

LB/TH/22/2025

TH5857

**NUMERICAL SIMULATION OF THIN MEMBRANES
WITH CURVED CREASES**

Kuruppu Achchige Lasith Hansaka Kuruppu

238037M

Master of Science (Major Component Research)

Department of Civil Engineering

Faculty of Engineering

University of Moratuwa

Sri Lanka

March 2025

NUMERICAL SIMULATION OF THIN MEMBRANES WITH CURVED CREASES

Kuruppu Achchige Lasith Hansaka Kuruppu

238037M

Thesis submitted in partial fulfillment of the requirements for the degree
Master of Science (Major Component Research)

Department of Civil Engineering
Faculty of Engineering

University of Moratuwa
Sri Lanka

March 2025

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. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: *UOM Verified Signature* Date: 2025-03-02
K.A.L.H. Kuruppu

The above candidate has carried out research for the Masters thesis under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Prof. H.M.Y.C. Mallikarachchi
Dr. H.M.S.T. Herath

Signature of the Supervisor: Date: 2025-03-03

.....
Prof. H.M.Y.C. Mallikarachchi

.....
Dr. H.M.S.T. Herath

DEDICATION

I hereby dedicate this to my family and all the teachers who have been the backbone of my life.

ACKNOWLEDGMENT

I would like to extend my gratitude to all the personnel who have given their immense support throughout completing this thesis.

I would like to first and foremost thank my supervisors Prof Chinthaka Mallikarachchi and Dr Sumudu Herath for giving me unwavering support and dedication towards me and my work. Your support has been a great motivation for me, and I am thankful for the knowledge I gained under you.

Also, I hereby thank you for the help provided by the head of the department and all the lecturers of the Department of Civil Engineering for the guidance and help given to me.

Also, I would like to thank my family and friends for their immense support throughout this journey.

To all the others who helped me thank you again for your support. Without your help completion of this thesis would not have been possible.

Sincerely,

K.A.L.H. Kuruppu

ABSTRACT

Deployable membranes are commonly used in the construction of solar sails, solar arrays, and sun shields. These structures are fabricated on the ground and then deployed to their operational configuration in space. These structures are very large in dimensions but need to be compacted into a very small package that can be stowed inside a launch vehicle. Membrane structures are often folded using different crease patterns and wrapped around a central hub to achieve the compacted state. The thickness of the membranes place and important role in selecting a folding pattern as one length of the membrane increases with layers overlapping around the hub. To get a smooth wrap, a viable option is to change the crease pattern geometry to a curved crease with changing curvature to accommodate increased thickness. Changing the geometry into a curved crease pattern needs to be analyzed properly to understand its suitability for use in deployable membrane structures. This study analyzes the effectiveness of curved and straight crease wrapping structures. Two numerical models are used for the analysis of each crease pattern to understand behavior. The curved crease wrapping pattern shows good overall wrapping motion with less stresses in the initial stages when compared to the straight crease wrapping pattern. The stress is reduced up to 26% in the initial stages. Also, a crease idealization technique is introduced in this study to incorporate the self-opening behavior of the membrane creases into the numerical model. This idealization technique is further evaluated for a multiple crease geometry with a Miura-Ori model. The crease modeling technique shows a good overall fit with the experimental results validating the numerical simulations.

Keywords: Deployable structures, membrane, wrapping structures, curved crease

TABLE OF CONTENTS

Declaration	i
Dedication	ii
Acknowledgment	iii
Abstract	iv
Table of Contents	v
List of Figures	vii
List of Tables.....	ix
Chapter 1	1
Introduction	1
1.1 Deployable Membrane Structures	1
1.2 Thickness Effect on Spirally Folded Membrane Structures.....	1
1.3 Scope and Aim	3
1.4 Chapter Organization	4
Chapter 2	5
Literature Review.....	5
2.1 Spirally Stowed Straight Crease Membranes	5
2.2. Studies on Spirally Stowed Curved Crease Membranes	7
2.3. Analysis of Crease Folding Structures	9
2.3.1. Straight Crease Folding Mechanics	9
2.3.2. Curved Crease Folding Mechanics	9
2.4. Numerical Simulation Techniques of Wrapping Structures.....	10
Chapter 3	11
Geometry of Curved Crease Wraps	11
3.1 Impact of Membrane Thickness on Folding.....	11
3.2 Generation of Curved Crease to Accommodate Thickness.....	12
3.3 Selected Geometry	13
Chapter 4	17
Experimental Analysis of Self-Opening Behavior for Multiple-Creased Structures.	17
4.1. Crease Mechanics of a Folded Membrane	17

4.2	Miura-Ori Specimen Preparation	19
4.3	Miura-Ori Folding Experiments	20
4.4.	Miura-Ori Experiment Results Analysis	21
Chapter 5		24
Simulation of Crease Folding Behavior		24
5.1.	Connector Definitions and Stiffness Assignment	24
5.2.	Miura-Ori FEM Model	25
5.2.1	Model Details	27
5.2.2	Abaqus/Standard Simulation Implementation	28
5.3	Analysis of Numerical Simulation Results	29
Chapter 6		31
Simulation of Curved Crease Wrapping Structure		31
6.1	Experimental Setup and Results	31
6.2	Numerical Modelling of a Single Curved Crease Fold	32
6.3	Numerical Modelling of Wrapping Structure	35
6.4	Numerical Model Results	36
Chapter 7		39
Conclusions and Future Work		39
References		41

LIST OF FIGURES

Figure 1.1 Geometric effects due to the thickness of panels.....	2
Figure 1.2 Bulging storage.....	2
Figure 1.3 Different folding and wrapping patterns.....	3
Figure 2.1 Guest and Pellegrino's spiral folding pattern.....	5
Figure 2.2 Scheel's fold pattern.....	6
Figure 2.3 Circumferential folding pattern.....	6
Figure 2.4 Circumferential folding pattern folding steps.....	7
Figure 2.5 Curved creases for spiral folding pattern.....	7
Figure 2.6 Beech leaf pattern.....	8
Figure 2.7 Spiral folding pattern.....	8
Figure 2.8 Two developable surfaces assembled through a developability constraint	9
Figure 3.1 Effective thickness approximations.....	11
Figure 3.2 Flat and folded geometry relationship.....	13
Figure 3.3 Variation of S and theta.....	14
Figure 3.4 Generated crease in radial coordinate system.....	15
Figure 3.5 Placement of creases parallelly.....	15
Figure 3.6 Constructed spiral folding pattern.....	16
Figure 4.1 Behavior of a crease.....	17
Figure 4.2 Moment rotation curves.....	18
Figure 4.3 Predicted rotational stiffness value respect to thickness.....	19
Figure 4.4 Specimen preparation.....	19
Figure 4.5 Miura-Ori specimen details.....	20
Figure 4.6 Experimental apparatus for Miura-Ori folding.....	21
Figure 4.7 300HN experimental results analysis.....	22
Figure 4.8 Experimental results of force vs displacement 200HN and 300HN.....	22
Figure 4.9 Experimental results of force vs displacement with vertex cut 200HN and 300HN.....	23
Figure 5.1 Single crease model.....	24
Figure 5.2 Numerical model geometry.....	26
Figure 5.3 Mesh sensitivity analysis for Miura-Ori model.....	26

Figure 5.4 Stages of folding simulations.....	27
Figure 5.5 Numerical model energy variations.....	28
Figure 5.6 Experimental and numerical results comparison.....	29
Figure 5.7 Experimental vs explicit numerical model results comparison	30
Figure 6.1 Spiral folding pattern membrane model deployed and wrapped state.....	31
Figure 6.2 Bottom view and side view during deployment	32
Figure 6.3 Single curved crease fold model boundary conditions.....	32
Figure 6.4 Number of discretization along the crease.....	33
Figure 6.5 Mesh sensitivity analysis for a curved crease.....	34
Figure 6.6 Different connector arrangements with gaps.....	34
Figure 6.7 Strain energy maximum value vs no of connector elements	35
Figure 6.8 Wrapping patterns.....	36
Figure 6.9 - Numerical model details.....	37
Figure 6.10 Experimental vs numerical results.....	37
Figure 6.11 Comparison of straight and curved crease numerical model results	38

LIST OF TABLES

Table 3.1 Wrapping pattern geometric properties.....	14
Table 5.1 Material properties	26
Table 6.1 Experimental model properties	31