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Mechanics of active anisotropic plates: A Föppl-von Kármán model for cell alignment on curved substrates

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Abstract

Active thin structures capable of shape adaptation through internal stress generation are central to soft robotics, biomechanics, and programmable materials [1-2]. When such structures also exhibit directional stiffness, as in fiber-reinforced composites or liquid crystal elastomers, the coupling between anisotropy, geometric nonlinearity, and activity governs their mechanical response. Despite progress on passive anisotropic plates and active isotropic sheets, a unified geometrically nonlinear framework combining these features has been missing. We address this gap by deriving Föppl–von Kármán equations for transversely isotropic plates with distributed active contractions. Using asymptotic reduction from three-dimensional elasticity with a multiplicative decomposition of the deformation gradient [3], we obtain coupled membrane-bending equations where anisotropy and activity interact naturally. Through-thickness variations in active strains generate bending moments, while the competition between active contractions and elastic resistance selects equilibrium configurations. The formulation accommodates spatially varying fiber orientations and contraction fields [4]. As an application, we analyze curvature-induced alignment of adherent cells, treating them as anisotropic active plates constrained to curved substrates. Specifically, for different prototypical surfaces such as cylinders, ellipsoids, and spheres, we determine the fiber orientation angle that minimizes the bending energy, for a biologically motivated active contraction field. The analysis reveals bifurcations in the preferential angle as a function of a parameter describing the competition between active contractions and surface curvature. Our predictions qualitatively agree with experimental observations and demonstrate how the framework connects material parameters to geometric response in active anisotropic systems.

Keywords:

Active materials Anisotropic plates Föppl--von Kármán theory Cell alignment

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