PREDICTION OF MECHANICAL PROPERTIES OF CREASES IN THIN FOLDED MEMBRANES

Seyon Mierunalan

178038C

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa
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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 :

Dr. H.M.Y.C. Mallikarachchi

Abstract

Thin membranes underpin many light weight deployable space systems. Folds introduced in these membrane structures for logistics and storage, alter their in-orbit behaviour while deploying. Numerical modelling is relied on as a promising tool in studying the deployment behaviour of these space structures. However, most numerical models aimed at studying deployment behaviour, fail to incorporate fold-line properties due to unavailability of reliable experimental data.

In this research, an attempt has been made to virtually predict the fold-line mechanics using finite element analysis. For this purpose, materially and geometrically nonlinear contact analyses using Abaqus FEA were performed to simulate creased geometry and conduct numerical tensile tests on single folded thin Kapton membranes. Moment - angle responses were plotted using results of simulations and compared with the data obtained from physical experiments and a justifiable agreement was achieved. A further comparison with results from Elastica theory highlights the viability of the proposed numerical approach over analytical models. The use of virtual simulations to characterize the mechanics of fold-lines has proved to be an efficient technique.

The developed fold-line behaviour model was then implemented in commercial finite element package, Abaqus for deployment simulation of single folded thin Kapton membranes using connector elements defined with rotational stiffness. The results were validated against physical experiments and compared with other simulation techniques found in literature. The proposed technique with connector elements is meritorious over other techniques as it captures both the deformed profile and axial displacements along the folded membrane with close agreement with experimental results.

A quasi-static deployment simulation of a solar sail model with thin membrane wrapped around a polygonal hub was carried out using Abaqus/Explicit package to study the deployment behaviour. The fold-line idealisation scheme with connectors defined with rotational stiffness was used to model the fold-lines in this multiply-creased membranes. However, the fold-line stiffness had little effect on the deployment force of the sail in the range of deployment carried out experimentally .

Keywords : *ultra-thin membranes, finite element simulations, fold-line mechanics, rotational stiffness, neutral angle*

Dedication

To my parents and brother, without whom none of this would be possible.

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Nomenclature

List of Abbreviations

DLR German Aerospace Centre (Deutsches Zentrum fr 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

List of Symbols

α Time scaling factor

β Connector constitutive rotation

β_i Connector initial angular position

Δt Minimum stable time increment

ϵ_{nom} Nominal strain

ϵ_{pla} Plastic strain

ϵ_{tru} True strain

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

μ_0 Contact damping coefficient

ν Poisson's ratio

ω_{max} Highest Eigen value of the model

ϕ Neutral angle

ρ Material density

σ_{nom} Nominal stress

σ_{nom} True stress

θ Current fold opening angle

ξ Fraction of critical damping in the fundamental frequency mode

A Nodal area

c_d Dilatational wave speed

c_v Viscous damping coefficient

D Current sail diameter

d Creasing gauge between parallel plates

D_f Fully deployed diameter of the sail

dt Assigned stable time increment

E Modulus of elasticity

e External load vector

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 of external forces

F Tensile load

f Mass scaling factor

f_{vd} Contact damping force for penalty contact

I Second moment of area

i Internal load vector

j Number of radial tabs

k Fold-line stiffness

k_o Fold-line stiffness during angle opening

k_r Fold-line stiffness during relaxation

l Length of the half membrane coupon

L^* Non-dimensional length

l_h Distance from the fold-line to the loaded tip

l_{min} Shortest length of the finite element

M Resistive moment at the fold-line

m Mass matrix

M_c Kinematic moment in the connector

M_i Bending moment in the i^{th} direction

N Number of sides of the polygonal hub

n Normal vector

p Viscous pressure

P_i^j Coordinates of j^{th} vertex in i^{th} fold-line

q Deployment rate

R Radius of the circumcircle of the polygonal hub

r_i Rotation about the i^{th} axis

t Thickness

u Spacing between adjacent layers in the folded configuration

u_i Displacement in the i^{th} direction

v Velocity

v_{rel}^{el} Rate of relative motion between two surfaces

w Width of the membrane coupon

z_j z coordinate of j^{th} vertex