ANALYSIS OF WARPAGE AND SPRINGBACK OF THICK UNIDIRECTIONAL CARBON-EPOXY LAMINATES CURED USING AUTOCLAVE

BY

MUHAMMAD MUSHAB BIN ZAKARIA

A thesis submitted in fulfilment of the requirement for the Master of Science (Mechanical Engineering)

Kulliyyah of Engineering
International Islamic University Malaysia

SEPTEMBER 2022

ABSTRACT

This thesis presents the study of the post-cure behaviour of thick carbon-epoxy composite laminates manufactured to Airbus specification AIMS05-27-002 cured using autoclave. The post-cure behaviour being studied is the warpage of flat laminates and the springback of curved or angled laminates. These laminates resemble the geometrical features found on the actual structure of the rib of the flap of Airbus A350. The gap left from previous works using similar material and process is the uncertainty that exists within the predictive finite element model for the thicker range of the laminates. This study thus attempted to close this gap by first extending the warpage and springback database from the thin laminates (16 layers and below) to thick laminates of up to 28 layers. Then the predictive model is iterated several times by changing the initial stress within the first layer of the elements until the warpage in the simulation matches that of the experiment respectively. The outcomes are a warpage and springback database covering both thin (less than 20 layers) and thick (more than 20 layers) range of thickness as well as a predictive finite element model that is able to predict the behaviour of laminates of the actual aircraft structure. Three categories of specimen were defined; flat unidirectional, curved unidirectional, and flat symmetrical. The effect of four parameters were studied; specimen size, corner angle, laminate thickness, and ply configuration. The results of the analysis indicate that the effect of specimen size for flat unidirectional and aspect ratio for curved unidirectional specimens is negligible. Quadratic response can be found for the effect of specimen size for curved unidirectional and aspect ratio for flat unidirectional. The effect of specimen thickness is linear for all specimen types. The accuracy of the predictive finite element model is mostly above 70% and peaking above 90% around the middle range of each parameter. Overall, the results of the experiment are satisfactory and the practicality of the predictive model is acceptable but more works are required in order to further improve the accuracy of the model.

ملخص البحث

تقدم هذه الأطروحة دراسة سلوك ما بعد المعالجة للصفائح السميكه المركبة من الكربون والإيبوكسي، المصنعة وفقا لمواصفات إيرباص نوع (AIMS0S-27-002)، والمعالجة باستخدام جهاز الأوتوكلاف. سلوك ما بعد المعالجة الذي يتم دراسته هنا هو انفتال الصفائح المسطحة والإرتداد الخلفي للصفائح المنحنية. هذه الصفائح تماثل الخصائص الهندسية الموجودة في الهيكل الحقيقي لضلع رفرف طائرة إيرباص (A350). الفجوة الباقية في الأعمال السابقة باستخدام نفس المادة وإجراء مماثل، هي الضبابية المتواجدة في نموذج العنصرالمحدود التنبؤي للصفائح ذات المدى السميك. حاولت هذه الدراسة حل هذه الفجوة أولا عن طريق توسيع قاعدة بيانات الانفتال والإرتداد الخلفي من الصفائح الرقيقة (16 طبقة وما دون ذلك) إلى الصفائح السميكة إلى حد 28 طبقة. ثم تم تكرار النموذج التنبؤي عدة مرات عبر تغيير الضغط الأولي داخل الطبقة الأولى للعناصر، حتى تتطابق الانفتال خلال المحاكاة مع التجربة. النتائج هي قاعدة بيانات للانفتال والإرتداد الخلفي للنطاق الرقيق (أقل من 20 طبقة) والسميك (أكثر من 20 طبقة)، وإضافة إلى ذلك، أثبت نموذج العنصر المحدود قدرته على التنبؤ بسلوك صفائح الهيكل الحقيقي للطائرة. ثلاث فئات تم تحديدها من العينة؛ مسطح أحادي الاتجاه ومنحني أحادي الاتجاه و مسطح متماثل. تمت دراسة تأثير أربعة معايير؛ حجم العينة، الزاوية، سمك الصفيحة، وتكوين الرقائق. تشير نتائج التحليل إلى أن تأثير حجم العينة على المسطح الأحادي ومعدل النسبة للعينات أحادية الاتجاه المنحنية لا يكاد يذكر. يمكن إيجاد الإستجابة التربيعية لتأثير حجم العينة للمنحني أحادي الاتجاه وكذلك معدل النسبة للمسطح أحادي الاتجاه. تأثير سمك العينة خطي لجميع أنواع العينة. كانت دقة نموذج العنصر المحدود التنبؤي غالبا أعلى من 70٪ وفي ذروتها أعلى من 90٪ حول المدى المتوسط لكل معيار. بشكل عام، كانت نتائج التجربة مرضية وكذلك التطبيق العملي للنموذج التنبؤي كان مقبول، ولكن هناك حاجة إلى مزيد من العمل لأجل زيادة تحسين دقة النموذج.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechanical Engineering).

…………………………………..
Mohd Sultan Ibrahim Shaik Dawood
Supervisor

…………………………………..
Jaffar Syed Mohamed Ali
Co-Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechanical Engineering).

…………………………………..
Hanan Mokhtar
Examiner

…………………………………..
Jamaluddin Mahmud
External Examiner

This thesis was submitted to the Department of Mechanical Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Mechanical Engineering).

…………………………………..
Fadly Jashi Darsivan
Head, Department of Mechanical Engineering

This thesis was submitted to the Kulliyyah of Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Mechanical Engineering).

…………………………………..
Sany Izan Ihsan
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Muhammad Mushab Bin Zakaria

Signature………………………………… Date ....

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

DECLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

ANALYSIS OF WARPAGE AND SPRINGBACK OF THICK UNIDIRECTIONAL CARBON-EPOXY LAMINATES CURED USING AUTOCLAVE

I declare that the copyright holders of this thesis are jointly owned by the student and IIUM.

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without prior written permission of the copyright holder except as provided below.

1. Any material contained in or derived from this unpublished research may be used by others in their writing with due acknowledgement.

2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institutional and academic purposes.

3. The IIUM library will have the right to make, store in a retrieved system and supply copies of this unpublished research if requested by other universities and research libraries.

By signing this form, I acknowledged that I have read and understand the IIUM Intellectual Property Right and Commercialization policy.

Affirmed by Muhammad Mushab Bin Zakaria

……………………………… ……………………..

Signature Date

ACKNOWLEDGEMENTS

Firstly, it is my utmost pleasure to dedicate this work to my dear parents and family, who granted me the gift of their unwavering belief in my ability to accomplish this goal. Thank you for your support and patience.

I wish to express my appreciation and thanks to those who provided their time, effort and support for this project especially to the staffs of CTRM AC and AMIC who were involved directly or indirectly.

Finally, a special thanks to Prof. Yulfian Aminanda and Dr. Mohd Sultan Ibrahim Shaik Dawood for their continuous support, encouragement and leadership, and for that, I will be forever grateful.

This thesis is dedicated to my parents for laying the foundation of what I turned out to be in life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	Area (mm^2)
AR	Aspect ratio
E	Modulus of elasticity (GPa)
E_{11}	Modulus of elasticity along fibre (GPa)
E_{22}	Modulus of elasticity perpendicular to fibre (GPa)
E_{33}	Modulus of elasticity normal to tape (GPa)
FAW	Fibre areal weight (g/m^2)
F_{cu1}	Compressive ultimate strength along fibre (MPa)
F_{cu2}	Compressive ultimate strength perpendicular to fibre (MPa)
F_{su12}	Shear ultimate strength (MPa)
F_{tu1}	Tensile ultimate strength along fibre (MPa)
F_{tu2}	Tensile ultimate strength perpendicular to fibre (MPa)
G_{12}	Modulus of rigidity in-plane (GPa)
G_{13}	Modulus of rigidity out-of-plane along fibre (GPa)
G_{23}	Modulus of rigidity out-of-plane perpendicular to fibre (GPa)
L_1	Length of first segment of measuring arm (mm)
L_{12}	Length of side of triangle between point 1 and point 2 (mm)
L_{13}	Length of side of triangle between point 1 and point 3 (mm)
L_2	Length of second segment of measuring arm (mm)
L_{23}	Length of side of triangle between point 2 and point 3 (mm)
L_3	Distance measurement of laser scanner (mm)
$L_{3'}$	Position of reflected spot along optical sensor (mm)
L_A	Length of Bar A (m)
L_B	Length of Bar B (m)
L_{flange}	Straight length of flange (mm)
P'_i	Deflection point coordinate (mm)
PAW	Prepreg areal weight (g/m^2)
P_i	Point coordinate (mm)
R	Radius of curvature before thermal expansion (mm)
R’	Radius of curvature after thermal expansion (mm)

R_{act}	Actual radius of curvature of corner region (mm)
R_{corner}	Radius of curvature of corner region (mm)
R_{flange}	Radius of curvature of flange (mm)
R_{nom}	Nominal radius of curvature of corner region (mm)
S	Arc length of curvature before thermal expansion (mm)
S’	Arc length of curvature after thermal expansion (mm)
S_{flange}	Arc length of flange (mm)
t	Cured part thickness per laminar (mm)
V_f	Volume fraction of carbon fibre
V_m	Volume fraction of epoxy matrix
x'_1	x-coordinate of point 1 of final contour (mm)
x'_2	x-coordinate of point 2 of final contour (mm)
x'_3	x-coordinate of point 3 of final contour (mm)
y	Layer position from tool surface
z'_1	z-coordinate of point 1 of final contour (mm)
z'_2	z-coordinate of point 2 of final contour (mm)
z'_3	z-coordinate of point 3 of final contour (mm)
α_{lam}	Coefficient of thermal expansion of laminate (°C^{-1})
α_{tool}	Coefficient of thermal expansion of tool (°C^{-1})
δ	Deflection (mm)
δ_A	Deflection of specimen A (mm)
δ_B	Deflection of specimen B (mm)
ΔT	Temperature rise from room temperature to curing temperature (°C)
δ_Z	Change of distance of specimen relative to laser scanner (mm)
$\delta_{Z'}$	Change in position of reflected spot along optical sensor (mm)
$\Delta\theta$	Change of angle (°)
$\Delta\kappa$	Change of curvature (mm^{-1})
$\Delta\kappa$	Warpage of specimen (mm^{-1})
$\varepsilon\delta_A$	Elongation or deflectionof Bar A (mm)
ε_B	Elongation of Bar B (mm)
ε_T	Thermal strain mismatch between tool and part
θ	Corner angle (°)
θ_1	Angle of first segment of measuring arm (°)
θ_2	Angle of second segment of measuring arm (°)

θ_{act} Final corner angle

θ_{act} Actual corner angle (°)

θ_{i} Incident angle (°)

θ_{mea} Measured corner angle (°)

θ_{nom} Initial corner aAngle (°)

θ_{nom} Nominal corner angle (°)

θ_{r} Reflected angle (°)

κ Line or surface curvature (mm^{-1})

κ_{act} Curvature of final or actual shape of specimen (mm^{-1})

κ_{flat} Warpage of flat specimen (mm^{-1})

κ_{guass} Gaussian curvature (mm^{-1})

κ_{max} Maximum principal curvature (mm^{-1})

κ_{min} Minimum principal curvature (mm^{-1})

κ_{nom} Curvature of initial or nominal shape of specimen (mm^{-1})

ν_{12} Poisson's ratio in-plane

ν_{13} Poisson's ratio out-of-plane along fibre

ν_{23} Poisson's ratio out-of-plane perpendicular to fibre

σ Normal stress (MPa)

σ_{peak} Peak stress (MPa)

LIST OF ABBREVIATIONS

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
AC	Aero Composites
AFP	Automated fibre placement
AMIC	Aerospace Malaysia Innovation Centre
ATL	Automated tape layup
BMI	Bismaleimide
BRDF	Bidirectional reflectance distribution function
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CFRP	Carbon fibre reinforced polymer
CNC	Computer Numerical Control
CSV	Comma-separated values
CTRM	Composites Technology Research Malaysia
FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
FEP	Fluorinated ethylene propylene
IBF	Inboard flap
IIUM	International Islamic University Malaysia
IQR	Interquartile range
MPA	Multi-phase array
MRO	Maintenance, repair and overhaul
MS	Microsoft
N/A	Not applicable
NDT	Non-destructive test
OBF	Outboard flap
XWB	Extra wide body

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

This study represents a part of a long-term roadmap in establishing a comprehensive database and a predictive finite element model of warpage and springback phenomena of carbon fibre reinforced polymers (CFRP). The motivation behind this research stemmed from the need to solve one of the manufacturing defects known as warpage and springback. The consequence of warpage and springback on the manufactured parts is critical because unlike metals, this defect in composites is not repairable and the affected parts must be scrapped. Additionally, geometrical tolerance such as surface profile of aero-structures is usually quite tight and meeting this requirement can be challenging. In some cases, where surface profile discrepancy is minor, customers are willing to accept the affected parts but only through concessions which would only cause delays and incur cost to manufacturers.

Warpage or springback defect is not necessarily structural on its own. However, affected panels would fail to be assembled in higher assembly level without the need to exert additional forces to bring mating surfaces together. This additional forces would induce unnecessary pre-load to the structures, reducing their load-carrying capability (L Liu, 2013). Worse still, assemblers may not be able to assemble the parts at all due to major misalignment. Some assemblers make use of shims to close whatever gaps (Krithika Manohar, 2018) that exist due to warpage or springback but this would lead to other issues. The use of shims introduces additional weight to the aircraft while the selection of fasteners would need to be tailored down to individual part and hole, increasing assembly time and cost significantly (Junhao Chang, 2019). Additionally, if the assembly surfaces are on the aerodynamic side, the surfaces mismatch would result in staggered profile and affect the aerodynamics (Wolf, 2021).

This study is a collaboration between a manufacturing company, CTRM Aero Composites Sdn. Bhd. (referred simply as CTRM AC), an industrial research institute, Aerospace Malaysia Innovation Centre (AMIC), and International Islamic University Malaysia (IIUM). CTRM AC mainly provided test specimens while AMIC managed the project from financial aspects in addition to providing the necessary measurement equipment.

1.2 STATEMENT OF THE PROBLEM

A good warpage and springback predictive model must be valid for and applicable to the actual aircraft structures such as the main rib of a wing flap in this case. The predictive model needs to be validated through experiments by comparing the result of the model with the actual measurement of fabricated specimens. This validation has been done by previous work (Mezeix, et al., 2015), (M N M Nasir L. M., 2016) in establishing springback database for thin laminates (4 to 16 plies). But the applicability of the model can be questioned if it is to be used to predict warpage and springback for structures of thicker dimension (20 to 28 plies) such as the main rib of flap since the validation did not cover such thicknesses. Nonlinearities which may exist in the real world may not have been accounted for in the existing model.

Therefore, this study, which employed similar methodology as the thin specimens, would expand the scope of the validation by extending the warpage and springback database to include specimens of thicker dimensions. With the database for thick laminates, additional validation of the predictive model were carried out to further improve the accuracy of the model. In addition, thicker laminates exhibited relatively smaller amount of springback (Nikhare, 2020). This small magnitude produced even smaller variation among specimens with different parameters. This situation demanded measurement equipment of higher accuracy in order to detect the small variation. For this reason, 3D scanning was brought into this study.

1.3 PURPOSE OF THE STUDY

The purpose of this study was to analyse the warpage and springback behaviour of laminates and to determine the parameters involved in the proposed predictive model in order to predict the warpage and springback behaviour of the laminates.

1.4 RESEARCH OBJECTIVES

There were two main objectives of this research work:

1. To analyse the effects of different thicknesses and shapes to the warpage and springback behaviour of laminates using controlled experiments.
2. To propose a predictive finite element model used to predict and estimate the warpage and springback of thick laminates with different construction.

1.5 RESEARCH QUESTIONS

When carrying out research works relating to the study of warpage and springback of thermoset composites, some questions were triggered in order to gain deeper understanding on the topic. These questions needed to be addressed through experiments and analysis. It is thus important to put forth these questions prior to determining the actions that need to be taken for data collection and analysis so that the results of the analysis did contain the information that was required to answer some, if not all, of these questions. There were six research questions that need to be answered:

1. What are the causes of warpage and springback phenomenon?
2. How can warpage and springback behaviour of laminates be described and quantified?
3. What are the parameters affecting the extent of warpage and springback of laminates?
4. What is the suitable model and method to predict warpage and springback behaviour of laminates?