PREDICTING BENDING BEHAVIOUR OF DEPLOYABLE BOOMS MADE OF THIN WOVEN FIBRE COMPOSITES

D.C.D.K. Karannagodage

178085P

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa

Sri Lanka

December 2018

PREDICTING BENDING BEHAVIOUR OF DEPLOYABLE BOOMS MADE OF THIN WOVEN FIBRE COMPOSITES

D.C.D.K. Karannagodage

178085P

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

Department of Civil Engineering

University of Moratuwa

Sri Lanka

December 2018

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.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

……………………………………… Date: 1st December 2018

D.C.D.K. Karannagodage

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

……………………………………… Date: 1st December 2018

Dr. H.M.Y.C. Mallikarachchi

Abstract

Design of advanced space structures like solar sails and reflectors are limited by the volume and payload capacity of launch vehicles. Thus, there is a trend to utilize deployable structures made of ultra-thin fibre composite materials over traditional mechanical hinges. Use of thin woven fibre composites enables them to self-deploy using stored strain energy and hence unfolds several benefits such as high strength to weight ratio, less complexity, negligible frictional effects during deployment.

Booms made of thin fibre composite with epoxy matrix have been widely used in space structures since 1980s. Even though the deformable booms with ultra-thin composites conquer the aforementioned limitations, folding of such structures are limited to their elastic regime. Once the folding is extended beyond the elastic region, these composites are either subjected to fibre failure or to plastic deformation of matrix. Thus, now scientists are investigating the possibility of using more flexible elastomers, i.e. silicone which allows the fibres to micro-buckle and hence survive under extreme curvatures.

However, use of soft elastomers in space structures can lead to poor structural performance after deployment. Also the composites like Carbon Fibre Reinforced Silicone (CFRS) are unable to store enough strain energy to provide required force for self-deployment when released.

Dual matrix fibre composites were invented to solve that problem. Dual matrix fibre composites contain a continuous fibre reinforcement with soft elastomeric matrix like silicon in specified hinge regions and traditional epoxy matrix elsewhere to stabilize the deploying behaviour. Thus, the dual-matrix composites can entertain the high curvatures up to 180^0 without failures in the deployable structures. As this matrix medium allows the fibres to micro-buckle (stress relief mechanism for the fibres in the compression zone) that enhance the folding mechanism to achieve higher curvatures without showing significant damage to the fibres in nonlinear region.

It has been observed that these woven fibre-silicone composites have a highly non-linear moment-curvature relationship while there is no significant variation in axial stiffness. Further it has been shown that the classical lamination theory is over predicting the bending stiffness by 2 – 4 times when it comes to woven composites made of one to three plies.

This research is focussed on understanding the influence of varying bending stiffness with the degree of deformation in predicting quasi-static deployment behaviour of dual-matrix composite booms. A case-study of a three-ply dual-matrix composite boom made of thin woven glass fibre has been selected and simulated with a commercial finite element package. It has been shown that bending stiffness of the soft-elastomer region needs to be varied with the degree of deformation for accurate predictions.

Change of bending stiffness is attempted in three different methods. First the analysis has been performed with a series of independent simulations with specified bending stiffness for each model. Secondly the possibility of using import analysis where stress and material state is imported from a previous step. Finally an attempt is made to develop user-subroutine where the bending stiffness properties of the structure can be concurrently updated with degree of deformation.

Key Words: deployable booms, dual-matrix composites, moment-rotation response, user-subroutine

Dedication

To my beloved parents and sister, without whom none of my success would be possible.

Acknowledgement

First of all I would like to express my sincere gratitude to my research supervisor and mentor Dr. Chinthaka Mallikarachchi for his technical guidance and encouragement throughout the research. I would also like to thank Prof. Priyan Dias and Prof. Rangika Halwatura for providing valuable comments and advices during progress reviews.

My special thanks goes to the academic staff of Civil Engineering Department, University of Moratuwa. I am grateful to Seyon Mierunalan, Varakini Sanmugadas, Milinda Yapa, Kanthasamy Ubamanyu, Hasitha Wijesuriya and Sahangi Dassanayake for helpful discussions and immense support given as research colleagues throughout this research.

Finally, I want to thank the Senate Research Committee of University of Moratuwa, National Research Council, Sri Lanka and Ceylon Steel Cooperation for providing financial support.

Table of Contents

List of Figures

List of Tables

Nomenclature

List of Abbreviations

DNSC	Danish National Space Centre
NASA	National Aeronautics and Space Administration
CFRS	Carbon Fibre Reinforced Silicone
FRC	Fibre-Reinforce Composites
CLT	Classical Lamination Theory
CFRS	Carbon Fibre Reinforced Silicone
UD	Unidirectional

List of Symbols

$\bar{Q}$	Ply stiffness
M	Deployment moment
θ	Rotational angle
ABD_E	Constitutive relationship of AQ/Epoxy
ABD_S	Constitutive relationship of AQ/Silicon
$\propto$	Time scaling factor
ξ	Fraction of critical damping in the fundamental frequency mode
l_{min}	Shortest length of finite element
c_d	Dilatation wave speed
E	Modulus of elasticity
P	Material density
$\dot{\epsilon}_{vol}$	Volumetric strain
c_v	Damping coefficient

v	Velocity
n	Normal vector
υ	Poisson's ratio
E_{tot}	Total energy stored and/or dissipated
E_{wk}	Work of external forces
E_i	Summation of internal energy
E_{vd}	Viscous dissipation
E_{ke}	Kinetic energy