite's constituents. The biaxial prestressing frame was used for providing biaxial fabric pretension load. Prestressed composites were manufactured with different levels of prestressing ranging from 25 to 100 MPa and prepared at different fibre orientation angles such as 0, 15, 30 and 45°. Lastly, experimental tests such as tensile, flexural and fatigue were conducted on the E–glass plain–weave/polyester resin composite in order to assess the advantages that might result from applying biaxial fabric prestressing.

Theoretical results showed that the level of the induced residual stresses within the composite's constituents depends on fibre prestress level, fibre volume fraction, and the elastic properties of the composite's constituents. Residual stresses calculated by the developed macro–mechanics theory were in agreement with those obtained by the numerical modelling and previous studies of no less than 1.53%. Numerical simulation of the prestressed composite showed that the maximum induced residual stresses due to fibre prestressing were located at the fibre–matrix interface. Increasing the fibre prestress level increases both the induced compressive residual stresses within the matrix and the fibre–matrix interfacial shearing stress. Experimental results showed that prestressing level of 50 MPa offered the highest improvement in the quasi–static properties and fatigue life behaviour. Enhancements in the tensile and flexural properties were about 20% (from 3.74 to 4.4 GPa of tensile modulus and from 35 to 42 MPa of critical stress) and 15% (from 2.54 to 2.96 GPa of flexural modulus and from 87.11 to 99.88 MPa of flexural strength), respectively. Fatigue cycles to failure were prolonged up to 43% (from 19949 to 28594 cycles) at 0.4 normalised peak stress in comparison with non–prestressed counterparts. The levels of improvement were reduced with increasing the fibre orientation to 45^o. Empirical functions were estimated to include the prestress effect in the tensile, flexural and fatigue behaviours. Prestressed composite specimens with 50 MPa showed a decline in the improved tensile strength, flexural strength and fatigue cycles to failure which were about 3.56 % (from 42.07 to 40.56 MPa), 1.96% (from 99.88 to 97.92 MPa) and 14.55% (from 28594 to 24432 cycles) after six months since they were manufactured, respectively. These declines resulted from the stress relaxation effect within the matrix.

Considering all findings, it was concluded that the proposed prestressing method enhanced the mechanical properties of the plain–weave composite. This improvement resulted from increasing the composite resistance against quasi–static and fatigue loadings by reducing both fibre waviness and the tensile residual stresses induced within the matrix. The fibre prestress method enhanced the mechanical properties of the plain–weave composite in both on–axis and off–axis directions. These improvements still existed after complete redistribution of the induced residual stresses within the matrix.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

KESAN PRATEGASAN FABRIK DWIPAKSI KE ATAS SIFAT-SIFAT MEKANIKAL KOMPOSIT E-KACA/POLIESTER TENUNAN-BIASA

Oleh

NAWRAS HAIDAR MOSTAFA

Mei 2017

Pengerusi : Profesor Madya Nur Ismarrubie Bt Zahari, PhD
Fakulti : Kejuruteraan

Adalah sesuatu yang diminati sama ada tegasan baki akan memberi kesan kepada sifat mekanikal bahan komposit bertetulang-gentian. Salah satu kaedah yang boleh digunakan untuk mengubah tegasan baki yang diaruhi di dalam matriks ialah kaedah prategasan gentian. Walaupun kaedah tersebut sebelum ini digunakan untuk membangunkan sifat-sifat mekanikal komposit satu-arah, penggunaanya bagi komposit tenunan sangat jarang berlaku. Terdapat banyak penggunaan bahan komposit di mana fabrik tenun telah digunakan dan bukan gentian satu-arah seperti untuk topi keledar, perisai, bot, dan komponen automotif. Sifat mekanikal komposit tenunan boleh ditambah baik tanpa meningkatkan isipadu dan/atau beratnya. Oleh itu, kajian ini memberi penekanan kepada peningkatan sifat mekanikal dan tingkah laku lesu komposit tenunan biasa dengan menggunakan prategasan fabrik dwipaksa.

Pertama, tegasan baki teraruh di dalam juzuk komposit akibat prategasan gentian dikira secara teori dengan membangunkan teori makro-mekanik. Kedua, pemodelan berangka bagi komposit prategasan telah dilaksanakan menggunakan perisian ANSYS® untuk mengesahkan hasil teori dan menganggarkan agihan sepenuhnya tegasan baki di dalam juzuk komposit ini. Bingkai prategasan dwipaksi digunakan untuk menyediakan beban prategangan fabrik dwipaksa. Komposit prategasan telah dibuat dengan tahap prategasan yang berbeza berjulat antara 25 hingga 100 MPa dan disediakan dengan sudut orientasi gentian yang berbeza seperti 0, 15, 30 dan 45^{o}. Keputusan ujikaji seperti tegangan, lenturan dan lesu telah dijalankan ke atas komposit tenunan-biasa sistem E-kaca/poliester untuk menilai kelebihan yang mungkin timbul daripada penggunaan prategasan dwipaksa fabrik.

Keputusan teori menunjukkan bahawa tahap tegasan baki yang teraruh di dalam juzuk komposit bergantung pada tahap prategasan gentian, pecahan isipadu gentian, dan sifat elastik juzuk komposit. Tegasan baki yang dikira dengan teori makro-mekanik yang dibangunkan adalah sepadan dengan yang diperoleh oleh pemodelan berangka dan kajian terdahulu dengan nilai kurang daripada 1.53%. Simulasi berangka komposit prategasan menunjukkan bahawa tegasan baki teraruh maksimum disebabkan oleh prategasan gentian terletak pada antara muka gentian-matriks. Meningkatkan tahap prategasan gentian boleh meningkatkan kedua-dua tegasan sisa mampatan teraruh di dalam matriks dan tegasan ricih antara muka serat-matriks. Keputusan ujikaji menunjukkan bahawa paras prategasan 50 MPa boleh memberikan peningkatan tertinggi bagi sifat-sifat kuasi-statik dan tingkah laku jangka hidup lesu. Tambahan pada sifat tegangan dan lenturan adalah lebih kurang 20% (daripada 3.74 hingga 4.4 GPa modulus tegangan dan 35 hingga 42 MPa tegasan kritikal) dan 15% (daripada 2.54 hingga 2.96 GPa modulus lenturan dan dari 87.11 hingga 99.88 MPa kekuatan lenturan) masing-masing. Kitaran sehingga kegagalan lesu telah dipanjangkan hingga 43% (daripada 19949 hingga 28594 kitaran) pada tekanan puncak normal 0.4 berbanding dengan yang tanpa-prategasan. Tahap peningkatan telah dikurangkan dengan meningkatkan orientasi gentian ke arah pincang. Fungsi empirikal dianggarkan termasuk kesan prategasan ke atas tingkah laku tegangan, kelenturan dan lesu. Spesimen komposit prategasan dengan 50 MPa menunjukkan penurunan dalam kekuatan tegangan, kekuatan lenturan dan kitaran lesu yang lebih baik hingga kegagalan yang kira-kira 3.56% (daripada 42.07 hingga 40.56 MPa), 1.96% (daripada 99.88 hingga 97.92 MPa) dan 14.55% (daripada 28594 hingga 24432 kitaran)selepas enam bulan dibuat, masing-masing. Penurunan ini adalah hasil daripada kesan tekanan santaian di dalam matriks.

Berdasarkan kepada penemuan, disimpulkan bahawa kaedah prategasan yang dicadangkan dapat meningkatkan sifat mekanikal komposit tenunan-biasa. Peningkatan ini hasil daripada peningkatan rintangan komposit terhadap beban kuasi-statik dan lesu dengan mengurangkan kedua-dua sifat berombak gentian dan tegasan baki tegangan di dalam matriks. Kaedah prategasan serat dapat meningkatkan sifat-sifat mekanik komposit tenunan di kedua-dua arahpaksi dan arah nentang-paksi. Peningkatan ini masih wujud selepas pengedaran semula sepenuhnya tegasan baki yang diaruh dalam matriks.

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Nawras Haidar Mostafa
May 2017

I certify that a Thesis Examination Committee has met on 29 May 2017 to conduct the final examination of Nawras Haidar Mostafa Al-Said Haidar on his thesis entitled "Effect of Biaxial Fibre Prestressing on the Mechanical Properties of Plain-Weave E-Glass/Polyester Composites" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBRIVATIONS

PMCs	Polymeric Matrix Composites
EFPPMCs	Elastically Fibre Prestressed PMCs
VEFPPMCs	Viscoelastically Fibre Prestressed PMCs
FEM	Finite Element Method
ANSYS	Analysis System
MEKP	Methyl Ethyl Ketone Peroxide
UNC	Unified Coarse
E–glass	Electrical–grade glass
EWR600	E–glass woven roving with area density of 600 g/m^2
UFRC	Unidirectional Fibre–Reinforced Composite
PWRC	Plain–Weave Fabric Reinforced Composite
ASTM	American Society for Testing and Materials
EFPI	Extrinsic Fabry–Pérot Interferometric
FBG	Fibre Bragg Grating
ERSG	Electrical Resistance Strain Gauge

CHAPTER 1

INTRODUCTION

This study investigates the effect of elastic fibre prestress on the performance of fibre– reinforced composites subjected to (i) a quasi–static load (tensile and flexural) and (ii) a fatigue load. The endurance aspect of the prestressed composites is examined over different periods of time. The present study includes theoretical, numerical and experimental investigations. The fibre pretension method has been used mainly to minimise the induced tensile residual stress and fibre waviness within composites.

This chapter highlights the problem statement, motivation, research hypotheses, main objectives and contributions to knowledge. A brief introduction to composite materials and their applications, along with the thesis layout are also presented.

1.1 General

The development of composite materials has been fast growing in recent times due to their influence on human life, whether civilian or military. The mechanical behaviour of the final composite product depends mainly on the mechanical properties of constituent materials, their fractional volume, their arrangement, and the manufacturing technology. Unfortunately, designing and manufacturing of a composite part with an improved mechanical behaviour are usually accompanied by relatively high–cost requirements. Low-cost-design is a very critical parameter that should be considered by designers in developing the behaviour of composite materials. One method that can be used to improve the structural properties of fibre–reinforced composites is the method of fibre prestressing.

The effect of equi–biaxial fabric prestressing on the quasi–static (tensile and flexural), fatigue and creep behaviours of a plain–weave fabric–reinforced composite has been considered in this study. This chapter briefly introduces the applications of composite materials, the problem statement, the scope of the work, the aims of the study, the contributions of the present study and finally the organisation of the thesis.

1.2 Composite materials and their applications

Modern structures that are made from fibre–reinforced based polymer composites have many advantages over the structures that are made from conventional materials such as high strength and stiffness–to–weight ratios, the ability to form complex shapes, high corrosion resistance, durability and low cost of maintenance in comparison with most metals (Andersson et al., 2014; Khan et al., 2014). However, the production cost of composites is relatively more expensive than common metals (Ashby and Jones, 2012; Lässig et al., 2012).

A composite material is simply defined as a combination of two or more materials, on a macroscopic scale, with significantly different properties to form a useful third material (Jones, 1999). The basic constituents of a composite consist of two phases, i.e. the reinforcement and the matrix. The essential role of the reinforcement is to absorb the traction force; however, the matrix has the role of transferring the load to the reinforcement phase, protecting the reinforcement phase from the environment, maintaining the cohesion of the component, providing the lateral support and resisting the shear and compression forces and to provide stable shape (Vigo and Kinzig, 1992). The usual reinforcing fibres used today are carbon, glass, boron, and aramid. While epoxy, polyester, and vinyl–ester are the most common resins used in the fabrication of the polymer composites (Murray et al., 2007).

Over the few last decades, composite structures have become popular in many applications where there is exposure to different external loadings and different environmental conditions. They are used instead of various conventional metallic materials for their relatively good chemical, physical and mechanical properties. Composite materials are widely used in many applications such as the aircraft, automotive components, military components, renewable energy, marine and offshore structures, and medical devices (Thomas et al., 2012). Components that are made from composite materials in aircraft structures can save the weight by up to a half in comparison with conventional metals (Greszczuk, 1975). The automotive industry has followed this with the successful use of composites in the production of the light and stiff components (Sapuan et al., 1995). Recently, the requirements for safer, faster cars have been achieved using the advanced technologies of composite materials (Thomas et al., 2012).

Generally, there are four common types of composite materials (Jones, 1999):

- Fibrous composites: this type consists of fibres (long or short) embedded in a matrix.
- Laminated composites: this type consists of different layers of materials.
- Particulate composites: this type is composed of particles in a matrix.
- Combinations of some or all of the above three types.

Fibrous composites with long fibres is used in this study as a reinforcement phase.

1.3 Motivation

Improving the composite's structural behaviour under quasi–static and/or cyclic loading, while keeping its mass and volume as low as possible, is one of the most significant challenges that designers might face. Fibre prestressing method can offer such improvement in the structural behaviour of the unidirectional composites. Because composites reinforced by plain–weave fabrics are widely used in most composite structures, the biaxial fabric prestressing method is intended to be investigated in order to see if this method can be exploited using such reinforcement form.

1.4 Problem statement

It is widely agreed that the use of composite structures is increasing, leading to an increased demand for the development of new techniques that can improve the mechanical behaviour of such advanced materials. In spite of the superior mechanical properties of the currently available composites compared with conventional metallic materials, research on their improvement is still ongoing. Moreover, the cost of producing composites that are more reliable is continuing to rise because they need either additive materials and/or improved fabrication techniques. Residual stresses are generated within the composites during manufacturing process (Shokrieh, 2014; Parlevliet et al., 2007b; Motahhari, 1998). These residual stresses can develop in composite materials due to several reasons such as the chemical shrinkage of the polymer matrix, the different thermo–mechanical properties of the constitutions, moisture absorption, and fibre pretension (Krishnamurthy, 2006). Residual stresses within the matrix can arise due to the phase change of the resin from liquid to solid state (chemical shrinkage). The mismatch in the coefficient of thermal expansion between the fibre and the matrix will produce residual stresses in the composite when it is cooled from its curing temperature (Shokrieh, 2014; Cao and Cameron, 2007; Krishnamurthy, 2006; Motahhari and Cameron, 1999; Motahhari, 1998; Fletcher and Oakeshott, 1994a, 1994b). Whereas moisture absorption by the polymeric matrix and the fibre leads to the deformation and expansion of the constituents of the composite at different levels depending on the swelling permeability (Li, 2000; Motahhari, 1998). Manufacturing processes such as the filament winding fabrication technique can add another source of induced residual stress in the final composite product due to the stretching of the fibre during the fabrication processes (Tabuchi et al., 2012; Mertiny and Ellyin, 2002; Binienda and Wang, 1999; Gabrys and Bakis, 1998; Cohen, 1997; Knight, 1972).

Residual stresses produced by resin chemical shrinkage and a mismatch in thermal expansion between the fibre and the matrix have a negative effect on the final mechanical properties of composites as their nature are always tensile (Krishnamurthy, 2006; Motahhari, 1998; Motahhari and Cameron, 1997). However, moisture absorption by the matrix generally acts to oppose the negative effects of both the chemical shrinkage and the thermal strains developed in the composites, but at the same time it may attack the fibre in a critical way (Li, 2000; Motahhari, 1998).

Fibre pretension could be one of the available options for enhancing the properties of polymeric matrix composites (PMCs) without increasing their section dimensions or mass (Graczykowski et al., 2016; Fancey, 2010). Up to now, the improvement obtained in the mechanical properties of fibre–reinforced composites due to using the fibre–prestressing method is not well established. However, some researchers have effectively confirmed the advantages of fibre prestressed composites for unidirectional composites. Prestressed PMCs were first used by Zhigun (1968) and this was followed by other researchers, such as Manders and Chou (1983) and Tuttle (1988).

Fibre pretension (prestressing) during matrix cure has in general a positive effect on the composite mechanical behaviour as it generates compressive residual stresses in the matrix. It is important to mention that fibre pretension has this beneficial effect only if it is applied to a limited level or range (Krishnamurthy, 2006; Jevons, 2004; Motahhari and Cameron, 1999; Motahhari, 1998). In particular, the existence of tensile residual stresses in composites can reduce the resistance to matrix micro–cracking. The presence of undesirable residual stresses and the waviness of the fibre may have a detrimental effect on the mechanical properties of composite structures and this may decrease the service life of a composite structure (Parlevliet et al., 2007a). Therefore, it is of importance to minimise the magnitude of the unfavourable residual stresses and the waviness of the fibre. It was previously proven that fibre pretension in simple laminates (unidirectional fibre) during curing process can generate compressive stresses in the matrix and thus help to support damage initiation and propagation (Krishnamurthy, 2006; Motahhari, 1998).

In case of using 2D woven fabrics as a reinforcement, the effect of fibre pretension on the mechanical properties of the composites is more complicated than those fabricated with unidirectional fibres. As the yarns of 2D woven fabric are crimped and interlaced between each other, pretensioning these yarns may affect the structural behaviour of composites in different kind. The main problems associated without having the fabric prestressing to plain–weave composite are directly related to fibre defects such as fibre waviness, wrinkling and high crimping. On the other hand, tensile residual stresses are induced during the fabrication process within the matrix at both the warp and fill yarn directions. The presence of tensile residual stresses within the matrix of the composite and fibre waviness have negative effects on the structural behaviour of the plain–weave composites.

The method of fibre pretension had confirmed its positive effects regarding the structural behaviour of the unidirectional fibre–reinforced composites under quasi-static and fatigue loadings (Sadiq, 2007; Krishnamurthy, 2006; Cao and Cameron, 2006a; Hadi and Ashton, 1998). However, from the author's knowledge this method is not assessed yet for a composite reinforced with a biaxially prestressed plain–weave fabric under these loadings. Therefore, investigating the effect of biaxial fibre pretension during the matrix cure process theoretically, numerically and experimentally on the behaviour of a composite reinforced by a plain–weave fabric needs to be considered.

1.5 Scope and limitation of the study

This work deals with the study of the quasi–static (tensile and flexural), fatigue and endurance aspect of the elastically prestressed composite behaviour fabricated from a plain–weave E–glass fabric (EWR600)/unsaturated polyester (Reversol P9509) system. The presence of the induced tensile residual stresses within the matrix has a detrimental effect on the mechanical properties of the composite; therefore, the tensile residual stresses within the matrix should be reduced, released or if possible reversed to compressive stresses. Therefore, prestressed composite samples are fabricated with different fibre pretension levels applied in biaxial directions (warp and weft yarn directions). The fibre prestress levels are within the linear elastic limit of the fibre materials. Specimens are then tested under quasi–static (tensile and flexural) and fatigue loadings at different orientation angles of the fabric (0, 15, 30 and 45^{o}). Theoretical analyses of the fibre pretension method for both unidirectional and bidirectional composite lamina are achieved. A numerical modelling and analysis of prestressed composites is performed to validate the theoretical analyses and to estimate the distribution and development of residual stresses within the composite's constituents. Reducing the tensile residual stresses within the matrix can improve the composite strength by preventing the cracks to develop easily. Several factors that can directly affect the tensile residual stress magnitude within the matrix are studied such as the elastic moduli of composite's constituents and fibre pretension level. The prospective practical applications of unidirectional fibre prestressed composites include filament winding to fabricate pressure pipes, vessels, wind turbine blades and cylindrical shells. However, fibre pretension can be performed for composites reinforced with 2D woven fabric such as helmets, armours, boats, bistable morphing structures, and automotive industry. The current study is limited to using composite samples fabricated with only a single layer of fabric at ambient conditions.

1.6 Research hypotheses

This research is carried out with three main hypotheses. They are as follows:

1. Fibre prestressing during the matrix cure process can change the state of the internal residual stresses of the fibre–reinforced composites. Upon releasing the fibre pretension, compressive residual stresses are imparted from the pretensioned fibres into the matrix. Therefore, it is expected that the new state of residual stresses within the matrix could prevent the initiation and development of micro–cracks.

2. The presence of the fibre pretension can increase its straightness. Thereby, it can provide the instantaneous load transfer from the matrix to the fibre. The architecture of the reinforced phase can improve significantly when pretensioned. Fibre waviness and crimping are decreased significantly, thereby leading to the enhancement of the structural behaviour of the composite as a whole.

3. Prestress have a significant effect on the total flexural stiffness of the composite structure. The remaining tension force in the fibre after releasing the pretension load in the fibre can reduce the deflection of the prestressed composite when subjected to transverse and/or bending load.

1.7 Research objectives

The objectives of this study are:

1. To develop material model for the fibre prestressed composites theoretically by deriving new equations and developing the macro–mechanical analysis of a laminated composite to include the term of biaxial fabric prestressing in the modelling of plain–weave composites.

2. To develop the model for the fibre prestressing method numerically using a commercial finite element software on the meso–scale in order to explore how fibre prestressing affects the state of internal stresses within the composite's constituents and verify the numerical results with those obtained from the developed theoretical equations.

3. To investigate the effect of applying different levels of biaxial fabric prestressing on the quasi–static (tensile and flexural) properties and fatigue behaviour of plain–weave composites tested at different fibre orientation angles. The same tests are performed at different timescales in order to include the effect of residual stress relaxation within the polymeric matrix on the mechanical behaviour of fibre prestressed composites.

1.8 Contributions of the study

The contributions of this study are:

1. Focusing on the prediction of the quasi–static, fatigue life and stress relaxation behaviour of such improved composite materials. Thereby, giving a good indication of the behaviour of the prestressed composite under the different loading conditions that it may be exposed to in practical applications.

2. The mechanical properties are improved without adding new material to the composite's constituent and neither increasing the volume nor the mass of the composite when employing the fibre pretension method. This could reduce the overall cost of composite production.

3. In most practical applications, composite structures are subjected to multi–directional or complex loadings that require improvements in the mechanical properties of the composite structures in each direction. The equi–biaxial fabric pretension method of a plain–weave fabric could offer this advantage efficiently.

1.9 Thesis layout

This study has been broken down into five chapters.

Chapter 1 presents a short background of the composite materials applications, the research motivation, the problem statement, the scope of the study, the hypotheses and objectives of the research, the contributions of the study and the layout of this thesis.

Chapter 2 presents a literature review on residual stresses accompanied with composite material manufacturing and their effects on the mechanical behaviour of the composite products. The failure modes in the polymeric matrix composite are reviewed briefly. This is followed by the description of mechanisms related to the fibre pretension method. The types of fibre prestressing methods and the associated application techniques are also reviewed in this chapter. The effects of the fibre pretension method on the structural behaviours of the composite under tensile, flexural and fatigue loading are reported. The final part discusses the assessment of the prestressing methodologies and their potential applications.

Chapter 3 presents the methodology used in the current study. The research methodology is explained and the prestressing philosophy has been described. This is followed by the derivation of new theoretical equations and development of the macro–mechanical theory to calculate and include the effect of the residual stresses induced in the composite due to prestressing the fibre before and during the matrix cure process. The finite element method is used to model the fibre prestressing method numerically and to validate the theoretical analysis results. The final section explains the experimental part such as raw material selection and manufacturing a suitable prestressing frame. Experimental tests such as tensile, flexural, fatigue, stress relaxation, percentage crimping and endurance aspect of the plain–weave E–glass fabric/polyester composites are described in detail.

Chapter 4 presents and discusses the results obtained using the theoretical, numerical and experimental procedures.

Chapter 5 provides the overall conclusions obtained in this study are given and directions for future research studies are presented.

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