

INVESTIGATION OF CREASES IN ULTRA-THIN MEMBRANES

D. M. S. P. Dassanayake

188037G

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa
Sri Lanka

September 2019

INVESTIGATION OF CREASES IN ULTRA-THIN MEMBRANES

D. M. S. P. Dassanayake

188037G

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

Department of Civil Engineering

University of Moratuwa
Sri Lanka

September 2019

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 :

D. M. S. P. Dassanayake

The above candidate has carried out research for the Master's thesis under my supervision.

..... Date :

Dr. H.M.Y.C. Mallikarachchi

Abstract

The use of thin membranes is widespread in a variety of applications in a range of industries owing to the lightweight nature and small packaged volume attainable by them. When facilitating the storage of large areas of membranes by folding—specifically in aerospace applications, the resulting creases alter the physical state and material properties of the overall membrane structure. Even though numerical modelling is preferred as a viable tool in replicating space environments on earth in the form of reduced gravity and air drag, the idealisations utilised in these analyses require validation via small-scale experiments. The significance of this process is highlighted due to past endeavours which failed to idealise the crease mechanics accurately, leading to inaccurate predictions and eventual failure in complete missions. Moreover, the use of virtual testing in this regard is limited by the unavailability of accurate experimental data.

In this research, an attempt has been made to characterise the crease mechanics of multiple creased thin Kapton 100 HN polyimide membranes using an experimental study. A combination of specimens consisting of two and three creases have been analysed in this regard, and moment–angle responses were plotted using results of physical experiments. The results indicated different crease stiffnesses for each crease in a parallel-creased specimen, with the highest stiffness observed for a crease nearest to the pinned support. However, all the stiffness values obtained herein were observed to be of a lower order than the simulation and physical experimental results obtained by previous researchers for membranes with a single crease, which could be attributed to the precise measurements taken during the experimental study and the incorporation of the effect of self-weight of the membrane into its moment–rotation response, which was neglected in earlier studies. The time dependence of the opening behaviour

was also studied, and it was identified that the membrane achieves a constant opening angle in a shorter time duration on being loaded.

An improved experimental setup was designed and developed, on identifying the limitations and inaccuracies observed in the experimental setup devised by previous researchers. This ensured controlled displacement being offered to the membrane for capturing its deployment behaviour over a wider regime of loading, along with precise force measurement. The setup included additional measures to facilitate its usage for specimens of a wider range of dimensions, and to ensure proper alignment of the membrane, thereby enhancing the accuracy of the results obtained via the physical experiments which would then be utilised for idealisation schemes of deployment simulations in virtual environment.

Crease stiffness determined for single-creased membranes utilising the improved setup was implemented in Abaqus/Explicit finite element package for the purpose of predicting the deployment behaviour of membrane structures with multiple creases accordingly. The crease-line was represented with connector elements specifying the rotational elasticity, and was observed to have negligible effect on the deployment which contradicts the experimental observations. Hence, further investigations are required for assessing the accuracy of this claim.

A quasi-static simulation was carried out for a simple creased unit based on traditional “Waterbomb” base for predicting the deployment behaviour consisting of intersecting creases. The simulation developed in Abaqus/Explicit environment was able to capture the deployment response observed in the physical experiments, in terms of maximum deployment ratio and shape on incorporating the effect of gravity to the simulation.

Keywords : *ultra-thin membranes, crease mechanics, rotational stiffness, multiple parallel creases, finite element simulations*

Dedication

To my parents, whose unyielding love, support and encouragement has enriched my soul and inspired me to pursue and complete this research.

Acknowledgement

First and foremost, I would like to express my sincere gratitude to my supervisor, Dr. Chinthaka Mallikarachchi, for providing me with technical guidance, valuable insights, advices and encouragement throughout the past year. Without his support, this would have not been possible. Secondly, I would like to thank Prof. Priyan Dias and Prof. Rangika Halwatura for their conducive comments and suggestions during progress reviews, which contributed greatly towards the research directives taken thus far.

Thirdly, I would like to extend my special thanks to Mr. K.H.J. Mangala, of the Department of Mechanical Engineering, University of Moratuwa for the immense support offered in the form of technical guidance and workmanship for the development of the improved experimental setup for controlled deployment of thin folded membranes. My sincere appreciation goes to Seyon Mierunalan, Varakini Sanmugadas, Hasitha Wijesuriya, Vishnu Punithavel, Roanga De Silva, Chameera Randil, Isuru Nanayakkara, Sujeeka Nadarajah and Hasini Weerasinghe for being great research colleagues and for their support and helpful conversations throughout my research work.

Further, I would like to recognise the technical staff of the Mechanics of Materials and Structural Testing Laboratories of the Department of Civil Engineering, University of Moratuwa for supporting me throughout the laboratory experiments. Moreover, for providing me with the necessary knowledge and expertise required to carry out this research, my heartfelt gratitude is extended to the academic staff of the Department of Civil Engineering, University of Moratuwa and also to the authors of the literature referred, which paved the way for this research.

Finally, I would like to thank the Ministry of Science, Technology and Research under Indo–Sri Lanka Joint Research Project, National Research Council, Sri Lanka and Senate Research Committee of the University of Moratuwa for the financial assistance provided, without which this would not have been a possible achievement.

Contents

Declaration	i
Abstract	ii
Dedication	iv
Acknowledgement	v
Contents	vii
List of Figures	x
List of Tables	xiii
Nomenclature	xiv
1 Introduction	1
1.1 Deployable Thin Membrane Structures	1
1.2 State of the Art	2
1.3 Alternatives to Physical Testing	5
1.4 Scope and Aim	8
1.5 Chapter Organisation	9
2 Literature Review	11
2.1 Creased Membrane Structures	11
2.1.1 Crease patterns	11
2.1.2 Applications	13
2.2 The Phenomenon of a Crease	15
2.2.1 Rigid Origami versus Non-Rigid Origami	15
2.2.2 Hinge Response at the Crease	16

2.3	Studies on Creased Membrane Structures	19
2.3.1	Analytical Studies	19
2.3.2	Experimental Studies	22
2.3.3	Numerical Studies	25
3	Multiple Parallel-creased Membranes	29
3.1	Moment–Rotation Response of Parallel Creases	29
3.1.1	Experimental setup	30
3.1.2	Moment and angle measurements	34
3.1.3	Self-weight of the membrane	34
3.1.4	Time dependence of opening angle	37
3.2	Results and Discussion	40
3.2.1	Limitations in the existing experimental setup	45
4	Improved Experimental Setup	46
4.1	Controlled displacement	46
4.2	Force measurement	48
4.2.1	Measuring scale	48
4.2.2	Extension of the thread	49
4.3	Boundary conditions	49
4.4	Horizontal and vertical alignment	50
4.5	Results and Discussion	51
5	Implementation in Finite Element Package	54
5.1	Modelling the crease-line and membrane panels	54
5.2	Finite element model of multiple creased thin membranes	55
5.2.1	Finite element model of membrane with two creases	56
5.2.2	Abaqus/Explicit Solver	59
5.3	Results and Discussion	60
5.3.1	Sensitivity of the simulation for membrane with two creases	60
5.3.2	Comparison with experimental results	63
6	Quasi-static Deployment Simulation of a Creased Unit	64
6.1	Crease pattern	64
6.2	Details of the experimental study	65
6.3	Finite element model of the creased unit	66
6.4	Results and Discussion	67
6.4.1	Sensitivity of the simulation for the creased unit	67

6.4.2	Comparison with physical experiments	69
7	Conclusions and Future Work	71
7.1	Conclusions	71
7.2	Recommendations for Future Work	72
	References	73
	Appendix A: Moment–Angle Data	81
1.	Single Crease Stiffness (Initial Experimental Setup)	81
2.	Single Crease Stiffness (Improved Experimental Setup)	84
3.	Stiffness of Membrane with Two Creases (Initial Experimental Setup)	86
4.	Stiffness of Membrane with Two Creases (Initial Experimental Setup - Different Orientations)	90
5.	Stiffness of Membrane with Three Creases (Initial Experimental Setup)	94
	Appendix B: Keywords of Abaqus Input Files	97
1.	Predicting Deployment Behaviour of Membrane with Two Parallel Creases	97
2.	Quasi-static Deployment Simulation of a Simple Creased Unit	99

List of Figures

1.1	(a) Artist's concept of LightSail-2 above Earth (b) An image taken during its sail deployment sequence	2
1.2	IKAROS Solar Sail Deployment Process	3
1.3	LightSail-2 spacecraft sitting on its low friction deployment table following a successful solar sail deployment test at Cal Poly San Luis Obispo on January 28, 2016	4
2.1	Miura-Ori Tessellation	12
2.2	Two waterbomb bases and their tessellations	13
2.3	Applications of creased membrane structures	14
2.4	The geometry of a single straight crease described by its length L and three unit vectors $(\vec{u}, \vec{v}, \vec{w})$	15
2.5	Geometric state of membrane	16
2.6	Schematic of the experimental setup used to calculate the moment–angle relationship in a crease	18
2.7	Relaxation process and the mechanical response of a single creased Mylar sheet to an external strain	23
2.8	(a) Moment–angle relationship for a Mylar sheet of $350 \mu\text{m}$ thickness (b) Stiffness k for different thicknesses	24
2.9	Sketch of the pinching experiment used for measuring dimensionless crease stiffness	24
2.10	Linear response between the resistive moment and opening angle .	25
2.11	Schematic diagram of the steps of simulation for creasing and subsequent uniaxial tensile test of thin Kapton membrane	26
2.12	Deformed shape of $25 \mu\text{m}$ Kapton membrane	27
3.1	Multiple parallel-creased membrane	29
3.2	Parallel-creased membrane specimens	31

3.3	Creasing procedure	32
3.4	Self-opening action of creases	32
3.5	Boundary conditions	33
3.6	Loaded specimens	34
3.7	Free-body diagram of creases	35
3.8	Free-body diagram for resistive moment derivation	36
3.9	Achieving static equilibrium - load cases	37
3.10	Static configuration - unloaded case	38
3.11	Static configuration - loaded case	39
3.12	Moment–rotation relationship for a single crease	41
3.13	Moment–rotation relationship for two creases	42
3.14	Orientations of the specimen	42
3.15	Moment–rotation relationship for two creases - different orientations	43
3.16	Moment–rotation relationship for three creases	44
4.1	Improved experimental setup	46
4.2	Controlling displacement	47
4.3	Calibration of measuring scale	48
4.4	Boundary conditions	50
4.5	Additional components	51
4.6	Improved experiments	52
4.7	Improved moment–rotation relationship for a single crease	53
5.1	Local axes and vector definitions for (a) crease region (b) a connector element	55
5.2	Mesh refinement at the crease	57
5.3	Node-based connectors placed perpendicular to the crease-line	58
5.4	Comparison of kinetic energy profile with the internal energy profile of the finite element simulation for membrane with two creases	61
5.5	Energy variation of the finite element simulation for membrane with two creases	62
5.6	Snapshots taken during deployment simulation at different ratios of deployment compared with the shape of membrane observed during the experiment	63
6.1	Crease pattern	64
6.2	Simple creased unit (experimental study)	65

6.3	Deployment of simple creased unit (experimental study)	66
6.4	Finite element geometry of simple creased unit	67
6.5	Comparison of kinetic energy profile with the internal energy profile of the finite element simulation for creased unit	68
6.6	Energy variation of the finite element simulation for creased unit .	68
6.7	Energy variation of the finite element simulation for creased unit .	69
6.8	Snapshots taken during deployment simulation at different ratios of deployment compared with the final shape of structure observed during experiments	70

List of Tables

3.1	Experimental data for a membrane specimen with two creases . .	40
3.2	Summary of crease stiffnesses obtained via regression analysis . .	44
4.1	Single crease stiffness	53
5.1	Material properties of Kapton used in the finite element simulation of multiple creased membrane	57

Nomenclature

List of Abbreviations

ARGOS Active Response Gravity Offload System

DLR German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt)

ESA European Space Agency

IKAROS Interplanetary Kite-craft Accelerated by Radiation of the Sun

JAXA Japanese Aerospace Exploration Agency

LEO Low Earth Orbit

NASA National Aeronautics and Space Administration

PDT Pacific Daylight Time

UTC Coordinated Universal Time

List of Symbols

\hat{V}_i^j Vector in the i^{th} direction for node j

ν Poisson's ratio

ω_{max} Highest Eigenvalue of the model

ϕ Neutral angle

ρ Material density

θ Current crease opening angle

ξ Fraction of critical damping in the fundamental frequency mode

c_d	Dilatational wave speed
c_v	Viscous damping coefficient
D_f	Fully deployed dimension of creased structure
E	Modulus of elasticity
E_i	Internal energy of the system (elastic, inelastic and artificial strain energy)
E_{ke}	Kinetic energy
E_{total}	Total energy of the system
E_{vd}	Energy absorbed by viscous dissipation
E_{wk}	Work done by external forces
F	Tensile load
k	Crease-line stiffness
k_o	Crease-line stiffness during crease actuation (and panel bending)
k_r	Crease-line stiffness during self-opening
l	Length of a membrane panel
L^*	Non-dimensional length
l_h	Horizontal distance from the crease-line to the loaded tip
l_{min}	Minimum length of the finite element
M	Resistive moment at the crease-line
M_c	Kinematic moment in the connector
t	Thickness
w	Width of the membrane coupon