'Buckliball' opens new avenue in design of foldable engineering structures (w/ video)

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(PhysOrg.com) -- Motivated by the desire to determine the simplest 3-D structure that could take advantage of mechanical instability to collapse reversibly, a group of engineers at MIT and Harvard University were stymied — until one of them happened across a collapsible, spherical toy that resembled the structures they'd been exploring, but with a complex layout of 26 solid moving elements and 48 rotating hinges.

The toy inspired the engineers to create the "buckliball," a hollow, spherical object made of soft rubber containing no moving parts, but fashioned with 24 carefully spaced dimples. When the air is sucked out of a buckliball with a syringe, the thin ligaments forming columns between lateral dimples collapse. This is the engineering equivalent of applying equal load on all beams in a structure simultaneously to induce buckling, a phenomenon first studied by mathematician Leonhard Euler in 1757.

When the buckliball's thin ligaments buckle, the thicker ligaments forming rows between dimples undergo a series of movements the researchers refer to as a "cooperative buckling cascade." Some of the thick ligaments rotate clockwise, others counterclockwise — but all move simultaneously and harmoniously, turning the original circular dimples into vertical and horizontal ellipses in alternating patterns before closing them entirely. As a result, the buckliball morphs into a rhombicuboctahedron about half the size (46 percent) of the original sphere.

The researchers named their new structure for its use of buckling and its resemblance to buckyballs, spherical all-carbon molecules whose name was inspired by the geodesic domes created by architect-inventor Buckminster Fuller. The buckliball is the first morphable structure to incorporate buckling as a desirable engineering design element. The buckling process induces folding in portions of the sphere — similar to the way paper folds in origami — so the researchers place their buckliball in a larger framework of buckling-induced origami they call "buckligami."

Because their collapse is fully reversible and can be achieved without moving parts, morphable structures such as the buckliball have the potential for widespread applications, from the micro- to macroscale. They could be used to create large buildings with collapsible roofs or walls, tiny drug-delivery capsules or soft movable joints requiring no mechanical pieces. They also have the potential to transform

Transformers and other kinds of toys. (The toy that provided the researchers' epiphany is the Hoberman Twist-O.)

The researchers — Jongmin Shim MS '05, PhD '10, a postdoc at Harvard; Claude Perdigo, a visiting graduate student at MIT; Elizabeth Chen, a recent graduate of the University of Michigan who will join Harvard as a postdoc in the fall; Katia Bertoldi, an assistant professor in applied mechanics at Harvard; and Pedro Reis, the Esther and Harold E. Edgerton Assistant Professor of Civil and Environmental Engineering and Mechanical Engineering at MIT — wrote a paper about this work that appears this week in the Proceedings of the National Academy of Sciences.

"In civil engineering, buckling is commonly associated with failure that must be avoided. For example, one typically wants to calculate the buckling criterion for columns and apply an additional safety factor, to ensure that a building stands," Reis says. "We are trying to change this paradigm by turning failure into functionality in soft mechanical structures. For us, the buckliball is the first such object, but there will be many others." For instance, a robotic arm could be built from a single piece of material using a precisely engineered pattern of dimples at the intended hinging points that, when activated by a pressure signal, would bend.

"The buckliball not only opens avenues for the design of foldable structures over a wide range of length scales, but may also be used as a building block for creating new materials with unusual properties, capable of dramatic contraction in all directions," Bertoldi says.

Reis's research uses precision tabletop-scale lab tests and mathematical analysis to determine the basic physics underlying the mechanical behavior of materials. Bertoldi's research group uses tools from continuum and computational mechanics to unravel the mechanics of soft structures. The two teams collaborated on the buckliball: Reis' team performed the lab experiments with the help of digital fabrication techniques (such as 3-D printing) to create objects with precise geometry, and Bertoldi's group used computation to further analyze the detailed mechanics of the process.

Chen, who was visiting Harvard at the time, determined that only five spherical geometric structures have the potential for reversible buckling-induced collapse. (The specific example of Fuller's 12-hole rhombicuboctahedron that collapses into a cuboctahedron is one of these five.) Design parameters for buckliballs include dimple size, the thickness of the thin shell inside the dimple and the stiffness of the material used to fabricate the buckliball.

Nature, it appears, has already figured this out. Viruses inject their nucleic acids into a host through a reversible structural transformation in which 60 holes open or close based on changes in the acidity of the cell's environment, a different mechanism that achieves a similar reversible collapse at the nanoscale.

“What’s exciting about this work is that it uses instabilities to basically amplify small or moderate pressures into dramatic motion,” says Carmel Majidi, an assistant professor of mechanical engineering at Carnegie Mellon University whose research in soft robotics focuses on stretchable skin-like materials containing sensors. “One limitation of working with soft-material robotics is that they’re soft; they can’t produce the high pressures you get with heavy machines, so you’re left with machines that provide only fairly moderate pressures. This makes it difficult to achieve dramatic deformations. If you use a robotic skin as an assistive medical device on a human, it can monitor motion. But with advancements like the buckliball, the skin may even be able to actively change its shape and directly help with motor tasks.”

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