DESIGN OF MULTIFUNCTIONAL FOLDED CORE STRUCTURES FOR AEROSPACE SANDWICH APPLICATIONS

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OVERVIEW

Sandwich constructions offer a high potential in weight and cost reduction compared to other construction methods. Newly developed folded core structures offer a high-performance alternative to conventional cores like foams and honeycombs, while eliminating certain shortcomings of these core types and incorporating secondary functions. Folded cores can be tailored to user needs and specifications including geometry, mechanical, acoustical and other properties. General properties of folded core structures are discussed and possible applications of folded cores in sandwich structures are presented. A variety of possible structures is shown.

1 SANDWICH STRUCTURE CONCEPTS

1.1 Use of sandwich construction

Performance and cost reduction are two main design drivers in the aerospace industry. Especially composite sandwich constructions offer a large potential in both categories compared with conventional construction methods (Fig. 1) [1, 2].

However, in the past sandwich constructions in civil aircraft manufacture have been largely confined to secondary structures. The use in primary and large-scale structures has been restricted due to problems with long-term behaviour concerning topics like water accumulation, shaping and impact resistance.

Fig. 1: CFRP double shell sandwich fuselage demonstrator (VeSCo concept) using folded cores produced by IFB and Foldcore GmbH

One key issue to overcome these problems and open the door for innovative sandwich design is the availability of core materials that help eliminate these problems.

1.2 Core material requirements

The primary requirements for a sandwich core in structural aerospace applications are of course high specific modulus and strength. However, many other factors are critical for the applicability of a certain material:

- Fire, Smoke and Toxicity (FST) properties
- Impact resistance
- Shaping possibilities
- Material compatibility
- Acoustical properties
- Water absorption / ventability
- Long-term behaviour under environmental stress
- Media resistance
- Ease of handling
- Cost effectiveness

1.3 Integration of secondary functionality

Apart from the pure constructional requirements mentioned above there is a growing demand of integration of secondary functions into primary structures. Structures are no longer only viewed as singular components, but as systems that incorporate different functions. In sandwich structures, the core plays an important role for the feasibility of such concepts.

1.4 Relevance of folded cores for sandwich applications

Folded cores can combine several advantageous properties that constitute an innovative core material offering new perspectives for the design and application of sandwich parts.

While several well-known core materials excel in different areas like mechanical performance, ease of handling or economics, there is a growing demand for multifunctional core alternatives that incorporate advantages of these materials while eliminating certain weaknesses. Properly designed folded cores can offer such a customised combination.

2 PROPERTIES OF FOLDED CORES

2.1 Principles of isometric folding

Folded cores in general use the principle of isometric folding, e.g. a plane sheet of material is folded free from distortion so that flatwise distances between points on the sheet stay the same during the folding process.[1] This enables the production of threedimensional structures without any need for cutting, bonding or plastic deformation[2] of the material. This method is gen-

1 In mathematical terms, this is also referred to as „flat foldability".
2 Except directly at the creases, where bending occurs.

erally associated with the ancient japanese art of *origami* („folding of paper"), although applied in a more sober engineering context.

For technical purposes specific repetitive patterns, so-called tesselations, are of special interest, because they can be repeatedly applied to design load-bearing structures that can be produced industrially. Hence most of the examined folded core geometries consist of very few simple folds building a unit cell that is repeatedly adjoined to form threedimensional open or closed cellular structures. One of the most basic non-trivial[3] core structures is the plane zig-zag core (Fig. 2).

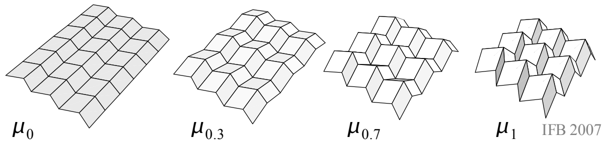

Fig. 2: Folding sequence of a basic symmetric zig-zag core structure (3x3 unit cells)

While the idea of providing such materials on an industrial scale is by no means new [3], successful ways to accomplish this have only been developed in the past few years [2,4].

2.2 Applicable Materials

Because of the isometric folding, a large variety of materials can and has already been used to produce folded cores. In contrast to deep-drawing methods for structuring, isometrically folded cores can be made of very brittle materials as well.

Some examples are:

- Composites (glass, aramid, carbon)
- Natural and synthetic fibre based papers and cardboard
- Metals (aluminium, steel, titanium etc.)
- Plastics

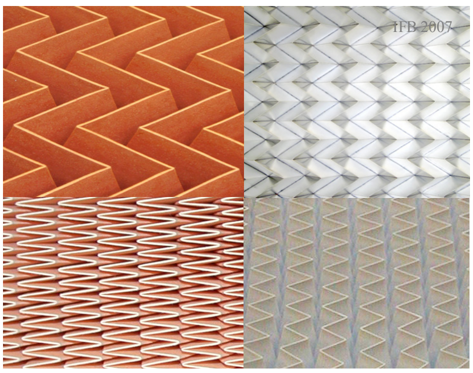

Fig. 3: Folded zig-zag cores made of aramid, aluminium, paper and thermoplastics.

2.3 Cellular Structure

Unit cell arrays can be designed to form open or (partially) closed cellular structures, resulting in varying degrees of ventability and drainability (Fig. 4). For large sandwich applications, these facilites are very much desirable to deal with the problem of water accumulation that occurs with closed-cell cores like honeycombs and to enable the integration of other secondary functions like fluid transport. Especially for some aerospace and most spaceborn applications closed-cell sandwiches and ensuing problems with decompression or water accumulation are prohibitive.

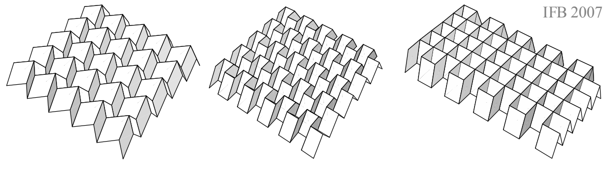

Fig. 4: Left to right: Open, partially closed and closed cellular structure of three basic folded cores at μ_1 (5x5 unit cells)

2.4 Kinematics

All non-trivial unit cells and subsequent structures possess a kinematic coupling of the contraction dependent on the folding degree μ, with μ_0 defining the unfolded plane state and μ_1 the desired end state.[4] This corresponds with a changing Poisson ratio of the structure during folding (Fig. 5).

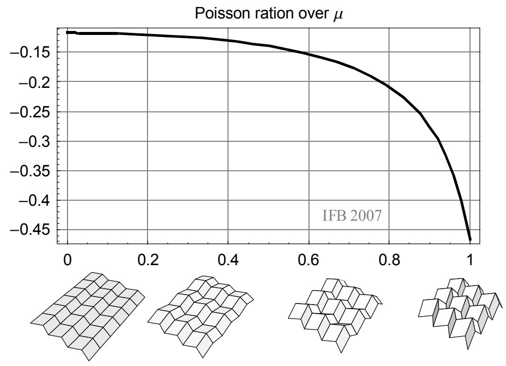

Fig. 5: Flatwise Poisson ratio of a core during folding

For structural applications the folding kinematics leading to a core structure are mostly irrelevant, because the mechanical properties only depend on the final geometry, but for the design and production of folded cores this knowledge is essential.

The kinematics can also be of interest to other scientific areas like e.g. robotics, since they can be easily applied to wireframe models of rigid struts building a kinematic chain. Although practically mostly irrelevant, the right combination of unit cells can result in a structure that describes certain complex spatial curves at defined effector positions.

2.5 Density

The density of a folded core depends on the unit cell geometry at μ_1 and the grammage of the used material. For a given core density ρ an infinite number of different unit cells is possible while retaining the same overall core dimensions. In reality, the possible shapes are additionally restricted by factors like material thickness and smallest possible folding fineness. The possible densities encompass a very wide range from ultra-light to nearly solid cores.

2.6 Auxetic and anisotropic properties

Most folded structures posess a negative Poisson ration in the flatwise directions (Fig. 5), because previously flat material is elevated during the folding and the thickness of the structure increases while the overall dimensions become smaller. These auxetic properties are e.g. interesting for acoustically damping materials.

In out-of-plane direction, the Poisson ratio is usually positive, but changes during folding as well. In consequence, the core volume (and the core density) can be a parabolic function that

3 Trivial: Only straight non-intersecting or perpendicular creases.

4 $\mu > 1$ is possible as long as no intersection of surfaces occurs, μ_{-x} essentially denotes a folding state symmetric to μ_x with inverted initial folding direction.

reaches a certain volume for different values of μ, but displays different core configurations for these values.

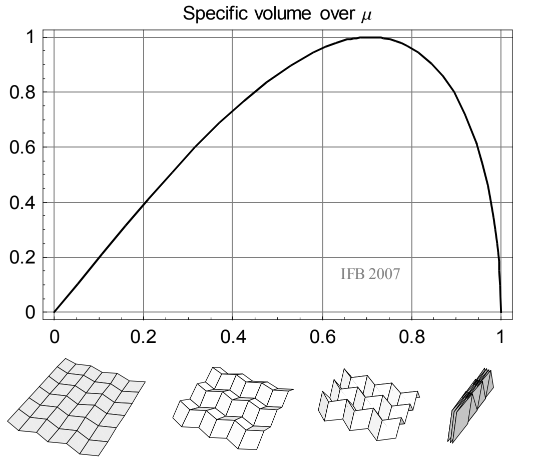

Fig. 6: Specific volume during folding process. All densities except ρ_{max} are reached for two different values of μ. For real world materials, minimal volumes are determined by material thickness.

In comparison to other core materials that either possess isotropic mechanical properties (foams) or a more or less fixed degree of anisotropy (wood, honeycombs), folded core properties can be designed from quasi-isotropic to completely anisotropic behaviour while retaining fixed overall core density and dimensions. This enables an optimization of the core geometry according to specific user requirements. In Figure 8, four different cores with similar density fit into the same core volume, but display very different mechanical properties.

2.7 Complex shaping

Folded structures have an infinite number of possible shapes. This phase space can be explored to obtain cores of nearly any shape, from flat panels to complex freeform surfaces. The applicability of these structures is limited by their complexity and available means of production, but for a large number of sandwich applications geometrically customised cores can be realised [5].

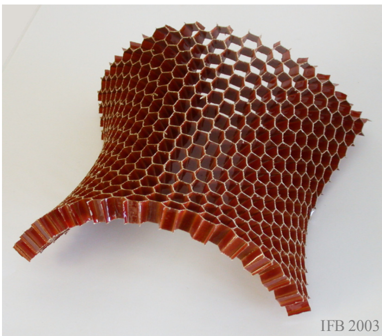

Fig. 7: Left: Hyperbolic deformation of a honeycomb panel due to applicaton of cylindrical bending [5]

The desired shape, e.g. a cylindrical volume, can be obtained without the need to apply force to the core, since the final shape is determined by the flat folding pattern and the resulting kinematics. In comparison to a standard honeycomb core a properly designed folded core can be fitted tensionless into a cylindrical or tubular volume (Fig. 7, 8).

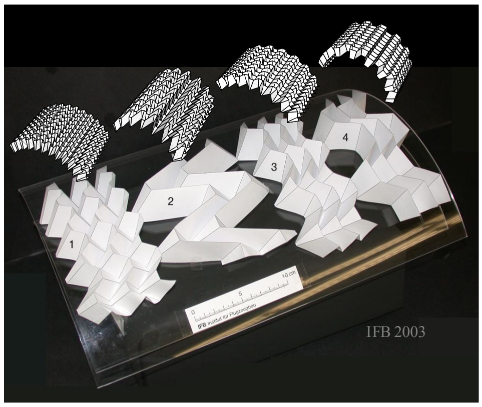

Fig. 8: Several cylindrical folded structures with similar density. The curved shape is reached without applying tension [5]

2.8 Production

Several types of folded cores can be produced in a continuous process. This enables economic large-scale production, a fact that is interesting for wide-scale application of sandwich constructions out of aerospace context as well [2].

Fig. 9: Early-stage output of continuous folding process demonstrator developed by IFB and Foldcore GmbH

3 DESIGNING FOLDED CORES

Isometrically folded cores are solutions to the flat-foldability problem. In a first step, the thickness of the used material is neglected. This approximation shows very good results for the usual small ratios of material thickness to unit cell dimensions.

The design of such structures can be achieved by different approaches showing specific benefits and limitations:

- A purely practical trial-and-error method using a piece of paper. This approach is limited to basic generic structures but can be useful for early-stage hands-on modelling.
- A very elegant design paradigm is to use the complete analytic description of the correlation between plane folding pattern and the resulting folded structure. Such a solution usually delivers a closed-form description of the kinematics and can easily be used to reverse-engineer cores with desired properties (e.g. density). For a large number of basic structures these parametric geometrical relations have

been derived [5]. These can afterwards be applied to a whole family of parametrized varieties, often with surprising results.

- For more complex structures this method can become tedious or unfeasible. Here a semianalytic approach can be chosen to generate solutions to defined geometrical constraints. This method is much more expensive in computing time than a closed solution but can be applied to a far wider spectrum of tasks. Here, certain design rules have to be iteratively observed to guarantee the validity of a proposed folding pattern. The right choice of design rules and applied solution strategy drastically reduces the computation time compared to pure number-crunching inverse kinematic approaches.

Due to the infinite number of possible shapes, the right choice of geometry depends heavily on the understanding of the application and the limits imposed by real-world factors like material thickness and foldability.

4 GEOMETRIC VARIETY OF FOLDED CORE STRUCTURES

4.1 Plane structures

Large, plane structures are a standard domain of sandwich panels. The plane zig-zag core and derivatives have already been shown. Because of their simplicity and their excellent mechanical properties, those structures are primary candidates for use in sandwich parts. While only a tiny fraction of the explored geometries is exemplarily shown, the chosen examples hopefully offer an insight into the huge flexibility that folded core design offers (Fig. 10-13).

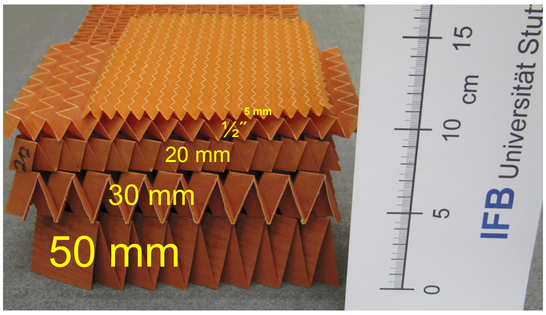

Fig. 10: Some plane core samples ranging from 5-50 mm in core thickness

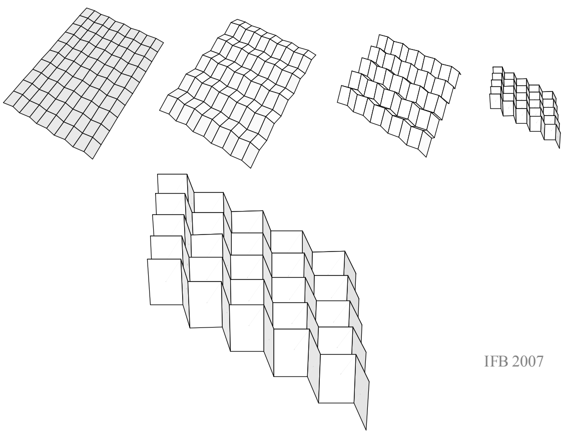

Fig. 11: Asymmetric zig-zag core (5x5). At first glance similar to the symmetric core, this variant shows asymmetric mechanical behaviour

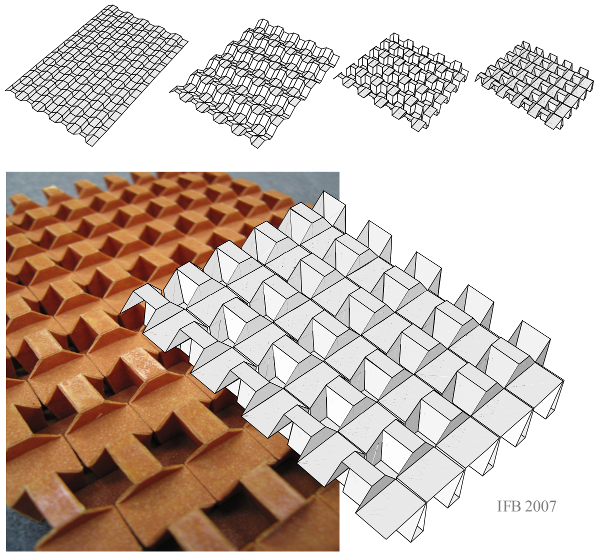

Fig. 12: "Stepstone" core structure (5x5). This core offers enhanced ventability

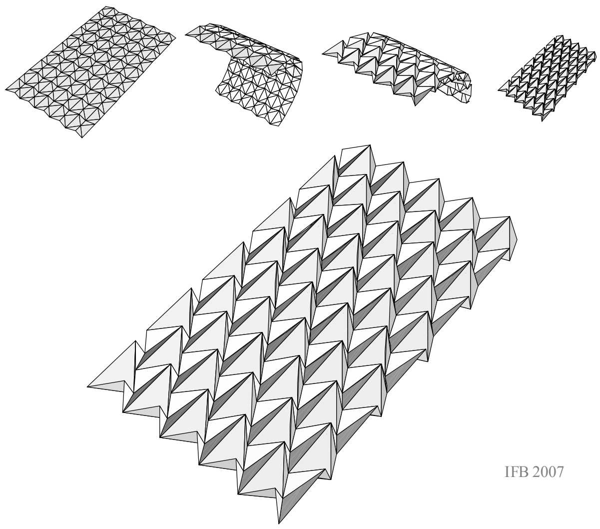

Fig. 13: "Pineapple" core structure (5x5). This core type shows interesting retrograde kinematic behaviour and can also be used for cylindrical applications

4.2 Curved structures

Folded cores can represent curved shapes. Especially cylindrical or tubular shapes are of interest, because the production of such cores can be carried out in a comparably simple continuous process.

Again, very different cores can be designed which have to be screened for their use in certain applications. Most plane cores can be modified slightly to develop a tubular shape or even display curved geometries at different folding states (Fig. 13-15).

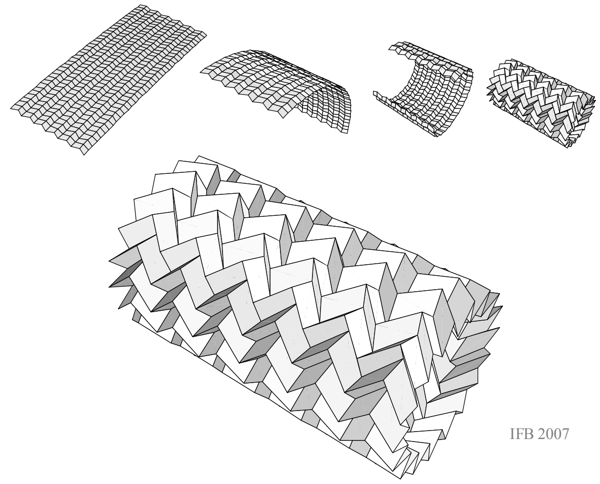

Fig. 14: Modified tubular zig-zag core with open cavities in longitudinal direction

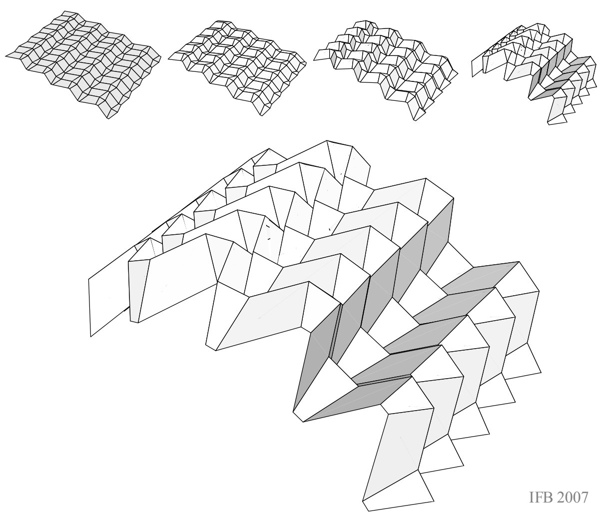

Fig. 15: "Trapezoidal" tubular core with open cavities in circumferential direction

4.3 Special cases

In addition to the already discussed core geometries that largely rely on one constant unit cell, cores with complex and changing unit cell geometries are also feasible. Apart from a more complex production, many interesting cores for specialised applications can be designed and produced.

These cores sometimes incorporate traits of different unit cell types and combine these to build free form surface cores and other, sometimes quite surprising – even if not practically relevant – structures. The examples in Figures 16 and 17 show one practically and one more artistically motivated core. Both structures were designed with the same tools and show the versatility of the developed algorithms and their implementation. Especially the automatic derivation of the kinematics even for complex cores offers new insights into the nature of flat-foldable structures.

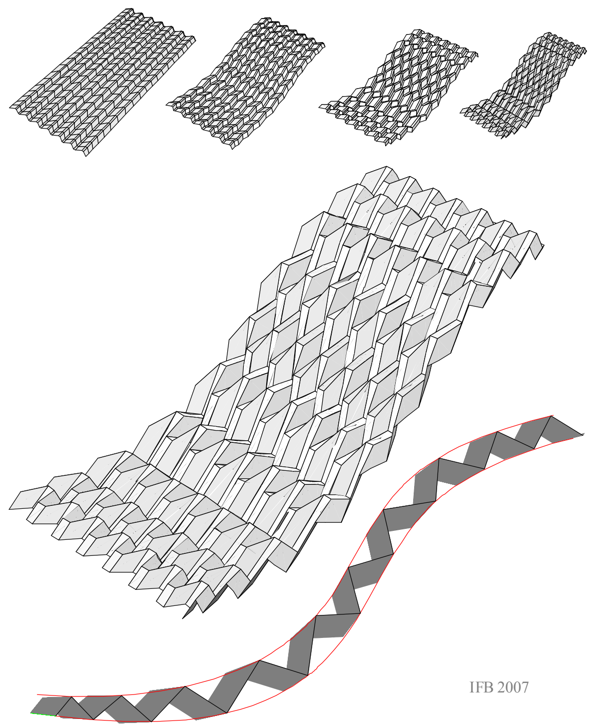

Fig. 16: Customised core structure with changing height, density and curvature.The core cross-section is defined in advance by the two enveloping curves

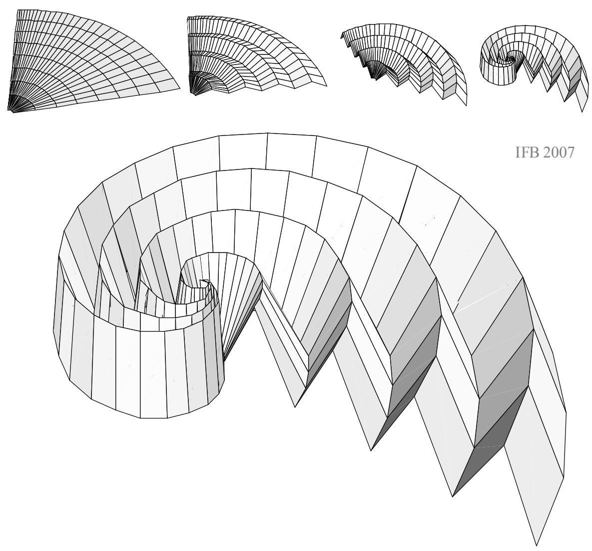

Fig. 17: "Ammonite" core study with archimedean spiral base

5 CASE STUDY CFRP SANDWICH FUSELAGE

5.1 Concept

The Airbus VeSCo (Ventilated Shear Core) study features a double shell CFRP sandwich fuselage (Fig. 18, 19). This concept aims at large weight and cost saving potential. The complexity of the fuselage can be dramatically reduced, minimising or even eliminating the need for frames and stringers and the accomanying rivets, clips and cleats.

For the realisation of this concept, folded cores provide several key features:

- Taylored mechanical performance

- Ventable core structure with gravity-assisted draining ability
- Cylindrical core shape
- Elimination of large-area potting by seamless panel application

5.2 Development

Several core generations for application in VeSCo shells have been developed at the IFB (Fig. 1, 20) [6]. Areas of research covered are:

- Development of geometric models and design tools
- Rapid Prototyping of folded cores
- Modelling of mechanical properties
- Testing of mechanical properties
- Material development
- Industrial scale manufacture of folded structures

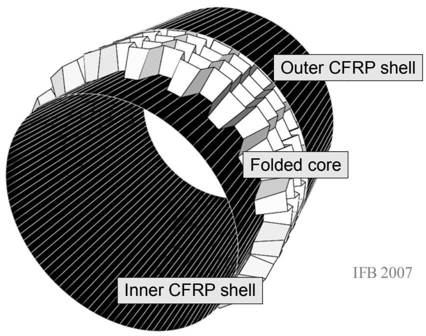

Fig. 18: VeSCo concept: Double CFRP sandwich shell using tubular folded core (illustration not to scale)

Fig. 19: Conceptual rendering of VeSCo fuselage structure (Source: Airbus)

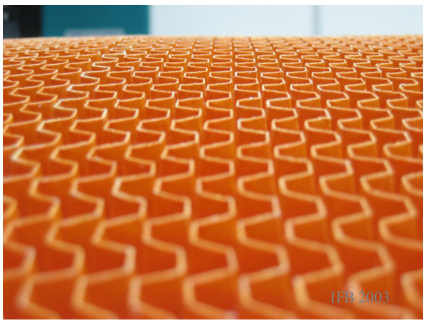

Fig. 20: View of VeSCo test panel section produced at IFB

6 CONCLUSION

Folded cores provide a high-performance core material for wide-scale application in aerospace structures. Some key features like ventability allow new structural concepts using large sandwich parts that were previously unfeasible due to lack of suitable core materials.

The geometric variety of folded structures allow for a multitude of specifically taylored cores that can incorporate additional functionality. Together with the shown feasibility of industrial-scale manufacture, folded cores will become an interesting alternative to already existing core materials.

ACKNOWLEDGMENTS

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