Predicting and assessing rupture in protein gels under oscillatory shear

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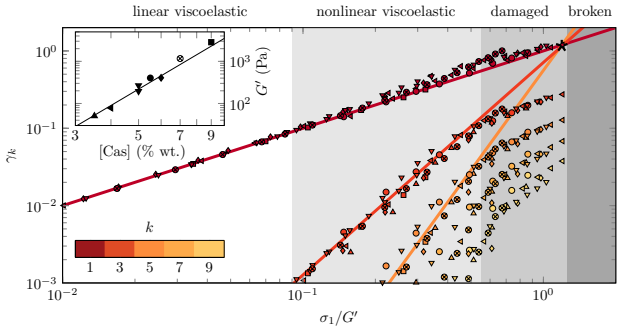

FIG. 1. Build-up of nonlinear modes γ_k of the strain response of casein gels subject to an oscillatory stress of amplitude σ_1 for various casein concentrations. Colors code for $k = 1$ to 9. The stress amplitude is normalized by the elastic modulus G' of the gel measured in the LVE regime. Solid lines show the best power-law fits of γ_k for $\sigma_1/G' < 0.5$. Background colors delimit the various regimes discussed in the text. Inset: G' as a function of $[cas]$. The symbols code for casein concentration in the main graph. The solid line is $G' \sim [cas]^4$.

Soft materials may break irreversibly upon applying sufficiently large shear oscillations, a process which physical mechanism remains largely elusive. In this work[1], we predict and access the rupture of protein gels made of sodium caseinate under an oscillatory stress.

The samples are gelled in the rheometer and subsequently submitted to an imposed oscillatory shear stress $\sigma(t) = \sigma_1 \cos(2\pi f t)$ with frequency f and amplitude σ_1. The sample strain response $\gamma(t)$ is recorded by the rheometer. Under medium and large amplitude oscillatory stresses, $\gamma(t)$ becomes nonlinear. This results in the presence of harmonics in the Fourier series decomposition of $\gamma(t)$:

$$\gamma(t) = \sum_k \gamma_k \cos\left(2\pi k f t + \phi_k\right) , \qquad (1)$$

where γ_k is the amplitude of the k^{th} harmonics and ϕ_k its phase with respect to $\sigma(t)$.

Upon increasing the stress amplitude σ_1, the build-up of harmonic modes in the strain response, γ_k, can be rescaled for all gel concentrations ($[cas]$). This rescaling yields an empirical criterion to predict the rupture point way before the samples are significantly damaged, Fig. 1.

"Fatigue" experiments under stress oscillations of constant amplitude can be mapped onto the former results, which indicates that rupture is independent of the temporal pathway in which strain and damage accumulate.

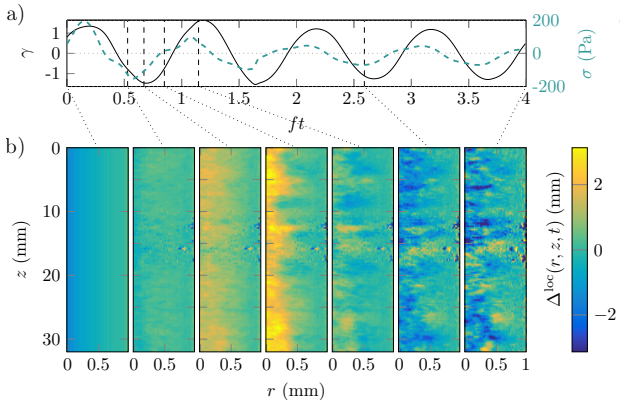

FIG. 2. Rupture of a casein gel under oscillatory shear. (a) Strain γ and stress σ as a function of ft. Note that the rheometer fails to apply a perfectly constant amplitude γ. (b) Local displacement maps $\Delta^{loc}(r, z, t)$ obtained with LORE[2] during gel breakdown.

Finally, using ultrasonic imaging, we measure the local mechanical properties of the gels before, during and after breakdown, showing that the strain field remains perfectly homogeneous up to rupture but suddenly gives way to a solid–fluid phase separation upon breakdown, Fig. 2.

We expect this work to trigger numerical modeling and theoretical efforts to explain the power-law evolution of the higher harmonic modes as well as the rupture criterion. We believe those scalings and the rupture prediction to be also relevant for biological networks and biopolymer gels made of, e.g., actin, alginate, gelatin or agar. Further experiments on these various systems are in line to check for generality. Our work also opens the way to deeper local investigations of the damage process of soft materials under oscillatory shear.

[1] Predicting and assessing rupture in protein gels under oscillatory shear B Saint-Michel, T Gibaud, S Manneville arXiv preprint arXiv:1612.07482 (2017)
[2] Local Oscillatory Rheology from Echography. Saint-Michel, B. and Gibaud, T. and Leocmach, M. and Manneville, S. Phys. Rev. Applied **5**, 034014 (2016).