Bistable Deployable Composite Booms with Parabolic Cross-Sections

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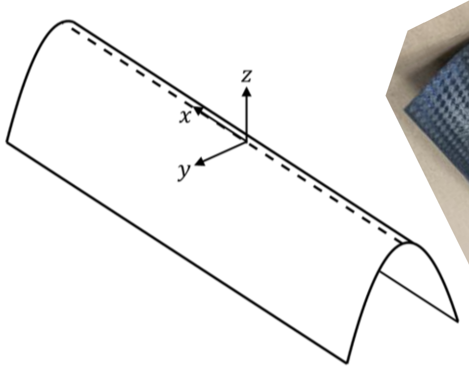
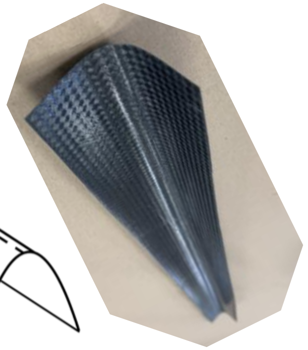
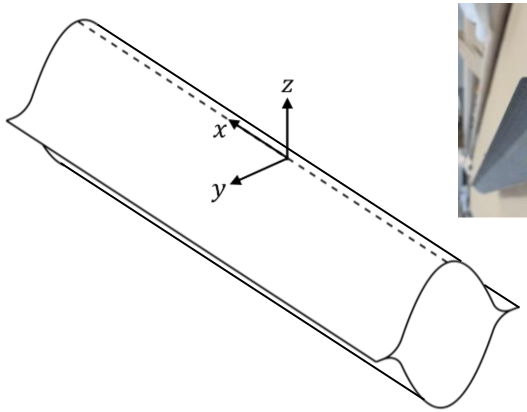
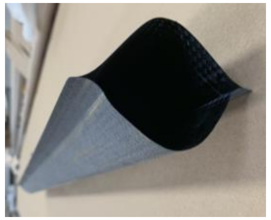
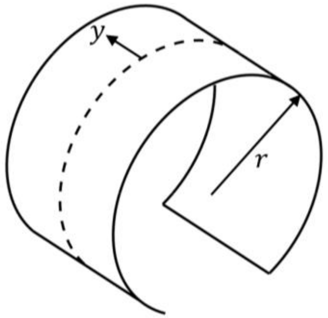
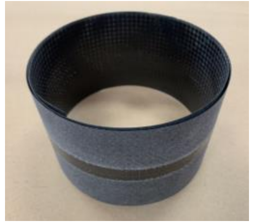
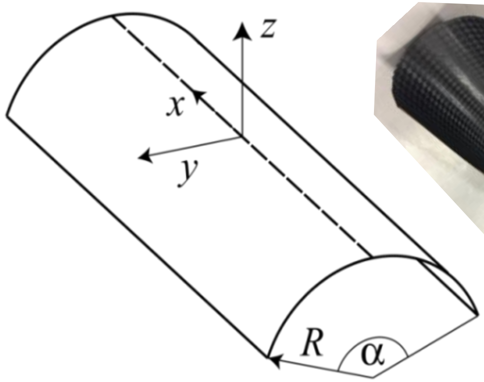
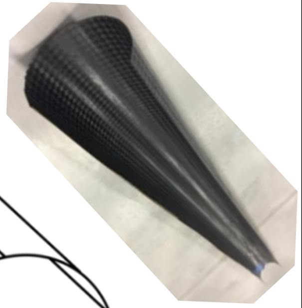
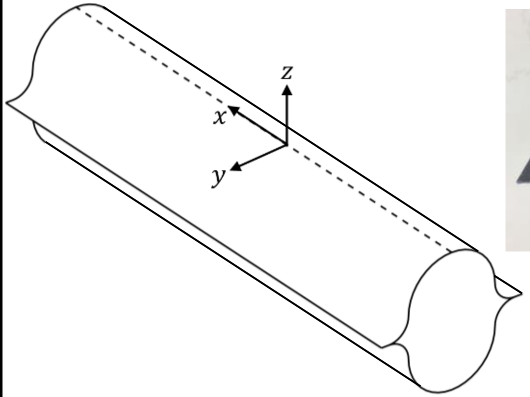
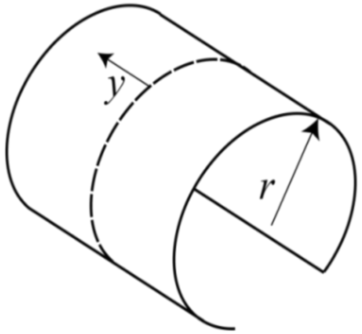
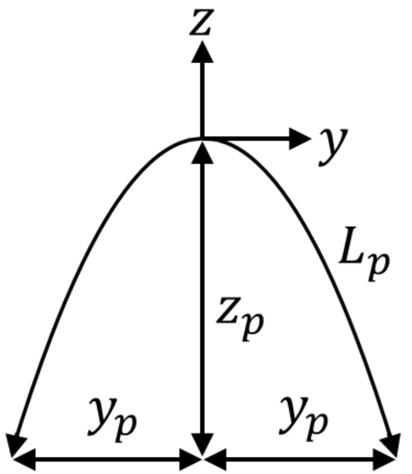
Background and Objectives

- Analytically model bistable configurations of thin-shelled composite booms with parabolic cross-sections
- Compare stiffness properties and stable coiled geometry between parabolic and circular booms
- Verify optimal design cases with finite element analysis (FEA)

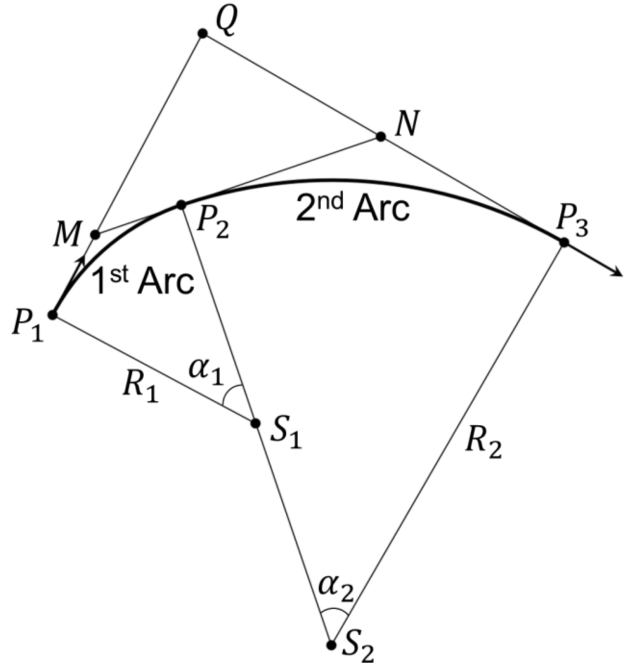
Cross-section	Extended State: Tape Spring	Extended State: Collapsible Tubular Mast (CTM)	Coiled State
Parabolic	 	 	 
Circular	 	 	 

Inextensional Model

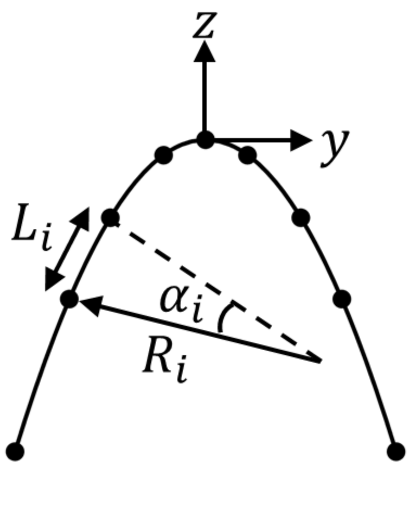
Specify parabolic shape with 2 independent parameters



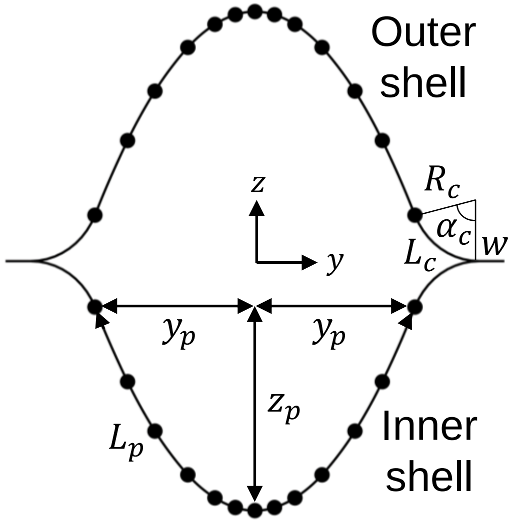
Discretize into circular segments with tangent continuity using biarc spline interpolation



Yields n circular arcs approximating parabola within a specified error tolerance



Tape spring (TS)



CTM boom

Sum non-dimensionalized strain energy per unit length of all segments and minimize to obtain equilibrium states

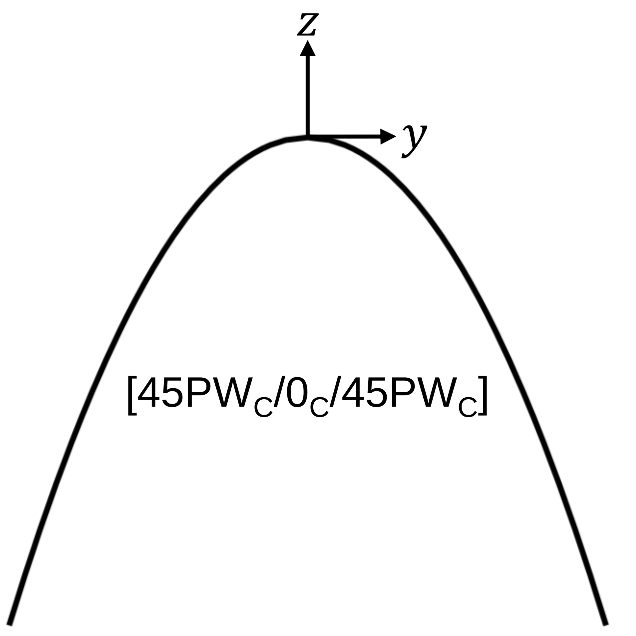
$$\hat{U}_{TS} = \frac{1}{2L_p} \sum_{i=1}^{n} L_i \hat{\boldsymbol{k}}_i^T \hat{\boldsymbol{D}} \hat{\boldsymbol{k}}_i$$

$$\hat{U}_{CTM} = \frac{1}{h}\left[\underbrace{L_{c_O} \hat{\boldsymbol{k}}_{c_O}^T \hat{\boldsymbol{D}}_{c_O} \hat{\boldsymbol{k}}_{c_O}}_{\text{Outer shell circular section}} + \underbrace{L_{c_I} \hat{\boldsymbol{k}}_{c_I}^T \hat{\boldsymbol{D}}_{c_I} \hat{\boldsymbol{k}}_{c_I}}_{\text{Inner shell circular section}} + \underbrace{w \hat{\boldsymbol{k}}_w^T \hat{\boldsymbol{D}}_w \hat{\boldsymbol{k}}_w}_{\text{Web section}} + \frac{1}{2} \sum_{i=1}^{n} \underbrace{L_{i_O} \hat{\boldsymbol{k}}_{i_O}^T \hat{\boldsymbol{D}}_{i_O} \hat{\boldsymbol{k}}_{i_O}}_{\text{Outer shell parabola}} + \underbrace{L_{i_I} \hat{\boldsymbol{k}}_{i_I}^T \hat{\boldsymbol{D}}_{i_I} \hat{\boldsymbol{k}}_{i_I}}_{\text{Inner shell parabola}} \right]$$

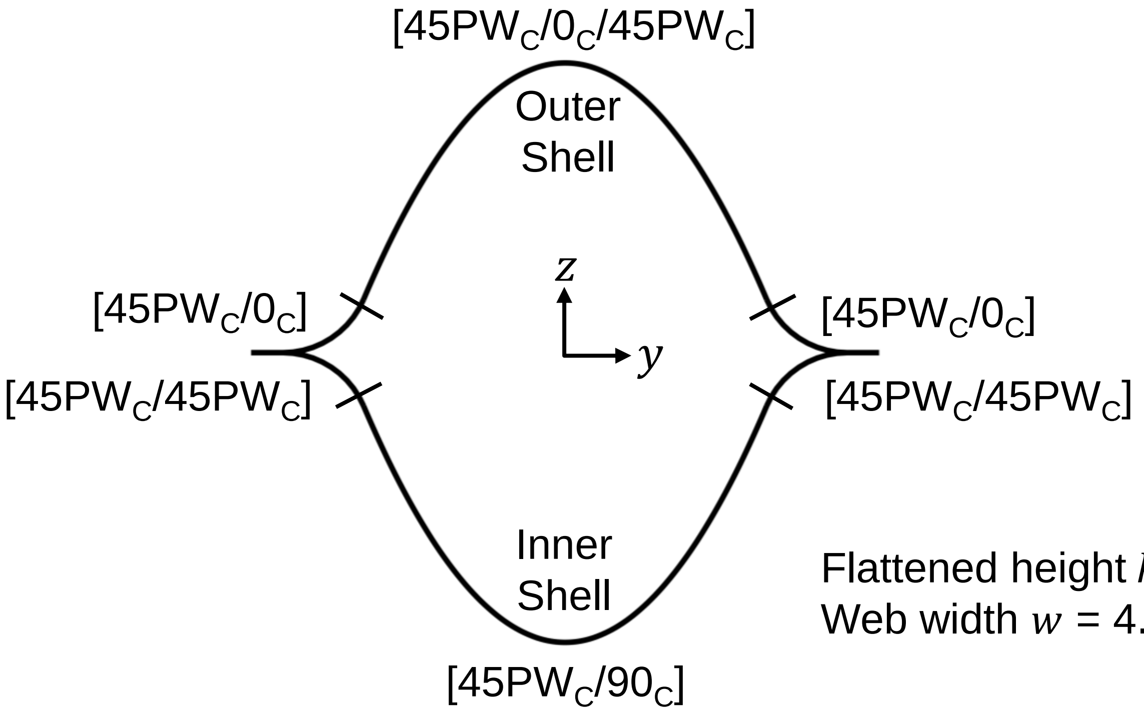
Material Properties and Layups

Material properties of thin-ply composites and adhesive

Label	Material Form	Fiber/Resin	E_1 (GPa)	E_2 (GPa)	ν_{12}	G_{12} (GPa)	Thickness t (μm)
C	Unidirectional Carbon Fiber	MR60H/PMT-F7	144.1	5.2	0.335	2.8	40.0
PW_C	Plain Weave Carbon Fiber	M30S/PMT-F7	89.0	89.0	0.035	4.2	58.2
A	Hysol EA9696 Film Epoxy	N/A	2.14	2.14	0.030	0.62	85.0



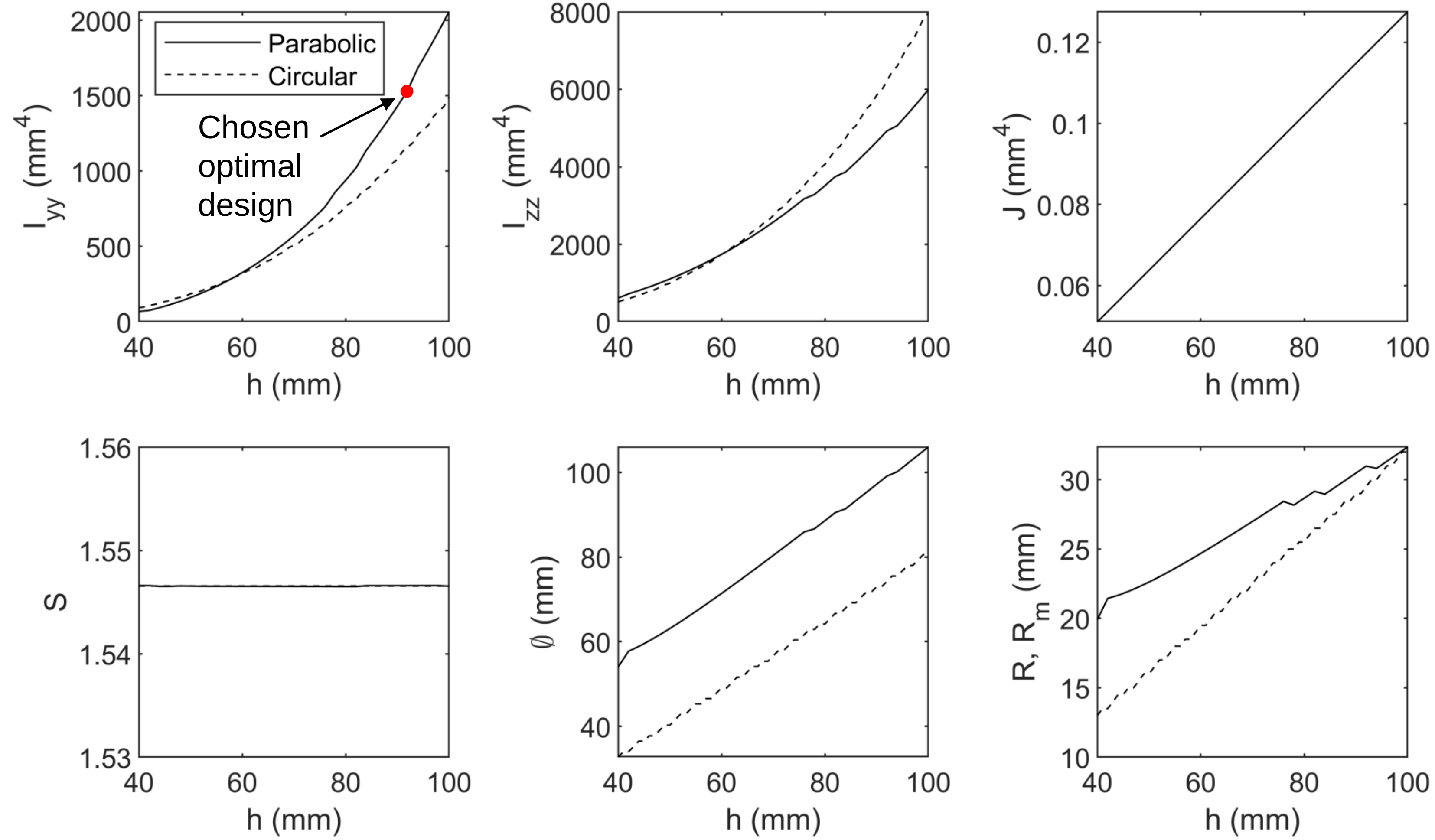
Flattened height h is the parabola length L_p



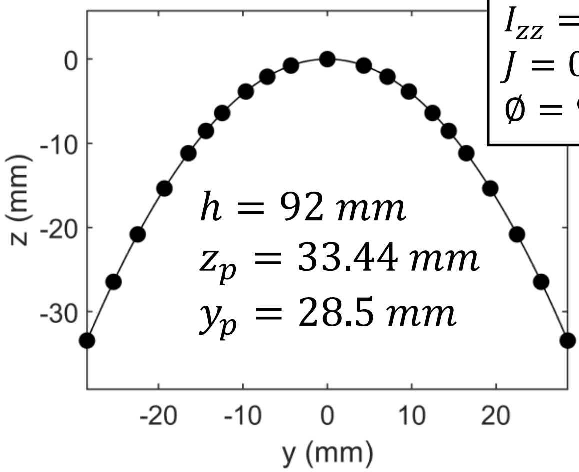
Flattened height h = 130 mm
Web width w = 4.5 mm

Tape Spring Comparison and Optimal Design

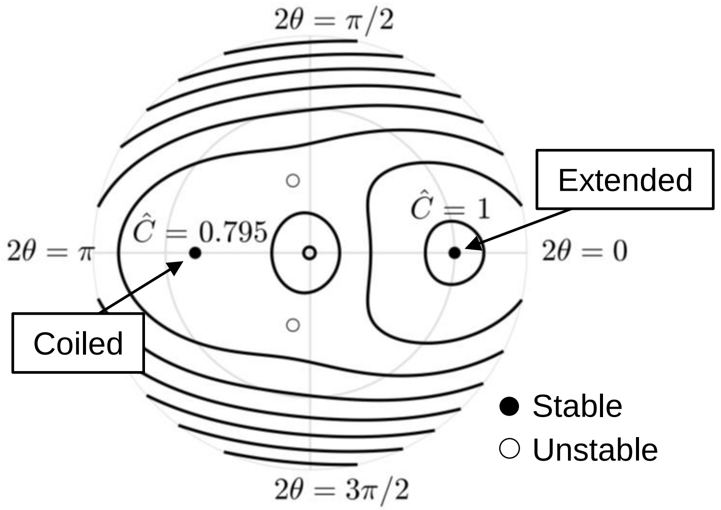
Parabolic tape spring has superior stiffness properties (I_{yy}) for larger h, but less favorable packaged volume (∅) when compared to circular tape spring



$I_{yy} = 1534\ mm^4$
$I_{zz} = 4926\ mm^4$
$J = 0.117\ mm^4$
$\emptyset = 99.11\ mm$



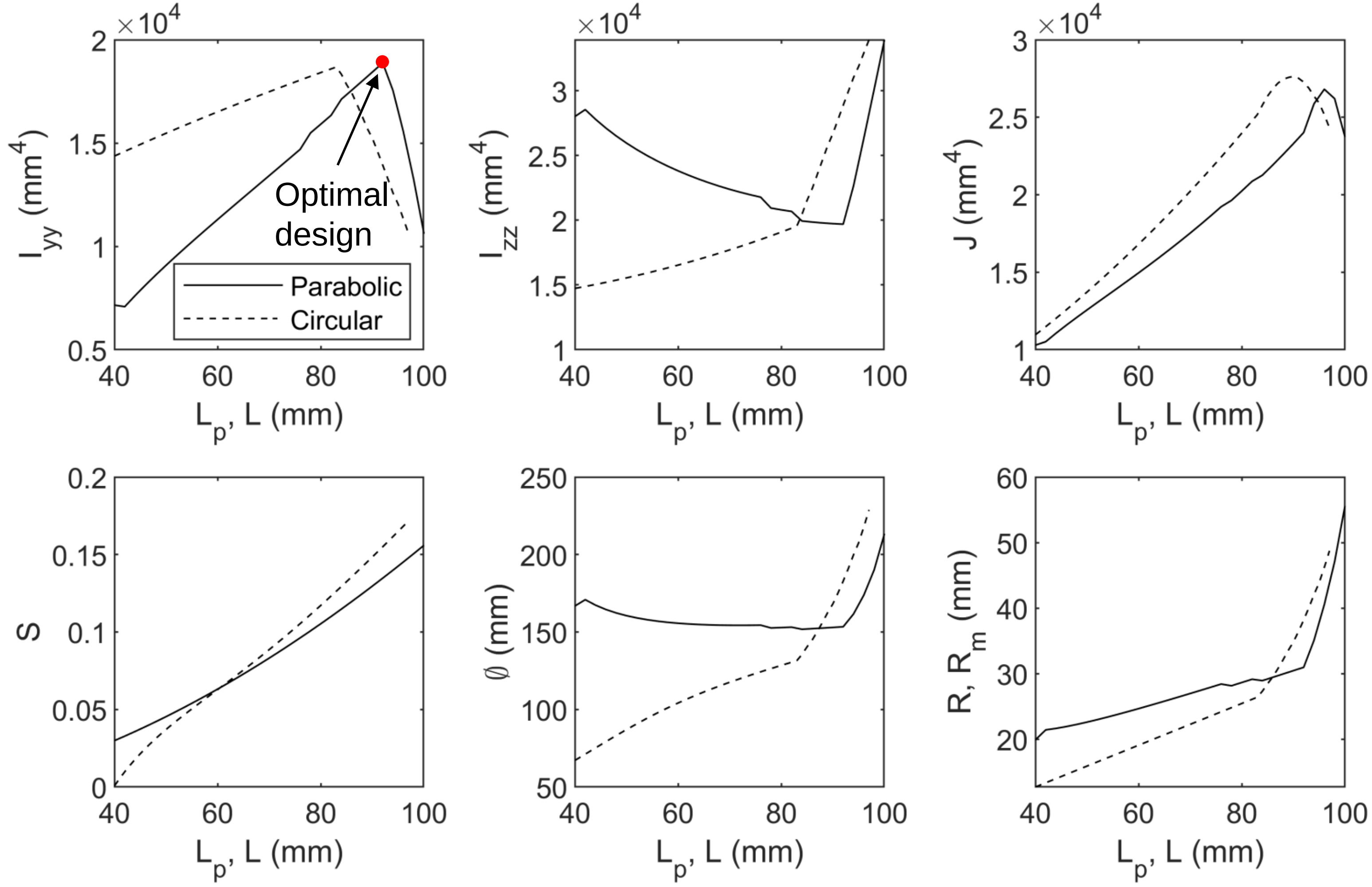
Optimal design cross-section

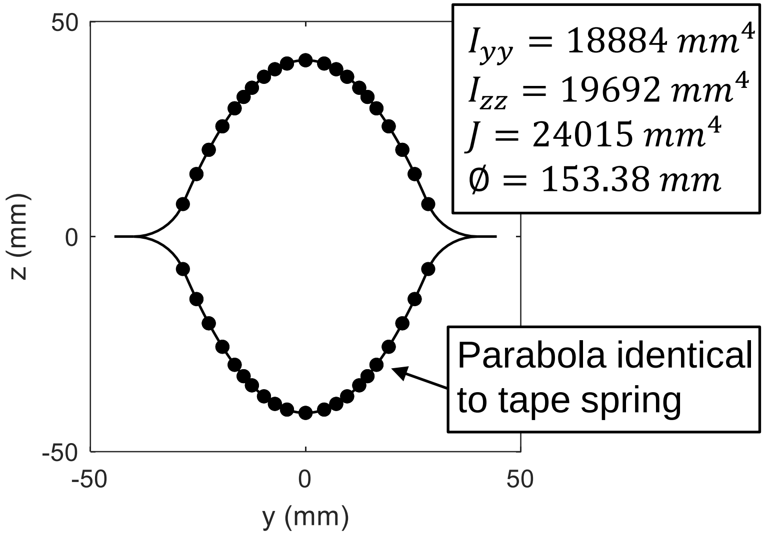


Polar contour plot of $\hat{U}(\hat{C}, \theta)$

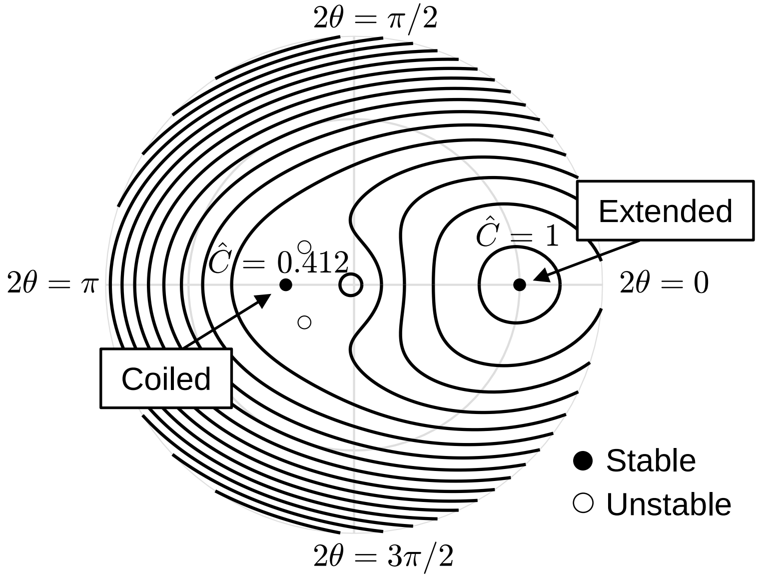
CTM Boom Comparison and Optimal Design

Parabolic CTM has superior stiffness properties (I_{yy}) and packaged volume ($\emptyset$) for larger L_p, L and vice versa for smaller L_p, L when compared to circular CTM





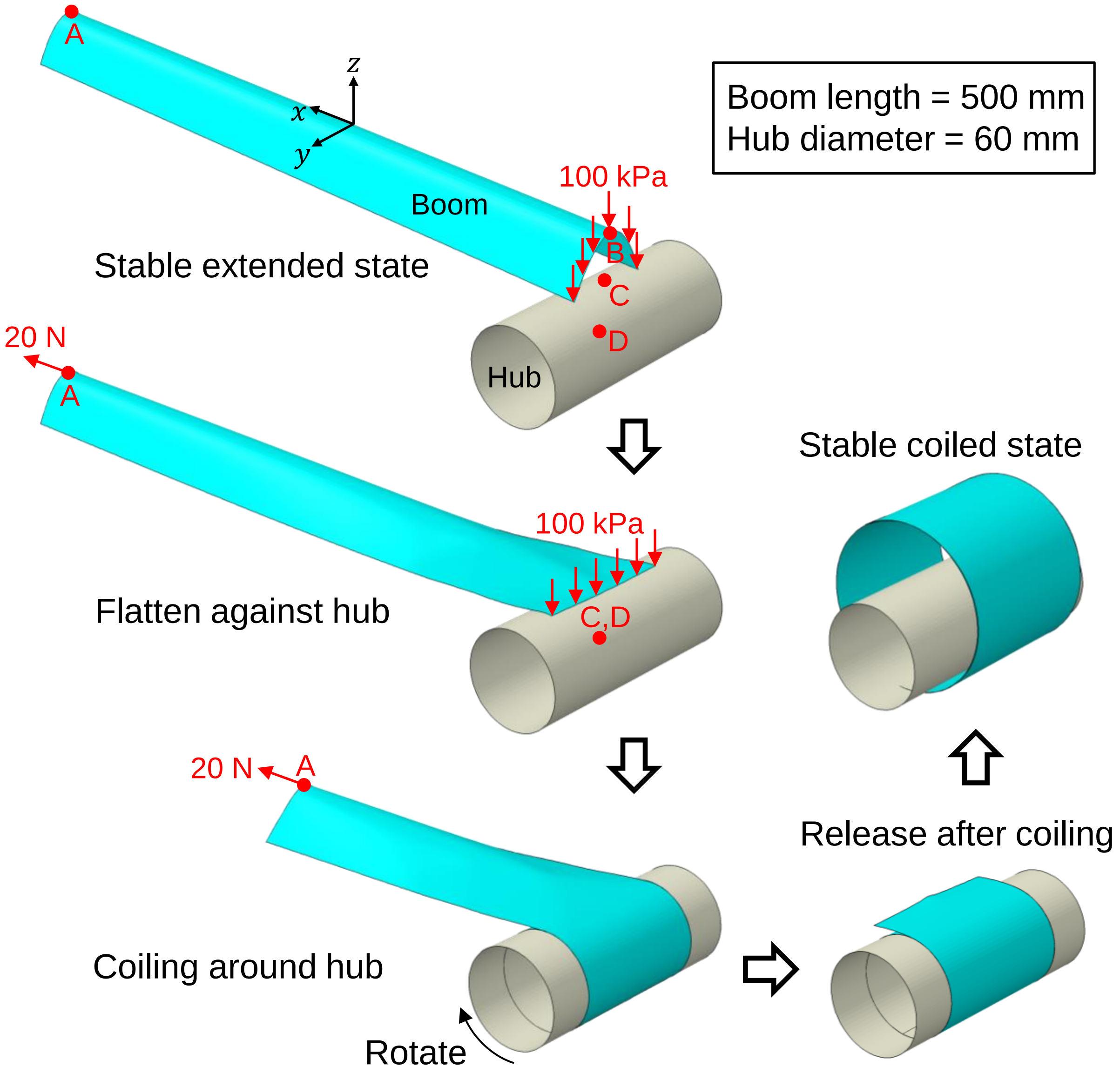
Optimal design cross-section



Polar contour plot of $\hat{U}(\hat{C}, \theta)$

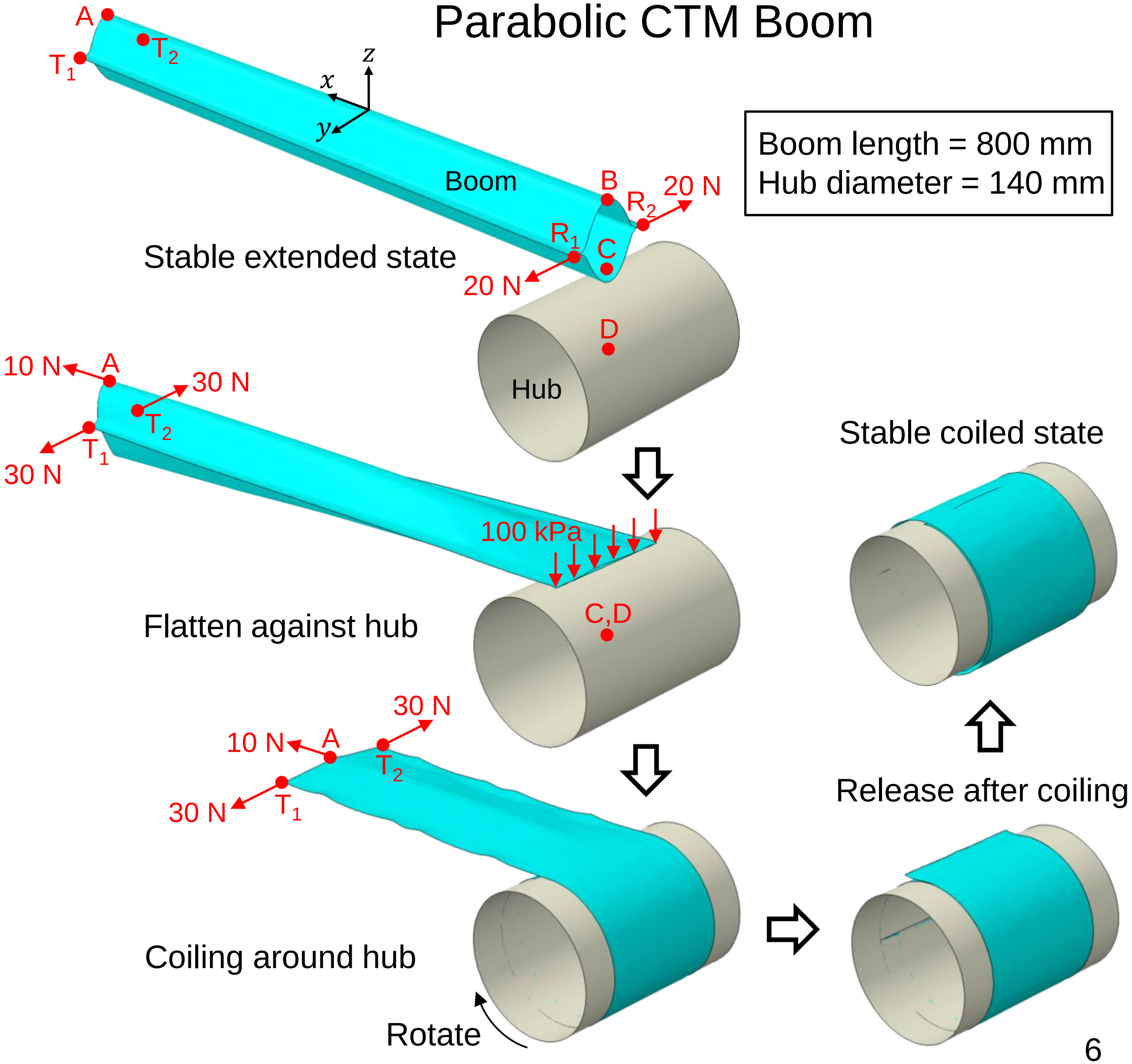
Quasi-static FEA of Boom Coiling in Abaqus/Standard

Parabolic Tape Spring



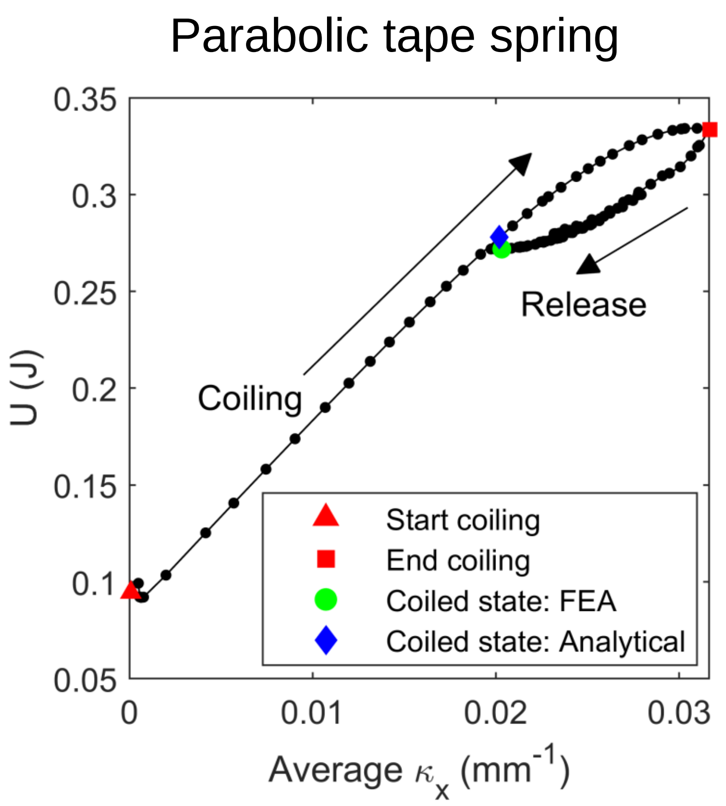
Boom length = 500 mm
Hub diameter = 60 mm

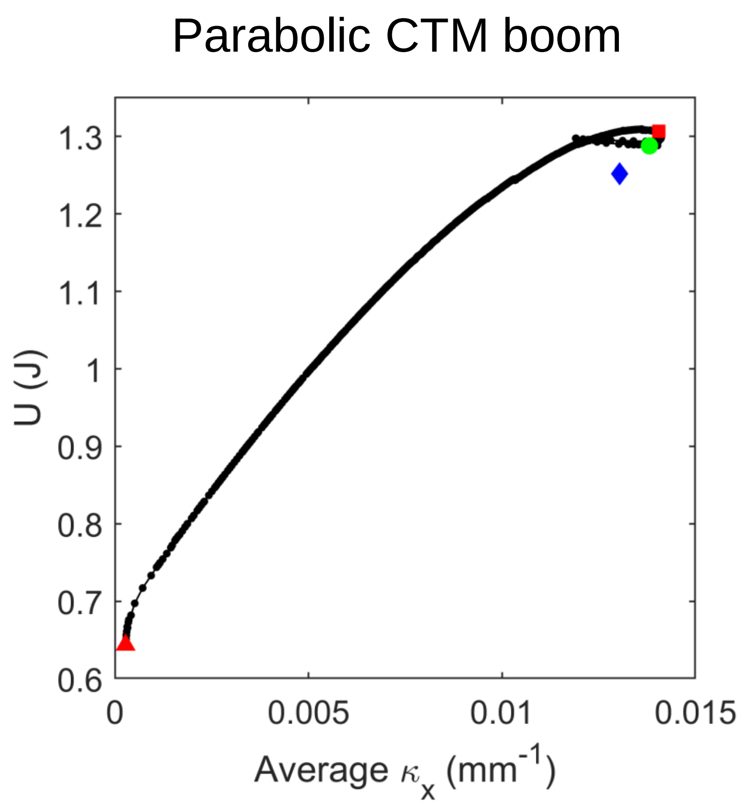
Parabolic CTM Boom

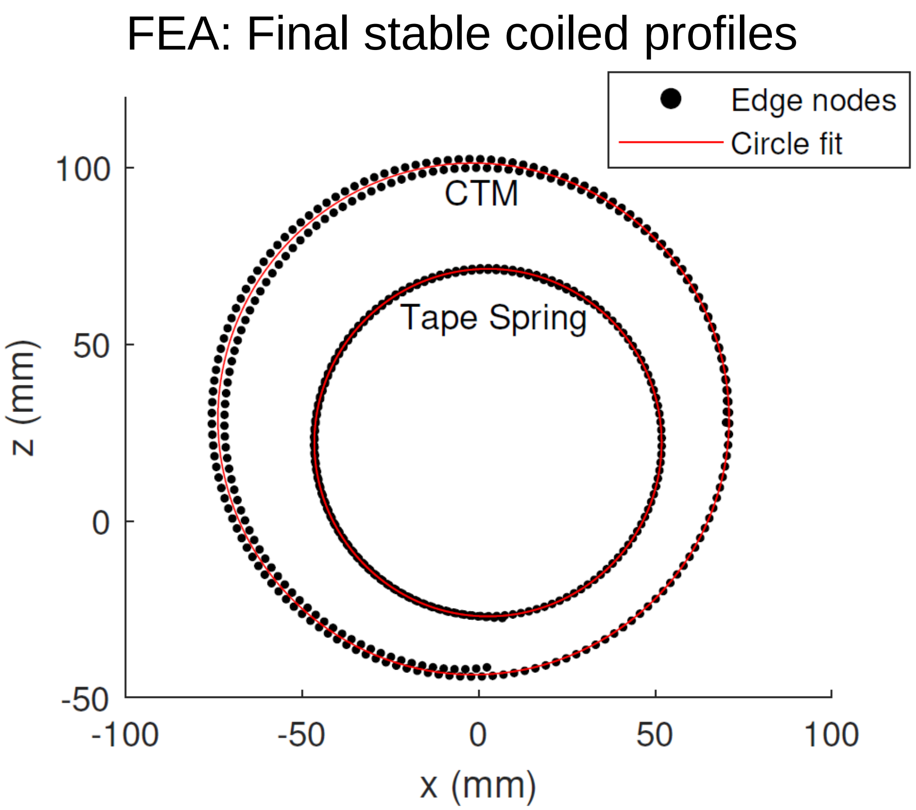


Boom length = 800 mm
Hub diameter = 140 mm

FEA Results and Analytical Predictions







Model	Tape Spring ∅ (mm)	Tape Spring U (J)	CTM ∅ (mm)	CTM U (J)
Analytical	99.11	0.278	153.38	1.252
FEA	98.42	0.272	144.87	1.288
Percent Error	0.70%	2.16%	5.55%	2.88%

Conclusions

- Analytical approach developed to model stable coiled configuration of deployable composite booms with parabolic cross-sections
  - Discretized parabolic section into circular segments with biarc spline interpolation
  - Summed and minimized strain energy of every discretized segment to obtain equilibrium states
  - Implemented for both parabolic tape spring and CTM booms
- Parabolic booms generally found to have better stiffness performance at the cost of larger coiled diameter when compared to circular booms
  - This difference is more minor for the CTM than for the tape spring
- Finite element analysis of optimal parabolic tape spring and CTM booms verify analytical predictions of the stable diameter and strain energy of the coiled state
  - Future work will compare these predictions with experimental measurements from manufactured parabolic booms at NASA LaRC