LATTICE SHELL METHODOLOGIES

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Abstract. This paper outlines a working methodology for the parametric development of lattice shell structures combining surface topology and form-finding with the material constraints of straight lath members woven into a geodesic network. By employing non-uniform grid spacing, a wider typology of spatial types can be employed than can be achieved with traditional flat-matt lattice shell construction. As a parametric design tool and working methodology, some of the heavy lifting in form-finding and geodesic analysis can be off-loaded to the tool, such that a more comprehensive attention can be placed on other design criteria such as spatial development and environmental response while maintaining the elegance and economy of lattice shells.

Keywords. gridshells; geodesics; form-finding; bending-active structures; wood; digital fabrication.

1. Introduction

Buckminster Fuller and Frei Otto are clear integrators between structural form, energy, and expression. This physical integration was part of a deeper economical principle to make the weaker the stronger through long-span lightweight and minimal material structures. For both Fuller and Otto, this economical principle developed from an ethical proposition connecting expression with ecology. However like-minded in this ethical stance, their design approaches and consequent formal outcomes could not have been more different. While Fuller’s Geodesic Domes employ rigid triangular units composed from standard length compressive struts to develop a pre-conceived pure form, Otto’s approach employed material experimentation from which unprecedented forms were the outcome. Fuller’s acceptance of the dome as an idealized model of surface to volume efficiency prioritized his emphasis on energy demonstrating the connection between form and energy flows. While Otto’s design for his own home demonstrates his interest in the
integration between form and energy, the complexity of his form-finding approach emphasized the integration of form, structure and materials rather than energy. While this paper does not address these energy issues, the motivation to outline a parametric methodology for lattice shell structures is to off-load some of this heavy cognitive load to the background such that focus on Fuller’s energy interests could be integrated with Otto’s balance between material economy and formal expression.

Lattice Shell Methodologies charts an incremental multi-year development of bending-active structures through teaching, research, and consultancy. This parametric approach provides a flexible framework that can capture the combination of a bottom-up approach driven through material constraints, economy, and structure, while maintaining a certain degree of top-down formal expression. The intention of this parametric methodology is not to automate lattice shell structures, but rather to identify the precise points at which human discretion is needed.

2. Principle Definitions

Due to their similar diagonal pattern, the terms gridshell and diagrid are often mistakenly used as interchangeable terms when in fact they point to two opposing structural approaches. The diagrid combines gravity bearing vertical elements, such as columns, with the lateral system, as an integrated solution to the braced frame, whereas gridshells are employed for long-span structures utilizing the shell-action of curvilinear surfaces. To conflate the diagrid with the gridshell overlooks the primary significance of form-finding in the gridshell - as a shell structure. While there are numerous form-finding approaches for shell structures (see Bechtold 2008), in general the surface can be conceived as a flexible membrane (soap film, hanging chains, catenary network) but it is the boundary curve that constrains the membrane to take its shape under a given load. Consequently, in a form-finding workflow it is the boundary curve, not the surface, which gives the designer primary discretion over form.

Lattice shells are a subclass of gridshells constructed from a multi-layered warp and weft lattice from continuous lath pieces. While lattice shells existed earlier, Ted Happold, while working for Frei Otto, brought lattice shells into contemporary discourse through the Mannheim Gridshell. Happold defined the lattice shell as “a doubly curved surface formed from a lattice of timber laths bolted together at uniform spacing in two directions” (Burkhardt 1978). Lattice shells are typically constructed from a flat matt lattice of alternative lath layers bolted together at uniform spacing, and then raised and/or lowered into place often with complex telescoping scaf-
folding (see Harris et al 2003). While there is elegance in this approach, it
does limit the formal morphology of lattice shells. The methodology devel-
oped here continues with the specific material constraints of the double layer
lattice structure, but departs from the flat matt technique employing instead a
non-uniform lath spacing. This has the potential for new formal types of lat-
tice shells than what is limited to the matt technique alone. The challenge
then is how to fit straight lath members onto shell structure surfaces.

This is made possible through geodesics. Geodesics are mathematically
defined as the shortest distance between two points on a surface. Because a
straight line is the shortest distance between two points, it follows that when
a geodesic curve on a surface is flattened or "unrolled" it will likewise be
straight. However, this is purely geometry without any material constraints
which need to be introduced into this methodology.

3. Surface Morphologies
Despite their flexible appearance, lattice shell surfaces are uniquely con-
strained. Lattice shells develop in reciprocity between the structural needs of
the shell and the lath material’s capacity and tendency (Delanda 2004) to
bend along this surface without failing or twisting. This approach employs
geodesics fit to a single NURBS surface, and therefore, the surface morp-
ology is likewise constrained to the basic constraints of NURBS surfac-
es. While the tendency of novice users is to simply loft everything and join
multiple surfaces into a formal representation, structural continuity and con-
tinuity of surface logic go hand in hand. If surfaces are joined, each surface
would then need a ridge beam at this joint to carry this load to the ground,
while each single surface in this assemblage would follow the same process
identified here (see Herzog 2000).

4. Lath Pattern: Projected, Applied, and Geodesic
From a given NURBS surface, a pattern can be projected onto the surface
(typically from the ground up), a pattern can be applied stretching this pat-
tern proportionally across the surface in reference to the density and shape of
the UV curves, or a pattern can be developed from a network of geodesic
curves. If lath surfaces are developed from projected or applied patterns, they
will not be straight. While these arc-shaped unrolled surface profiles could be
cut from standard board sections on a CNC router, not only would this be
materially inefficient, but in fact cutting across the grain would lead to mate-
rial splitting when stressed in its curved position on the surface.

Only a geodesic pattern is able to be unrolled into straight laths, and yet
developing a lattice pattern from a network of geodesic curves presents a
unique challenge. As the geodesic curve is a mathematical solution to find the shortest path, it does not necessarily yield useful results (Figure 1). While mathematically accurate, these "failures" need to be resolved through the reciprocity between form-finding and pattern logic.

5. Previous Work

Previous work (Cabrinha 2008) found that by employing surface relaxation to a given surface a geodesic network can be evenly distributed, and is therefore able to be developed from straight laths (Figure 2). While successful as a first step, this solution neither accounted for the constraints of material to bend into this position, nor if the relaxed surface was structurally viable. To evaluate the structural stability of this relaxed surface, a preliminary analysis by Buro Happold, Los Angeles found that a combination of surface relaxation with an upward load vector was necessary. Perhaps not surprising in hindsight, this upward load vector resulted in a catenary cross section.

6. Parametric Lattice Shell Development

The intention of outlining an explicit working methodology for lattice shells is so to allow this methodology to be parametrically defined. This parametric approach has been developed incrementally in teaching, research, and consultancy.

6.1. Parametric Wood Seminar

In Winter 2011, my parametric wood seminar made two developments from this previous work. First, a parametric solution was achieved that developed a four-layer geodesic lattice network over a given surface, while unrolling each unique individual member for rapid fabrication of laser-cut models. This parametric solution enabled a matrix to be developed from a family of solutions including changes in warp and weft lath densities, as well as variations of different lath cross sections (Figure 3). Second, through empirical testing
of minimum bending radii of physical lath samples, minimum curvature circles were measured so that a simple parametric model would be limited by this minimum curvature (Figure 4). These values were then tested at full-scale through a rain-screen application using ¾” x 3.5” pine laths. From this work, the remaining thread was to introduce form-finding into this parametric workflow.

6.2. SMART GEOMETRY GRID-SHELL

The Smart Geometry Gridshell introduced form-finding into the previously developed parametric workflow and tested this out through a full-scale installation. This served as a proof-of-concept of the non-uniform spacing approach resulting in a formal type that could not have been developed through the flat matt technique (Figure 5).
Along with streamlining the previous work of the Parametric Wood Seminar, form-finding was integrated into this workflow through the introduction of Kangaroo. This solution established the boundary condition from a catenary control rig, from which the surface was form-found through a network of springs in Kangaroo which balanced the equalization of spring lengths (surface relaxation) with an upwards load vector (inverse hanging-chain model). Curvature analysis was employed to make sure that the individual 1 ½” x ¼” pine laths could be bent into the shape proposed (Figure 6).

Rather than unrolling individual laths for full-scale construction, perhaps the most interesting development in the Smart Geometry Gridshell is that the only output required for full-scale fabrication was the lath length and the spacing between holes supplied through output to a spreadsheet compiled in a single 11”x17” fabrication table for each of the four layers. A single plan drawing was all that was needed for assembly by organizing the laths round the central ring. After the first attempt to raise the entire surface into place proved impossible, the structure took shape easily when lifted from smaller catenary arch sections. With the first two layers assembled, the surface was highly unstable until the additional two
layers were put into place piece by piece. Consequently, in the future a simple frame scaffold at precise surface targets would enable a much quicker, precise, and more logical assembly process.

The Smart Geometry Gridshell provided a proof-of-concept that a parametric loop between form-finding, material constraints, and geodesic lattice network with a simple fabrication process and (somewhat) simple assembly process could be achieved. However, as a working methodology for full-scale structures, this approach needed to be tested beyond installations with flexible thin pine laths, to structural lath members such as the 1 3/8” x 2” (35 x 50mm) laths of the Weald and Downland Gridshell to the 2” x 3 1/8” (50x80mm) laths of the Savill Building.

6.3. KORLANDIA GRIDSHELL

This methodology is currently being implemented for a 50’ x 140’ lattice shell for a residence in California. The parametric model provided a feedback loop between the owner’s programmatic needs and formal interests, quick export for structural analysis, and real-time feedback of the bending capacity for the 1.5” x 3.5” Laminated Veneer Lumber (LVL) members proposed by the engineers. To give the owner control of the shape generation, the parametric geometry set-out included geometry rationalization from the given plan geometry, a control surface to manipulate the undulating boundary curve, and a series of catenary arches fit between column lines to form the structural surface (Figure 7). While form-finding was initially developed in Kangaroo, simply developing the form through parametric catenary curves
proved to be computationally more efficient, enabling a quicker feedback loop in this iterative approach. In either approach, structural and material criteria need to be incorporated into the system as the parametric force values are not calibrated to real world criteria. While the structural engineers for the residence analysed several iterations of the surface using deflection analysis in RISA, in the end, it was an understanding of the material constraints that provided the balance between economy, aesthetics, and structure.

Custom milled green timber was beyond the budget for this project, and the code requirement for high-strength timber member pointed the way to engineered lumber. Nominal 2x4 LVL members were readily available in 60’ lengths as they are typically used as chord members in wooden trusses. Green lumber in typical lattice shell construction allows the laths to plastically deform over time, literally stretching the wood cells. The use of engineered lumber, however, would restrict us to only elastic bending due to the laminated nature of the material. At the same time, an elastic approach to bending was more appropriate for the non-uniform lath-by-lath assembly developed in this methodology. Based on the manufacturer’s load values of the LVL, the engineers were confident the material had sufficient strength. However, we did not know if we could actually bend the laths into the curvature necessary. Working with the owner in consult with the structural engineers, we conducted 3-point bending tests with 20’ long members to identify the minimum radius in bending of these members. Based on the current design at that point, we needed 24” of displacement at the center-point of the member, which established our target.

Using a come-a-long, nine members were bent at ½” increments until they failed, noting and logging audible sounds of cracking along the way. One member failed prematurely before the tar-

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**Figure 8:** Results of 3 point bending tests with 1.5” x 3.5” LVL samples to determine radius of curvature at bending failure.

**Figure 9:** The material analysis in Figure 8 can then be applied in the parametric model to identify areas at risk of failure, so the catenary displacement can be minimized.
get, but the rest of the members made it past the target curvature before failing (Figure 8). Based on these displacements, the radius of curvature fit through these displacements was drawn so this minimum radius could be analyzed in the parametric model forming a real-time material feedback loop (Figure 9).

During this final adjustment, the parametric model also provided a particular insight into future construction logic. As was known, many of the lath members were beyond the 60’ length of each individual lath and a future connection joint would have to be determined and tested. However, through a real-time quantitative assessment of all the lath lengths easily made possible by the parametric model, after a couple iterations it was found that with a 6’ offset in the boundary curve combined with a slight angle of rotation in the lath grid, every lath would fit within the standard 60’ lengths. With this parametric approach, the bending capacity of the members constrained the shape, and the length of the members established the extents of the shell (Figure 10).

7. Conclusion

Lattice shells combine an elegance of form with the efficiency of structure driven by the construction simplicity and material economy of straight lath members that can be bent into shape. While formally expressive, the form is in fact the result of an explicit methodology. As the boundary curve establishes the constraints of the system, it is the boundary curve, not the surface, which gives the designer discretion over form. From this boundary constraint, the form is developed through the forces applied in the form-finding process such as a vertical load vector (pushing) and/or surface relaxation (stretching or equalizing). Although these values can be adjusted by the designer, they are only meaningful when calibrated by material constraints. This can be established through physical testing to find the minimum bending radius, from which real-time material feedback can be embedded into the parametric system. Through the combination of form-finding and material constraints, a
geodesic network can be fit onto this surface enabling the compound curved surface to be constructed from straight lath members.

As an elegant response to how material can inform form, the intent of articulating a parametric methodology is to off-load some of the cognitive task at the surface to enable a more comprehensive spatial integration. As historian of structural engineering David Billington has noted, there is a distinction between scale, use, and form that has separated architecture from engineering. While architecture is focused on creating space, the structure is designed to control force, rather than space (Billington 1983). By developing a parametric lattice methodology for architects, some of the computational heavy lifting can be off-loaded to the tool, such that a more comprehensive attention can be placed to other design criteria including spatial development and environmental response while maintaining the elegance and economy of lattice shells.

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References