BUCKLING ANALYSES OF TRIAXIAL WEAVE FABRIC COMPOSITES UNDER THERMAL AND MECHANICAL LOADING

MUHAMMAD NOR HAFIDZI BIN MAHAT

UNIVERSITI TEKNOLOGI MALAYSIA

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MUHAMMAD NOR HAFIDZI BIN MAHAT

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For all the reason HE knows so great..

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ABSTRACT

This thesis presents the formulation and numerical computation of the buckling behaviour of triaxial weave fabric (TWF) composites subjected to mechanical and thermal loads. The formulation was constructed by adopting two types of numerical method, namely the finite element method (FEM) and the meshfree (MFree) method, based on the classical plate theory. A combination of Lagrange and Hermite interpolation functions was adopted in the FEM formulation whereas the Multi-Quadrics radial basis function was employed in the MFree formulation. The formulation complexities, high time-consumption and tedious computation attributed to previous studies, which considered a variety of modelling techniques for the description of the complex tow geometry, were identified as the primary disadvantages, preventing them from widespread use. Therefore, simplification of modelling the TWF is vital for convenience and practicality. Such simplification was provided from the literature by describing the constitutive relation of the TWF using the contemporary 6 × 6 ABD matrix, adopting the homogenized and segmentation methods. The former employs the periodic boundary condition while the latter considers the volume segment of a unit cell. These material expressions were employed in both FEM and MFree methods in order to study the behaviour, especially the stability of the TWF composite when subjected to uniaxial compressive mechanical and uniform thermal loads, focusing on the cases of all edges clamped and simply supported. The source codes for the mechanical buckling and thermal buckling for both FEM and MFree were developed in this study. Authentication and verification of the source codes were done by making comparison with selected problems from the literature. As aspect ratio increases, the TWF plate was found to be less resistant towards mechanical buckling, which was in contrast to the thermal buckling behaviour. Overall, good agreement has been found in models adopting the homogenized and segmentation methods especially for the plates that were fully clamped for both thermal and mechanical bucklings using the FEM and MFree methods. The plates with fully clamped edges were identified to have higher resistance towards mechanical and thermal loads in comparison with those of simply supported edges.

ABSTRAK

Tesis ini membentangkan perumusan dan pengiraan berangka untuk tingkah laku kestabilan komposit fabrik anyaman tiga paksi (TWF) yang dikenakan daya mekanikal dan termal. Perumusan telah dihasilkan dengan menggunakan dua kaedah berangka, iaitu kaedah unsur terhingga (FEM) dan kaedah tanpa jejaring (MFree) yang berdasarkan teori plat klasik. Gabungan interpolasi *Lagrange* dan *Hermite* telah diadaptasikan di dalam perumusan FEM manakala fungsi *Multi-Quadrics radial basis* telah digunakan untuk perumusan MFree. Kaedah perumusan yang kompleks, tempoh pengiraan yang lama, dan kesukaran pengiraan dengan menggunakan pelbagai kaedah untuk memodelkan geometri *tow* yang kompleks telah dikenalpasti daripada literatur sebagai kelemahan utama, yang menyukarkan penyebaran penggunaan secara menyeluruh. Usaha pemodelan TWF secara ringkas adalah penting untuk kemudahan dan praktikaliti. Pemudahan tersebut telah disediakan dalam literatur dengan menerangkan hubungan konstitutif TWF dalam bentuk matrik ABD 6 × 6 yang kotemporari dengan menggunakan kaedah *homogenized* dan kaedah sekmentasi. Kaedah pertama menggunakan keadaan batas berkala manakala yang kedua adalah berdasarkan sekmen isipadu bagi satu unit sel. Ekspresi bahan ini telah diterapkan di dalam FEM dan MFree untuk kajian kestabilan bahan TWF terhadap daya mampatan searah mekanikal dan beban termal yang sekata dengan memfokuskan tumpuan kepada kes semua batas diapit sepenuhnya dan disokong mudah sepenuhnya. Kod pengaturcaraan untuk pengiraan kestabilan mekanikal dan termal untuk kedua-dua FEM dan MFree telah dibangunkan di dalam kajian ini. Pengesahan pengiraan daripada kod pengaturcaraan diuji dengan perbandingan dengan beberapa pemasalahan pilihan daripada literatur. Dengan kenaikan nilai nisbah aspek, plat TWF didapati memberikan kurang rintangan terhadap kestabilan mekanikal dan ini berbeza dengan tingkah laku kestabilan termal. Kesimpulannya, persetujuan dikenal pasti bagi model yang menadaptasikan kaedah *homogenization* dan sekmentasi terutama sekali untuk plat yang diapit sepenuhnya bagi kestabilan termal dan mekanikal dengan menggunakan kaedah FEM dan MFree. Plat yang diapit penuh didapati memberikan rintangan yang tinggi terhadap beban mekanikal dan termal berbanding dengan kes disokong mudah.

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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS:

$\overline{\varepsilon_{ij}}$	-	Mid-plane strains
$\overline{\kappa_{ij}}$	-	Mid-plane curvatures
Δl_i	-	Lengths of unit cell
ε_{ij}	-	Strains
κ_{ij}	-	Curvatures
V_1^f	-	Volume segment of 1-tow element
V_2^f	-	Volume segment of 2-tow element
V_s^f	-	Ratio of volume
$\hat{C}_{ij}^k$	-	Global stiffness
t_k	-	Thickness of the lamina/tow
b_{tow}	-	Width of the tow
A_{ij}, A_{ji}	-	Component of plate extensional stiffness
B_{ij}, B_{ji}	-	Component of plate coupling stiffness
D_{ij}, D_{ji}	-	Component of plate bending stiffness
N_{xx}, N_{yy}, N_{xy}	-	In-plane forces per unit length
$N_{xx}^T, N_{yy}^T, N_{xy}^T$		Thermal in-plane force per unit length
M_{xx}, M_{yy}	-	Bending moments per unit length about *x*- and *y*-axis, respectively
M_{xy}		Twisting moment per unit length
M_{xx}^T, M_{yy}^T		Thermal bending moments per unit length about *x*- and *y*-axis, respectively
M_{xy}^T		Twisting thermal moment per unit length
ε_x, ε_y	-	Strain in *x*- and *y*-direction, respectively

ε_{xy}	-	In-plane shear strain
κ_x, κ_y	-	Curvature in *x*- and *y*-direction, respectively
κ_{xy}	-	Twisting curvature
$\mathcal{N}$	-	Nonlinear expression
I_i	-	Mass moment of inertia
u_0, v_0, w_0	-	Displacement in *x*-, *y*- and *z*-direction, respectively
ψ_j^e	-	Lagrange interpolation function
φ_k^e	-	Hermite interpolation function
ζ, η	-	Natural coordinate of *x*- and *y*-axis
K	-	Stiffness matrix
G	-	Geometric stiffness matrix
F	-	Force vector
F^T	-	Thermal force vector
$R_i(x)$	-	Radial basis function
$p_j(x)$	-	Monomial function
$\phi_k^u, \phi_k^v, \phi_k$	-	Shape functions of meshfree for displacement in in *x*-, *y*- and *z*-direction, respectively
ϕ_k^x, ϕ_k^y	-	Shape functions of meshfree for rotation with respect to*x*- and *y-axes*, respectively
δ_{ij}	-	Kronecker delta property
λ	-	Buckling load
λ_{cr}	-	Critical buckling load
E_1	-	Longitudinal Young's modulus
E_2	-	Transverse Young's modulus
v_{12}	-	Poisson's ratio in 12 plane respectively
h	-	Thickness of plate
a	-	Length of plate
b	-	Width of plate
α_1, α_2	-	Longitudinal and Transverse coefficient of thermal expansion, respectively
ΔT	-	Change in temperature
$\alpha_x, \alpha_y, \alpha_s$	-	Transformed lamina coefficients of thermal expansion

T_{cr}	-	Critical temperature
q	-	Distributed transverse load

ABBREVIATION :

BWF	-	Biaxial weave fabric
FEM	-	Finite element method
MFree	-	Meshfree method
RBF	-	Radial basis function
RVC	-	Representative volume cell
RUC	-	Representative unit cell
TWF	-	Triaxial weave fabric

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CHAPTER 1

INTRODUCTION

1.1 Overview

Tremendous efforts have been laid down this past decades to seek upon suitable material that able to meet the requirements of high structural performance for various possible applications. Such applications are not only limited to aerospace industry but also to areas such as building industry, defence industry, automobile, marine, space exploration and sport. The urge of satisfying such rigor applications brings us to the wonders of textile composites. Various attractions that have been identified have made the use of textile composite highly potential for practical application. One of the primary attractions is the ultra-lightness of the material, which has high ranging structural uses including those with both rigid and deployable features. Fabric composites are highly suitable for applications like reflectors, communication satellites, and structural components in building which require low mass and flexible properties. An example of such uses can be seen in Figure 1.1, which shows a spacecraft reflectors constructed with triaxial weave fabric composite materials. Transparency features is visible as one able to see through the material due to the high degree of porosity of the material. Moreover, the reflector is able to be folded and deployed due to the high flexibility of the material.

Figure 1.1 Spring back reflectors one folded (top) and one deployed (bottom), on MSAT-2 spacecraft (Courtesy of Canadian Space Agency)

It should be stressed that the application of textile composite is wide ranging in all existing engineering areas. Textile composite is considered as thin material and such material has the tendency to bend. Hence, the material is susceptible to stability failure due to extreme thermo-mechanical environment. Even though textile composite is lightweight and has high performance, exposure of the thin material to mechanical load and environmental heat under extreme condition may lead to possible eventual structural failure. Therefore, study on this issue would greatly help in analysis and design as such stability precaution can be exercised to prevent catastrophic failure.

In practice, there exist several compositions and dimensions of textile composite. In the present study, textile composite with triaxial woven formation is considered. The main focus of this research project is on the buckling of triaxial weave fabric (TWF) composites due to an independently prescribed uniaxial mechanical load and uniform thermal load, studied using Finite Element Method (FEM) and Mesh Free method (MFree) and emphasizing on plate problem. Basically, TWF consists of two constituents, the fibers and the matrix, that make up the tows and are arranged along three axes on a plane, at 0º and ±60º, and woven in a fabric form (Figure 1.2). TWF is impregnated with resin and cured in an autoclave, like a standard composite. Even though the arrangements are profoundly aesthetic or decorative in the eyes of human, the technical performance and functional properties of the woven arrangement should not be neglected.

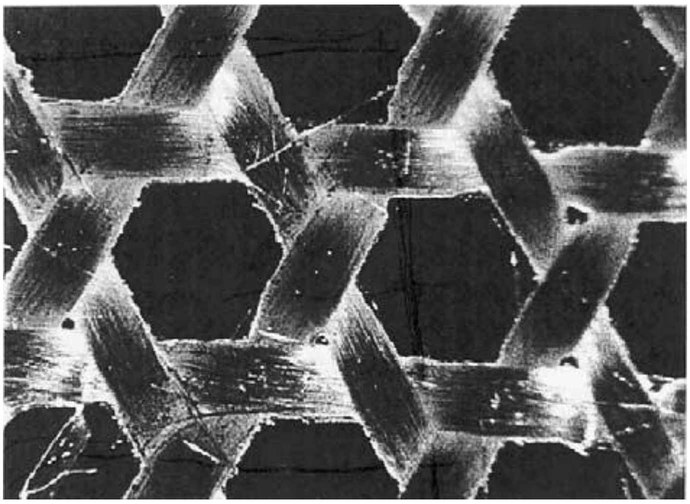

Figure 1.2 TWF composite structure (Xu et al, 2005)

Such unique arrangement of tows gives a significant advantage comparable with biaxial arrangement. The weave produced from triaxial weave are structurally superior to most conventional, biaxially woven types. This includes high strength, stiffness coupled with low weight and considerably less density. The main factor in contributing to the mass reduction of the composite is due to existence of hexagonal voids that are well distributed over the surface area. The arrangement of the woven tows results in a better resistance to in-plane shear loads compared with other woven arrangement especially biaxial weaves (Kueh et al, 2005). Furthermore, fracture toughness as well as poor inter laminar strength encountered by unidirectional (UD) material can be addressed substantially by TWF since all textile composites offer interlocking mechanism between tows attributed to their interwoven nature.

1.2 Problem Statement

Fiber composites are known these past few years as one of the best potential material that can help human to construct an advanced deployable and lightweight structure. Even though these composites are known to other develop countries for a quite a while now, it is still relatively new to Malaysian industries. By looking at this scenario, it will be a good opportunity for us to explore and apply the material into any engineering discipline especially in civil engineering. Although it is lightweight and has high performance, the stability of the material as a structural element is of high concern in a heat environment. In attempt to better utilize this material, its full behavior for design application needs to be discovered. Of particular interest would be the behaviors of material when exposed to different types of uniaxial mechanical and thermal loads focusing on the buckling due to compressive stresses.

MFree method can be considered as at its infancy and currently more research has to be done to improve and develop this promising method. High computational cost which is common in creating FEM meshes has led to the concept of MFree methods. The dependency of using elements or mesh in the formulation stages by FEM especially during convergence study remain as one of the most hassled procedures in applications. Hence, in depth investigation on MFree has to be done to pave more opportunity to apply this method thoroughly for future application.

Thus far, previous studies on textile composite have successfully modeled the complexity of the weave geometry. However, the complexity of computation has inhibited the widespread use in particular among practicing engineers. This can be seen in the proposed solid modeling techniques (Zhao and Hoa, 2004; Zhao et al, 2003; Xu et al, 2004) which require long formulation and computational analyses. The disadvantages of hassled computation are seen as weakness and the needs to simplify the solution is by representing the mechanical properties of composite material to a lower structural order, preferably in terms of what commonly known as ABD stiffness matrix especially for plate-like structures. In the current study, the material expressions are taken from Kueh and Pellegrino (2007) and Kueh (2012).

Both sources pioneered the simplified approach for computation of ABD stiffness matrix of TWF using homogenization and segmentation methods, respectively. Both constitutive have its unique differences and the computational features of both are of interest to be explored using FEM and MFree methods. It is the aim of this research to continue investigating the stability of this highly potential material and reliability of both FEM and MFree numerical methods for plate problem in structural applications.

1.3 Objectives of the Study

The primary objectives of this study are summarized as follows:

1. To formulate the finite element and meshless models for TWF adopting composite plate approach.
2. To study the size effects of TWF on thermal and mechanical loaded stabilities.
3. To recognize the effects of various geometrical boundary conditions in addition to force boundary conditions.

1.4 Scope of Study

The chief concern of the study is centered on the buckling of a single ply TWF composite due to uniaxial mechanical and thermal loads. Thermal load prescribed on the structure is uniformly distributed throughout the volume. Note that post buckling is not considered in this study. The materials used are T300 carbon fibers and Hexcel 8552 epoxy resin. The material inelasticity is not taken into account in the numerical solution. The material is assumed to be fully cured and no imperfection is applied.

Classical plate theory (CPT) provided by Reddy (2004) will be adopted in the formulation due to ultra-thin feature of single-ply TWF, 0.156 mm in average, which is suitably defined as thin plate. Non-conforming shape functions will be used for FEM which comprises 20 degrees of freedom in total. Also, the radial point interpolation method (RPIM) with the multi-quadrics (MQ) radial basis function (RBF) are to be used for the function approximation for describing the MFree shape functions. Two types of boundary conditions, simply supported and fully clamped, are considered.

1.5 Significance of Research

This study concerns with thermo-mechanical behavior of TWF composite stability subjected to mechanical and thermal loads. As far as the scope of the research is concerned, the significance of this study would be on the application of simplified computational materials expressions proposed by Kueh and Pellegrino (2007) and Kueh (2012), which are homogenized and segmentation method, respectively. Although other solid element modeling techniques have been previously employed for the material, complex formulation and computation are considered as drawbacks that hinder the efficiency of the solution process. Application of the material on MFree is seen as another effort in studying the reliability of MFree although applications in other fields have shown some promising results. With the approach used in this study, it is hoped that the understanding on the buckling of TWF composites when subjected to mechanical and thermal loads can be obtained. Effects such as changes of dimensional aspect ratios and boundary condition can be used for practical purposes in design and analysis of TWF. In addition, this study will provide a platform for other researcher to venture into more extensive behavior of TWF in the scope of homogenized and segmentation material expressions.

1.6 Chapter Organization

This thesis comprises six chapters. Subsequently after the first introductory chapter, Chapter 2 discusses various studies of TWF in literature. Review of existing model will be given thoroughly, including the details on simplified homogenized and segmentation methods to obtain the ABD matrix of TWF. Basic introduction regarding MFree method that is used in the present problem solution will also be explained, specifically on weak forms with main highlight on radial point interpolation method (RPIM).

Chapter 3 is divided into two sections emphasizing on formulation of FEM and MFree, respectively. The discussion of FEM formulation begins from the equation of motions to the development of its weak forms and finally the stiffness matrix. Similar approaches are applied for formulation of MFree.

Chapter 4 is dedicated for explanation of the MATLAB program for both FEM and MFree that have been developed. Validation of linear deflection as well as mechanical buckling and thermal buckling will also be demonstrated in this chapter.

Chapter 5 is devoted to the discussion of results obtained by the verified models in Chapter 4. Necessary comparison of FEM and MFree with homogenized and segmentation constitutive relations on the thermo-mechanical buckling problems is discussed thoroughly.

Chapter 6 ends the thesis with the conclusions on the behavior of linear mechanical and thermal buckling of TWF that has been studied with both homogenized and segmentation constitutive relations, respectively. The efficiency and reliability of

MFree are given with respect to comparison with FEM. The chapter is followed by a list of recommendations for future study.

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