Influence of Meso-Scale Parameters on the Large-Deformation Behaviour of Ultra-Thin Woven Fibre Composites

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Degree of Master of Science

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February 2026

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Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering

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Declaration

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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The above candidate has carried out research for the Masters thesis under my supervision.

.... Date : 07/02/2026

Prof. H.M.Y.C. Mallikarachchi

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Dr. H.M.S.T. Herath

Abstract

Ultra-thin woven composite laminates are widely used in deployable space structures, in which they experience large curvatures during both folding and deployment. Under such conditions, these laminates exhibit pronounced non-linear bending behaviour characterised by a progressive reduction in stiffness. Accurate prediction of this response is essential for reliable structural design. This study presents a comprehensive numerical framework to investigate the non-linear bending behaviour of ultra-thin two-ply plain-weave composite laminates using a representative unit cell based homogenisation approach.

A multi-scale finite element model was developed that integrates an explicit geometric representation of the woven architecture, geometric non-linearity associated with large deformations, strain-dependent material non-linearity of tows and cohesive traction–separation behaviour at tow–tow and inter-ply interfaces. The proposed framework enables direct evaluation of the laminate moment–curvature response and extraction of homogenised stiffness parameters.

The numerical predictions show strong agreement with experimental results over the full range of curvatures investigated. The model accurately captures the progressive reduction in bending stiffness with increasing curvature and reveals that this degradation arises from the combined influence of geometric effects, inter-tow interactions and material non-linearity of carbon fibres. At moderate curvatures, stiffness reduction is dominated by geometric mechanisms, including tow flattening, cross-sectional deformation and neutral-axis shift. At higher curvatures, cohesive damage and micro-slipping between adjacent tows become the primary contributors.

Inclusion of resin layers between plies was shown to be critical for accurate stiffness prediction, as the resin constrains inter-ply motion and increases the number of effective contact interfaces, enabling close replication of experimentally measured initial bending stiffness. A comparative investigation of fibre in-phase and out-of-phase stacking arrangements demonstrated that ply alignment has a significant influence on bending stiffness.

Overall, the proposed homogenisation framework provides a robust and physically grounded tool for predicting the complex bending behaviour of ultra-thin woven composites. In addition to reproducing experimental responses with high accuracy, the approach enables extraction of homogenised ABD stiffness matrices suitable for macro-scale modelling and design of deployable composite space structures.

Keywords : *cohesive behaviour, damage criterion, non-linear bending behaviour, representative unit cell, ultra-thin woven fibre composites*

Dedication

To my parents and brother, whose support made all of this possible.

Acknowledgement

First and foremost, I wish to express my sincere and profound gratitude to my supervisors, Prof. Chinthaka Mallikarachchi and Dr. Sumudu Herath, for providing me with the invaluable opportunity to undertake this research under their expert supervision. Their exceptional technical expertise, insightful guidance and unwavering support were instrumental throughout the course of this study and continually motivated me to strive for the highest academic standards. This research would not have been possible without their dedicated mentorship and commitment.

I would also like to extend my sincere appreciation to Prof. Priyan Dias for the constructive comments and valuable advice provided during progress reviews. His insightful suggestions encouraged critical thinking and inspired alternative perspectives in addressing complex research challenges.

My special appreciation is extended to Uditha Weerasinghe for initiating the incorporation of material non-linearity into meso-scale modelling, and to Eroshan Gamage for compiling and summarising the experimental results referenced in this study. I am also grateful to Chamika Wanasinghe and Nirodha Sandaruwan for their consistent support and engaging technical discussions, which significantly enriched the quality of this research.

I would like to acknowledge with gratitude the academic staff of the Department of Civil Engineering at the University of Moratuwa for their encouragement, guidance, and support throughout my academic journey.

I am deeply thankful for the financial support provided by the Indo–Sri Lanka Joint Research Programme, without which the successful completion of this research would not have been possible.

Finally, I gratefully acknowledge all those who, in any capacity, contributed to the successful completion of this work.

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Nomenclature

Δl	Nominal weave length, mm
δ'	Traction separation, mm
γ	Engineering shear strain, mm/mm
κ	Mid-plane curvature, 1/mm
ν	Poisson's ratio
ϕ	Rotation angle change, Rad
ρ	Density, kg/m^3
θ	Initial angle, Rad
ε	Mid-plane strain, mm/mm
ε_m	Meso-scale finite strain tensor, mm/mm
A_{ij}	Coefficients of upper-left 3 $\times$ 3 sub-matrix of ABD, N/mm
A_{tow}	Average cross-sectional area of a tow, mm^2
B_{ij}	Coefficients of upper-right 3 $\times$ 3 sub-matrix of ABD, N
C_M	Macro-scale material constitutive tensor
C_m	Meso-scale material constitutive tensor
d	Major axis diameter, mm
D_{ij}	Coefficients of lower-right 3 $\times$ 3 sub-matrix of ABD, Nmm
E	Elastic modulus, N/mm^2
F	Nodal force matrix
G	Shear modulus, N/mm^2

h Minor axis diameter, mm

K Traction stiffness, MPa/mm

k Non-dimensional parameter

l Arm length, mm

l_s Free length of the specimen, mm

M Moment per unit length stress resultant, Nmm/mm

N Force per unit length stress resultant, N/mm

n_m Normal vectors

P Applied load, N

P_i Control points

P_M Macro-scale finite stress tensor, N/mm^2

r Moment arm length, mm

s Non-dimensional path parameter

t Traction stress, MPa

t_{tow} Average tow thickness, mm

U Nodal displacement matrix

u Translations in x direction, mm

U_M Macro-scale deformation gradient, mm

U_m Meso-scale deformation gradient, mm

v Translations in y direction, mm

V_f Fibre volume fraction

W Areal weight, g/m^2

w Translations in z direction, mm

w_m Meso-scale micro-fluctuations

w_{tow} Average tow width, mm

X_M Position vector in reference configuration

x_m Position vector in deformed configuration