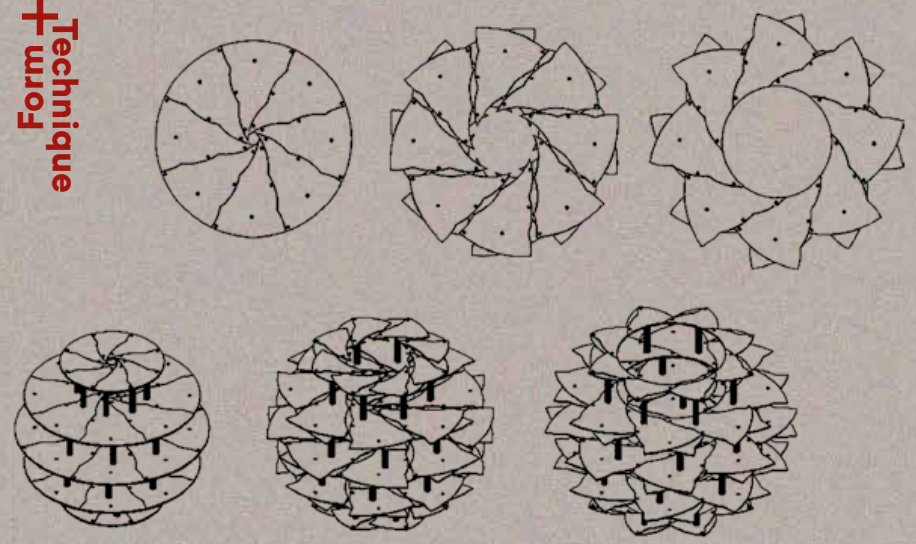
Form + Technique



Deployable Structures

Deployable structures can expand and contract due to their geometrical, material and mechanical properties – offering the potential to create truly transforming environments. This book looks at the cutting edge of the subject, examining the different types of deployable structures and numerous design approaches.

Filled with photographs, models, drawings and diagrams, *Deployable Structures* is packed with inspirational ideas for architecture students and practitioners.

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ESTHER RIVAS ADROVER

Form + Technique

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CONTENTS

FOREWORDS

In *The Seven Lamps of Architecture*, written in 1849 at the height of the Industrial Revolution, John Ruskin drew a boundary around the definition of architecture that rejected the then-emerging steel structures as a corrosive influence on the pure principles of timeless static stone.

Le Corbusier exploded this definition in the early twentieth century, declaring the house to be a 'machine for living' and setting the scene for a new architecture that would embrace the emerging technologies.

In the 1960s Ron Herron of Archigram proposed the 'Walking City' and in the BBC's 1989 television series *Building Sites* Norman Foster chose the jumbo jet as his favourite building.

With this trajectory, a book reviewing the influence of deployable structures on architecture seems like a natural progression. Esther Rivas Adrover's opening sentence – 'This book is living proof of the intrinsic synergy that connects all life with architecture' – proposes an exciting new chapter in the history of the 'Mother of the Arts'.

Within this emerging field the author proposes a classification of deployable structures, providing an interesting basis for a structured approach to thinking about the typologies that have been developed and illustrating clearly the potential of a dynamic architecture.

Architects will find in this book many inspiring examples of ingenious ways of transforming structures to create a responsive, organic architecture. Structural engineers will be stimulated to equip themselves with a deeper understanding of how they can support the flights of fancy that will inevitably emerge from the architect's imagination, as they extend their palette to incorporate this challenging new technology.

TIM MACFARLANE, 08 NOVEMBER 2014.
Founder of Dewhurst Macfarlane and Partners in 1985
Founder of Glass Light and Special Structures in 2012

Open Esther Rivas Adrover's book and you have deployed it. It's the start of a fascinating trail from folding (*ori-*) paper (*-kami*) to unfolding buildings. The magic of nature's *ori* never fails me. The unfolding poppy petal conceals so much. Where do the creases go? The wings of a newly emerged butterfly will expand even when cut away from the insect's body. What tricks is nature showing us that we have yet to see?

Deployment is a basic attribute of living organisms, whether as growth (deployment of cells) or movement (stretch out your arm – you are deploying it!). Perhaps this is why deployment is such a fascinating topic: inert mechanisms and objects become live and moving. The bird, and the beetle alike, can protect its wings by folding them away and, in its new streamlined form, invade new areas; while the dragonfly, which can't fold its wings, has to fly and roost in open spaces. A moth can have red or yellow hindwings, folded beneath the forewings; when disturbed it deploys its camouflaging forewings and flashes bright warnings. And it feeds through a tube that it keeps coiled away beneath its head. Cunning systems of levers and joints open and close roofs and the mouths of fish. The elastic-powered pipe-fish can suck in its prey in milliseconds: now you see it … now you don't!

Maxwell's Lemma tells us that the lightest (and therefore cheapest) structure separates compressive and tensile elements: the prescription for tensegrity. So we find such structures in outer and in inner space – satellite masts and cells use the same principles to keep and extend their shape. Can we learn from Maxwell how to deploy our resources to greater effect? Is this Esther Rivas Adrover's most important message?

JULIAN VINCENT, 10 NOVEMBER 2014.
Professor of Biomimetics at the University of Bath

PREFACE

This book is living proof of the intrinsic synergy that connects all life with architecture. I have always believed that everything is connected: give me any two apparently disparate elements, and I will find a connection between them – and architecture. 'Syntegration' is a term that I propose as a portmanteau of 'synergetic' and 'integration', and it is explained in the final chapter of this book.

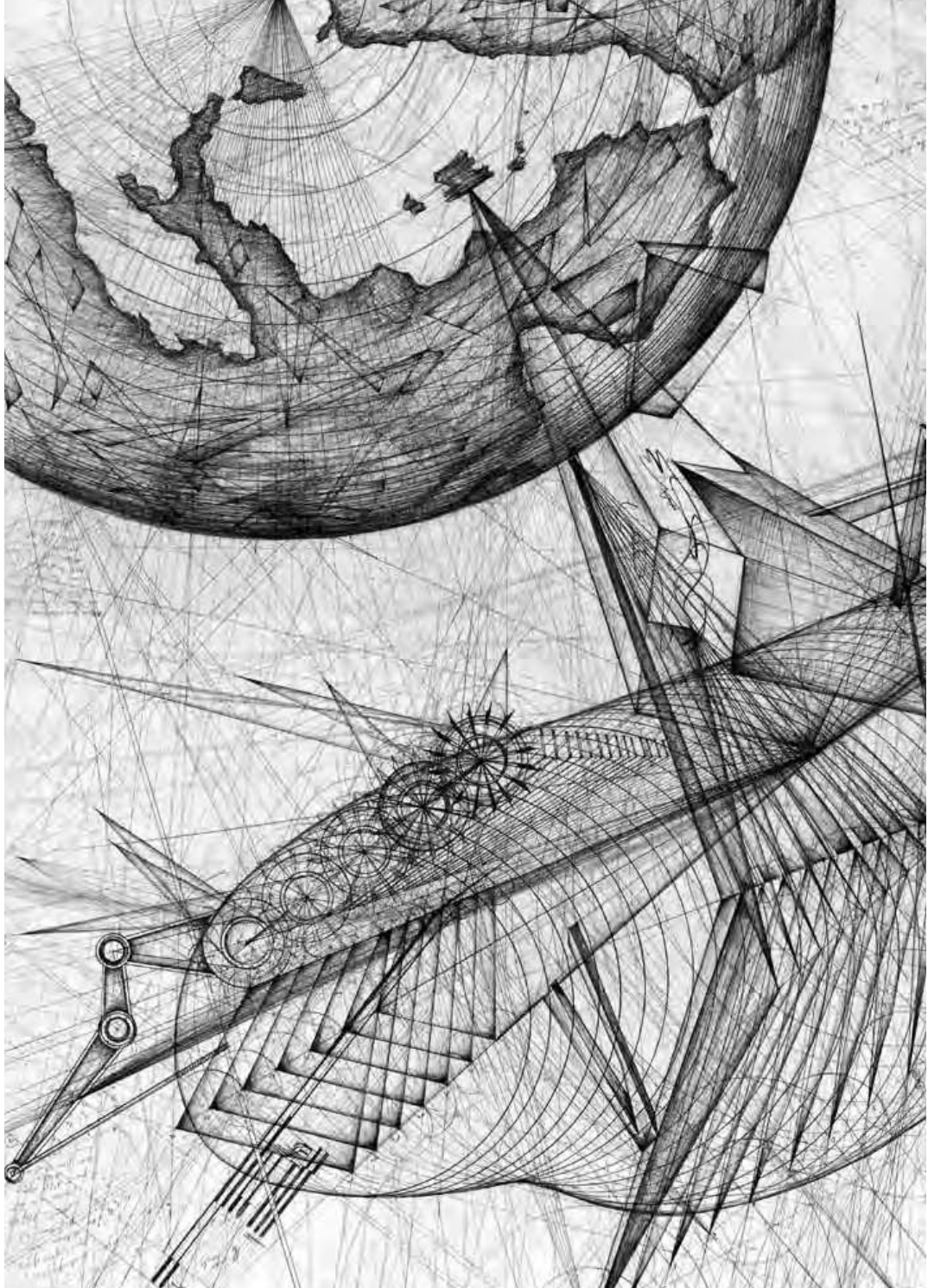
But what does a carnivorous plant have to do with architecture? The research conducted on this emerging field has taken various interesting turns, and a curious example is a fascinating study of the carnivorous plant *Aldrovanda vesiculosa* (see p139). However, despite my 'syntegric' approach, I never expected to become a member of the International Carnivorous Plant Society as part of this journey!

From my chair I have travelled to the International Space Station, where ingenious masts have been used to deploy solar arrays effortlessly. Solar-powered satellite systems can be up to 1 kilometre (0.6 miles) long, vast structures the size of London's Regent's Park orbiting in silence, in space.

From intricate structures floating in space to organisms 5 millimetres (0.2 inches) small living under water, one could say that *Deployable Structures* can take you to any part of the Earth and beyond, quite literally. It would seem as if deployable structures can acquire meaning almost universally. But how can we travel around such vast and open coordinates with a sense of direction? Can any map connect such apparently disparate subjects? And how does that reconcile with architecture? The key is in 'Geometric Syntegration'.

No one knows everything about anything, thus there is a great deal yet to be learned, and never more so than about the incongruous subject of Deployable Structures in Architecture.

Fig 1. Space Elevator, by Esther Rivas Adrover



INTRODUCTION

1

INTRODUCTION

Kinetic design and deployable structures have been used throughout history, but it was not until the beginning of the twentieth century that there was an emergence of thought inspired by the speed and technological advances of the Industrial Revolution. Movements such as Italian Futurism and schools such as the Bauhaus in Germany formed a cradle of ideas including kinetic principles that were explored in art, industrial design and architecture. These early explorations looked to challenge the establishment and its static convention, introducing the fourth dimension of Time as a key element of the process of transformation (RA 2014).

In the 1950s the aerospace industry took an interest in deployable structures, and today probably dominates the research in this field. Deployable structures have found many uses in this industry. Large structures such as satellites, telescopes, solar arrays and antennas have to be packaged in much smaller volumes in spacecraft, and once in space they are deployed.

Transportation has also been a concern for earth-bound applications. Today there is also strong research being carried out on mobile and rapidly assembled structures, mostly made of lightweight deployable structures, for adaptable building layers and for mobile or temporary applications, such as emergency shelters for disaster relief or military operations.

As this is still an emerging field, there is no single agreed definition of a deployable structure. These structures are sometimes referred to as foldable, reconfigurable, unfurlable, auxetic, extendible or expandable structures; however, they are perhaps best understood from these descriptions:

Deployable structures are structures capable of large configuration changes in an autonomous way.

TIBERT, 2002, P1

Such structures may pass from a 'folded' to an 'erect' state; and in many cases the component parts are connected throughout topologically, but alter their geometry through the process of deployment. In the process of deployment the initial mobility is transformed into a final rigidity. But that is by no means the only possible scheme for structural deployment.

CALLADINE, 2001, P64

By the application of a force at one or more points, it [a deployable structure] *transforms in a fluid and controlled manner. Despite such ease of transformation, these structures are stable, strong and durable.*

HOBERMAN, 2004, P72

The following is the author's own definition, which, it is believed, can be applied to any deployable type:

Deployable structures can expand and/or contract due to their geometrical, material and mechanical properties.

It would seem that deployable structures offer great potential for creating truly transforming, dynamic experiences and environments. Their lightness and transportability allow them to adapt to a society that is

constantly evolving and changing. Furthermore, these are reusable structures that make efficient use of energy, resources, materials and space, thus embracing the concept of sustainability.

Today, not only engineers and architects, but origami scientists, biomimetic researchers, astrophysicists, mathematicians, biologists, artists and others are studying, designing and developing applications for an extraordinarily vast range of deployable structures. This includes mechanisms that have yet to be tested in architectural applications and are relatively unknown outside their scientific field. From these, the author has selected a variety of deployable structures (or principles) believed to have potential for technology transfer into architecture and design. This research also includes built projects and prototypes that are deployable or contain deployable elements.

This selection of deployables has been classified in typologies, classes and subclasses, shown in a tree diagram created and used as a navigational map, on pages 18–19.

This is novel design space.

DEPLOYABLE TYPOLOGIES

We are at an early, formative stage of its development, where we know and understand relatively little; where experiments are of the essence; where there are plenty of surprises in store; and where we have a long way before we reach that remote state where 'principles' can be enunciated and the whole business reduced to a branch of axiomatics.

CALLADINE, 2001, P64

This emerging field is rapidly changing and evolving in unpredictable ways. Research in this subject is carried out in disparate scientific fields, which do not necessarily always meet. But equally, many deployable inventions come from people who are not formally carrying out scientific research, such as artists. It is a field where applications spread across unforeseeable territories such as medicine, aerospace, art, industrial design, stage design, architecture, portable architecture, military equipment, infrastructure, vehicle components and fashion. Simultaneously, there are deployable structures for which no application has been found. Beyond pragmatic applications, deployable structures can also have philosophical implications (explored in Responsiveness, p146). The nature of this subject also seems to lie on the border of other research lines, such as robotics and material science. The scale of deployable mechanisms can range from a few millimetres (such as a deployable stent graft that can open a narrowed artery to treat oesophageal cancer; Kuribayashi, 2004) to vast structures that extend over thousands of metres (such as solar arrays deployed in space). Furthermore, this is a subject where ideas emerge that are difficult to articulate

in words, and concepts can be best understood by acquiring experience with those deployable objects themselves, rather than entangling ideas in semantics and sophisms.

All these unattainably vast and incongruous parameters in which deployable structures operate seem to have made the task of giving an overall view of the subject a difficult one.

In 1973 Frei Otto classified typologies for deployable roof systems. Other classifications have been developed based on their one- or two-dimensional structural elements. There is also a classification by Ariel Hanaor for deployable structures capable of creating an enclosure, based on their morphology and their kinematic behaviour (De Temmerman et al, 2014).

The following is a holistic classification of a selection of deployables that offers an introduction to the subject and was carried out during my postgraduate studies in 2006 at the Oxford School of Architecture.

The principal issue that becomes apparent when attempting to classify deployable structures is that there are in fact two distinct approaches to developing a deployable. The first one is based on the structural components of the deployable mechanism: structures using this approach are classified under Structural Components. The second concentrates on movement and form inspired by various sources; these structures are described under the heading Generative Technique.

Two general types of Structural Components have been identified by experts in this field. These are Rigid Component Deployables and Deformable Component Deployables (You, 2006). These two main types have been used as a starting point for creating an assembly of typologies (including classes and subclasses) with potential for architecture and design. Other structural typologies cannot be classified within these two main existing types, thus other main types are created, Flexible Deployables and Combined Deployables.

Generative Technique includes deployable principles inspired by origami and paper pleat techniques, and systems inspired by biological phenomenology (a field known as biomimetics, i.e. morphology and motion in animals and plants). Generative Technique thus contains deployable studies which have originated through conceptual principles and can later be developed with numerous structural systems.

These deployables, which have until now remained as isolated pieces of research, have been placed in an architectural context by adding examples of built projects and prototypes that are deployable, or contain deployable elements, thus illustrating the potential of technology transfer of deployable concepts in architecture.

The tree diagram presented on the following page displays the selection and classification of over thirty deployables and it aims to highlight the diversity (not quantity) of deployable approaches and to introduce this emerging field to the reader.

It is impossible to approach the field of deployable structures with a single, general concept or theory.

MIURA AND PELLEGRINO, 1999

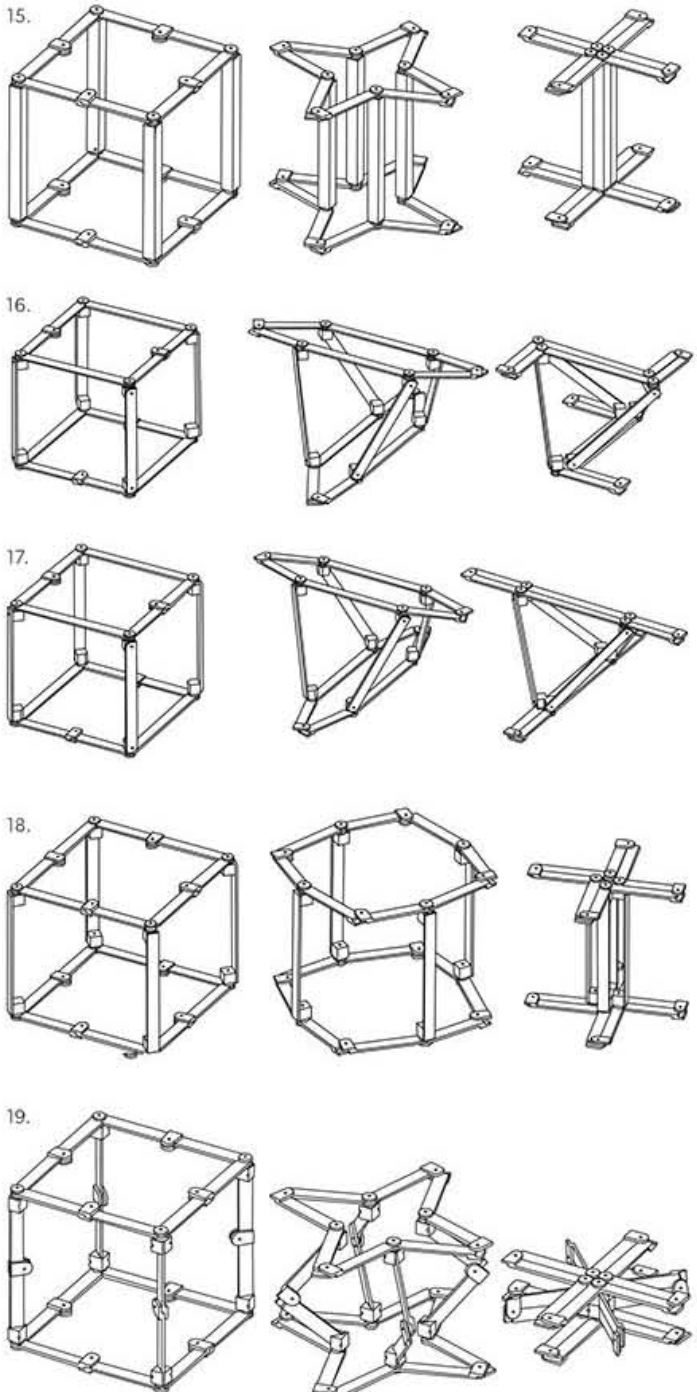


Fig 19. Variation of Fig 15 with identical symmetry but exhibiting a morphological change that allows greater compactness.

Deployable Structure based on Bennett linkages

Yan Chen and Zhong You
United States Patent Number: 6,941,704 B2. 2005.

Chen and You have developed a series of mechanisms that deploy smoothly into arches, towers and tend-like structures. These mechanisms are based on particular arrangements of 'Bennett linkages'. What follows is the study of one of those particular arrangements that deploys into a tent-like shape and has been patented in the US.

Figure 1 illustrates the deployment of a Bennett linkage. This mechanism was devised in 1903 by Geoffrey Thomas Bennett and consists of 4 rods connected in a loop with rotational joints that move in three-dimensional space.

The present invention consists of a particular geometrical array of interconnected rigid bars (Bennett linkages) connected by rotational joints forming a deployable structure that has a single degree of freedom (it can expand in one direction only), and that deploys in a curved manner.

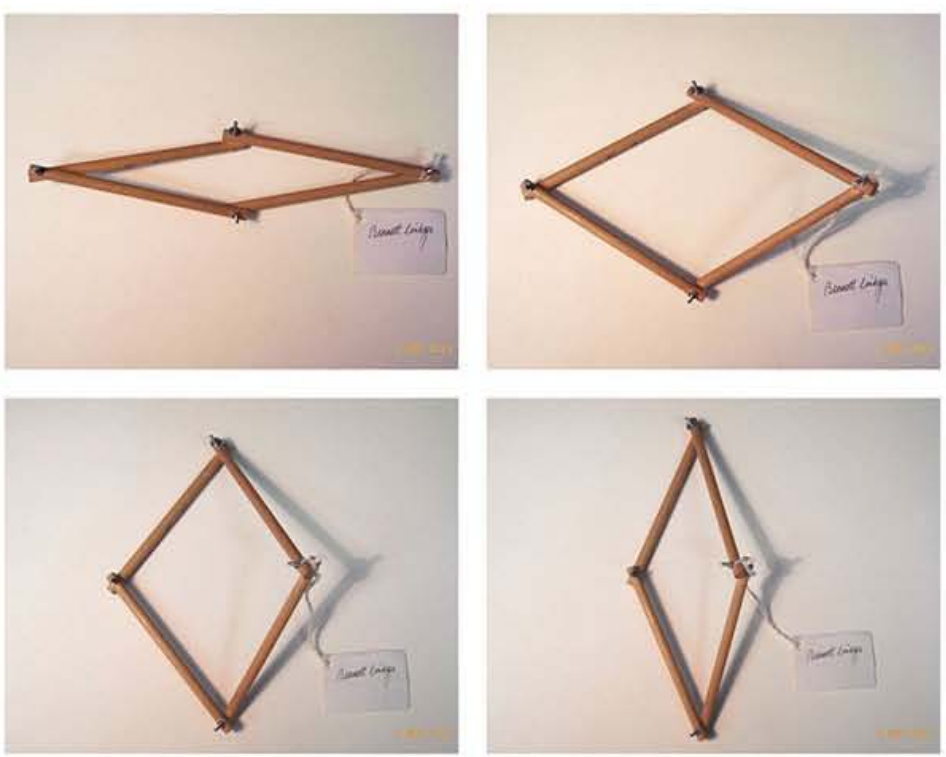


Fig 1. Deployment sequence of a Bennett linkage.

Rolling Bridge

Paddington Basin, London, UK, 2004
Heatherwick Studio

This deployable bridge consists of eight modules. Each module consists of two fixed trapezoidal steel frames either side of a section of deck at the base. Each module is hinged at its base to the next, with two pinned rigid struts linking the top of each trapezoidal frame. The actuators that produce the movement to deploy the structure are hydraulic rams linked to these pinned struts between frames. As the rams extend the rigid struts fold and the modules move causing the curling of the bridge. In its deployed state, the top of the frame and the struts between form the handrails, with the rams set into this. In the packaged state the bridge completely curls back onto itself forming a circle on one side of the bank.

Pinned struts forming handrail, with hydraulic ram actuator.

Deployment motion of the bridge.

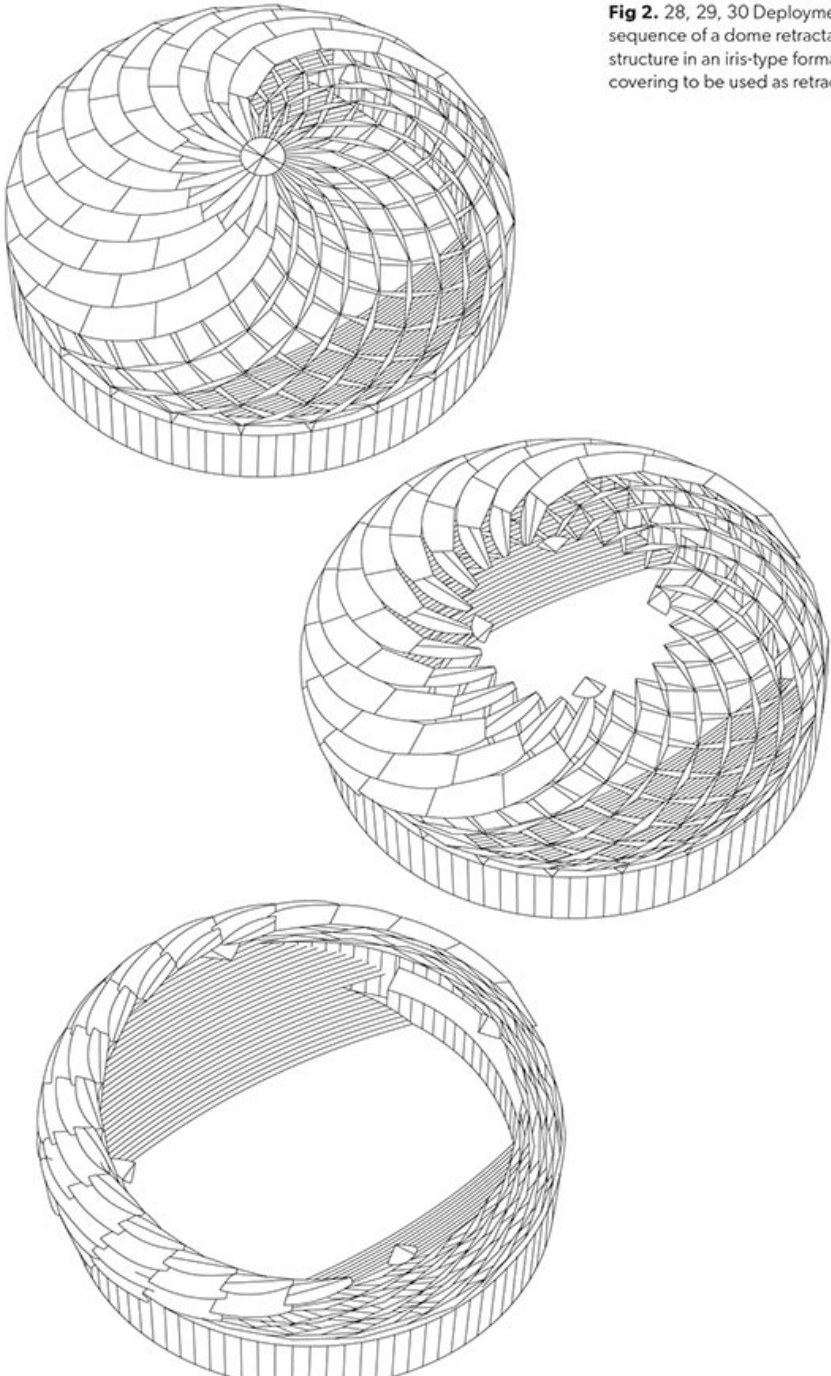


Fig 2. 28, 29, 30 Deployment sequence of a dome retractable structure in an iris-type formation with covering to be used as retractable roof.

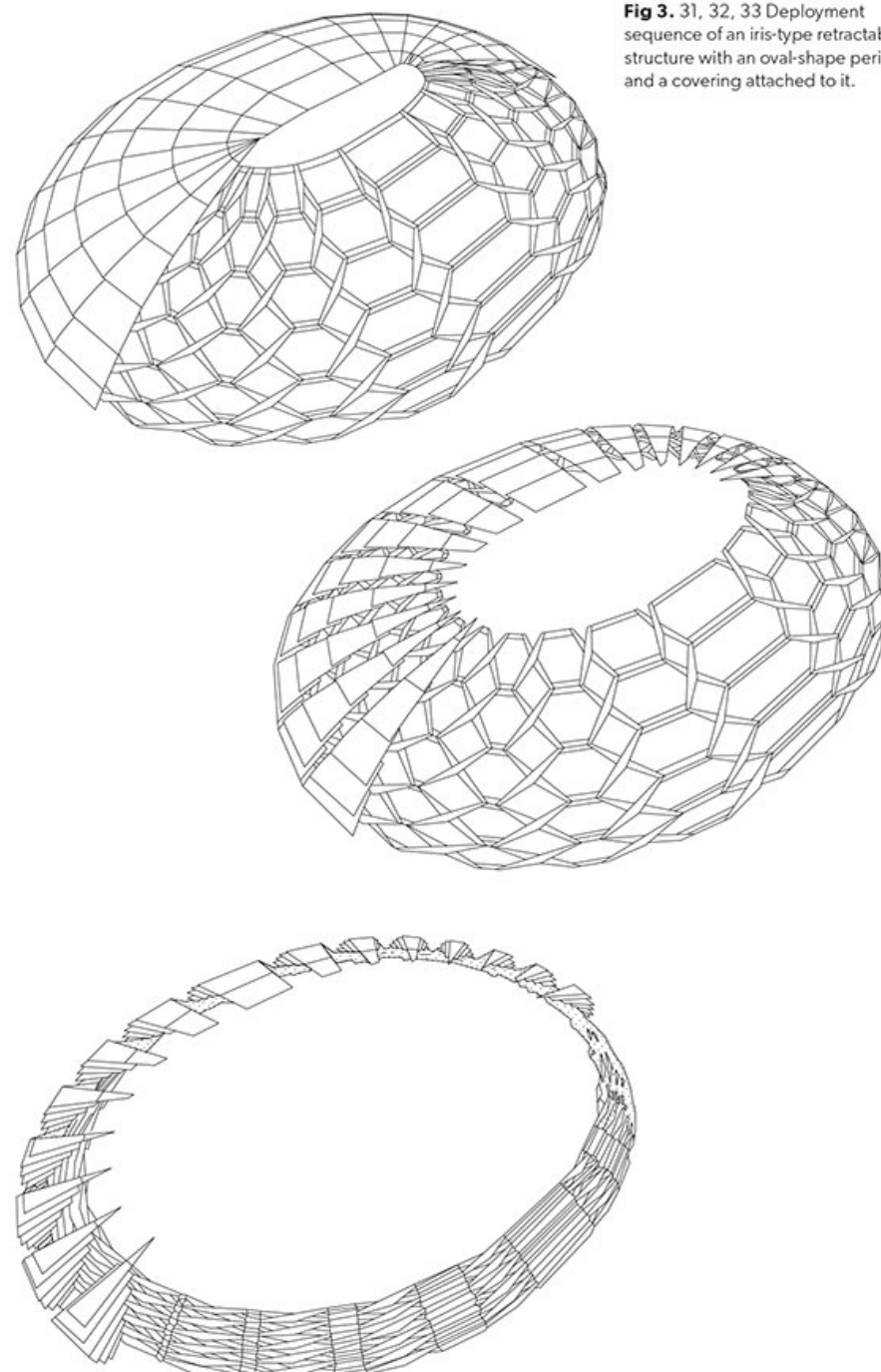


Fig 3. 31, 32, 33 Deployment sequence of an iris-type retractable structure with an oval-shape perimeter and a covering attached to it.

Push Button House 1

Adam Kalkin

This portable shipping container opens at the push of a button revealing an apartment with 6 different living areas: dining area, kitchen, double bed, bathroom, library, and a living room with a sofa.

The synchronized opening sequence utilizes 8 hydraulic rams to deploy all the side planes of the shipping container in less than a minute, leaving only as fixed elements the top and bottom planes and its 4 corner posts. Both long sides of the container rotate down, tripling the footprint of the main living area. The end sides deploy in two different motions, one opens as door pivots and the other extends horizontal floor and ceiling planes.

Opening sequence of the Push Button House 1.

Fig 5. Night view.
Fig 6. Sky view through opened roof.
Fig 8 (opposite). Roof plan (closed configuration).

Commonwealth aerostat

Delhi, India 2010
Architect Mark Fisher, Lindstrand Technologies, Elementenergy

The 2010 Commonwealth Games in Delhi saw the rise of large body emerging effortlessly into the air as the centre piece for the opening ceremony.

An aerostat gains its lift through its 'aerostatic' buoyant force by using a lighter than air gas, in this case helium. This aerostat was the largest in the world and was used as a 'white canvas' on which to project videos and images which would set the mood and rhythm of the ceremony. Its design is based on the geometry of a torus, which is a surface revolution generated by a circle revolving around a coplanar axis in three-dimensional space.

This gigantic aerostat (80 meters long, 40 meters wide and 12 meters height) was tethered to the ground with ropes connected to specific structural points.

Elementenergy was approached to provide assessment on the aerodynamic loads in order to ensure a safe deployment of the aerostat.

Fig 1. Daytime view of torus on site.
Fig 3. Night time view of the opening ceremony.

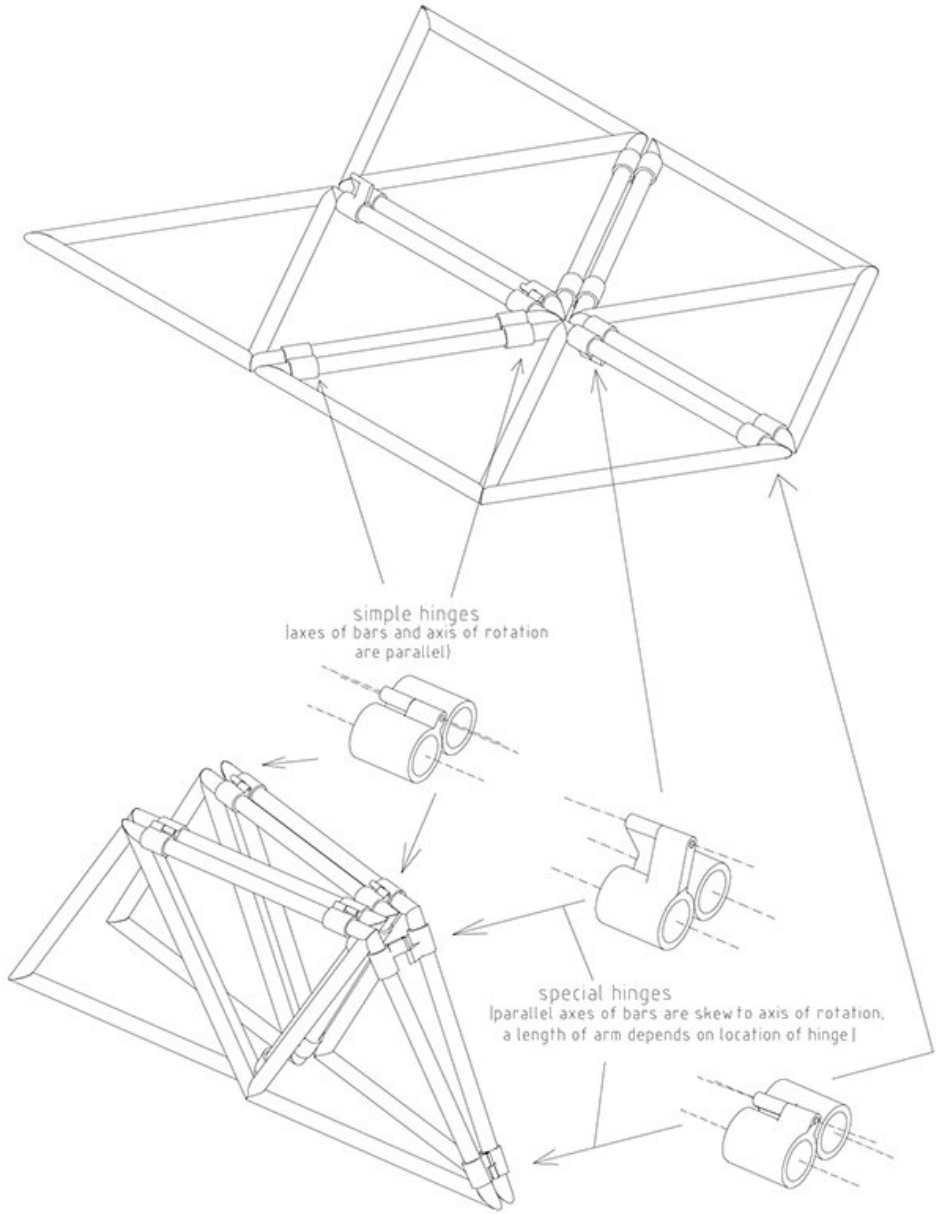


Fig 7. Principle of operation and construction of a two-way-fold deployable space truss build from planar frames connected by hinges.

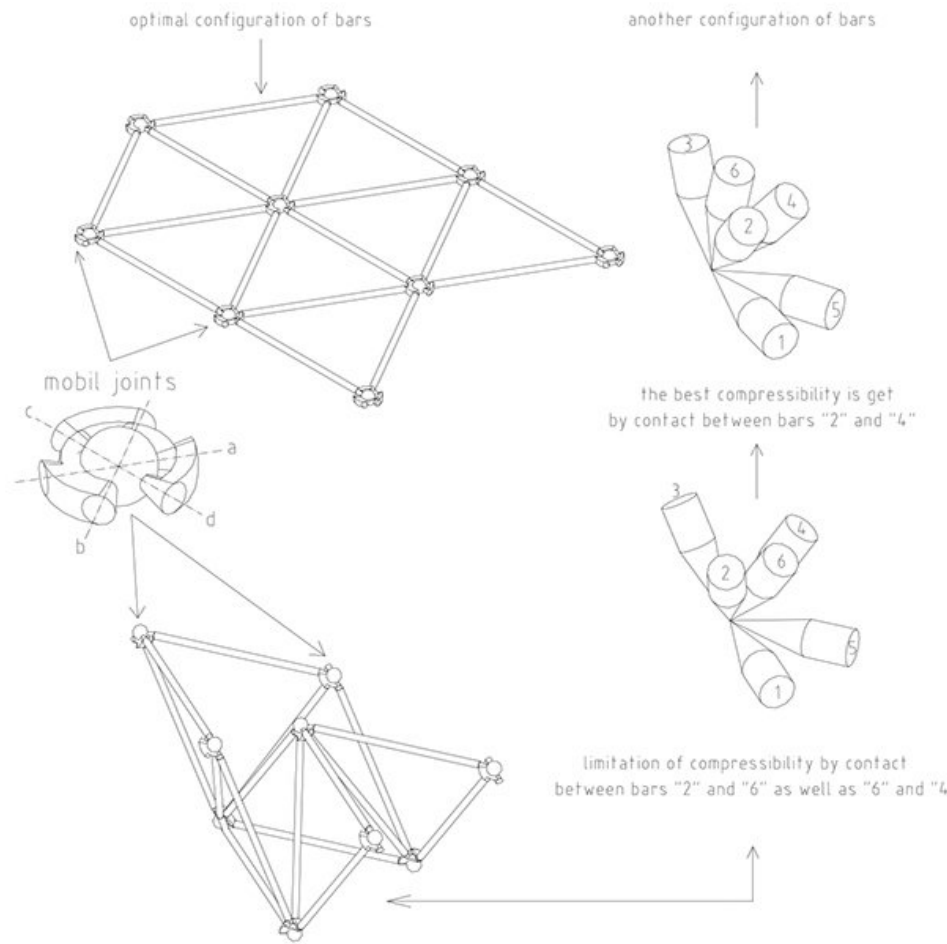


Fig 8. Construction and limitation of compressibility of two-way-fold deployable space truss build from bars connected by movable joints.

Two half-leaf models with different vein angles have been simulated and illustrated in a graph (Figure 4), one with and angle of 30 degrees and another with 85 degrees. Although both models are identical when fully unfolded, the unfolding process is significantly different. The leaf with 30 degree vein angle deploys gradually as the leaf unfolds and achieves a relatively large deployment in the early stages of unfolding. The one with a vein angle of 85 suffers a dramatic elongation in the final stages of deployment. Although both require more energy to deploy in the later stages of unfolding, the larger the vein angle is, the more energy will be required to fully unfold the leaf, while allowing a more efficient packaging in the initial stages.

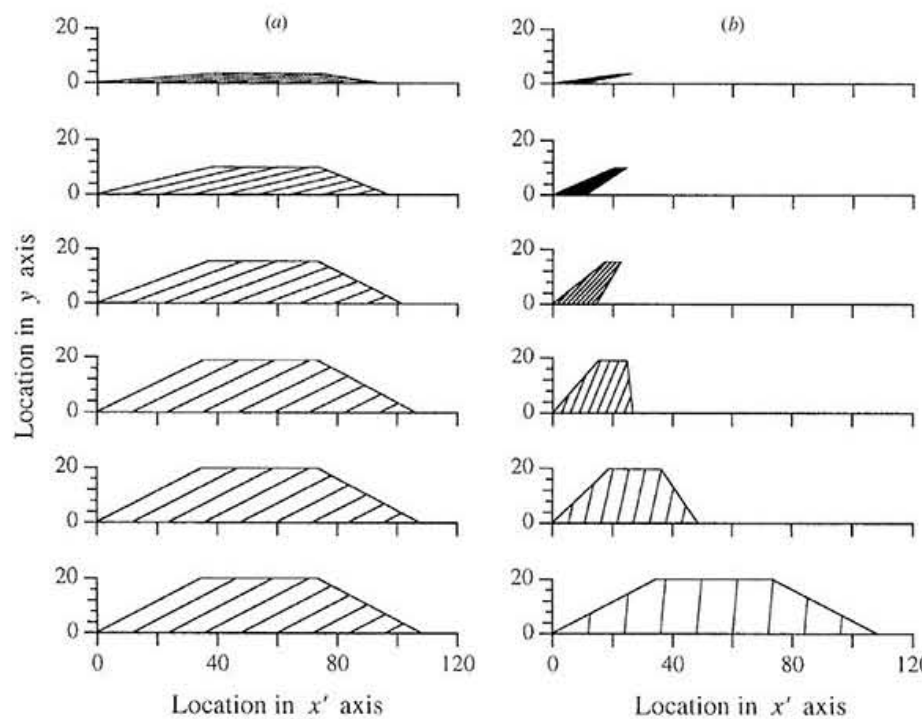


Fig 4. Unfolding process of half-leaves paper models with a vein angle of (a) 30 degrees and (b) 85 degrees. © Royal Society.

Fig 2 (opposite). Hornbeam branch that displays the opening sequence of the corrugated leaves.

Elastic Kinematics concepts for Adaptive Shading Systems

Simon Schleicher, Julian Lienhard, Simon Poppinga, Tom Masselter, Thomas Speck, Jan Knippers and Markus Milwich.

This multidisciplinary collaboration of biologists, engineers and architects has formulated a novel elastic mechanism inspired on plant biomimetics that can be used as shading for facades, without the restrain of current rigid shading components and without hinges or joints and therefore ideal for free form facades.

Plants have special anatomical and morphological characteristics that allow them to bend with a high degree of flexibility while retaining their structural stability. Although this is quite common in nature, the notion of pliable principles is rare in the field of architectural structures.

The following two case studies, one of a flower opening and the other of a leaf folding, will test their complex reversible elastic deformations and their potential application for architectural concepts.

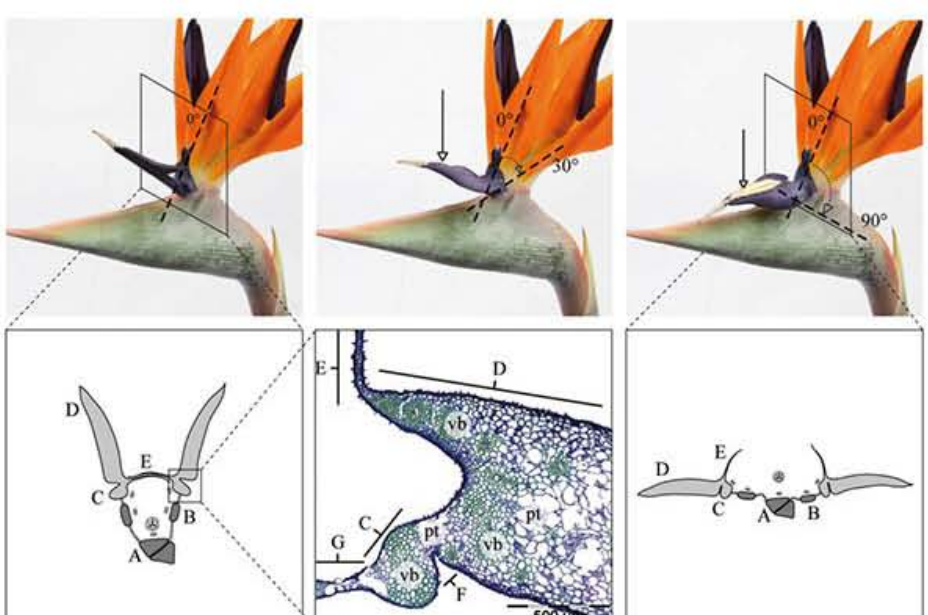


Fig 2. (a)-(c) Photos and (d)-(f) cross section of the elastic deformation of Strelitzia reginae. © IOPscience 2011 Bioinspir. Biomim. 6 045001.

Abstraction of the Elastic Kinematics of Strelitzia Reginae, Flectofin®

This case study examines the biological deformation of the Strelitzia reginae (also known as the Bird-Of-Paradise, Figure 1), which is then abstracted to a pliable structure and a flap named Flectofin® (Figure 3).

The Bird-Of-Paradise is ornithophilous, which means that birds transfer the pollen from one flower to another which leads to sexual reproduction. In order to reach the nectar, the birds land on the flower perch made of two joint petals or flaps. The weight of the bird causes the petals to bend down and sideways revealing the anthers and style (male and female sexual organs) while the pollen sticks to the bird. Once the bird leaves the flower, the open perch returns to its original closed state due to its elastic morphology.

Figure 2 shows the above principle and its morphology. The cross section of the perch reveals that there are three lateral reinforcing ribs at both sides connected with a thin flexible lamina. The lower ribs in both sides are fused together and the top ribs merge into a large flap lamina at either side that overlaps covering the anthers. This mechanism is reversible and durable; it is reliable enough to perform 3000 cycles without signs of deterioration.

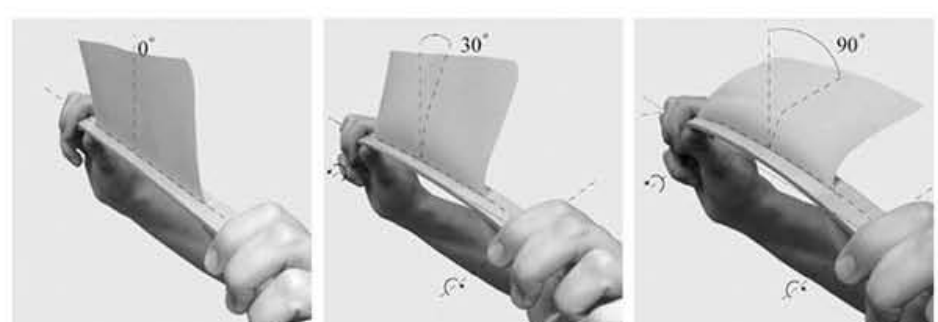
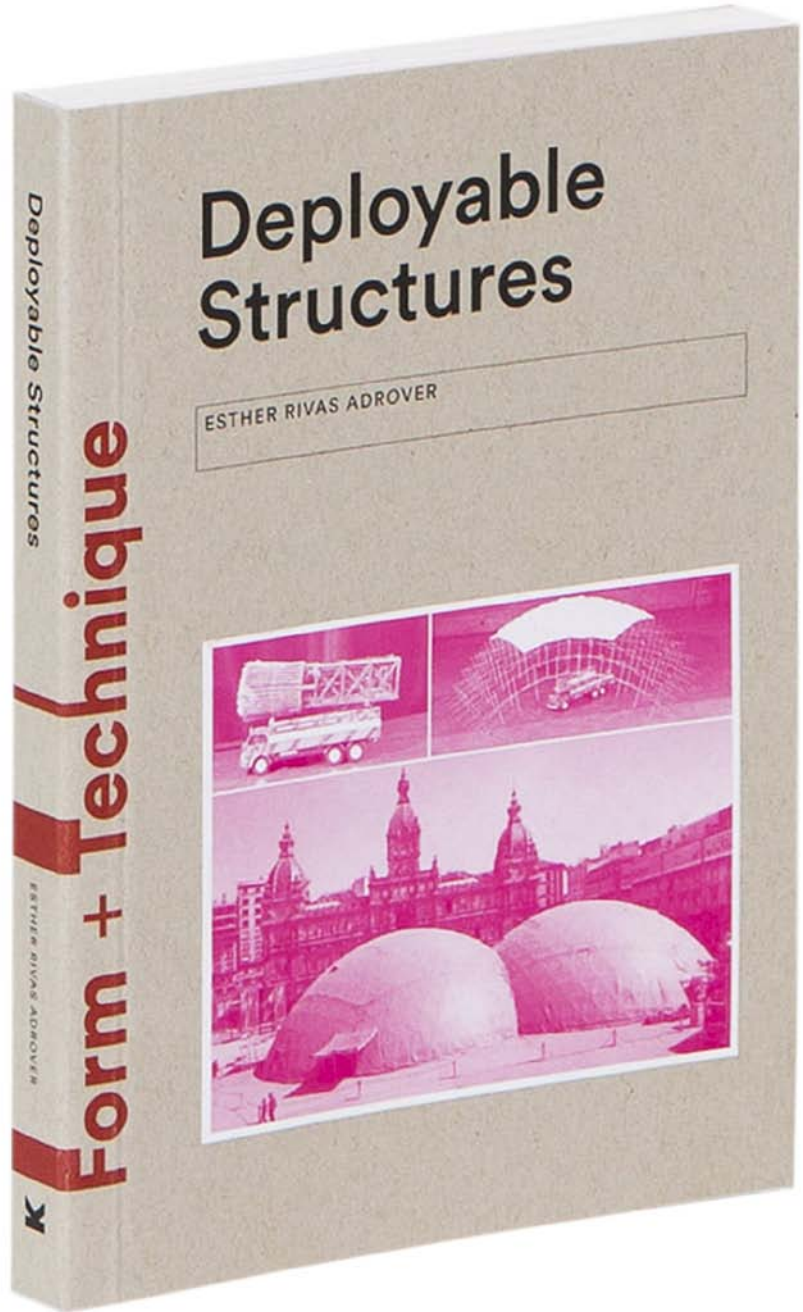


Fig 3. Basic physical model of Flectofin® principle. © IOPscience 2011 Bioinspir. Biomim. 6 045001.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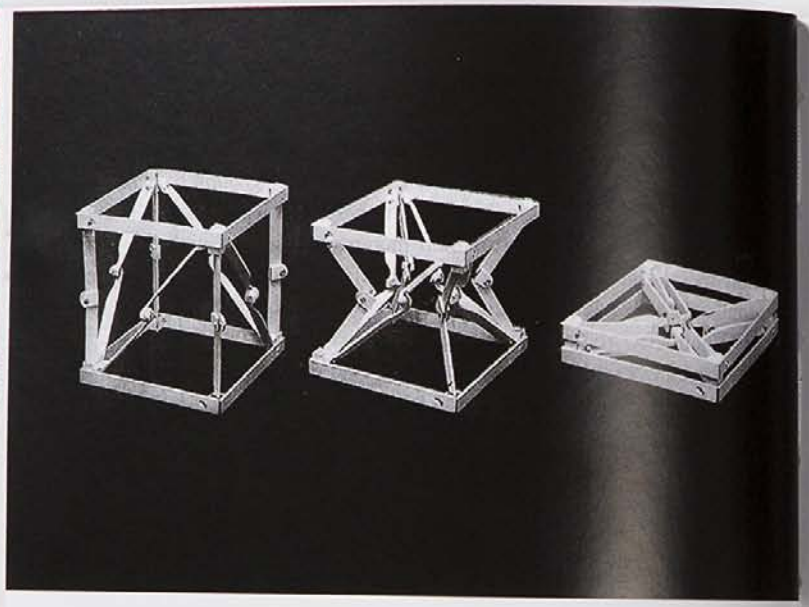
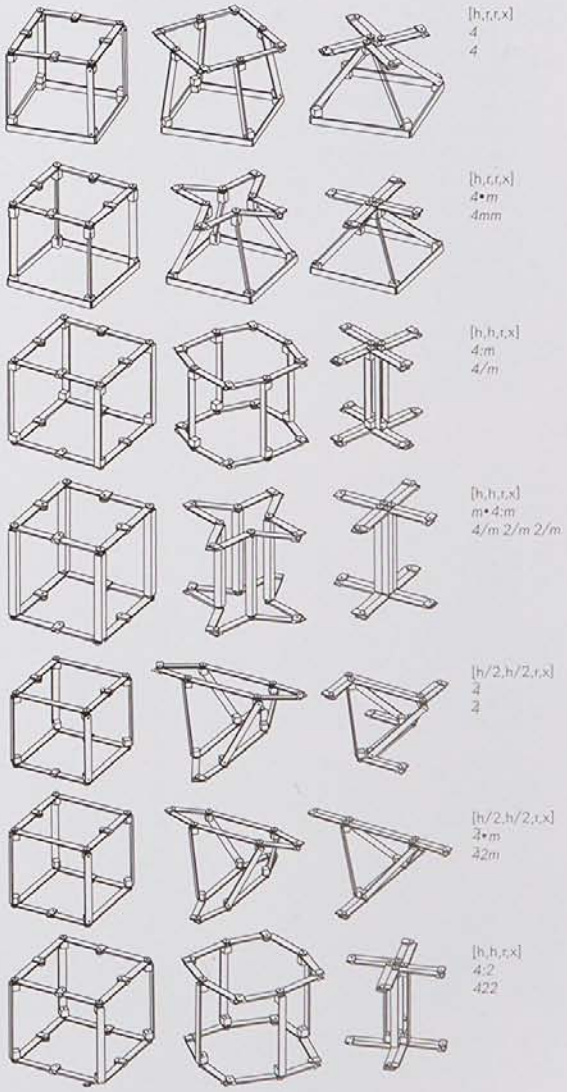


Fig 3. Deployment sequence of NASA's STAC-BEAM geometry model.

The team aims to define a morphological design method that can generate deployable structures based on crystallographic symmetry and on variants of three NASA structures, the PACTRUSS, the X-BEAM and the STAC-BEAM. The latter two are used as extendable support structures for platforms such as solar concentrators and phased arrays. In order to define their structural morphology the team develops a four-letter notation (t, b, v, d) that corresponds to the four structural component groups of a cubic cell. The first letter (t) corresponds to the top horizontal members, the second (b) to the bottom horizontal members, the third (v) to the vertical members and the fourth (d) to the diagonal members.

The notation then describes whether the member is rigid (r) or hinged (h). The morphological notation for the PACTRUSS seen in figure 1 is (h, h, r, h) (representing hinged top members, hinged bottom members, rigid vertical members and hinged diagonal members).

Figs 4–10. Deployment sequence of deployable structures representing each of the seven symmetry classes of order four.



Rolling Bridge

Paddington Basin, London, United Kingdom, 2004
Heatherwick Studio

This deployable bridge consists of eight modules. Each module is formed of two fixed trapezoidal steel frames on either side of a section of deck at the base. The base of each module is hinged to the next, with two pinned rigid struts linking each trapezoidal frame at its top. Hydraulic rams linked to these pinned struts generate the movement to deploy the structure. As the rams extend, the rigid struts fold and the modules move, causing the bridge to curl back on to itself, forming a circle on one side of the basin. When the bridge is deployed, the tops of the frames and the struts between them form the handrails, with the rams set into them.

Fig 1. Pinned struts forming the handrails, with hydraulic ram actuator.

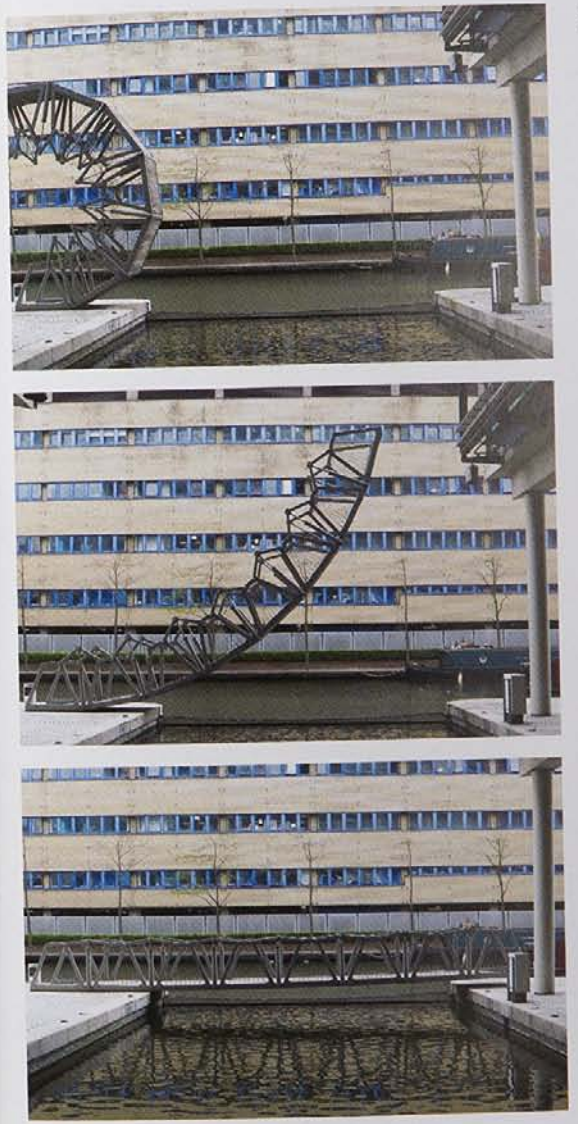


Fig 2. Deployment motion of the bridge.

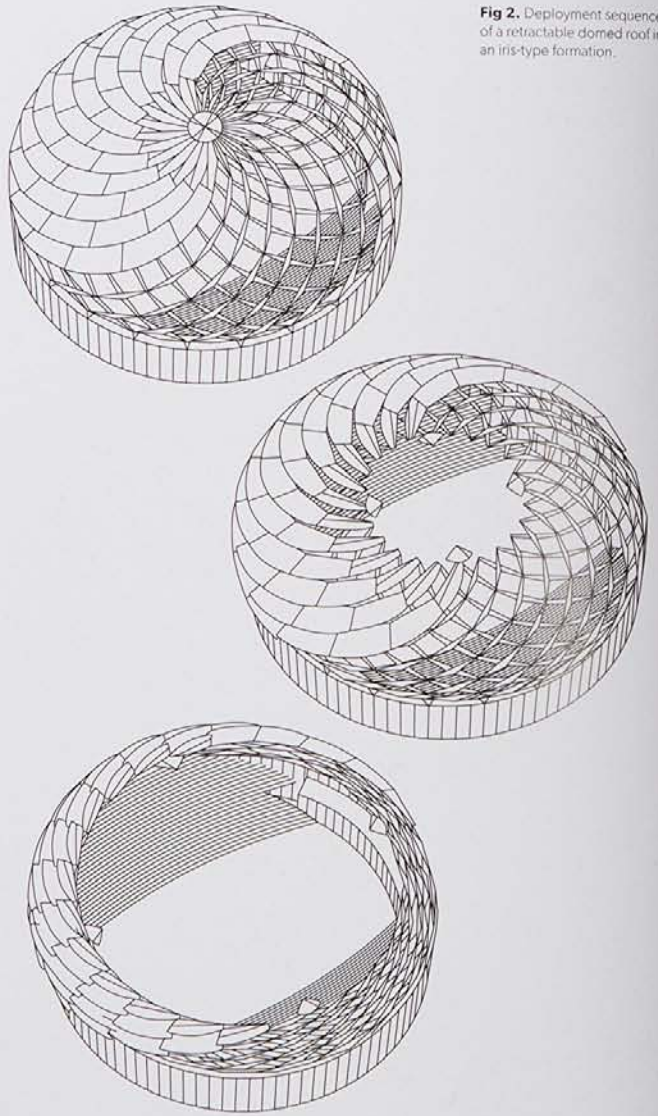


Fig 2. Deployment sequence of a retractable domed roof in an iris-type formation.

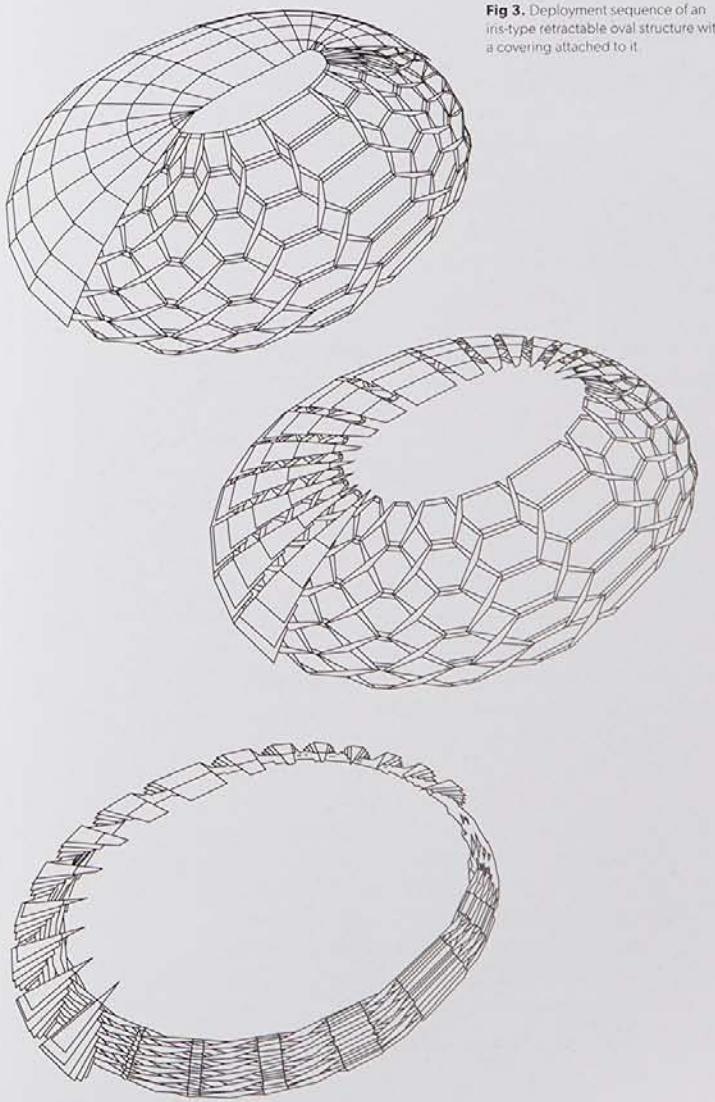


Fig 3. Deployment sequence of an iris-type retractable oval structure with a covering attached to it.

Push Button House 1

Adam Kalkin

This portable shipping container opens at the push of a button, revealing an apartment with six different living areas: a dining area, a kitchen, a double bedroom, a bathroom, a library and a living room.

The synchronized opening sequence utilizes eight hydraulic rams to move all the side planes of the shipping container in less than a minute, leaving as fixed elements only the top and bottom planes and the four corner posts. Both long sides of the container roll down, tripling the footprint of the main living area. The two ends deploy in two different ways: one opens as door pivots and the other extends floor and ceiling planes horizontally.

Figs 1–3. Opening sequence of the Push Button House 1.

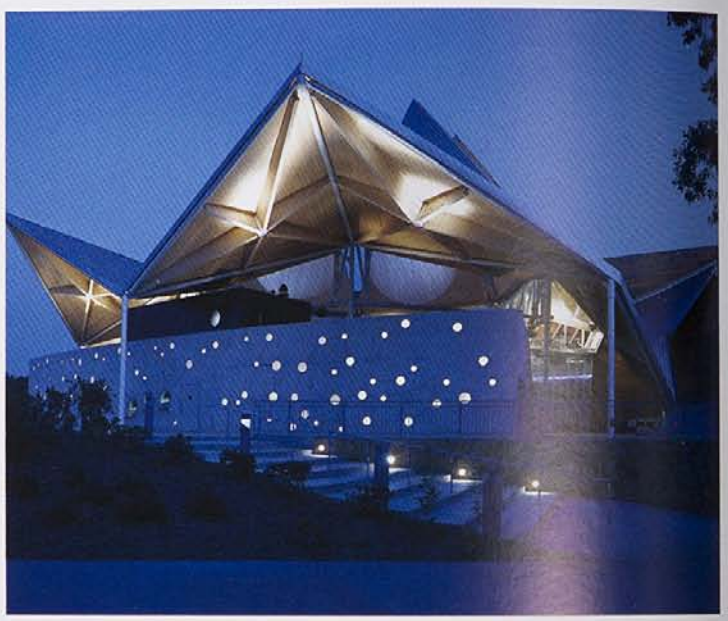


Fig 3. Night time view (above).

Fig 4. View of the night sky through opened roof (left).

Fig 5. Roof plan (closed configuration, opposite).

Fig 2. FAST Mast being tested.

Fig 3. NASA astronaut Clayton Anderson works during the third spacewalk of Space Shuttle mission STS-131 in 2010, with Earth and one of the International Space Station's solar arrays deployed by the FAST Mast as a backdrop.

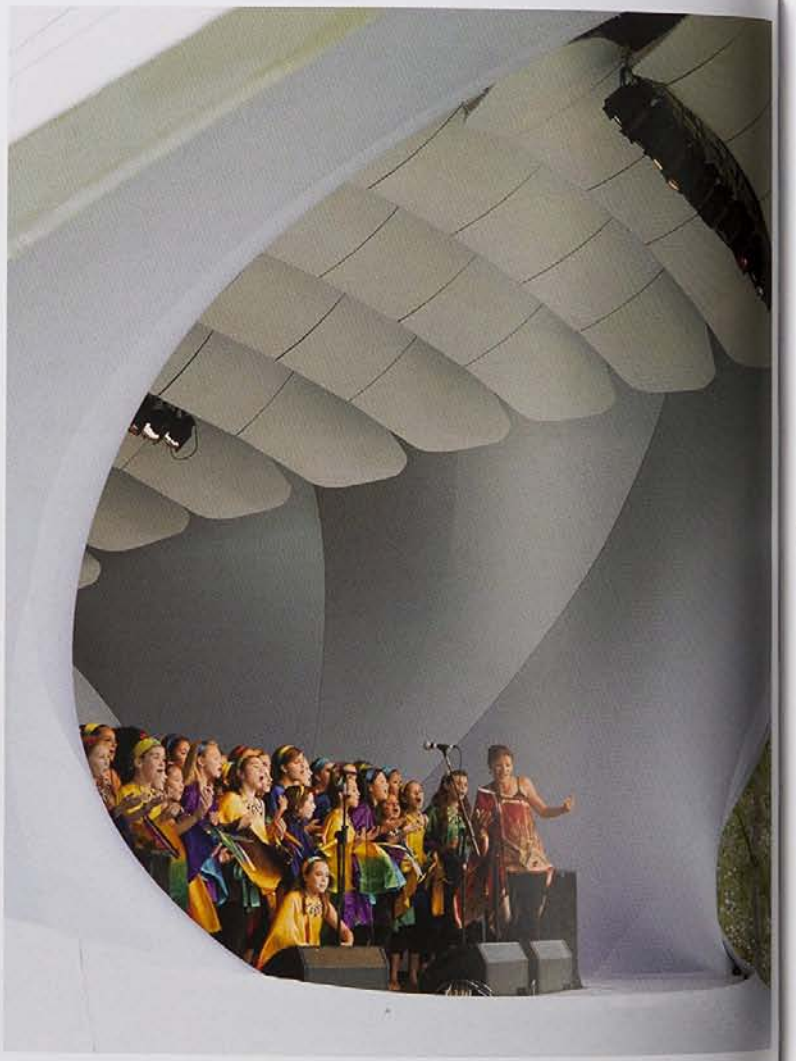
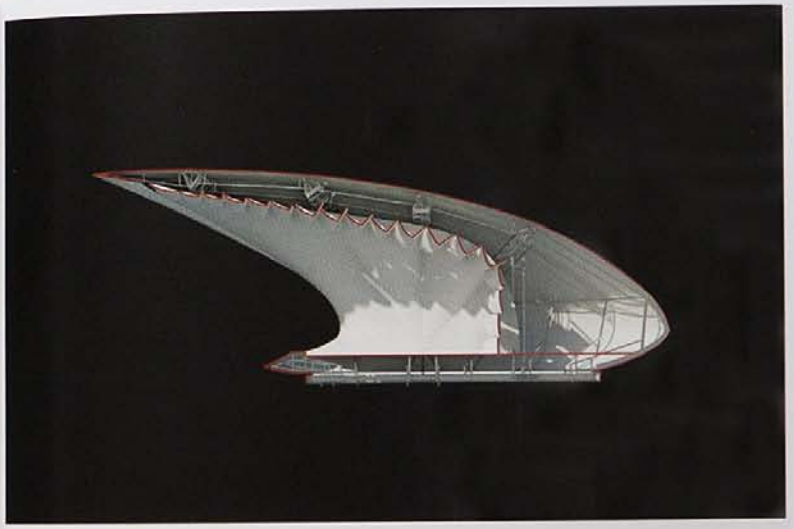
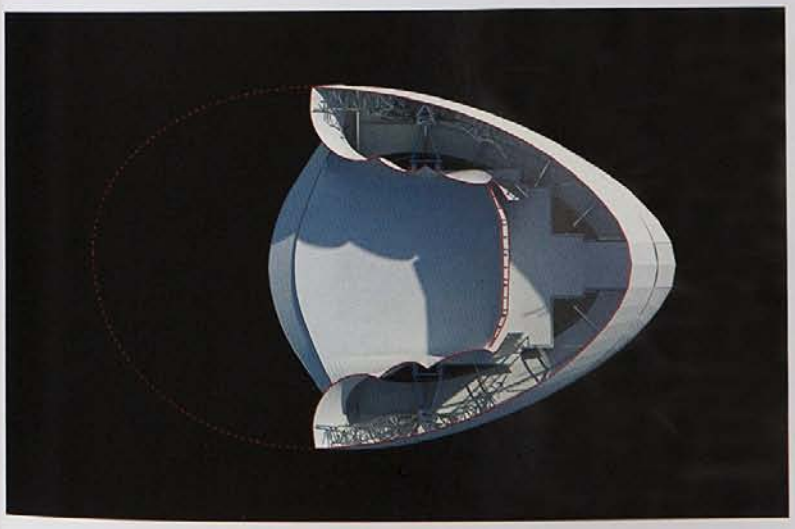


Fig 1. Close view of stage during a performance.





Figs 2–3. Cross section of the structure (top), plan view of the structure (above).

The abstraction of the elastic kinematics of *Aldrovanda vesiculosa* is highly complex. A very small linear displacement actuates the complex deformation of multiple surfaces. In order to understand how the patterns deform, a Rigid Origami Simulator software is used. The biological lobe is converted in a quad-dominant mesh with planar faces so as to study the pattern.

Various simulations of the pattern kinematics use FEM simulations with a laminate thickness of 10 millimetres (0.4 inches) in the central portion, 5 millimetres (0.2 inches) in the lobes of the marginal portion, and a curved line of 1 millimetre (0.04 inches) to allow motion. The pattern is further improved by the addition of rib stiffenings along the curved-line bending zone as well as in the midrib (figure 8).

This novel bio-inspired pliable shading system is ideal for architectural applications with double-curved, free-form geometries.

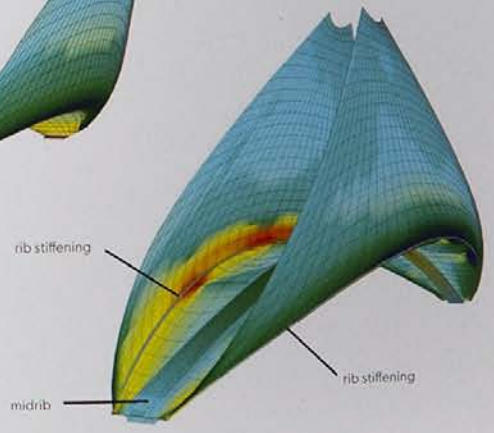
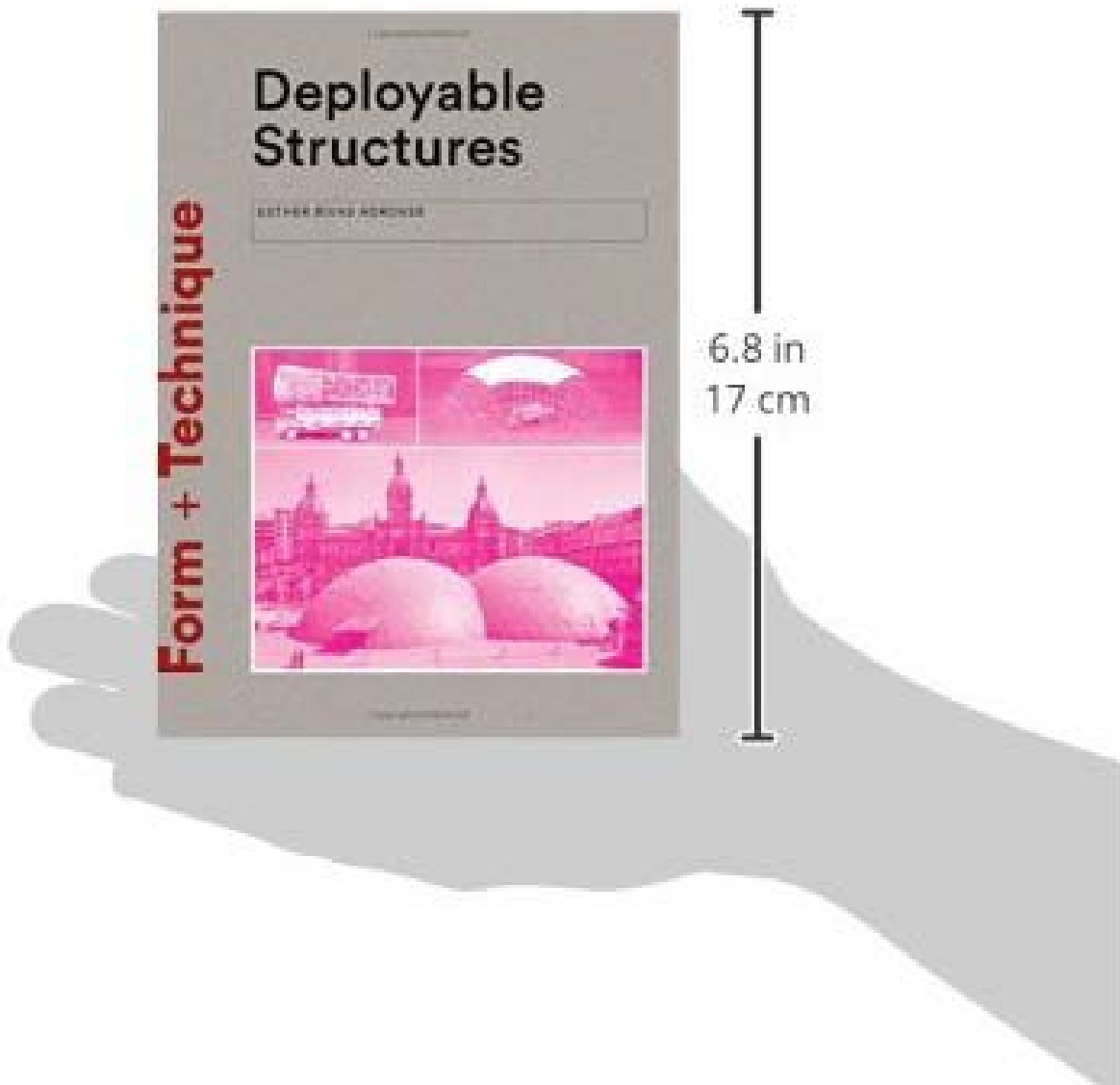


Fig 7. Simulation with bending zone.

Fig 8. Simulation with bending zone stiffened by ribs.


Deployable Structures
Form + Technique
6.8 in
17 cm