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Folded Cardboard Sandwiches for Load-bearing Architectural Components

ABSTRACT

The high resource demand of the building sector clearly indicates the need to search for alternative, renewable and energy-efficient materials. This work presents paper-laminated sandwich elements with a core of corrugated paperboard that can serve as architectural components with a load-bearing capacity after a linear folding process. Conventional methods either use paper tubes or glued layers of honeycomb panels. In contrast, the folded components are extremely lightweight, provide the material strength exactly where it is statically required and offer many possibilities for design variants. After removing stripes of the paper lamination, the sandwich can be folded in a linear way at this position. Without the resistance of the missing paper, the sandwich core can be easily compressed. The final angle of the folding correlates with the width of the removed paper stripe. As such, this angle can be described by a simple geometric equation. The geometrical basis for the production of folded sandwich elements was established and many profile types were generated such as triangular, square or rectangular shapes. The method allows the easy planning and fast production of components that can be used in the construction sector. A triangle profile was used to create a load-bearing frame as supporting structure for an experimental building. This first permanent building completely made of corrugated cardboard was evaluated in a two-year test to confirm the efficiency of the developed components. In addition to the frame shown in this paper, large-scale sandwich elements with a core of folded components can be used to fabricate lightweight ceilings and large-scale sandwich components. The method enables the efficient production of linearly folded cardboard elements which can replace normal wooden components like beams, pillars or frames and bring a fully recycled material in the context of architectural construction.

Keywords: Adaptable design, Green construction technology, Folded components, Corrugated cardboard sandwich, Architecture, Construction

1. INTRODUCTION

Future-proof architectural constructions must possess many characteristics. They should be constructed solid and durable as well as inexpensive and sustainable, while the quantity of used material and production energy has to be as low as possible. Components made of corrugated cardboard can make an important contribution in this context because of many ecological advantages like low embodied energy, excellent recycling rate and residue-free production process. However, they are currently rarely used in the architectural field. Only in some cases they are used as core material in walls [1] or as thermal insulation panels [2].

As corrugated cardboard materials are rarely used in the construction sector, only a small selection of literature and projects can be found. Lu et al. [3], Nordstrand [4] and Abbès et al. [5] provide an approach to the issue of stability of corrugated sandwich panels. The strength values of the presented material (compressive strength, tensile strength, bending) as well as the use of folded components are discussed in detail by Schütz [6]. Tian and Lu [7], Ayan [8] and Pohl [9] explore the structural and architectural use of corrugated cardboard. Eekhout et al. present basic approaches and implemented architectural projects [10]. Basic knowledge on folded paper objects are presented by Jackson [11], [12] and Zeier [13]. Miura and Sakamaki analyse folding in a deeper way [14] and folded lightweight structures are presented by Hilmar [15].

In this paper, five hypotheses are postulated. First, an exact zone of folding is definable by removing a strip-like part of the inner face material (e.g. with a CNC controlled milling machine). Second, the width of this zone relates to the resultant angle of the folded component and this relation can be described with a simple equation. Third, the profiles are solely producible by longitudinal folding. Fourth, the paper removal on both sandwich surfaces allows more sophisticated profiles with convolutions in two directions and leads to a huge amount of design varieties. Fifth, the production of folded multipart elements with load-bearing capacity is possible.

2. MATERIAL

The core of the sandwich plate consists of corrugated and flat paper layers that are glued with Sodium silicate (CAS 1344–09–8) to form a block. The sinusoidal corrugated layer has a wave separation of 8 to 9,5mm and a wave height of 4 to 5,3mm (coarse wave A). The core consists of 100% recycled paper with a weight of 110g/m^2. This paper has a thickness of 140 to 159µm and the weight of a block is 65kg/m^3 with a tolerance of 15%. The block is cut into flat panels of 5 to 100mm thickness. The surfaces of the panels are covered with so-called kraft paper by using PVA-glue. This paper consists of about 30% recycled material, has a weight of 280g/m^2 and a paper thickness of 348µm. The maximum size of the sandwich panels is 3130 x 1260mm. The here presented methods and results refer to sandwich panels with a material thickness of 30mm and linear folds.

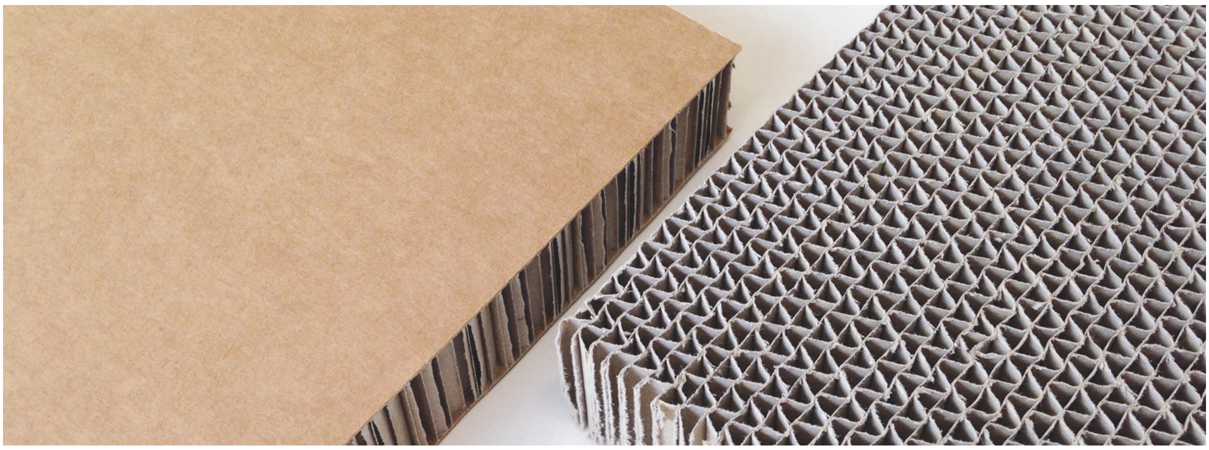

Figure 1: Corrugated cardboard sandwich (left) and core material (right)

3. METHODS

The folding of a flat element generates a zero line that divides the material into an inner zone of compression and an outer zone of elongation. In a homogeneous material like a metal sheet, the zero line runs through the geometric centre. This can be seen in the left section of figure 2.

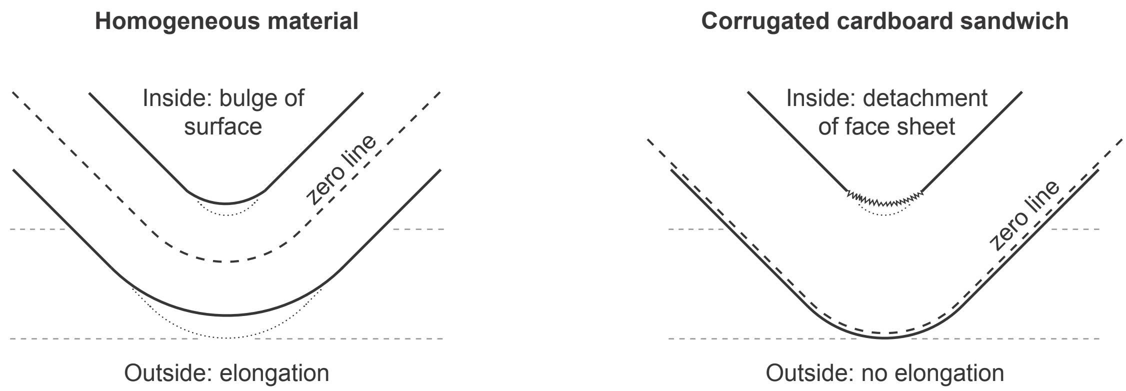

Figure 2: Folding of homogeneous material (left) and corrugated cardboard sandwich (right)

Corrugated cardboard sandwiches are inhomogeneous, therefore the structure of core and cover material should be considered separately. The surface paper has a high tensile strength and flexibility due to bending. The core is very pressure-resistant under vertical load but it is very sensitive to lateral compression. This feature turns out to be a great advantage in this case. The zero line migrates close to the outer surface paper and just a zone of compression remains at the inside. This can be seen in the right section of figure 2. The resultant curve describes a circular arc segment, which results in a unique aesthetic appearance. During the folding process, the inner surface is compressed in such a way that it separates itself from the core structure. To avoid this detachment a stripe-like part of the inner surface paper is removed. Then, the folding process runs effortless and the longitudinal edges of the remaining papers touch each other. This indicates the end of the folding process. Figure 3 shows the section through a corrugated cardboard plate before and after the folding process. It clarifies the relation between starting angle α_1 and resultant angle α_2.

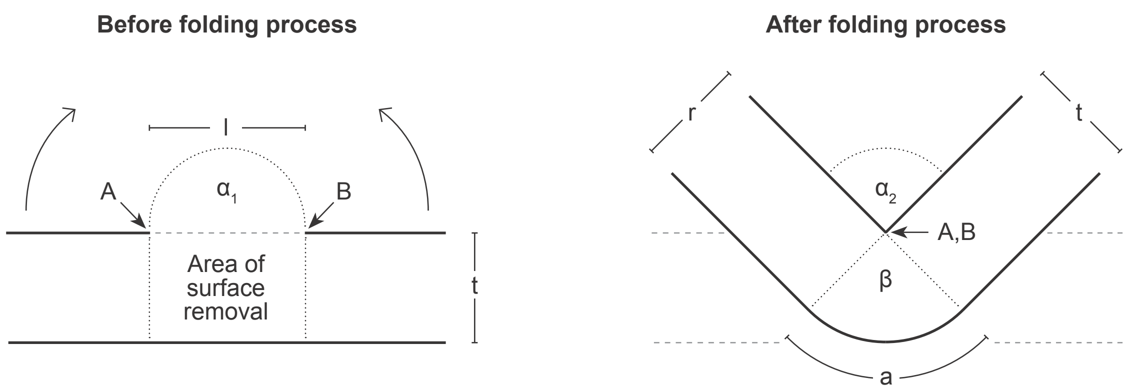

Figure 3: Unfolded corrugated cardboard sandwich (left) and folded element (right)

This folding process can be described geometrically by an equation. Their derivation is as follows. The material thickness t corresponds to the radius r. The width l of the removed paper defines the distance $\overline{AB}$ between the longitudinal edges of the remaining surface paper. The folding process to the resultant angle α_2 creates the internal angle β. The arc length a corresponds to l as well as A and B are congruent. If a final angle α_2 is given, the strip-like paper removal can be calculated by using the formula of the circular arc:

$$a = \pi \cdot r \cdot \frac{\beta}{180°} \quad \text{Eq. (1)}$$

Since r is known by the given material thickness t, the angle β remains as the only unknown parameter. Because a is equal l, the final formula reads as follows:

$$l = \pi \cdot r \cdot \frac{(180° - \alpha_2)}{180°} \quad \text{Eq. (2)}$$

The equation shows, that the width of the paper removal is inversely proportional to the resulting angle. More material must be removed to obtain a smaller angle. The geometric coherences relate only to the inner angle and the arc length. That is why the equation can be used for any material thickness.

4. RESULTS

A load-bearing architectural component like a beam or a pillar is producible by multiple folding of a formerly flat plate into a profile. The following example of a pillar is based on an equilateral triangle and shows the application of the presented formula. Figure 4 shows the folding process schematically.

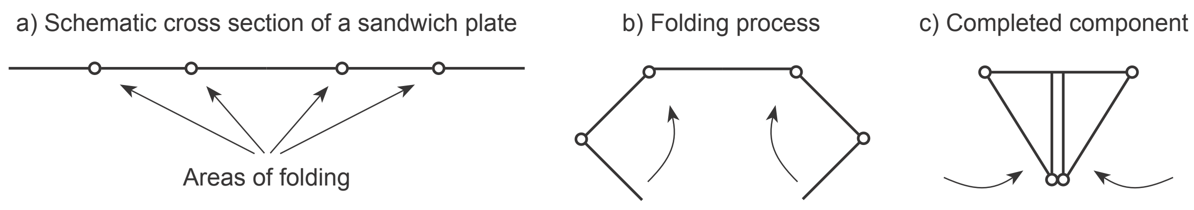

Figure 4: Folding process of a triangular pillar

The profile is made of a honeycomb plate with a thickness of t=30mm. The dimensions are w = 308mm and h = 223mm. One half of this symmetric profile is considered for identification of the areas of paper removal. This is shown in Figure 5.

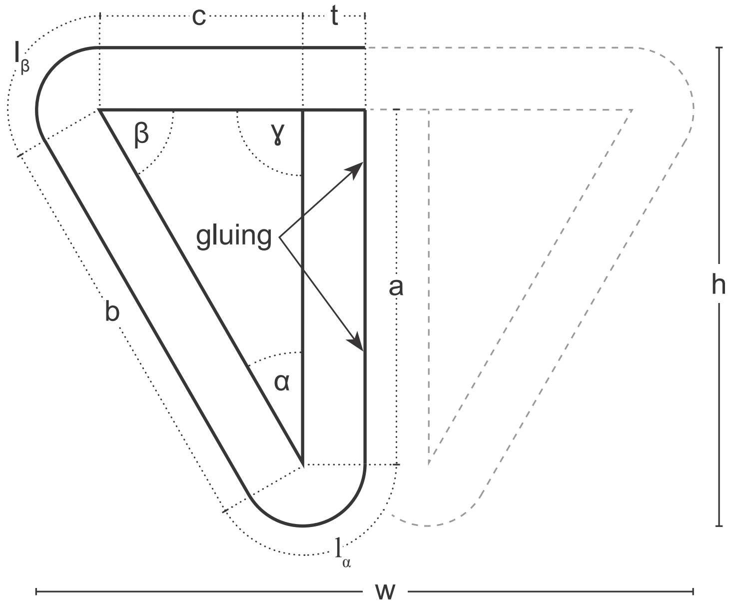

Figure 5: Half section of the described pillar with single segments

The half of the profile is a right triangle with the opposite side a, the hypotenuse b and the adjacent side c. These lengths are calculated by using the angle laws and the given dimensions for w (width) and h (height) as well as t (material thickness) of the desired profile. The two surfaces that touch each other after folding are glued with standard PVA glue. The total developed view of the component is composed of a sequence of lengths whose sum must to be doubled. The two important areas of paper removal are l_α and l_β. Both can be calculated with equation (2). The total length of the developed view l_{total} is calculated with the following equation:

$$l_{total} = 2 \cdot (t + c + l_\beta + b + l_\alpha + a) \quad \text{Eq. (3)}$$

With the method presented here a variety of different types of profiles can be produced. Figure 6 shows the horizontal section through a selection of pillar-profiles based on basic geometrical shapes. In principle, hollow profiles (see Fig. 6a, 6b, 6c) and double material profiles (see Fig. 6d, 6e, 6f) can be distinguished.

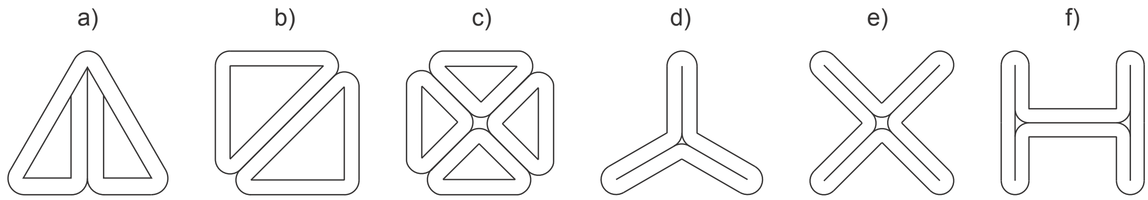

Figure 6: Hollow profiles (a,b,c) and double material profiles (d,e,f)

The profiles shown above can be used as role models for ceiling structures. Figure 7 shows the vertical section through two individual beams (see Fig. 7a, 7b) as well as a ribbed slab (see Fig. 7c). This is enabled by continuous folding and gluing of the substructure. The extension to a large-size ceiling sandwich is possible by gluing of an additional plate on the bottom side (see Fig. 7d).

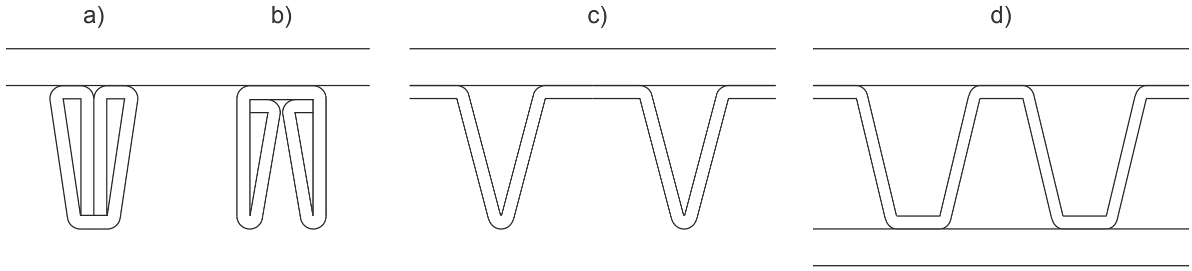

Figure 7: Single horizontal beams (a, b), a ribbed slab (c) and a sandwich ceiling (d)

The profile shown in Figure 5 is the starting point of a framework that serves as load-bearing structure of an experimental building, which is entirely made of corrugated cardboard panels. The building is called "Open Source: Cardboard" and combines the advantages of folded elements for construction and flat sandwich panels for thermal insulation. With a length of 5.05m, a width of 3.36m and a height of 3.58m, the permanent pavilion offers space for at least six student workplaces. Figure 8 shows the views and the interior. [16]

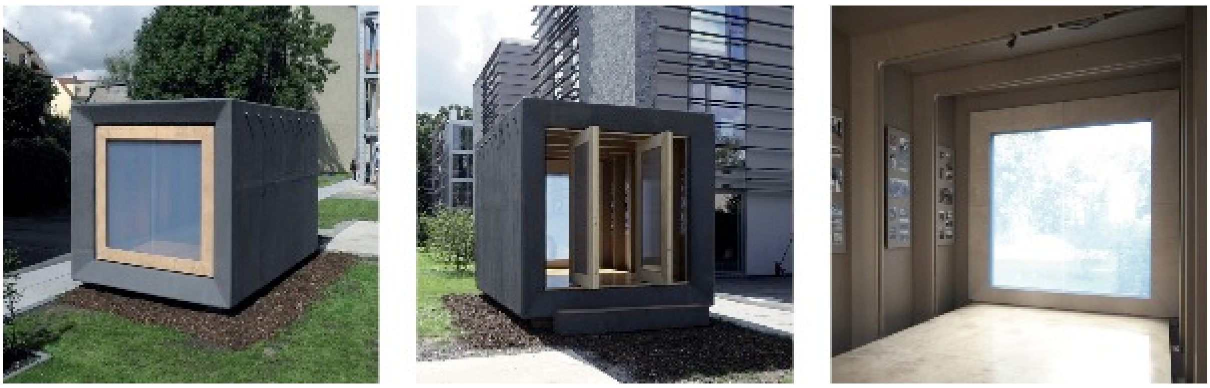

Figure 8: South facade (left), north facade (centre) and interior (right)

5. DISCUSSION

The results confirm the hypotheses made above and show the simple planning and production of load-bearing folded corrugated cardboard elements. The profiles possess aesthetic curves in the area of folding and thus a continuous surface. Thereby, open cut edges are avoided what facilitates stability and uniform appearance. The production is simple with a standard two-axe milling machine.

Now, a hitherto rarely considered material can be used in in the construction sector. It has a great potential to replace normal wooden beams and pillars as well as ceilings. A beam with a length of 300cm and a height of 22cm carries a load of 400 kg with only little deformation. Beside the here presented profiles, other hybrid components can be created by the addition of thin wooden plates. This opens up an entirely new field of research.

The method provides an enormous variety of profile variants whose shape not only depends on static aspects but also on aesthetic design specifications. The way of calculation and the principle of production are comprehensible and the used material is cheap. Even complicated folds are feasible and allow the production of multi-folded supporting elements. Two ways of production can be distinguished. First, the simpler so-called wrapped profile with material removal on just one side and second, the zigzag profile with processing on both surfaces. The profiles are adaptable to almost any every construction principle with elongated load transfer and also slab-like elements are producible. As seen in Figure 8, the successful application of folded cardboard sandwiches as load-bearing elements was proven in a two-year evaluation between July 2014 and July 2016.

Despite all the advantages, some problems should not go unmentioned. Not all types of sandwich board can be folded in the manner described herein. The core material must be compressible in direction of the folding force effect. The surface material should be elastic enough to bear the bending due to folding without breaking. Future research should explore other materials that provide similar material properties like corrugated cardboard panels. The maximum dimensions of the described sandwich panels are the reason for limitations in the length and profile size of the folded parts. Additions by overlapping are possible but that increases the production costs. The double material profiles as well as the ribbed slab and the sandwich ceiling require a paper removal on both surfaces. This should not pose a big problem with using modern CNC machines, however, it also increases the production costs. Finally, also the basic properties of the paper material should be considered. Its sensitivity against water or fire remains even though the facing material is resistant against such influences. This still causes problems in building approval of such components.

6. CONCLUSION AND OUTLOOK

I reported the efficient design and production of load-bearing components that are made of folded corrugated cardboard panels. A simple design strategy allows the easy planning and the fast production. An evolutionary step could be the production without milling. In this case the core material of the sandwich is covered partly in the production process. An advanced research field could be the prefabrication of large-scale walls and ceilings for architectural projects. Here, the folded sandwich components can serve as core material as well as stiffening components. Hybrid constructions with wooden parts are also conceivable in this context. All in all, the method enhances the capability of corrugated cardboard sandwiches and offers a new way of construction to the architectural sector.

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