Cross-linked and Aligned Polymer Chain Pairs under Tension

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Cross-linked and aligned polymer structures are commonly found in biological systems, such as parallel arrays of actin filaments in filopodia, or bundles of collagen fibrils forming tendons. These systems constantly experience mechanical stresses arising from both external and internal sources. Although their mechanical response is governed by complex interfilament coupling and environmental variability, it is instructive to examine minimal, isolated model systems that capture the essential physics, with potential relevance to a broader class of soft-matter systems exhibiting similar structural organization.

In this poster, we present two cross-linked, aligned polymer systems under tension at the two-filament level: (1) a cross-linked polymer chain pair and (2) a polymer necklace (a necklace-like architecture). Each system is described using both the freely jointed chain (FJC) and wormlike chain (WLC) models within the weakly bending (harmonic) regime.

In (1), we model the cross-linking interaction as a harmonic potential and examine the influence of a single terminal cross-link on the tensile elastic response. We obtain analytical expressions for the force-extension relation and for conformational fluctuations in the longitudinal and transverse mismatch between the two filaments. In the thermodynamic limit, the cross-link does not affect the tensile elasticity but significantly suppresses transverse fluctuations, effectively inducing a loop structure. This loop behaves as a single object with twice the stiffness of an individual chain, suggesting that tensile stiffening is effectively additive in the number of strands.

In (2), we address the force-regulated binding behavior of a sequence of reversible cross-links in the thermodynamic limit, a problem closely related to the melting of double-stranded DNA. We calculate the mean fraction of cross-linked sites as a function of the tensile force and find that two distinct binding regimes (weak and strong) can emerge, exhibiting a force-induced crossover. Here, the crossover does not correspond to a genuine phase transition, in contrast to the flexible counterpart of the system, which undergoes a continuous transition [1]. To analyze the phase behavior, we employ two complementary approaches, drawing on the two-dimensional statistics of a single chain and on the mathematical analogy between a directed polymer and a two-dimensional quantum particle in the continuum limit.

Overall, in the weakly bending regime, the transverse fluctuations and the associated binding behavior are largely insensitive to the underlying microscopic model (FJC vs WLC). The results presented in this poster are based on our recent publication [2].

References:

[1] G. Noh and P. Benetatos, Phys. Rev. E 110, 014501 (2024).

[2] G. Noh and P. Benetatos, Phys. Rev. E 113, 035415 (2026).