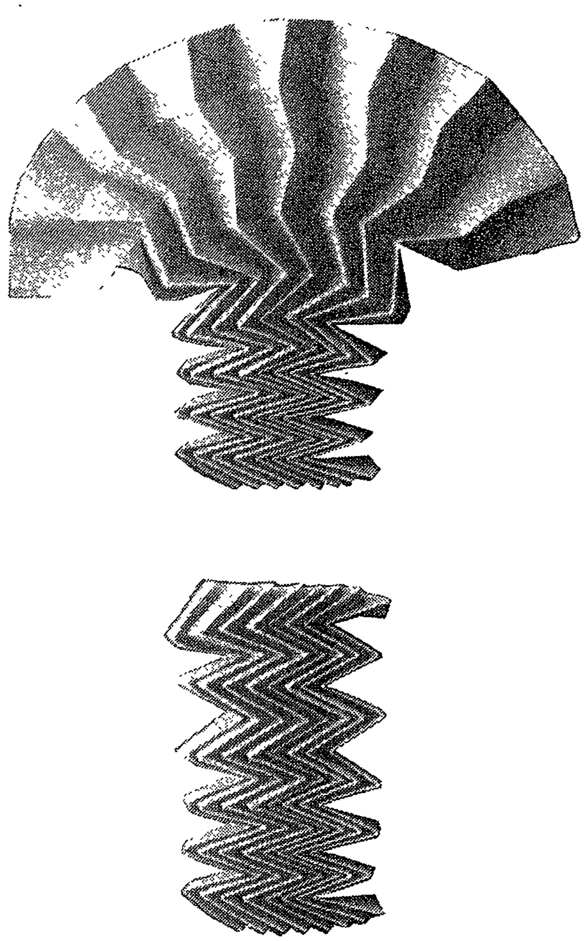
# Symmetry: Culture and Science

Origami, 1

The Quarterly of the
International Society for the
Interdisciplinary Study of Symmetry
(ISIS-Symmetry)

Editors:
György Darvas and Dénes Nagy

Volume 5, Number 1, 1994



The *Miura-ori*
opened out like a fan

*Symmetry: Culture and Science*
*Vol. 5, No. 1, 23-36, 1994*

# *HOMMAGE À MIURA*

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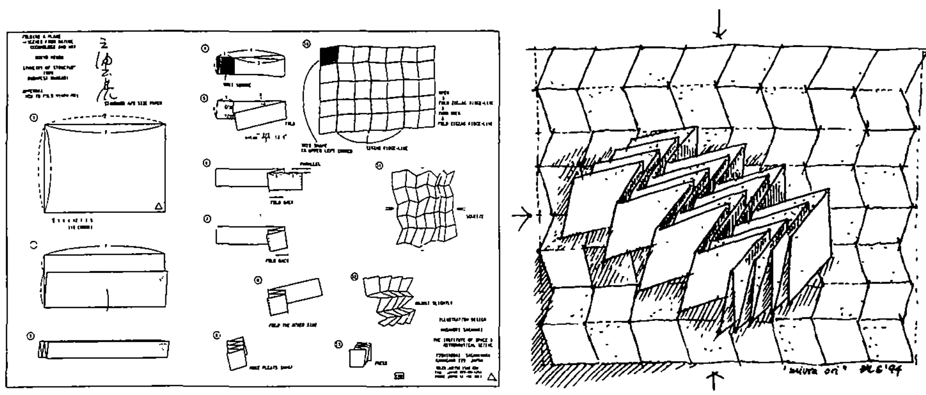
According to an old tradition in my native country of Germany, every young lad had to spend several months or even years of his life as a *Fahrender Geselle*, or 'travelling apprentice', going from one master to the other in order to gain knowledge and perfection in his profession. My favourite Grimm's fairy tale, lengthily entitled in German *"Tischlein-deck-dich und Knüppel-aus-dem-Sack"* (Table, cover thyself and stick, out of the sack) tells of one such fellow who worked in the shop of a cabinet-maker. Once he had finished his apprenticeship, his master gave him the farewell gift of two masterpieces: a table, that looked quite ordinary, but that was covered with the nicest and tastiest dishes imaginable at the simple command of its new owner, and a club that occasionally flung out of its sack to punish violently, but with great justice, any rascal, who pierced the secret of the table and tried to take it for himself.

Nowadays is there any sense in looking for a master? Haven't we got the quickest and most efficient techniques in history? Techniques, that give us access to a huge mass of information? Why look for a man whose knowledge and craftsmanship must be transmitted through personal instruction? One may argue that information appears in an incoherent and random order. To discriminate, we need a guide and a master. If that is true, how may it come about? It happened to me when I met Koryo Miura.

Strangely enough, when I met Miura, whom I now consider as my master, I was unaware of my apprenticeship. It happened in August 1989, at a congress in Budapest, organised by the ISIS-Symmetry Society. Miura, at that time professor and director of the Department of Air & Spacecraft Engineering at the University of Tokyo and director of the Laboratory on spacecraft engineering research at the ISAS (The Institute of Space and Astronautical Science) in Sagamihara, gave a 30-minutes lecture and, in the evening of the very same day, a short workshop that lasted another 15 or 20 minutes, on the theme of Folding a plane – Scenes from nature, technology and art (Miura, 1989).

## A WORKSHOP ON *MIURA-ORI**

Miura presented his very impressive invention of a folding technique he called *Miura-ori*, whose mechanical principle he could demonstrate with a simple sheet of paper. At the very first sight of it, exposed on a table under a poster in the congress hall, the folded paper intrigued me. Throughout the conference it became more and more astonishing and during the workshop that I attended in the evening, simply marvellous. Miura proposes using this folding technique for lightweight structures (the sandwich panel 'zetacore'), for guided folding devices such as the solar energy collectors of space platforms, and for so-called 'solar sails' driven in space by means of solar wind, i.e. by the pressure of the Sunlight (Figs. 1). In all cases, a simple and reliable device had to be found. The paper folding, made from a single sheet, that opened by diagonal stretching without jamming and that closed again so easily, without causing fatigue to the hinges, contained all the secret of Miura's art. Like the marvellous table in the Grimm tale, this sheet of paper revealed to its new owner not only the physical properties of a folded solar sail but the secret of the whole treasure of eastern origami and the culture surrounding it.



**Figures 1:** (a) The original folding exercise of the *Miura-ori*; (b) A folding obtained by squeezing (bilateral compression).

In order to practice the folding of his *Miura-ori* during the short workshop, Miura first gave us an A4 size copy of a map of Budapest, which we were to fold using the city's points of reference. Then, when we were sure to do it correctly, he gave us a yellow, A3 size sheet of paper with the instructions printed directly on it. When I showed my final 'apprentice piece' to the 'master', he signed it kindly with his

* Note: *ori-gami* means Folding-the-Paper (*ori*: folding and *kami*: paper), hence *Miura-ori* means The folding of Miura Nature's folding techniques.

Japanese signature and gave me the authorization to teach *Miura-ori* to my own students. At the end of the workshop, I promised Mr. Miura to send him all the scientific papers I could find on folding of insect wings.

## NATURE'S FOLDING TECHNICS

The foldable insect wing is a fascinating topic. For several years I regularly spent all my summer holidays on the Mediterranean coast in the South of France, where I could directly observe flying insects and study their wings and the patterns of the venation with a magnifying glass and draw them. I was especially interested in the folding techniques that allow *coleoptera* to fold and unfold their delicately pleated membranes during take-off or landing (Figs. 2).

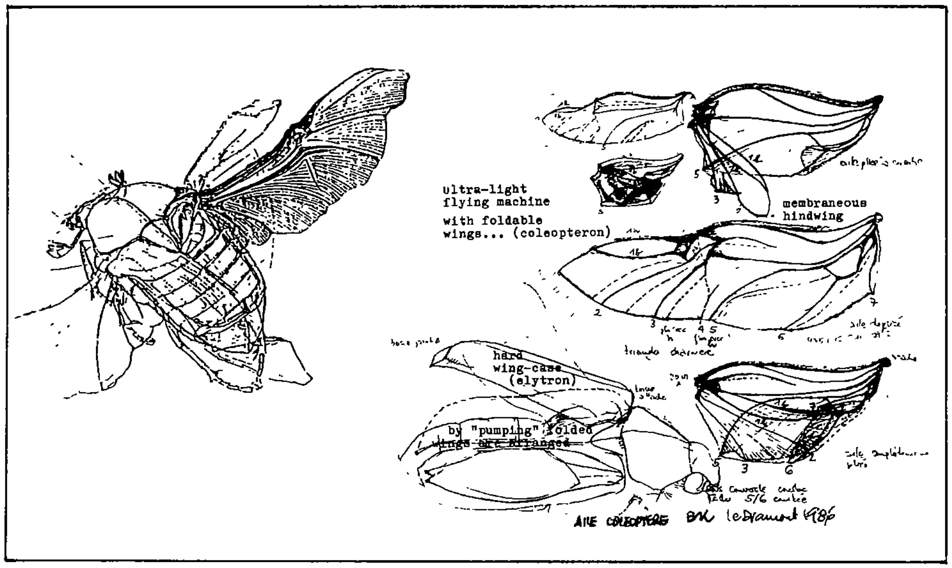



**Figure 2**: (a) Spread wings, ready for flight; (b) Folding mechanism in the membranous hindwing of a beetle (original drawings by B. Kresling).

For many years I also had the opportunity of following the research carried out under Werner Nachtigall at the Zoological Institute at the University of Saarbrücken, Germany. He is the author of *Insects in Flight*, a book that compiles information on this topic (Nachtigall, 1974). There, in the laboratories of Möhl, Dreher and Wisser, I observed the flight of the migratory locust (*Locusta migratoria*) and of the blue bottle-flies (*Calliphora erythrocephala*), using either stroboscopic flashing and videotapes, or oscillographs, or pictures from smoke-wakes.

Back in Paris, extremely happy at having Miura's instructions on the method and the algorithm of his folding, I began to introduce the topic in my own courses. But I soon realised, that I had promised Miura too much. I didn't understand anything yet about the folding of *coleoptera* wings and decided to learn more about biological *origami* and to show Miura only once I fully understood it myself.

Together with the students in courses on 'bionics' and 'dynamic folding' (designers, computer graphists and architects) we began exploring the particular mechanical behaviour of the *Miura-ori* and tried to find analogous mechanical principles in natural structures:

## *MIURA-ORI* AND THE BUDDING LEAF

When pulled in one direction, the *Miura-ori*, though an elastic structure, doesn't shrink, but on the contrary also stretches out perpendicularly. We discovered that such a 'negative Poisson's ratio' is also characteristic of leaf development: after the two lobes of a budding leaf of a tree are freed from the *involucra* and opened up, the 'V'-shaped pattern of the leaf's ribs constrains the folded membrane to stretch symmetrically outward from the central vein. Since growth largely depends on mechanical constraints, the 'V'-shaped pattern similar to a detail of the *Miura-ori* provokes elongation combined with symmetrical outstretching (Fig. 3).

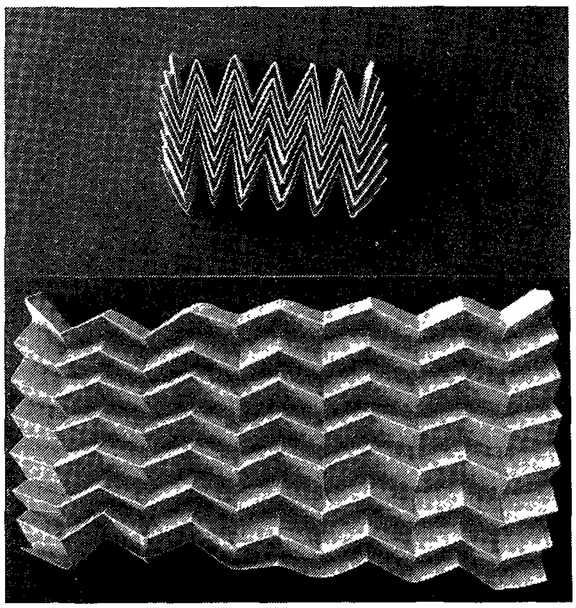


**Figure 3**: Negative Poisson's ratio of the *Miura-ori*: (a) Opening the 'V'- shaped angles equals (b) stretching out the whole surface.

## *MIURA-ORI* AND ZIGZAGGED CENTRAL LEAF VEINS

Mechanically speaking, a single straight fold acts as a hinge. This means that pivoting neither creates shear stress nor deforms the neighbouring faces. But considered as a whole, the folding system of the *Miura-ori*, (which presents three series of zigzag-lined folds), transmits a deformation of any one part to any other part of the surface. The 'W'-shaped folds act in the same way as curved folds: when folded or stretched, convexity and concavity respectively decrease or increase. The folds relieve shear stress. The surface behaves as an elastic kinetic chain, and is synergetic.

Pivoting of any part provokes either (1) a general change of all dihedral angle values (while the faces remain flat), or (2) changes that are more geometrically and mechanically complex (while the faces are twisted). Whereas in the first case the released surface automatically finds its state of minimum energy expenditure, in the second case the surface is constrained and stores a great amount of energy.

The mechanical property of a simultaneous change in all dihedral angles type 1 is used for securing the middle-layer in Miura's sandwich panel 'zetacore' (Fig. 4a). In a bending-test, however, the axes of symmetry constitute failure lines, since the stability depends on the precision of the points of intersection. The resulting deformation is analogous to certain leaf-patterns (Fig. 4b).

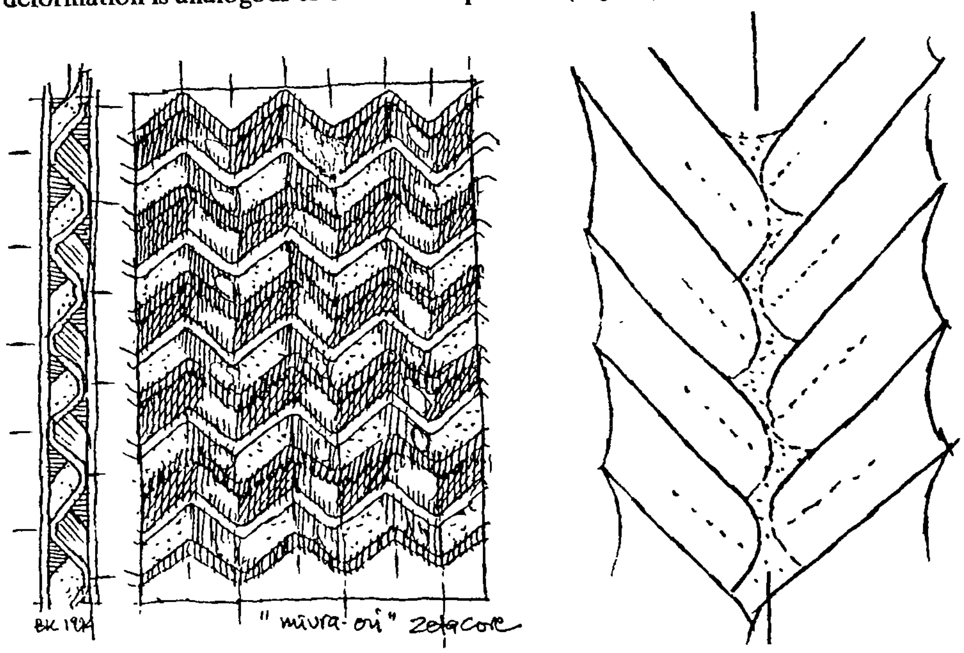



**Figure 4:** (a) The sandwich panel 'zetacore'. Used as a middle-layer between two flat faces the *Miura-ori* stiffens the panel. (b) The axes of symmetry constitute failure lines, analogous to certain leaf-patterns

The property of the energy-storing twisted faces type 2 may be used for prestressing a structure, now able to support heavier loads. In nature, several such 'prestressed' patterns help to 'control' the mechanical behaviour of a system:

– 'V' shaped or curved folds prevent a growing structure from reversing itself from convex to concave or collapsing (as in a budding leaf, Fig. 5)

– A *Lambda*-shaped pattern alternating with a 'V'-shaped pattern creates axes of shear stress and helps to form palmate leaves (Fig. 6) or lobate leaves (Fig. 7) (Kresling, in prep.).

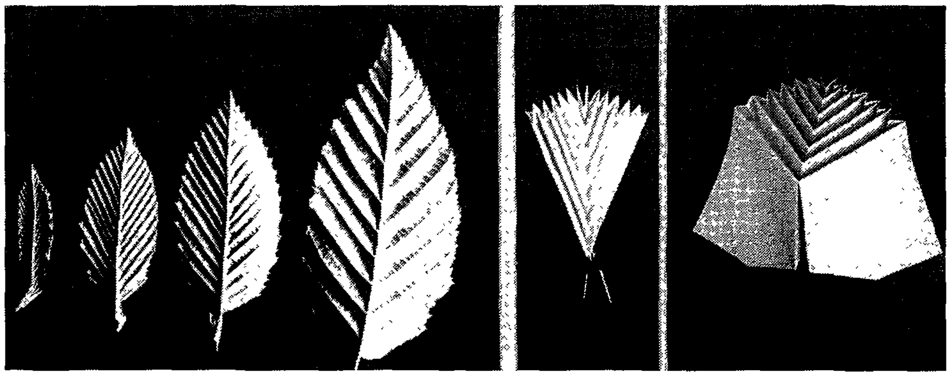


**Figure 5**: Simulation of the budding mechanism in a leaf: parallel secondary ribs (leaf of the hornbeam).

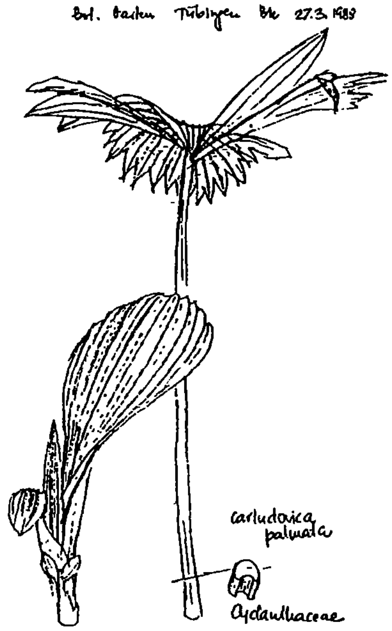



**Figure 6**: Development of a palmleaf: concentric primary ribs stiffen the folds. The membranes tear off at the periphery, thus bending the fan.

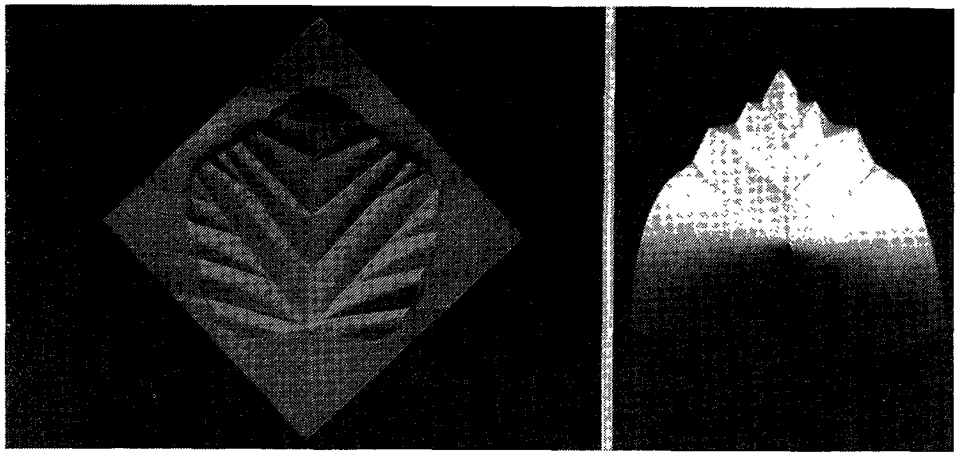


**Figure 7:** Simulation of the budding mechanism of a leaf (lime or maple-tree): convergent secondary ribs deform the lobes from concave to convex.

## *MIURA-ORI* AND THE MICRO-PLEATING OF A BIOLOGICAL MEMBRANE

In October 1992, I attended a symposium in Stuttgart, Germany, on 'Natural Structures', organised by the SFB 230, a research-group with wide-spread interests on engineering, architecture and biology. After my conference on "Folded structures in nature – Lessons in design", Helmut W. Meyer from the medical department of the University of Jena, Germany, asked me for a model of the *Miura-ori*, that I had presented. He told then me, that he was studying the micro-texture of biological membranes by freezing and breaking the samples. In an early state (the so-called P$\beta$-phase) between fluidity and viscosity, when a biological membrane gets defined, certain double-layer lamellae form ripples, others have patterns similar to the papier-mâché egg cartons, but here were certain patterns whose texture was similar to the *Miura-ori* (Fig. 8). When he slipped the folded piece of paper into his pocket, he said that he was very happy at the coincidence, because for a biologist it was important to have a model that could explain the possible mechanism of such a pattern.

## *MIURA-ORI* AND THE INSECTS WING FAN

The mechanical behaviour of a paper fan is of the second type (2). The bamboo sticks and the paper strips interact and deform one another. Such a structure is bistable: at two positional extremes – outstretched or folded – the system is at rest. In order to move the system from one extreme position to the other, energy is needed. We discovered that a similar effect is responsible for the opening of insect wing fans. More or less convergent curved folds provoke the opening of the folds near the thorax in to a stretching motion of the distal fan. The folding system of the insect wing also corresponds to the *Miura-ori*, but this time is used as a fan with convergent zigzag-folds (Fig. 9).


**Figure 8**: Miura-ori type micro pleating of a biological membrane (Lecithin in the Pβ'-phase), by courtesy of Helmut Werner Meyer, University of Jena.

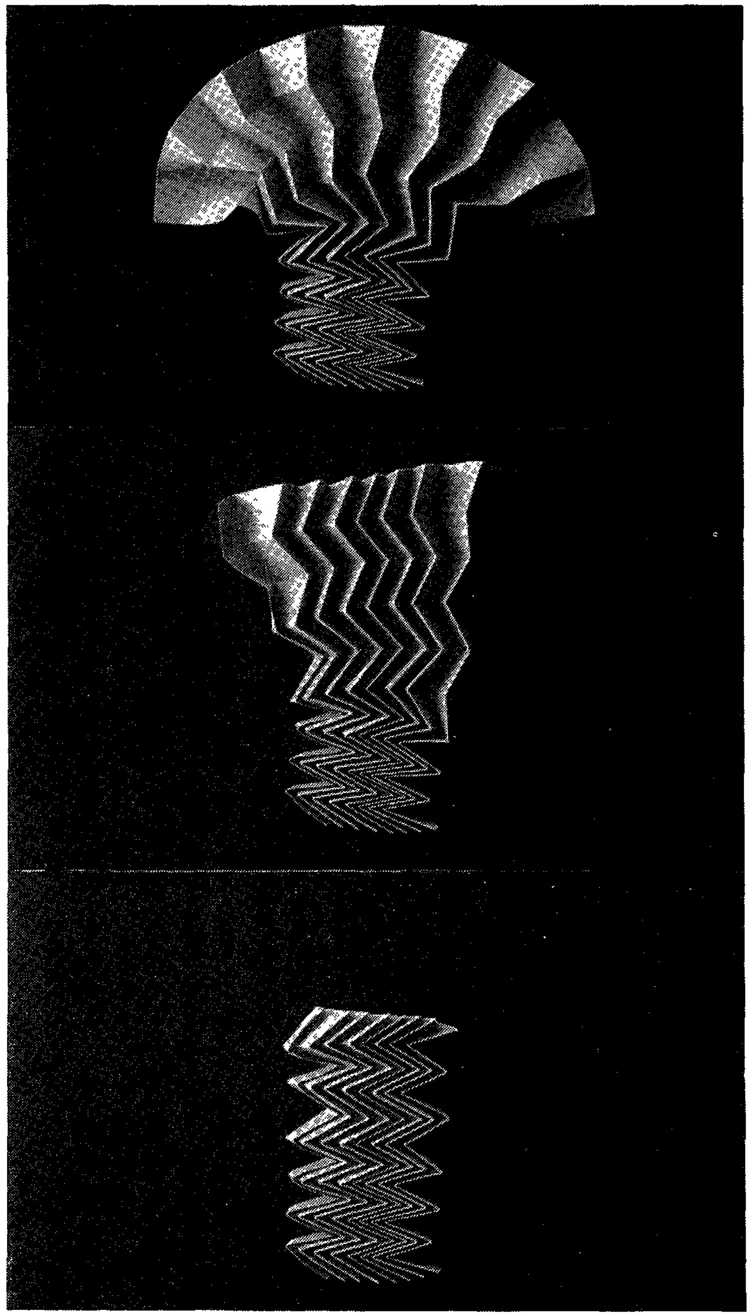


**Figure 9:** (a) The *Miura-ori* opened out like a fan, simulates the mechanism responsible for the outstretching of the beetle's membranous hindwing.

To complete the picture, we would like to point out that, as far as closing again, the folding mechanism is not fully automatic: it must be assisted. By using 'pumping' motion in its abdomen, the beetle fits its wings around the protuberant main hinges in the hard wing-cases (the elytra), thereby folding its membranous wing like a parachutist folds his parachute.

We have applied the mechanical principles we analysed in *Miura-ori* and in natural structures to industrial design. For instance, in order to stabilize folded lightweight structures and to avoid failure caused by weak lines or weak points, we used a new technique: a surface with curved folds which is (a) constrained and (b) combined with its own system before deformation. This technique suits tubular structures especially well. Current research is shown in Figure 10.

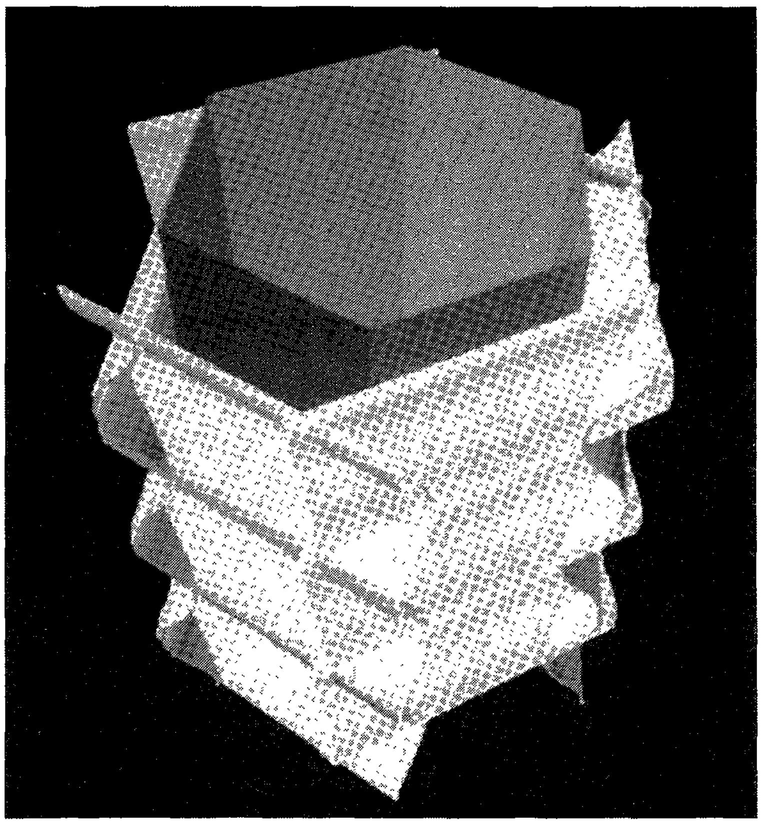


**Figure 10:** Computer simulation by N. Maillard (student in courses on 'dynamic folding' at Supinfocom Valenciennes, 1992) of the stabilization technique of a tubular structure. Curved fold lines equal interlocked corrugated surfaces. The risk of failure due to deformation of the elastic prestressed structure (increased shear stress of the curved folds) is avoided by combining with a second straight-folded tube.

## DESIGN BETWEEN STABILITY AND FAILURE

In August 1992 I made my first trip to Japan. On the way to the 2nd ISIS-Symmetry Congress at the Synergetics Institute in Hiroshima, I was happy to stop in Sagamihara and meet Koryo Miura at the ISAS-Institute. He was able to measure the amount of information transmitted by the single sheet folded in the *Miura-ori* technique when looking at the number of foldable structures that our European students had designed simply by analysing its mechanical principles. For us Europeans *origami* meant making simulations with the sensitive material of paper – "showing constraints directly, it's a material that does not lie" – and working out our design projects on the limit between stability and failure (Figs. 11-22).

While a great part of Japanese origami enhances the elegance of algorithms and creates charming pieces out of neatly folded parcels, we actually crush structures in 'one-second-experiments' and observe their spatial development and stabilization, as well as its load-carrying capacity. At the ISAS-Institute, I discovered, that our students had unknowingly developed several tubular structures quite similar to the Yoshimura-patterned designs that Miura had proposed as models for under-water shelters and for supersonic fuselages.

Over the last two years, ever inspired by the lessons of Miura's masterpiece, we have worked out other sandwich panels and stable tubular structures. We have also turned to another extreme of technical origami, provoking failure: controllable destruction and recycling of space-taking design.

In spring 1995, the German biologist Fabian Haas plans to come to Paris for research on the mechanics of the folding systems in *coleopteran* wings and its biological evolution, and to exchange ideas on folding with us. Eventually, it will have taken not less than six years to keep our promise: to send to Miura all we know about insect wing folding ...

Acknowledgement: I thank Letitia Farris-Toussaint for kindly revising the English version.

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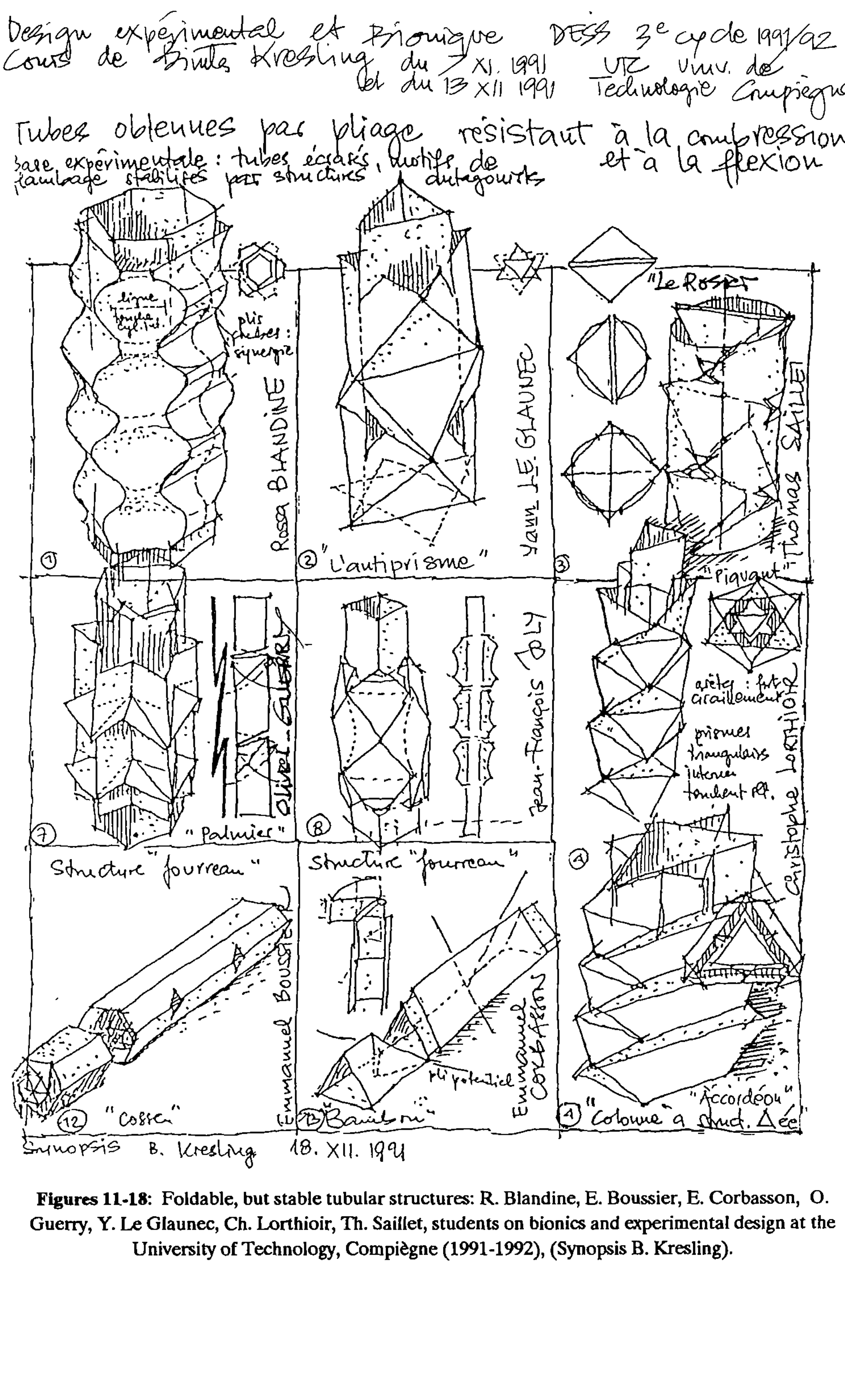
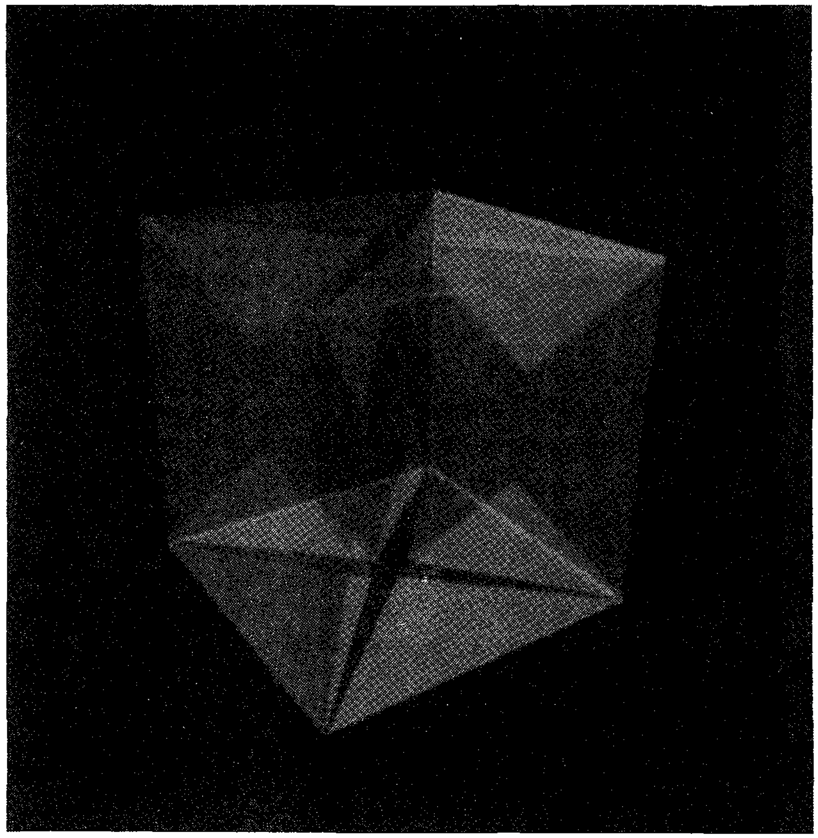
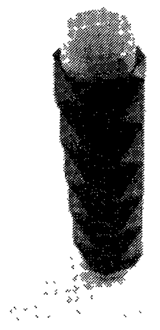
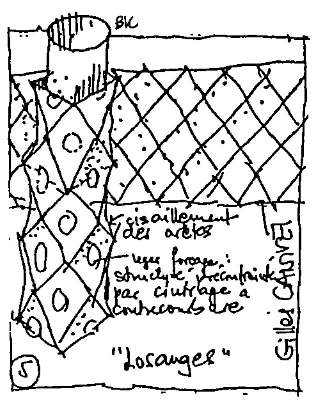
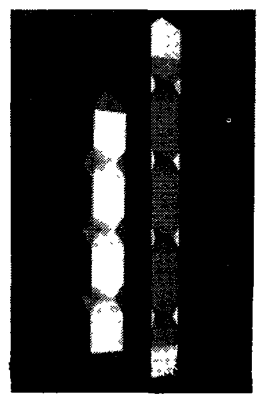



**Figures 11-18:** Foldable, but stable tubular structures: R. Blandine, E. Boussier, E. Corbasson, O. Guerry, Y. Le Glaunec, Ch. Lorthioir, Th. Saillet, students on bionics and experimental design at the University of Technology, Compiègne (1991-1992), (Synopsis B. Kresling).







**Figures 19-22:** Foldable, but stable structures: Multi-purpose packaging *Oméga-cube* (Patented 1990), D. Bourlet, B. Kresling and SupInfoCom, Valenciennes, computer simulation by N. Maillard. Tubes showing Yoshimura-pattern: G. Canivet, UTC Compiègne, N.N. ISD, Valenciennes (1991-1992), students on dynamic folding.

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