



Chapter 1

Spatiotemporally-resolved Kinematic and Stress Measurements of Interfacial Cavitation in Soft Matter via DIC

Jin Yang, Alexander McGhee, Zixiang Tong, Lehu Bu, Sicong Wang, Griffin Radtke, Mauro Rodriguez, and Christian Franck

Abstract Inertial cavitation is a common phenomenon found in nature and many engineering systems. When harnessed carefully, laser or ultrasound-focused, energy-driven cavitation can be a very beneficial tool in a wide range of medical and materials applications, including laser surgery, lithotripsy, drug delivery, and more recently, soft material characterization. Recently we have developed a novel material property characterization method, called Inertial Microcavitation Rheometry (IMR), to investigate laser-induced inertial cavitation (LIC) in soft matter, where the surrounding material is subjected to ballistic and ultra-high strain rates ($10^3 \sim 10^8 \text{ s}^{-1}$). Through IMR, we can precisely quantify the nonlinear viscoelastic, finite deformation constitutive behavior of soft materials at ultra-high strain rates. Following this, we will present our recent findings on the dynamics of laser-induced inertial cavitation (LIC) near the gel-water interface. Historically, studies of cavitation dynamics at liquid-solid interfaces have been limited to observations of surface deformations and cavitation bubble morphology due to challenges in measuring subsurface behavior. However, understanding the intricate dynamics of cavitation at these interfaces has significant implications for engineering and medical applications. By utilizing Digital Image Correlation (DIC), we provide high-fidelity and high-throughput full-field measurements on the spatiotemporal deformation behavior and wave propagation within soft materials near interfaces due to laser-induced inertial cavitation at extremely high rates. Our results provide critical insight into how soft biological tissues respond to the immense forces generated by the violent collapse of a cavitation event. These measurements will be particularly useful for minimizing collateral damage to non-target tissues in cavitation-based medical therapies.

Keywords cavitation · soft materials · high speed imaging · interface · DIC

Jin Yang · Zixiang Tong · Lehu Bu · Sicong Wang

Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712

e-mail: jin.yang@austin.utexas.edu; zachtong@utexas.edu; lhbu@utexas.edu; sicongw@utexas.edu

Alexander McGhee

Department of Biomedical Engineering, The University of Arizona, Tucson, AZ 85721

e-mail: mcgheeaalex@arizona.edu

Griffin Radtke

John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138

e-mail: gradtke@fas.harvard.edu

Mauro Rodriguez

School of Engineering, Brown University, Providence, RI 02912

e-mail: mauro_rodriguez@brown.edu

Christian Franck

Department of Mechanical Engineering, University of Wisconsin-Madison, Madison, WI, 53706

e-mail: cfranck@wisc.edu

Jin Yang

To whom correspondence should be addressed

e-mail: jin.yang@austin.utexas.edu

Introduction

Cavitation is a fascinating phenomenon observed across a wide range of biological and engineering systems, from the prey-stunning capability of the snapping shrimp to cavitation erosion on metallic pumps and propellers, and cavitation-induced cell and tissue damage [1–6]. When harnessed properly, energy-driven, focused cavitation can serve as a powerful tool in a diverse set of applications, including tissue phantom modeling, laser surgery, lithotripsy, DNA injection, and more recently, high- to ultra-high strain-rate soft material characterization [7–15]. Inertial cavitation can be triggered by various external stimuli, such as ultrasound, laser, shock waves, hydrodynamic variations, electrical discharges, and microwave radiation. Particularly, laser-induced inertial cavitation (LIC) utilizes a high-energy laser focused on a small region of liquid or soft solid materials, rapidly vaporizing the liquid and forming a bubble. As this bubble expands and collapses, it generates powerful shock waves and high temperatures, resulting in diverse effects and applications. LIC exploits the complex interactions between light, heat, and mechanical forces. The laser parameters can be precisely controlled to tailor the cavitation process for specific outcomes, making LIC a versatile and effective tool for scientific research and industrial applications.

Recently, by leveraging the laser-induced inertial cavitation in soft biological materials, we developed a novel experimental technique called Inertial Microcavitation Rheometry (IMR), which enables the extraction of bulk soft biological materials' viscoelastic properties at extremely high strain rates ($> 10^3 \text{ s}^{-1}$) [15–19], allowing us to resolve and predict inertial cavitation in soft materials away from surfaces or impedance-changing interfaces.

In many biologically and clinically relevant applications, cavitation often occurs or is deliberately produced along material interfaces, particularly at soft matter-liquid interfaces. Examples include cancer cell removal, targeted drug delivery, cataract removal, histotripsy, noninvasive ocular surgeries, and even blast-related traumatic brain injuries. Whether cavitation is generated intentionally or occurs as an unintended side effect, it is critical to understand its impact on surrounding tissues. Therefore, quantitatively describing, modeling, and predicting the complex dynamics of cavitation at these interfaces is vital to achieving successful outcomes in these applications.

Unlike cavitation in bulk materials, inertial cavitation near interfaces and surfaces presents more complex physics due to the asymmetry of the material domain [20–23]. The dynamics of inertial cavitation near interfaces often involve complex, non-spherical bubble shapes and instability patterns, which can lead to high-speed re-entrant or emerging jets at the interface. These instabilities, along with highly dynamic pressure and stress fields, depend on factors such as the distance between the nucleation site and the interface, the maximum bubble radius, and the impedance differences across the interface. Soft materials exhibit large, nonlinear deformations in response to these pressure and stress fields, sometimes resulting in material failure. This creates a strong, nonlinear coupling between the solid and fluid, which remains poorly understood.

To identify the key physical phenomena involved in inertial cavitation at impedance-mismatched boundaries, we developed a novel experimental procedure combining three state-of-the-art techniques. We integrated (i) laser-induced cavitation (LIC) [17] with (ii) the internal, embedded speckle pattern technique [24, 25] to generate optically-focused, single cavitation bubbles at various stand-off distances from a speckled gel-water interface, and analyzed the results using (iii) SpatioTemporal Adaptive Quadtree mesh Digital Image Correlation (STAQ-DIC) [26]. These experiments provided the first high-resolution, quantitative spatiotemporal kinematic and stress fields of inertial cavitation along a soft hydrogel-water interface. Specifically, our data offered rich insight into the complex subsurface deformations and wave propagation within the surrounding soft solid material during interfacial cavitation. We measured for the first time the LIC-induced material damage and residual stress near the gel-water interface caused by laser pulse ablation. These highly controlled experimental investigations enable for a detailed analysis of single inertial cavitation events near a water-gel interface with unprecedented resolution. Beyond single cavitation events, repeated laser pulses can accumulate cavitation-induced damage as the number of pulses increases. We also aim to quantify the residual strain and stress caused by these cumulative effects.

Materials and Methods

Material preparation

In this work, we synthesized 10 wt% gelatin hydrogels using porcine gelatin (gel strength 300, Type A, Sigma-Aldrich). A speckle pattern of microscale inkjet toner particles was embedded in the middle plane for each hydrogel sample following the protocol developed by McGhee et al. [17]. After solidification, the gel samples were stored at 4°C for more than 24 hours. Before the laser-induced cavitation experiment, the samples were acclimated to room temperature for one hour to

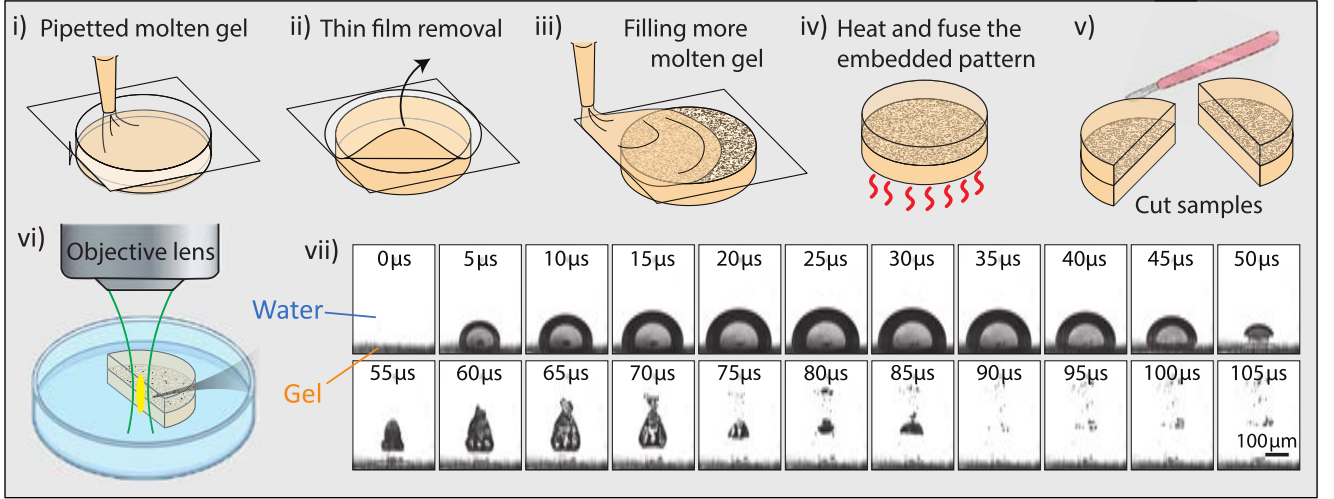


Fig. 1 Experimental setup for the laser-induced inertial cavitation (LIC) experiments at the gel-water interface. (i-v) Experimental procedures for preparing the embedded speckle pattern in a hydrogel sample; (ii) A single nanosecond pulsed-laser focusing within gel samples; (vii) Selected experimental images of laser-induced inertial cavitation events (adapted from Ref [27]).

reach thermal equilibrium. Then a gel-water interface was created by a scalpel cutting through the gel perpendicular to the speckle pattern (see Fig. 1(i-v)).

The prepared 10 wt% gel's quasistatic, ground-state shear modulus was determined using an ARES-G2 rheometer with a 25 mm stainless steel smooth plate force transducer (TA Instruments, DE). The gel presents rate-dependent material properties. To characterize the high strain-rate, viscoelastic properties of our gelatin hydrogels, as most relevant to the laser-induced inertial cavitation experiments investigated here, we also employed our previously established Inertial Microcavitation Rheometry (IMR) technique [15–18]. The measured quasistatic and dynamic shear moduli are $G_{\infty} = 3.08 \pm 0.01$ kPa and $G = 29.85 \pm 6.20$ kPa, respectively. The measured viscosity is $\mu = 0.055 \pm 0.061$ Pa·s [28].

Laser-induced inertial microcavitation

We utilized the same laser-induced inertial microcavitation (LIC) setup as previously described in Refs [15–18]. Briefly, a single ~ 6 nanosecond-long laser pulse is focused via a $10\times$ microscope objective directly onto the embedded speckle pattern plane within each gel sample, and positioned at various distances from the interface, as illustrated in Fig. 1(vi). While the z -position of the cavitation bubble is controlled by the objectives focal point, the x, y position can be precisely controlled via the motorized microscope stage. In our experiments, various combinations of maximum bubble radius and distance from the interface were tested. To normalize these parameters, we utilize the same dimensionless variable ($\gamma = d/R_{\max}$) as first introduced by Brujan et al. [20, 21], where the bubble standoff distance from the interface is denoted by d , and the maximum bubble radius by $R_{\max}$. Here, positive and negative values of γ correspond to initial cavitation nucleation sites in either the water (positive γ s) or gel (negative γ s), respectively. In this paper, we focus on studying when the cavitation events are induced very close to the gel-water interface, i.e., $\gamma \sim 0$.

Each cavitation event was recorded using an HPV-X2 high-speed camera (Shimadzu Corporation, Kyoto, Japan) at 1 million frames per second. Pulsed illumination for each frame was achieved through a Cavilux Smart UHS laser illumination system with a 20 ns pulse duration (Shimadzu Corporation, Kyoto, Japan) and synchronized with the high-speed camera via a trigger. Selected frames depicting a typical cavitation event are shown in Fig. 1(vii).

Beyond single cavitation events, we also repeatedly shot laser pulses at the same spot, with an estimated time interval of 1 minute between any two consecutive laser pulses. This time interval was chosen based on the assumption that, after 1 minute, the transient effects of the previous LIC event would have reached a near-equilibrium state, where the changes in surrounding material strain and stress become significantly slower than the cavitation dynamics timescale. Although much slower diffusion processes may still occur, they take on the order of 10 minutes or more to fully equilibrate—much longer than the transient timescale of cavitation dynamics.

SpatioTemporally Adaptive mesh Digital Image Correlation (STAQ-DIC) analysis

We employed our previously developed SpatioTemporally Adaptive Quadtree mesh Digital Image Correlation (STAQ-DIC) method [26] to analyze material deformations resulting from cavitation event. This method compares the deformed frames with the undeformed frame to directly resolve the incremental change in the deformation of the surrounding material for each frame [29]. In addition to displacement and strain fields, we also calculated velocity fields by dividing the incremental displacement by the time elapsed between two successive image frames. We used $20 \text{ pixels} \times 20 \text{ pixels}$ as the DIC post-processing window size, and $16 \text{ pixels} \times 16 \text{ pixels}$ as the DIC window spacing. We also apply adaptive quadtree meshes where the finest DIC window spacing is further refined to $4 \text{ pixels} \times 4 \text{ pixels}$ near the bubble wall [30].

Results and Analysis

Captured bubble dynamics using ultra-high-speed imaging

In this study, we investigate cavitating bubbles at the gel-water interface where stand-off distances are effectively zero, i.e., $\gamma \sim 0$ (the effect of stand-off distances is our planned future work). Repeated laser pulses were focused on the same spot, and the resulting bubble dynamics, along with the surrounding soft material deformations, were captured using ultra-high-speed imaging at 1 million frames per second. This allowed us to quantify the accumulated material damage from twenty successive cavitation events. For our case study, we used 10 wt% gelatin, and the applied laser pulse energy was $337.7 \pm 5.9 \mu\text{J}$.

Figure 2 presents a high-speed imaging sequence showing the evolution of the 10 th laser pulse-induced cavitation bubble near a 10 wt% gelatin hydrogel-water interface over a time span of $2 \mu\text{s}$ to $207 \mu\text{s}$. The images reveal the dy-

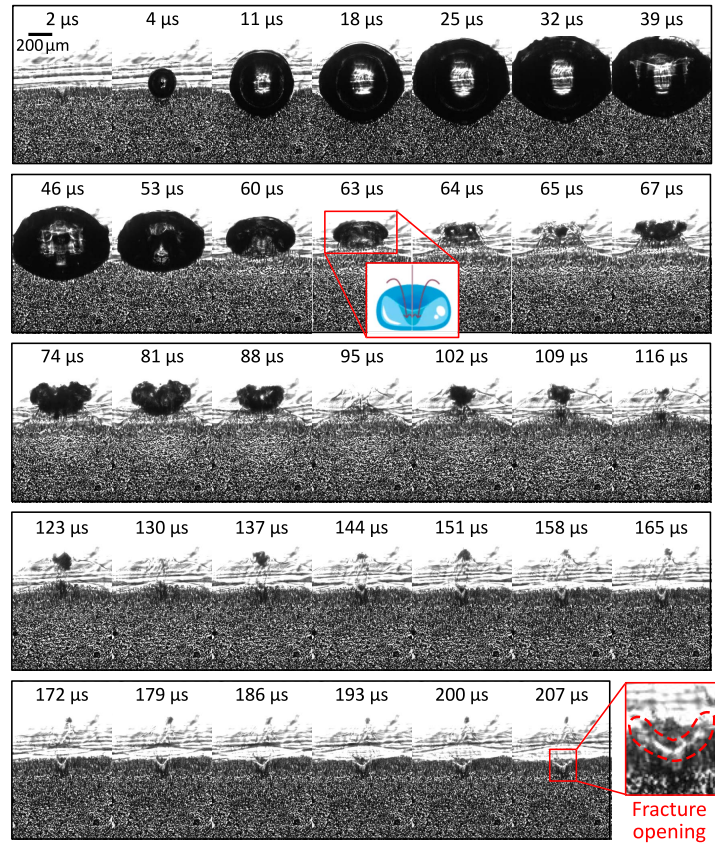


Fig. 2 High-speed imaging sequence showing the evolution of the 10 th laser pulse-induced cavitation bubble near a gelatin hydrogel-water interface. The inset at $63 \mu\text{s}$ provides a detailed view of the formed cavitation jet interacting with the interface. The inset at $207 \mu\text{s}$ shows the cavitation induced surface fracture opening.

namics of bubble expansion, collapse, and subsequent jet formation, all significantly influenced by the proximity of the gelatin interface. During the initial stages, from 2 μs to 39 μs , the cavitation bubble undergoes spherically symmetrical growth. As the bubble expands and approaches the interface, its interaction with the boundary becomes more pronounced, resulting in the formation of a cavitation jet around 63 μs . The inset at this time point provides a detailed view of the jet directed toward the interface, highlighting the strong hydrodynamic interaction between the collapsing bubble and the gelatin substrate.

As the bubble collapses further, the imaging sequence between 74 μs and 207 μs shows the aftermath of the jet's impact on the surface. The inset at 207 μs highlights the surface damage caused by the cavitation event, revealing the localized deformation and potential erosion at the gelatin-water boundary. This progression indicates the destructive potential of cavitation-induced jets in soft materials, which is relevant for applications involving cavitation near biological tissues, soft interfaces, or hydrogel-based materials.

Experimentally measured kymographs of hyperelastic von Mises strain and stress generated by each laser-induced inertial cavitation event

For each DIC image sequence, we extracted a 10-pixel-wide vertical slice along the bubble's axis of symmetry from the full-field results. These slices were then concatenated to create kymographs, which visualize the spatiotemporal evolution of the von Mises strain and stress fields within the surrounding gelatin hydrogels, as shown in Fig. 3 and Fig. 4.

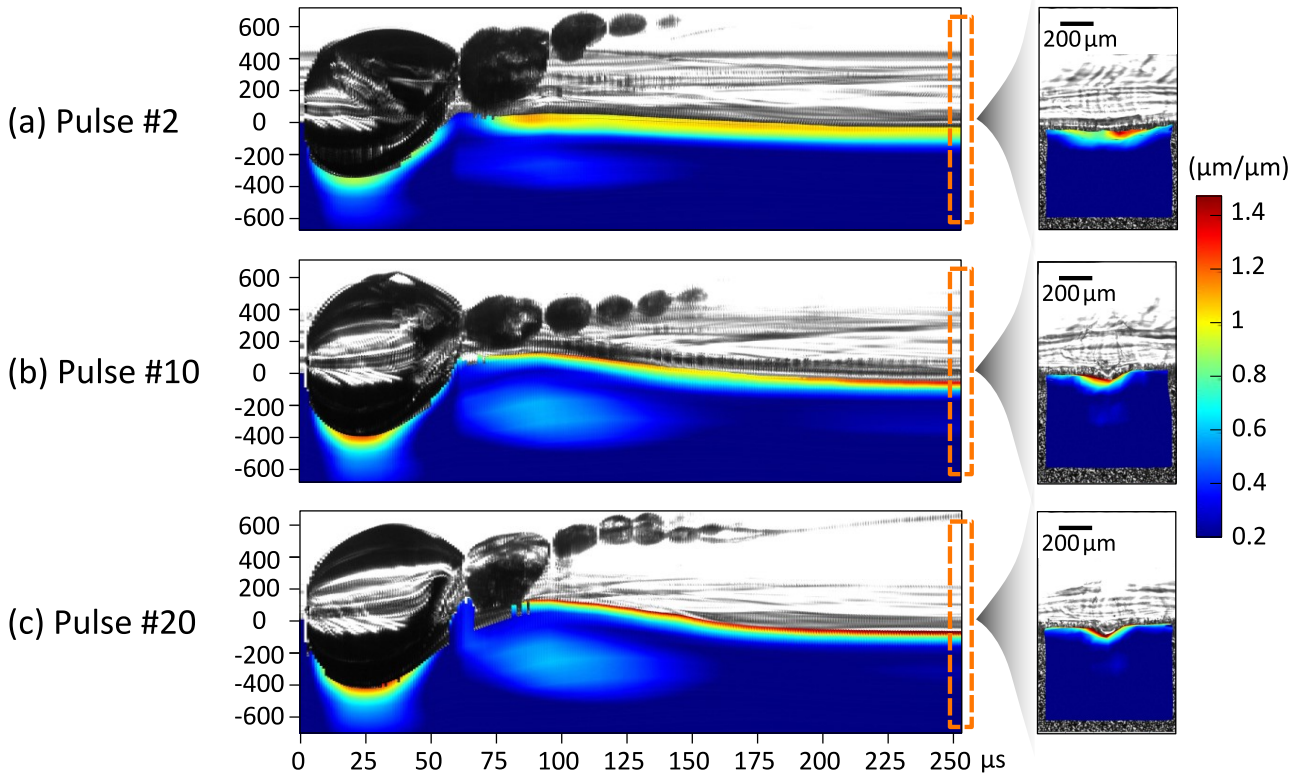


Fig. 3 Comparison of the von Mises strain kymographs from DIC results for laser-induced cavitation at pulse #2 (a), pulse #10 (b), and pulse #20 (c). The strain maps illustrate the distribution and evolution of localized strain, with inset zooms highlighting strain distributions at the last frame when the surface damage reaches an equilibrium state. Each DIC result compares the net strain change of each laser pulse-induced cavitation event, indicating cumulative damage from repeated cavitation events.

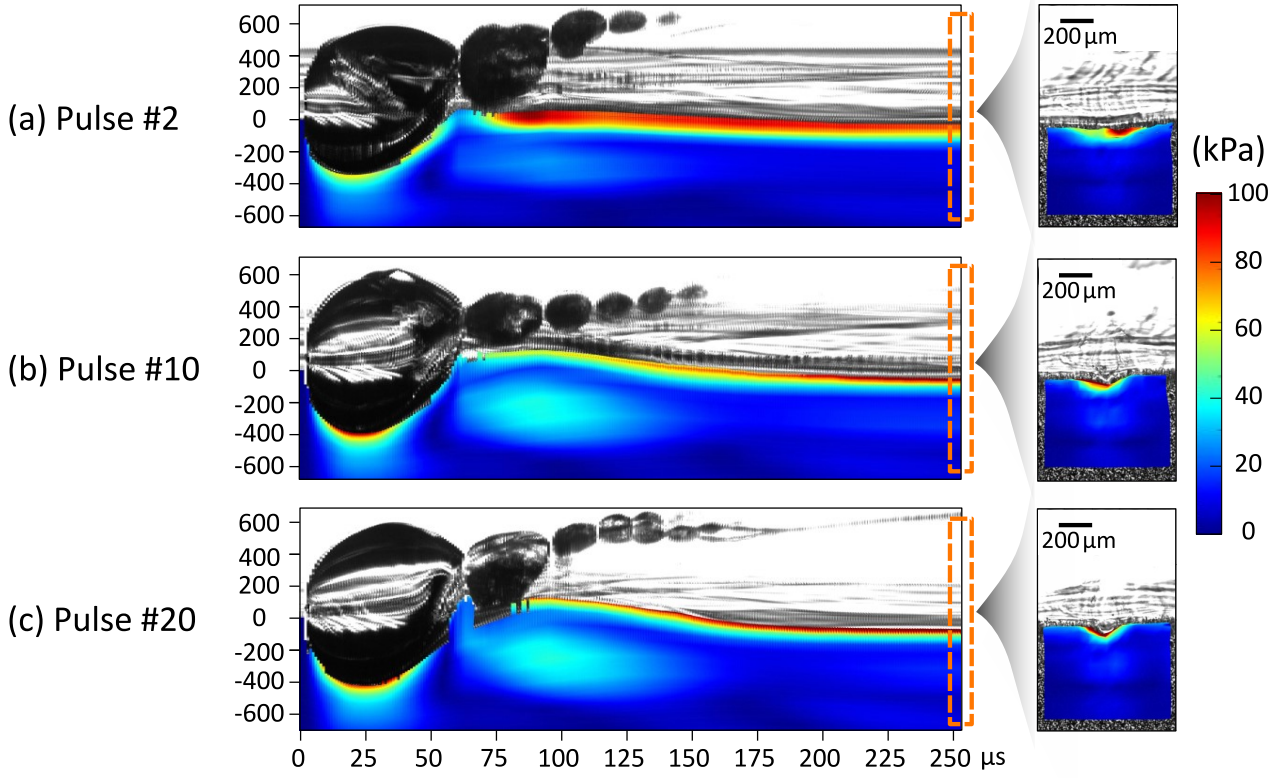


Fig. 4 Comparison of the von Mises stress kymographs from DIC results for laser-induced cavitation at pulse #2 (a), pulse #10 (b), and pulse #20 (c). The stress maps illustrate the distribution and evolution of localized stress, with inset zooms highlighting stress distributions at the last frame when the surface damage reaches an equilibrium state. Each DIC result compares the net stress change of each laser pulse-induced cavitation event, indicating cumulative damage from repeated cavitation events.

Here we assume the bubble dynamics is axisymmetric whose displacement field is denoted as $\mathbf{u} = [u_r, u_\theta, u_z]^\top$. The infinitesimal strain is defined as

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \frac{\partial u_r}{\partial r} & 0 & \frac{1}{2} \left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} \right) \\ 0 & \frac{u_r}{r} & 0 \\ \frac{1}{2} \left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} \right) & 0 & \frac{\partial u_z}{\partial z} \end{bmatrix} \quad (1)$$

The von Mises stain is defined as

$$\varepsilon_{VM} = \sqrt{\frac{1}{2} \left[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 \right]}, \quad (2)$$

where $\varepsilon_1, \varepsilon_2$, and ε_3 are three principal values of infinitesimal strain $\boldsymbol{\varepsilon}$.

We model the surrounding hydrogel as an incompressible neo-Hookean material with shear modulus G . The resulted hyperelastic Cauchy stress follows

$$\boldsymbol{\sigma} = G \text{dev}(\mathbf{B}), \quad (3)$$

where $\text{dev}(\cdot)$ takes the deviatoric part, and $\mathbf{B}$ is the left Cauchy-Green deformation tensor. The von Mises stress is further defined as

$$\sigma_{VM} = \sqrt{\frac{1}{2} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]}, \quad (4)$$

where σ_1 , σ_2 , and σ_3 are three principal values of Cauchy stress tensor σ .

Figures 3 and 4 compare the von Mises strain and stress fields generated by laser-induced cavitation across multiple cavitation events at pulse #2, pulse #10, and pulse #20. The first frame of each image sequence was set as the reference image, with subsequent frames treated as deformed images. The high-speed imaging, combined with the corresponding kymographs derived from DIC measurements, reveals the dynamic interactions between the cavitation bubbles and the gelatin hydrogel-water interface. For each pulse, the strain maps display the “net gain” in strain distribution and the evolution of the localized strain along the interface, with the highest concentrations occurring near the bubble collapse regions. The insets in the right of each subplot highlight the strain distribution in the final stage of each pulse, where the surface damage appears to stabilize and reaches a near equilibrium state.

In this context, near equilibrium refers to the point at which the temporal changes in the surrounding material strain and stress states become significantly slower than the cavitation dynamics timescale. While much slower diffusion processes can still occur, they take approximately $O(10)$ minutes to reach equilibrium, which is considerably longer than the transient timescale of the cavitation dynamics.

The results also emphasize the cumulative nature of surface damage caused by repeated cavitation events. As seen in the progression from pulse #2 to pulse #20, the net strain change increases with successive pulses, indicating that strain does not fully relax between events. This suggests that cavitation-induced surface damage accumulates over time, particularly in the regions closest to the hydrogel-water interface.

Cumulative Material Damage from Repeated Laser Pulses

In this subsection, we examine how repetitive laser pulses ablate tissue and accumulate surrounding material damage. Figure 5 illustrates the progression of surface deformation at the gelatin hydrogel-water interface due to repeated laser-induced cavitation events over 20 consecutive pulses. Specifically, Figure 5(a) provides a schematic of the experimental setup, showing the laser focus point positioned near the interface. Figure 5(b) presents high-speed imaging of the hydrogel surface, with zoomed-in insets tracking the development of localized surface deformations after each laser pulse.

As the number of pulses increases, the deformation becomes more pronounced, particularly after pulse #7, suggesting that the repeated cavitation events induce cumulative surface damage (see Fig. 5). The hydrogel’s surface exhibits progressive material degradation and surface depression, which is highlighted by the magnified regions. This result highlights the critical role that repeated cavitation plays in surface erosion and the importance of understanding how soft materials respond to such cyclic loading conditions. The observations can be applied to a variety of fields, including biomedical applications where cavitation occurs near biological tissues or at soft material interfaces.

Figure 6 illustrates the displacement fields generated by repeated laser-induced cavitation events at the gelatin hydrogel-water interface. Figure 6(a) shows the z -displacement maps (vertical displacement) for pulses #2 to #20, while Fig. 6(b) displays the x -displacement maps (horizontal displacement) for the same sequence. We also note that the absolute value of the x -coordinate in the xz -plane shown in Fig. 6 corresponds to the radial coordinate r in the 3D cylindrical coordinate system. The color maps depict how cavitation bubbles influence surface deformation. Early in the sequence, the displacements are localized near the laser focus point, but as the number of pulses increases, the deformation spreads across a larger area, indicating an accumulation of surface damage.

The z -displacement maps in Fig. 6(a) show significant vertical movement at the interface, particularly as the cavitation bubble expands and collapses, generating surface deformations that grow more pronounced with each pulse. Similarly, the x -displacement maps in Fig. 6(b) reveal the horizontal shifting of the interface, which becomes more evident in later pulses. This progressive deformation, seen in both the vertical and horizontal directions, highlights the cumulative effects of repeated cavitation, suggesting that the surface damage is not confined to the immediate vicinity of the cavitation event, but spreads over time, impacting the overall integrity of the hydrogel surface. These results underscore the importance of understanding cavitation-induced surface degradation, particularly in applications where soft material interfaces are exposed to cyclic cavitation loading.

Figure 7 illustrates the strain fields generated by repeated laser-induced cavitation events at the gelatin hydrogel-water interface. Initially, the strain fields (both e_{zz} and e_{rr}) remain minimal, as seen from pulse #2 to pulse #7, with low strain values represented by the blue regions. As cavitation events progress, there is a noticeable increase in strain, particularly after pulse #10, where a more significant deformation occurs near the bubble collapse region including compression strain in e_{rr} component and tension strain in e_{zz} component. These results demonstrate and quantify the cumulative nature of material damage and surface deformation as laser-induced cavitation is applied repeatedly.

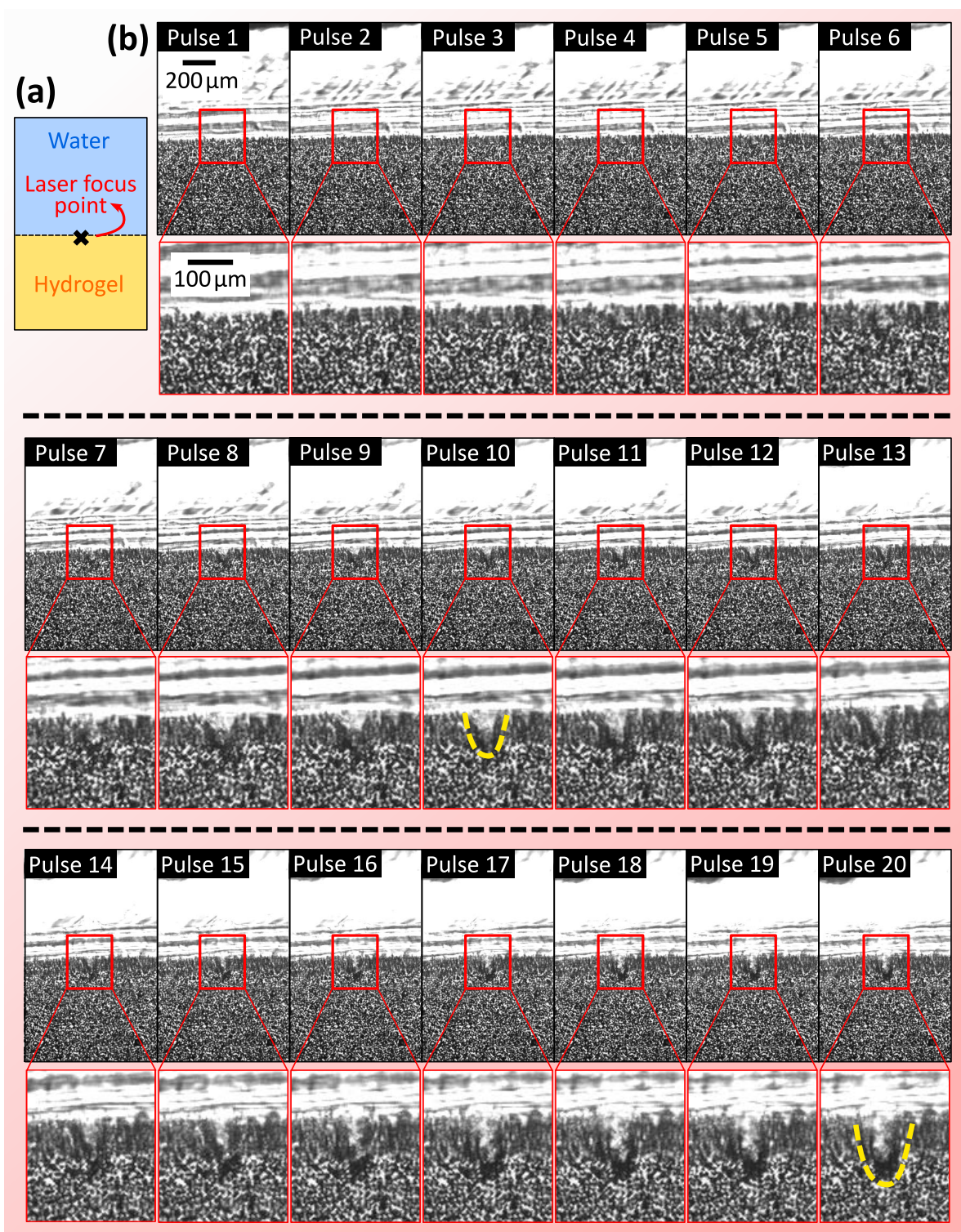


Fig. 5 (a) Schematic of the experimental setup showing the laser focus point at the gelatin hydrogel-water interface. (b) High-speed imaging sequence displaying the cumulative effects of laser-induced cavitation from pulse #1 to pulse #20. Each frame captures the localized surface response at the hydrogel interface, with magnified insets highlighting regions of interest. Yellow dashed-line markers indicate the cavitation-induced surface fracture openings after pulse #10 and pulse #20, visualizing the accumulation of damage with repeated cavitation events.

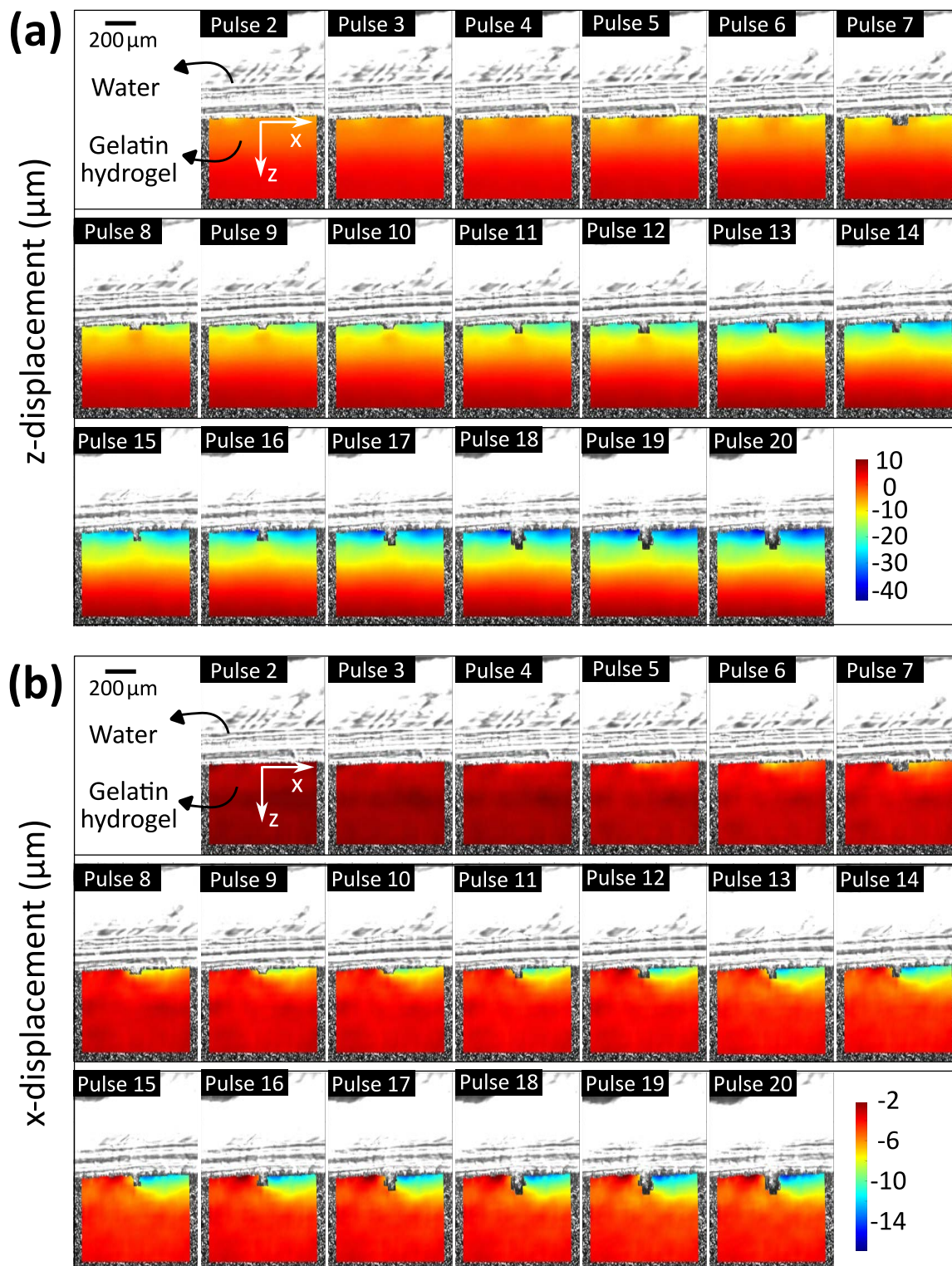


Fig. 6 (a) z - and (b) x -displacement maps showing the evolution of surface deformation in the gelatin hydrogel-water interface due to laser-induced cavitation across pulses #2 to #20. Each frame captures the strain fields generated by successive cavitation events, with positive and negative values represented by the color scale.

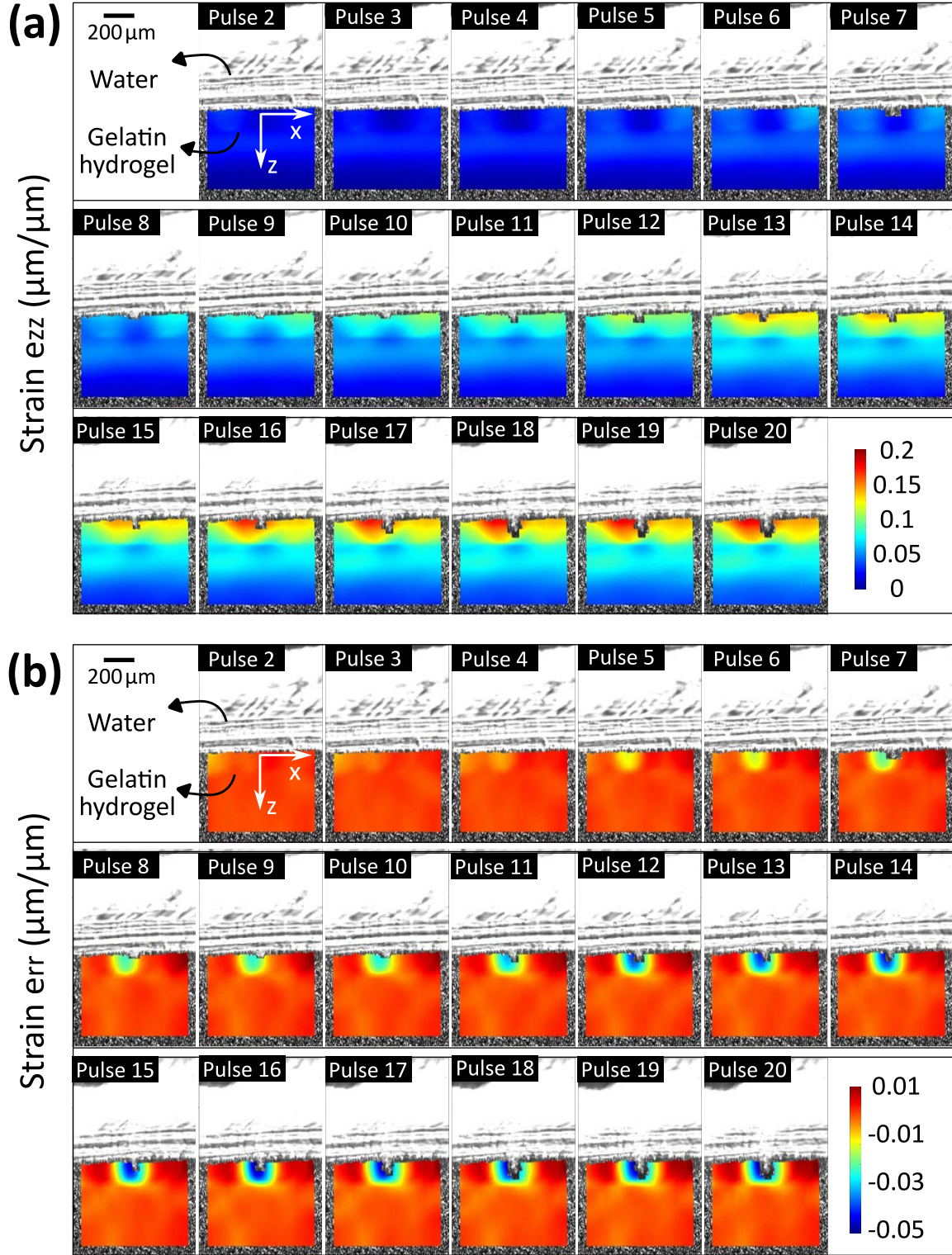


Fig. 7 (a) Strain e_{zz} and (b) e_{rr} distribution maps showing the evolution of surface deformation in the gelatin hydrogel-water interface due to laser-induced cavitation across pulses #2 to #20. Each frame captures the deformation fields generated by successive cavitation events, with positive and negative displacement values represented by the color scale.

Conclusion

In conclusion, the experimental investigation of laser-induced cavitation near a gelatin hydrogel-water interface reveals critical insights into the dynamic interaction between cavitation bubbles and soft material surfaces. The displacement and strain maps obtained through Digital Image Correlation (DIC) offer detailed views of the full-field deformation behavior, with progressive damage accumulation observed across successive cavitation events. As the number of pulses increases, the hydrogel surface experiences significant strain and deformation, leading to permanent surface alterations.

Here we highlight our study on the cumulative nature of cavitation-induced damage, particularly in soft materials exposed to repeated cavitation events. The detailed strain and displacement maps show how cavitation bubbles induce localized surface deformations, which intensify with each subsequent pulse. These findings are essential for understanding the long-term impact of cavitation on soft material interfaces, with implications for a range of applications, including biomedical devices, material testing, and tissue interaction during therapeutic laser procedures. The results underscore the importance of developing strategies to mitigate cavitation-induced damage in soft materials, particularly when used in environments subject to repeated cavitation exposure.

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