

Where design meets construction: a review of bending active structures

Alessandro LIUTI*, Carlotta MAZZOLA^a, Alessandra ZANELLI^b

* Faculty of Architecture, Building and Planning, MSD, University of Melbourne, Australia
aliuti@student.unimelb.edu.au

^a Politecnico di Milano, Architecture, Built Environment and Construction Engineering Dept., Milan, Italy

^b Politecnico di Milano, Architecture, Built Environment and Construction Engineering Dept., Milan, Italy

Abstract

This paper overviews the design-to-construction interfaces in bending-active structures, which still show considerable gaps and discontinuities between the increasingly precise computational-based design stages and the often artisanal/empiric manufacturing and construction stages. Such discrepancies can either introduce redundant structural elements or develop highly resource-intensive construction methods. The first part of the paper reviews a selection of historical and recent built structures through multi-criteria matrixes that analyse the relationship between structural typologies, generative approaches, construction methods, life-span, and material systems. Drawing from these considerations, the paper then focuses on the interfaces between design simulations and construction, emphasising on the monitoring/controlling of the bending process. Conclusively, a small-scale experimental application opens speculations upon the future of bending-active structures, augmented reality, and interactive prototyping/manufacturing.

Keywords: active bending, lightweight structures, gridshell, textile hybrid, design, construction, manufacturing, monitoring

1. Typologies, lifespan, and scale in bending-active structures

Bending-active structures comprise several lightweight/ultra-lightweight structural typologies which are obtained by elastically deforming an initially straight/flat set of load-bearing elements (the “released configuration”); among these: gridshells, plate structures, and textile hybrid structures. As the term bending-active refers to a physical behaviour rather than to a specific structural typology, both material and geometrical features, as well as detailing and construction methods, can vary considerably. Each material system allows for different construction methods, which must account for the scale, lifespan, and budget, of each structure [1, 6, 13].

The following review shows that, when design informs manufacturing and construction seamlessly (and vice-versa), bending-active systems can facilitate the tasks of manufacturing, assembly, and dismantling. These lightweight/ultra-lightweight structures can demand a “lighter” or “heavier” amount of resources during construction, since it is not always easy to replicate or scale the design process in a simple manner; construction methods, moreover, still seem underdeveloped in comparison to design methods, which, on the contrary, are currently evolving rapidly due to materials and computational advancements. When design, manufacturing and construction are well thought through, these structures can be used (and re-used) for both the short-term and the long-term; however, given the experimental nature of bending-active structures, the consistent advancements in design and materials, and the limited applications to architecture, it can be difficult to account for manufacturing/construction aspects in the design phase, and vice-versa. Whereas having initially flat elements can simplify the manufacturing process, it also requires careful material and structural considerations across both the stages of design, manufacturing, and construction. A suitable bending-active material must enable for large deformations during construction (thus low bending stiffness) while providing enough load-bearing properties during

operational life (thus high strength); timber, bamboo, and composite materials can be suitable candidates for the task. The need for high flexibility and stiffness of the material must be accounted in both conceptual and detailed design; besides, scaling the structural elements is also a delicate matter, which involves non-linear geometric and material relationships [7].

The authors analysed twenty-four built bending-active structures; Figure 1 sorts these across three sectors, according to their structural typology (gridshells, plate structures, and textile hybrid structures), and lifespan. Those projects closer to the centre feature a shorter lifespan (i.e. installations), whereas those further out feature a longer lifespan (i.e. permanent buildings). The size of each balloon expresses the extension of the project (also reported inside each balloon), whereas colour-coding refers to the different materials. To begin with, the structural elements should work in a state of main-compression, where shear is negligible, and the thrust line falls within a convenient portion of the cross-section. Thin/slender cross-sections are generally suitable, as they can reach small radii of curvature if made by an appropriate material.

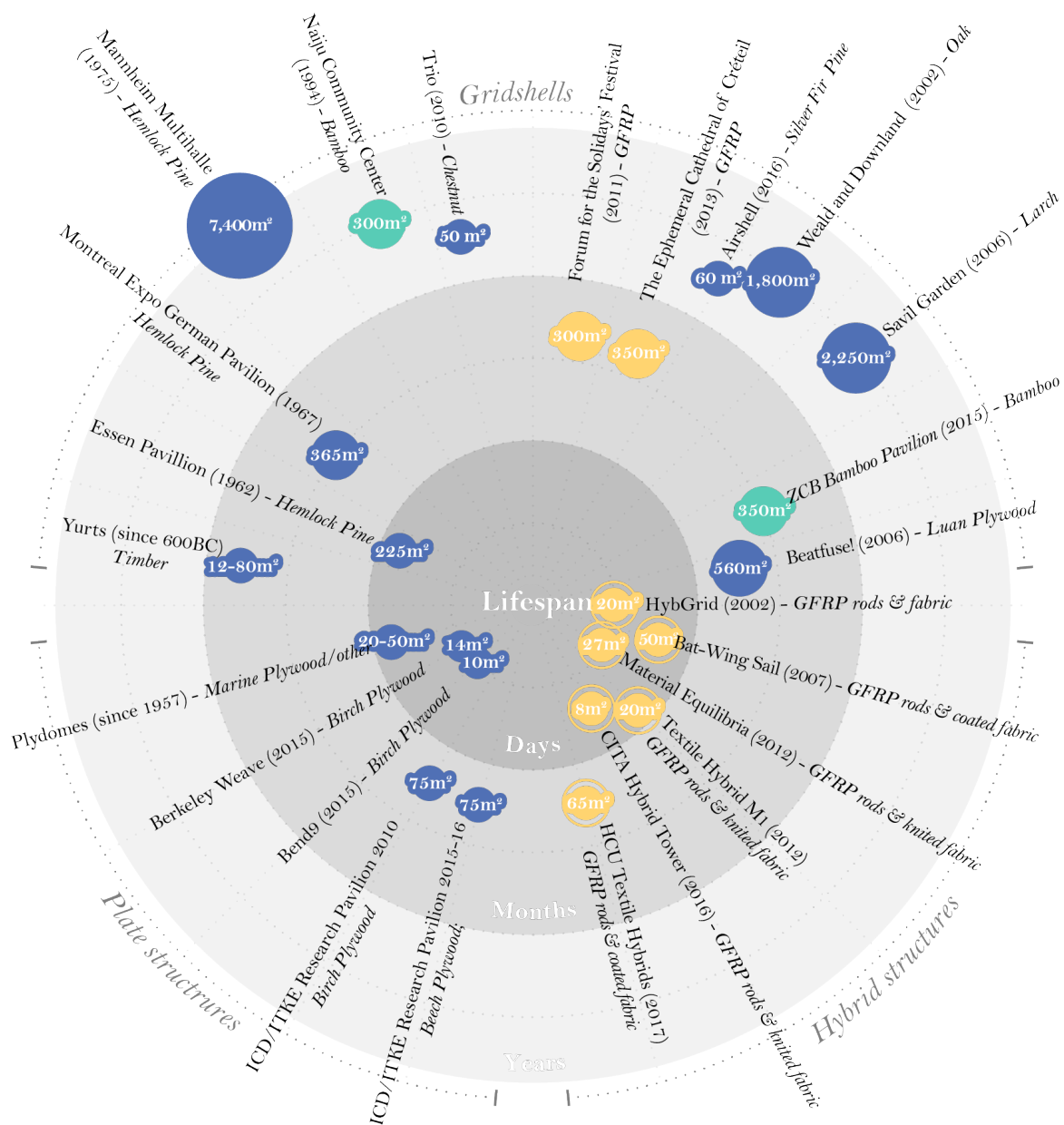


Figure 1: Synoptic map of the twenty-four bending-active structures selected and analysed by authors. Comparison/Relation between structural typology, life-span, materials and extension of each project.

However, viscous-plastic phenomena can dampen the bending-active behaviour in time; this implies that, according to the lifespan of the project, the form-finding of bending-active structures must negotiate for both short-term and/or long-term performances. Whereas the shape of short-term installations and/or seasonal structures can use a wide range of materials and effectively follow the criteria of the *elastica* curve, permanent structures must negotiate material criteria with shapes closer to the funicular.

The lifespan of a structure also enables to adopt different detailing and construction solutions; temporary installations such as the Material Equilibria (2012) and the Textile Hybrid M1 (2012) feature a small-scale, since their main aim was to prototype and test design and construction principles, as well as exploring the possibilities around composite materials and knitted membranes – two materials still not fully experienced and still not covered by international standards and regulations. The ultra-lightweight structures made by GFRP and knitted or coated fabrics feature small and medium scale and are mostly ephemeral (see yellow circled balloons in Figure 1). Differently, the traditional Yurts are among the few bending-active structures that are meant to be mounted/dismantled seasonally; this happens at the small-scale due to transportability and constructability reasons. More ambitious experimentations such as the ZCB Bamboo Pavilion (2015), the ICD/ITKE Pavilion (2015-16), and the Ephemeral Cathedral of Créteil (2013), are emblematic examples of how the construction process can assume a complex role due to the longer lifespan and larger scale of the project. The structural use of timber, bamboo, and GFRP, enabled to cover consistent spans and provide a more durable piece of architecture. Permanent projects such as the Mannheim Multihalle, (1975) the Weald and Downland, (2002), the Najju Community Centre (1994) gridshells illustrate how the larger scale introduces more contingencies related to construction, requiring more careful detailing and engineering processes. The larger the scale, the more important the financial and environmental sustainability of the material; natural materials such as timber (blue in Figure 1) and bamboo (cyan) furthermore can be easily manufactured using either industrial or artisanal tools, both on-site and off-site, by both skills and unskilled workers.

2. From design to construction

The design and construction of bending-active systems tightly relate structural principles and construction criteria; however, advancements in both construction and design have different impacts on each other. Whereas advancements in design methods can find rapid applications, construction methods often feature slower evolution. The construction industry can be resilient to changes in established building methods and techniques, thus requiring lengthy times to process/absorb seminal innovation for construction systems. Differently, incremental innovation can find more rapid applications, as it occurs directly inside the building sector and aims to overcome specific problems and needs. According to the lifespan, the scale, and the architectural concept to express, gridshells, plates structures, and textile hybrid structures, can feature a wide range of design-to-construction interfaces, and higher or lower explorative potential toward spatial complexity and design creativity. The evolution of bending-active structures has speeded up incredibly in the last fifty years; despite the many incremental small innovation advancements, times could be mature for disruptive innovation to take place. Given the relevance of the design-to-construction interface a fertile area could be the development of “light” and updated design tools, developed to enable an easier/safer control/monitoring of the erection process. Figure 2 analyses the afore-introduced selected projects according to design and construction methods; the size of each balloon expresses the emphasis put in design (white circles) and construction (black/coloured balloons). The closer the two balloons, the more seamless their design-to-construction interface.

To begin with, gridshells are made by joining and bending grids of slender flexible rods/beams; the structural grid can be made of materials such as wood, bamboo, and composite, and it can be either deployable, or non-deployable. The construction of a deployable gridshell (i.e. the Mannheim Multihalle, the Weald and Downland Museum) begins by assembling the overall structural topology; then, this is deformed into a double-curved configuration. On the one hand, a pre-fixed grid locks the relative position of each node from the very beginning, providing a first tool of control over the shape; on the other, such a grid requires careful detailing regarding its bending stiffness. This often translates into laborious/expensive joint connections, which must be locked against shear and moment after the bending is completed. The construction of a non-deployable gridshell (i.e. the Savill Garden and the

ZCB Bamboo Pavilion) starts by preparing a guiding system such as scaffolds or formworks, onto which laying and bending each piece individually; in this case, the topology builds up incrementally piece after piece during construction. Although a non-deployable grid imposes a higher degree of monitoring to control the position of each node during the whole process, it also demands lower bending forces, since the stiffness of a single element is lower than that of the overall grid. Furthermore, the structure can be assembled in its final configuration, and joints can be locked during construction (and not only after). The literature shows that construction is generally finalised through the “incremental” method.

Plate structures are made by joining patterns of flat/slender plate-elements, which are bent and coupled together either at the edges or surface-on-surface. In the Bend 9 project, the pattern of flat plywood panels was sorted and pre-assembled into groups of elements, thus facilitating the construction process. Otherwise, the ICD/ITKE Research Pavilion (2010) and the Berkeley Weave (2015) were built by adding and bending piece after piece.

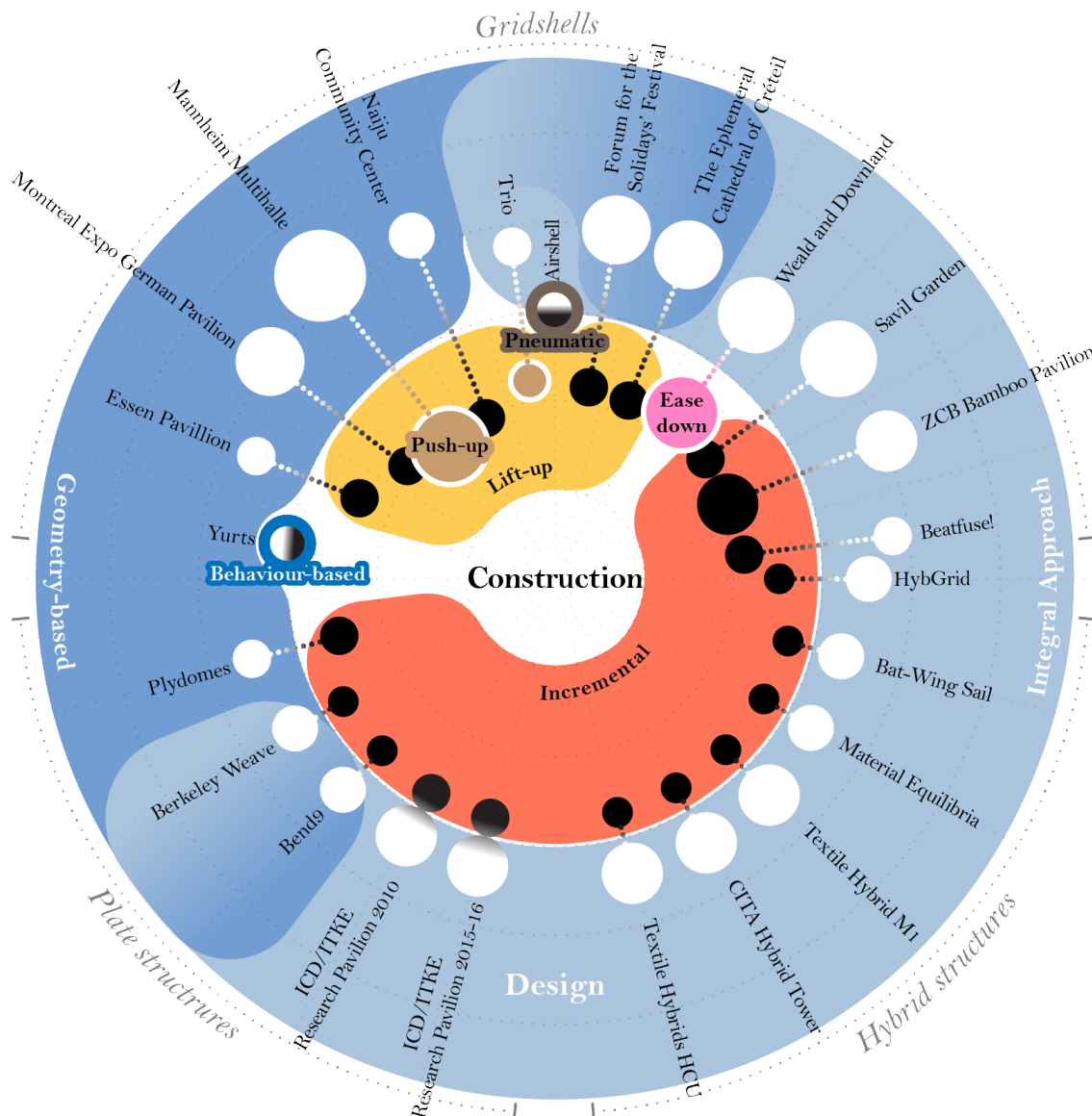


Figure 2: Synoptic classification of the selected structures analysed by the authors; the sorting follows the different design methods (outer ring) and construction methods (inner ring).

Textile hybrid structures combine bending rods with stretching tensile elements; this mix combines the section-active behaviour of the bending elements with the surface-active behaviour of the tensile elements (i.e. membrane surfaces or cables) [5-7]. The combination of non-linear buckling and (viscous-)elastic stretching makes it challenging to form-finding and analysing the two systems interacting, while also demanding precise and effective manufacturing and erection methods.

2.1. Design methods and design tools

The field of design has featured consistent and frequent innovation so far, evolving after the advancements in geometric modelling and FEM tools. A comprehensive classification outlines three main design approaches: the “behaviour-based approach”, the “geometry-based approach”, and the “integral approach” [5, 6]. Each approach uses a different toolset and different methods to generate the form. The *behaviour-based approach* consists of the empiric construction and deformation of physical systems. This approach to bending is rather intuitive. Referring to vernacular structures such as the Iraqi Mudhif, the Iranian Kutuk or the Mongolian Yurt, this empirical approach dates back to centuries before Christ; however, these structures only feature a rather limited range of forms, which are nevertheless effective in their assembly, disassembly, and transportation.

Geometry-based form-generation involves modelling analytical geometries and experimental form-finding methods. Frei Otto adopted this approach to form-find gridshells such as the Essen Pavilion, the Montreal Expo German Pavilion, and the Mannheim Multihalle. In these projects, the physical model acted as a fundamental design tool aimed to understand, represent, and design the bending form; whereas the simple form of the Essen Pavilion was aimed to test a basic tectonic benchmark, the Montreal Expo German Pavilion and, most notably, the Mannheim Multihalle provided considerable advancements in terms of modelling complexity [1, 9]. Frei Otto’s two-stage design method consisted of the first stage of conceptual design, which used simplified physical models to draft the deformation process from the flat to the curved configuration; the second stage used more complex models to better assess the geometric, structural, and technological aspects of the project. Frei Otto started using analogical models as active design entities, useful to inform the several design (and construction) stages, and vice-versa. This heavily analogic approach was not extremely flexible regarding form-exploration and highly resource-demanding, revealing its limits soon – see the use of stereo-photogrammetry and the impossibility of accounting for the grid’s bending stiffness during form-finding. This experimental approach has evolved into more flexible analytical modelling methods, based on geometric and mathematical discretisation/patterning rules, such as the “compass method” and the “variational principles method”. Numerical applications of these methods illustrate how design can account structural criteria, achieving optimised and more compelling “freeform” shapes. The numerical form-finding of the Ephemeral Cathedral of Créteil was implemented by firstly defining a suitable target geometry; secondly, the target surface discretisation was optimised using geometrical criteria, such as the radius of curvature and cross-sectional properties. Subsequently, a dynamic relaxation algorithm form-found the structural grid, which could then be analysed according to its structural performance [3]. Improved communication between form-generation and analysis enabled to implement a more streamlined design process, which had common traits to the more recent integral design approach.

The *integral approach* implements elastic bending deformations through more comprehensive numerical form-finding methods, which can better account for the material and structural performances of each geometric form [5, 6]. Current non-linear computational techniques allow a more interactive understanding, representation, and analysis of complex bending forms; the “Shape approximation” and the “Least Strain Energy method” streamline the design of consolidated structural typologies such as gridshells, whereas further relaxation methods such as “Ultra-elastic contracting cable approach” have more recently triggered explorations towards innovative textile hybrid structures, plate structures, and adaptive kinetic structures [4-7, 12]. In projects like HCU Textile Hybrid (2017) and the Hybrid Tower (2016), physical prototyping still plays a significant role during the design process since the hybrid behaviour cannot be fully performed by numerical simulations. Once the analogical and digital models are carefully paired, computational design tools can seamlessly interface and drive the geometric, structural, and physical features of a shape within a flexible process. The architectural outcomes are

mainly experimental and ephemeral at the moment, nevertheless providing promising explorations towards innovative shapes and tectonics.

2.2. Construction methods

Erection/bending is a key construction task for bending-active structures since this is often when the most penalising loading conditions arise. Erection/bending is meant to replicate form-finding and gradually/homogeneously distribute bending actions on the flat elements; whereas currently available methods can vary according to the scale, the structural typology, and the material system, five main erection methods can be outlined: the “incremental method”, the “lift-up method”, the “push-up method”, the “ease-down method”, and the “pneumatic falsework method” [1, 8, 11].

The incremental method can be finalised in manifold ways (see projects inside the orange cluster in Figure 2). At the small scale, such as in the Research Pavilion ICD/ITKE (2010), this consists of incrementally assembling/bending in space freestanding pieces, mostly using shop drawings, labelling systems, and joint connections. The assembly process aims to locate each individual element in a precise sequence and position since the structural topology is built through the process. These operations can require consistent amount of on-site labour; whereas the small scale enables to perform this task mostly manually, the larger scale often requires the preparation of extensive jigs or beds of guides, on top of which to incrementally assemble and bend the individual profiles by additive layering – such as in the case of the Savill Garden (2006). The ZCB Bamboo Pavilion (2015) also adopted an analogous method, however structuring the construction process in a more open-ended way, that enabled the designers and builders to absorb construction imprecisions through precise protocols of error [2]. The majority of textile hybrid structure, such as Textile Hybrid M1 (2012) and the Hybrid Tower (2016) use the incremental construction: firstly, the bending-active elements are bent in order to create a self-stable structure; then, bent elements are coupled with textile elements to stabilise and self-equilibrate the structure [12].

Conversely, the following erection/bending methods are carried after pre-assembling a starting structural topology. These methods streamline the construction and sorting tasks through off-site manufacturing and prefabrication; after the pre-assembled pieces are carried and assembled on-site, these should preserve their reciprocal position throughout the erection/bending process. These methods mostly apply to the construction of elastic gridshells deployable. The *lift-up* method consists of craning-up the flat configuration (projects inside the yellow cluster in Figure 2); despite this method can appear rapid and straightforward, problems can arise to control/contain the position and horizontal push at the edges. Furthermore, cranes have limits in reach and load and have considerable operational costs, which can be absorbed mainly in projects of with consistent budgets (i.e. semi-permanent or permanent). This method is effective to erect small/medium-sized structures such as the Essen Pavilion (1962), the Montreal Expo German Pavilion (1967), the Forum for the Soliday’s Festival (2011), and the Ephemeral Cathedral of Cretéil (2013). The *push-up* method is a low-budget adaptation of the *lift-up* method (light brown balloons in Figure 2); the method bends/uplifts the flat configuration from below, using either mechanical or manual actions. Whereas the process can demand lower operational costs, especially in large-sized projects, projects such as the Mannheim Multihalle (1975) and the Trio gridshell (2010) show how this method can be either imprecise or laborious, featuring analogous controllability and scalability issues to those of the *lift-up* method [10, 11]. The *ease-down* performs bending at a raised level, combining the action of gravity, modular scaffolds, and mechanical formworks (pink balloon in Figure 2). This method imposes prefixed trajectories on the bending elements, enhancing the control and the precision over such prescribed displacements. The Weald and Downland (2002) museum shows that this method provides a better continuity between design and construction, however demanding a high degree of engineering sophistication and machinery and thus consistent resources and time for preparation, operation, and finalisation [1]. Despite the advancements brought by the *lift-up*, the *push-up*, and the *ease-down* methods, erection/bending still face problems in scaling the form-finding model into a 1:1 scale construction model. The Airshell project (2016) illustrates that the *pneumatic falsework* erection enables to bypass some of these setbacks; pneumatic forming replicates form-finding at a 1:1 scale, providing a homogeneous distribution of bending forces, and streamlining and automating the whole erection process. [8].

2.3. Design to construction interfaces

The afore-introduced projects illustrate the importance of interoperability between design and construction criteria. Figure 2 renders the extent of the gaps at this interface; the longer each dotted line, the larger the gap/disconnection between design and construction. These gaps often generate procedural diseconomies and require bridging through laborious a-posteriori engineering, which can be limited with more seamless interfaces. Several monitoring methods can be extrapolated from the proposed projects; these can feature either analytical or digital technological solutions, providing real-time or a-posteriori feedback. The proposed classification distinguishes between “a-posteriori analogic”, “real-time analogic”, “a-posteriori digital”, and “real-time digital” monitoring interfaces.

The erection/bending of small-scale and medium-scale projects demands fewer resources (see smaller black balloons in Figure 2); the Essen Pavilion (1962), the Trio gridshell (2010), and the Ephemeral Cathedral of Cretéil (2012) were engineered a-posteriori and monitored with *a-posteriori analogic* methods such as manual measuring throughout the process. This common interface informs the construction process through a rather laborious and repetitive set of manual operations, while not requiring the preparation of any complex/special tools/devices. The working with pre-fixed and pre-assembled material topologies can assist and facilitate the monitoring task, as shown by the Research Pavilions ICD/ITKE (2010, 2015-16), the Beatfuse! Gridshell (2006), and the Bend9 (2015). Monitoring operations can be streamlined with the use of *real-time analogic* mechanical guides and bending devices. The use of jacking towers enabled to control the pitch of the Mannheim Multihalle (1975) at strategic points, and provide a gradual *push-up* lifting action; nevertheless, the size of the project made the whole procedure incredibly labour-intensive, and not proportionately precise. The *ease-down* erection/bending of the Weald and Downland gridshell further streamlined the *real-time analogic* monitoring/control system using modular PERI props to trace the precise trajectories of each edge of the mesh, thus unifying the bending and the monitoring devices. Both the Savil Garden (2006) and the ZCB Bamboo Pavilion (2015) were bent over a bed of guides defining the position of each node; however, the Savill Garden was built with higher precision, whereas the bending of the ZCB Bamboo Pavilion coped with high indeterminacy and errors, which led to discrepancies in the order of the meter. *A-posteriori digital* measurements then assessed the actual shape of the bent geometry and tailor the cover cloth on it [2].

These technological solutions enable to monitor a-posteriori engineering solutions with more or less ease and continuity. The Airshell gridshell provided a more radical interface; at a first level of integration, 1:1 pneumatic forming blended the generative construction principle within the design and vice-versa, bypassing further a-posteriori engineering. Furthermore, the use of Arduino® distance sensors provided a *real-time digital* monitoring interface, streamlining the whole erection/bending process [8]. In the perspective of incremental innovation, augmented-reality/mixed-reality interfaces can provide a more flexible *real-time digital* monitoring system; this could provide a more precise control over the position of each single nodes in space (even for larger structures), reduce the use of shop drawings, and real-time layer digital information on top of the physical parts (i.e. stress/curvature trend). In the perspective of disruptive innovation, mixed-reality interfaces could enhance the creative process through innovative real-time prototyping workflows, in which to merge rapid human craftsmanship with digital precision. Figure 3 shows stages of the “Making in Mixed Reality” workshop carried out at the Melbourne School of Design in April 2018; the gridshell on the right was sketched in space by bending single rods on the hologram in the centre over the hologram of the main stress-lines of a simple catenary shell – which provided an intuitive guide to where to place the rods in space.



Figure 3: mixed-reality prototyping interface (images © A. Liuti, S. Colabella, A. Pugnale)

3. Conclusions and future developments

This overview discussed significant design-to construction interfaces for active bending, comparing twenty-four structures. This selection enables already to correlate factors such as structural typology, scale, lifespan, design method, construction method, and monitoring/control method. Since the field is still in an early explorative stage, experiments are mostly done at the small/ephemeral scale, where construction can be carried out in a rather artisanal and intuitive manner. Where the scale and the lifespan increase, more complex criticalities arise at the interface between design and construction, thus requiring more conscientious planning and interoperability during bending/erection. The increasing availability of digital design tools has revamped interest in bending-active structures; to begin with, digital and parametric modelling tools enable to accurately simulate material and structural behaviour, streamlining drafting and detailing tasks. Furthermore, digital and parametric platforms also provide a flexible interface to bridge design and construction, thus reducing or bypassing those gaps that can often generate scalability issues, diseconomies, and errors.

Reference

- [1] Chilton, J., & Tang, G. "Timber gridshells: Architecture, structure and craft": New York: Routledge, 2017.
- [2] K. Crolla, A. Fingrut, "Protocol of error: The design and construction of a bending-active gridshell from natural bamboo," presented at the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA) "Living Systems and Micro-Utopias: Towards Continuous Designing", Melbourne, 2016.
- [3] L. Du Peloux, O. Baverel, J.-F. Caron, and F. Tayeb, "From shape to shell: a design tool to materialize freeform shapes using gridshell structures" presented at the Design Modelling Symposium Berlin, 2013.
- [4] R. La Magna, "Bending-active plates: strategies for the induction of curvature through the means of elastic bending of plate-based structures". Dissertation, University of Stuttgart, 2017.
- [5] J. Lienhard, H. Alpermann, C. Gengnagel, and J. Knippers, "Active bending, a review on structures where bending is used as a self-formation process" *International Journal of Space Structures*, vol. 28, no. 3-4, pp. 187-196, 2013.
- [6] J. Lienhard and J. Knippers, "Bending-active structures" Dissertation, University of Stuttgart, 2014.
- [7] J. Lienhard, R. La Magna, J. Knippers, "Form-Finding Bending-Active Structures with Temporary Ultra-Elastic Contraction Elements", *Mobile and Rapidly Assembled Structures IV*, 2014
- [8] A. Liuti, A. Pugnale, and S. Colabella, "The Airshell prototype: a timber gridshell erected through a pneumatic formwork" presented at the International Association for Shell and Spatial Structures (IASS) Annual Symposium "Interfaces: architecture.engineering.science", Hamburg, Germany, 2017.
- [9] F. Otto, J. Henniecke, and K. Matsushita, "Gitterschalen gridshells" *Institut für Leichte Flächentragwerke, IL*, vol. 10, p. 340, 1974.
- [10] S. Pone, B. D'Amico, S. Colabella, B. Parenti, D. Lancia, and A. Fiore, "Construction and form-finding of a post-formed timber grid-shell," *Structures and architecture. Concepts, Applications and challenges*, pp. 245-252, 2013.
- [11] G. Quinn and C. Gengnagel, "A review of elastic grid shells, their erection methods and the potential use of pneumatic formwork" presented at the *Mobile and Rapidly Assembled Structures IV*, 2014.
- [12] E. L. Slabbinck, S. Suzuki, J. Solly, A. Mader, J. Knippers, "Conceptual framework for analyzing and designing bending-active tensile hybrid structures" presented at the International Association for Shell and Spatial Structures (IASS) Annual Symposium "Interfaces: architecture.engineering.science", Hamburg, Germany, 2017.
- [13] E. S. Slaughter, "Models of construction innovation" *Journal of Construction Engineering and management*, vol. 124, no. 3, pp. 226-231, 1998.