Transformable active bending: 
a kinematical concept

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Abstract

Transformable structures facilitate reuse of components and structures by increasing the speed and ease of erection and lowering the stacking volume during transportation. Thanks to its unique ability to use structural members under different curvatures and return bent elements to their initial straight or planar geometry, active bending has the potential to expand the existing morphology of transformable structures. This paper discusses the development of such structural and kinematical systems on a theoretical level. First we will give a review of the existing systems for transformable and active-bending structures. By combining these, we have developed new kinematical systems of which three were selected for the scope of this paper: deployable grids, active bending kit-of-parts systems and pliable textile hybrids. These will be discussed in more detail and applied on a first design case, illustrating the potential applicability in a real case. The kinematical study shows the potential of active bending in transformable structures. Using elastic deformations lowers the complexity of the structures and can be actively used in the structural transformation. However, questions about the structural behaviour and technical detailing remain for future research.

Keywords: active bending, transformable structures, deployable structures, kinematics, digital modelling.

1 Introduction

In a context of constant changes, adaptation is vital to the existence of the built environment. The often-static nature of our building structures however limits this adaptation and contributes to a high economical and environmental cost. The
construction industry accounts for the largest share in material consumption and waste production, representing 40 to 50% of the total waste disposal in Europe [1]. Additionally, the inability of our building stock to adapt to demographic, economical and other societal changes leads to the proliferation of worldwide sustainability problems. Transformable structures offer speed and ease of erection and facilitate transportation thanks to a small stacking volume, thus allowing reuse on a component and structural level. Integrating them in our current building stock can increase the adaptive capacity of our built environment, enabling it to adapt to changes and lowering the economical and environmental cost by decreasing the material and waste production. To achieve this, structurally and material efficient, lightweight transformable structures need to be engineered that can easily be deployed or disassembled for storage and transportation [2].

As the instrumentalisation of bending deformations, active bending allows using initially straight or planar elements under different curvatures, avoiding permanent deformations and thus enabling the (structural) elements to return to their primary, unbent shape [3]. This kinematical manipulation of the structural members offers promising possibilities for new and innovative systems in the field of mobile, adaptable and rapidly assembled structures: transformable active-bending structures. Therefore, the kinematical behaviour of these structures needs to be studied in more detail, to shed light on the different kinematical principles and corresponding transformational capacity that can be achieved. Yet, the complex relation between the material behaviour and the geometry of active-bending structures poses important challenges. The internal stress concentration needs to be limited to the elastic domain of the material to prevent permanent deformations throughout the different geometrical configurations. At the same time the geometrical stiffness, which is directly proportional to this bending stress, needs to be sufficiently high during the different functional states of the structural space enclosure.

In this paper, we present a theoretical framework for transformable active bending. We discuss different existing systems and principles in a state-of-the-art of transformable structures and active bending. These existing systems are combined in a series of transformable active bending concepts. The authors of this paper selected and defined three of these concepts that show the most potential based on the strong integration of active bending in their kinematical behaviour. Finally, a design case illustrates the theoretical principles by developing a specific kinematical system for one of them.

2 Previous work/state-of-the-art

Although the number of realisations is quite limited for transformable structures as well as active bending, researchers have already developed multiple models and (structural or kinematical) systems. In the next part of this paper we will discuss these systems and make a rough categorisation: three principles for active bending and two for transformable structures.
2.1 Active bending

As a structural principle, active bending is not a new concept. Already in primal nomadic cultures, elastic bending was used to create small living environments out of lightweight and elastic materials, such as the Madan Mudhif and the Mongolian Yurt [3]. Yet apart from these basic settlements and a handful of gridshells, the principle has never really found its way towards everyday practice and realisation. Today, the evolutions in digital modelling and numerical analysis motivate a growing interest in active bending, resulting in the realisation of several experimental and research-oriented structures. Based on the constituent components and the way in which they are assembled into a structurally performing structure, a first categorisation can be made between three principles: surface structures, textile hybrids and gridshells.

Active-bending surface structures are composed of flat plate elements. Bending and connecting the elements allows generating a curved surface structure. In this case, no additional membranes or cover materials are needed. A recent example is the ICD/ITKE research pavilion of 2010 (figure 1a), which is composed out of thin plywood plates [4]. The coupling of these elements ensures a partly self-tensioned system, thus lowering the bending resistance in the supports. Textile hybrids owe their structural performance to the combination of slender linear elements and a membrane. Connecting them creates a self-tensioning system in which the bent elements become geometrically restrained by the membrane that is in turn pretensioned by the bending resistance of the linear elements. This concept has already become common practice in the camping industry. On a larger scale, experimental set-ups such as the M1 at La Tour de l’Architecte in Monthoiron (figure 1b) show promising results [5]. During the 20th century, several gridshells were realised, of which the Multihalle in Mannheim (figure 1c) is probably the most well-known. Their form-finding was usually done with analytical tools, such as the hanging chain model, whereas recent developments allow to study and develop gridshells also in a numerical way [6]. Thanks to the elastic bending of the members, gridshells can be easily assembled on the ground and given their final shape by moving the boundary points. Additional stabilizers are needed to remove the rotational freedom provided by the connecting hinges.

2.2 Transformable structures

Transformable structures are characterised by a kinematical behaviour that allows them to transform from one (functional) state or configuration to another with minimal time and effort, e.g. from a small-packed stacking configuration to a large space enclosure. This allows them to rapidly adapt to changing boundary conditions. Generally, a distinction can be made based on two concepts: kit-of-parts systems and deployable structures [2].

A kit-of-parts is a set of compatible (structural) elements that can be combined and re-combined in different configurations. Its ‘kinematical’ behaviour or transformation is based on the use of reversible connections,
allowing disassembly and reconfiguration. The transformational capacity of these systems depends on the ease of disassembly as well as the number of configurations that can be achieved with one kit. A special case of kit-of-parts is the universal component. A kit of multiple reproductions of one and the same universal ‘element’ can be used to produce a myriad of structural configurations. In this case the universal component should be compatible with (a copy of) itself. The strength of kit-of-parts systems is the large design space that is generated by allowing assembly and re-assembly in different geometrical configurations. The designer creates a system rather than an object, enabling a wide variety of ‘solutions’ depending on the (changing) boundary conditions. The principle is also applied in small-scale products and children’s toys, such as Lego and Meccano®.

Figure 1:  (a) ICD/ITKE pavilion 2010, (b) M1 at Tour de l’architecte and (c) Mannheim Multihalle [7–8].
Deployable structures are designed as structural mechanisms and base their transformation not on the reversibility of their connections, but on their deployment. Through the use of hinged connections (often rotating in multiple directions) they can be deployed from a small stacking volume to a full-scale space enclosure. An important group of deployable structures are the scissor structures, consisting of a system of straight bars connected by an intermediate revolute joint or hinge. Adjusting the length of the bars or the location of the intermediate hinge allows generating different 3D spatial structures [9]. Deployable structures have the advantage of very rapid erection. Contrary to the kit-of-parts systems, deployable structures don’t necessarily generate different functional configurations. Thanks to the deployment however, they can be transformed from small stacking volume to functional space enclosure and vice versa without the need for assembly and disassembly in a minimal amount of time.

The universal scissor component combines the rapid deployment of deployable structures with the large design space of kit-of-parts systems. The component can be assembled into multiple deployable structures with specific deployed geometries [10].

![Deployable structures](image)

Figure 2:  (a) Demountable kit-of-parts system (© Michael Lefeber), (b) deployable bar structure (© Grupo Estran).
3 Elastic bending as structural transformation

In active bending, the process of elastically deforming the structural elements can also be regarded as a process of transformation. This does not mean that every active bending structure is necessarily (what we call) a transformable structure. The construction of gridshells and most of the other recently built bending pavilions still takes quite a lot of time compared to the rapid erection of deployable structures and their geometry is designed for one specific configuration that doesn’t allow reconfiguration or multiple design solutions. Yet, active bending does show a lot of potential for transformable structures. Thanks to the reversible bending, curved 3D-structures can easily be realised with straight or planar elements, reducing the complexity of the structure as well as the transportation and stacking volume. Additionally, using bending as intrinsic transformation can avoid a high complexity of the joints, reducing the self-weight in comparison to e.g. deployable scissor structures. The main difference between active bending as an erection process and active bending in transformable structures is that for the latter a functional or bent state is expected of the members in different configurations and for different curvatures. The complex relation between the geometry, material behaviour and stability poses important challenges in this respect. On one hand, the curvature and corresponding internal stress needs to be limited to avoid permanent deformations or failure of the bent material. On the other hand, the (geometrical) stiffness, which is directly proportional to the internal stress and thus to the curvature, needs to be sufficiently high. Consequently, a restrictive geometrical domain exists in which the bent elements are structurally viable, thus limiting the number of configurations. Researchers of the Institute for Building Structures and Structural Design (ITKE) at the university of Stuttgart developed such kinematical active bending systems for responsive facades based on plant movements, e.g. Flectofin® [11]. Thanks to the intrinsic bending properties of such systems, very elegant and low-tech shading systems can be realised [12].

4 Transformable active bending: three concepts

Based on the existing concepts of transformable structures and active bending, we can set up a combinatorial matrix to extract new kinematical principles with bending integration (see figure 3). We take the aforementioned grids (1), surface structures (2) and textile hybrids (3) as active bending principles. The kinematical systems of deployable structures (a) and kit-of-parts (b) are supplemented by elastic bending as transformation (c). Combining these generates nine theoretical, kinematical concepts that each illustrates a possible synergy between transformability and active bending. For the scope of this paper, the authors selected and defined three principles with great potential and particular correspondence: deployable gridshells (1a), active bending kit-of-parts systems (2b) and pliable textile hybrids (3c).
4.1 Deployable grids

The detailing of deployable scissor structures often leads to complicated connections. To generate 3D structures, the revolution joints need to allow rotation in multiple directions. In gridshells, the connections allow rotation only in one direction, around the rotational axis perpendicular to their (unbent) plane. A third dimension (height) is added by elastic bending. Thus, the complexity of the connections can be reduced considerably. Yet so far, most gridshells don’t allow rapid, manual erection and reuse. Additionally, creep affects the often-wooden structures, disabling full return to their primary, unbent shape. In nomadic yurts a deployable scissor-grid is used to create the walls for the cylindrical space enclosure. This can be highly compacted, deployed into a large, planar grid and elastically bent to create a curved geometry. In this system, a separation is thus made between two phases: the two-dimensional scissoring mechanism and the elastic bending deformation. Another system for deployable active bending structures can consist of a grid in which the elements are three-
dimensionally curved/bent during deployment. To a limited extent, this principle is already included in so-called bi-stable deployable scissor structures [13]. Here, an intermediate snap-through effect occurs during the deployment in which the linear elements are elastically deformed and internal stresses occur before returning to a ‘stable’, fully deployed state. These elastic deformations are induced by geometric incompatibilities between the member lengths. In this system, the scissoring action and elastic bending occur simultaneously, during one phase of deployment.

4.2 Active bending kit-of-parts systems

Due to their design for disassembly and the need for reconfigurable connections, kit-of-parts systems often have difficult and highly complex nodes. Active bending creates curvature by deforming the members and enables reconfiguration by the degree of bending, resolving the 3D shaping and transformation on an intrinsic, element-level and thus relieving the nodes. In general, three aspects are of main importance when designing a kit-of-parts system: the compatibility of the components, the ease of (dis)assembly and the resulting, geometrical freedom. The compatibility of the components is evidently assured by the detailing of the nodes, allowing (different) components to be connected in a volumetric, structural entity. Therefore, also the dimensions of these elements need to be compatible in a way. Conventional kit-of-parts, with rigid components, often use generative dimensioning systems to generate this set of compatible proportions. Active bending can alter the dimensions of the elements (or rather their span and curvature) by inducing elastic deformations, assuming of course that the internal stress is kept within the aforementioned boundaries. This increases the proportional compatibility, but does however not necessarily lead to a larger set of viable design configurations. Ease of assembly and disassembly relates to the nodes as well. The reversibility of the connections allows the structures to be dismantled and transported in a small stacking volume. Larger (three-dimensional) entities are often subdivided into smaller units to reduce this volume. Active bending generates three-dimensional elements out of linear (1D) or planar (2D) elements, thus combining a compact volume in flat state with the ease of creating curved spatial structures through elastic bending. The geometrical freedom of a kit-of-parts is based on the number of different geometrical configurations that can be realised with the same kit of elements, depending of course on the compatibility of the elements and possibility of re-assembly. In addition to the possibilities of conventional ‘rigid’ systems, active bending introduces reconfiguration on the element-level. Big challenges remain however in combining these different configurations in a large-scale, structurally viable space enclosure.

The concept of active bending kit-of-parts systems is further illustrated by a design case in the next part of this paper.
4.3 Pliable textile hybrids

Thanks to their structurally efficient behaviour, textile hybrids can be realised with very thin, elastic rods. The extensive bending (and high resulting stress) and the structural interaction with the membrane compensate the high level of elasticity and create geometrical stiffness. The thin, linear elements can be subjected to very large elastic deformations, allowing them to be ‘elastically folded’. On a small, product scale, the 2-second tent is a popular example of such pliable textile hybrids. Here, the system is highly restrained during stacking and the bending stresses are used during deployment. However, the folding induces high internal stresses in the elements and special care has to be taken to limit these to the elastic limit strain. These small-scale examples show a transformation from stored volume to functional space enclosure. Intermediate functional states are not incorporated. Therefore the structural behaviour of the rods under different curvatures needs to be studied in detail. Additionally, the membrane needs to be tensioned during the different functional configurations to remain structurally effective.

5 Design case: an active bending kit-of-parts system

As an illustrative case of transformable active bending, we present an active bending kit-of-parts system in the following part of our paper. The kit is based on a universal component that can be combined into different geometrical configurations. The component’s geometry is created by a curved-line folding pattern, as shown in figure 4a. Folding the plate creates a linear, curved element that is stiffened by the bending pretension. Different curvatures can be achieved, depending on the degree of bending. The maximal curvature is defined by the curvature of the folding line. A finite element simulation shows the deployment of the component with the corresponding stress distribution (figure 4b). Combining the components linearly (1 on 1) creates an arch-like structure (figure 4c), of which the dimensions can be adapted depending on the individual curvature of the components. Connecting three elements can create a three-dimensionally curved structure, such as a dome (figure 4c).

Although still in a conceptual design phase, the system already shows an interesting correlation between the active bending and kit-of-parts principles. Its kinematical behaviour can be subdivided in two layers: that of the component and the assembled structure. Active bending generates the component out of a flat plate element, simplifying the production process as well as transportation. Even before assembly, the component can be shaped in different configurations. The resulting, assembled structure owes its geometry to the component’s configuration and the mode of assembly (2 or 3 components). This layering thus allows both generating different ‘shapes’ (e.g. arch of dome) and adjusting the dimensions (depending on the curvature of the individual components).

However promising, the system also highlights important challenges that still need to be overcome, such as the structural behaviour under loading and the detailing of the connections and elements.
Figure 4: (a) Composition of the universal component, (b) geometry generation through FE-modelling (Sofistik) and (c) different configurations.
6 Conclusions

As a structural principle, active bending shows a lot of potential to expand the existing morphology of transformable structures. Although the principles are still in a theoretical phase, different systems can be produced that show the advantages of applying elastic bending in the kinematical/transformation process of transformable structures. Here, the kinematical behaviour is not limited to the level of the structural entity (by deployment or disassembly of the entire structure), but is expanded by integrating the elastic deformation of the elements. The system is in this case not a pure mechanism (like deployable scissor structures), but can either be a hybrid system, such as the deployable grid, or a pure kinematical bending system, such as the pliable textile hybrid that can be completely elastically folded. Using the intrinsic properties of the elastic materials can greatly reduce the complexity of transformable structures and use them in a more material-efficient way. However, a lot of questions remain, e.g. concerning the structural behaviour under loading and the detailing of the structures and their connections.

7 Future research

The kinematical exploration presented in this paper is a first part in a more extensive research on the development of transformable structures based on active bending, introduced by the authors as transformable active bending. A next step will be to develop the presented theoretical systems in more detail and develop physical and digital models. One of the main questions will be about their structural behaviour, both during erection or transformation and under external loading. These test cases will be an important tool in developing more general, parametric models for transformable active bending structures. They will also be used to develop the systems in a more detailed way, e.g. by designing the connections, thinking about materialisation and testing the deployment and kinematical behaviour.

References


