Multi-scale analysis of wrinkling during consolidation of thermoset composites

by Vu An Le

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of
Dr Sanjay Nimbalkar
Dr Sardar Malekmohammadi
Dr Emre Erkmen
Dr Navid Zobeiry

University of Technology Sydney
Faculty of Engineering and Information Technology

July 2022

Declaration

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Vu An Le declare that this thesis, is submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program Scholarship.

Signature: Production Note: Signature removed prior to publication. Vu An Le

Date: 15/07/2022

Acknowledgements

This work would not have been possible without the support of my colleagues, friends and family and I owe all of them my most profound thanks.

I am sincerely grateful to all my supervisors, Dr Emre Erkmen, Dr Sardar Malek, Dr Rijun Shrestha, Dr Sanjay Nimbalkar and Dr Navid Zobeiry for their invaluable support, encouragement and guidance throughout my PhD study. I would like to thank Dr Emre Erkmen for accepting me as his PhD student, giving me a chance to work with Dr Sardar Malek when he was about to leave UTS and still providing me with his supervision remotely. Great appreciation for the excellent inspiration and continuous support from Dr Sardar Malek is expressed. His constructive criticisms and encouragement constantly motivated me. Particular gratitude is given to Dr Sanjay Nimbalkar for his kindness and assistance in the final year of my PhD. I would like to acknowledge and thank Dr Navid Zobeiry who was always willing to provide me with important advice for achieving my major milestones during my 4-year study. Without his advice, detailed comments and constructive feedback, my work would not have been possible.

My sincere and deep respect goes to the staff at the Faculty of Engineering and IT, especially Prof Hadi Khabbaz, Dr Nadarajah Gowripalan and Mrs Van Le for their dedicated encouragement, attention and support throughout my PhD candidature. I would like to acknowledge the financial support provided by International Research Scholarship and UTS-VIED scholarship. I also truly value the friendship of several close friends who I met in Sydney. I appreciate their time for listening, sharing and encouraging me during my PhD.

Lastly, I would like to thank my family without whom this work would not have been accomplished. I would like to thank my beloved parents for their endless and unconditional love throughout my life. I would like to thank my dear sisters and brothers for standing at my side and encouraging me to follow my passion. Special thanks go to my parents-in-law for taking care of my lovely son, as this helped me to accomplish my PhD program as planned.

List of publications

Le, A., Zobeiry, N., Erkmen, E. & Malek, S. 2019, 'Buckling analysis of multilayered beams with soft and rigid interfaces', *ICCM22*, Engineers Australia, Melbourne, Vic, pp. 204-12.

Le, V.A., Zobeiry, N., Erkmen, E. & Malek, S. 2021, 'Buckling behaviour of laminated viscoelastic composites under axial loads', *Mechanics of Materials*, 159, 103897.

Le, V.A., Nimbalkar, S., Zobeiry, N. & Malek, S. 2022, ' An efficient multi-scale approach for viscoelastic analysis of woven composites under bending', *Composite Structures*, 292, 115698.

Le, V.A., Nimbalkar, S., Zobeiry, N. & Malek, S. 2022, ' Multi-scale viscoelastic bending analysis of laminated composites with soft interfaces', Full paper submitted to *ECCM20*, Lausanne- Switzerland.

Table of content

List of figures

List of tables

Abstract

Carbon fibre is known for its high strength, light weight and durability. The aerospace and automotive industries have demonstrated a strong interest in utilising carbon fibre when designing their structural parts. However, there are still barriers preventing other industries from realising the full potential of such advanced laminated composites. Among these challenges are the formation of wrinkles and defects throughout the manufacturing process. Currently, manufacturing composite parts with mitigation of defects greatly relies on the designers' experience and the outcomes of trial-and-error procedures. Due to the high cost of experiments and a large number of process parameters involved in composite manufacturing, an improved understanding of wrinkle formation is desirable for industries. Therefore, predictive modelling to aid design engineers in their understanding of the wrinkling phenomenon has become vital over the past two decades.

According to a few recent studies, fibre waviness, misalignment and the complex viscoelastic behaviour of a composite's layered structure during cure are the primary causes of defects, wrinkle formation, and eventual rejection of large composite components. However, the relationship between these factors and the wrinkling of plies caused by micro-buckling has not been investigated quantitatively. Furthermore, these effects are not fully captured in current process models. This research aims to develop an efficient strategy for analysing the multi-scale mechanisms of wrinkling due to buckling of plies during the composite consolidation process. A multi-scale approach that can be incorporated into current process models is proposed for this purpose. Using the suggested approach, the wrinkling response of plies under compressive and bending loads are predicted numerically. Wrinkling wavelengths and critical buckling strength of flat laminates are compared with wrinkling profiles and the strength values reported in the literature. Unlike previous studies, the viscoelastic contribution of resin as well as fibre stiffness and fabric architecture (for woven composites) are taken into account. The effect of these parameters on the buckling behaviour of fibres and the orthotropic nature of plies are also investigated at different scales, quantitatively. Results highlight that the viscoelastic properties of the resin have a considerable effect on the buckling response of woven composites and thus on wrinkle formation during the early stage of cure. Experimental studies are suggested for characterizing the viscoelastic behaviour of resins and its effect on the micro-buckling response of fibres during cure.