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Imperfections: using defects to program designer matter

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1. Introduction

1.1. The importance of imperfections

Errors are everywhere. Mechanical failures are especially common: from buckled grain silos and tubes that balloon when they had better not, to cracked support columns (Fig. 1.1). These types of mechanical failure are, justly, seen as an issue to be avoided. Entire fields of study are dedicated to engineering structures and materials that can withstand extreme circumstances.

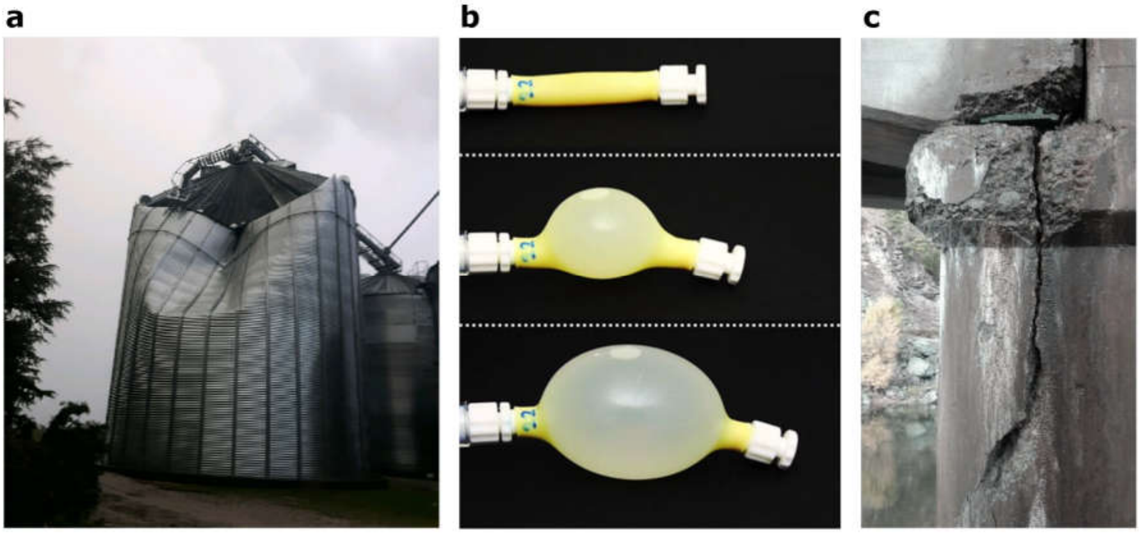

Fig. 1.1.: Imperfections to be avoided. a, Buckled grain silos in Iowa after the 2020 USA Midwest derecho (a thunder-gust event). Photo: Iowa Governor's Office, via radioiowa.com. **b,** Ballooning in an inflated cylindrical tube: a prototypical model of aneurysms. Image adapted from Ref.[1]. **c,** Cracked concrete columns supporting a bridge in Washington, 2014. Photo: Washington State Department of Transportation, via methowvalleynews.com.

Crucially, such research provides not only the means to prevent mechanical failure, but also the means to understand its sources: different flaws, errors, imperfections- each provides a distinct and unique challenge. This understanding of mechanical flaws' sources and effects allows us to expand our horizons: flaws can be *used* to design materials with unique functionalities. For example, buckling is harnessed to create structures that morph between different shapes[2] (Fig. 1.2a); carefully textured balloons inflate to soft robotic grippers, suited for manipulating fragile objects[3] (Fig. 1.2b); and crack paths can be engineered to produce controlled trajectories and edge patterns[4] (Fig. 1.2c). The special behaviour of these functional structures exists by the grace of defects.

In the work presented here, we follow the same idea: defects can be put to use. Throughout this dissertation, we use two types of imperfections to create functional

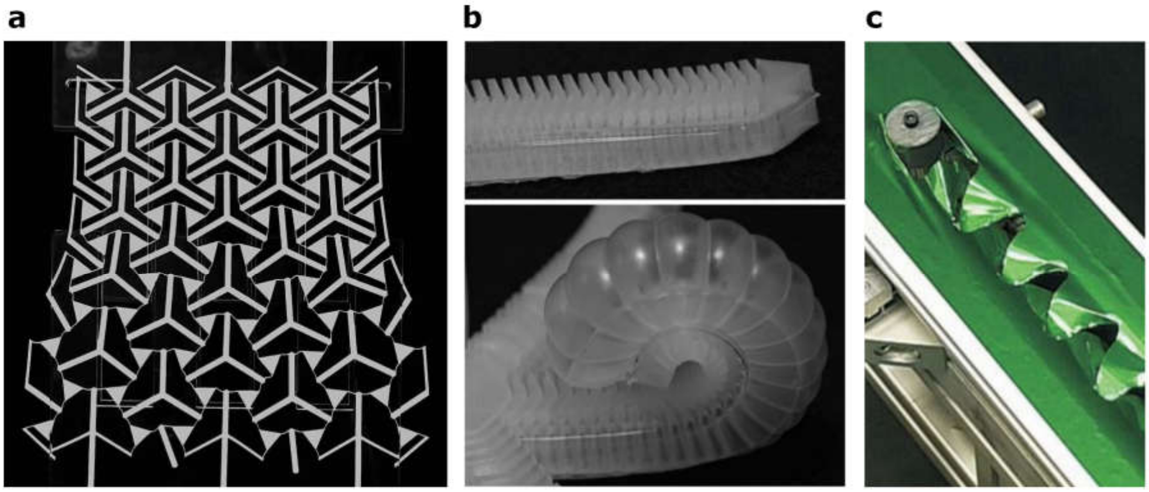

Fig. 1.2.: Useful imperfections. **a,** Buckling in a 2-D geometric structure produces a shape-morphing structure that can expand and contract quickly. Image adapted from Ref.[2]. **b,** Ballooning in a thin rubber structure is harnessed to make a curling soft robotic gripper. Image adapted from Ref.[3]. **c,** Tearing cracks in a thin film with a moving cylindrical rod results in a characteristic and controllable periodic cut pattern. Photo: Benoît Roman, via Ref.[4].

structures. First, we design materials that are locally stiff or soft, depending on how they are actuated, using topological imperfections: mistakes in their underlying architecture (chapters 2-4). Second, we create structures that shape-morph, because their individual elements fail, buckle, and snap- features that should be avoided otherwise (chapter 5). We briefly discuss their background and our main findings below.

1.2. Topological defects

In chapters 2-4, we harness topological defects to create materials in which deformations and stress are steered to different parts of the structure, depending on how it is actuated. Here, we discuss the basics of topology, and show the special behaviour of a material with a topological imperfection.

In essence, topology helps describe how different parts of an object, whether it is abstract or real, are interconnected. This means that topology can be used to distinguish materials with fundamentally different internal architectures. To get an intuition for how this works in different contexts, Fig. 1.3 shows three classic examples. In Fig. 1.3a, we show a thin strip of plastic that has been connected back to itself into a ring. The ring has a simple topology, with an inside and an outside surface. But when the strip is twisted once, its topology changes drastically. Imagine walking around this Möbius loop: to get back to your point of departure, you have to circle the strip twice. As a different example, a pair of topologically distinct doughnuts is shown in Fig. 1.3b. The pastries' topology is set by the number of holes: the jam doughnut has none, the regular doughnut has one. Interestingly, the number of holes can be counted locally by keeping track of the patisserie's surface curvature. We finish with an inedible case in Fig. 1.3c: liquid crystals. These are long and thin molecular rods that, under the right circumstances, align alongside each other into a simple topology. However, mismatches in alignment

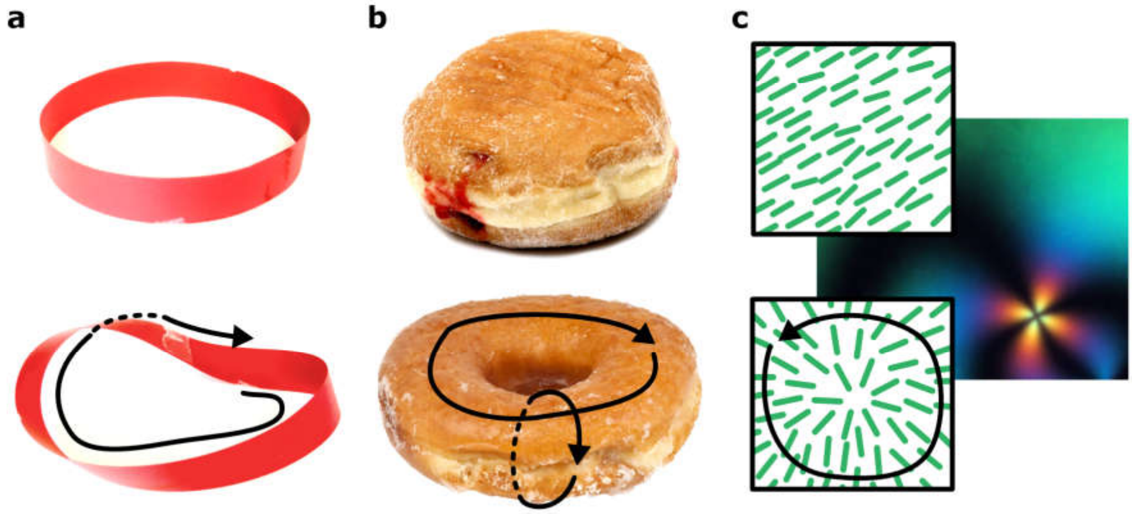

Fig. 1.3.: Topology can be used to classify objects. a, A thin plastic strip is looped back on itself into a ring (top). Twisting the strip once produces a Möbius loop with a distinct topology: traversing the Möbius loop once gets you to the opposite side (bottom, arrow). **b,** A jam doughnut (top) and a regular doughnut (bottom) are topologically distinct: one has a hole, which can be detected by tracking the doughnut's local curvature across the surface (arrows). Photos: Evan Amos. **c,** Liquid crystal rods can be aligned (top) or not (bottom): alignment disruptions produce topological defects that can be distinguished by tracking the rod orientation around a loop (arrow). A typical Schlieren texture of a defect in a liquid crystal film is shown. Image: Oleg D. Lavrentovich, Kent State University.

produce defects with a distinct topological signature. The presence of these defects can be detected by tracking the rods' orientation along a closed loop at the outer boundary of the system. In short: topology describes the internal structure and connectedness of a large spectrum of objects.

While the examples shown above appear distinct, they have one thing in common. Their topological character—whether they are twisted, have holes, or other defects—is *measurable*. And measuring topology is done by looping around the object in question. Specifically, we have to keep track of the structures' local properties while traversing closed loops around it. If there are topological defects in the system, these local properties show a characteristic signature that flags whether there is mismatch: a topological defect (chapter 2).

We use topological defects with a characteristic Möbius-like loop signature to design functional structures in chapter 3. Fig. 1.4 shows the end result of this design process. To keep things simple, we work with two-dimensional structures built up out of discrete slender rods arranged in a triangular structure, as illustrated in Fig. 1.4a. The material shown there has a simple topology, analogous to a simple ring: it has no defects, topological or otherwise. As a result, compression of the structure produces a smooth, soft deformation that is even reproduced in experimental, 3D-printed samples (Fig. 1.4b). By contrast, changing the internal architecture of the structure by switching just a few rods produces a structure with a topological defect (Fig. 1.4c). Like the Möbius loop, this structure has structural mismatch that produces strange effects. When this structure is pushed (Fig. 1.4d), one half of the material deforms nicely; however, the other half is

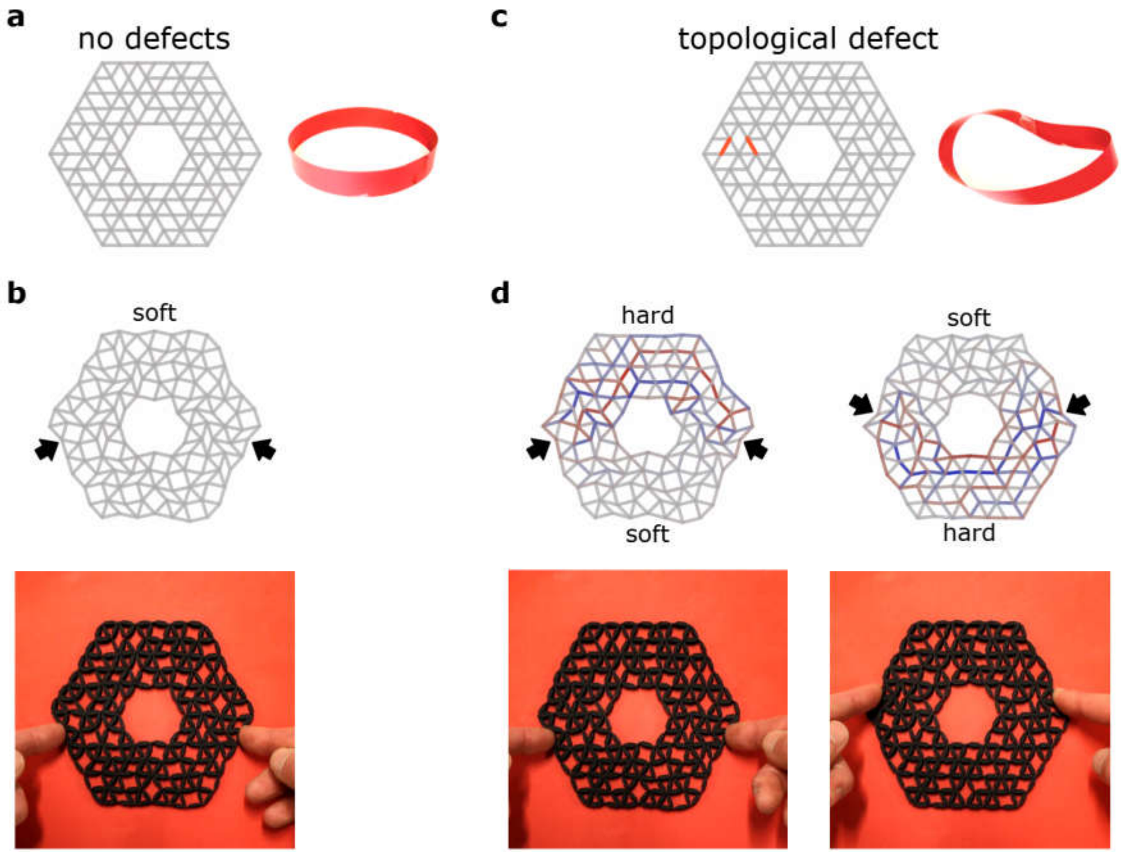

Fig. 1.4.: Topological defects steer forces and deformations. a, Top to bottom: a ring-like structure built up out of thin elastic rods (grey bars) has a simple topology, analogous to a ring (inset). **b,** Under compression (arrows), the structure deforms smoothly and easily by hinging at the bars' connecting points. Experimental realizations reproduce this behaviour (bottom). **c,** Modifying the structure by switching a few bars (red highlights) produces a topological defect, similar to twisting a strip to produce a Möbius loop. **d,** When the structure is compressed at two points, one half deforms easily, while stress (colours) builds up in the other half (left). This stress-steering response can be switched around by choosing different loading points (right). Real samples show the same effect (bottom).

stiff, does not deform, and builds up stresses. While this behaviour is unusual, build-up of stresses is not unique in the presence of mechanical defects (chapter 4). However, due to the unique topology of the material, this stress-steering response can be flipped in space: by changing where we compress the structure, stresses and deformations are steered to opposite sides of the system.

Our work thus demonstrates that topological defects can be harnessed to design functional materials, in which external actuation controllably steers stresses and deformations to different parts of the system.

1.3. Snap-through defects

Besides topological defects, we harness snap-through instabilities in chapter 5 to design shape-morphing structures. These materials switch quickly and reversibly between multiple stable states. We discuss the basic idea behind snapping and shape-morphing here, and illustrate the shape-shifting qualities of our material.

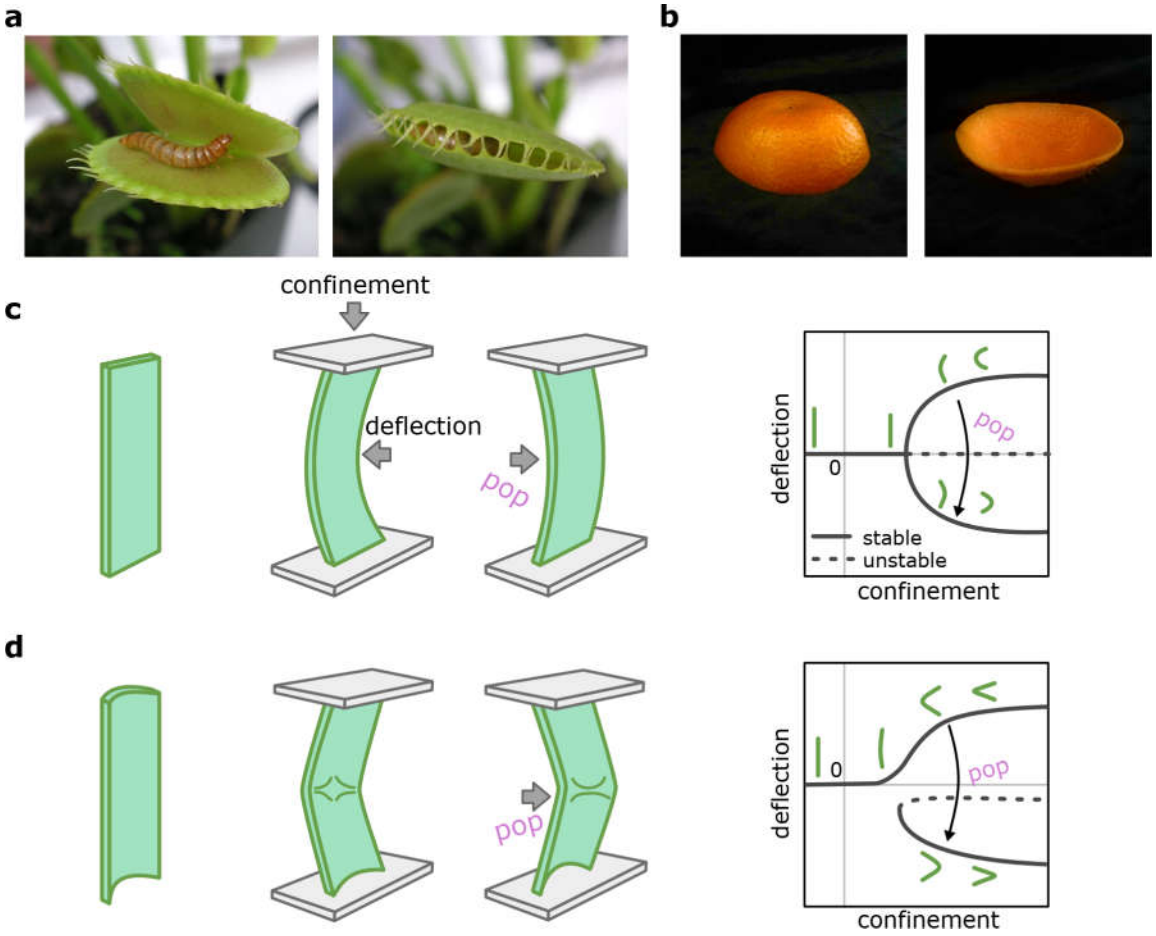

Fig. 1.5.: Snap-through instabilities allow shape-morphing. a, Venus flytrap leaves are shaped like shallow caps. The leaves invert through swelling to a closed configuration. Photos: Beatrice Murch (CC BY-SA 2.0). **b,** Snapping through geometric frustration: a convex cap cut from a tangerine (left), pops into a stable inverted shape (right). **c,** Prototypical snapping model. Left: a thin strip is confined between two plates. The strip buckles, as measured by its deflection. Right: phase diagram showing the strip's stable states. After buckling, a pitchfork bifurcation produces two stable states: left-and right-buckled. A snap-through instability, triggered by external probing, switches the state and pops the strip from left to right. **d,** Snapping with asymmetry. Left: a pre-curved groove can buckle and pop. The left- and right-buckled state are not the same. Right: the phase diagram shows a typical imperfect pitchfork bifurcation. The groove buckles left under confinement, but can be popped through into the right-buckled state.

Generally, snap-through instabilities occur in structures that have multiple stable states. The two states are separated by an energy barrier, which can be traversed if the structure is actuated with a large enough force. Snapping instabilities are common: Fig. 1.5 illustrates two instances from the natural world. For example, the leaves of a Venus flytrap (Fig. 1.5a) can snap shut to trap prey: the leaves are shaped like shallow shells, that can snap through to an inverted shape. This transition appears to be activated by differential swelling in each leaf [5]. The role of swelling can be taken up by simple mechanical action as well, as illustrated in Fig. 1.5b. There, we show a shallow spherical cap, cut from the peel of a tangerine. Though the cap is naturally convex, it can be popped through to a concave shape by pushing the top. The energy barrier that separates these two states is mostly elastic, and arises from the tangerine's spherical shape and the slenderness of its peel. To create a shape-shifting structure, we will likewise make use of elastic, geometry-induced snapping in thin structures.

Fig. 1.5c shows a prototypical model for geometric snapping in thin sheets. The narrow elastic strip shown there does not snap spontaneously; but confining the strip between two plates forces it to buckle through. Due to the strip's symmetry, it can buckle either left or right. Thus, the confined sheet has two stable states—left- or right-buckled—and can snap between these two, reversibly, by applying an external deflection. This idea is illustrated in the state diagram (Fig. 1.5c, right) which shows the typical pitchfork bifurcation that this system undergoes: at small confinement, the sheet stays straight; after a critical confinement, the sheet buckles, and can snap back and forth between its two buckled states.

Now contrast the behaviour of a straight strip with that of a pre-curved groove, illustrated schematically in Fig. 1.5d. The groove shown is not symmetric: under external confinement, it snaps through preferentially toward its convex side (reminiscent of a tape spring). However, the groove can be popped toward its concave side under external deflection into what we call its *defect state.* Crucially, when several grooves are tiled together into a *groovy sheet* (Fig. 1.6a), the groove's defect state is stable even without external confinement. Thus, groovy sheets can snap reversibly between resting and defect configurations, due to their geometry.

We harness the reshaping capacities of groovy sheets to create shape-shifting materials. This concept is illustrated in Fig. 1.6. Fig. 1.6a shows the base material: a thin sheet, made with multiple adjacent grooves. Each groove can be popped into a defect state, in which a localized disruption curves the underlying structure into a bent shape. Fig. 1.6b shows groovy sheets with one, two, and four grooves in their defect state; crossed polarisers highlight the defect loci in colour, resulting from the plastic sheets' intrinsic birefringence. Even sheets with only a few grooves can switch to a shape that is quite drastically different from the initial flat configuration. Increasing the number of grooves allows for the creation of a wide array of defect patterns, and produces an even wider spectrum of sheet shapes: selected examples are shown in Fig. 1.6c. Curled, twisting, spiralling, and disordered shapes are observed.

Importantly, our work shows that defect patterns can be created mechanically with relative ease. Under the right conditions, defects do not produce permanent deformations in the underlying material, and one sheet can thus snap reversibly into many different shapes, one after the other. Thus, this work provides a platform that harnesses geometry-induced snap-through instabilities to create shape-morphing structures.

The work presented in this dissertation thus harnesses imperfections for functional design. We show how topological defects steer stresses and deformations inside mechanical structures, and how geometry-induced snap-through defects produce shape-morphing materials. We hope that our findings can contribute to the ever-expanding field of functional design of mechanical structures[1,2,6–12].

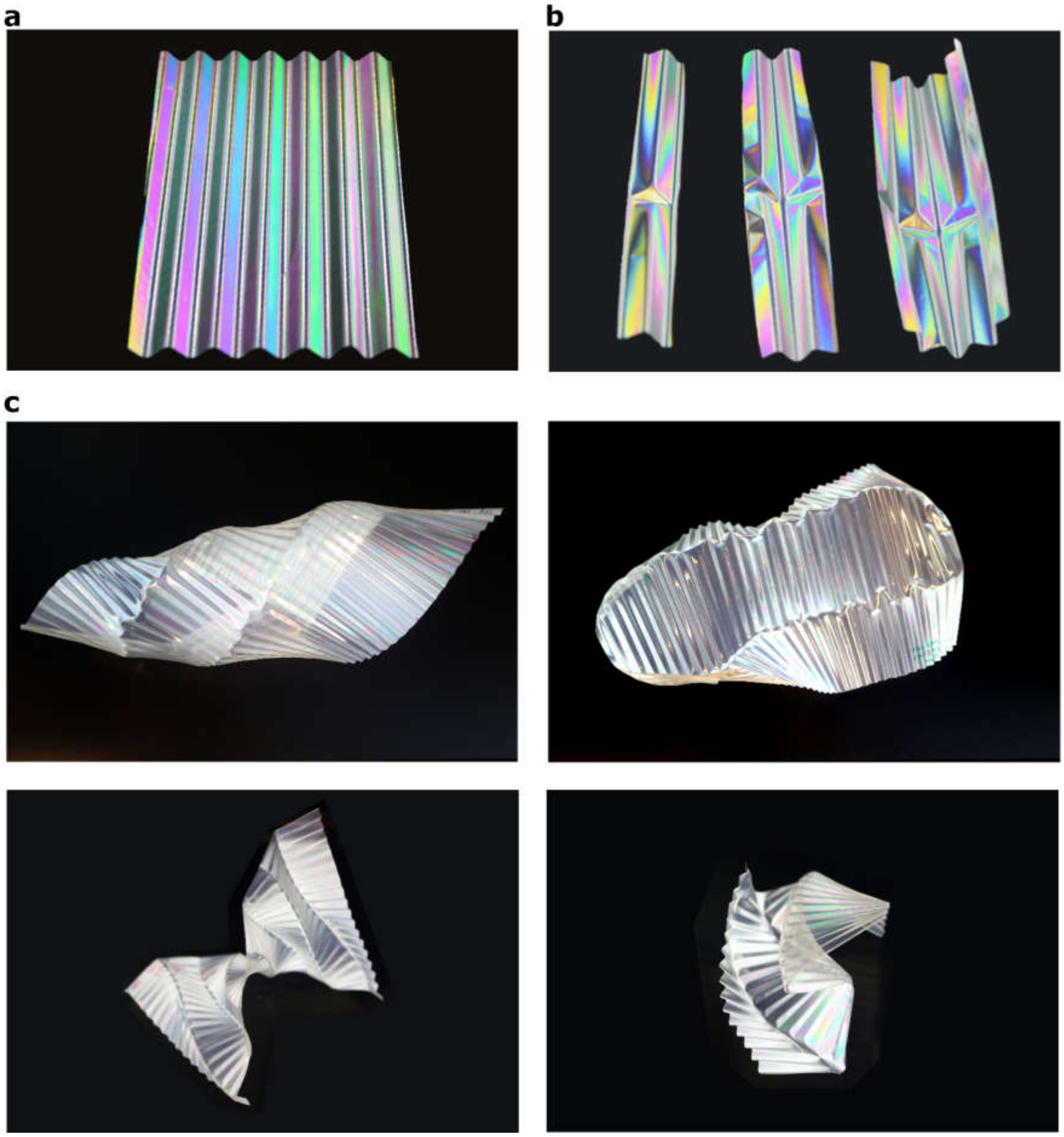

Fig. 1.6.: Undulating groovy sheets snap reversibly into complex shapes. a, A groovy sheet: thin plastic, tens of microns thick, with undulations on the centimetre scale. Colours arise from viewing between crossed polarizers. **b,** Undulations of a groovy sheet support snap-through defects. Examples of one, two, and four undulations are shown. **c,** Larger sheets snap between complex spiralling and curving three-dimensional shapes, from ordered to disordered. The sheets' shape varies depending on the location of snap-through defects in its grooves.