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CUTTING EDGE CORES: MULTIFUNCTIONAL CORE STRUCTURES

Y. Klett, K. Drechsler
Universität Stuttgart
70569 Stuttgart
Germany

OVERVIEW

Isometrically folded cellular structures, so-called foldcores, provide an innovative core material for lightweight sandwich structures with advantageous properties. Using the basic rules of origami, these structures are folded from one flat sheet of material without cutting, glueing or stretching of the base material. The isometric folding allows for the use of high-grade materials and very flexible customisation of the core materials.

To develop and produce these high-performance MIOs (Modular Isometric Origami), both mathematical design and hardware manufacturing methods have been developed at the Institute of Aircraft Design (IFB). We present typical MIO structures and discuss their properties in relation to well-known core materials and show how foldcore properties can be tailored on multiple levels to satisfy different requirements and include secondary functionality.

1 TECHNICAL RELEVANCE OF FOLDED STRUCTURES

Folded structures perform countless duties during everyday life. From tea bags and cardboard boxes to oil filters and airbags, clever folding can result in surprising – and surprisingly functional – results. This branch of applied folding is termed *origami sekkei* (technical origami) [1], and mostly uses the same, very basic principles that are used to fold paper sculptures, namely [2]:

- Start with a flat, thin sheet of material
- Just folds, no cuts, no glue
- Paper does not stretch

While this simple set of rules looks trivial at first, it describes a way to produce complex functional structures in an elegant, energy-efficient way. Folded paper is so ubiquitous and the folding process so straightforward that it does not seem to merit a lot of research at first glance. Nevertheless, the design and manufacturing of kinematically non-trivial folded structures can be both a complex and promising task.

2 MOTIVATION

Sandwich construction is one key method to produce lightweight parts with high specific performance-to-mass ratios. Our research focuses on the design of innovative core materials that offer new possibilities for sandwich applications [3]. These have to compete with several available and well-proven materials including foams and honeycomb cores in primary areas like mechanical performance, handling and cost.

The motivation behind the design of foldcore structures is not exclusively to match or exceed those properties, but also to: [4]

- Eliminate or work around certain weak spots of conventional materials that at the moment prevent the use of sandwich in certain applications
- Provide new possibilities to integrate additional functionality into the core and the sandwich itself and facilitate integrated lightweight design concepts.

3 MODULAR ISOMETRIC ORIGAMI (MIO)

The principle behind all presented MIO foldcores is the modular, isometric folding of flat, thin materials into three-dimensional structures. This corresponds exactly with the mentioned origami principles – with each of those serving a technical purpose (Table 1):

Principle	Benefit
Start with a flat sheet	A broad range of sheet materials is available.
Just folds	The folding process is not interrupted or complicated by additional work steps.
Paper does not stretch	No deformation (except at creases). Use of tough/brittle materials possible. No/very small residual stress. Energy-efficient process.

Table 1: Benefits of origami principle application.

Contrary to processes that employ deep-drawing, thermoforming or other methods to generate a shape by plastic deformation, isometric folding allows deformation only at the creases, otherwise no strain is introduced into the material. As a consequence, high-performance materials with small breaking elongation (e.g. carbon and other high-modulus fibres) can be processed, resulting in corresponding favourable mechanical core properties [3,5,6,7].[1]

Figure 1 shows the folding sequence of one basic MIO structure. The flat material is folded according to a simple,

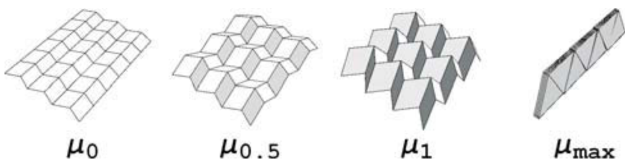

Figure 1: Isometric folding sequence of a 3x3 MIO unit cell block.

1 Another consequence is that on the unit-cell level only surfaces with zero Gaussian curvature are allowed

repetitive and tileable tessellation pattern. The smallest non-repeating element defines the characteristic unit cell, the folding state is defined by the parameter μ *(Table 2).*

$\mu=0$	Flat state
$\mu=1$	Design state
μ_{max}	Block folding state

Table 2: Characteristic folding states. Other values denote intermediate states, folding states with $\mu<0$ define symmetric configurations with inverted initial folding direction.

A modular structure consisting of an arbitrary number of seamlessly joined similar unit cells is essential for industrial manufacture of foldcores. While amazingly complex structures can be folded by hand, economic automation processes rely on a small set of ever-repeating steps.

The relative simplicity of most technically relevant MIO unit cells is also a consequence of optimised structural and functional efficiency. In general, multiple overlapping folds and material layers do not add much performance to the resulting core but result in higher mass and material consumption.

While efficient unit cells mostly consist of a small number of creases, the shape and resulting properties of foldcores can be manipulated on a number of different levels and result in a multitude of functional structures.

4 DESIGN LEVELS

Foldcore design is restricted by the use of isometric folding steps. Additionally, all presented MIOs consist of non-trivial crease patterns, resulting in a structure that has only one kinematic degree of freedom.[2]

This is important for the mechanical performance, because the kinematic coupling results in favourable buckling modes, but also means that theoretically every relative motion of two faces will influence the position and folding degree of all other unit cells in the structure.[3]

With the methods and tools developed at IFB, it is possible to observe these boundary conditions while designing complexly shaped folded structures.

4.1 Macro-Level

The macro-level relates to the overall shape of the core volume. In the geometrically trivial and predominant case, flat sandwich panels demand cuboid core volumes. Some varieties of possible (and realized) MIOs for this case are shown in Figure 2.

While cuboid core sheets are available for all conventional core materials, it is more difficult and/or expensive to provide high-grade cores for complex volumes.

For these complex shapes like cylindrical, tubular, prismatic or even spherical volumes, MIOs offer the potential to design cores that fit exactly into the target volume without the need for additional machining or forming steps. This makes handling easier and avoids unnecessary cutting scrap and processing time (Figure 3).

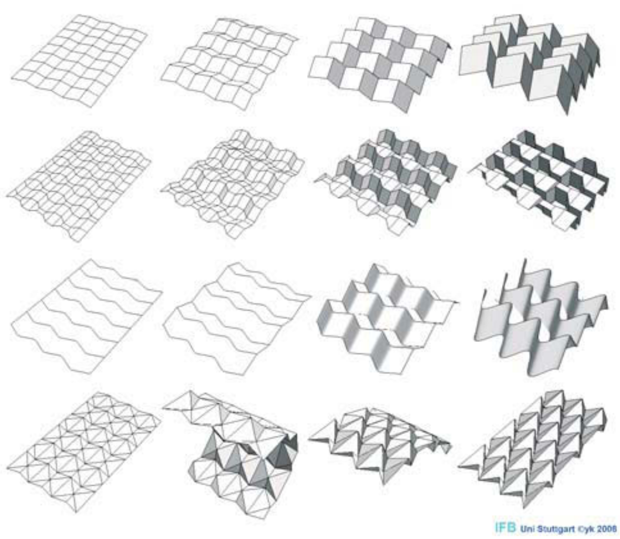

Figure 2: Different MIO (3x3 unit cells) folding sequences with constant height for flat panels (at μ_1).

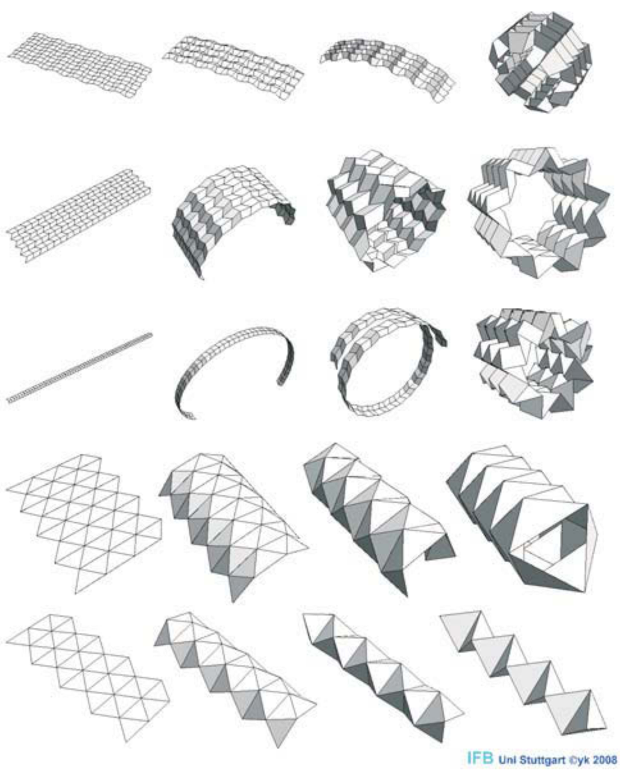

Figure 3: Some exemplary MIO configurations for tubular, cylindric and prismatic volumes.

4.2 Meso-Level

The meso-level describes the geometry of the unit cell. For any macro-shape there is an arbitrary number of possible unit cells that fit. These unit cells can have very different shapes and exhibit very different properties while still fitting into the same volume.

2 Examples of trivial cases: straight or perpendicular creases
3 In reality, this is not always the case, because slight elastic deformations occur during folding.

The final choice of unit cell type and shape depends on the desired core properties and given restrictions, including:

- Mechanical performance (compression, transverse shear, impact etc.)
- Isotropy / Anisotropy
- Ventability
- Ease of manufacture / Feasibility / Price

Several examples are shown in Figures 3 and 4, the latter showing unit cells of equal height and density that offer completely different ventability.

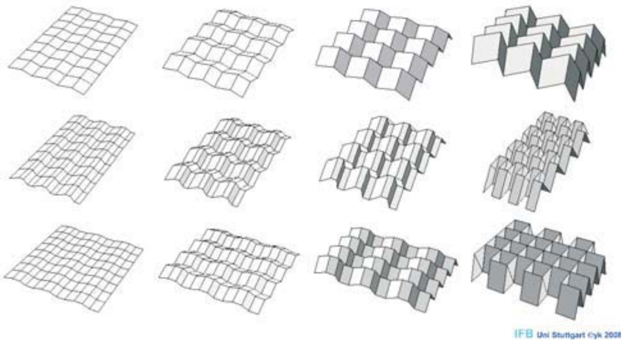

Figure 4: Different unit cells lead to different structures for the same macro-volume.

4.3 Micro-Level

The micro-level comprises everything on sub-unit-cell level. This concerns the semi-finished material of the core, but also the surface structure, embossings, coatings, markings, cut-outs, perforations etc. that can influence the core properties in many different ways.

Because the starting point for a foldcore is always sheet material and the kinematics of the structure are precisely known, it is straightforward to apply such additional processes to the flat material, which is often simpler than postprocessing of the finished core and allows a high degree of control over the result.

One example of this method is shown in Figure 5. Here the task was to produce precisely defined and located cutouts for an aerodynamic application [8].

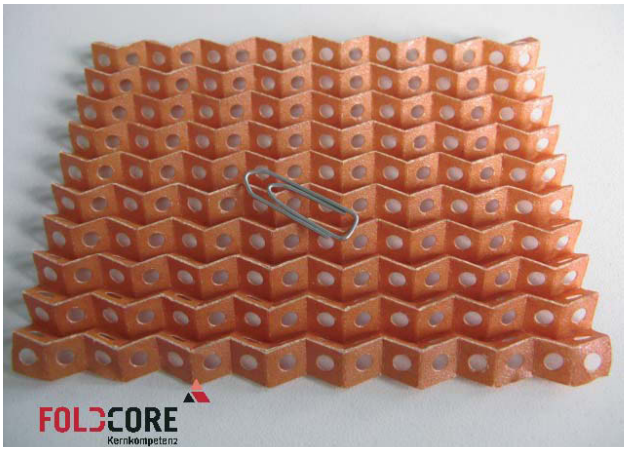

Figure 5: Micro-structured core with precision perforation.

5 FUNCTIONALITY

For technical application, folded structures have to serve clearly defined purposes. Depending on the intended use of a core, the versatility of MIO design can be used to develop materials with mandatory primary and desirable secondary functionalities.

5.1 Mechanical properties

For all lightweight sandwich parts, mechanical performance is perhaps the most important overall factor (Figure 6). Foldcores can offer good mechanical performance that about matches that of comparable honeycomb cores, which are regarded as one main benchmark [9].

Because the unit cell geometry can be tailored flexibly, cores with anisotropic properties are easily realized and optimisation according to the user specifications is possible. One example are sandwich cores that with high shear but low compression moduli.

Impact behaviour is another important mechanical parameter for mission-critical parts. Studies concerning impact on foldcore structures are ongoing [10].

Figure 6: Foldcore sandwich beam during flexural test.

5.2 Multi-Material approach

Apart from the unit cell geometry, the sheet material determines the characteristics of a foldcore structure (including price). Making use of isometric folding, a wide range of materials can be used.

Some successfully tested materials include (Figure 7):

- Papers and cardboards (synthetic / natural)
- Reinforced plastics (Carbon-/Glass-/Aramid-Fiber)
- Thermoplastics (e.g. PP, PE, PET, PC, PEEK)
- Metals (aluminum, steel, titanium)

Depending on the intended use, hybrid combinations of these and more materials are possible, e.g. a multi-layer setup.

Foldcores are specifically not restricted to the use of high-grade and often expensive material. The manufacturing process works just as well with cheaper materials that in a lot of applications still perform adequately [3]. This is an important factor to propagate the use of sandwich construction in cost-critical industries.

5.3 Ventability

One feature that clearly distinguishes MIO cores from foams and honeycombs is the potential to provide excellent ventability and drainage. Closed-cell sandwich setups are prone to water accumulation that especially in aerospace applications can result in critical material degradation or even failure. Foldcore panels provide large

Figure 7: Foldcores made out of: paper, aluminum, aramide paper, synthetic paper, thermoplastic, CFRP.

free cross-sections that can be easily drained or vented (Figure 8).

This feature can also be used to actively climatize a sandwich panel or transport media and exchange heat in general, while still retaining a structurally functional part (as demonstrated in Figure 5).

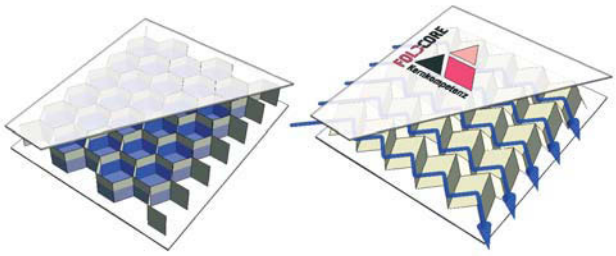

Figure 8: Honeycomb sandwiches form closed cavities that are susceptible to water accumulation. Folded cores offer large ventable sections.

5.4 Handling

To cover large areas, core materials have to be assembled from smaller panels whose maximum dimensions are determined by the production process. For cellular cores, this normally involves application of potting materials, adding mass and expense.

Folded cores can be joined seamlessly without the need for additional potting (Figure 9). This even applies for cores with differing but compatible geometries as demonstrated in Figure 10 for three cores with relative densities of 0.5, 1 and 2.

Figure 9: Cylindrical foldcore test shell: Assembly of 165.000 creases. Source: Airbus Deutschland GmbH

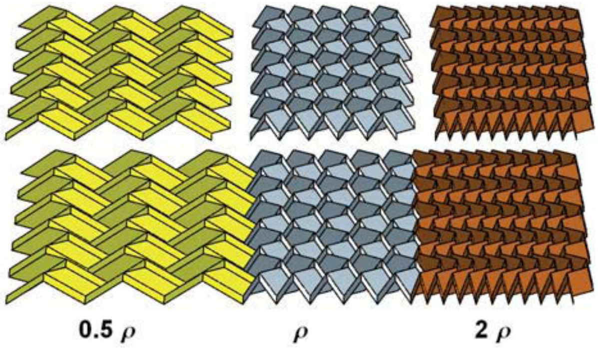

Figure 10: Cores of different densities can be joined seamlessly in jigsaw-fashion.

5.5 Transport

Logistics can add a substantial financial overhead for core materials. While only small masses have to be transported, these occupy a lot of volume mostly consisting of air. Properly designed MIO structures can be nested to minimize the volume during transport, and require only a fraction of the space of an equivalent amount of foam or honeycomb cores (Figure 11).

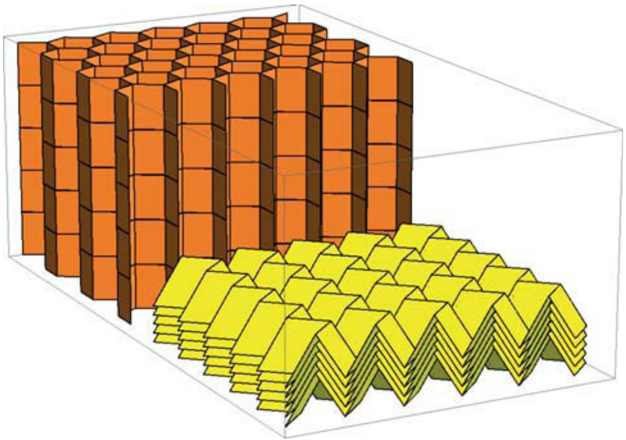

Figure 11: Transport volume for equivalent amounts of stacked honeycomb and nested foldcores.

5.6 Kinematics

For the end-user the kinematic behaviour of a MIO sandwich core is mostly irrelevant. In contrast, for manufacture precise knowledge of the involved kinematic behaviour is essential. A key module of the tools developed at IFB is the folding simulation of MIO structures using rigid inverse kinematics [6].

For non-sandwich applications, this knowledge can be of considerable interest, especially for storing/deployment scenarios of planar structures (Figure 12). For example, for solar sails [11] and airbags, interesting *origami sekkei* solutions have already independently been developed, but only scant information on the used design methods is available.

Variations of several presented cores have already been mentioned in literature and folded by hand in the origami

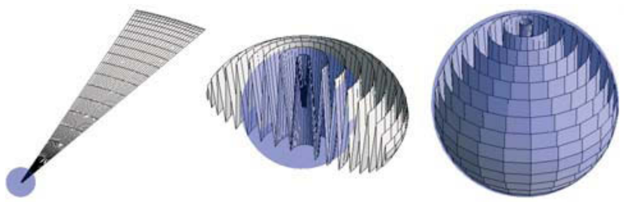

Figure 12: Unconventional MIO for a spherical target volume.

community, but for precise design and large-scale production of high-grade MIO foldcores the implementation of a flexible computational framework was essential. This framework is continuously expanded and based on general design paradigms that allow broad-spectrum use [12].

More readily available and useable tools to apply modular isometric kinematics to industrial problems can help to find optimised solutions in numerous other areas as well.

6 CONCLUSION

Isometrically folded structures provide a sandwich core material that can be adapted flexibly to serve a wide range of tasks.

MIO foldcores can be tailored on different levels and integrate additional primary or secondary functionality. A robust set of design and manufacturing methods has been developed.

These tools support the ongoing efforts to supply innovative core materials that open up new possibilities for sandwich applications not only for aerospace but also transportation in general. In addition, the expanded knowledge of folding processes can be applied to other tasks and supplies surprisingly neat solutions to complex technical problems.

ACKNOWLEDGEMENT

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