PNAS COMMENTARY

Unfurling packed-flat tubes into self-locked stiff structures

Damiano Pasini[a,1]

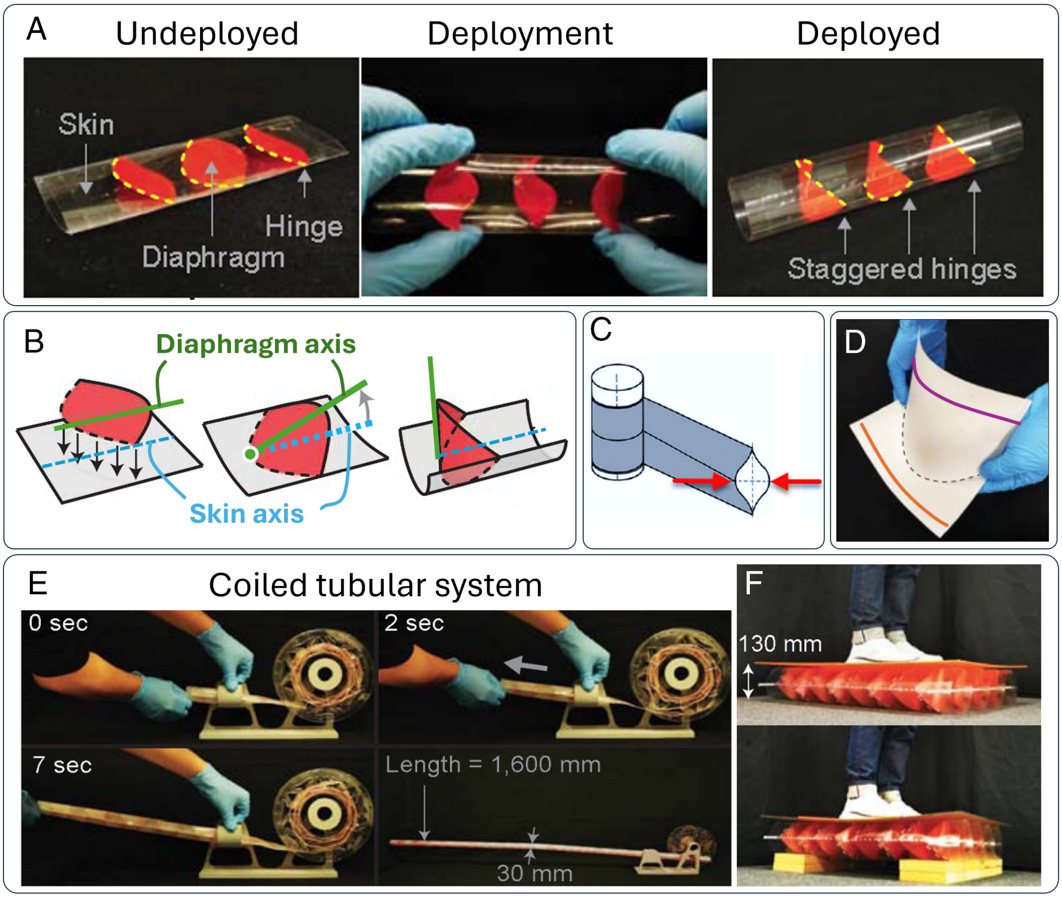

Fig. 1. Deployable tubular structures. (*A*) Deployment of two skins with internal stiffeners into a rigid tube with stable partitions (2). (*B*) Reorientation of the diaphragm axis during deployment from parallel to perpendicular to the skin axis (adapted from ref. 2). (*C*) Example of rollable and extendible tubular boom used in space. (*D*) Sheet folding around a curved crease (adapted from ref. 2). (*E*) Coiled tube with stiffeners gradually pulled through an annulus to reach a locked and stiff deployed state (2). (*F*) A collection of deployed stiff tubes forming the core of a lightweight load-bearing panel (2). Image credit: Adapted from ref. 2.

Structural deployment denotes a transformation that typically produces substantial changes in shape and size, often involving volumetric reconfiguration. Structures that deploy from a compact to an expanded form are ubiquitous in both the natural and artificial realms. The petals of several flowers, e.g., poppy and dandelion, pack and unpack in response to an external stimulus such as light. The leaves of hornbeam, beech, and other plants fold and roll inside the bud before uncurling. The wings of some insects, such as locusts, offer another instance, where the wings at rest are highly retracted and crumpled before extension for flight (1). Analogously, our technological world is rich in familiar examples. Umbrellas, tents, foldable furniture and staircases, telescopic gear, and rollable shades, to name a few, permeate our everyday lives. This capacity to collapse an object into a small volume for storage and/or ease transport before unfurling it into an operational configuration has been pursued for several decades across sectors and length scales from aerospace and architecture to medicine and soft robotics. A new study by Lee et al. (2) presents a clever strategy to transform a flattened floppy cylinder into a stiff tube with interior reinforcements that do not sag under external forces. The deployment process from soft to stiff is reversible and starts from two rectangular skins, i.e., the flattened cylinder, that sandwich-shaped stiffeners, namely diaphragms (Fig. 1*A*). One

Author affiliations: [a]Department of Mechanical Engineering, McGill Institute for Aerospace Engineering, McGill Institute for Advanced Materials, McGill University, Montreal, QC H3A0C3, Canada

Author contributions: D.P. wrote the paper.

The author declares no competing interest.

See companion article, "Self-locking and stiffening deployable tubular structures," 10.1073/pnas.2409062121.

[1]Email: damiano.pasini@mcgill.ca.

Published November 11, 2024.

edge of each diaphragm is connected to one skin along curved segments and staggered to form living hinges (yellow dash) around which each stiffener can bend and rotate during deployment. In the initial state, skins and diaphragms are flat with parallel axes (Fig. 1*B*), but under manual pressure on the exterior skin surfaces, the internal diaphragms start to bend and gradually rotate until their axes become perpendicular. At the deployed stage, the diaphragms are bent into curved shells that snug tightly against the opposing skins, preventing reverse motion due to collision and conferring structural rigidity to the entire tube.

A new study by Lee et al. presents a clever strategy to transform a flattened floppy cylinder into a stiff tube with interior reinforcements that do not sag under external forces.

Strategies to endow a system with deployability are numerous, diverse, and often—but not always—dependent on length scale and application requirements. What differentiates one from the other is the interplay between the type of deployment mechanism and the architecture of the constituents. The former can be loosely classified as purely rigid, entirely flexible, and a combination thereof (rigid-flexible) (3). The latter refers to the morphology formed by the constituent elements, such as struts in trusses, creases in origami, and slits in kirigami, as well as their material and geometry. Purely rigid mechanisms deploy through either axial translation of coaxial members, such as in telescopic masts, or relative motion of rigid bodies connected by revolute joints forming linkages, i.e., kinematic chains with mainly one degree of freedom. Rigid bodies and revolute joints here are intended in general terms regardless of dimensionality. In a planar scissor, for example, they become struts and pin joints (4), and in three dimensions, they act as robs and revolute joints that can deploy a spatial truss system (5). In contrast, the deployment of an entirely flexible mechanism is controlled by the compliance of the constituents, either by using them standalone (flexible rods, tape springs, and soft membranes) or in combination. Coilable extendible masts, inflatable structures, and wrappable membranes are examples of entirely compliant systems (6, 7). Others include nonrigid folding patterns, such as Kresling and Yoshimura origami (8, 9), where the flexibility of both faces and creases strongly contribute to their reconfiguration. Between the two are rigid-flexible mechanisms, where both rigid and flexible elements make up a deployable structure. For example, rigid links forming a truss can be partitioned with either flexible joints, pretensioned cables, or compliant membranes, as demonstrated by solar arrays consisting of a structural lattice with flexible joints, umbrella reflectors with cable net, and antenna reflectors with rigid exoskeleton and reflective meshes (4). In the realm of rigid-foldable origami, the rigid links take the form of nondeformable faces that deploy around their creases, acting as living hinges. Regardless of the deployment mechanism and architecture type, the design of deployable structures typically requires reconciling two conflicting requirements: ease unpacking from a folded form versus rigidity once deployed.

With a focus on a particular system, a thin-walled deployable tube, Lee et al. (2) address the fundamental challenge of balancing high expandability for deployment with high stiffness for operation in service (10). Typical concepts address the former by relying on the high deformability of their base materials. A familiar example is a bistable tape spring ruler, which is stable in both its fully coiled and fully extended states. Similarly, in space systems, coilable systems and foldable tubes with cut-out slots support large-scale membranes or reflectors in space systems (11). Another classic example is a rollable boom (Fig. 1*C*), whose hollow cross-section is designed to collapse and coil up for compact storage before full extension (3). While easily uncoilable under a pull, the fully deployed tube offers low resistance to transversal forces (red arrows) applied to its lateral surface, making it prone to collapse. A common strategy to reinforce thin-walled cross-sections is to insert internal stiffeners that improve lateral resistance and provide internal stability (12). Once fabricated, however, these embeddings confer a permanent rigidity that cannot be suppressed, hence preventing any form of collapsibility and coilability. The work by Lee et al. (2) resolves the apparent conflict by desynchronizing the emergence of collapsibility and stiffness in sequential stages: first, high floppiness for early-stage unfurling, and then, locking to secure a rigidly deployed state (Fig. 1*A*). The chief enabler is the diaphragm geometry, which plays a subtle yet essential role in interacting with the skins during the deployment process. The diaphragm shape and motion are inspired by the folding of a curved crease, where a curved crease line (Fig. 1*D*–dash line) in a flat sheet gives rise to a curved folding motion bestowing distinct curvatures (orange and purple curves in Fig. 1*D*) to the initially flat shape. Despite its resemblance to curved-crease origami, the rotating curved diaphragms cannot be strictly defined as such because they are not generated from a continuous sheet with creases. Rather, they are appendages attached to the flat skin via a hinge layer and forming a compliant mechanism. In addition, their assemblage foregoes the property of developability as it cannot be flattened without overlap or separation.

To reach a locked deployment, a subtle physical mechanism of interaction takes place between the skins and diaphragms. The manual pressure exerted on the tube exterior (Fig. 1 *A*, *Middle*) serves to confine the diaphragms, reduce the internal space, and create geometric interference with the skins under changing boundary conditions. The diaphragms undergo elastic shell buckling during their rotational motion till they snap into a final unbuckle shape that is locked due to collision against the skin. This strategy for self-locking stands apart from other passive and active (relying on an external stimulus) strategies harnessed in origami and other metamaterials (13–20). Existing strategies mainly rely on principles of collision or energy barrier. The former refers to the emergence of contact between kinematically interacting elements, preventing further motion beyond a specific point. This ensures stability once deployed and is often leveraged to provide load-bearing capacity. The latter denotes the creation of stable states induced by bistable snap-through and separated by an energy barrier that maintains a stable shape without any external mechanisms. The self-locking mechanism that takes place in the deployed tube by Lee et al. (2) advances the field because it leverages both methods in a complementary manner: The rotating buckled diaphragms snap into a stable free-stress state due to geometric interference, while their collision with the skin secures them in place, preventing further rotation. As a result, the interior tube is braced with stable and locked partitions that supplement the tube with lateral rigidity.

After unveiling the physical mechanism of self-locking, the authors demonstrate its implications, showcasing elegant examples with promising advantages for applications in aerospace, robotics, and structural engineering. The unfurling of a coilable flattened tube (Fig. 1*E*) with internal stiffening can resolve the lack of lateral rigidity of some rollable masts used in space (Fig. 1*C*). The inflatable deployment of a power-free shape retention system can maintain its final deployed state without a pressure supply, hence being less vulnerable to puncture and bursts. Demonstrations of metamaterial architectures comprising a grid with multiple tubes are also given in the form of an adaptive structure with direction-dependent stiffness, a deployable cantilever boom, and a load-bearing panel for large-scale construction (Fig. 1*F*). As the field at the intersection between deployable structures and reconfigurable metamaterials is gaining momentum, the study of Lee et al. (2) is poised to be an inspirational landmark for next-generation lightweight systems that can be packed flat and pop up into load-bearing materials for applications across industries and length-scale.

1. J. F. V. Vincent, Deployable structures in nature: Potential for biomimicking. *Proc. Inst. Mech. Eng. Part C* **214**, 1–10 (2000).
2. T.-U. Lee *et al.*, Self-locking and stiffening deployable tubular structures. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2409062121 (2024).
3. X. Zhang *et al.*, Deployable structures: Structural design and static/dynamic analysis. *J. Elast.* **146**, 199–235 (2021).
4. L. Datashvili, Foldability of hinged-rod systems applicable to deployable space structures. *CEAS Space J.* **5**, 157–168 (2013).
5. T. Kitamura, K. Yamashiro, A. Obata, M. Natori, "Development of a high stiffness extendible and retractable mast "Himat" for space applications" in *AIAA 31st Structures, Structural Dynamics and Materials Conference* (American Institute of Aeronautics and Astronautics, Long Beach, CA, 1990).
6. S. Pellegrino, *Deployable Structures* (*International Centre for Mechanical Sciences*, Springer, Vienna, 2001), **vol. 412**.
7. X. Ma *et al.*, Design, modeling, and manufacturing of high strain composites for space deployable structures. *Commun. Eng.* **3**, 78 (2024).
8. B. Kresling, "Natural twist buckling in shells: From the hawkmoth's bellows to the deployable Kresling pattern and cylindrical. Miura-ori" in *Proceedings of the 6th International Conference on Computation of Shell and Spatial Structures*, J. F. Abel, J. R. Cooke, Eds. (IASS-IACM, Cornell University, Ithaca, NY, 2008), pp. 12–32.
9. M. Schenk, A. D. Viquerat, K. A. Seffen, S. D. Guest, Review of inflatable booms for deployable space structures: Packing and rigidization. *J. Spacecr. Rockets* **51**, 762–778 (2014).
10. S. A. Schlothauer, P. Ermanni, Stiff composite cylinders for extremely expandable structures. *Sci. Rep.* **9**, 15955 (2019).
11. J. Block, M. Straubel, M. Wiedemann, Ultralight deployable booms for solar sails and other large gossamer structures in space. *Acta Astronaut.* **68**, 984–992 (2011).
12. P. Khanchehzar, A. Niknejad, S. G. Amirhosseini, Influences of different internal stiffeners on energy absorption behavior of square sections during the flattening process. *Thin Walled Struct.* **107**, 462–472 (2016).
13. E. T. Filipov, T. Tachi, G. H. Paulino, Origami tubes assembled into stiff, yet reconfigurable structures and metamaterials. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 12321–12326 (2015).
14. Z. Zhai, Y. Wang, H. Jiang, Origami-inspired, on-demand deployable and collapsible mechanical metamaterials with tunable stiffness. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 2032–2037 (2018).
15. S. J. Kim, D. Y. Lee, G. P. Jung, K. J. Cho, An origami-inspired, self-locking robotic arm that can be folded flat. *Sci. Robot.* **3**, eaar2915 (2018).
16. A. Jamalimehr, M. Mirzajanzadeh, A. Akbarzadeh, D. Pasini, Rigidly flat-foldable class of lockable origami-inspired metamaterials with topological stiff states. *Nat. Commun.* **13**, 1816 (2022).
17. D. Melancon, B. Gorissen, C. J. García-Mora, C. Hoberman, K. Bertoldi, Multistable inflatable origami structures at the metre scale. *Nature* **592**, 545–550 (2021).
18. E. W. Hawkes, L. H. Blumenschein, J. D. Greer, A. M. Okamura, A soft robot that navigates its environment through growth. *Sci. Robot.* **2**, 3028 (2017).
19. L. Wu, D. Pasini, Zero modes activation to reconcile floppiness, rigidity, and multistability into an all-in-one class of reprogrammable metamaterials. *Nat. Commun.* **15**, 3087 (2024).
20. V. Deshpande, Y. Phalak, Z. Zhou, I. Walker, S. Li, "Golden Ratio Yoshimura" for meta-stable and massively reconfigurable deployment. *Philos. Trans. A Math. Phys. Eng. Sci.* **382**, 20240009 (2024).