Soft Matter

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Supplementary Information: Amorphous Entangled Active Matter[†]

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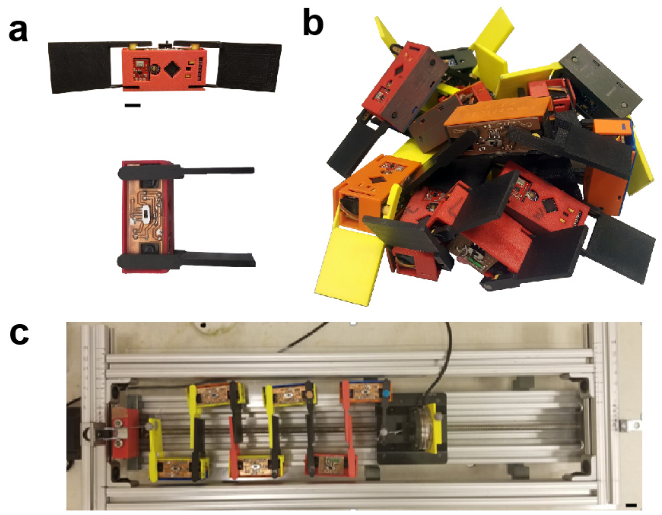

Fig. 1 Smarticles in robophysical experiments. (a) Front view of robotic smarticle used in experiment. (b) An entangled pile of smarticles as robophysical model. (c) Smarticles in experiment.

1 Robophysical Experiment

To test the physical attributes of a configurable chain of non-convex granular materials, we built three-link robots [1,2]. These robots, called "smarticles", are shown in Fig. 1. The arms were controlled by two servos (Power HD, HD-1440A) to a precision of ($< 1°$) and with an accuracy of $\pm 6°$. All processing and servo control was handled by an Arduino Pro Mini 328 - 3.3 V 8 MHz. Each robot was powered by a 3.7 V 150 mAh 30 C LiPo battery (Venom;Rathdrum, ID.).

Due to the size of the servos and the thickness of the body, the dimensions of the smarticles prevented it from performing 3D entangling tests mentioned in simulations; the thickness of a robotic smarticle's center link limits the number of simultaneous particle interpenetrations (see Fig. 1(e)). Despite this shortcoming, we found interesting results for these smarticle robots in 2D tests which depend on their non-convex nature.

The u-shaped particles, when strained, produce auxetic behavior because of their concave shape. Furthermore, the strength of a "chain" of smarticles, defined by its resistance to fracturing under strain, is affected by the confinement of the chain.

2 Results and Discussion

Strain tests are a common method to test the elastic, plastic and yielding properties of materials. Here, we perform a strain test for a chain of smarticles. In all trials, smarticles were initially centered between the confining walls Fig. 2(a). The positions of each smarticle in the chain were randomized between each trial to account for any variance in the servos' strength due to manufacturing differences or general wear that may accumulate over time. Experiments were performed with two different amounts of smarticles, $n = [2, 6]$. The chains were arranged as shown in Fig. 2(a,b) in a repeating $\sqcup - \sqcap - \sqcup - \sqcap \ldots$ pattern, where a "$\sqcap$" is the same shape as a "$\sqcup$" but rotated by π rads. This pattern interlocks adjacent smarticles together. For chains of $n > 1$, stress was transmitted between smarticles via the entanglement between their barbs. The barbs on the ends of the chain that are not in contact with an adjacent smarticle were connected to the apparatus via a string. On one side the chain is a force sensor which is affixed between the final smarticle and the mobile part of the apparatus' structure. The sensor was connected on the side of the chain where the strain was imparted. The force sensor was a custom device with strain gauges in a full-Wheatstone bridge configuration. All force measurements, F(t), were sampled at 1 kHz. The strain was imparted by a modified linear actuator kit (OpenBuilds; Monroeville, NJ.) as shown in Fig. 3(a-c). All strains were performed at a strain-rate $v = [5\ \text{mm/s}]$. The strain was measured by tracking infrared markers on the smarticles, where all positions and orientations of the smarticles were tracked using an infrared video recording hardware/software suite (OptiTrack; Corvallis, OR) (see Supplementary Movie S4).

We begin the investigation of some of the elastic properties of our system. With two types of trials, one for each value of n, we measure force as a function of strain for the chain. There is a small decrease in force at a strain of $\varepsilon = 0.4$, for $n = 2$ and $\varepsilon = 0.2$ for $n = 6$ (see Fig. 4), the same mechanism causes the decrease in both systems. The decrease in force happens as a result of a sud-

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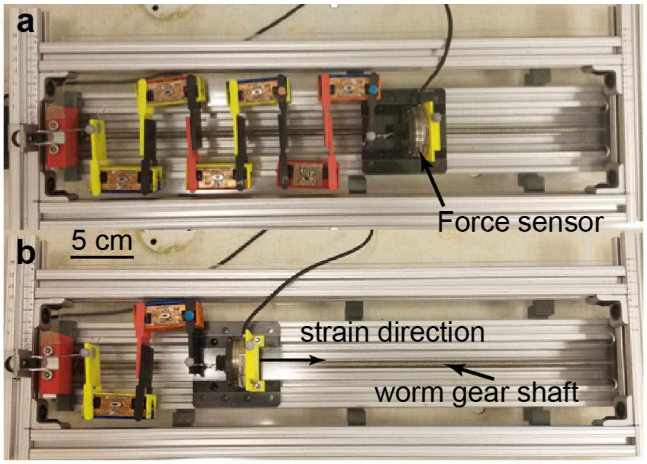

Fig. 2 Smarticle chains of varying size, $n = 6$ and $n = 2$. (a) Top view of an $n = 6$ system. (b) Top view of an $n = 2$ system.

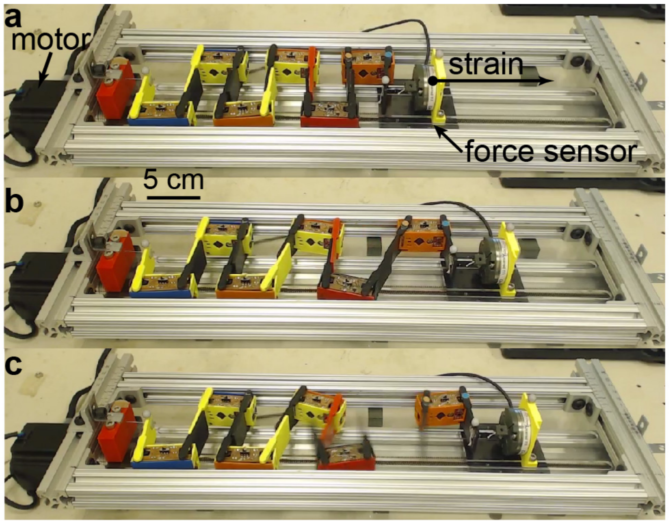

Fig. 3 Time sequence of chain fractures in experiment. (a-c) Three snapshots of an $n = 6$ chain of smarticle. (a) shows the chain before strain starts, (b) shows right before fracture, and (c) shows immediately after fracture. (Supplementary Movie S3)

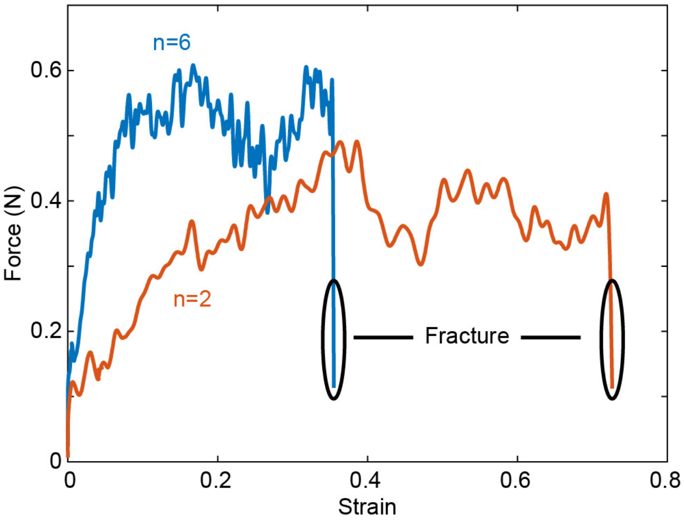

Fig. 4 Single fracture trial for n=2 and n=6 smarticles. Single trials of force as a function of strain for smarticle chain at different n, both strains were continued until the chain fractured.

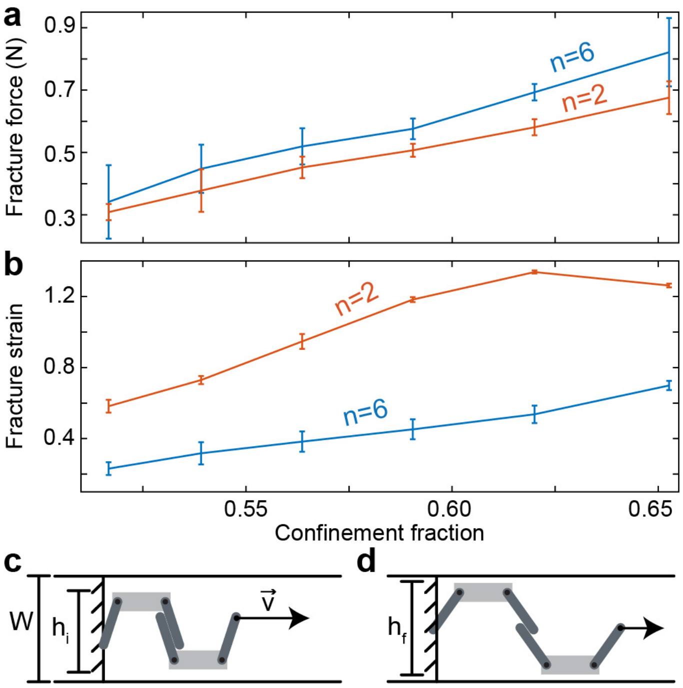

Fig. 5 Auxetic behavior in smarticle chain and dependency on number. (a) Peak force before fracture. (b) Peak strain before fracture. (c) Schematic of smarticle chain setup. (d) Configuration after smarticle chain has been strained. $h_f > h_i$.

den and rapid increase in the chain's length. This sudden change in length corresponds to the yield stress, the point at which rearrangement in the chain occurs. Surpassing the yield stress indicates a material has undergone plastic deformation. After reaching this yield stress point during a cyclic strain test, the force as a function of strain will produce a different curve than in cycles before the yield point was reached. As n increases, force also increases but elongation decreases. When arranged in a chain, the PD-controlled servos can be expected to act approximately as a chain of springs for small strains; therefore, the force should increase linearly with strain distance.

Fracture is defined as the separation of a body into two or more pieces in response to an imposed stress[3]. Fracture tests give insight into when materials plastically deform and fail. For our second experiment, we measured properties related to fracture in the chain system, specifically, the peak force and strain before fracture. Trials were run with $n = [2, 6]$ smarticles and the smarticle order was rearranged between each trial. All trials were repeated 5 times for confinement widths between $h/H = [0.52 - 0.65]$, where $h = 6.2$ cm is the initial width of the smarticle chain.

In the chain system, the fracture mechanism is related to the arm opening angle and friction. When the chain is strained, the barbs' angle is forcefully increased beyond the ⊔-shape or $\alpha_i = 90°$. As α_i increases with stress, the barb's contact with the adjacent smarticle will begin to slip away from the adjacent smarticle in a direction lateral to the strain direction. The chain fails, or fractures, when the expansion reaches a certain threshold such that the static friction is overcome and adjacent barbs slip lose contact. As the smarticles slip due to their geometry, they displace outwards. This phenomenon of dilation in the direction lateral to the strain is called auxeticity[3]. The width of the chain as it is strained can change, but the system is bounded and has a maximum of H (see Fig. 5(a)). In trials where the chain width expands to equal the confining width H before it fractures, the maximum force before the fracture is affected. Some of the stress from the chain is offloaded and supported by the walls, effectively reducing the load on the arms as shown in Fig. 5(a-b). As the confinement increases, (H decreases), the maximal force measured before a fracture will increase. The force increases linearly with the confinement fraction. Moreover, the functional form of an $n = 2$ and $n = 6$ smarticle chain is qualitatively similar and only the magnitude changes. We find similar results in Fig. 5(b) for the maximum strain at fracture. As confinement increases, maximum possible strain increases as well. This is consistent with the spring chain approximation of the servo chain.

In our smarticle system, based on "smarticle cloud" results [2], we hypothesize the existence of gaits which can reliably produce contraction as well as an expansion for a smarticle cloud system. In a contracting case, smarticles at the center of the pile experience confinement. With that as our motivation, we tested how confinement affected fracture. We found that the maximum force before fracture steadily increases with confinement fraction, similarly, we found the maximal strain distance before fracture increases as well. By leveraging future capabilities of smarticle swarms, we could effectively employ other smarticles to enforce the confinement conditions, allowing a chain to exhibit improved tensile strength performance on command.

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