

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

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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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Date : 07/02/2026

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.

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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 3×3 sub-matrix of ABD, N/mm
A_{tow}	Average cross-sectional area of a tow, mm ²
B_{ij}	Coefficients of upper-right 3×3 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 3×3 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