Transforming architectures inspired by origami

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Paper folding is found across cultures for both aesthetic and functional purposes, with its most widely recognized exponent being the ancient art form of origami. More recently, there has been an upsurge of interest for translating origami designs into mathematics, natural sciences, engineering, and architecture. Across these different fields, origami is becoming a fountain of inspiration for new reconfigurable and multifunctional materials and structures. However, the use of origami designs as engineering elements is typically compromised by limitations in structural performance. A new study by Filipov et al. (1) presents an innovative approach for the design of strikingly rigid deployable structures. Their strategy is based on tubular building blocks, which are themselves built on Miura-ori; a regular folding pattern that maps a flat sheet into a one degree-of-freedom deployable structure (2). Two neighboring Miura tubes can be set in a zig-zag ("zipper") arrangement; together, the pair is remarkably stiff and effectively possesses a single degree of freedom by resisting other bending and twisting modes. These zipper tubes can then be combined to generate other structures, including more complex tubular systems and cellular assemblies. In Fig. 1 *A* and *B*, we present two particular examples from their study: a model bridge with load-bearing capacity and an architectural canopy that can be deployed to cover a wide span. Filipov et al. (1) borrow well-established tools from structural mechanics that are commonly used in civil and mechanical engineering and port them to this new emerging field of origami-inspired design.

Much of the recent research inspired by origami spans across fields, from mathematics, physics, and computer science to materials engineering, biotechnology, aerospace, and architecture. In mathematics and computational origami, the kinematics is usually simplified by considering rigid panels (also known as rigid foldable origami), with a focus on geometry and topological considerations (3–5). There is a substantial body of literature in this domain (6) and powerful simulations tools have been developed to produce remarkably complex crease patterns for origami (7). A drawback of these approaches is that they tend to exclude considerations on mechanical properties, which are required if we are to predict the mechanical response of origami structures. With the goal of rationalizing the coupling of the mechanics and geometry of origami, the physics and mechanics communities has stormed the field with great interest. The epicenter of the activity is on configurations based on the Miura-ori pattern and revolves primarily around issues related to the strong geometrically nonlinear behavior with multistability (8), tunable metamaterials (9), and self-assembled structures at different scales (10). On the robotics and fabrication front, there have also been significant advances in programmable foldable sheets (11), printable self-foldable robots (12), and self-folding microstructures and nanostructures (13), to mention just a few examples.

Starting from a structural mechanics viewpoint, Filipov et al. (1) base their study on techniques originally developed for frame structures (14) that have been adapted to study the mechanics of foldable structures by relaxing the condition of rigidity of the planar faces (15). Here, origami was modeled as a pin-jointed truss structure and each fold represented by a bar element,

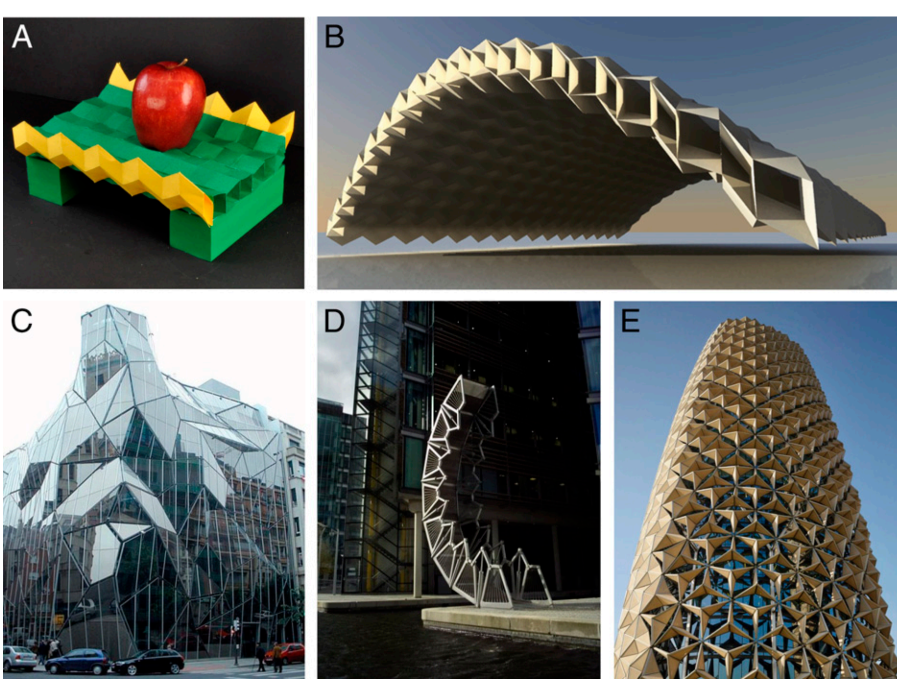

Fig. 1. Origami-inspired engineering. (*A*) Model bridge designed by Filipov et al. (1) comprising a series of zipper-coupled tubes. (*B*) Computer-generated architectural canopy. Adapted from ref. 1. (*C*) Headquarters of the Basque Health Department, Bilbao, Spain. (*D*) The Rolling Bridge, London, United Kingdom. (*E*) Deployable curtain wall for indoor light control, Al Bahr Towers, Abu Dhabi, United Arab Emirates. Images courtesy of (*C*) Wikimedia Commons/Zarateman, (*D*) Steve Speller (photographer) and the Heatherwick Studio, and (*E*) Christian Richters (photographer).

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jointed at the vertices. Including additional bars to triangulate the faces prevents the existence of trivial internal mechanisms and provides a means to approximate the bending stiffness of the faces. The compatibility and stiffness matrices of this truss frame yield the mechanical response of the origami structure.

Efforts in connecting origami and engineering may be more thoroughly categorized under three classes of origami-inspired structures: (*i*) origami-looking, (*ii*) origami-shaped, and (*iii*) deployable (that use origami patterns). We proceed by providing examples in the context of civil engineering and architecture. First, origami-looking structures, such as the curtain walls of some buildings (Fig. 1*C*), are static and lightweight, and resemble origami geometries, merely for aesthetic purposes. Second, origami-shaped structures make use of controlled folds to achieve enhanced and sometimes tunable mechanical properties (8, 9, 16). The sawtooth roof of many factories is a simple example that simultaneously provides enhanced out-of-plane stiffness of the roof diaphragm, as well as superior natural light and ventilation conditions in their interior.

Third, truly origami-inspired structures are fully deployable with folding patterns that are derived from origami (in contrast to other deployable strategies, such as scissor mechanisms). These structures are typically built with rigid elements connected by mechanical components (hinges and joints), the simplest example of which is the regular door. (Self-) foldable devices at the microscale and nanoscale (13) tend to follow this strategy and comprise relatively simple networks of plates and hinges, albeit powerful and versatile. One major advantage of these designs is that they can be built of a simple piece of material. At the large scale, origami-inspired structures have been explored less but offer tremendous opportunities that are yet to be fully leveraged. Two recent inspiring examples are the Rolling Bridge at the Paddington Basin in London, United Kingdom (Fig. 1*D*), and the deployable curtain wall of the Al Bahr Towers in Abu Dhabi, United Arab Emirates, for on-demand tunable shading of sunlight (Fig. 1*E*). Origami-inspired structures obey kinematics similar to that of traditional origami but are also fundamentally different in that they are typically not made of a continuous piece of material. Moreover, their relatively low rigidity has limited their widespread use as structural elements.

The work of Filipov et al. (1) suggests feasible engineering designs that are inspired by origami, with simultaneous deployable and load-bearing characteristics. Starting from the well-known Miura-ori, the authors have devised foldable tubes that can be used as a modular structural element. It is important to highlight that these tubes are made of continuous sheets of material. Following an approach similar to that in ref. 15 for their new designs, the study demonstrates how assembling these tubular designs in a zig-zag ("zipper") manner significantly increases the rigidity of all deformation modes, except the one for deployment. As a result of an eigenvalue analysis, they rationalize the enhanced stiffness of their tubular structures by a robust band gap that is continuous over the whole extension phase. This improved mechanical performance arises from the difference between bending versus stretching energies of the folds and plates, as well as the high moment of inertia of the underlying tubular building blocks. Together, these effects can make the other deformation modes up to two orders of magnitude stiffer than the deployment mode. Having identified and characterized the zipper-coupled tube as a base unit, the authors then apply it to a variety of designs of cellular structures that can sustain significant mechanical loading. A bar hinge model is derived and contrasted against finite element simulations, with excellent agreement, and some of the designs are instantiated by analog physical models made out of paper. Three of the elegant examples considered include (*i*) the zipper-coupled tube that can be deployed with a single degree of freedom through actuation from one of the boundaries, (*ii*) a bridge-like structure (Fig. 1*A*), and (*iii*) a deployable architectural canopy (Fig. 1*B*). The intrinsic band gap can be exploited for structures that deploy or in static configurations. A hybrid approach may also be followed such that the structure is deployed up to a target point, until the system self-locks with superior mechanical properties compared with those of the deployment stage.

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Structural origami, such as the examples studied by Filipov et al. (1), are bound to lead to innovative metamaterials and structures with unprecedented functional and mechanical properties, across scales. This may be the straw that will break the door for load-bearing applications of origami-inspired designs and unfold their use in architecture and civil engineering.

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