



## Learning-Based Bending Stiffness Parameter Estimation by a Drape Tester

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Weiwei Xu<sup>1</sup> Huamin Wang<sup>2</sup>

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<sup>2</sup>Style3D Research, China

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# Introduction

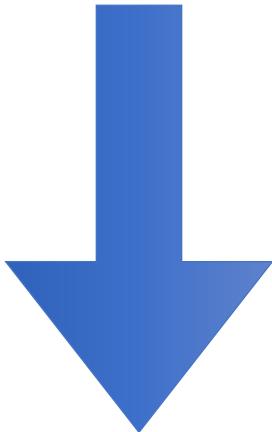


Physics-based simulation / animation: 1980s-Now



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Physics-based simulation / animation: 1980s-Now



Inverse problem for Physics-based simulation: 2000s-Now



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# Introduction

What problem do we want to solve?

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# Introduction Bending Rigidity Effects Realism



Soft Skirt



Rigid Skirt

# Introduction Bending Rigidity Effects Realism

Soft Skirt



Plain satin

Rigid Skirt



Denim

# Introduction Bending Rigidity Effects Realism

Soft Skirt



Plain satin

Bending Rigidity: **684.3** g.mm<sup>2</sup>



Rigid Skirt



Denim

Bending Rigidity: **77331** g.mm<sup>2</sup>

# Introduction Our Question



An Anonymous Fabric



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# Introduction Our Question

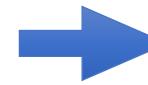


An Anonymous Fabric

Estimated  
Bending  
Parameters

In-house Simulator

# Introduction Our Question



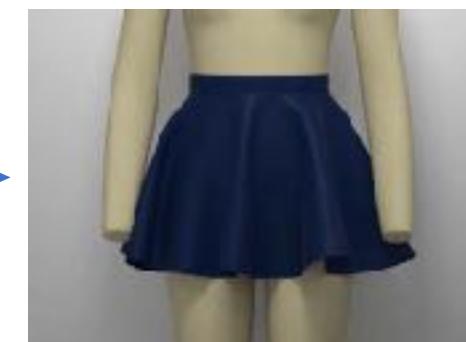
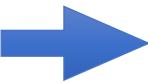
Simulation  
Result

An Anonymous Fabric

Estimated  
Bending  
Parameters

In-house Simulator

# Introduction Our Question



Simulation  
Result

An Anonymous Fabric

Estimated  
Bending  
Parameters

In-house Simulator

〃 As Close As Possible

Question:

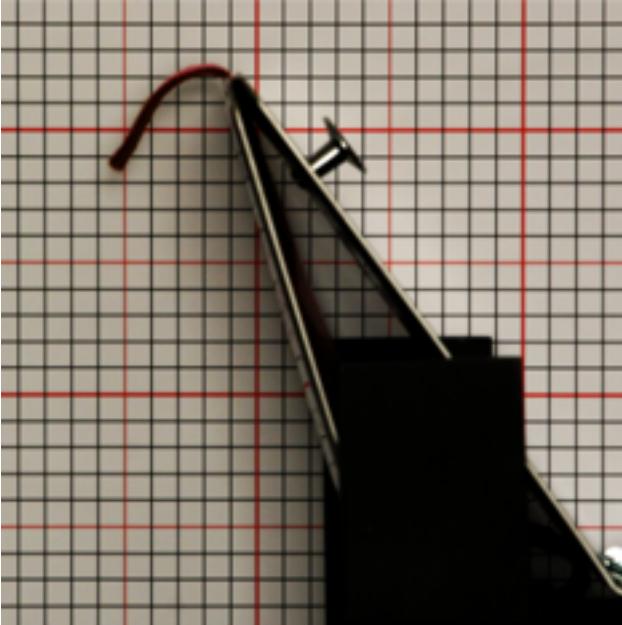
How to **estimate bending parameters**  
to achieve the **most realistic** behavior?



Real Behavior

# Introduction

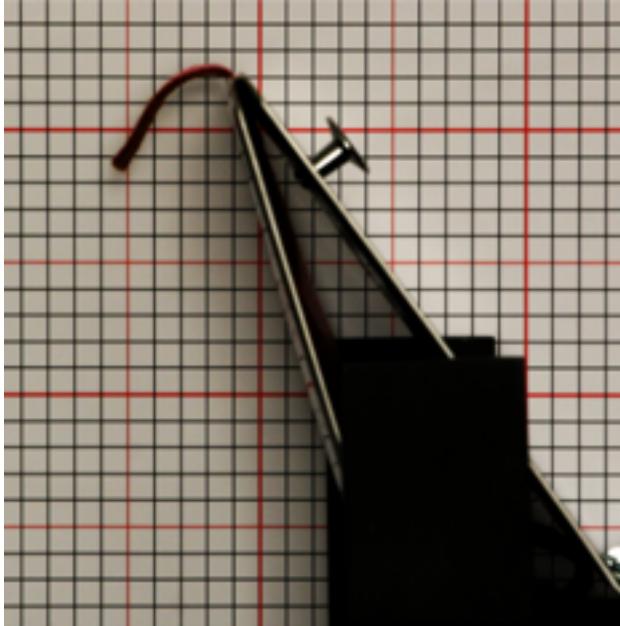
## Related Work



[1]

[1] Wang, et al. “Data-Driven Elastic Models for Cloth: Modeling and Measurement.” SIGGRAPH 2011

# Introduction Related Work



[1]



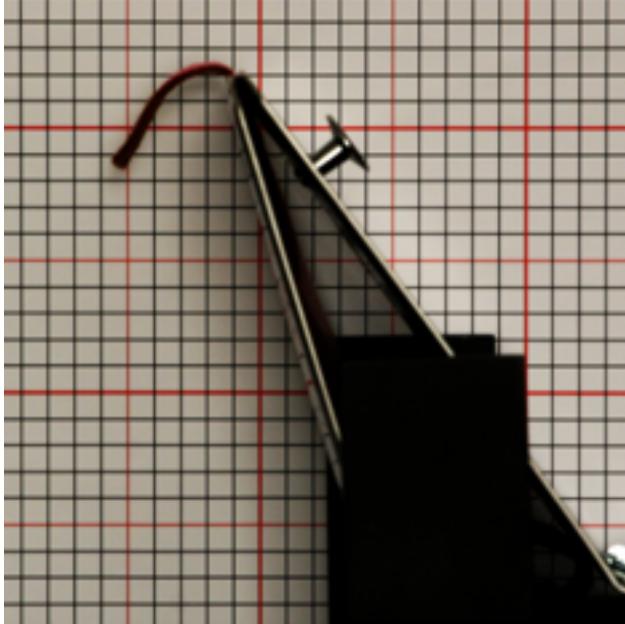
[2]

[1] Wang, et al. “Data-Driven Elastic Models for Cloth: Modeling and Measurement.” SIGGRAPH 2011

[2] Miguel, et al. “Data-Driven Estimation of Cloth Simulation Models.” Computer Graphic Forum (Eurographics) 2012

# Introduction

## Related Work



[1]



[2]



[3]

[1] Wang, et al. “Data-Driven Elastic Models for Cloth: Modeling and Measurement.” SIGGRAPH 2011

[2] Miguel, et al. “Data-Driven Estimation of Cloth Simulation Models.” Computer Graphic Forum (Eurographics) 2012

[3] Yang, et al. “Learning-Based Cloth Material Recovery from Video.” ICCV 2017

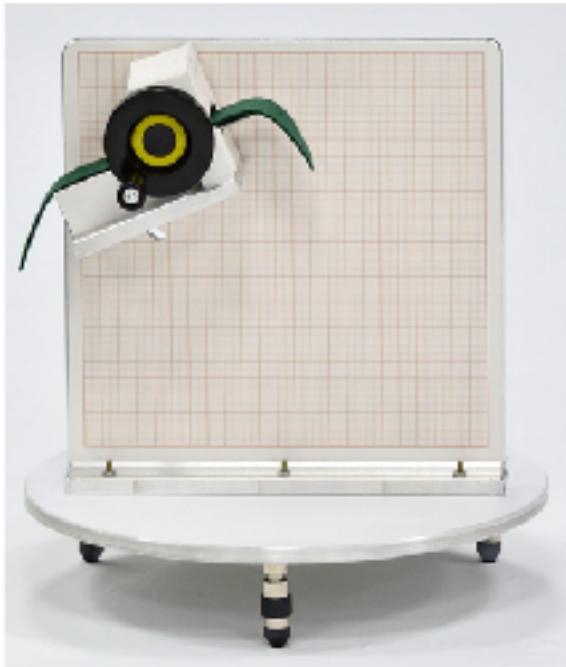
# Introduction Challenges: Curly Effect



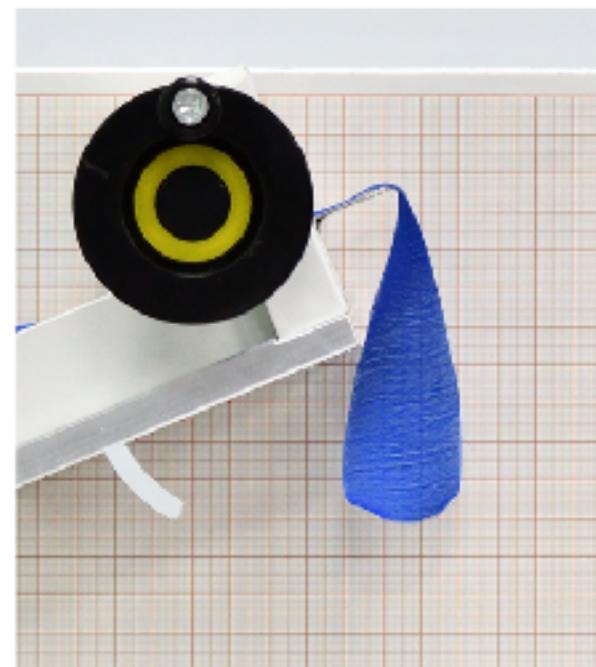
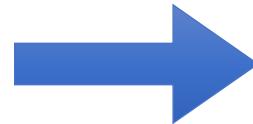
Cantilever Tester<sup>1</sup>

[1]: ASTM. 2018. ASTM D1388: Standard Test Method for Stiffness of Fabrics. (July 2018).

# Introduction Challenges: Curly Effect



Cantilever Tester<sup>1</sup>

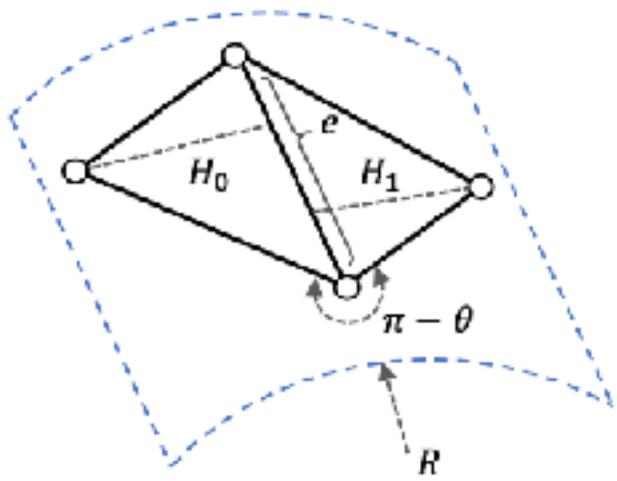


Curly Effect in Cantilever Tester

Curly edge effects the measurement result.

[1]: ASTM. 2018. ASTM D1388: Standard Test Method for Stiffness of Fabrics. (July 2018).

# Introduction Challenges: Complex Bending Model



Dihedral Angle-based Model<sup>1</sup>

$$E(x) = \alpha \left( \frac{2\theta(x)}{e(H_0 + H_1)} \right)^2$$

Diagonal Spring bending Model<sup>2</sup>

$$E(x) = \beta \left( \frac{\|x_0 - x_3\| - r}{e(H_0 + H_1)} \right)^2$$

Quadratic Bending Model<sup>3</sup>

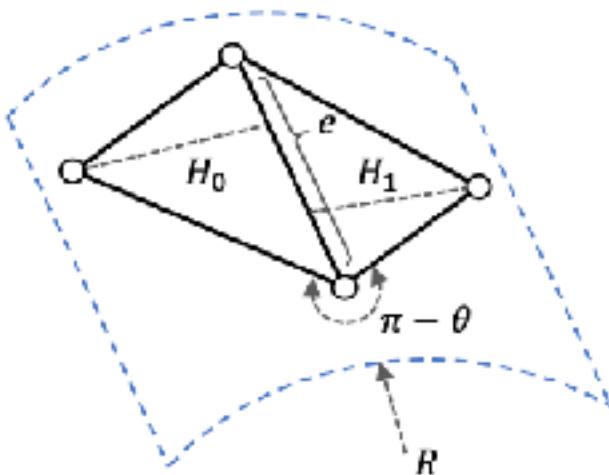
$$E(x) = \frac{3\gamma}{(H_0 + H_1)e} \|Kx\|^2$$

[1] Bridson et al, “Simulation of Clothing with Folds and Wrinkles.” SCA 2003

[2] Bouaziz et al, “Projective Dynamics: Fusing Constraint Projections for Fast Simulation.” SIGGRAPH 2014

[3] Bergou, et al. “A Quadratic Bending Model for Inextensible Surfaces.” SGP 2006

# Introduction Challenges: Complex Bending Model



$$E(x) = \alpha \left( \frac{2\theta(x)}{e(H_0 + H_1)} \right)^2$$

$$E(x) = \beta \left( \frac{\|x_0 - x_3\| - r}{e(H_0 + H_1)} \right)^2$$

$$E(x) = \frac{3\gamma}{(H_0 + H_1)e} \|Kx\|^2$$

Bending Parameters

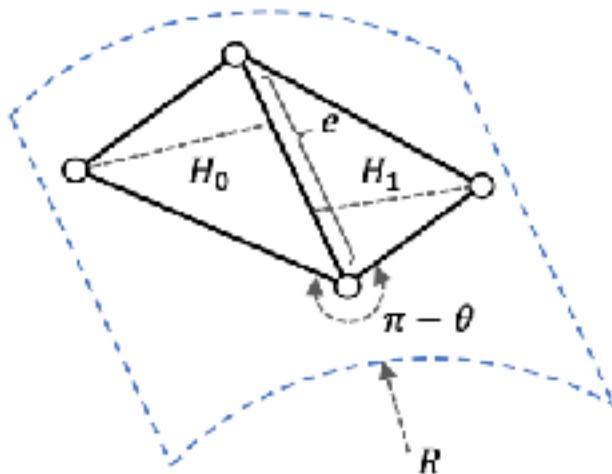
$$\alpha$$

$$\beta$$

$$\gamma$$

- { Bending Rigidity: The material property which associate torque and curvature.  
Bending Parameter: Parameters used in simulator for bending effect.

# Introduction Challenges: Complex Bending Model



$$E(x) = \alpha \left( \frac{2\theta(x)}{e(H_0 + H_1)} \right)^2$$

$$E(x) = \beta \left( \frac{\|x_0 - x_3\| - r}{e(H_0 + H_1)} \right)^2$$

$$E(x) = \frac{3\gamma}{(H_0 + H_1)e} \|Kx\|^2$$

Bending Parameters

$$\alpha$$

$$\beta$$

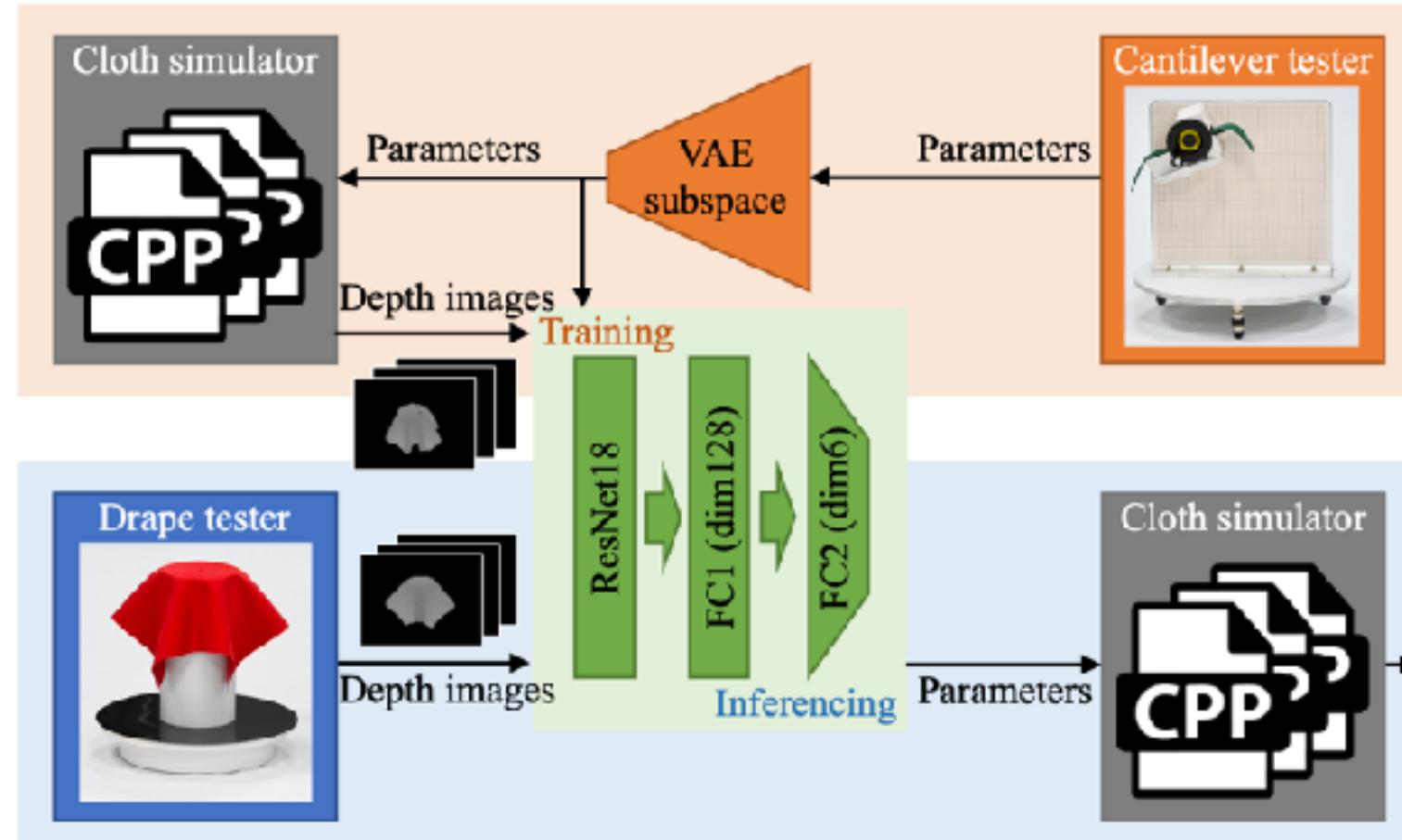
$$\gamma$$

Estimate **bending parameters**, which are applicable in the simulator directly.

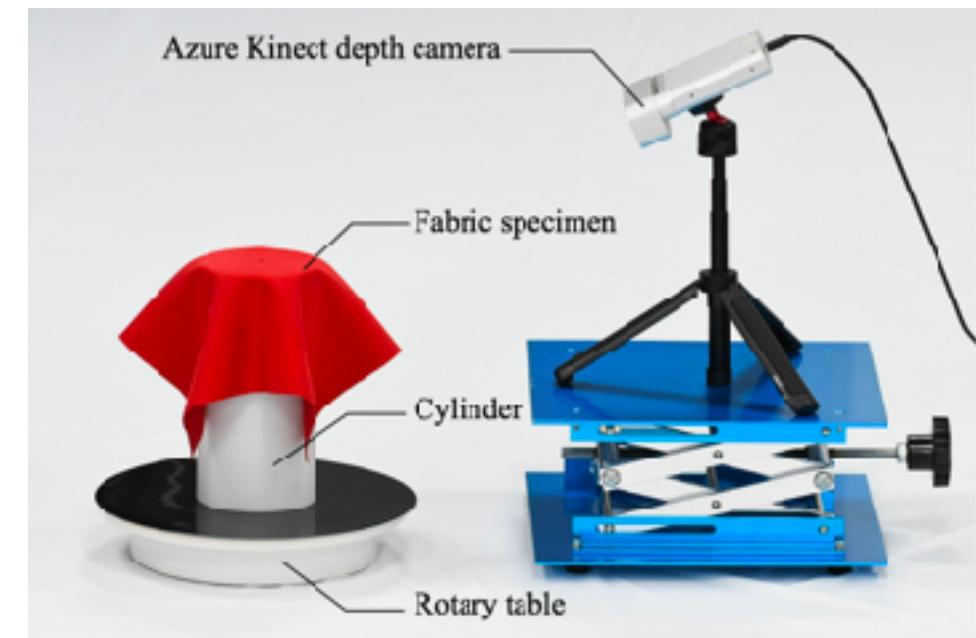
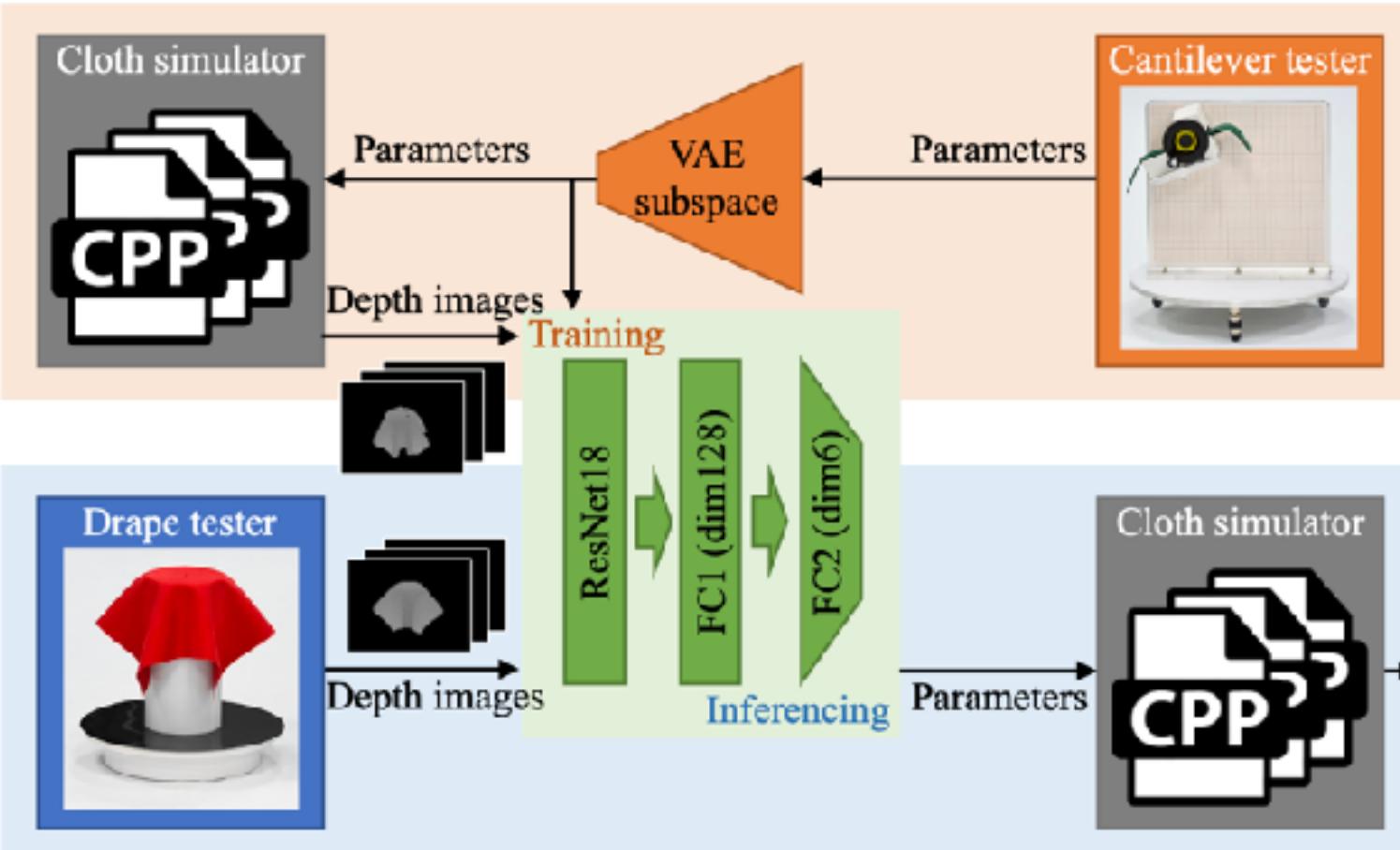
# Introduction System Pipeline



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# Introduction System Pipeline





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# Methods

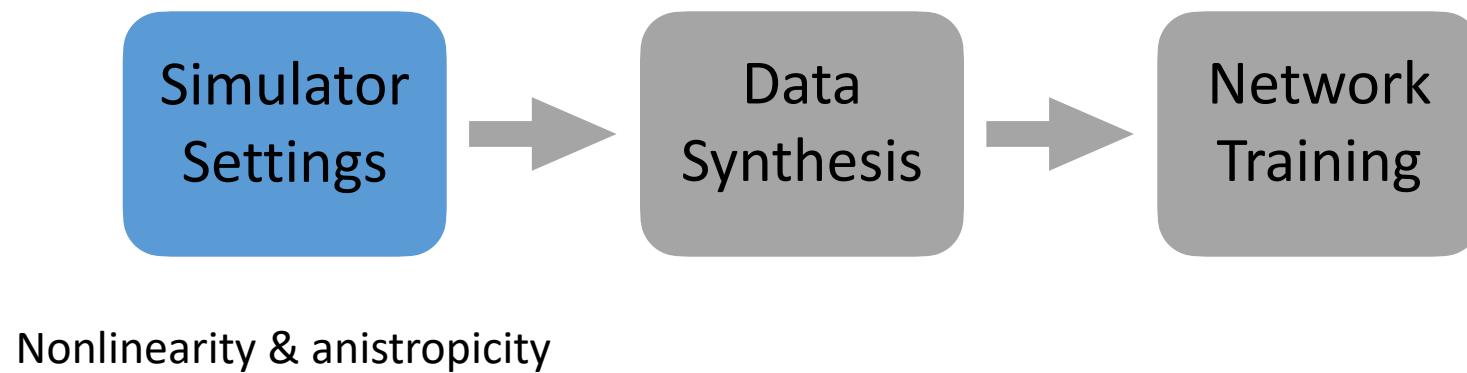
The details of our work.

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# Methods

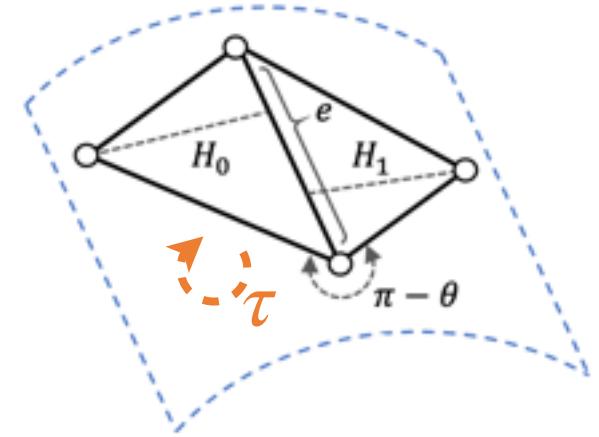
## Simulator Settings



Nonlinearity & anisotropicity

# Methods Nonlinear Bending Model

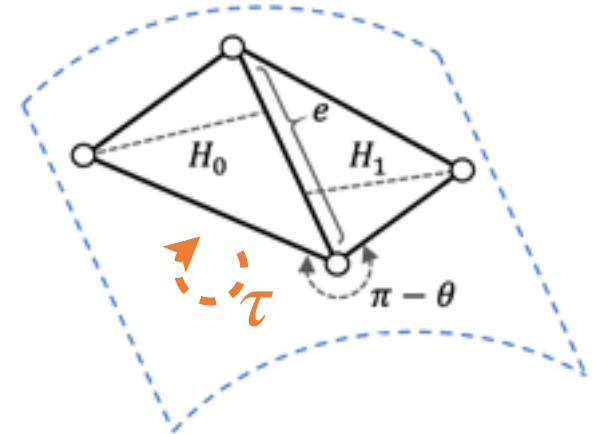
Bending Energy:  $E(\theta) = \int_0^\theta \tau(\kappa(\xi), e) d\xi$



# Methods Nonlinear Bending Model

Bending Energy:  $E(\theta) = \int_0^\theta \tau(\kappa(\xi), e) d\xi$

Bending Force:  $f_i = -\nabla_i E = -(\alpha\kappa + \beta\kappa^2)e \nabla_i \theta(x)$

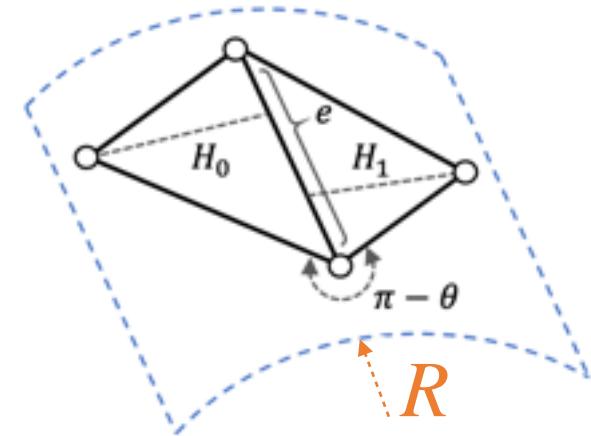


# Methods Nonlinear Bending Model

Bending Energy:  $E(\theta) = \int_0^\theta \tau(\kappa(\xi), e) d\xi$

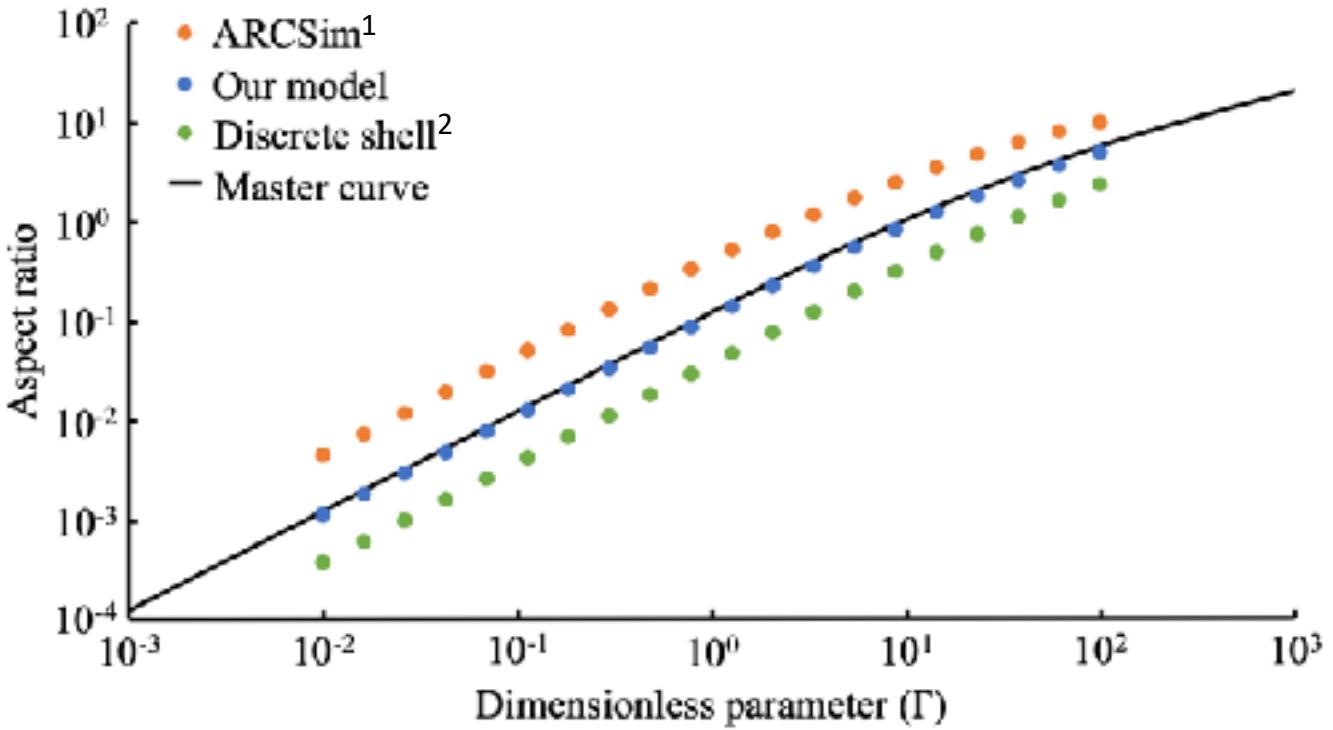
Bending Force:  $f_i = -\nabla_i E = -(\alpha\kappa + \beta\kappa^2)e \nabla_i \theta(x)$

$$\kappa = \frac{1}{R} = \frac{2 \sin \theta}{\sqrt{H_0^2 + H_1^2 - 2H_0H_1 \cos(\pi - \theta)}} \approx \frac{2\theta}{H_0 + H_1}$$



# Methods Nonlinear Bending Model

## Master Curve Validation<sup>3</sup>

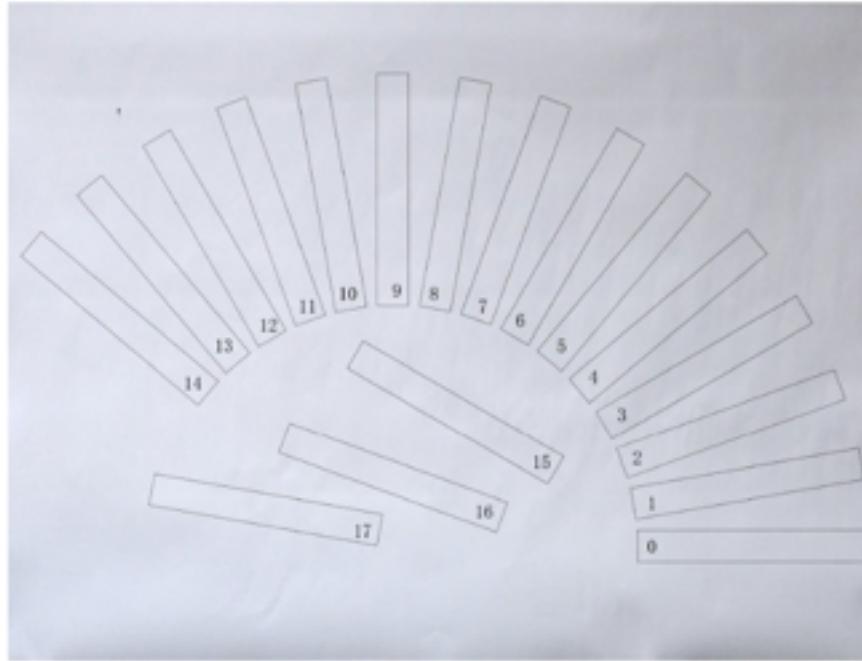


[1] Narain, et al, “Adaptive Anisotropic Remeshing for Cloth Simulation.” SIGGRAPH Asia 2012

[2] Grinspun, et al, “Discrete shells.” SCA 2003

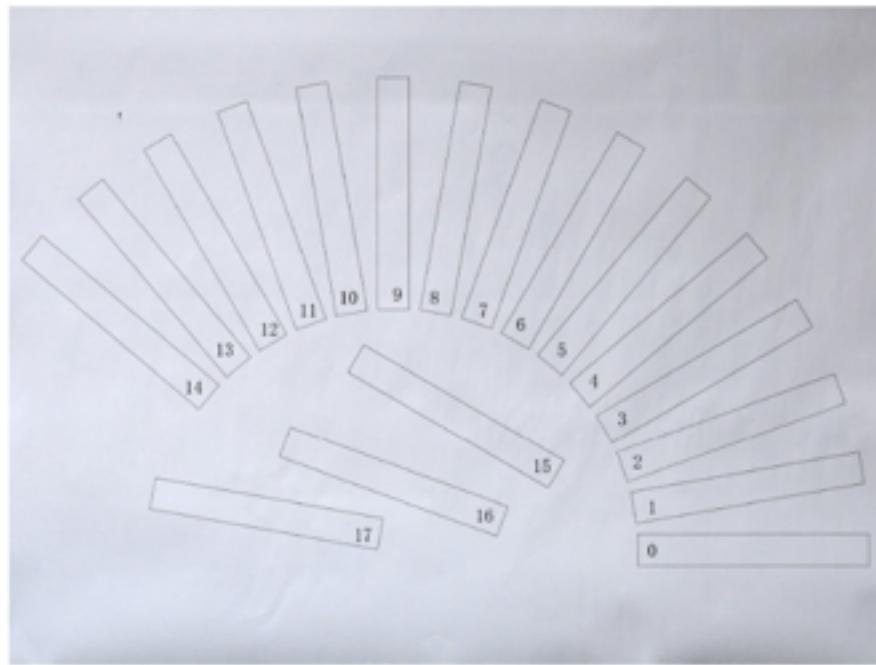
[3] Romero, et al, “Physical Validation of Simulators in Computer Graphics: A New Framework Dedicated to Slender Elastic Structures and Frictional Contact”.SIGGRAPH 2021

# Methods Anisotropicity Implementation

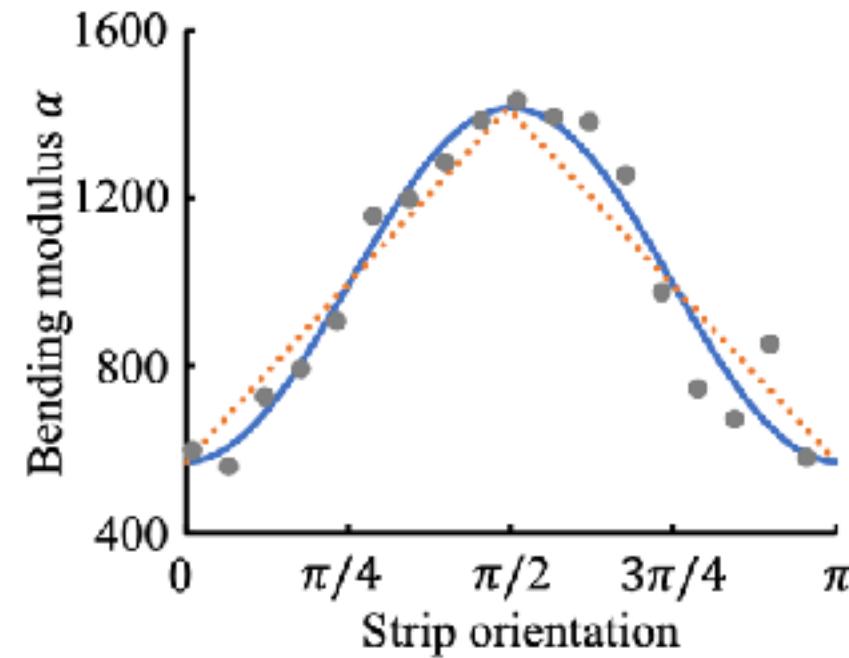


The Strip Template

# Methods Anisotropicity Implementation



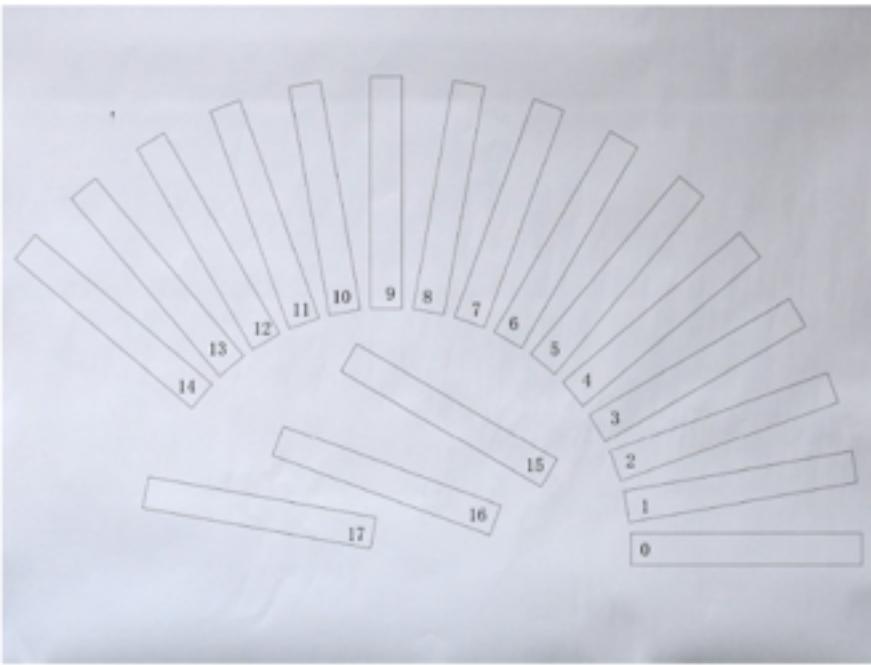
The Strip Template



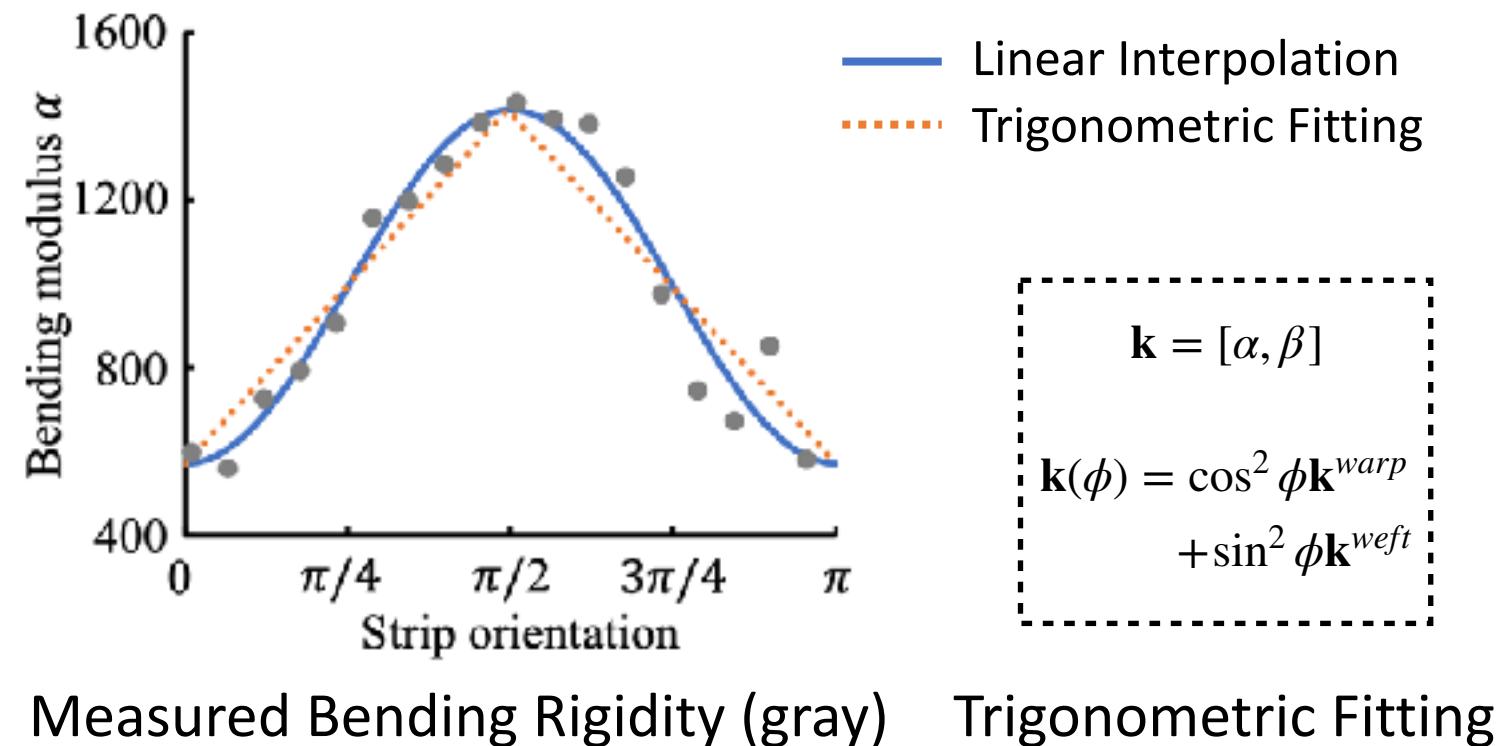
Measured Bending Rigidity (gray)

# Methods

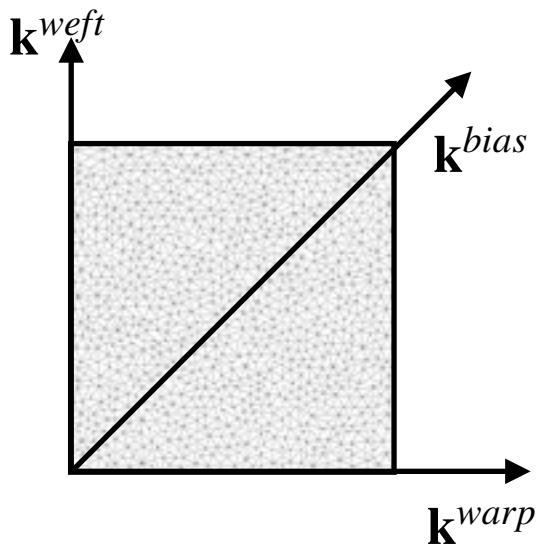
## Anisotropicity Implementation



The Strip Template



# Methods Anisotropicity Implementation

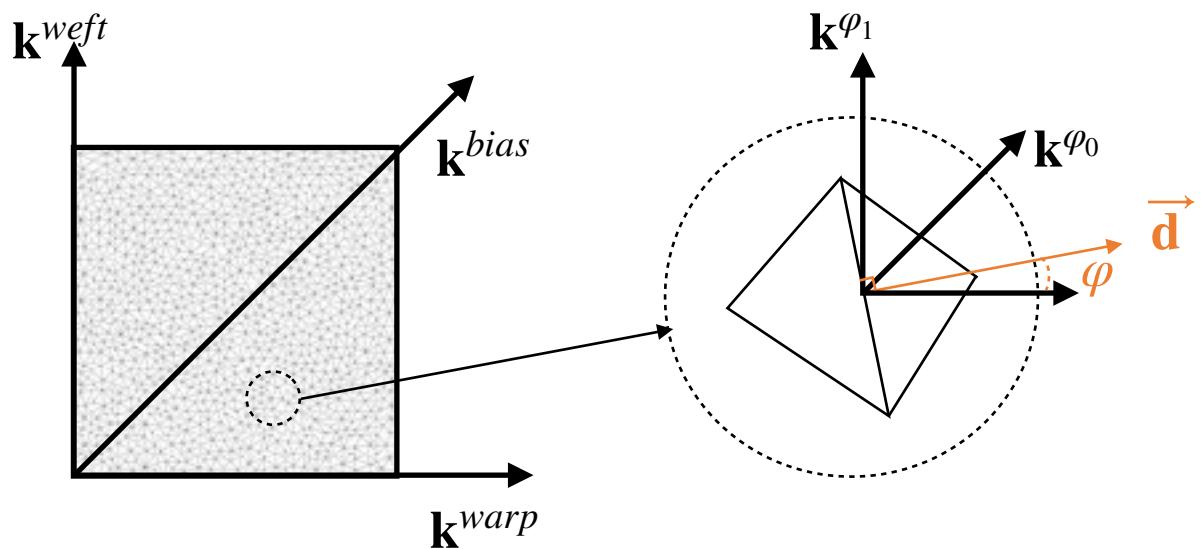


Given a Fabric

$$\mathbf{k} = \begin{bmatrix} \mathbf{k}^{warp} \\ \mathbf{k}^{bias} \\ \mathbf{k}^{weft} \end{bmatrix} \in \mathbb{R}^6$$

Three Directions Bending Parameter Vector

# Methods Anisotropicity Implementation



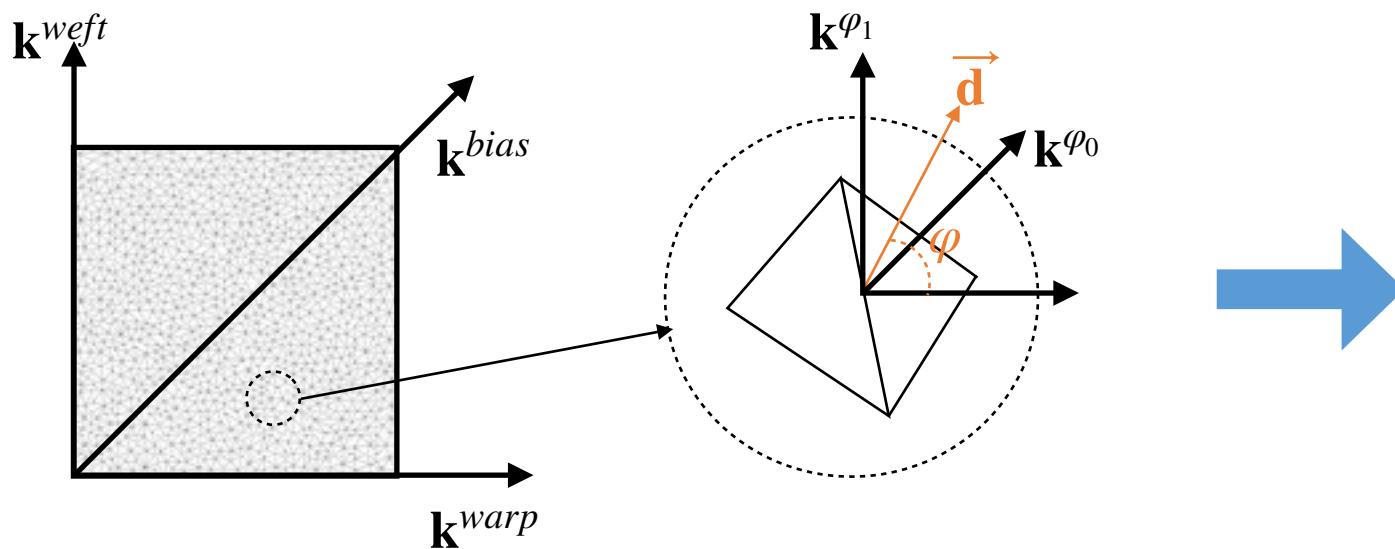
Given a Fabric

$\vec{d}$  is Edge Direction

Edge-based Bending Stiffness

$$\mathbf{k}(\varphi) = \begin{bmatrix} \cos^2 \varphi \\ \sin^2 \varphi \end{bmatrix}^T \begin{bmatrix} \mathbf{k}^{\varphi_0} \\ \mathbf{k}^{\varphi_1} \end{bmatrix}$$

# Methods Anisotropicity Implementation



Given a Fabric

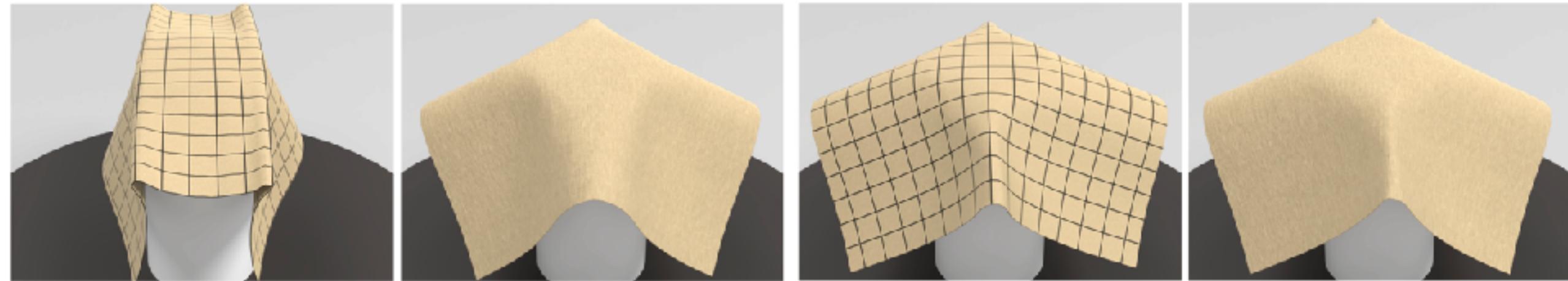
$\vec{d}$  is Current Bending Direction

$$\mathbf{k}(\varphi) = \begin{bmatrix} \cos^2 \varphi \\ \sin^2 \varphi \end{bmatrix}^T \begin{bmatrix} \cos^2 \varphi_0 & \sin^2 \varphi_0 \\ \cos^2 \varphi_1 & \sin^2 \varphi_1 \end{bmatrix} \begin{bmatrix} \mathbf{k}^{\varphi_0} \\ \mathbf{k}^{\varphi_1} \end{bmatrix}$$

Curvature-based Bending Stiffness

# Methods

## Anisotropic Implementation

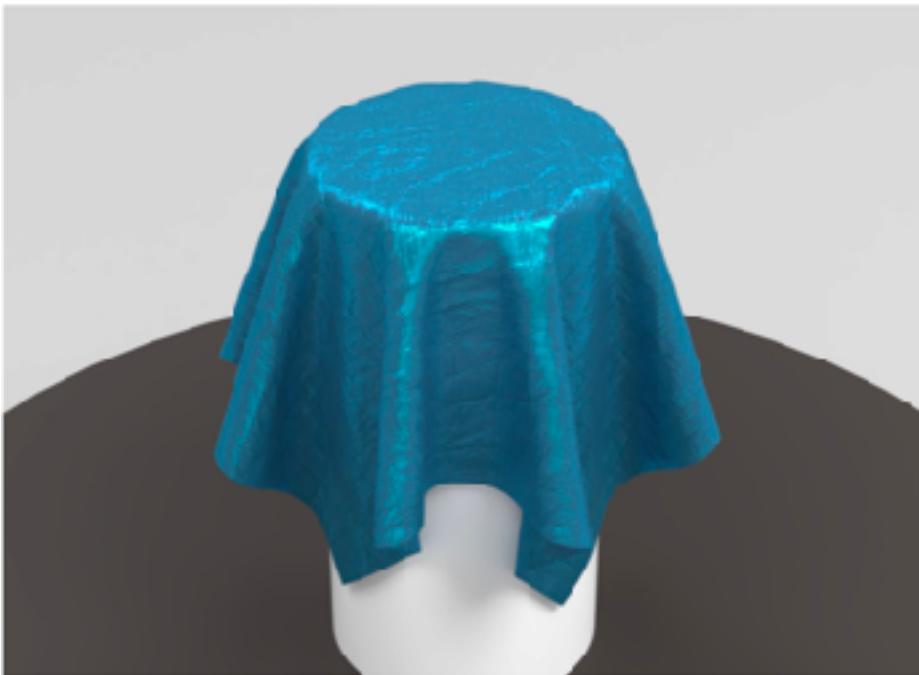


(a) Grid-structured mesh with edge-based anisotropic bending stiffness    (b) Unstructured mesh with edge-based anisotropic bending stiffness    (c) Grid-structured mesh with curvature-based anisotropic bending stiffness    (d) Unstructured mesh with curvature-based anisotropic bending stiffness

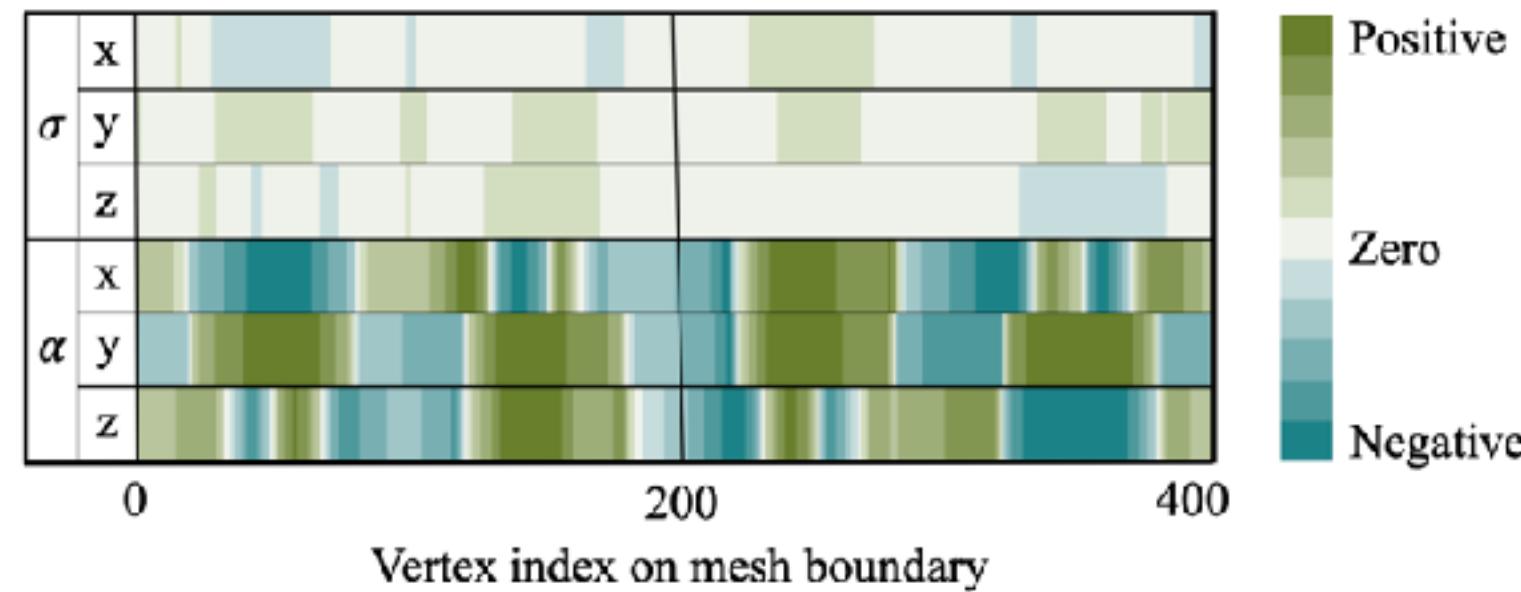
Mesh-Independent Simulation in Strong Anisotropic Case

# Methods

## Correlation Analysis



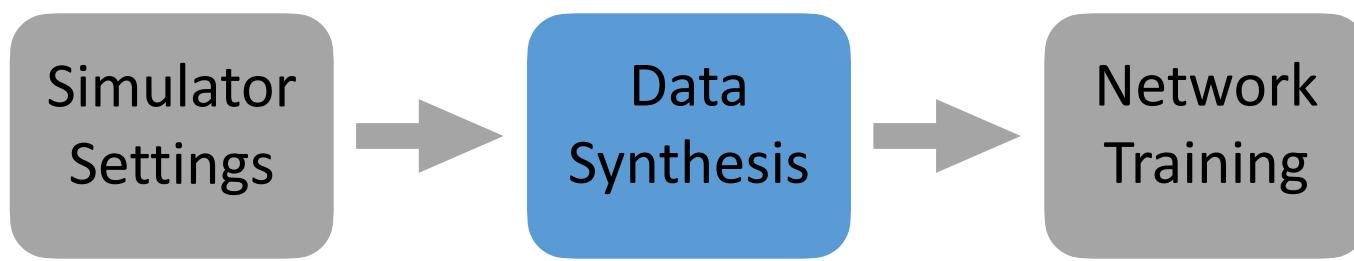
Cusick Drape Pose



Correlation Analysis indicates stretch parameters affect little on Cusick Drape

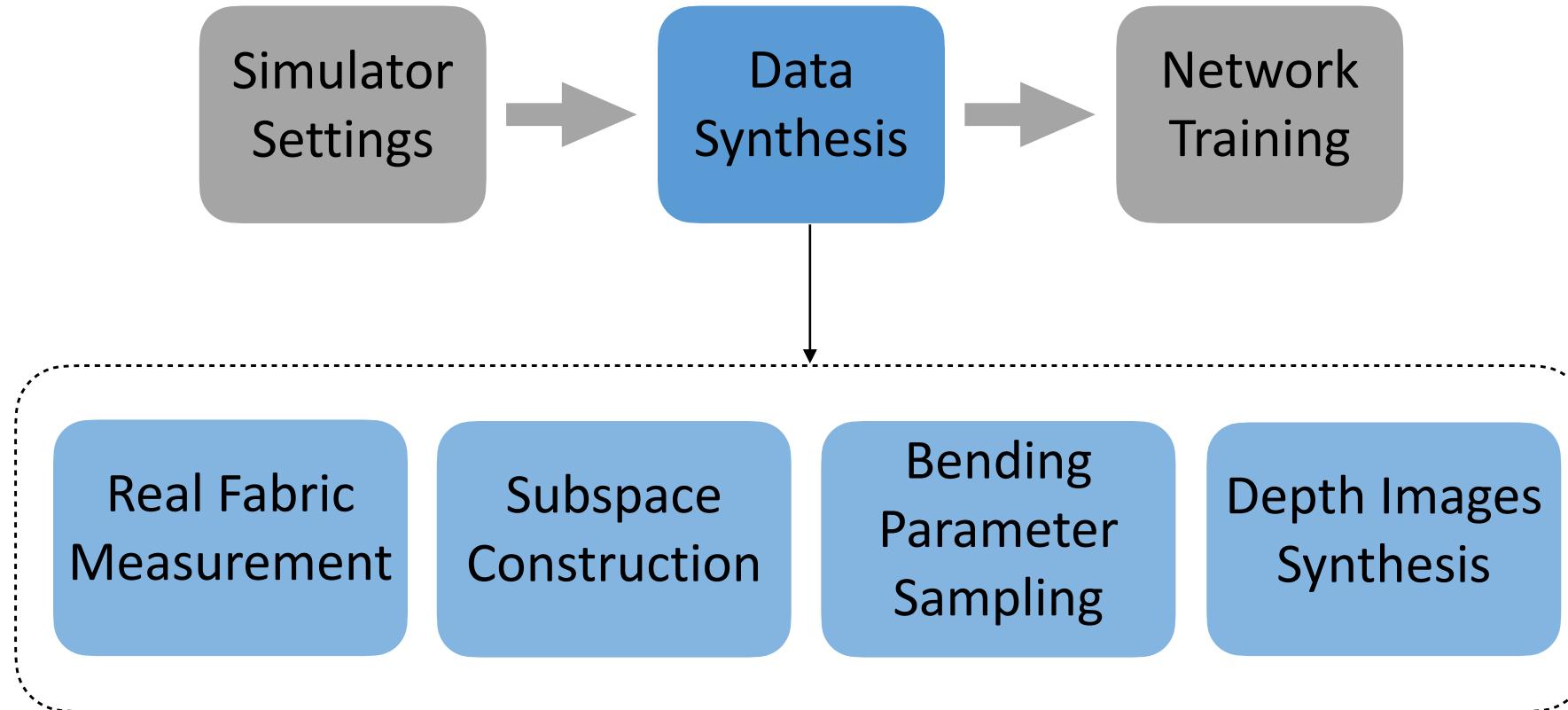
# Methods

## Data Synthesis



# Methods

## Data Synthesis



# Methods

## Real Fabric Measurement

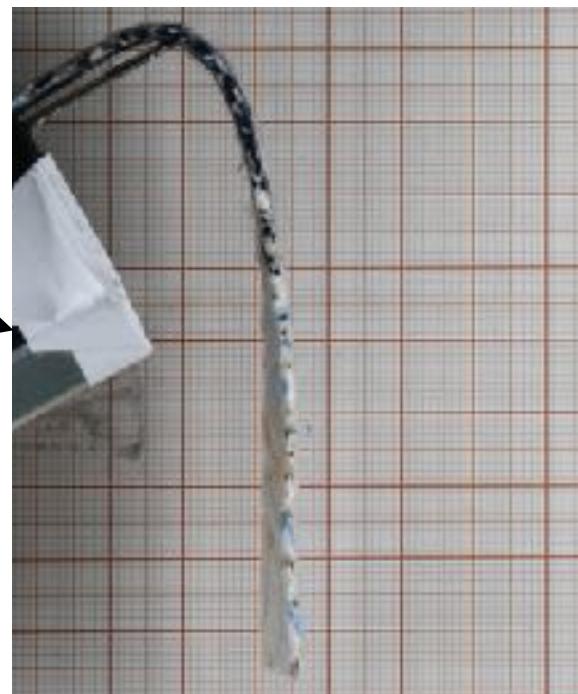
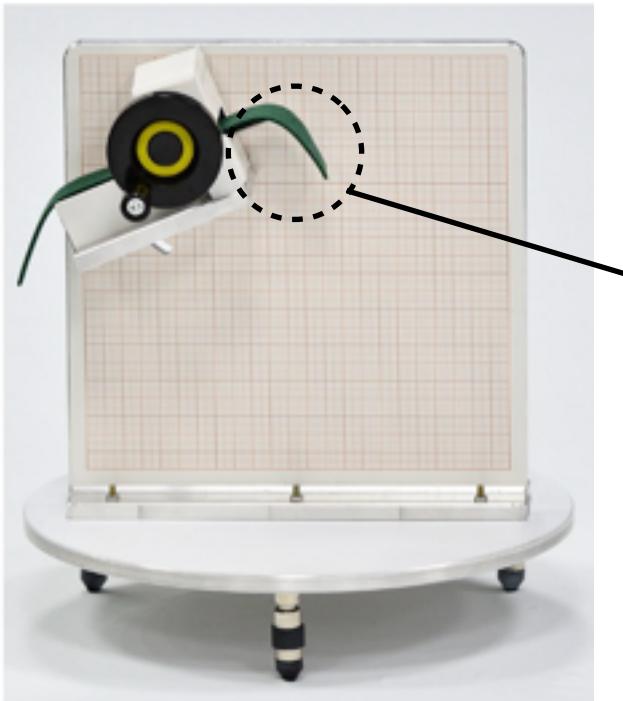
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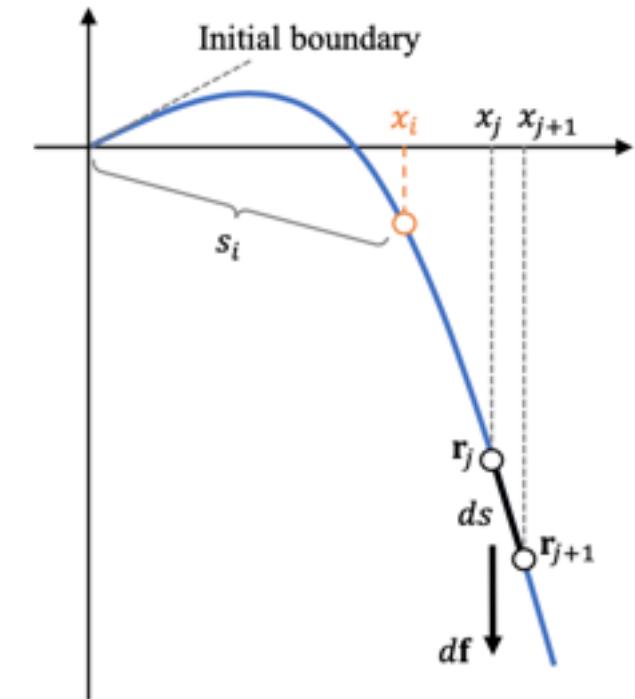
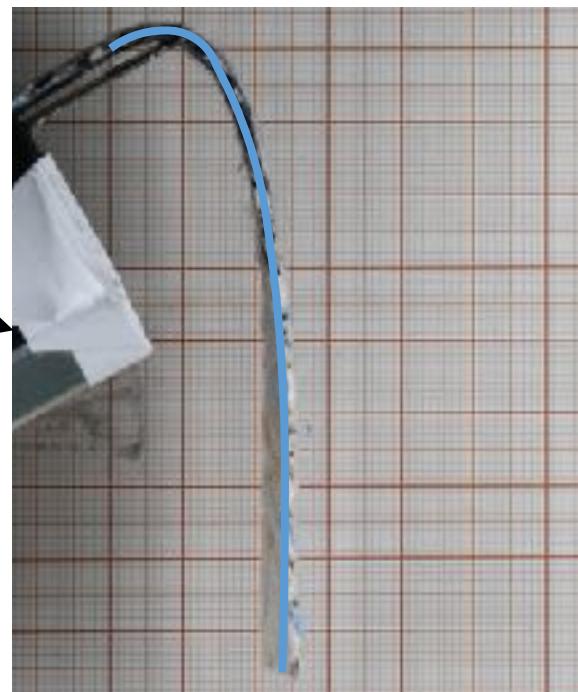
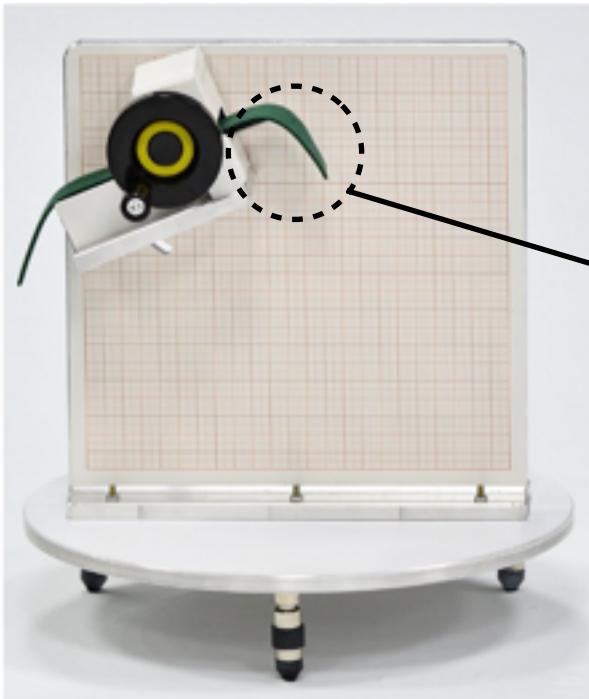
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# Methods

## Real Fabric Measurement

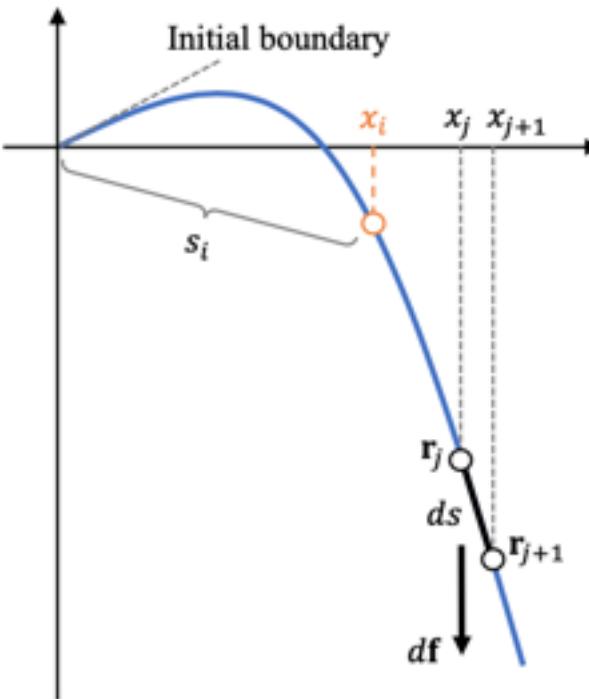
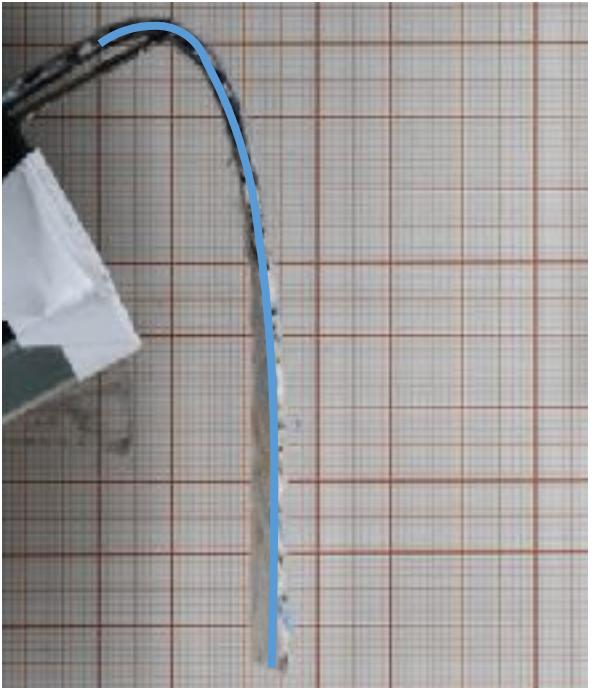


# Methods Real Fabric Measurement



# Methods

## Real Fabric Measurement



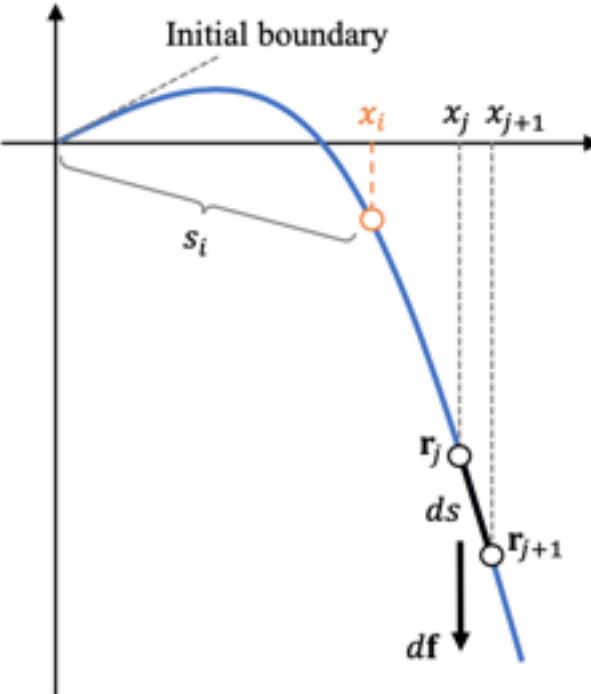
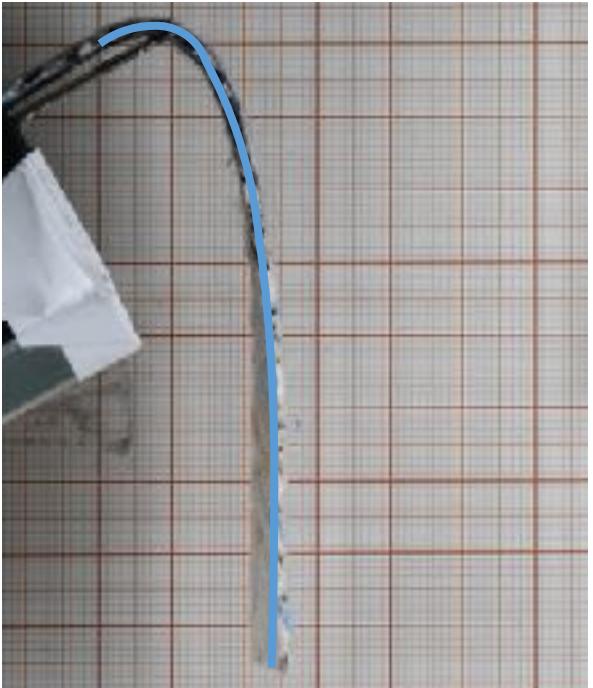
$$\tau_i = \rho g E \sum_{j=1}^{N-1} \frac{x_j + x_{j+1} - 2x_i}{2} \|\mathbf{r}_{j+1} - \mathbf{r}_j\|$$

$$\alpha^*, \beta^* = \underset{\alpha, \beta}{\operatorname{argmin}} \sum_{i=1}^N \|\tau_i - (\alpha \kappa_i + \beta \kappa_i^2) E\|$$

Get the Bending Parameters  
in Single Direction

# Methods

## Real Fabric Measurement



$$\alpha^*, \beta^* = \underset{\alpha, \beta}{\operatorname{argmin}} \sum_{i=1}^N \|\tau_i - (\alpha \kappa_i + \beta \kappa_i^2) E\|$$

Single Direction

$$\mathbf{k}^{warp} = [\alpha^{warp} \quad \beta^{warp}]$$

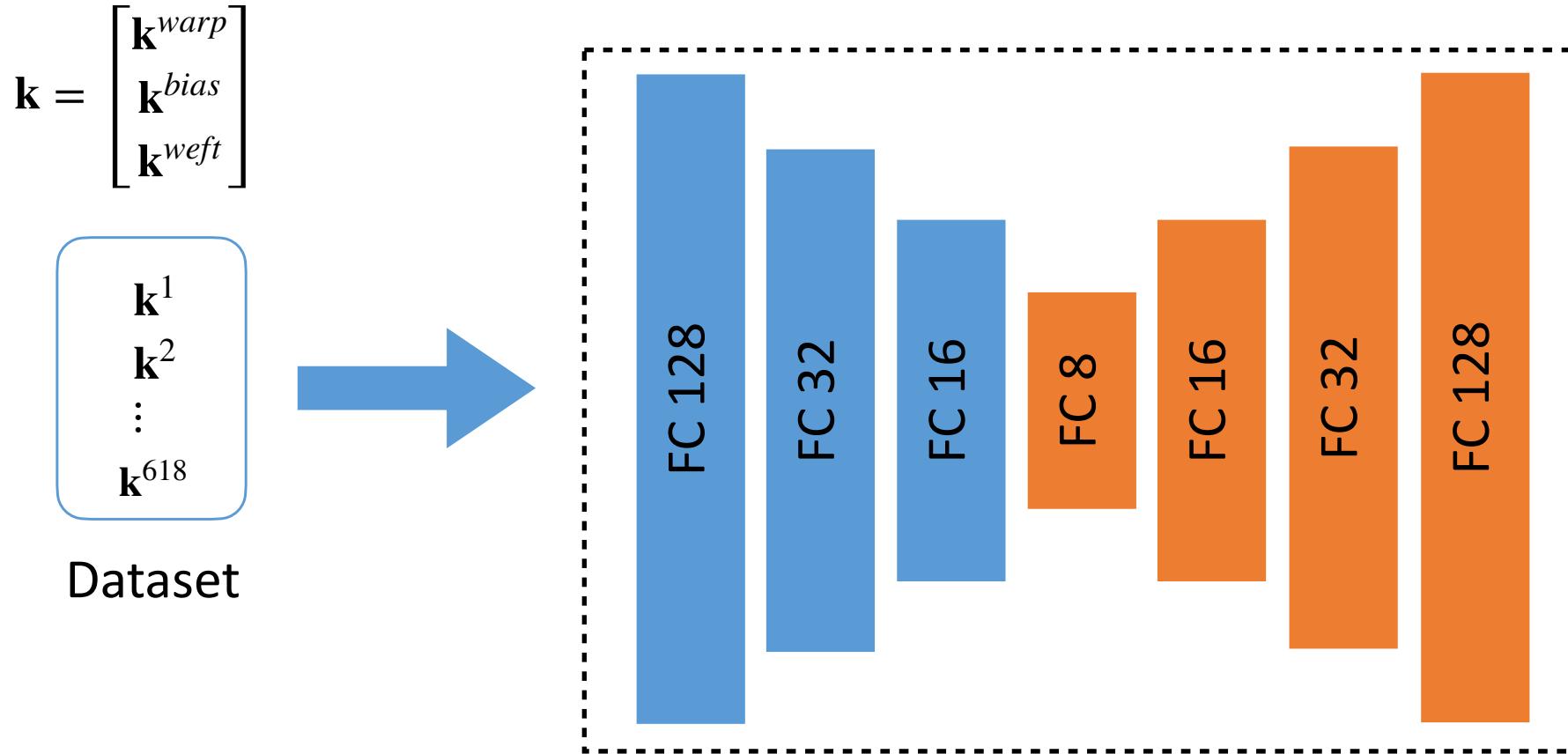
$$\mathbf{k}^{bias} = [\alpha^{bias} \quad \beta^{bias}]$$

$$\mathbf{k}^{weft} = [\alpha^{weft} \quad \beta^{weft}]$$

$$\mathbf{k} = \begin{bmatrix} \mathbf{k}^{warp} \\ \mathbf{k}^{bias} \\ \mathbf{k}^{weft} \end{bmatrix}$$

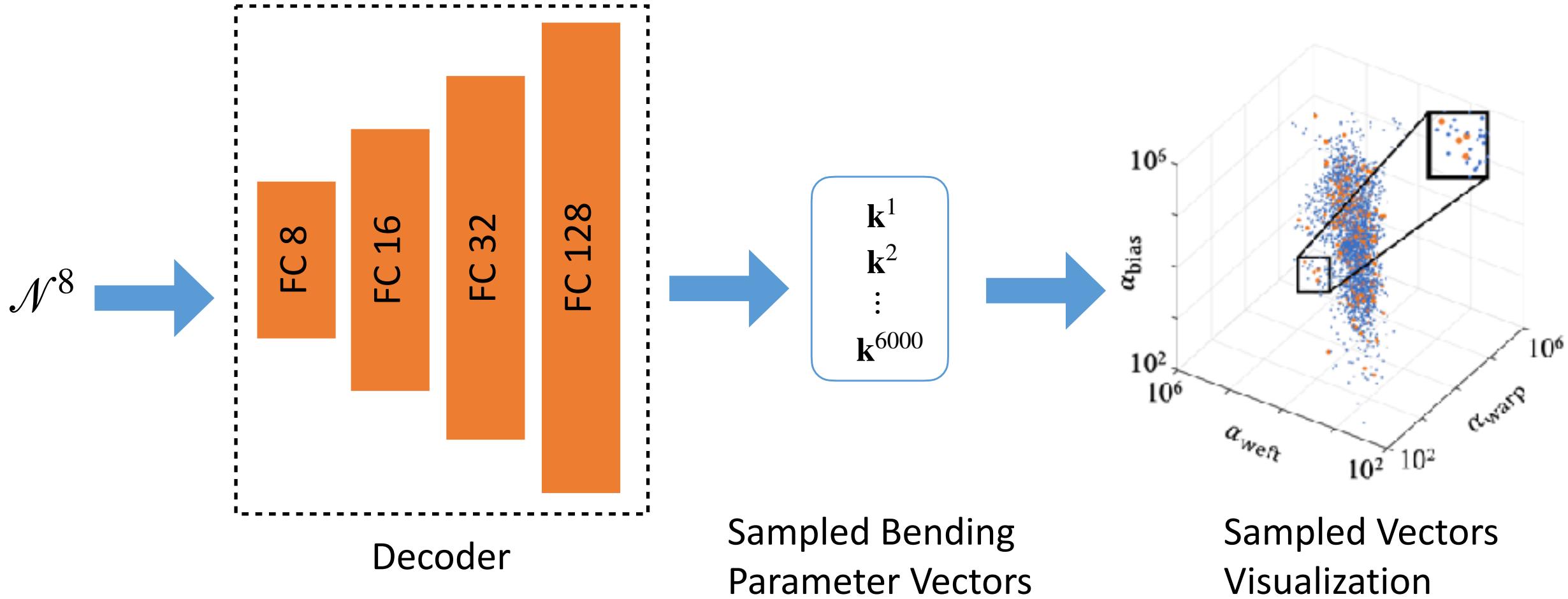
Three Directions (Whole Fabric)

# Methods Subspace Construction



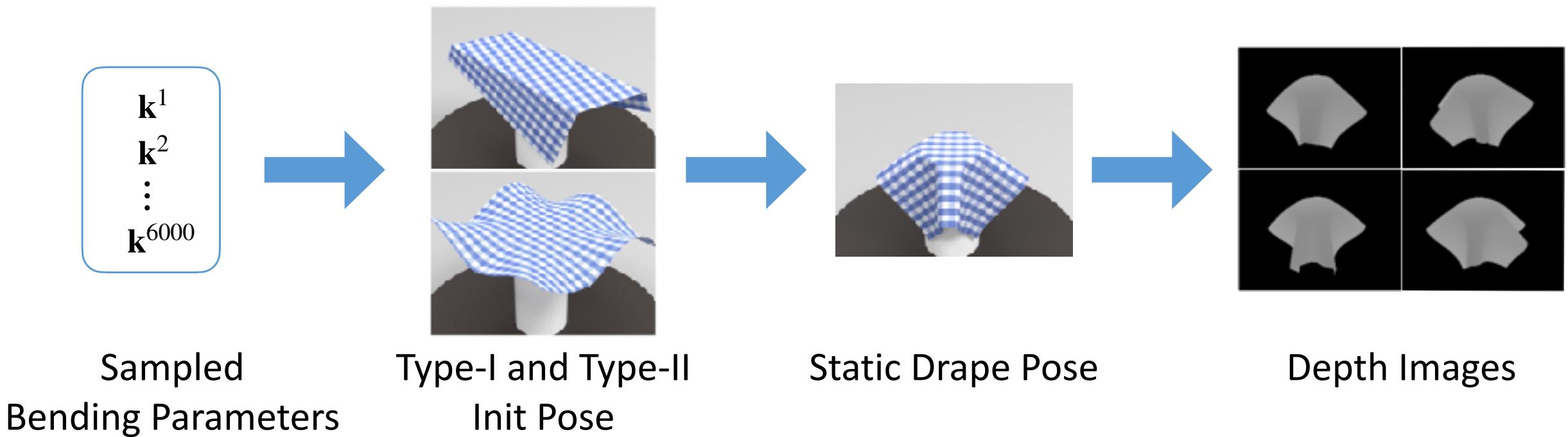
# Methods

## Bending Parameter Sampling



# Methods

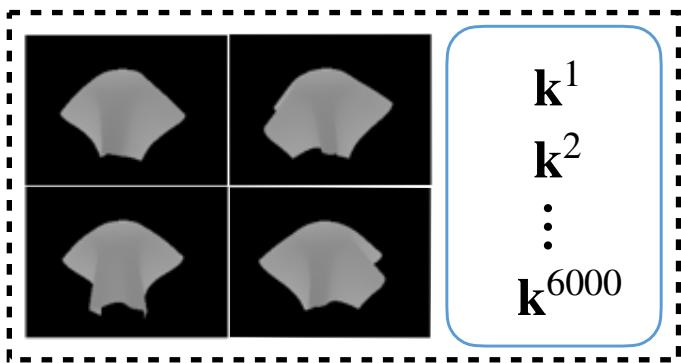
## Depth Images Synthesis



# Methods



# Methods Network Architecture



Dataset

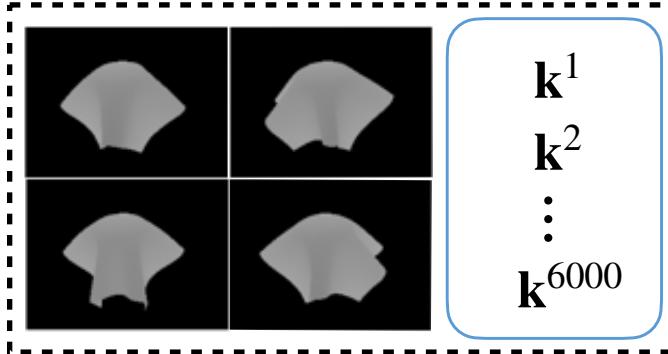
$$\mathcal{L} = \left( \frac{\sum_{i=1}^I \| \mathbf{g}_i - \mathbf{p}_i \|^2}{I} \right)^{1/2}$$

Loss  
Function

Ground truth  $\mathbf{g}_i$   
Prediction  $\mathbf{p}_i$

# Methods Network Architecture

Dataset



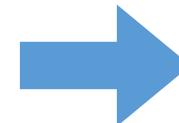
+

Loss  
Function

$$\mathcal{L} = \left( \frac{\sum_{i=1}^I \| \mathbf{g}_i - \mathbf{p}_i \|^2}{I} \right)^{1/2}$$

Ground truth  $\mathbf{g}_i$

Prediction  $\mathbf{p}_i$



Name	Training time (hrs)	Number of variables	RMSE (training)	RMSE (validation)
VGG16	100.8	105M	0.153	<b>0.122</b>
AlexNet	<b>12.4</b>	46M	0.252	0.224
ResNet-18	12.7	13M	<b>0.147</b>	0.127
EfficientNet B0	27.0	4M	0.187	0.142

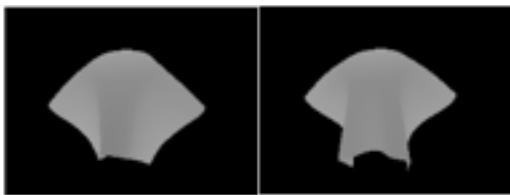
# Methods

## Number of Views

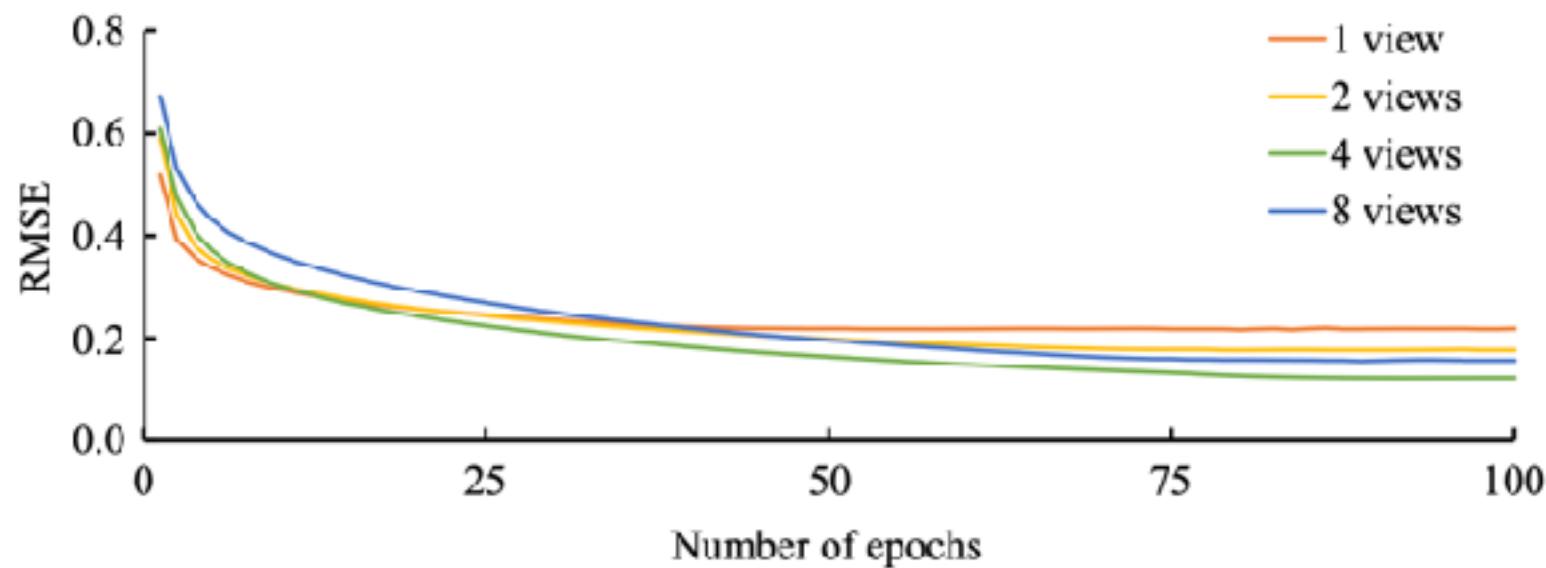
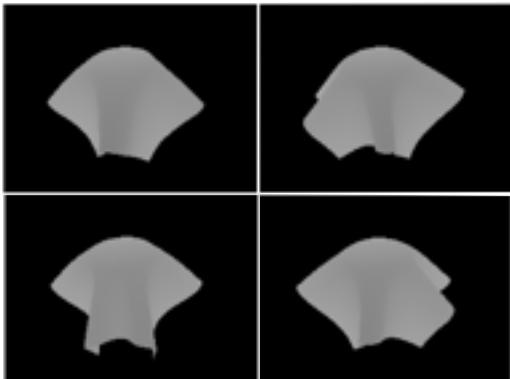
One View?



Two Views?



Four Views?





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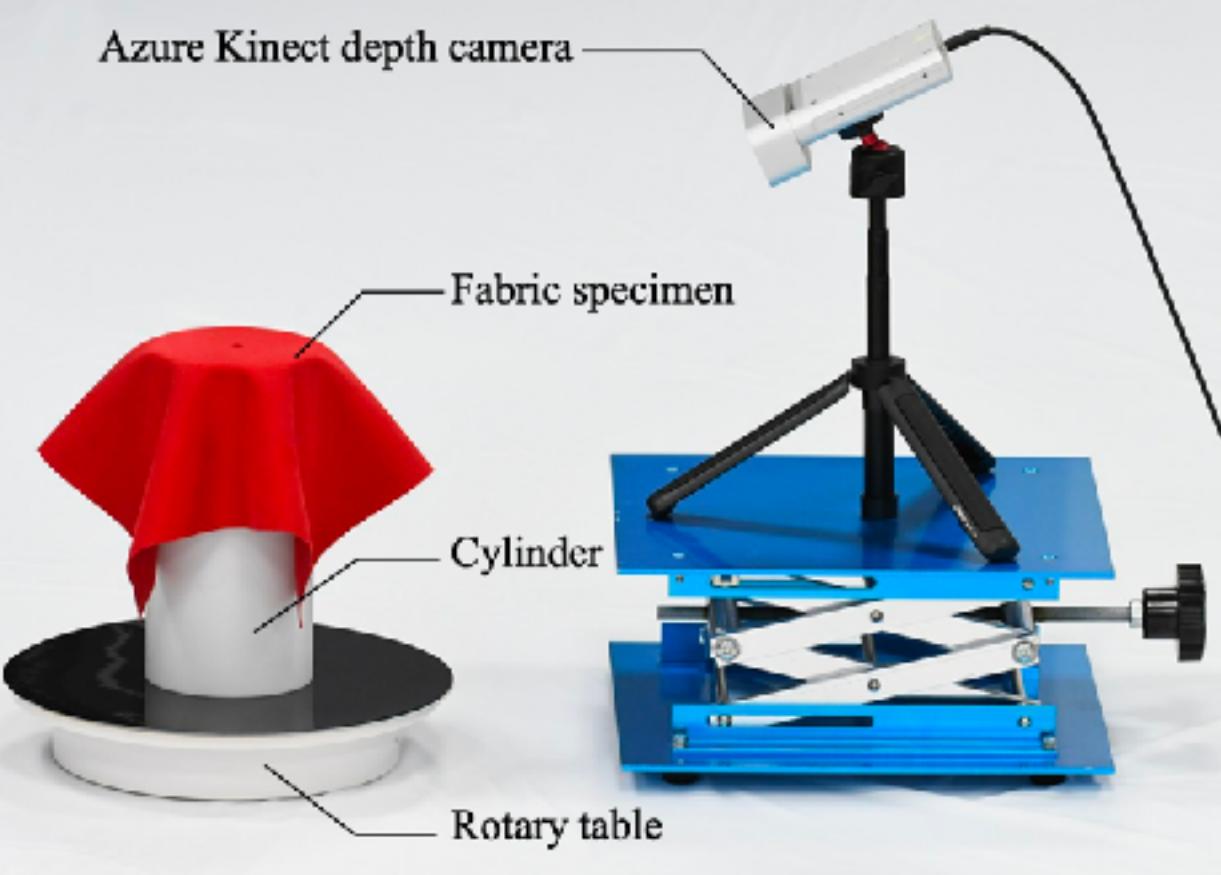
# Results And Evaluations

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# Results And Evaluations

## Cost Analysis

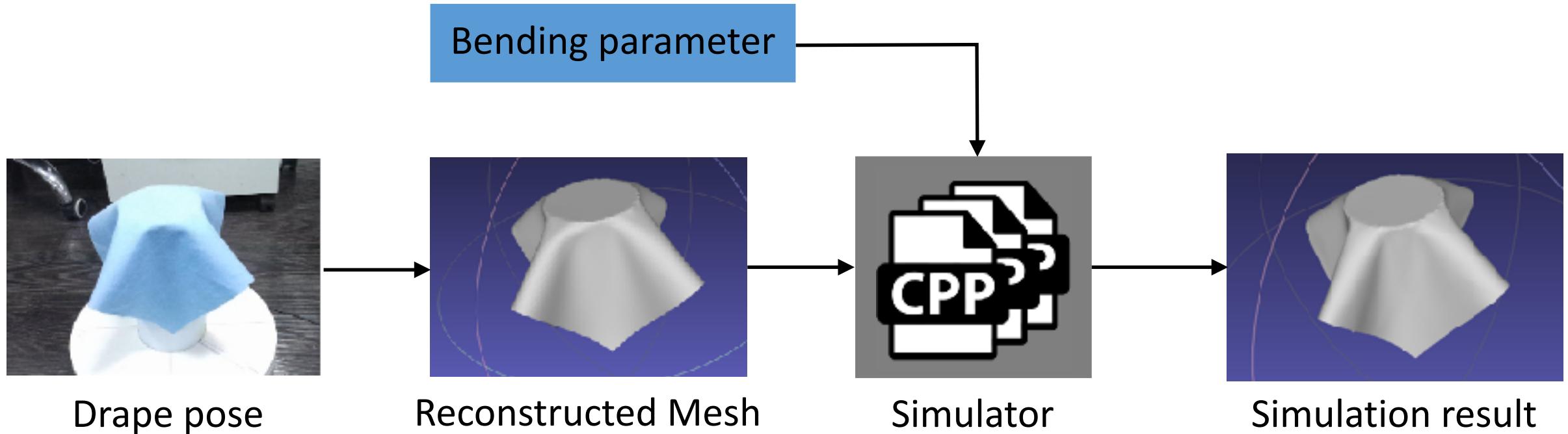


Cantilever Tester: 10min per Fabric, Cost > \$500.

Our Drape Tester: 3min per Fabric, Cost < \$30.

# Results And Evaluations

## Fidelity Analysis



Drape pose

Reconstructed Mesh

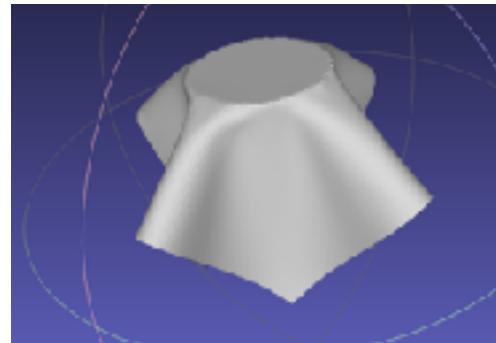
Simulator

Simulation result

# Results And Evaluations

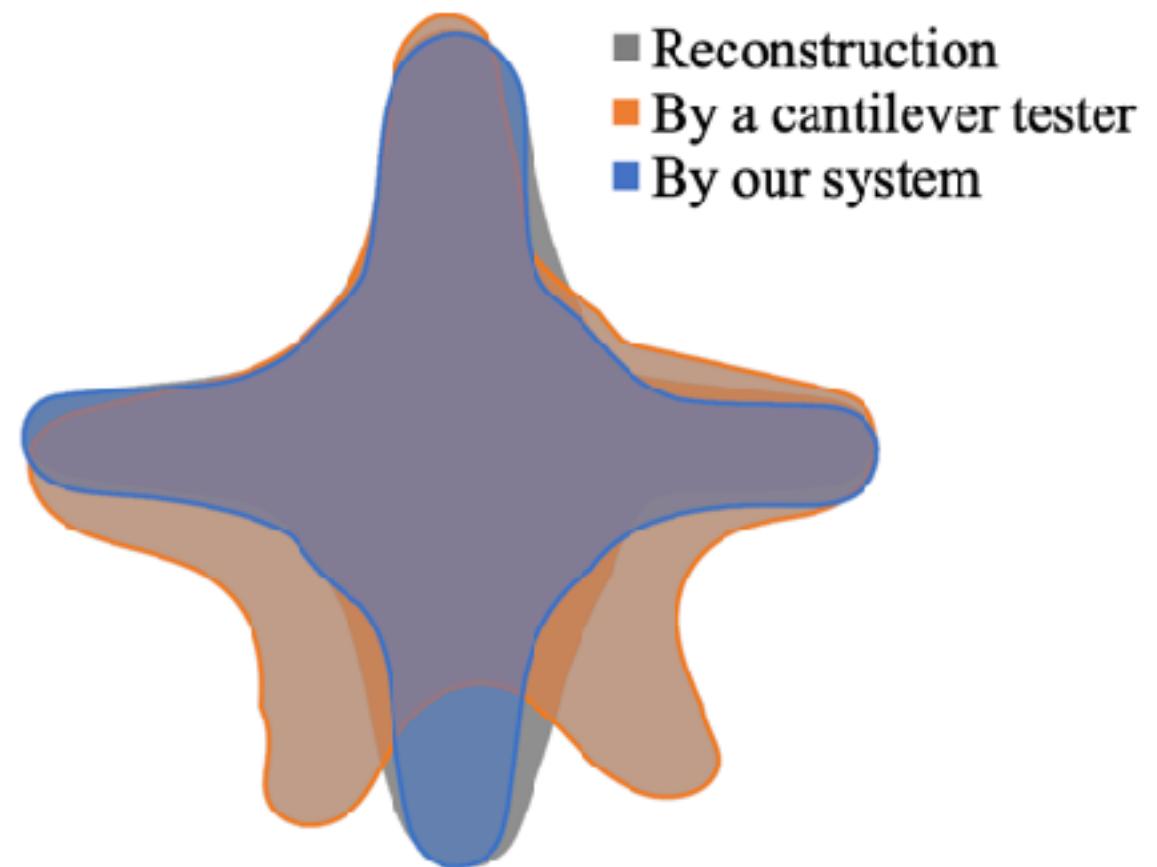
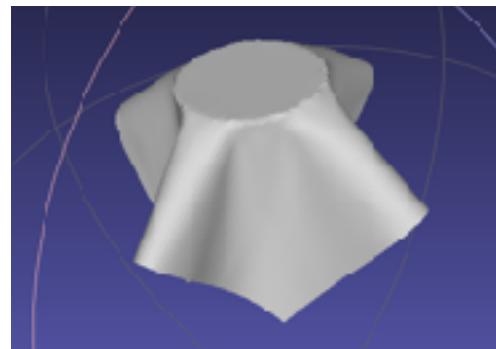
## Fidelity Analysis

Reconstructed Mesh



Compare

Simulation Result



# Results And Evaluations

## Fidelity Analysis

Fabric index	Cantilever nonlinear dihedral	Classification [Yang et al. 2017]	GMM nonlinear dihedral	linear quadratic	VAE linear dihedral	nonlinear dihedral (ours)
#1	1.3 (8.0%)	1.8 (12.7%)	<b>1.2 (8.0%)</b>	1.3 (7.0%)	1.6 (7.6%)	1.3 (5.6%)
#5	1.9 (14.6%)	4.6 (8.8%)	1.9 (6.6%)	1.7 (5.8%)	1.4 (5.2%)	<b>0.9 (3.3%)</b>
#7	2.5 (14.5%)	2.7 (18.0%)	2.7 (13.7%)	1.9 (7.5%)	1.7 (12.0%)	<b>1.7 (4.4%)</b>
#9	1.4 (4.9%)	3.5 (8.9%)	1.1 (1.5%)	1.1 ( <b>1.1%</b> )	<b>0.8 (1.3%)</b>	1.0 (1.2%)
#11	1.3 (11.0%)	4.6 (18.6%)	1.2 (14.3%)	1.6 (6.6%)	1.1 ( <b>6.5%</b> )	<b>1.0 (7.4%)</b>
#12	2.6 (6.6%)	4.3 (6.6%)	2.3 (7.5%)	1.7 (6.8%)	1.1 (6.1%)	<b>0.7 (5.9%)</b>
#24	1.4 (6.9%)	2.9 (14.2%)	0.9 (5.5%)	0.9 (5.8%)	1.1 (6.6%)	<b>0.7 (3.5%)</b>
#27	2.8 (5.7%)	2.9 (10.6%)	1.9 (4.7%)	1.9 (3.1%)	2.0 ( <b>2.6%</b> )	<b>1.7 (2.7%)</b>
#28	3.2 (6.8%)	3.3 (8.9%)	2.5 (6.9%)	2.7 (3.9%)	<b>2.2 (3.5%)</b>	<b>2.6 (3.3%)</b>
#29	2.8 (6.4%)	4.7 (7.2%)	2.3 (4.1%)	2.1 (3.3%)	2.5 (3.4%)	<b>2.0 (2.8%)</b>

metric1: mean vertex displacement (in mm) between the reconstructed and simulated shape

metric2: mean of the relative mean curvature difference (in parentheses)

# Results And Evaluations

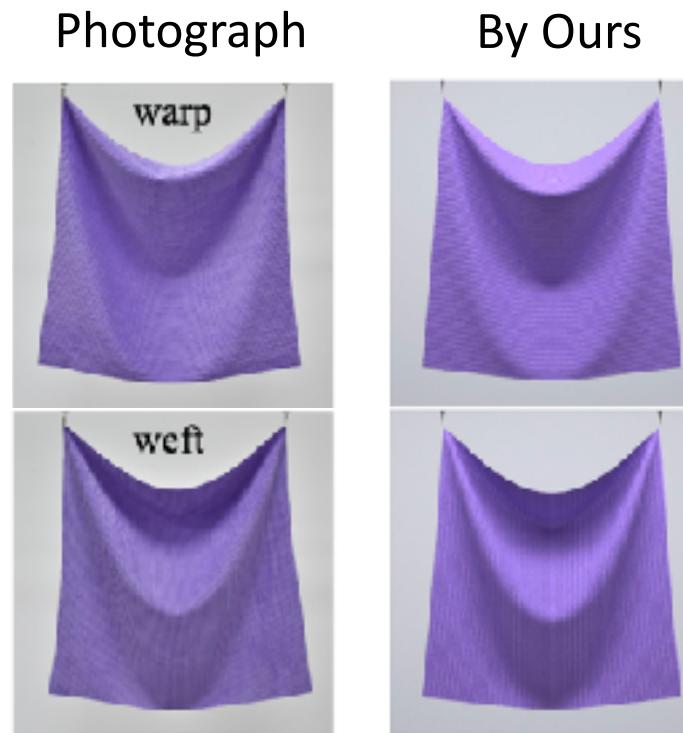
## Hanging Test

Photograph



# Results And Evaluations

## Hanging Test



# Results And Evaluations

## Hanging Test

Photograph



By Ours



By Cantilever Tester



weft



By Ours



Photograph



warp

By Ours



By Cantilever Tester



weft



# Results And Evaluations

## Skirt Test



(g) Simulation (cantilever)



(h) Photograph



(i) Simulation (ours)

More Test Cases in Our Appendix.



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# Conclusions and Limitations

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# Conclusions and Limitations



## Conclusion:

We justify the effective use of deep neural networks in the development of a novel bending stiffness parameter estimation system.

## Limitations:

1. Hysteresis effect
2. A unified test for both stretch and bending parameters
3. The test pipeline can be automated and improve further more





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# Thanks!



Style3D research job hiring  
(internship, full-time job)

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