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Active Bending, A Review on Structures where Bending is used as a Self-Formation Process[1]

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ABSTRACT: In this paper structures that actively use bending as a self-forming process are reviewed. By bringing together important material developments and various historical as well as recently built samples of such structures, the aim is to show coherences in their design approach, structural systems and behaviour. Different approaches to bending-active structures are defined and described. By making this work accessible and categorising it, this paper aims to contribute to an emerging development.

A differentiation of such structures is suggested based on their design approaches. Three such approaches are differentiated: the behaviour based approach, the geometry based approach and current research that seeks to integrate the two. In this paper the nature of these approaches and some important project samples are discussed.

1. INTRODUCTION

Active bending is understood to be systemised elastic deformation i.e. bending. The main motivation behind using it lies in the simplicity of producing curved elements. In the past, the lack of alternative manufacturing techniques for curved building components or entire structures made active bending a widely spread and recognised building technique. Today, economic reasons, advantages in transportation and the assembling-process, as well as the performance and adaptability of the structure, support the use of active bending.

While various empiric construction methods known from vernacular architecture make use of the elastic behaviour of their building materials, only few such examples are to be found in 20th century architecture. Here, the use of elastic deformation is mainly utilised as an economic construction method for double curved shell structures whose forms were developed and approximated by hanging models or simple analytical approaches. Recent developments in simulation techniques now render it possible to form-find and analyse structures that derive their complex curved geometry solely from an erection process in which they are elastically deformed. This has formed the basis for various explorations that include new types of surface- and gridshells, hybrids composed of membranes with elastically bent battens, and various types of adaptive and elastic kinetic structures. On a structural level, they are curved structures that are influenced by residual stress in their load bearing capacity and behaviour, which may, in most cases, not be summoned or compared on the level of structural typologies. Yet, they all share the approach of creating

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curved geometries based on straight or planar building elements by means of bending, within the elastic range of a certain material. On this level of a material driven design approach, a number of strategies can be differentiated which will be used to relate the projects presented in this review to certain groups and building periods.

2. PREMISE OF MATERIAL DRIVEN FORM

In order to guarantee sufficient load bearing capacity of a structure that includes considerable self-equilibrating bending stress, materials of high breaking strain must be chosen. The traditional building materials of softwood, bamboo and reed offer such characteristics, leading to an extensive use of active bending in the constructions of vernacular architecture across cultures and continents. An indication for their lightweight potential and economical material use becomes apparent when considering the fact that, historically, such structures were predominantly found in areas where either wood was rare, mainly softwoods were available, or in cultures that had not yet developed the technologies to process larger timber pieces [1] (p. 652).

The industrial revolution advanced iron as a building material; in the on-going developments, steel and reinforced concrete became the dominant materials of 20th century architecture. Along with these materials, a split from a master-builder to a planning architect and a structural engineer using simplified static theories and a constructor took place. Building what is designed by others systematically limits the highly integrated concept of active bending in building structures. A set of well-defined geometrical and structural typologies are the practical basis for most styles of 19th and 20th century architecture, which enabled the control of technological complexity, yet limited geometrical and structural variety. Form defining strategies based on material and forces have been developed, not surprisingly then, by only a few but widely recognized individuals, such as Vladimir Shukov, Antonio Gaudi and others.

Their work led to a new interest in alternative, lightweight construction principles around the 1950's, with people like Buckminster Fuller, Félix Candela, Heinz Isler, and Frei Otto. Their interdisciplinary teams of architects and engineers contributed to the development of force and material informed structural concepts and the therefore, necessary form-finding techniques. This re-introduced the use of active bending principles (see geometry based approach below) which gave traditional construction materials like softwood and bamboo [10] a new meaning in construction. However, the enormous time and effort needed for the form-finding, engineering and planning of visionary projects like the Multihalle Mannheim from 1974 [18] reserved such construction principles to a few seminal projects. Until recently, the lack of engineering techniques for form-finding and structural analysis of bending-active structures inhibited a broader consideration of bending-active structures.

Parallel to the development of lightweight structures, fibre reinforced polymers (FRP) were introduced broadly around the 1950's, offering a unique ratio of high strength to low bending stiffness. The sports industry quickly recognized the potential of FRPs for their elasticity in products like tennis rackets, golf shafts, pole vaults and the camping tent. On the contrary, architects were using these materials to generate primarily free form geometries and to aid in the prospect of industrially manufactured modularized structures. Other more industrially oriented building applications use FRPs for reasons of chemical durability and low electrical conductivity. The first architectural constructions made of glass fibre reinforced polymers (GFRP) were the "House of the Future" by the Monsanto Chemical Company in 1954 and the "Futuro" by Suuronen in 1968. Both examples suggest high-tech technology in their formal appearance, yet rely on labour intensive manual lamination techniques for the production of their curved surfaces. With Buckminster Fullers "Fly's Eye Domes" in 1975, GFRP reached an intermediate peak in architectural application, with a subsequent sudden drop in implementation related to the oil crisis [2].

In the space industry where planning and material costs play a comparatively minor role, the use of new materials and their development are closely associated. Here, carbon fibre reinforced polymers (CFRP) were used to develop elastic deployable structures starting with early investigations on linear deployable booms [3] and tubes [4] in the 1960's and reaching high complexity in flexible shells such as the "Ultrathin deployable reflector antennas" [5]. Next to the significance of material research, these developments also relied on the theoretical analysis of nonlinear structural behaviour. New analytical approaches from engineers like Timoshenko in the 1950's [6] led to the development and general availability of nonlinear Finite Element Methods and created the basis of modern engineering mechanics, now offering a complete framework for the form-finding and analysis of bending-active structures.

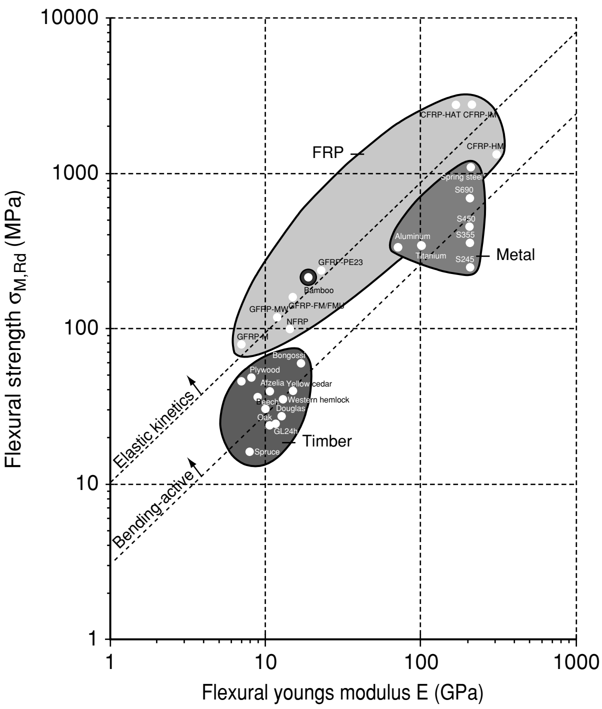
Today, industrial manufacturing processes for semi-finished FRP products like pultrusion make them more economical and guarantee consistency in mechanical behaviour. Since 2012, the first GFRP products were granted national technical approval (abZ approval) for use in German building projects [7]. This is a long awaited and important achievement to enable the step from research labs to the building industry for bending-active structures made of GFRP. A first project that has taken this step is the adaptive façade shading system for the ‘Softhouse’at IBA Hamburg 2013 [44].

In Fig. 1, a choice of common building materials is listed and plotted on a graph with their ratios of flexural strength to stiffness, based on the ‘Ashby diagrams’ [8]. Staying in context with building structures, the values are taken from the Eurocodes DIN EN 1993-1995 and 1999, DIN 1052:2004-08, DIN 17221 as well as [2] and [10]. Based on the experience of built examples, adequate materials for bending-active structures offer a ratio of $\sigma_{M,Rd}/E > 2.5$ (with $\sigma_{M,Rd}$ [MPa] and E [GPa]). For elastic kinetic systems the additional requirements for fatigue control further limit the permissible permanent elastic stress, therefore ratios of $\sigma_{M,Rd}/E > 10$ are needed. Indicated by the inclination of $\sigma_{M,Rd}/E$, the listed materials are thereby separated into different groups.

Additionally, long term behaviour must be taken into consideration. In static bending-active structures, creep deformation and consequential loss of pre-stress may be of little consequence to the system’s integrity. If the pre-stress is not playing a decisive role in the system’s stiffness, materials like timber may be chosen. Next to a high material yield strength and low bending stiffness, adaptive and elastic kinetic structures also rely on advantageous long term behaviour, allowing for cyclic exposure of large elastic deformation. Furthermore, the resetting effect can only be exploited if no long term permanent creep deformation occurs. Here, some fibre reinforced polymers (FRP) may provide the required material behaviour. (see paper on *Fibre-reinforced polymers for actively-bent structures* this Journal)

3. APPROACHES AND TYPES

Based on the material selection presented above a large variety and combination of structural systems can be generated based on the form-defining strategy of elastic deformation. Taking the potential of a certain material behaviour as a starting point, bending-active structures are understood to be an approach rather than a distinct structural typology. Their common denominator is not a circumscribed load bearing



Type: metals	Flexural strength $\sigma_{M,Rd}$ (MPa)	Flexural youngs modulus E (GPa)	Ratio
S245	245	210	1.17
S355	355	210	1.69
S450	450	210	2.14
S690	690	210	3.29
Spring steel	1100	210	5.24
Titanium	340	102	3.33
Aluminum	330	70	4.71
Timber			
Spruce	16	8	2
Pine	24	11	2.18
Douglas	30	12	2.5
Western hemlock	35	13	2.69
Yellow Cedar	40	15	2.67
Oak	30	10	3
Beech	35	10	3.5
Afzelia	40	11	3.64
Bongossi	60	17	3.53
GL24h	24	11.6	2.07
GL28h	28	12.6	2.22
GL32h	32	13.7	2.34
GL36h	36	14.7	2.45
Plywood F25	25	5.5	4.54
Plywood F40	40	6.0	6.67
Plywood F50	50	7.0	7.14
Plywood F60	60	9.0	6.67
Bamboo	213	19.13	11.13
FRP*			
CRFP-HAT	2800	165	16.97
CRFP-IM	2800	210	13.33
CRFP-HM	1350	300	4.5
P E 23	300	23	13.04
GRFP-M	80	7	11.43
GRFP-MW	120	12	10
GRFP-FM/FMU	160	15	10.67

Figure 1. Common building materials with ratio of strength σ_M (MPa) to stiffness E (GPa).

behaviour or geometrical definition, but a formation process during which they are elastically bent. Consequentially, a further differentiation of bending-active structures is suggested based on their design approaches. In a summarising graph (Fig 2), three such approaches are shown: the behaviour based approach, the geometry based approach and current research that seeks to integrate the two.

– In a **behaviour based approach** bending is initially used intuitively; the system's geometry and structural behaviour is studied empirically. Material limitations are tested physically.
– In a **geometry based approach** the system's geometry is predefined based on analytical geometry or experimental form-finding methods, both of which are used as a controlled means to approximate the actual bending geometry. Material limitations are considered analytically based on momentum curvature relation.
– In an **integral approach** the elastic bending deformation is analysed through numerical form-finding, which enables full control of material behaviour based geometry. Material characteristics and limitations are included in the numerical analysis model.

Looking at the historical development, starting with the behaviour based approach, it becomes apparent that this approach leads to the most realised projects and is a recognised construction type still used today. It took until the 20th century for an analytical, geometry based approach to appear. The research on lightweight structures which became very active in the middle of the last century led to this approach, where elastic deformation is used as an economic way to construct double curved shell structures whose geometry is, however, not directly based on the bending shape itself but various other analytical and experimental form-finding approaches. Enabled by the powerful simulation methods we are equipped with today, the two approaches may be combined by simulating the large bending deformations of the erection or shape adaptation themselves and thereby fully tap the potential of active bending.

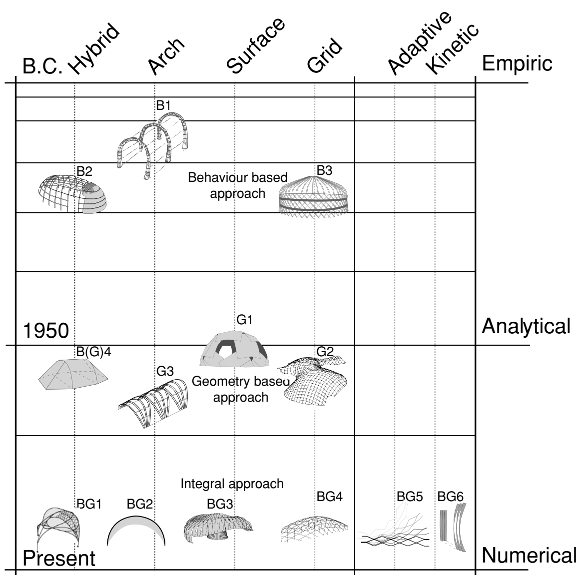


Figure 2. Development of bending-active structures.

The vertical axis in Figure 2 indicates a historical order of the presented examples and also groups the design approaches according to the analysis tools available, reaching from empiric to analytical and finally, modern numerical analysis. The aforementioned interest in alternative, lightweight construction principles around the 1950's becomes visible in the centre of this graph with an accumulation of projects based on a geometric approach.

The horizontal axis offers a loosely formulated categorisation of various expressions of bending active structures into known structural types. Most of the recent examples are deliberately placed off of the exact axis as they begin to explore new in-between fields and hybrid forms of the known structural types.

The project samples are discussed further in the following chapters and referred to by the given codes. The nature of these approaches is discussed based on some important project samples.

4. BEHAVIOUR BASED APPROACH

Various construction methods known from vernacular architecture make use of the elastic behaviour of their building materials, leading to a recognised construction type which prevails in some cultures and in certain applications. In the encyclopaedia of vernacular architecture [1], these structures are referred to as tension arch systems. The review on bamboo structures [10] differentiates more precisely between curved compression rods and curved tension rods. Putting bending itself in the centre of attention, we suggest a more differentiated view as shown in Fig 2.

There are samples of elastically formed arch and shell structures found in various cultures on every continent. The empiric development of construction methods based on the elasticity of their building materials predominately resulted in similar structures. Among theses, the Mudhif cane huts in Ma'dan (South Iraq) are a well-documented example [8, 10] (sample B1 in Fig 2 and Fig 3 left). They are permanent structures using reed bundles that are first

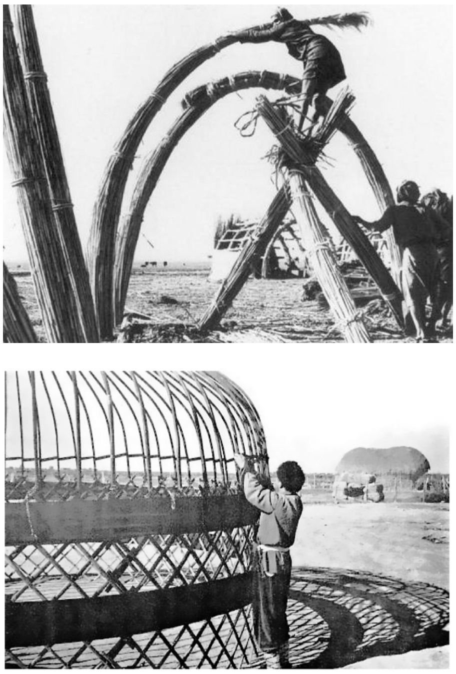


Figure 3. Mudhif (B1) [8], Atabay Yomut [11].

Figure 4. Loop, New York 2006 [14] and Elastic habitat Saint-Etienne 2006 [15].

vertically fixed into bucket foundations and later connected at the top to form elastically bent arches. Another very common application is bending-active construction systems for temporary or mobile shelters. Typical examples are the tents of the nomadic tribes in the Middle East. Skeletons of partially bent wooden ribs in combination with a surface made of black, goat-hair, felt or vegetable fibres are the basic elements for various rapid deployable light weight structures offering minimal packing volume. The Iranian Kutuk or Kantuk, for example, uses date-palm ribs as frames (arches), traversed by cane stringers, and covered with a thatch of canes (sample B2 in Fig 2) [31]. Another example is the Yomut [11] of the Afghan Turkmen or the Mongolian Yurt [1], which use a bent pantographic grid for the skeleton of the walls and, in the case of the Yomut, also bent elements for the roof construction (sample B3 in Fig 2 and Fig 3 right).

Still today, there are various examples of bending-active structures that are predicated on the behaviour based approach. Next to various arch and gridshell structures built out of green wood or living willow stems [12], Vo Trong Nghia's [13] considerably large Bamboo structures are, for example, built in this manner.

New high strength materials combined with low bending stiffness such as Glass Fibre Reinforced Plastic (GFRP) and high strength aluminium became popular as of the 1970's. This enabled the first mountaineering and expedition tents with elastically bent supporting arches. The tent poles could easily be bent by hand into a dome (gridshell) or tunnel (series of arches) configuration (sample B4 in Fig 2). These high tech tents were developed based on experimental tests of full scale prototypes. In-depth empiric analysis of the products allowed for a secure industrial production. As the analytical understanding and numerical simulation of these tent structures is starting to be considered, they clearly are a significant stepping stone towards the integrated behaviour and geometry approach described below.

Today, there is an increasing interest by designers and architects to use the advantages from polymers for active bending in various kinds of experimentally conceptualized installations and small pavilion structures. Projects like 'The Loop' [14] and the 'elastic habitat', both from 2006, underline a keen interest in the freedom of creating complexly curved shapes in situ (Fig. 4).

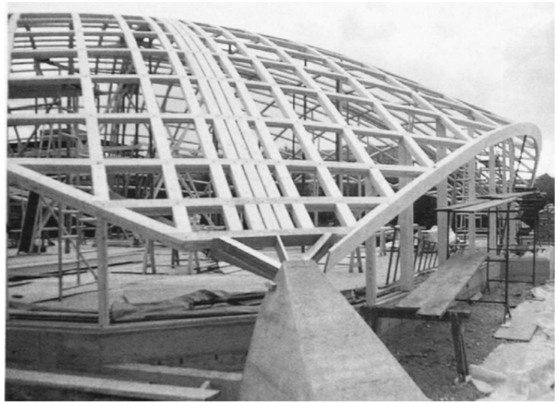
5. GEOMETRY BASED APPROACH

The intense research on lightweight structures that commenced in the middle of the last century led to an intensified interest in double curved surface- and gridshells. However, the simulation techniques which were starting to be developed were not yet able to simulate large elastic deformations. The most common form-finding method of the time was the hanging model, which could be handled both experimentally and analytically. Some experimental tests additionally proved the similarity of the hanging chain and the elastica curve [10].

In the 1960's, Frei Otto started intensive research on gridshells [17]; after a few prototype structures, the Multihalle Mannheim built in 1974 was the first large span gridshell [18] (sample G2 in Fig 2 and Fig 5 left).

Only a few more gridshells have been built to further develop this approach. The Hooke Park Workshop (1990) [17] (sample G3 in Fig 1) was not a gridshell as such; however, using a set of elastically bent timber arches whose form is based on studies of the hanging model makes the approach similar to that used for the Multihalle Manheim. Both structures were engineered by Buro Happold where an outstanding knowledge in gridshell structures was developed [24]. This led to more recent examples such as the Downland Gridshell from 2002 (Fig 5 right) [19] and the Savill Garden Gridshell (De Groot, 2007) [22].

Additional examples of gridshells that use the elasticity of timber to bend the grid into a given analytical geometry are the Polydôme (Fig 6 left) [20] which uses multi-layered timber to shape the geometry of a sphere, the Japanese Pavilion at Expo 2000 in Hannover [21] using cardboard tubes, and the Helsinki Zoo tower [23] that lets the grid follow geodesic lines on a free form surface. The advantage of an easy erection procedure where the geometry is automatically set in position was however partially lost in the aforementioned projects due to the necessity of controlling the final geometry in the erection process.



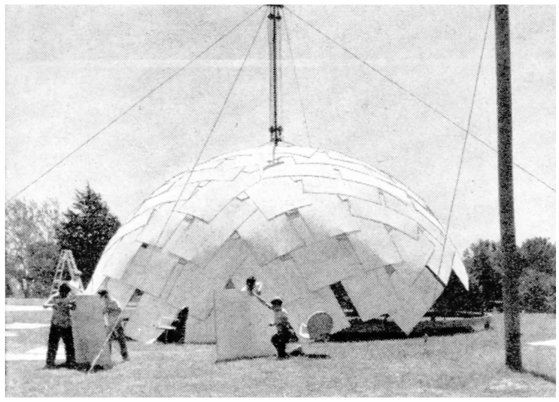


Figure 6. Polydôme 1991 [20] and Plydome 1957 (G1) [16].

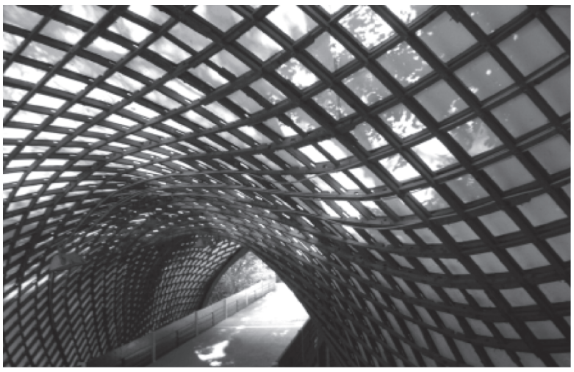


Figure 5. Multihalle Mannheim 1974(G2), and Downland Gridshell 2002.

A unique approach for making surface shells was introduced by Buckminster Fuller. As part of his studies on geodesic domes, Buckminster Fuller developed the Plydome Structures in 1957 [16] (sample G1 in Fig 2 Fig 6 right). The global shape is defined by a sphere, while he uses plywood panels that are predominantly bent around one axis and interconnected on the topological points of the geodesic dome .

6. BEHAVIOUR BASED GEOMETRY

Recent developments in simulation techniques now allow form-finding and analysis of structures that derive their complex curved geometry solely through the erection process in which they are elastically deformed. This has provided the basis for various probes that include new types of surface- and gridshells, membranes with elastically bent battens, bent structural components with membranes as a restraining system and various types of adaptive and elastic kinetic structures.

The integration of elastic beams (sail battens) in a form-active surface for extremely light and integrated primary structures in mechanically pre-stressed membranes has been a challenge for numerical form-finding methods. Such hybrid structures have recently been investigated in the work on ‘Spline Stressed Membranes’ [26]. This work was motivated by a membrane structure for the Expo Seville 1992 with integrated curved tensegrity beams [25]. Some prototypical work has also been done on the so called Bat sail [27]. In 2011, a 12 m span funnel shaped membrane umbrella was built as a hybrid structure. It features 7.5 m long glass fibre rods that pre-stress the membrane by means of elastic bending. The structure serves as courtyard shading for an architecture school in Marrakech, Morocco [28]. While this shape still represents a classical membrane shape, the M1 project at La Tour de l’Architecte in France 2012 shows the further potential of form- and bending-active hybrids to extend the formal and functional vocabulary of tensile membrane structures (sample BG1 in Fig 2) [29]. As the stiffness of a hybrid system is much higher than the stiffness of the bent element itself, very small cross-sections are feasible. These characteristics make the combination of active bending particularly applicable for temporary and mobile constructions [30, 31]. The Lightweight Structure Unit - a group of Architects and Engineers from the University of Dundee and the Technical University of Munich developed small (Fig 6 left) and medium span Prototypes for rapid deployable shelters based of this conceptual idea between 1999 and 2004. On-going research explores the possibilities of combining elastically bent elements with restraining membranes on the level of building components as membrane restrained arches [32, 33] (sample BG2 in Fig 2 and Fig. 7 left) or membrane restrained columns and girders [34]. The shape of the bent elements can be controlled by the patterning of the membrane and the pre-stress in the membrane restraining system. The membrane stabilises the slender beam elements against buckling and reduces deformation.

On the level of bending-active building components, the prototypical pedestrian bridge in [35] and the timber arch component in [36] must also be mentioned.

In 2010, the Research Pavilion ICD/ITKE was built. Here, planar strips of plywood are subsequently coupled into a self-equilibrating arch structure of 4 m span. A radial arrangement and interconnection of the arches led to the final torus-shaped design which developed real shell properties in its load bearing. Since the structure was form-found based on a simulation of the erection, the final geometry was entirely controlled by the given connection points [37] (sample BG3 in Fig 2 and Fig 7 right).

Figure 7. Membrane restrained arch (BG2) and Research Pavilion ICD/ITKE 2010 (BG3).

Over the past ten years, several research studies have focused on methodologies to generate developable grid configurations and to simulate their resulting geometry after the erection process [38, 39, 40] (sample BG4 in Fig 2). The final geometry of highly elastic gridshells results from a shaping process where the grid members are progressively elastically bent. In order to obtain the resulting gridshell geometry, several research studies have developed form-finding methods reproducing this erection process. Current studies analyse these structural effects for a variety of surface geometries and grid configurations. In addition, the potential of using NFRPs as an environmentally-friendly alternative for gridshell structures has been studied [41].

Providing the right material properties and a reversible deformation process, active bending may also be used for adaptive structures. A visionary project was constructed in 2002 at the AA in London. The so

Figure 8. Hybgrid 2002 (BG5) [42] and Thematic Pavilion at EXPO 2012 in Korea Yeosu (BG6).

called Hybgrid [42] (sample BG5 in Fig 2 and Fig 8 left) is an adaptive grid shell with three locally curved layers of GFRP lathes. The global curvature of the shell can be adapted by changing the coupling length between the locally curved elements. Similar studies of spatial adaptations were undertaken in 2004 by the ‘Hyperbody Research Group’ [43]. An adaptive façade shading system for the ‘Softhouse’ at IBA Hamburg 2013 now combines tensile membranes and elastic GFRP board in continuous shape adaptive strips [44].

With shorter time intervals between the adaptive deformations we may also speak of elastic kinetics. Some research projects and prototype constructions have investigated the use of active bending for kinetic structures. While this approach has already been taken quite far in disciplines like aeronautics, only a few projects have been realised in a large scale architectural context, such as the currently developed Flectofin® project [45]. The first kinetic façade that works solely on the basis of elastic bending is constructed for the Thematic Pavilion at EXPO 2012 in Korea Yeosu [46] (sample BG6 in Fig 1 and Fig 8 right). The kinematic media facade promotes 108 individual GFRP lamellas that are deformed by controlled buckling. The facade can therefore adapt to light and physical building conditions and allows the artistic staging of special lighting effects. It has a total length of 140 m and a height between 3 and 14 m.

7. CONCLUSION

Even though the presented examples may differ in their general design approach and construction type, they all share the approach of creating curved geometries based on straight or planar building elements. Their common denominator is a formation process during which they are elastically bent, leading to similar questions of materiality, form-finding and planning processes. The on-going developments of new materials and simulation tools suggest that the presented recent projects, which exhibit active bending in various typological expressions, have by no means exhausted their field of application. There is a growing international number of scientists committing themselves to research and development of design, material and simulation questions related to bending-active structures. This opens the field for future applications of bending-active structures; however, it does not mean that they will replace established building techniques on a larger scale. Despite the apparent freedom of formal expressions that the built examples show in this review, all bending active structures rely on physical form defining mechanisms which design intentions have to subordinate to. On a structural level, the form defining residual bending stress leads to a material dependent relation of curvature and element size which restricts these structures in scale. The general field of application will therefore remain a niche in the greater picture of building and construction. The most potential for future applications of bending-active structures may be seen in forward-looking applications, such as the 2012 Expo Korea façade, that exploit the possibility of shape adaptations, as well as the integration bending-active elements in hybrid systems such as the 1992 Expo Seville roof and recent research projects introduced above. These particular aspects are subject of current research and will be explored further in the years to come.

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