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Low-Tech Geodesic Gridshell: Almond Pavilion

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Abstract

Traditional timber gridshells are extremely efficient but the required calculation experience and erection complexity make them neither appealing for the industry nor accessible. This paper shows the research in progress conducted on the universalization of alternative irregular gridshells based on geodesic patterns. The paper defines geodesic gridshells and discusses their suitability for scarce budgets and low-tech manufacturing of free-form shells. We introduce the research motivation, the historical framework, the geometrical properties of geodesic curves, and their structural corresponding advantages. We expose then our geodesic pattern design method on a free-form surface, obtaining a simple layout for the manufacturing of a multilayered gridshell. Finally, we discuss the benefits and challenges based on the experience from testing the concept with a built low-tech elastically-bent green timber gridshell.

Keywords

Geodesic gridshell, timber gridshell, low-tech fabrication.

Introduction

In recent years the blossoming of computational tools in design has led both to the emergence of free-form architecture and to a very interesting field of architectural geometry enabling its conception, optimization, rationalization and fabrication. These optimized symbiosis of form and manufacturing, although very efficient, often requires of exclusionary multiaxial numerical control, not always accessible. This paper is concerned with the manufacturing by not only efficient but also universal means of efficient forms namely thin shells. We define universalization as the accessibility of efficiency: investing the effort in design rationalization while keeping a low advanced machining dependency.

Shells are structures defined by a curved surface and often a doubly curved surface and by being very thin in the perpendicular direction to the surface (Naicu et al., 2014). Shells use the minimum amount of material to carry imposed loads using primarily membrane action, gaining strength through form rather than mass (Chilton and Tang, 2017). Nevertheless, it has the problematic of curved and often bespoke manufacturing. In this sense, gridshells defined as structures “with the shape and strength of a double-curvature shell, but made of a grid instead of a solid surface” (Douthe et al., 2006) are a solution by concentrating the structure into its strips (Johnson, 2017). These strips or laths can describe the gridshells in two groups (Naicu et al., 2014): from node to node or with long elements spanning across the structure, defined as continuous grid members. The traditional elastic gridshells are included in this latter group of long continuous beams, and ground its form in the elastic deformation of a flat deployable regular grid mat. Despite its benefits (large spans at small material, transport and assembly cost), elastic gridshells have been undermined by the cost and complexity of their erection method from its inception in the late 1960’s (Quinn et al., 2014).

Alternatively to elastic gridshells, ribbed gridshells arose by the same period under the lead of Julius Natterer as a “rational development of the original Frei Otto foldable lattice shell” (Chilton and Tang, 2017). Both elastic gridshells and ribbed gridshells ground their manufacturing in the principles of active bending in a geometric based approach (Lienhard et al., 2013), by exploiting the material properties and the cost-efficiency of obtaining form by means of elastic deformation, with the difference that the ribbed gridshell “was constructed directly onto the final profile on temporary supports rather than being assembled flat and coaxed into the double-curved form” (Chilton and Tang, 2017). But above all, ribbed gridshells were different in the “use of thinner and wider boards” for the laths, “more easily bent to a curved profile and less likely to break during bending” (Chilton and Tang, 2017). In order to reduce unfavorable stresses, the geometry of laths is restricted to follow geodesic curves in a surface in order to simply twist and bend along the weak axis.

From this pioneering strategy, a large collection of research and built examples exploited the geodesic curves as an efficient method for assessing the construction or cladding of free-form shells. This paper is concerned with the gridshells in which network of curves are intentionally following geodesic curves in a surface, and that we can define as geodesic gridshells.

Background

2.1 Geodesic network

A geodesic line on a surface is defined as a locally distance minimizing curve, where the normal vector of both curve and surface are parallel or antiparallel at each point (Pirazzi et

al., 2006), this is, the second derivative to any point of a geodesic lies along the normal to a surface at that point (figure 1.c). We can imagine them as the paths a non-steering vehicle would follow at constant velocity (no acceleration) on a landscape: geodesics preserve a direction on a surface. Otherwise said, geodesic curves in surfaces are the curves of zero geodesic (sideways) curvature (Pottman et al., 2010) although they have normal curvature and torsion.

These geometrical properties produce very useful constructive contingencies :

- Geodesics, also called plank lines, can be built out of inexpensive flat and straight boards where bending in the strong axis, is avoided, and are subjected only to bending about their weak axis and to torsion (Pirazzi, 2006). Inversely, "straight strips, ribbons, are geodesic lines that roll out "autoparallel" on a surface" (Lind, 2007) (figure 1).
- When two geodesic curves cross, they both share their the normal vector at the intersection point, thus the joint can be built with a simple inexpensive rotational joint. On the unrolled rectangular flat stripe, the location of the intersection is directly taken from the distance along the geodesic, and can be manufactured by simple universal means (figure 2).

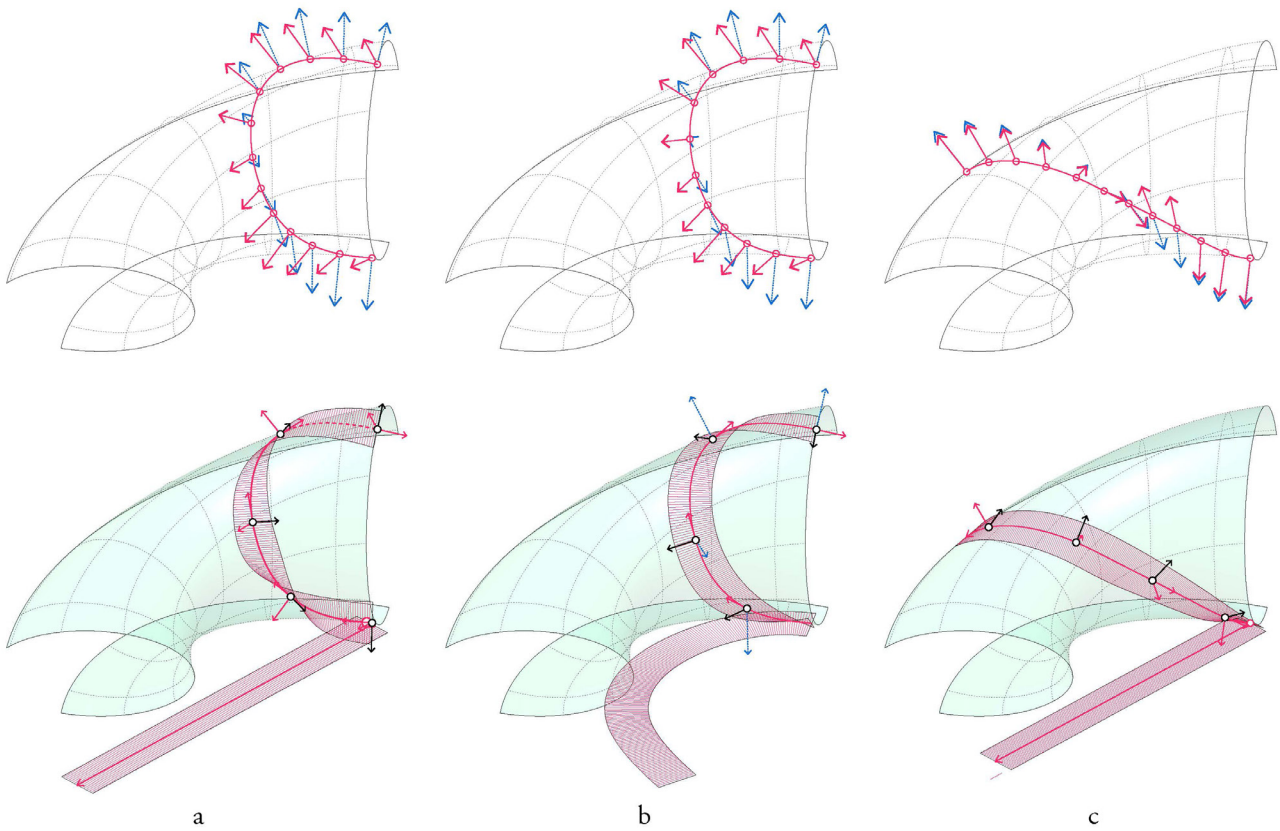
Geodesic gridshells are the network of at least two intersecting discrete families of geodesics, and their convenient properties spread across the surface. A geodesic net (Lind, 2007) is the built non-orthogonal and non-conformal coordinate system of geodesic lines describing a curved surface. Assembling "thin and long material-strip elements to follow the coordinate lines" form a curved mesh structure (Lind, 2007) namely a geodesic gridshell. Furthermore, geodesic gridshells can be specially interesting as supporting structure of a curved shell (Pottman et al., 2010). First, geodesic networks can be orientated and spaced intentionally. Second, geodesics are "the equilibrium shapes of elastic curves constrained to the surface" (Pottman et al., 2010). Third, the complexity of the manufacturing of a bespoke curvature is simply concentrated in the specific location of the joints, and the curvature emerges directly by the assembly of deformed planks.

2.2 Geodesic gridshells

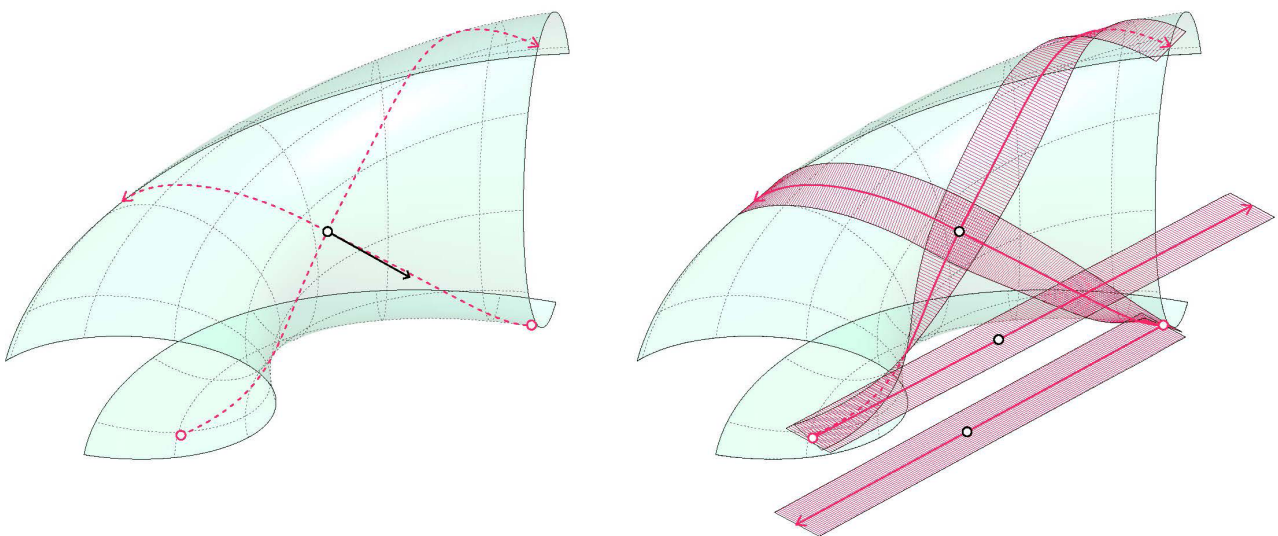
Traditionally, the empirical taming of the elastic behaviour of some materials has allowed the manufacturing of thin shells (Liendhard et al., 2013). In some types of basketry, wide pliable strips are empirically bent and braided. "Since the material-strip element's width greatly exceeds their thickness, the introduction of geodesic curvature k_g is prevented" (Lind, 2007). The paths of the strips can then be assimilated to geodesic curves and somehow the grid of basket strips is describing a surface by a geodesic net. Similarly, in ancient shipbuilding the use of geodesics have been underlying in the iterative plank attachment to the master frame.

Nevertheless, an intended use of the geodesic paths was already established by Sir Barnes Wallis: "enlarge the internal skeletal structure to full streamline dimensions, by forming its members as geodesics in the surface of both wings and fuselage, thus getting a much lighter, stiffer and stronger structure than ever before". The pioneering design, first applied in airships in 1920's and then in airplane designs in 1930's, was providing a solution to the manufacturing of complex streamlined surfaces: By having the geodesic curves form two helices at right angles to one another, the members became mutually supporting in a manner that the torsional load on each cancels out that on the other (www.barneswallisfoundation.com, 2017).

Decades later the IBOIS-EPFL lead by J.Natterer developed a new kind of shell structure by the name of ribbed shells in which simple planks following geodesic curves were creating a network of ribs. Layers of laths were waved together, completely filled in between and screwed (Natterer et al., 2008) The first application was the Polydôme in the early 90's: a spherical dome was created by laying the planks in a diagonal pattern (segments of great circles) over temporary supports (Chil-

**Figure 1.**

Curves on surface (top: surface normal in blue, curve normals in magenta; bottom: unrolling of developable surfaces lying on the curve and tangent to the binormal vector in black) a.Arbitrary curve: free twisting stripe not tangent to surface unrolls straight b.Arbitrary curve and developable surface with imposed surface normal: stripe unrolls in curved trajectory. c.Geodesic curve: stripe is tangent to the surface and unrolls straight.

**Figure 2.**

a.Two geodesic curves intersecting.
b.the unrolling of the developable surfaces lying on the geodesics, and the intersection point marked on both

tong and Tang, 2017) (figure 3.a). One of the benefits of designing an irregular grid is the intentional variability of the rib spacing, concentrating density where loads flow. The successful strategy was used in several projects, varying surface definition and grid parameters until the very ambitious project Expodach in Hannover, where the two geodesic pattern had the additional constraint of intersecting orthogonally (figure 3.b) in a minimal surface. The complete roof thin shell is discretized in prefabricated modules. More recently Toyo Ito architects have implemented the same structural technique for a large roof, with the particularity of having three families of geodesics flowing along a continuous surface.

Many alternative and experimental systems appeared during this period, exploring free-form surfaces, or expanding the grid. The Kupla gridshell (2002) was the outcome of an intuitive approach to geodesics: curves were digitally reconstructed based on the behaviour of small laths on physical models of complete free-form surface. The final construction consisted in the assembly of squared 60x60mm battens “bent and twisted on-site from seven pre-bent profiles” (Chilong and Tang, 2017) (figure 4.a). In a larger scale, the Waitomo gridshell (2010) takes advantage of the prefabrication of individual elements by cleverly imposing a regular grid of spiraling geodesics on a regular elliptic torus: a single twisting curve is needed for the anticlastic surface. Then, prefabricated twisting 160x36mm LVL laths were assembled on site and clamped together with shear blocks already glued in the lower chord (figure 4.b). However, methods for the design of geodesic patterns on free-form surfaces, were presented (Kensek et al., 2000), and successfully tested (Pirazzi et al., 2006) by simple elastic deformation with very thin laths, which simplifies and universalizes the technology. It is argued that the extra cost of manual labor in the assembly is compensated with the rationalization of planning and manufacturing (Pirazzi et al., 2006). This research triggered our curiosity to test the concept in a larger scale with limited resources.

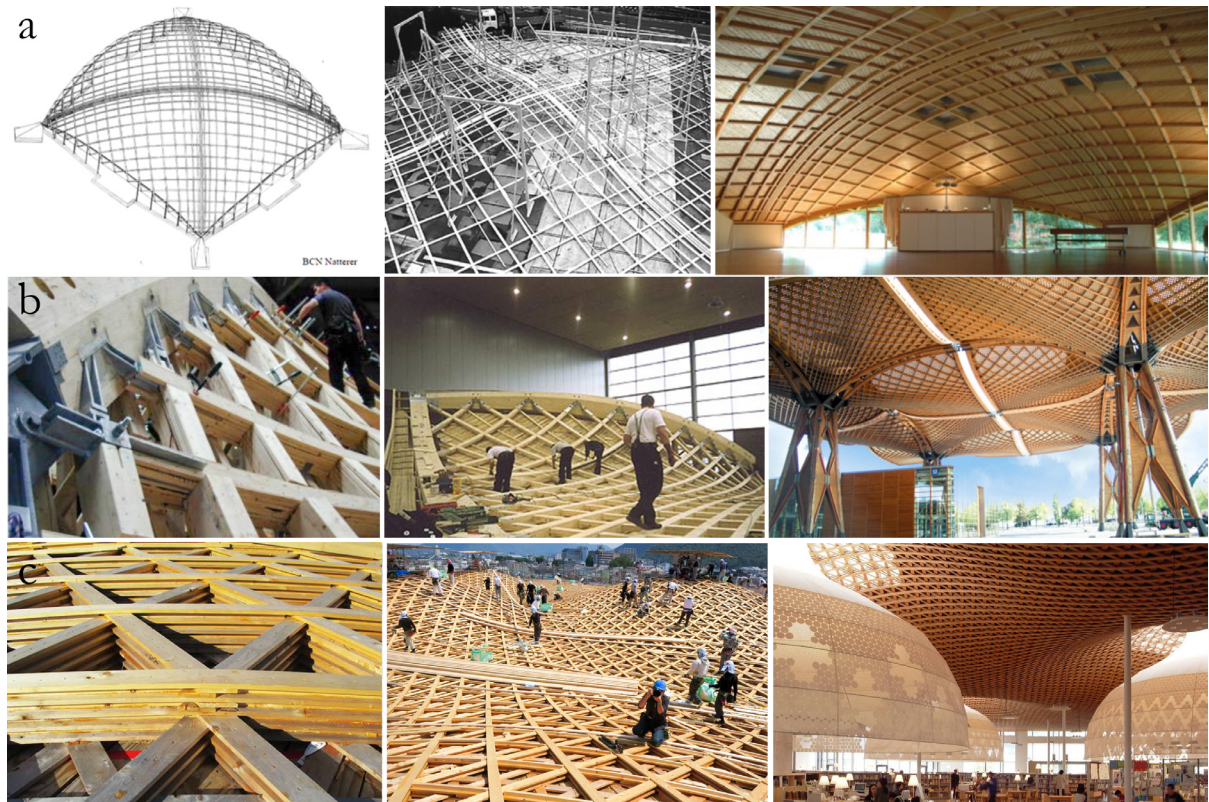
Design Process

In the parametric modelling environment Grasshopper, we adopt a similar process as shown in (Pirazzi et al., 2006), although we include the construction system and the material properties as constraints for defining the surface.

The first part consists in the form definition, taking as extrinsic input (fixed) the boundary conditions which are curves and the material properties (thickness, length of boards, splice length), and as intrinsic inputs (editable) the starting grid parameters, and an arbitrary curve control points. The first step builds an adjustable nurbs surface with the input curves which will be midway of the layers of the gridshell. The next step is the generation of the geodesic network over the surface: the density is controlled by n evenly spaced starting points on boundary curves and the grid angle aspect is controlled by the shift of corresponding points in the next curve. For the calculation of the geodesic we make use of the native algorithm inside Grasshopper, which minimizes the length of a curve between two points on a surface. The generated geodesics will lay on the virtual mid surface and will be the only which won't be built, but serve as guide.

Regular grids on double curvature surfaces trims the borders which needs to be collected by perimetral beams, whereas in this case the grid starts conveniently from defined supports but the grid spacing is uncontrolled if not prevented with evenly spaced geodesics (Pottman et al., 2010) tending to widen in the convex areas (Pirazzi et al., 2006). Given the material properties, the final step validates the network by verifying the normal curvature of the geodesic paths: for thin boards “the width has no influence on the bending stress which can therefore be expressed proportional to the thickness t and curvature” (Liendhard et al., 2011).

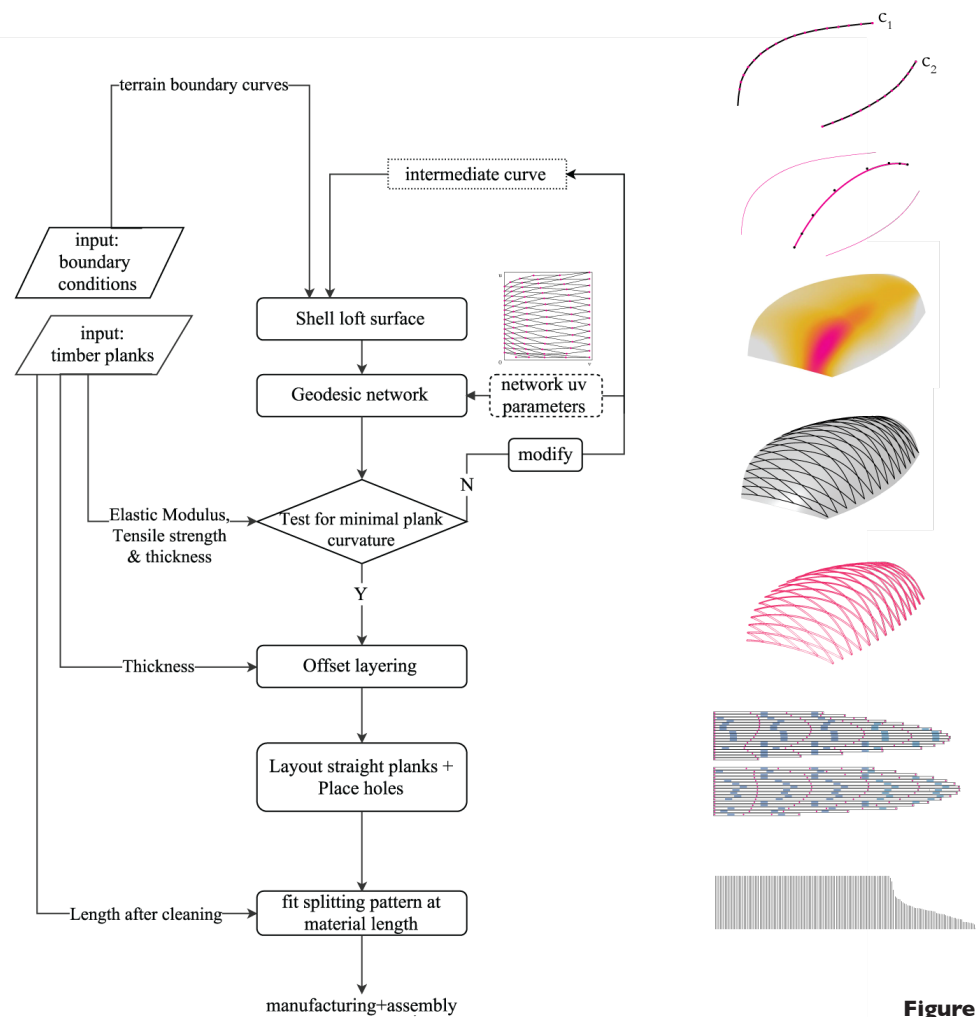
The second part is the process of fabrication rationalization and documentation, which takes into

**Figure 3.**

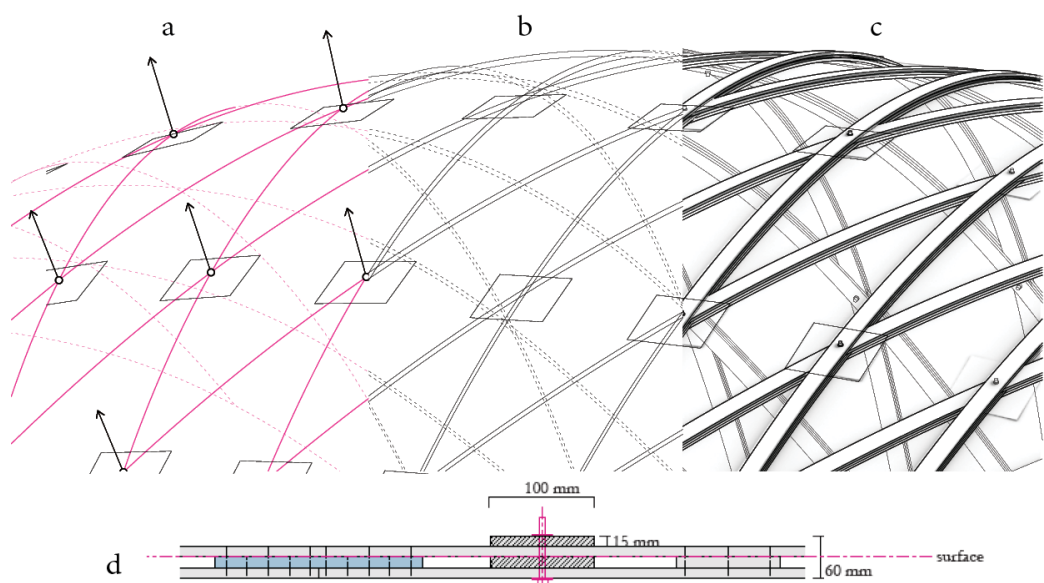
Ribbed shells a. Polydôme (1993) b. Expodach (2000) c. Mina-no-mori (2015)

**Figure 4.**

Assembly of individual pre-bent geodesic laths. a. Kupla observation tower (2002). b. Waitomo Caves

**Figure 5.**

Form defining process and procedural documentation

**Figure 6.**

a. Geodesic curves over neutral fiber surface and surface normal vector at their intersection
 b. Geodesic offset curves c. Visualization of layering. d. Composition of layers and splicing.

account the materiality of the construction system. The first step is simply extrapolating the geodesics on the surface normal according to the board thickness and number of layers, and although these curves won't be exact geodesics of the "enveloping surface to which they belong" the inaccuracy seems negligible (Pirazzi et al., 2006). Next, the planks are laid by taking the geodesic curve lengths and redrawing straight lines of the same length. The intersection loci of the network provides the distances to place the joints on the straight lines. Finally a custom algorithm locates the splicing joint avoiding the overlap with the node joint, while maximizing the number of standard lengths of planks.

Implementation

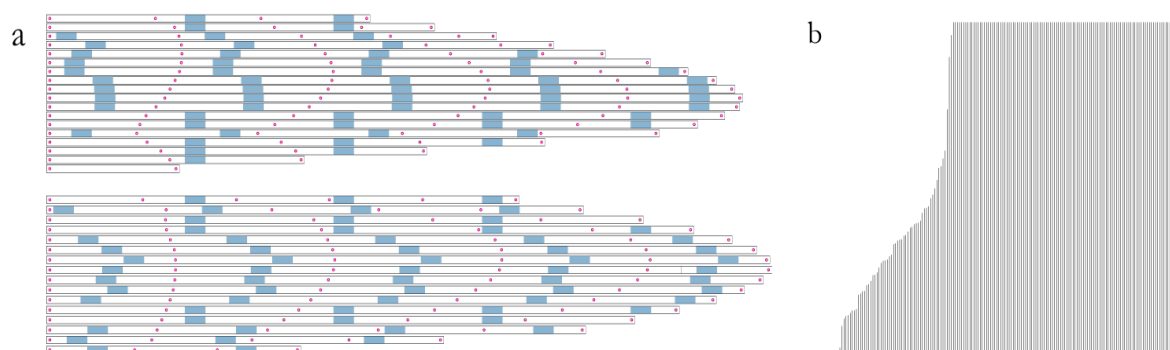
At the end of 2012, the ETSAV architecture school organized a landscape competition. As we (the CODA team) were eager to build more timber gridshells, we proposed a multipurpose geodesic gridshell which would be supported by the Catalan Institute of Wood, which happened to be the office next door. Despite losing the competition, we still presented the feasibility of the idea and availability of material, and seduced the academic community. After some months, in a bright and cold weekend, we converted the cantine terrace into a plank manufacturing facility, and we transformed the 1,5 m³ of freshly sawn green timber fitting in a van into a gridshell.

Varying the external inputs, the same parametric model was used for the competition model and the final construction. The surveying of the curved boundary conditions consisted in the photogrammetric reconstruction of two elastically bent plywood battens, placed on the site hill, which were then manually rebuilt in CAD. Supports allowed free rotation in the normal and tangent plane of the planks but no twist was allowed. The surface was designed in order to reduce curvature in the boundaries. The supports were made out of corrugated bar and twisted plates.

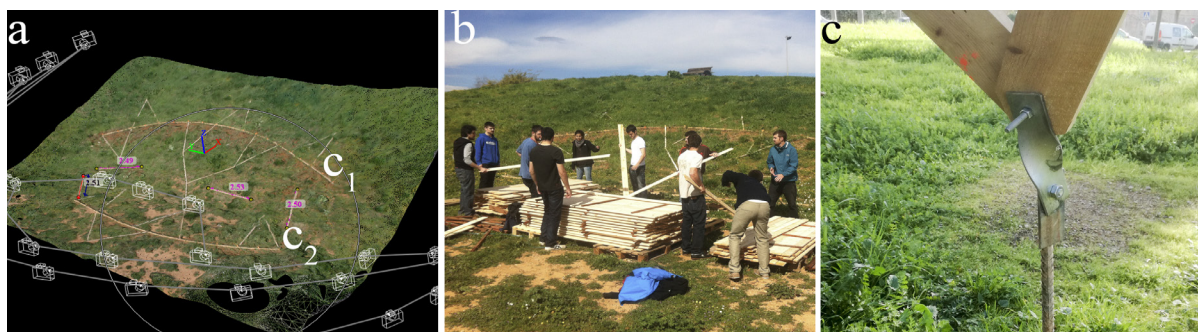
In order to promote the use of local timber, the sponsor provided the widespread *pinus halepensis*, even though it's normally used for non-structural uses and we asked to be green in order to facilitate the assembly. The boards arrived in rough sections of 100 x 15 mm with a large variation of grain and lengths. Once the planks were sorted by grain quality, leaving the denser and cleaner grains for structural use, they were cut in specific length, and spliced with overlapping pieces of reclaimed shortened planks. The reduced size of the shell, and the fibrous nature of timber provided enough tolerance to absorb the possible small errors due to the manual process of measuring and boring of the assembled planks, and no piece nor hole needed to be repeated (Figure 6). Interestingly the complexity of a doubly curved shell could be solved with a one-dimensional drilling tool.

The assembly consisted in the sequential bending of coupled planks without scaffolding. Similarly to akin sized bending-active shells (Lienhard et al., 2011), the system was already stable with a few bent and coupled planks. When both layers were placed, discontinuous shear blocks of same thickness were inserted connecting both layers, in addition the splicing joint. The final section consisted in two chords, commonly used in timber gridshells. In this case, bending-active is used in a geometrical approach strictly as a manufacturing affordable technique (Lienhard et al., 2013). Planks are easy to place because of the low torsional stiffness of timber (Naicu et al., 2014) and their deformability around their weak axis although as soon as they get connected, they quickly participate in the global coupling stiffening effect (Lienhard et al., 2011). In fact, the shell initially storing bending stresses will quickly transition from an elastic to a rigid shell, not only by the natural creep process in the timber, but mainly by its drying natural process, which will conform the internal structure of the fibres.

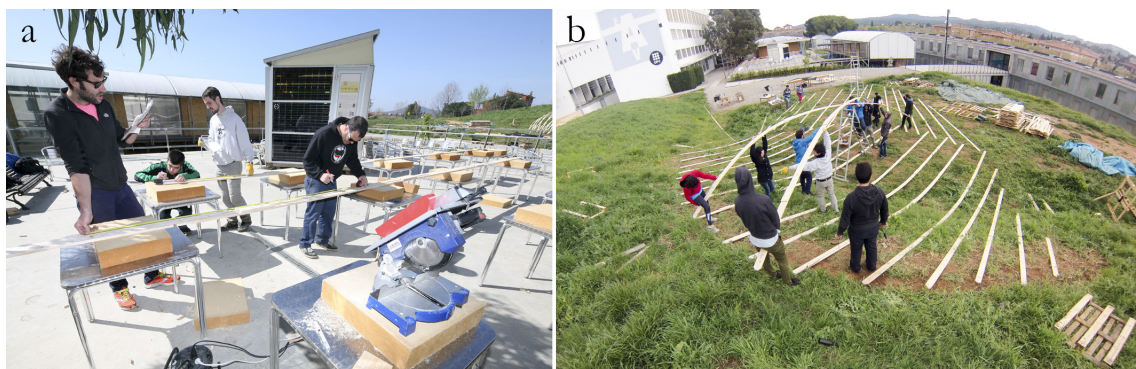
In any case, the lack of specialized manufacturing machines proved to be not a restriction: simple drilling tools and tapes are universal and all the necessary information is concentrated in the hole placement. When properly spliced, relatively short planks, fitting in a van for instance, are not a

**Figure 7.**

a. Avoidance of splicing joints and intersection joints b. Scattering of lengths of planks.

**Figure 8.**

a. Input curves. b. Sorting of boards. c. Support detail

**Figure 9.**

a. Spliced planks are bored at intersection. b. Erection of coupled planks

restriction either due to the discontinuous and assembled nature of the final thickened gridshell member. However, the structure stood half a year without any noticeable deformation, but, with the arrival of the rain, the increased weight and moisture, provoked a change of curvature in a relatively flat area. We think the form should have been “weighted” with dynamic relaxation to ensure a more funicular and efficient load flow, or increase the density and number of layers.

Conclusions

-This paper has presented an affordable and low hardware dependent implementation of the geodesic gridshell construction system

-We present a mechanically-free erection method, based in elastically bending by pushing and coupling planks.

-Bending-active structures implemented with green timber can be an affordable strategy to timber doubly curved forming. In this case, slowly carried out by sun drying, transitioning from an elastic bending shell to a rigid compressive shell

-Parametric modelling could embrace the complexity of design restraints in order to provide the best suitable forms according to physical restrictions.

Future research: Investigate the increase of stiffening effect that torsion may provide. More, investigate the control of the grid spacing by controlling evenly spaced geodesics.

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**Figure 10.**

Long planks are conveniently deformable until they get bent and coupled.

Figure 11.

Bottom layers. Bolts are pointing the normal vectors, and waiting for the upper chords.

**Figure 12.**

a. Sometimes many hands are needed to give the needed twist to a board.

b. breakages due to grain can be repaired on the fly, with more more shear blocks. c. detail of two beams arriving to a support.

**Figure 13.**

Final rigid shell after summer.

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