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Tow-Path Based Modeling of Wrinkling during the Automated Fiber Placement Process

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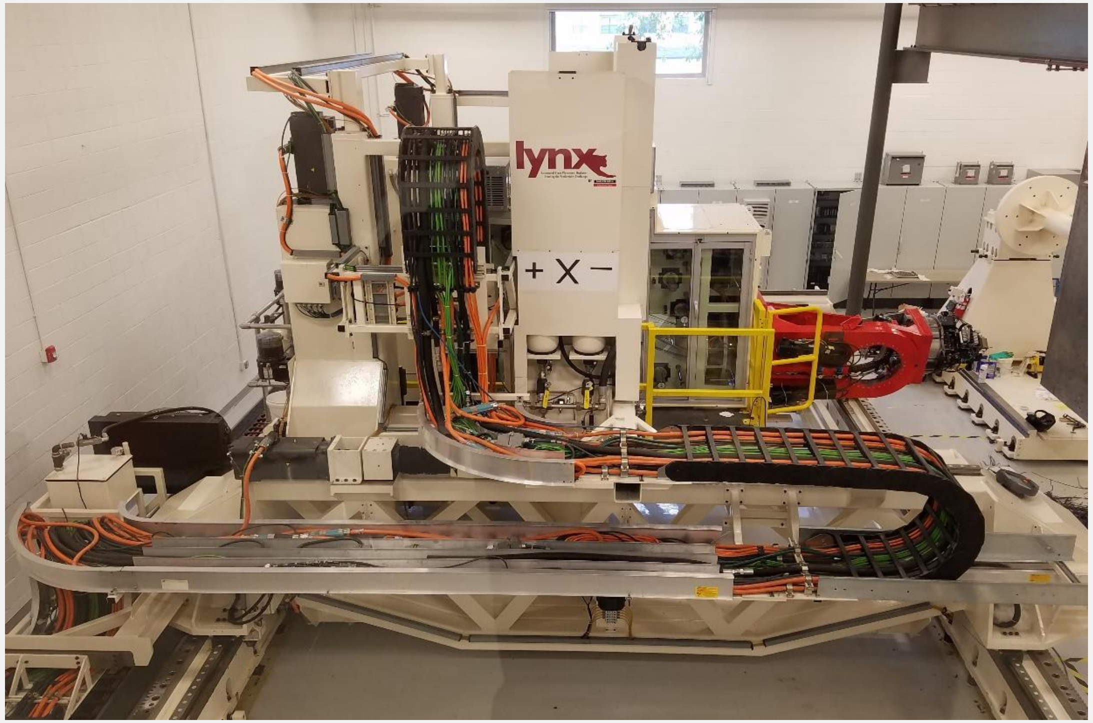
Introduction

- AFP machines are used to manufacture large aerospace structures.
- Typical material that is laid down using AFP machines have a width of ⅛ in, ¼ in, or ½ in.
- AFP delivers up to 32 tows in a single sequence to form a course, while a sequence of courses is termed ply.
- During the process, the layup speed, temperature, roller compaction, and tow tension are controlled to obtain a good layup quality.
- Some defects might appear during the process, such as wrinkling, tow twisting, folding, missing tows, and others…

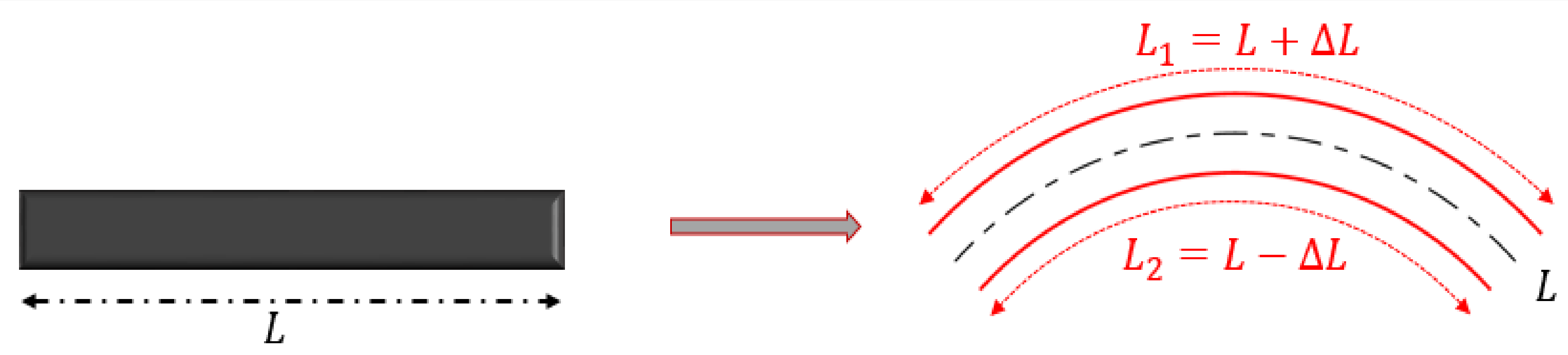


AFP machine at the McNair Center

AFP machine head with 32 tows [1]

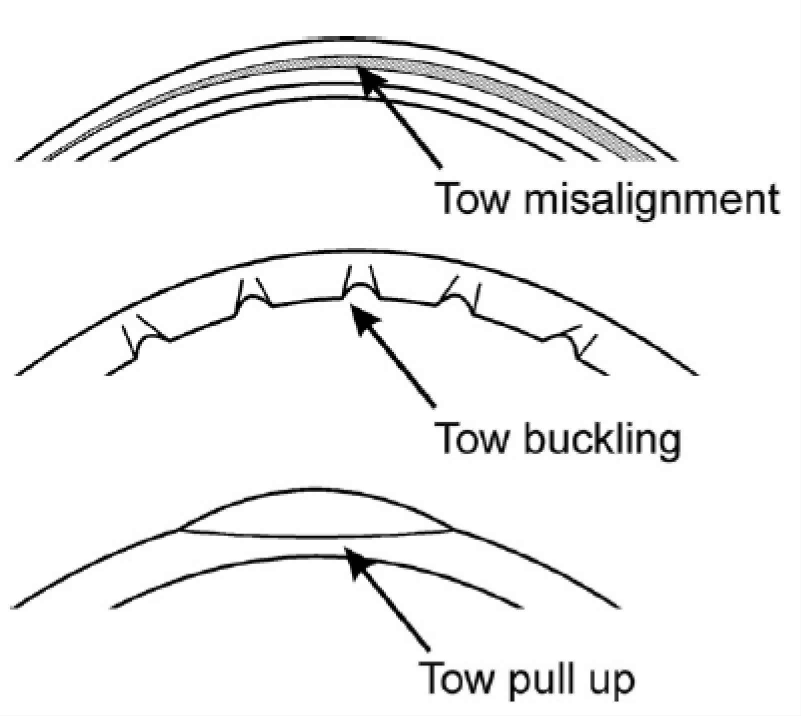
[1] Beakou, A., Cano, M. & Le Cam, J. B., "Modeling slit tape buckling during automated prepreg manufacturing: A local approach." *Composite Structure* 93 (2011): 2628-2635

Origin of Wrinkling in AFP

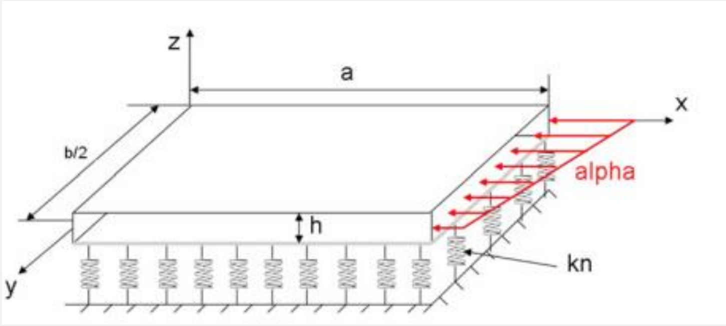


- The main reason for wrinkling occurrence is the mismatch in length between the prescribed path on the surface and the actual delivered tow from the machine head.
- This mismatch in length can be detected during the design phase, hence the possibility of improvement.

Wrinkling in the Literature

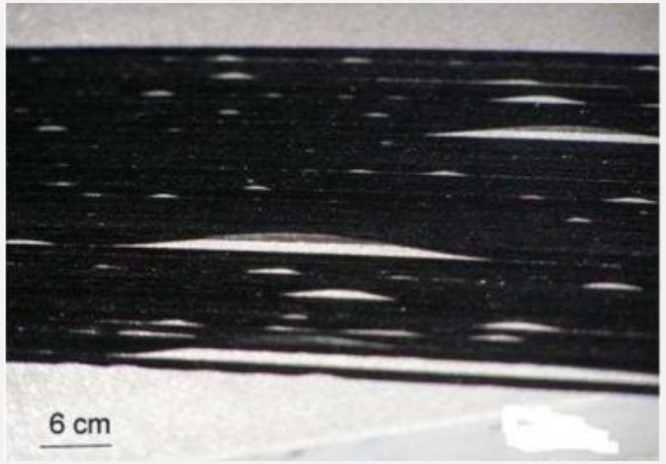


Most common tow steering defect [2]

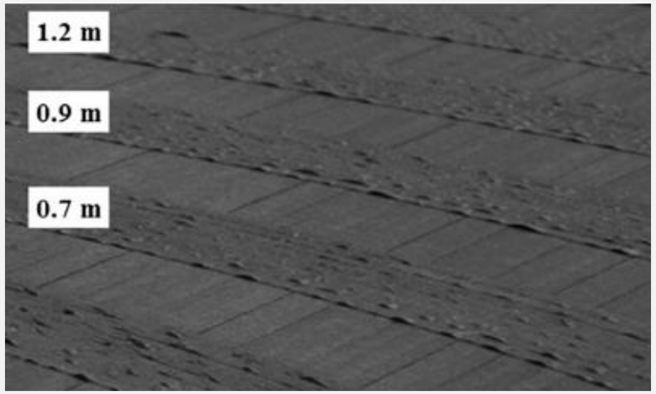


Wrinkling model: Buckling of plate on elastic foundation[2]

- [1] tow buckling occurs on the inside radius of the tow if the compressive forces are too high, and tow pull-up (or folding) occurs on the outside radius of the tow due to tensile forces.
- [2] and [3] use a buckling analysis applied to a tow during AFP based on the model of an orthotropic plate laying on elastic foundation



Buckling of steered prepreg tows [1]

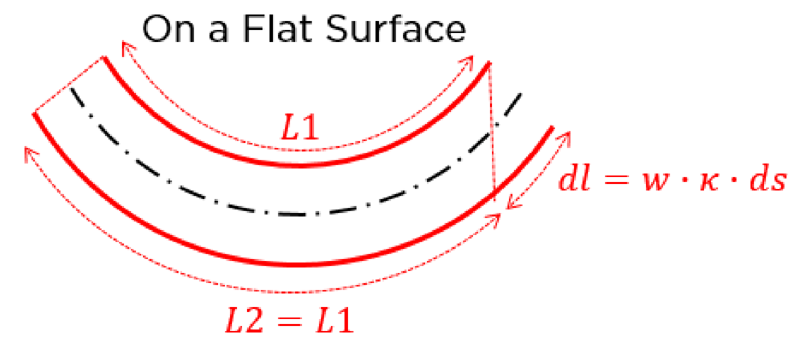


Wrinkles in steered dry fiber [3]

[1] Beakou, A., Cano, M. & Le Cam, J. B., "Modeling slit tape buckling during automated prepreg manufacturing: A local approach." *Composite Structure* 93 (2011): 2628-2635
[2] Lukaszewicz, D. H.-J.,Ward, C. & Potter, K. D., "The engineering aspects of automated prepreg layup: History, present and future." Composites: Part B 43 (2012): 997-1009
[3] Matveev, M. Y. , Shubel, P. J., Long, A. C. & Jones I. A., "Understanding the buckling behavior of steered tows in Automated Dry Fibre Placement." *Composites: Part A* 90 (2016): 451-456

Modeling Approach

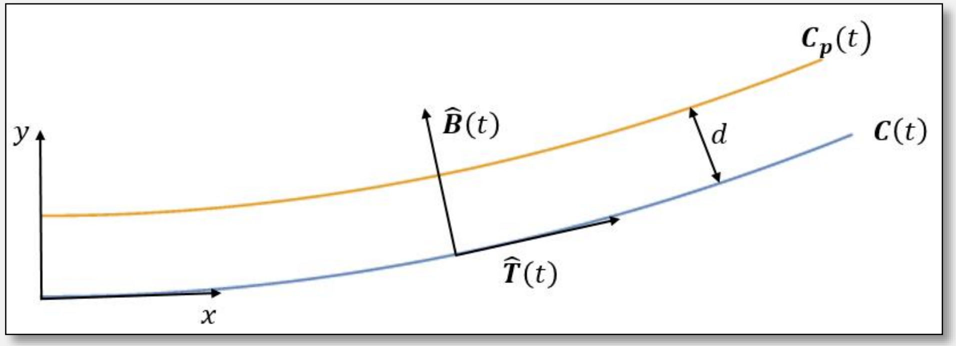
- The stability analysis based on finite size plate-like element assumption is abandoned in favor of a functional form of the tow-path with finite width
- 0th Order
  - Ignore elasticity, viscoelasticity, and tackiness
  - Assume the slit tape to be a membrane with large in-plane stiffness but small bending stiffness
- 1st Order
  - Include elastic deformations
- 2nd Order
  - Include viscoelastic and nonlinear deformations.



Tow-Path Modeling on Flat Surface

- In 2D: the boundary curves are generated by following the normal vector to the original path $C(t)$ using the following equation:

$$\boldsymbol{C}(t) : \begin{cases} x(t) = u_c(t) \\ y(t) = v_c(t) \end{cases} , \quad \boldsymbol{C_p}(t) : \begin{cases} x_p(t) = u_c(t) - \mathrm{d}\, \hat{v}_c'(t) \\ y_p(t) = v_c(t) + \mathrm{d}\, \hat{u}_c'(t) \end{cases} ,$$



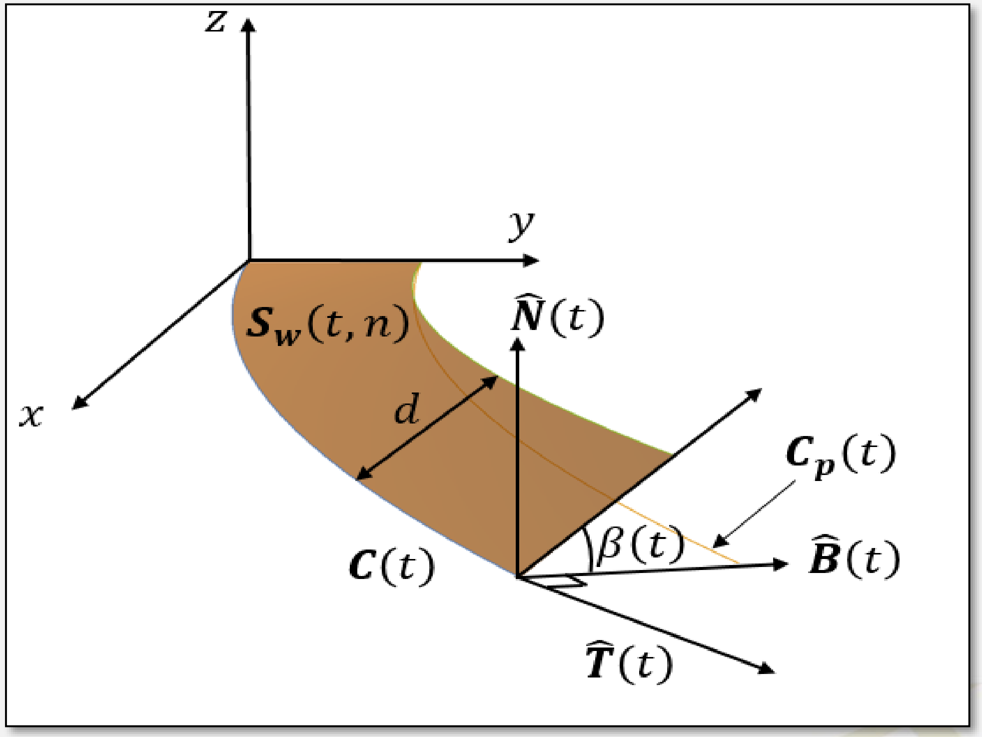
- Since the two sides of the paths have different length, the tow will lift up from the shorter side and buckle. The shape of the buckle is assumed to be a cosine function similar to a clamped beam.

$$\boldsymbol{S_w}(t,n) = \begin{cases} x_w(t,n) = u_c(t) - n\, d\, \hat{v}_c'(t) \cos\big(\beta(t)\big) \\ y_w(t,n) = v_c(t) + n\, d\, \hat{u}_c'(t) \cos\big(\beta(t)\big) \\ z_w(t,n) = n\, d\, \sin\big(\beta(t)\big) \end{cases}$$

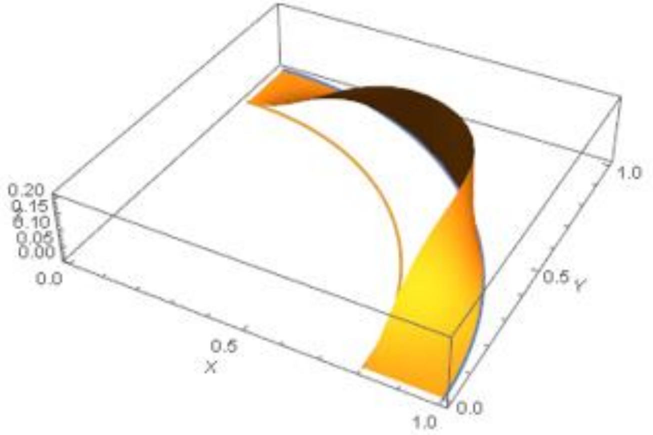
$$\beta(t) = k\left(1 - \cos\left(\frac{2\pi(\mathrm{t} - t_{i-1})}{t_i - \mathrm{t}_{\mathrm{i}-1}}\right)\right)$$

$$\int_{t_{i-1}}^{t_i} \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2}\, dt = \int_{t_{i-1}}^{t_i} \sqrt{\left(\frac{dx_w}{dt}\right)^2 + \left(\frac{dy_w}{dt}\right)^2 + \left(\frac{d\, z_w}{dt}\right)^2}\, dt = \frac{L}{N}$$

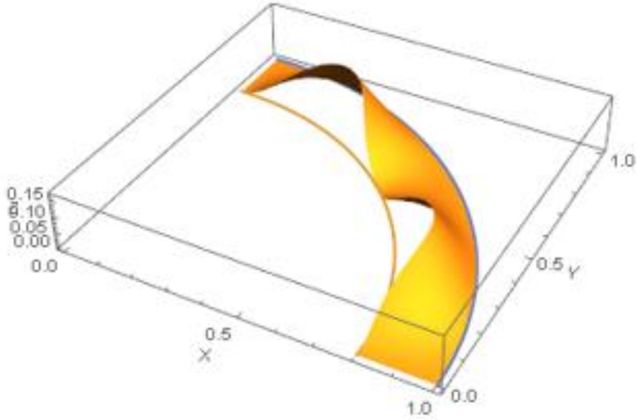
$$for\ i = 1, \dots N\, .$$



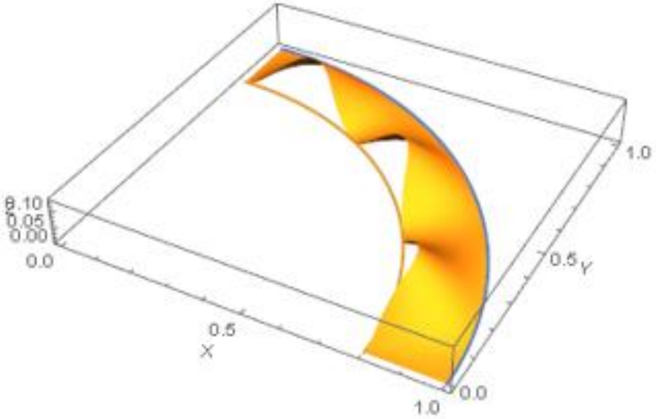
Results for a circular arc



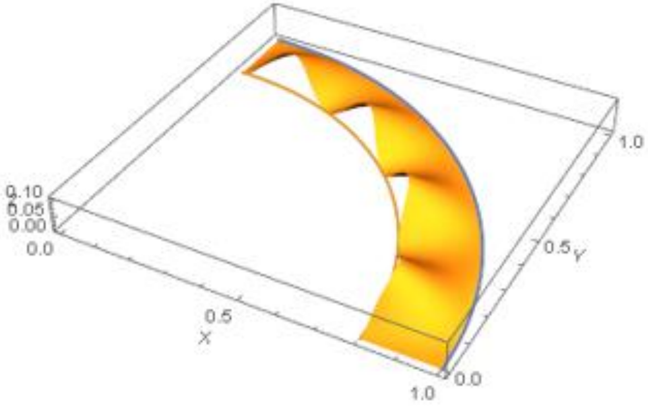
(a) $N = 1$ wrinkle



(b) $N = 2$ wrinkles



(c) $N = 3$ wrinkles



(d) $N = 4$ wrinkles

- The following reference path is defined:

$$\boldsymbol{C}(t) = \{\cos t\,, \sin t\} \quad , \quad 0 \le t \le \pi/2$$

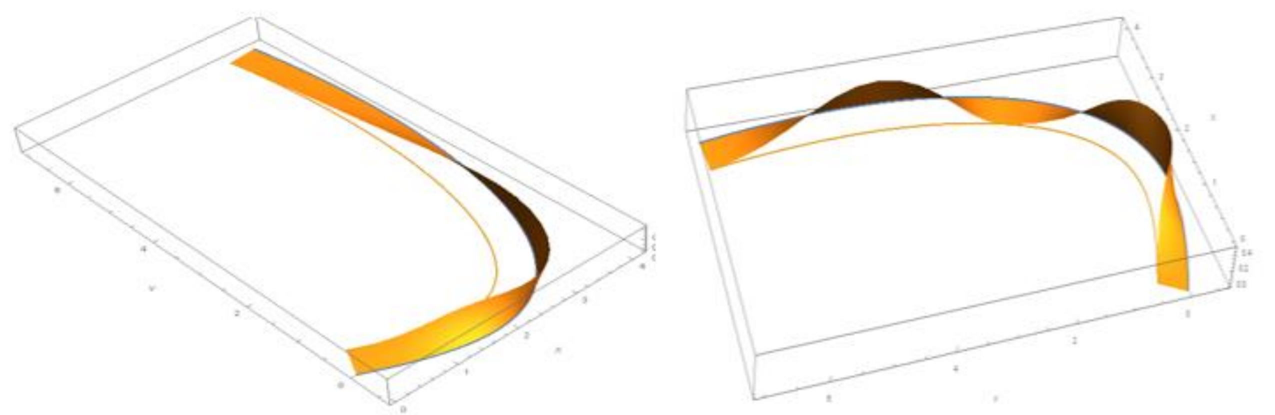
$w = 0.1$ (non dimensional units)

$\kappa = 1$ (constant curvature)

Analysis:

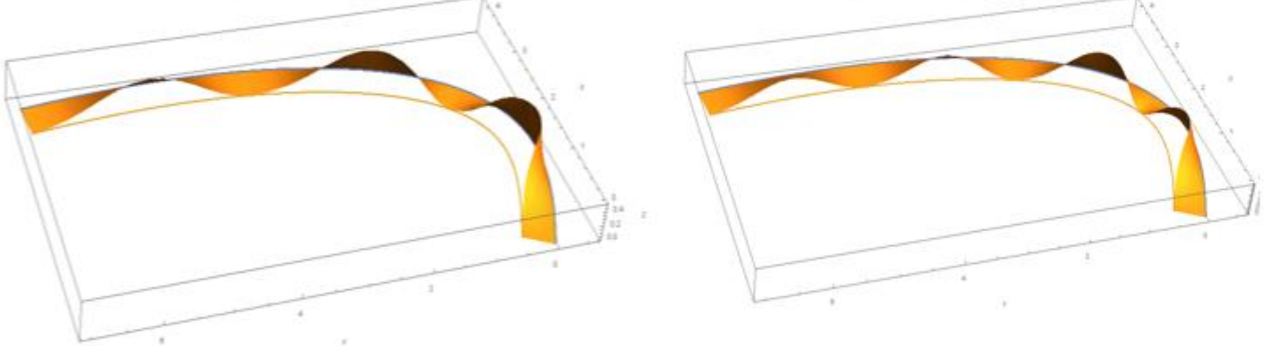
- As the number of wrinkles increases the amplitude decreases.
- The amplitude of the wrinkles is proportional to the curvature.
- Higher number of wrinkles can be obtained at higher energy level

Results for a curvilinear NURBS path



(a) $N = 1$ wrinkle

(b) $N = 2$ wrinkles

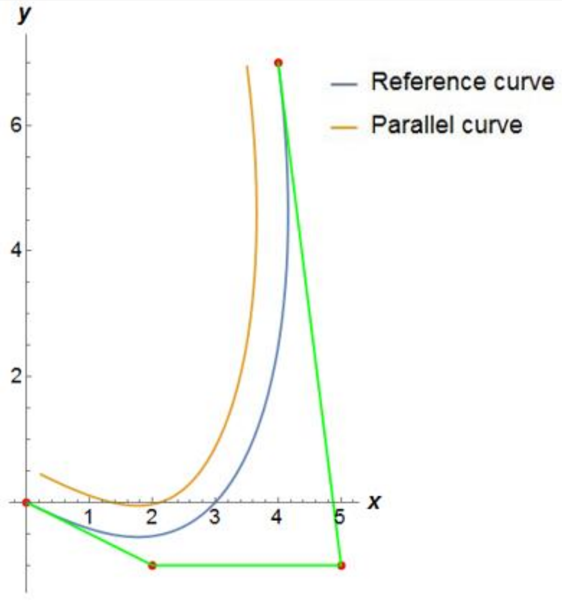


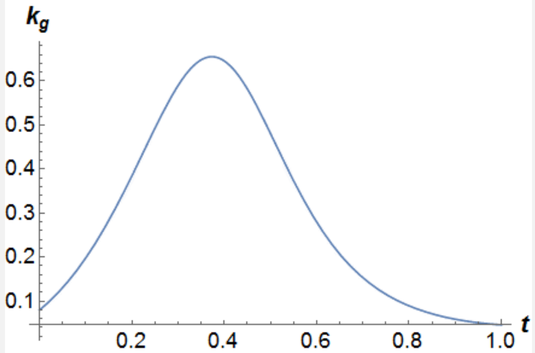
(c) $N = 3$ wrinkles

(d) $N = 4$ wrinkles

Analysis:

- As the number of wrinkles increases the amplitude decreases.
- The amplitude of the wrinkles is proportional to the curvature.





A random curvilinear path is defined in NURBS form with the following parameters:

$$P_i = \{(0,0),(2,-1),(5,-1),(4,7)\},$$

$$w_i = \{1, 1.5, 1, 1\}.$$

$$KV = \{0,0,0,0,1,1,1,1\}$$

$$p = 3 \quad and \quad w = 0.5$$

Tow-Path Modeling on General Surfaces

- Start by defining a surface in parametric form:

$$\boldsymbol{S}(u,v) = X(u,v)\hat{\imath} + Y(u,v)\hat{\jmath} + Z(u,v)\hat{k} \quad ,$$

- Compute the unit tangents and normal vectors to the surface:

$$\widehat{\boldsymbol{S}}_{\boldsymbol{u}}(u,v) = \frac{\partial \boldsymbol{S}(u,v)/\partial u}{\|\partial \boldsymbol{S}(u,v)/\partial u\|} \quad , \quad \widehat{\boldsymbol{S}}_{\boldsymbol{v}}(u,v) = \frac{\partial \boldsymbol{S}(u,v)/\partial v}{\|\partial \boldsymbol{S}(u,v)/\partial v\|} \; ,$$

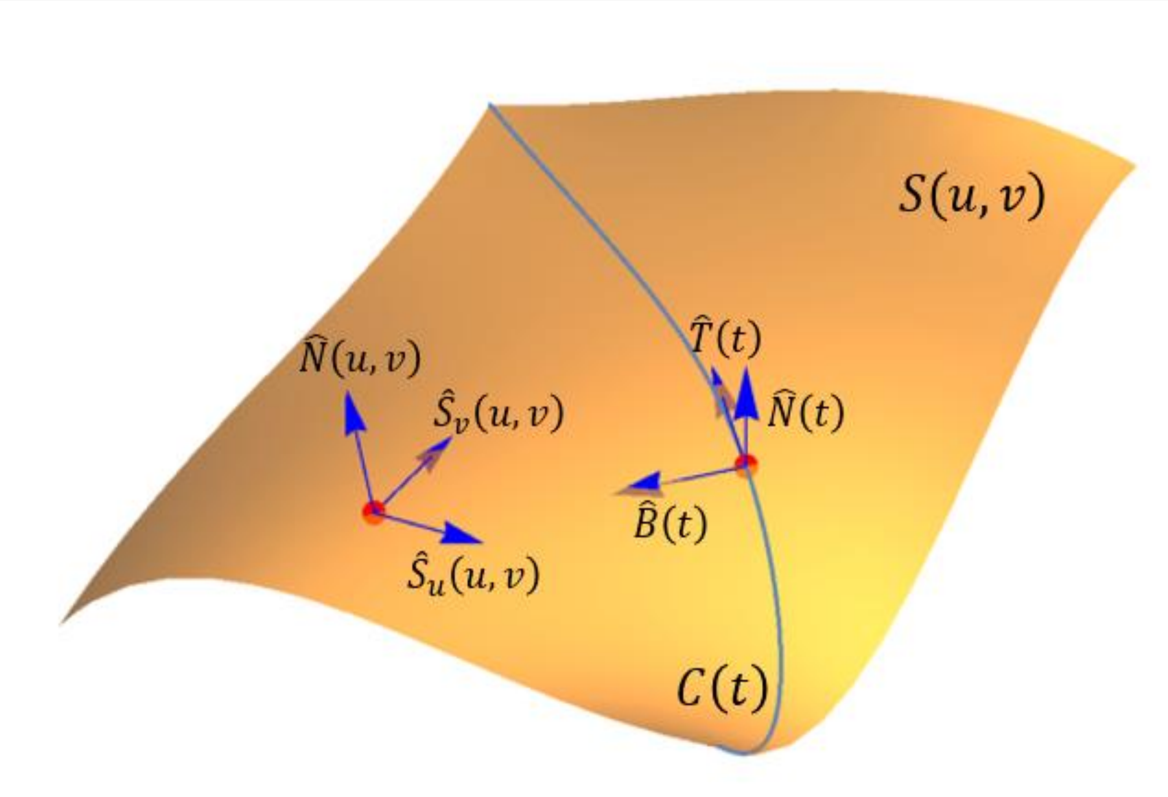
$$\widehat{\boldsymbol{N}}(u,v) = \widehat{\boldsymbol{S}_{\boldsymbol{u}}} \times \widehat{\boldsymbol{S}_{\boldsymbol{v}}}$$

- Define an arbitrary path on the surface:

$$\boldsymbol{C}(t) = \boldsymbol{S}\big(u_c(t), v_c(t)\big)$$

- Compute the path tangent, normal, and binormal vectors:

$$\widehat{\boldsymbol{T}}(t) = \frac{d\boldsymbol{C}(t)/dt}{\|d\boldsymbol{C}(t)/dt\|} \quad , \quad \widehat{\boldsymbol{B}}(t) = \widehat{\boldsymbol{N}}(t) \times \widehat{\boldsymbol{T}}(t) \, .$$

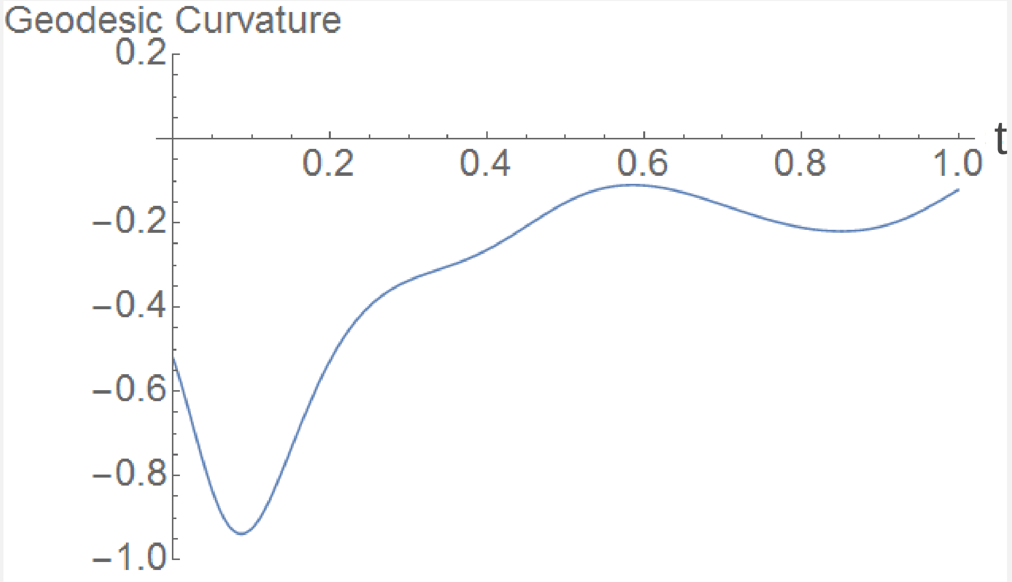


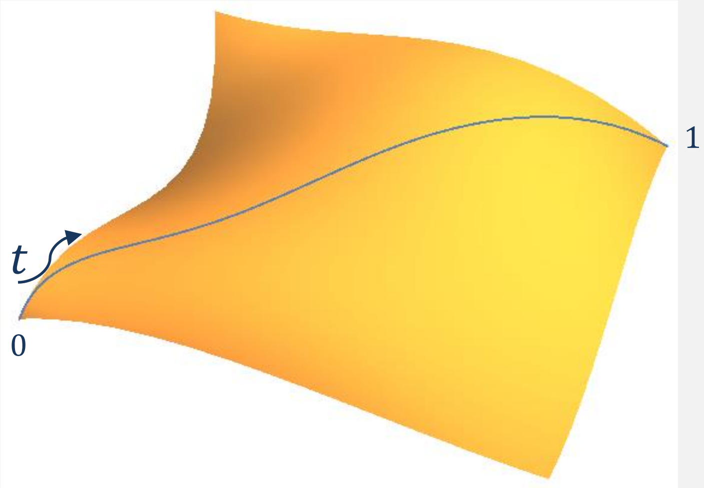
Geodesic Curvature

- An important feature of the path along the surface is the geodesic curvature. It has a similar physical meaning of the curvature of a curve in 2D.

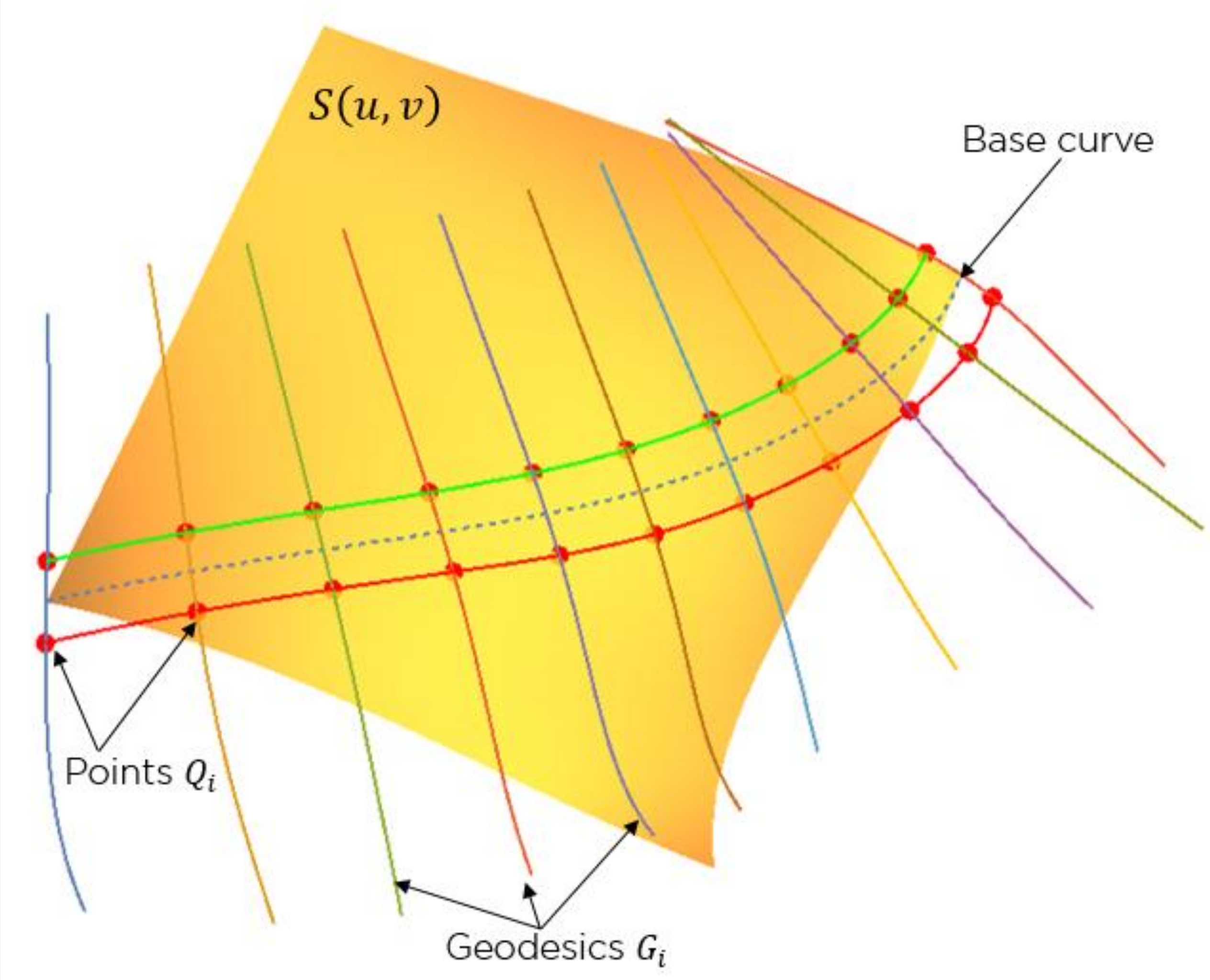
$$k_g = \sqrt{E\,G - F^2}\left[-\Gamma_{11}^{2} {u_c'}^{3} + \Gamma_{22}^{1} {v_c'}^{3} - (2\Gamma_{12}^{2} - \Gamma_{11}^{1}) {u_c'}^{2} v_c' + (2\Gamma_{12}^{1} - \Gamma_{22}^{2}) u_c' {v_c'}^{2} + u_c'' v' - v_c'' u_c'\right] \times \left(E\, {u_c'}^{2} + 2\,F\, u_c' v_c' + G\, {v_c'}^{2}\right)^{-\frac{3}{2}}$$

- E, F and G: first fundamental coefficients
- $\Gamma_{\mathrm{ij}}^{\mathrm{k}}$: Christoffel symbols
- u, v path parameters





Parallel Curves on the Surface



<u>Algorithm:</u>

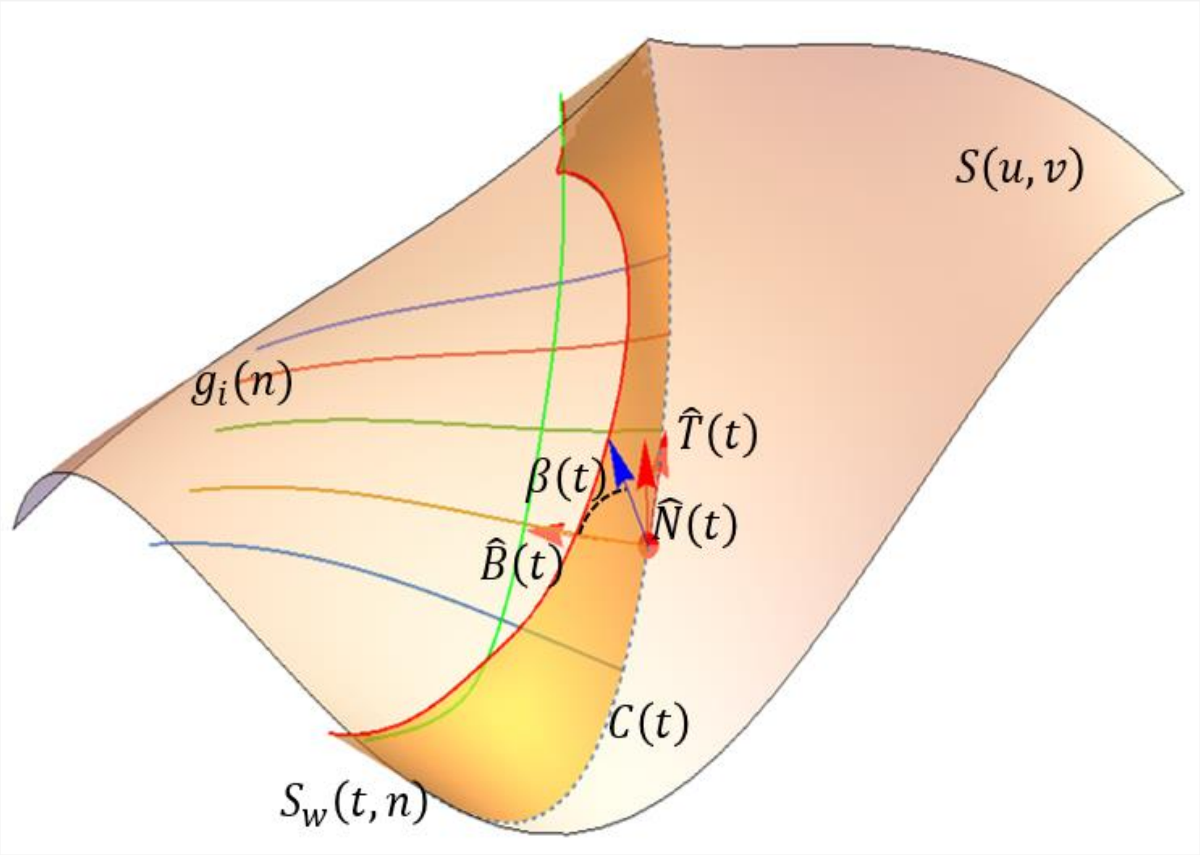
- Take n points P_i along the base curve: $P_i = \{P_1, P_2, \dots, P_n\}\ , i = 1 \dots n$
- Find each geodesic G_i starting at P_i in the direction orthogonal to the base curve
- Find the points Q_i on the geodesics at a distance $d_i$equal to the tow width
- Generate the parallel path by interpolating the points Q_i

Geodesic paths can be found by solving the following system:

$$\begin{cases} u'' + \Gamma^1_{11}u'^2 + 2\Gamma^1_{12}u'v' + \Gamma^1_{22}v'^2 = 0 \\ v'' + \Gamma^2_{11}u'^2 + 2\Gamma^2_{12}u'v' + \Gamma^2_{22}v'^2 = 0 \end{cases}$$

Wrinkles on General Surfaces

- A similar approach to the 2D path is used to find the wrinkled shape by following a rotational motion around the reference path:

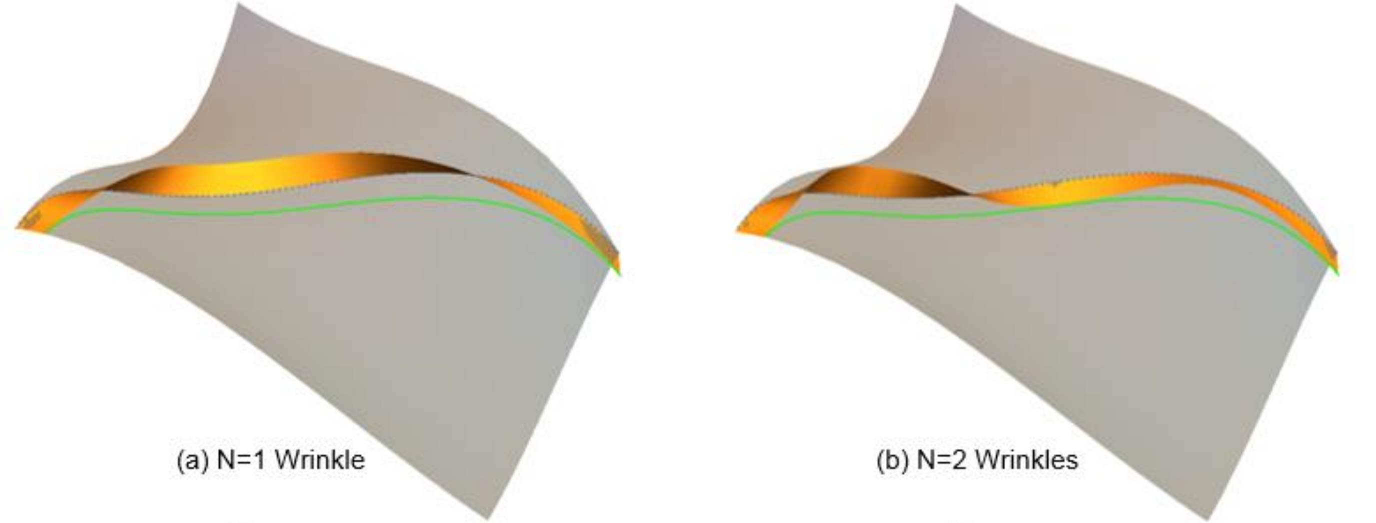


$$\boldsymbol{S_w}(t,n) = \left(\boldsymbol{S_{tow}}(t,n) - \boldsymbol{S_{tow}}(t,0)\right) \cdot \mathcal{R}\left(\boldsymbol{\hat{T}}(t), \beta(t)\right) + \boldsymbol{S_{tow}}(t,0)$$

$$\beta(t) = k\left(1 - \cos\left(\frac{2\pi(t-t_0)}{t_1 - t_0}\right)\right)$$

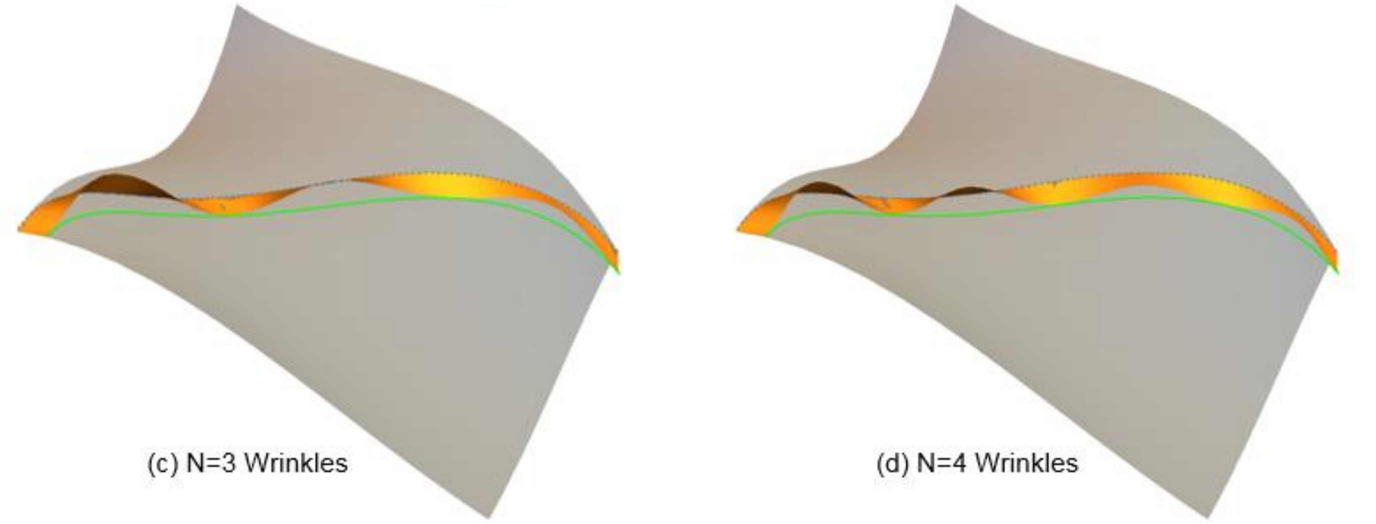
$$\int_{t_{i-1}}^{t_i} \sqrt{E\left(\frac{du_c}{dt}\right)^2 + F\,\frac{du_c}{dt}\,\frac{dv_c}{dt} + G\left(\frac{dv_c}{dt}\right)^2}\,dt = \frac{L}{N} \quad , \quad for\ i = 1, \ldots, N\,.$$

Results for General Surfaces



(a) N=1 Wrinkle

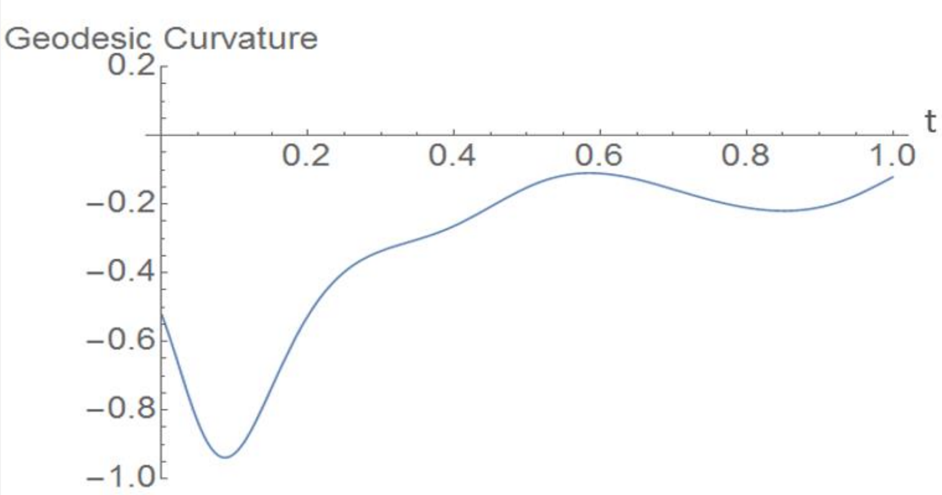
(b) N=2 Wrinkles



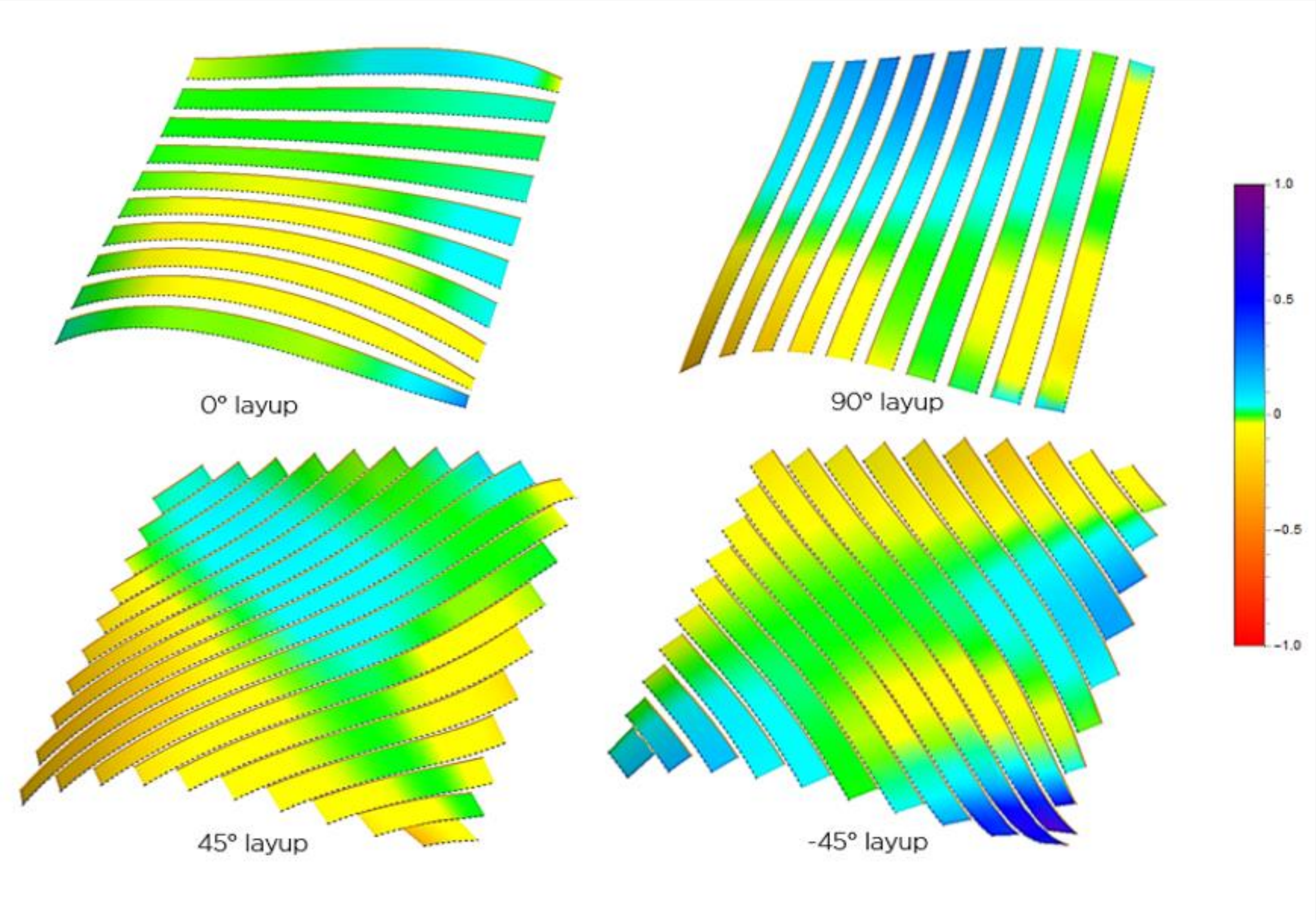
(c) N=3 Wrinkles

(d) N=4 Wrinkles

- **Analysis:**
- As the number of wrinkles increases the amplitude decreases.
- The amplitude of the wrinkles is proportional to the geodesic curvature.



Wrinkling Color Map



- Positive areas mean that possible wrinkles might appear on the dashed side of the tow
- Negative areas mean that possible wrinkles might appear on the solid side of the tow
- Different layups have different critical regions

Conclusion & Future Work

- A tow-path based formulation for wrinkling is developed and implemented for flat and general surfaces
- The shape of the wrinkles is assumed to be a cosine function, and it was found that the amplitude is proportional to the curvature
- A color map for different layups is presented to detect possible regions of wrinkling
- Next Steps:
  - Include material properties and elastic deformations (1st order)
  - Include viscoelastic and non-linear deformations (2nd order)

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