

# **CHARACTERISING MECHANICS OF DEPLOYABLE COILABLE TAPE-SPRINGS**

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## Declaration

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## **Abstract**

Deployable structures play a vital role in a variety of applications such as aerospace structures, rapid development civil engineering projects, medical devices, reconfigurable robotics and many other engineering applications. Deployable thin-walled booms make use of elastic strain energy during storage and are capable of self-deploying to their fully deployed configuration which is an ideal candidate to overcome the bottleneck of limited launch vehicle capacity faced in space applications.

In this research, an attempt has been made to characterise the mechanics of tape spring booms which are the simplest form among the coilable booms. Numerical and analytical frameworks are established to investigate the large deformation analysis of deployable coilable tape springs during the flattening process, which is the initial process of coiling. Geometrically non-linear finite element models implemented in Abaqus/Standard are used to characterize the flattening mechanics of isotropic tape springs under compressive deformation. The effects of geometric and material properties on flattening behaviour are investigated through a numerical parametric study. A simple analytical model is developed to predict the stresses and forces during compression flattening, and a good correlation has been found with the numerical study.

The tension stabilized coiling behaviour of longer tape booms is then investigated through analytical and numerical studies. A useful analytical model is developed to determine the required minimum tension force to prevent instabilities such as blossoming instability and buckling instability. The influence of varying coiling radius due to the thickness of multiple turns is taken into account in the developed analytical framework. Also, the required minimum torque and power for tension stabilized coiling of tape spring are developed considering energy conservation where the effect of friction is also considered.

Coiling of isotropic tape spring booms is simulated in commercially available finite element software Abaqus/Explicit. A good correlation has been found between the numerical and analytical results in terms of the required torque for coiling of longer tape-spring. Furthermore, a novel approach to predict the minimum required

tension force to prevent the instabilities is proposed. A numerical parametric study is conducted utilizing this technique in order to study the effect of the coiling ratio on the required tension force. In terms of the bending and tension-dominated regimes, the numerical findings exhibit good qualitative agreement with the established analytical model. Furthermore, a linear trend is observed in the numerical results for the loss of uniqueness region, which is helpful for the development of analytical models.

**Keywords:** *deployable structures, deployable coilable booms, tape springs, coiling mechanics, flattening mechanics*

## **Dedication**

To my parents and sisters, for their unwavering love, support, and inspiration, which have enriched my life and motivated me to pursue and finish this research.

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# Table of Contents

<b>Declaration</b> .....	<b>i</b>
<b>Abstract</b> .....	<b>ii</b>
<b>Dedication</b> .....	<b>iv</b>
<b>Acknowledgement</b> .....	<b>v</b>
<b>Table of Contents</b> .....	<b>vi</b>
<b>List of Tables</b> .....	<b>xii</b>
<b>Nomenclature</b> .....	<b>xiii</b>
<b>CHAPTER 1</b> .....	<b>1</b>
1. INTRODUCTION .....	1
1.1 Overview .....	1
1.2 Strain Energy Deployed Thin-walled Booms State of the Art .....	2
1.3 Alternative to Physical Testing .....	6
1.4 Scope and Aims .....	7
1.5 Outline of Chapters .....	10
<b>CHAPTER 2</b> .....	<b>11</b>
2. LITERATURE REVIEW .....	11
2.1 Strain energy deployed thin-walled coilable booms .....	11
2.2 Mechanics of tape spring booms .....	13
2.3 Bistable composite tape spring booms.....	18
2.3.1 Strain energy .....	22
2.3.2 Woven composite model and material modelling techniques.....	24
2.4 Flattening mechanics of deployable coilable booms .....	25
2.5 Problems associated with coiling and uncoiling mechanics and existing solutions .....	29
2.6 Studies on coiling, stowage and deployment mechanics of booms .....	37
2.7 Simulation techniques to reduce the computational effort .....	46
2.7.1 Use of symmetry .....	46
2.7.2 Co-simulation .....	46
2.7.3 Shell-beam idealisation .....	47
2.7.4 Rod model with highly deformable cross-section.....	48
<b>CHAPTER 3</b> .....	<b>49</b>

3. FLATTENING MECHANICS OF DEPLOYABLE COILABLE TAPE SPRING BOOMS.....	49
3.1 Analytical Study .....	49
3.1.1 Flattening force-displacement relationship.....	49
3.1.2 Developed maximum stresses .....	53
3.2 Numerical Study .....	55
3.2.1 Initial Model Development .....	55
3.2.2 Numerical Simulation Results .....	56
3.3 Comparison of Numerical and Analytical Results .....	58
3.3.1 Flattening force-displacement relationship.....	58
3.3.2 Stress Distribution.....	60
3.4 Parametric Study.....	62
3.4.1 Effect of Thickness .....	62
3.4.2 Effect of Transverse Radius .....	63
3.4.3 Effect of Subtended Angle.....	64
3.4.4 Effect of Elastic Modulus .....	65
3.5 Summary.....	67
<b>CHAPTER 4 .....</b>	<b>68</b>
4. ANALYTICAL STUDY FOR COILING OF LONGER TAPE SPRING BOOMS.....	68
4.1 Isotropic Tape Spring Booms .....	70
4.1.1 Bending dominated Region.....	70
4.1.2 Loss of Uniqueness (Transition) Region .....	74
4.1.3 Tension dominated Region .....	75
4.2 Bistable Composite Tape Spring Booms .....	79
4.3 Energy model during the coiling process .....	80
4.4 Summary.....	84
<b>CHAPTER 5 .....</b>	<b>85</b>
5. NUMERICAL MODELLING OF COILING OF TAPE SPRING BOOMS .	85
5.1 Overview.....	85
5.2 Abaqus/Explicit Simulation Techniques .....	86
5.3 Finite Element Model of Coilable Tape spring Boom Configuration .....	89
5.4 Coiling Simulation.....	92



5.5 Simulation Technique to Find the Tension Force.....	94
5.6 Setting simulation parameters.....	95
5.7 Results and Discussion .....	97
5.8 Summary .....	105
<b>CHAPTER 6 .....</b>	<b>106</b>
6. CONCLUSIONS AND FUTURE WORK.....	106
6.1 Flattening mechanics .....	106
6.2 Coiling mechanics.....	107
6.3 Recommendations for Future Work .....	108
<b>REFERENCES .....</b>	<b>110</b>

## List of Figures

Figure 1.1: SIMPLE boom configuration. ....	3
Figure 1.2: LightSail 2 system. ....	3
Figure 1.3: MARSIS antenna booms .....	4
Figure 1.4: NASA’s Deployable Composite Boom (DCB) system for HIPERSail. ...	5
Figure 1.5: Overview of the methodology .....	9
Figure 2.1: Different classes of Deployable booms .....	13
Figure 2.2: Moment-rotation relationship for a general tape spring. ....	14
Figure 2.3: Tape spring subject to end moments. ....	15
Figure 2.4: Fold line correspond to 2D & 3D folds .....	16
Figure 2.5: Geometry of the tape spring during large deformation. ....	17
Figure 2.6: Transition from more stable (straight) configuration to less stable (coiled) configuration of a bi-stable composite tape spring. ....	18
Figure 2.7: Classical strain energy plots for bistable and non bistable tape spring booms. ....	19
Figure 2.8: Rolled up configuration of antisymmetric & symmetric laminate layups .....	21
Figure 2.9: Uniform bending of a cylindrical shell .....	22
Figure 2.10: Total strain energy contour plot for a bistable composite cylindrical shell .....	23
Figure 2.11: Thin-walled lenticular tube.....	25
Figure 2.12: Deformation of the DCB under tension flattening. ....	26
Figure 2.13: Deformation of the DCB under compression flattening.....	27
Figure 2.14: (a)Tensile flattening deformation of a lenticular DCB (b) simplified model with rods and springs. ....	28
Figure 2.15: Instabilities during coiling of a tape spring boom around the hub .....	29
Figure 2.16:Strategies to eliminate instabilities. ....	30
Figure 2.17: Three regimes of opposite sense coiling of a tape spring.....	31
Figure 2.18: Schematic of different equilibrium configurations of shorter length tape spring coiled around a hub .....	32
Figure 2.19: Bending strain energy plots of uniformly coiled, single fold and two-fold configurations .....	33
Figure 2.20: Force profile corresponding to wrapping of a steel tape spring along with snapshots from experimental and numerical studies .....	34
Figure 2.21: Schematic of boom deployment .....	35
Figure 2.22: CubeSail deployment sequence .....	36
Figure 2.23: Schematic representation of a tape spring coiled around a freely rotating spool.....	38
Figure 2.24: Undeformed & coiled configurations of a tape spring. ....	40
Figure 2.25: (a) Chaotic deployment (b) electrically driven tip deployment (c) deployment by inflation (controlled gas flow).....	42
Figure 2.26: (a) CubeSat dummy and deployed boom suspended from the Gravity Off-Loading System (b) simulated models in Abaqus.....	43

Figure 2.27: Schematic diagram of partially flattened and restrained tape spring due to deployment drum .....	44
Figure 2.28: BeCu tape spring and 3D printed drum .....	45
Figure 2.29: Cross-section of the tape spring.....	46
Figure 2.30: Schematic illustration of coiling model using co-simulation technique	47
Figure 2.31: Shell beam idealization of a tape spring during coiling .....	47
Figure 2.32: Parametrization of tape spring for one dimensional rod model.....	48
Figure 3.1: Schematic representation of idealized configuration of tape spring undergoing flattening. ....	50
Figure 3.2: Flattening force profile corresponding to the flattening process of tape spring.....	52
Figure 3.3: Flattening process (a) undeformed (b) fully flattened configurations.....	53
Figure 3.4: Finite element model for flattening of tape spring using rigid plates.....	56
Figure 3.5: Evolution of stresses during flattening process of the tape spring .....	57
Figure 3.6: Snapshots from simulation during the flattening process.....	58
Figure 3.7: Comparison between numerical simulation and analytical model results .....	59
Figure 3.8: Normalized distance $L'h$ versus normalized platen distance $d'$ . ....	60
Figure 3.9: Comparison between numerical simulation and analytical model results in terms of maximum developed stresses.....	61
Figure 3.10: Variation of maximum flattening force, transverse and longitudinal stresses with the thickness.....	63
Figure 3.11: Variation of maximum flattening force, transverse and longitudinal stresses with the transverse radius. ....	64
Figure 3.12: Variation of maximum flattening force, transverse and longitudinal stresses with the subtended angle.....	65
Figure 3.13: Variation of maximum flattening force, transverse and longitudinal stresses with the elastic modulus .....	66
Figure 4.1: Approximation of coiled geometry of a longer tape spring to an Archimedean spiral. ....	68
Figure 4.2: Coiled geometry of a tape spring undergo change in radius due to the application of tension force .....	72
Figure 4.3: Variation of required tension force with coiling angle for tape spring. ..	73
Figure 4.4: Different equilibrium configurations for different hub radii .....	74
Figure 4.5: Tape spring undergoing transverse flattening together with longitudinal bending.....	75
Figure 4.6: Schematic representation of transverse flattening of a tape spring as a curved beam bending. ....	76
Figure 4.7: Comparison of Tension force in tension dominated regime for model developed in, numerical results from and curved beam model.....	77
Figure 4.8: Variation of required tension force with coiling angle for tension dominated regime of tape spring.....	78
Figure 4.9: Schematic diagram of tension stabilized coiling of a longer tape spring.	81

Figure 4.10: Schematic representation of frictional forces acting between hub and boom and boom itself during tension stabilized coiling process. ....	82
Figure 4.11: Variation of required torque with coiling angle during coiling of tape spring.....	83
Figure 5.1: Symmetric finite element model.....	90
Figure 5.2: Simulation steps.....	93
Figure 5.3: Schematic illustration of method to find the required minimum tension force.....	95
Figure 5.4: Comparison between internal energy and kinetic energy profiles for coiling simulation.....	96
Figure 5.5: Energy histories for coiling simulation .....	97
Figure 5.6: Snapshots taken during coiling simulation of shorter tape spring booms. ....	98
Figure 5.7: Comparison between hub geometry and coiled geometry of tape spring boom when $T = 3.25$ N. ....	98
Figure 5.8: Energy histories for coiling simulation of longer tape spring boom. ....	99
Figure 5.9: Coiled configuration of 3.15 m long tape spring boom.....	100
Figure 5.10: Torque profile during coiling of longer tape spring boom. ....	101
Figure 5.11: Force profile corresponding to coiling simulation of tape spring boom. ....	102
Figure 5.12: Comparison between hub geometry and coiled geometry of tape spring boom when $T = 2$ N. ....	102
Figure 5.13: Variation of required minimum tension force with coiling ratio.....	103

## List of Tables

Table 3.1: Material properties of steel used in the numerical model. ....	56
Table 5.1: Tape spring boom properties used in the numerical simulation. ....	89
Table 5.2: Summary of boundary conditions used in the simulation.....	94

## **Nomenclature**

### **List of Abbreviations**

ACS3 – Advanced Composites Solar Sail System Technology demonstration mission

CFRP – Carbon Fibre Reinforced Polymer

CLT – Classical laminate theory

CTLT – Composite Thin-walled Lenticular Tube

CTM – Collapsible Tubular Mast

DCB – Deployable Composite Boom

DLR – The German Aerospace Center (German: Deutsches Zentrum für Luft- und Raumfahrt e.V.)

FE – Finite Element

FEA – Finite Element Analysis

FEM – Finite Element Method

FLHD – Four-cell Lenticular Honeycomb Deployable

FRP – Fibre Reinforced Polymer

MARSIS – Mars Advanced Radar for Subsurface and Ionosphere Sounding

NASA – National Aeronautics and Space Administration

NSGA-II – Non-dominated Sorting Genetic Algorithm-II

RVE – Representative Volume Element

SIMPLE – Self-contained Linear Meter-class Deployable

SQP – Sequential Quadratic Programming

STEM – Storable Extendible Tubular Member

TRAC – Triangular Rollable and Collapsible

## List of Symbols

$ABD$	constitutive matrix in coordinate system $x$ and $y$
$A_{ij}$	coefficients of upper-left $3 \times 3$ submatrix of $ABD$
$A$	area of the curved section of the fold
$A'$	nodal area
$B_{ij}$	coefficients of upper-right $3 \times 3$ submatrix of $ABD$
$b$	arc length along the cross-section of the tape spring
$C$	damping coefficient
$c_d$	dilatational wave speed
$c_i$	coiling ratio
$c_v$	viscous pressure coefficient
$D_{ij}$	coefficients of lower-right $3 \times 3$ submatrix of $ABD$
$D$	bending stiffness of the shell
$E$	elastic modulus
$E'$	energy required for the coiling
$E_A$	artificial strain energy
$E_{CD}$	energy dissipation due to viscoelasticity or creep
$E_E$	elastic strain energy
$E_{FD}$	frictional dissipation energy
$E_{KE}$	kinetic energy
$E_I$	internal Energy
$E_P$	energy dissipation due to inelastic process

$E_{VD}$	energy absorbed by viscous dissipation
$E_W$	work done by external forces
$E_{Total}$	total energy in the system
$F_c$	flattening force
$(F_c)_{max}$	maximum flattening force
$F'$	external load on the system
$f$	flattened length
$h$	thickness of the tape spring
$I$	second moment of area of the section
$K$	stiffness
$L$	length of the tape spring boom
$L'$	half of the chord length of tape spring cross-section
$l_{min}$	shortest length of finite element
$L_p$	length of the poly region
$M$	moment per unit length stress resultant
$m$	mass
$M'$	moment at the tangential point during the flattening process
$N$	force per unit length stress resultant
$n$	number of turns or layers in the coiled tape spring boom
$\mathbf{n}$	unit surface normal
$p$	pressure per unit length
$R$	transverse radius of the tape spring
$r_c$	radius of the hub



$r_s$	fold radius of the tape spring at the secondary stable state
$T$	required minimum tension force to prevent instabilities
$t$	time
$U$	total strain energy per unit length of the shell
$U_b$	bending energy per unit length of the shell
$U_{bs}$	bending energy per unit length of the bistable shell at the secondary stable state
$U_s$	stretching energy per unit length of the shell
$u$	displacement
$u_x$	displacement in $x$ direction
$\dot{u}$	velocity
$\ddot{u}$	acceleration
$\mathbf{v}$	velocity vector
$\nu$	Poisson's ratio
$u_{rel}^{el}$	rate of relative motion between the two surfaces
$W_T$	work done by the applied tension force
$W_B$	boom bending energy
$W_f$	work done by friction torque
$W_\tau$	work done by hub torque
$x$	longitudinal direction
$y$	transverse direction
$z$	through thickness direction
$\alpha$	subtended angle of the tape spring

$\beta$	ratio of orthogonal Young's moduli
$\phi$	total swept angle by the turns in the coil
$\delta$	deflection
$\rho$	density
$\varepsilon^0$	mid plane strain
$\varepsilon_{xx}$	longitudinal strain
$\varepsilon_{yy}$	transverse strain
$\varepsilon_{xy}$	shear strain
$\kappa$	curvature
$\kappa_{xs}$	longitudinal curvature at the secondary stable state
$\Delta\kappa$	curvature change
$\omega$	angular velocity
$\sigma_{xx}$	longitudinal stress
$(\sigma_{xx})_{max}$	maximum longitudinal stress
$\sigma_{yy}$	transverse stress
$(\sigma_{yy})_{max}$	maximum transverse stress
$\sigma_{xy}$	shear stress
$\tau_{Hub}$	torque required for coiling
$\tau_{f_{hb}}$	torque due to friction between hub and the boom
$\tau_{f_{bb}}$	torque due to friction between the boom itself
$\xi$	fraction of critical damping in highest frequency mode
$\mu_0$	damping coefficient