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# Embracing failure

Engineers typically do all they can to stop structures from mechanically failing. But as **Daniel Rayneau-Kirkhope** and **Marcelo A Dias** explain, we can exploit such “elastic instability”, with inspiration from nature

Bridges should not collapse when crossed, rail tracks should not buckle on a hot day and cement should certainly not yield under a building’s weight. At least that’s the prevailing mindset among engineers, who want to limit deformations and avoid structures from failing under a compressive load at all costs. But some researchers are now saying that it is time to embrace such “elastic instability”.

As with so many adventurous design concepts, nature got there first; many plants and organisms rely on “failure” to stay alive. One of the most striking examples of useful elastic instability in the plant world is the carnivorous Venus flytrap. A helpless fly landing on a leaf will stimulate tiny trigger hairs on its surface. The plant ignores the first trigger, but the second often proves fatal for the fly; it sets in motion the rapid closing of the leaves around the fly, which hold it captive while the plant slowly digests its meal.

How these leaves snap shut defied explanation for many years. The leaves move too quickly for the snapping to be explained by some sudden swelling, and it is now thought that while swelling is involved, it merely initiates the motion. The speedy action hap-

pens instead thanks to the geometry of the leaves. When a fly lands on a leaf – which is convex from the fly’s perspective – its shape is right on the edge of mechanical stability. All it takes is a tiny change in curvature, caused by the swelling, to lead to a “snap-through” instability, in which a pair of leaves jump from one stable (convex) state to a second stable (concave) state, encasing their prey so that it cannot escape (see box on p26). Because the plant needs to control only the initial perturbation, it can rely on a relatively slow mechanism to initiate the leaves snapping closed in less than a tenth of a second – faster than the fly can flee the trap.

Embracing a different form of failure, certain bacteria control their motion by means of a slender helical tail. Rotating this “flagellum” faster causes the bacterium to exert more force on the surrounding fluid. But if the flagellum rotates too fast, the forces on it go so high that it elastically fails – the tail buckles, and the bacterium loses forward propulsion (*Nature Phys.* 9 494).

This intentional weakness is built into the system for a practical purpose: as the tail buckles, a turn-

**Daniel Rayneau-Kirkhope** is an Academy of Finland postdoctoral researcher at Aalto University, Finland, and **Marcelo A Dias** is an assistant professor of physics at James Madison University in the US, e-mail [daniel.rayneau-kirkhope@aalto.fi](mailto:daniel.rayneau-kirkhope@aalto.fi) and [diasma@jmu.edu](mailto:diasma@jmu.edu)

## Ready to snap

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**Killer snap** Nature's use for bi-stable structures.

As exploited by the Venus flytrap, “snap-through buckling” is a form of elastic instability where a small increase in loading causes a structure to jump from one configuration to another. A classic example of such behaviour is when a slender beam is used to form a shallow arch. When a force is applied from above, it initially causes a small change in the geometry, making the arch more shallow. At some point, however, a tiny additional amount of force eventually causes the structure to invert, or “snap through”, to form a valley shape. The elastic potential energy that can be released by this instability is evident in the hollow hemispheres of rubber used as “popping” toys. In these playthings the domes are inverted by hand from their most stable structure, placed on a surface and then, when the cap suddenly reverts to its initial shape, the toy jumps up by a considerable distance, creating an audible “pop” as it does so.

ing force (torque) is created. So when the flagellum returns to its original configuration and resumes forward motion, it does so in a new direction. For engineers, miniaturizing systems that can move is an inherently difficult challenge, but the method by which these bacteria combine propulsion and direction control into one system using elastic instability minimizes the number of elements required. That could inspire scientists and engineers contemplating similar problems.

These examples from nature showcase the potential of an extremely active and promising area in engineering in which elastic instability is used to create structures with novel and useful mechanical properties. Made up of elements that are individually bi-stable – i.e. have two stable configurations like the leaves of the Venus fly trap – a whole material can be created that has numerous stable configurations.

While no-one wants a collapsing bridge, and catching flies is for most of us not a high priority, engineers can use snap-through instabilities to slow fast-moving objects. When the material is squashed (say, by a falling object, or a speeding bullet), the kinetic energy can be transferred into mechanical energy as the elements snap through to another stable configuration. The designer can then choose the size of the deceleration and tune the energy barriers between different configurations by tailoring the geometry of the elements. What's more, if the deformation doesn't take the material beyond its elastic limit, it can simply be “popped” back into its original

configuration ready for reuse. This concept could be used to create reusable protective clothing, or crumple zones in cars.

**Cracking up**

A feature so dangerous it's often viewed as the death knell of structural integrity is the crack. At first appearing small and innocent, a crack causes small regions of nearby material to experience stresses much greater than elsewhere in the bulk. These stresses cause a crack to grow, and if it reaches a critical size, propagate quickly through a material. In this way, a tiny engineering flaw can grow even when the gross stress is many times less than would normally be needed to cause tensile failure in a material.

We risk terrible tragedy when cracks are neglected. In 1943 the SS *Schenectady* – thankfully while moored up – suddenly cracked in half and jackknifed when a crack propagated throughout almost its entire hull. In the 1950s, meanwhile, 13 Comet planes – the world's first class of jet airliner – had fatal crashes leading to 426 deaths. While some of these accidents were due to pilot error, in many cases the planes broke up in mid-flight, with inquiries finding that the failure began with metal fatigue and mechanical overstressing.

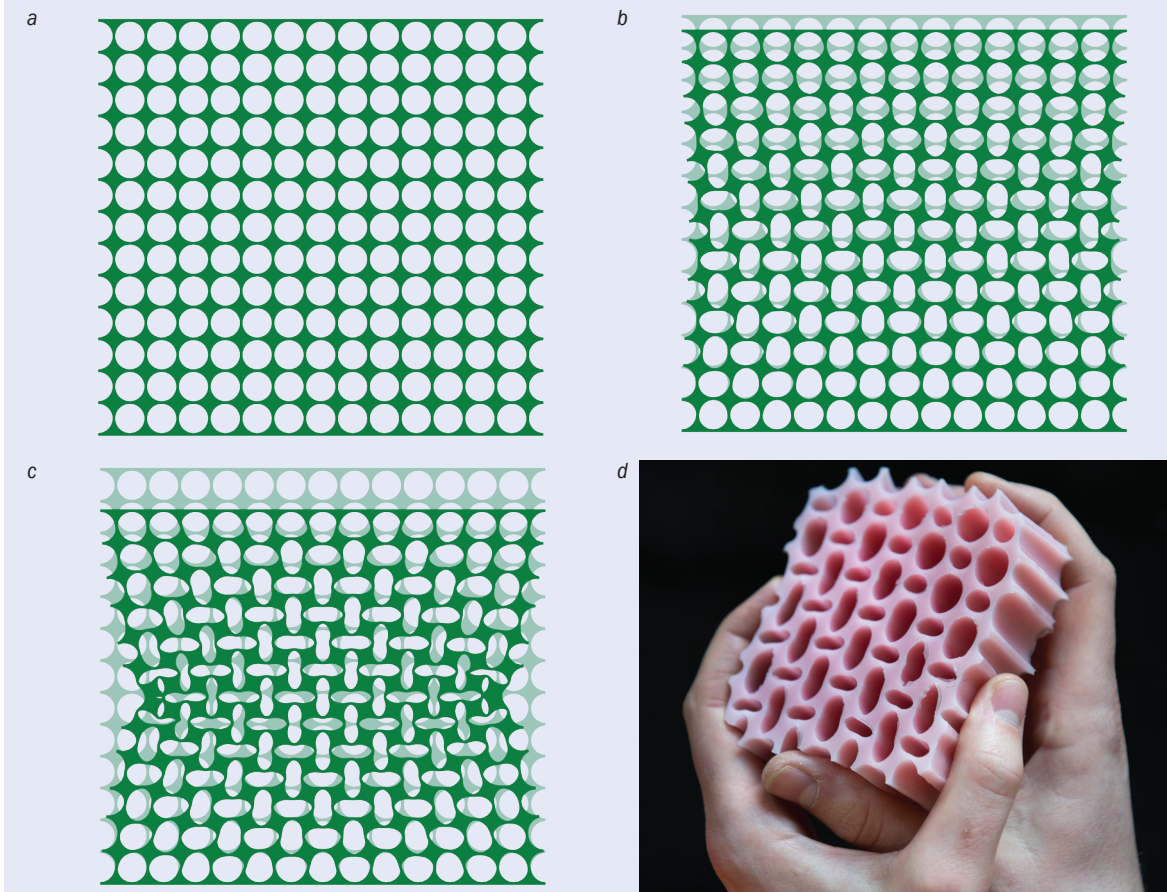
Cracks are, however, not always bad. In certain situations, a well-designed crack motif can be useful as it provides designers with an extra degree of freedom. This ability to “functionalize” cracks is therefore emerging as a new research direction in physics.

For example, if you apply tension (outward force) perpendicular to a single crack, it starts to open and the sheet raises out of the plane, creating a 3D surface. Researchers are now trying to characterize these out-of-plane deformations and to understand how and why they grow. Also being considered are the interactions between multiple cracks in a single sheet. Depending on the geometry, a huge range of deformations can be obtained, including out-of-plane elevation, and pitch and roll (rotation around the two in-plane axes).

Designing motion into sheets using carefully placed cuts has many promising applications, including in robotics, in which motion is usually achieved using motors and gears. But because these components limit the robot's size and speed, the authors, along with colleagues at Boston University in the US, are seeing if we can create tiny robotic systems using kirigami, the Japanese art of cutting paper (in contrast with origami, the art of folding paper). By introducing cuts that allow roll, yaw and pitch – i.e. rotation around all three axes – we have created the building blocks of super-lightweight robots, using thin elastic sheets made of either silicon or graphene. As in the Venus flytrap, the motions could be triggered by swelling or shrinking components rather than by using motors, thereby providing a route to tiny machines.

Another way to manipulate kirigami-based structures is to control the tension applied at the ends of a cracked sheet, which changes the direction in which the surface of a sheet points, even at those parts of the sheet far from the applied loads. This allows, for

## 1 Bizarre behaviour



Compressing a soft holey structure leads to a negative Poisson's ratio, also known as auxetic behaviour, in which the squashed structure is both shorter and thinner than its unloaded counterpart. Simulations by the authors show (a) the unloaded lattice structure and (b–c) the reconfiguration through buckling. A similar holey silicone slab (d) was created and studied by Bastiaan Florijn and coworkers at the University of Leiden in the Netherlands (2014 *Phys. Rev. Lett.* **113** 175503).

In certain situations, a well-designed crack motif can be useful as it provides designers with an extra degree of freedom

B Florijn/University of Leiden

example, for an array of solar panels to be warped so that it tracks the motion of the Sun across the sky. Materials scientist Max Shtein and colleagues at the University of Michigan in Ann Arbor showed in 2015 that this method could increase the efficiency of an array of solar panels, without the complexity of controlling each panel separately. The same out-of-plane-deformation method could in future be used to create temporarily textured keyboards on touch-screen phones.

### Beyond nature

We are now arriving at a situation where, thanks to clever design, we can even create materials with properties not seen in nature. Rather than relying on a material's intrinsic properties, we can implement architecture on small length scales to create a “meta-material”, designing the mechanical properties of a material to suit a given application.

A beautiful, yet simple, example of this notion is provided by a soft, holey sheet. When a material is squashed, it usually becomes compressed parallel to the applied force and expands in a perpendicular direction. Such materials have a positive Poisson's ratio, but as the great Richard Feynman once pointed out: “it is reasonable that [Poisson's ratio]

should be generally positive, but it is not quite clear that it must be so”. It is now apparent that there are numerous ways to design materials with a negative Poisson's ratio – also known as “auxetic” materials. The holey sheet is just one of many.

What happens with the holey sheet is that the initially circular holes turn into ellipses, with each ellipse having its long axis pointing perpendicular to those of its neighbours (figure 1). The result is a structure that is both shorter and thinner than its unloaded counterpart. The reordering can be attributed to classical Euler buckling of the thinnest parts of the material, where the holes are closest to their neighbours and the material is at its weakest. The thicker joints in the system mean it costs a lot of energy to bring neighbouring beams closer together, so to avoid this large energy penalty, the joints simply rotate. The result is striking: an ordered, short-wavelength buckling occurs and the material shrinks in both height and width (2010 *Adv. Mater.* **22** 361).

Ahmad Rafsanjani and Damiano Pasini at McGill University in Canada have even created a material that has both snap-through instability and a negative Poisson's ratio (2016 *Extreme Mech. Lett.* **9** 291). Using a 3D printer, and inspired by patterns found on the millennium-old Kharraqa towers in Iran, the duo cre-

# Research in Astronomy and Astrophysics

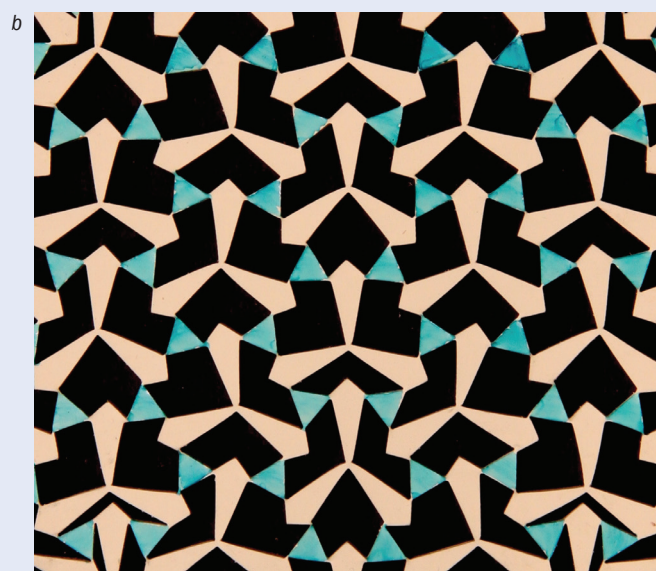
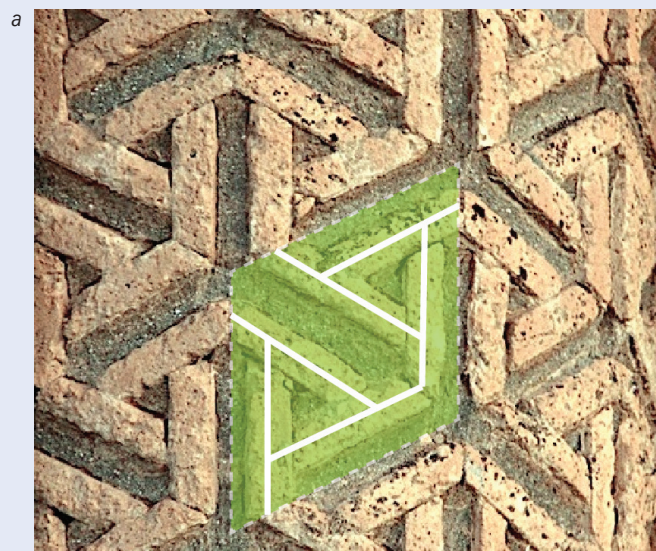
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## 2 Inspired by Islamic art



Auxetic materials have been inspired by geometry taken from Islamic art. When a configuration based on the Kharraqan towers (a) is placed under tension, it jumps to another configuration (b). The structure simultaneously exhibits auxetic and snap-through properties.

ated materials made of tessellating shapes linked to their neighbours at certain corners (figure 2). When a large enough tension is applied to these materials, they jump from a closed configuration with no gaps to one that is open as shown in figure 2b; and vice versa if the open configuration is compressed. This simultaneous exhibition of snap-through and auxetic behaviour could give such a material novel uses, such as fasteners that expand to fill a hole into which, prior to their expansion, they can be freely placed.

We are at an exciting time in the field of mechanical metamaterials, which could redefine failure. By harnessing qualities that have traditionally been seen as weaknesses we can design structures with never-before-seen behaviour. The design possibilities of functionalizing failure are huge. We are only at the beginning of what promises to be a very exciting period of exploration. ■