Imperfections: using defects to program designer matter

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Summary

The research presented in this dissertation spans several years of work that I've done at AMOLF and Leiden University, where I've been active in the field of material design. Collectively, our community works to design mechanical structures. These structures have a mechanical function, just like mattress foam or door hinges do. We invent special architectures and fabricate prototypes with various techniques, from casting rubber in 3D-printed moulds, to laser-cutting foam and thermoforming plastic. The goal is to create novel materials that function differently than traditional ones do: concrete, wood, solid rubber. The unusual behaviour of the structures we design comes from their internal geometry, rather than from the basic stuff they are made of. This idea is certainly not new: knitted fabric is definitely different from a skein of yarn, which is why we wrap ourselves in scarves instead of thread. The underlying idea, then, is that novel structural designs can be made out of whatever material is on hand; it just needs to be cast into the right shape.

But inventing a material that does a specific job (and does it well) is not easy. A huge number of design strategies exist. Many designs (brick-laying, knitting, and weaving patterns, for example) have been invented centuries or even millennia ago, and continue to be passed on through the years. But (historically) recently, our quickly industrializing world has seen enormous developments in materials science, engineering, rapid prototyping and computation. And along with this has come an explosion of new material design methods: biology-inspired approaches, genetic algorithms, topology optimization, and other mouthfuls. Each technique has its own benefits and drawbacks. There is no unified approach to material design. What we have instead is a rich and growing variety of tactics available to those of us who want to design functional structures.

In this dissertation, I present material design strategies that revolve around defects. Errors, flaws and imperfections in mechanical structures are usually better avoided. But from one (perhaps rather dry) point of view, we can reframe flaws: they are manifestations of underlying physical principles. In and of themselves, they are neither good nor bad: they are. Understanding their origins helps us avoid mechanical failure, from broken windows to buckled grain silos. But it also allows us to *use* flaws, on purpose, to create new materials with novel and useful behaviour.

I use two kinds of mechanical flaws to create materials with new properties: topological defects, and snap-through instabilities.

Chapters 2 to 4 of this dissertation deal with the first design strategy, using topological defects. In Chapter 2, we start by designing the basic structure: a flat material, made out of slender rods connected by flexible hinges. At first, the structure is soft and deforms easily when squeezed. But then, by switching the positions of a few rods, we introduce a topological error. Topology, here, refers to how the structure's rods are interconnected: the right way (which produces a soft material) or the wrong way (which gets us a topological defect). It turns out that this topological error leads to new behaviour, which we

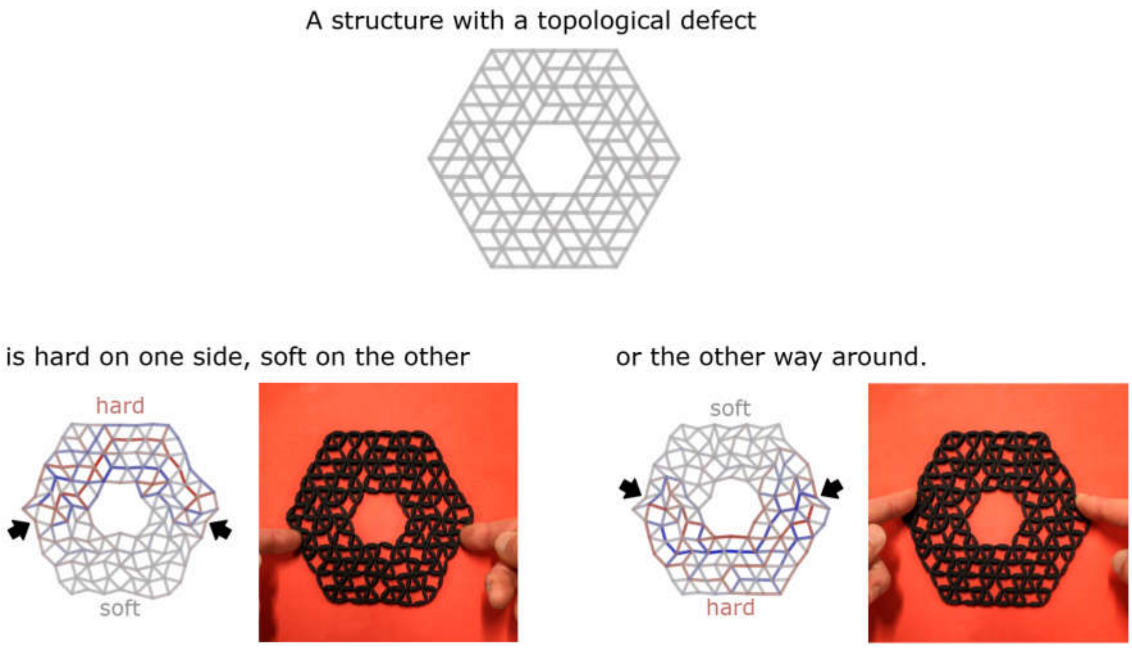

Fig. S1.: Topological defects control where a material is hard or soft, depending on how it is pushed.

explore in Chapter 3. There, we show that materials with a topological error have adaptive regions that are soft or stiff; where these regions are depends on how the structure is squeezed. In Chapter 4, we dive into the mathematical nitty-gritty, and describe what exactly happens mechanically when we switch those few rods. Figure S1 summarizes the overall result: topological flaws allow us to design material that can be both soft and hard, depending on where it is pushed.

Finally, Chapter 5 introduces a material that shape-shifts via snap-through defects. The basic idea behind this shape-morphing behaviour is illustrated in Figure S2. Everything starts with a thin sheet with parallel grooves, like miniature corrugated roofing: a groovy sheet. The curved shape of the grooves is important here: because of its shape, each groove can be snapped through with a pop. This effect is also seen in very long tape measures, which can click into a folded shape. Crucially (and unlike tape measures) the grooves in large sheets *stay* snapped, bending and curving into a new, three-dimensional shape. What shape the sheet takes on depends on where the grooves are popped through: different popping patterns lead to different shapes. Intuitively, all this snapping action might break up the material, but as long as the sheet is thin enough, it stays intact. That means that groovy sheets are true shape-shifters: because they can handle these snap-through defects, groovy sheets can be popped, unpopped, and re-popped at will.

In short: the research reported in this dissertation shows how imperfections can be used to create functional mechanical structures. I hope that this work will find its place in the ever-growing field of material design.

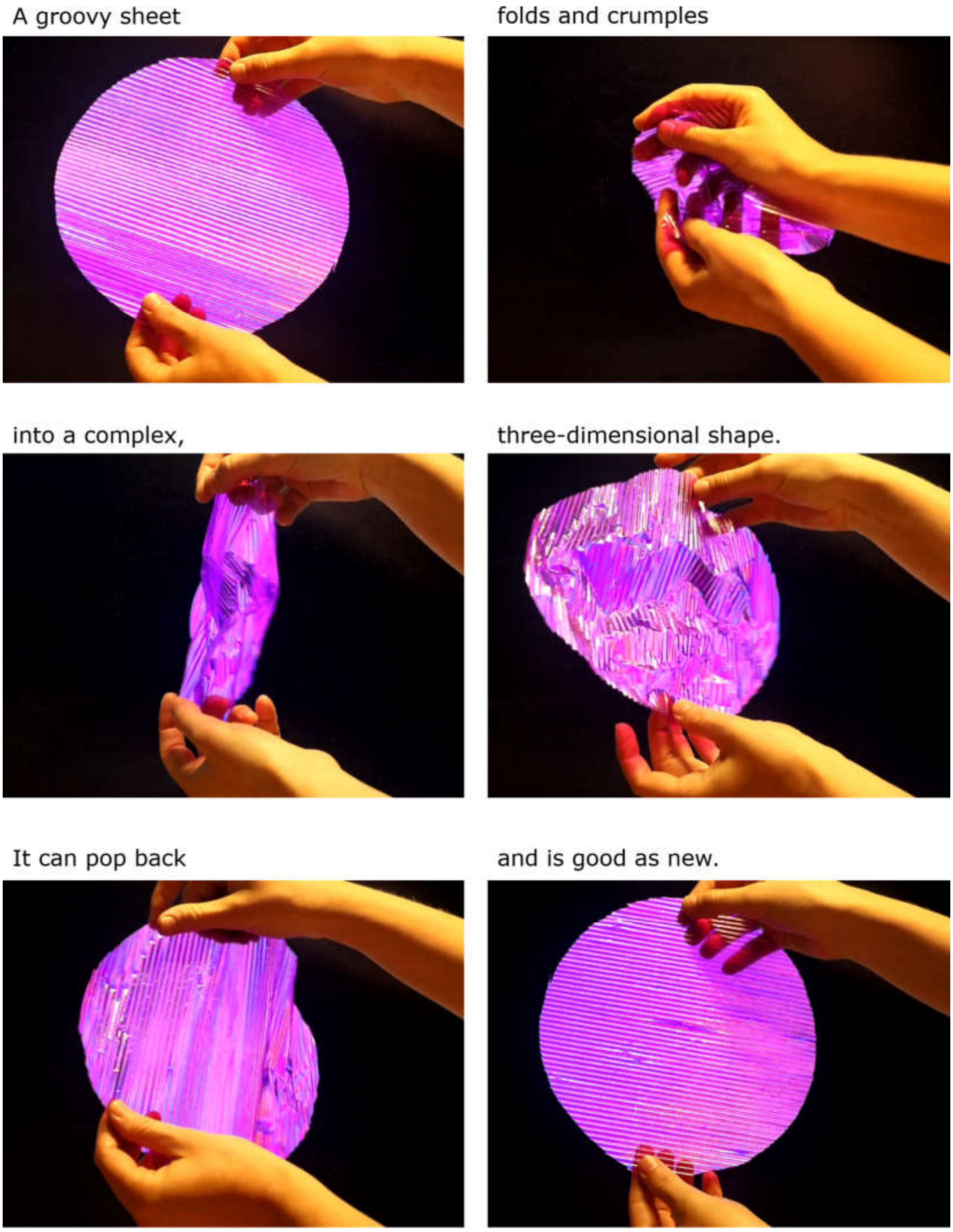

Fig. S2.: Flat groovy sheets snap back and forth into complex three-dimensional shapes.