

Four-dimensional structural dynamics of sheared collagen networks

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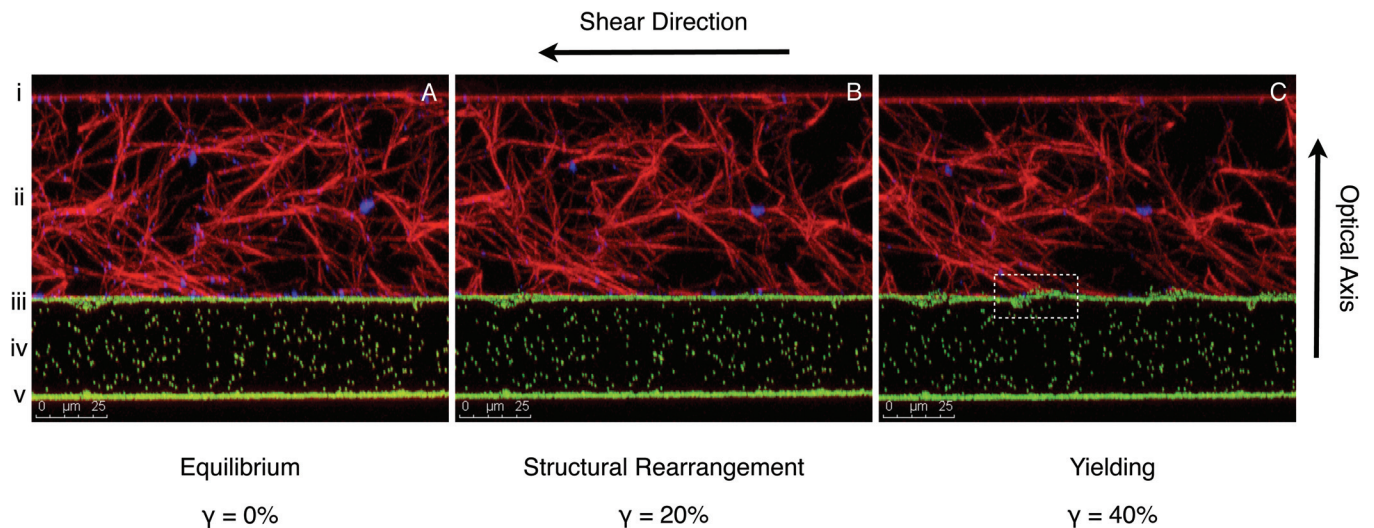


FIG. 1. (Color) (i) Rheometer steel plate, (ii) 70- μm -thick fluorescently labeled collagen fiber network (red) with concentration $c = 0.25 \text{ mg/ml}$ and stiffness $G_0 = 2 \text{ Pa}$ embedded with blue fluorescent microspheres, (iii) interface, (iv) 34- μm -thick polyacrylamide gel with stiffness $G_0 = 376 \text{ Pa}$ embedded with yellow-green fluorescent microspheres accumulated primarily at the gel boundaries, (v) glass coverslip. Collagen gel preparation is similar to the procedure described in Ref. 3. Continuous shear strain γ is applied at a strain rate $\dot{\gamma} = 10\% \text{ h}^{-1}$. Each image is a 25- μm -thick maximum-projection in XY with the optical Z-axis in the vertical direction and applied shear in the horizontal direction (enhanced online) [URL: <http://dx.doi.org/10.1063/1.3666225.1>].

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Soft biopolymer networks undergo substantial bulk stiffening and contraction when subject to shear strain. These nonlinear rheological signatures have been well-documented for a wide range of semiflexible and stiff biopolymers.^{1,2} but there is limited information about the underlying geometric fiber rearrangements and the resulting propagation of stress through the microscopic networks.

We apply precisely controlled shear strain γ to *type I* rat tail collagen gels adhered to thin elastic polyacrylamide gel substrates embedded with fluorescent microspheres while simultaneously imaging the three-dimensional networks over time with a coupled confocal-rheometer (Fig. 1(a)). Stress propagates along the collagen fibers, rearranging the network (Fig. 1(b)). Fibers attached to the polyacrylamide gel surface pull or compress the surface, displacing the yellow-green microspheres (Fig. 1(c) *white box*) (see supplementary video). Beyond a critical yield strain, fibers tear at the plate and within the bulk, signaling the loss of network integrity,

and discrete snap-back events of extended and compressed regions at the collagen/polyacrylamide interface are observed (Fig. 1(c)).

Our novel dynamics imaging technique reveals highly localized regions of nonuniform microsphere displacements centered about fiber-gel contact points, indicative of an inhomogeneous distribution of stress propagating through the network. The collagen network dramatically realigns in the direction of shear, driven by the buckling, rotation, and stretching of undulated constituent fibers. Blue microspheres adhered to individual fibers follow complex trajectories suggesting a gradual transition from nonaffine to affine network rearrangement strongly correlated with the concurrently measured bulk stiffening. These observations elucidate the physical mechanisms governing contraction, strain-stiffening, and our recent finding of the system-size dependence of the stiffening effect.³

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