Predicting the shape of curved and tilted microfibers generated by bending deformation

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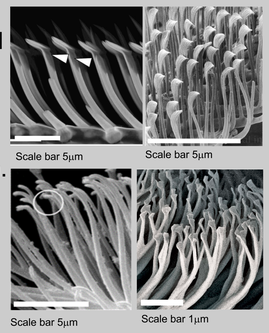
BIOMS BIO-INSPIRED MECHANICS & SYSTEMS

Background and Motivation

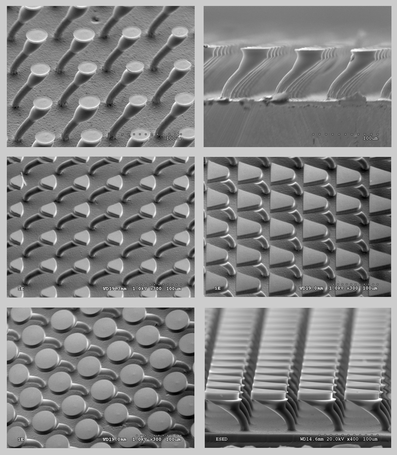
Curved fibrillar adhesives in nature

- Many organisms rely on densely packed, tilted and curved fibers to attach to surfaces. [1]
- Curvature is a key feature for fibers to enhance/control compliance, surface adaptability and direction dependent adhesion.
- Established methods (e.g. lithography) are mostly limited to generate vertically aligned or slightly tilted straight synthetic fiber arrays.



Post-fabrication to generate tilted/curved fibers

- Method: Replicate the deformed shape of an array by molding during deformation. [2]
- Effective method to generate curved fibers with extreme effective tilt angles.
- Precise control over applied forces on the tip and tip displacements.
- The elastic modulus of the backing layer controls the relationship between curvature and effective tilt angle.

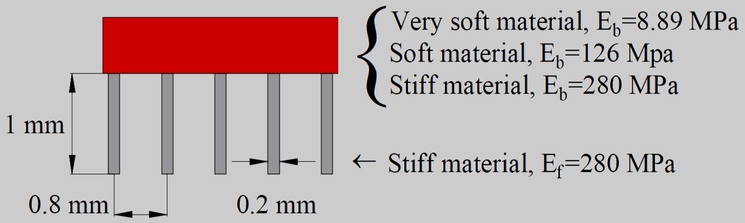


Motivation

- ***Can we control the shape of the fibers in an array by modulating the stiffness of the backing they are attached to?***

Approach

- Develop a technique to fabricate samples of vertically-aligned fiber arrays using different combinations of materials for the fibers and the base.
- Deform the fiber-backing assemblies on an optical microscope by tip displacements and record both the deflections and the applied forces.
- Develop a large deformation-based analytical/numerical model and compare with experimental results.



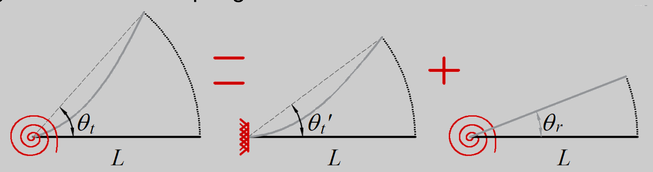
Objective

- **Develop a mathematical model to predict the final shape of the fibers attached to deformable backings due to bending deformation.**

Mathematical Model

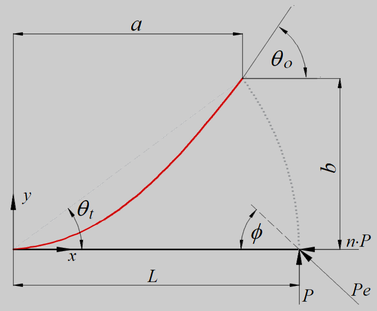
Principle of superposition

- Model uses the principle of superposition to combine the deformation from a fixed end cantilever beam and the rotation of a rigid beam hinged to a torsional spring.



$$\theta_t = \theta_t' + \theta_r$$

Large deformation of cantilever beams



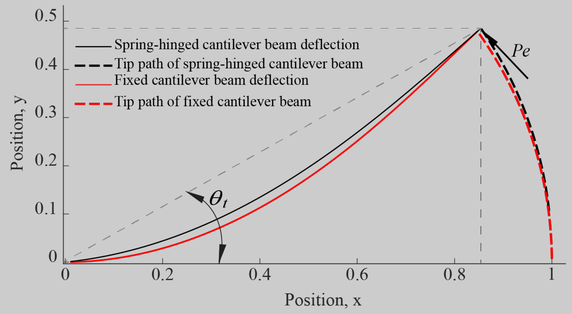
$$\alpha^2 = \frac{Pl^2}{EI}$$

$$\alpha = \frac{1}{\sqrt{2}}\int_0^{\theta_o} \frac{d\theta}{\sqrt{\lambda - sin\theta + n\cdot cos\theta}}$$

$$\frac{x}{l} = \frac{1}{\sqrt{2}\alpha}\int_0^{\theta_o} \frac{cos\theta\cdot d\theta}{\sqrt{\lambda - sin\theta + n\cdot cos\theta}}$$

$$\frac{y}{l} = \frac{1}{\sqrt{2}\alpha}\int_0^{\theta_o} \frac{sin\theta\cdot d\theta}{\sqrt{\lambda - sin\theta + n\cdot cos\theta}}$$

Evaluation of the angle of rotation of the base, θ_r



$$\theta_r = \frac{M}{K} \rightarrow K = \frac{\sqrt{a^2+b^2}\cdot[P'\,cos(\theta_t) + P'\,sin(\theta_t)]}{\theta_r}$$

E_b[MPa]	θ_t[°]	θ_r[°]	θ_t'[°]	α'	P'[mN]	K[mN·m]
8.89	30	25	5	0.4962	$1.72\cdot10^{-1}$	$5.39\cdot10^{-4}$
	41	34	7	0.583	$2.38\cdot10^{-1}$	$5.65\cdot10^{-4}$
	56	41	15	0.8386	$4.98\cdot10^{-1}$	$9.59\cdot10^{-4}$
126	30	2	28	1.15	13.70	$5.24\cdot10^{-1}$
	41	4	37	1.3568	19.71	$3.83\cdot10^{-1}$
	56	6	50	1.7026	32.98	$4.08\cdot10^{-1}$

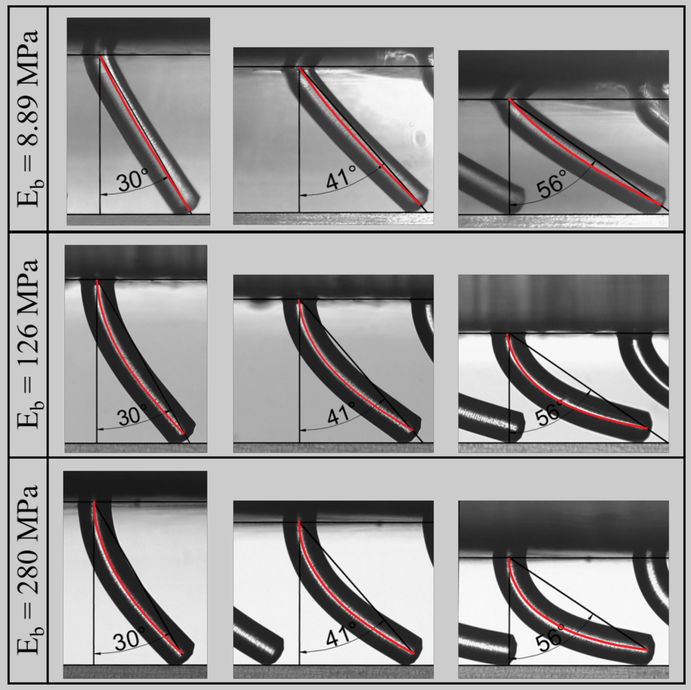
- Fibers on softer backing materials require less equivalent force P' to be bent to the same deflection angle θ_t compared to fibers with stiffer backing.
- The torsional spring constant K calculated for both cases differ by three orders of magnitude.

Citations

[1] E. Arzt, S. Gorb, and R. Spolenak. 2003, *Proceedings of the National Academy of Sciences of the United States of America,* 100, pp 10603-10606.

[2] Geikowsky, E., S. Gorumlu, and B. Aksak. 2018, *Beilstein Journal of Nanotechnology,* 9, pp 2893–2905.

Experimental Results



- Experimental fiber deflection images are compared with the prediction of the model using different angles of rotation.
- Once the angle θ_r that produce the best fit between experimental and analytical results is obtained, the equivalent angle θ_t' is determined.
- The angle θ_t' is used to calculate α' and the equivalent force P'. The torsional spring constant K from the bending moment at the base and the rotation of the base.

Conclusions

- The proposed model reasonably predicts the deformation of fibers for a wide range of deflection angles and two different combinations of materials for fibers and backing.
- Change in torsional spring constant *K* for varying deformations can be attributed to measurement accuracy and non-linear deformation of the soft base for high tilt angles.
- Model provides a simple tool to obtain tilted/curved fibers in the microscale for applications including biomimetic adhesives, anisotropic high friction surfaces, and biomimetic superhydrophobic surfaces.

Future Applications

- Experimental validation of the model for fabrication of microscale fiber arrays.
- A more accurate model for base rotation at high tilt angles and soft backings.
- Understanding of the effect of curvature on adhesion and friction of bioinspired fibrillar adhesives.
- More accurate synthetic biomimetic adhesives, anisotropic high friction surfaces, biomimetic superhydrophobic surfaces, micro pillar energy harvester can be fabricated.