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Timber Post-formed Gridshell: Digital Form-finding / drawing and building tool

Sergio Pone[1], Sofia Colabella[2], Bernardino D'Amico[3], Andrea Fiore[4], Daniele Lancia[5], Bianca Parenti[6]

[1] Professor, Department of Architecture – Federico II University, Naples, Italy, *sergio.pone@gmail.com*
[2] PhD, Lecturer, Department of Architecture – Federico II University, Naples, Italy, *sofia.colabella@gmail.com*
[3] PhD student, Centre for Timber Engineering - Edinburgh Napier University, Edinburgh, UK, *bernardinodamico@gmail.com*
[4] Architect, *Cmmkm Architettura e Design*, Naples, Italy, *andrea.fiore@live.it*
[5] Architect, *Cmmkm Architettura e Design*, Naples, Italy, *andrea.fiore@live.it*
[6] PhD, Architect, *Cmmkm Architettura e Design*, Naples, Italy, *bianca.parenti@cmmkm.com*

Summary: This research deals with design, structural analysis and construction of timber post-formed gridshells. Starting from the scale modelling experience, from 1:20 to 1:1 scale, a digital form-finding strategy was early developed with a Building Process Finite Element (FEA) simulation (GBP-FEAs), with which a real scale experimental structure was designed (and built). Then in a further experimentation building the digital form finding was performed with aid of a graphical algorithm editor (Gfft – Gridshell form finding tool), that uses generative algorithms. At present time both strategies are used together: with the Gfft a "correct" form – and the correspondent flat square mesh - is searched, structural analyzed and improved; then GBP-FEAs finding out the resulting stresses ratio at every deformation stage. The next goal to achieve is the development of an integrated software to design a "correct" gridshell without any knowledge of FEA or graphic algorithms software's.

Keywords: *timber post-formed gridshell, digital form-finding, form-improvement, generative tools, free form construction*

1. INTRODUCTION

Our research on timber post-formed gridshell, at present time, can be separated in three stages:

1. Analyze and deepening of post-formed Gridshell typology in which the smartness of form resistance could be combined with the use of small dimension wooden products also derived from coppice. The request of these products, in Italy, in the last 50 years heavily decrease causing the recession of forest industry with huge loss for the woodland heritage and for the society which lied hits economy on wood cutting and manufacturing. Our intention was deepening gridshell construction method to contribute to the growth of use of locally sourced materials and to the growth of local trades creating a new market for wood. We still try to follow what Frei Otto explained: using minimum amounts of material to reduce environmental impacts within a wider idea of social and environmental sustainability.

2. The definition of a Timber post-formed Gridshell designing protocol that keeps together the reasons of architectural design, structural behaviour, drawing and worksite organization, coexisting in a unique design effort, could define a system of **necessary forms** that qualifies the design thinking through construction and structure and vice versa. This research stage, still related to a scale modelling form-finding through a 1:1 scale models, verified [confirmed] - step by step - up to what point the expressive freedom of gridshell is two-way linked to their structural behaviour and building procedures, and how much form and structure are weaved together to become a **resistant form.**

The scale-model approach to define form resistant shapes (Hook's law, Galileo, Isler, Otto, Nervi, etc.) has been tested as well as the forming steps of digital simulations, to assess the stress of each lath during the assembly.

3. When the acquisition stage of the essential knowledge needed to the construction was enhanced, the research was directed toward the acquiring of new digital tools able to replace entirely the scale-model approach.

The main feature of this second research stage is to be deeply linked to the construction's knowledge previously earned: each tool aspect is gathered from the technological awareness of the construction, of which the entire tool is an emulator. The practise, gained working on site, introduces in effect a number of restrictions and constrains that has to be followed and reproduced in the digital protocol. In addition a structural behaviour cluster must be attached in order to give, right from the first design steps, a rough feedback about gridshell structural performance in order to avoid "wrong" shapes where stress values are too high, with a low overall stiffness, or more generally to find a form which "mainly" works like a shell-membrane rather a shell-plate. Is for that reason that the tool must be supplied with wood mechanical properties, resistant sections, starting flat square mesh spacing and sides to constrain. When is reached a form that satisfies the best architectural, structural and constructive needs, the real structural analysis can take place. As a consequence of these tests (dead weight, permanent and live loads) until now there wasn't any need to alter the tool obtained shape, as a good validation to the analysis protocol provided in the tool.

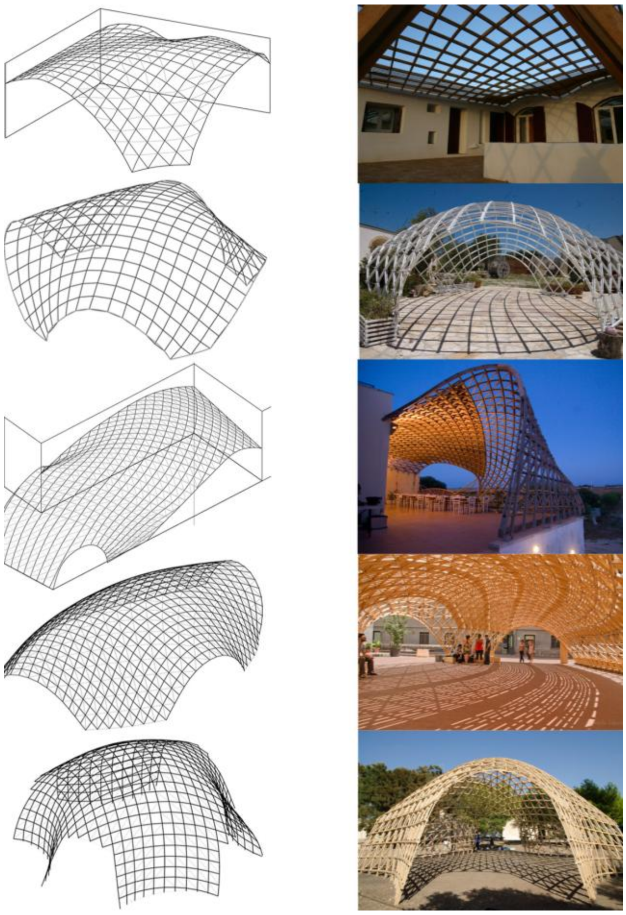

Fig. 1. Five of nine gridshells designed and build by the research group in the city of (from the top): Ostuni 2007, Lecce 2010, Lecce 2010, Napoli 2012, Selinunte 2012 - Italy.

2. BACKGROUND: THE TRANSITION FROM "ANALOGICAL" DESIGN METHOD TO THE "HYBRID" ONE

In the analogical phase of this research, great importance was given to the study of twentieth century's great engineers and architects (Antoni Gaudì, Frei Otto, Pierluigi Nervi, Eduardo Torroja, Heinz Isler, Franz Dischinger, etc) on complex geometry structures, especially those concerning simulations of forms derived from the structures found in nature [1], in which there is a balance of forces according to the "Form-finding" principles. In particular, we analyzed the ways in which Mannheim Lattice Shell scaled models were made, from preliminary steps up to the executive, through the vector drawings expressed by prof. Klaus Linkwitz with the support of the Institut für Anwendungen Der Geodäsie im Bauwesen - Universität Stuttgart, by the photographic and mathematical methods he had developed during the design of the German Federal Pavilion at Montreal and the Munich Olympic stadia [2] It was needed the measurement of the hanging scaled model to obtain the initial shape of the gridshell to submit to a series of structural verifications in a recursive sequence of curvature radii adjustments. Because of the unprecedented complexity and dimension of this structure, it was necessary a close integration between physical models testing and the limited computer analysis possibilities available at 1973 [2][3].

The chosen funicular shape, already experimented in Frei Otto tensile structures, was only a starting point, not strictly necessary for a lightweight structure, as explained by Ted Happold and Ian Liddel: «The shape for the shell is established by photogrammetric measurement of a hanging chain model and is funicular. If the shell is loaded with its own weight only, no bending forces result. This is an ideal condition, as in practice the imposed loads on the shell are greater than the self-weight and are not uniformly distributed at the nodes. A funicular shape is an advantage but is not essential.» [2]

Therefore, it's not surprising that the Weald & Downland Open Air Museum gridshell shape was developed from non-funicular models, thus, its structure doesn't reacts in pure compression scheme under self weight [3].

During the long phase of our research on achievable lightweight structures form-finding methods referenced to timber post-formed gridshell, we started from Happold and Liddell statements, bypassing hanging models and trying to find out a new method for a different form-finding that had to return information about the correctness of the tectonic choices.

Firstly, scaled models were made of wire mesh mosquito nets; this material, very malleable, was perfect to follow the desired shape, although completely ineffective for a first strength testing, see fig. 2.

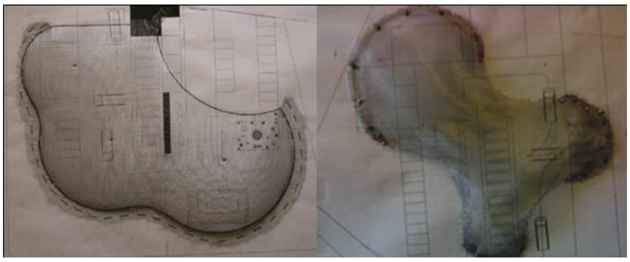

Fig. 2. Scaled models made of mosquito nets

For this reason the mosquito net was replaced with a mesh of woven wooden sticks (2x1 mm) to reproduce 1:20 scaled models; the achieved shapes geometry, in this case, was not funicular but simulating quite closely the gridshell behavior during assembly phase, from flatten lattice to final double curvature shape, see fig. 3.

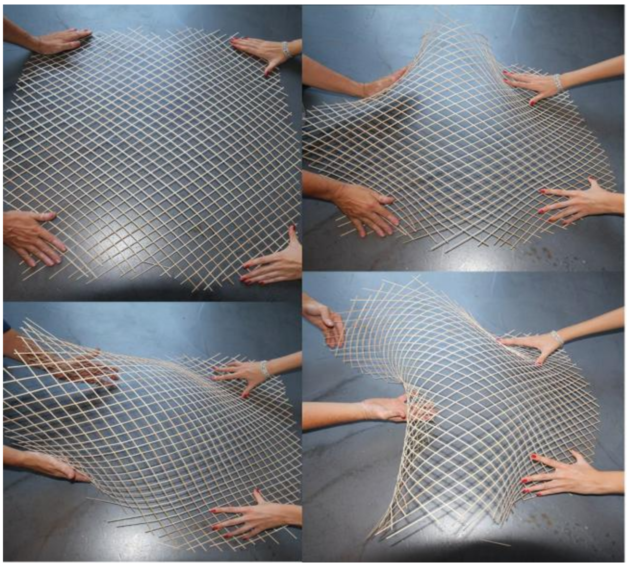

Fig. 3. 1:20 scale model, made of wooden stick (2x1mm)

As consequence of the gained experience with woven wooden models, we assumed a general and simple principle, connected to what happens in the construction site: when a mesh of woven wooden sticks breaks under a small external force, it is likely that the wooden laths of the real gridshell will be subjected to excessive stresses to get the desired final configuration, this means that the real gridshell has a "wrong" shape. We already knew that the key for modeling complex three-dimensional shell structures is the computer-aided design awareness, but we also believed that it was necessary learning more about the gridshell behavior by making scale model and 1:1 prototypes with our hands. Studying for long time scaled models behavior, indeed, we assumed what Galileo Galilei first explained about the limited strength of animal bones whose dimensions can't be scaled up linearly. As actually explained by Bill Addis: «At an intuitive level, most people would assume that the behavior of a model test can be scaled up linearly to full size. However, this is not the case for all types of structure. There are two types of structural phenomena or behavior. Those that can be scaled up linearly, such as:

• the linear dimensions of a structure

• the shape of a hanging chain of weights or a membrane; and, by Hooke's inversion law, of funicular arches, vaults and domes

• the stability of masonry compression structures, including arches, vaults and domes and those that cannot, such as:

• the mass of a structure

• the strength and stiffness of a beam

• the buckling load of a column or thin shell» [4]

The second issue deals with the slowness of this design process, due to the not straightforward form-finding process for post formed gridshells: when the scaled model shows structural deficiencies it's necessary to start from scratch with a new sticks' mesh and a new base.
The last but not least inconvenience deals with the transferring of the obtained shape into a tridimensional CAD model; once the tridimensional gridshell has mapped and drawn into a CAD software, it has to be analyzed and modified to gain an optimized structural shape through the use of nonlinear finite element analysis (FEA). First attempts to reproduce the physical model shape into CAD was performed by hand insertion of the node's spatial coordinate for the whole geometry; in a second phase, to reduce working time, a continuous equivalent NURBS surface was modeled, then, through the "compass method" [5], we were able to draw a mesh of equidistant points from each other, corresponding to the grid of nodes.

This method was faster and more accurate, although the reliability of the virtual geometry would still be affected by the surveying accuracy. In addition, very approximate information in terms of stresses can be obtained.

A completely different experiment has been developed for a 600 sqm gridshell (never built); here we tried to better reproduce the behavior of the real structure by modeling in deep detail the gridshell technology: a tin pin simulating the bolt and the flat lattice was made up of modules in imitation of real 3x3 m wooden laths modules. At the end of this process we were able to get a vector tridimensional drawing thanks to a 3D laser scanner: an equivalent Point cloud was the raw output from which we deduced the corresponding mesh with vertices at each connection among laths, thus the mesh edges coinciding to the laths axis. This interesting procedure has been lately discarded because of its complexity especially due to the need of cleaning up the vector model from all the physical model inaccuracies, too faithfully reported by the scanner., see fig. 4.

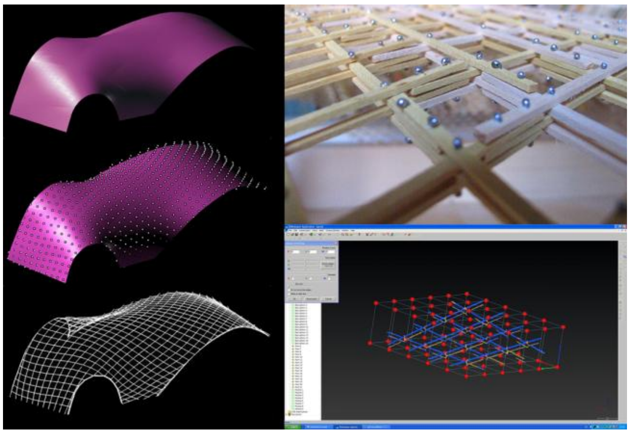

Fig. 4. Left: Transformation of a double curved surface in a net mesh. Right: drawing by 3d scanner

In conclusion, since making the scale model of a gridshell was the first step of our design procedure, the whole process resulted too slow yet: as the input parameters for the form-finding simulation come from physical model, a change in the shape required the making of a new scale model and so on. Perhaps we should have established a scientific relationship between the performance of the scaled mesh of woven wooden sticks and the full-size prototype. But we didn't; we rather preferred proceeding with the deepening of digital form-finding method.

For this reason, an important goal in our research has been achieved with a computer methodology for digital form-finding procedure with the Abaqus [6] finite element software developed by Bernardino D'Amico [7].

In this case, with a given flat lattice geometry and the vector of imposing displacements (both previously found by scale models) a geometrically nonlinear finite element analysis is set to simulate once more the forming process. Further, bending strength verification is performed for each beam element, assessing the laths cross section for timber strength and elastic modulus variation. The implicit FE analysis requires a high computational time, as well as the setting of imposed displacements to be carefully calibrated in order to avoid small iterations values, so to achieve eventually the solution's convergence. For this reason the FE analysis is performer in a latter design stage, with flat lattice geometry previously defined by scale model. The need of solving a highly nonlinear system involving large displacements (as the case) explain why dynamic (or pseudo dynamic) explicit analyses are the most followed approach so far [8][9] one for all: the Dynamic Relaxation method [10][11]. Nevertheless, the development of a form-finding tool for post formed grid-shells based on static nonlinear FE analysis is currently under development at the Centre for Timber Engineering of Edinburgh Napier University [12], see fig. 5.

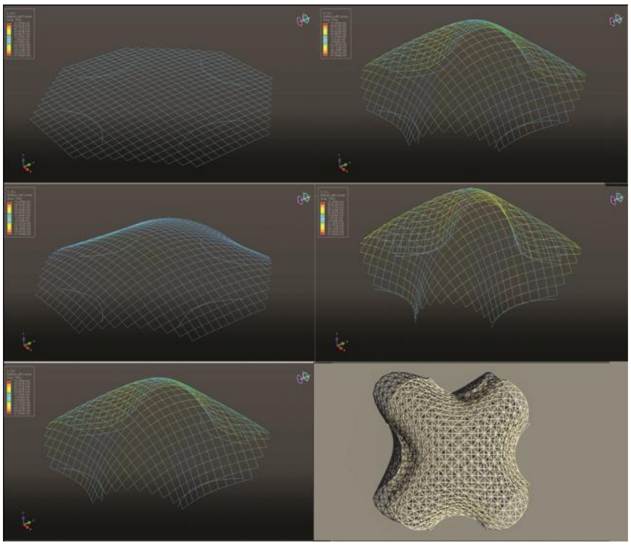

Fig. 5. Simulation process in Abaqus

Another method to bypass the need of physical models has been proposed by Kuijvenhoven [9] consisting of a tool which performs, in a first step, the forcing of a general flat grid onto an imposed surface while in a second step, boundary constraint are added and the exceeding grid and external forces (springs jointed between grid and target surface) are deleted so the grid settles again to its final shape. Although this tool represents a novel approach to the problem, it remains as general design method, not usefully applicable for professional practice. In fact only grid-shell with a "continuous" and "plane" boundary curve can be performed, which means that no gates and no spatial boundary curve (like in the Savill Garden grid-shell) can be considered.

3. THE TRANSITION FROM THE HYBRID TO THE DIGITAL DESIGN METHOD: THEORETICAL ASPECTS

One of the main objectives throughout our research about the gridshell is the development of a software, smoothly applicable and with a plan interface, in order to allow the designer to anticipate, already at the preliminary level, a substantially correct form and compatible with the construction method that will be used. This particular type of digital Form Finding, in fact, should contain all the information related to the behavior of gridshell, both during the construction phase that during its design life cycle, with the scope of easily configure the architectural form but also the flat grid which will generate the surface itself. The immediacy of the digital process is not yet fully achieved and is one of the topics for future studies. It is clear, in fact, that the ease of use for the program is the last piece with respect to the knowledge of the great complexity of this building process, from the technological aspects to the structural ones, without which the software itself would be configured as one of many generators of complex shapes already present in the field of form resistant structures. For this reason, once defined the general protocol that goes from the preliminary drafts until buildable, it became necessary to create two specific software: an engineering tool specific to the research group and one specifically built for the architectural design supplied with a database for designs types, types of wood, construction materials, details and cost estimates, in order to finally enter the wooden post-formed gridshell into the panorama of widespread architecture as a consequence of the improvement in data exchange and working flow efficiency among the different figures involved in the whole production process (architect, structural engineer, supplier, contractor, etc.) industry.

The transition from the analog form-finding process to the digital one, which uses of software for the three-dimensional representation according parametric algorithms, replaces (with a real-time control of the shape) the slow, repetitive and non-reversible phases concerning the analog method.
This process has started with the occasion of the graduation thesis by Andrea Fiore and Daniele Lancia [13], for which we set ourselves the objective of creating a digital tool that would have allowed to design in a fast and flexible way a plausible gridshell's shape starting defining the problem in terms of architectural requirements (footprint, height, size, position and number of entrances), without passing through the realization of a timber model.
The aim was to develop a proper computerized shape research methodology called Gfft (Gridshell Form Finding Tool) peculiar for post-formed gridshell. The method uses as a base platform a three-dimensional graphics software particularly suitable for complex geometries and for the free form on which are grafted some plug-ins that make their operation more suitable for the heuristic phase of the project. In particular, the first application allows to configure the forms in a parametric way through some steps of simplified programming. Basically, instead of drawing an object it is necessary to configure the logical, mathematical and geometric path leading to that specific form.

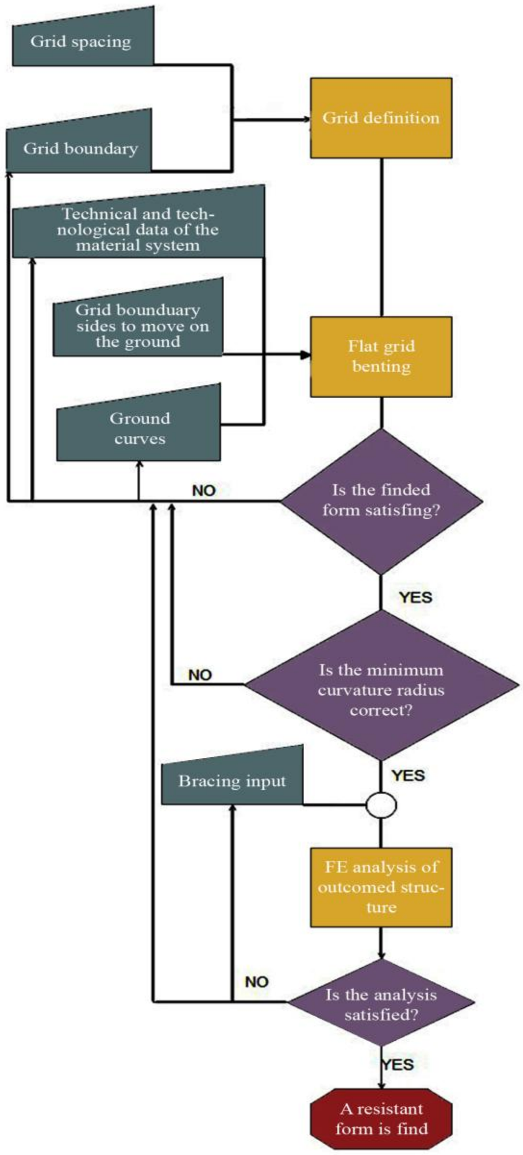

Fig. 6. Gfft workflow

Ex post facto, the software remembers each step and, at any time, the user may modify the data: for example, the first step requires the design of the flat grid: using the *gridshell form finding tool*, the user can change the shape and dimension of the grid by simply drawing a new cutting line.

In the same way, the user can proceed to the subsequent steps, where he can change the position of an external constraint or the strength needed to force the grid to assume its final shape. This goal has been achieved using another plug-in, necessary to introduce physical parameters of the chosen sections and materials.

The results of this new process offered, after a suitable calibration procedure, comparable and even overlapping results with the previous method, by the addition of more control options of the obtained shape. The user can immediately display, through a different coloring of the rods, their level of deformation so cheking in real time, which of these exceeded the maximum limits of curvature and, consequently, correct the errors in the shaping.

4. THE GFFT DESIGN TOOL

The tool has been developed as extension of third part existing CAD software by using Grasshopper, a freeware available plug-ins for scripting by visual interface, thus allowing the user to create generative algorithms without having strong programming skills.

4.1. Input

The gained experience, both in terms of scale model shaping that on-site hand-work, represented the starting point for the definition of the tool's framework, and input definition, which can summarized as follow:

- Starting flat grid: one or more orthogonal overlapping layers made of laths following a given direction.
- Intermediate connection: cylindrical hinges positioned at 50cm spans for both orthogonal direction.
- Timber species: as a function of several parameters (home-grown species availability and suitability to required design service class)
- Laths direction: the structural behavior varies as function of the lattice weave.
- Bracing: the gridshell structural behavior is highly dependent of the presence/absence and direction of brace elements.

4.1.1. Starting flat lattice

The gridshell is made of an equal pair of layers. The amount of pairs and the laths cross sectional thickness are designed in order to resist the working life actions. The firs built prototype in Ostuni, was made of just one couple of layers for the boundary arches. In the following realizations we opted to use four layer of laths, thus increasing the bending stiffening of the arches. Each lath is modeled by its centroid axis. Further improvements of the geometrical model regard the offset between layers, firstly ignored in the early model assumptions. The updated lattice geometry with layer offset gave a more realistic representation of the real structure.

Equivalent numerical model of the starting flat lattice:

The lattice is geometrically defined by the shape of the polygon corresponding to the lattice cutting silhouette while the distance among internal nodes is ruled by a length parameter "L" ($40cm < L < 60cm$); The axial and bending stiffness for each element is computed as a function of the elastic modulus and inertia and area cross section, see fig. 7.

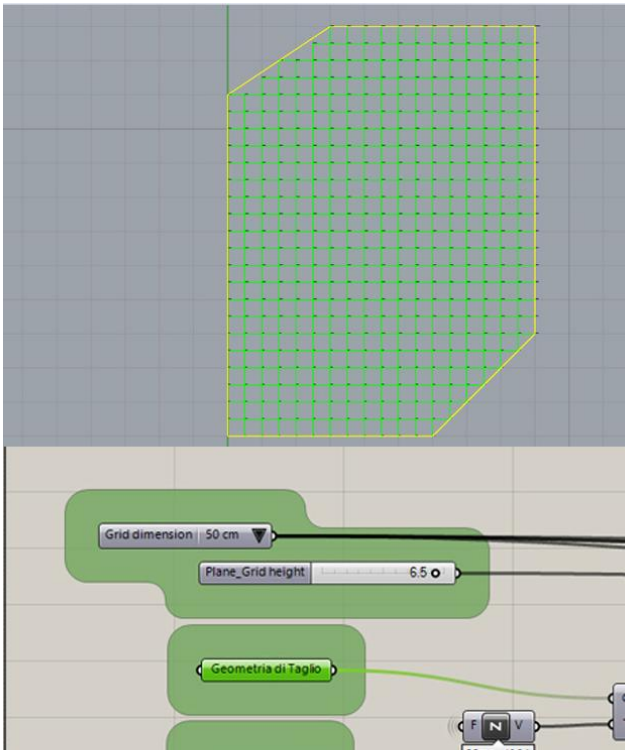

Fig. 7. Example of geometry cutting

4.1.2. Connections

The element of connection between the two layers (bolt) allows only the rotation around its longitudinal axis while the remaining five degree of freedom (two rotation and three translation) are assumed as fixed. This notation, resulted to be very important, making the difference with the other software analyzed in the study cases, where the assumption of a fixed distance among node connection is ignored. In our case, this represents an important issue since requirements such as lightweight, fast on-site assembling, easy transportation an cost efficiently represents key points of our research. In particular the patented connection technology [15], see fig.8, is the outcome of our willing to maximize the prefabrication factor. This kind of connection allows to assembling the grid in macro-modulus, to be posed and joint together once on the on-site working ground. For this reason, the connection has to work in three different circumstances: transportation, erection (forming), life-cycle. This simple “machine-node” allows the macro-modulus assembling in the first step, the laths rotation in the second step and the proper structural role once bracing are added to the primary structure. The node distance is set at 50cm, which is slightly higher than the distance among studs for balloon frame (40cm) and the same of Mannheim Lattice Shell (50 cm).

Numerical modeling of the cylindrical joint in the Gfft:

Initially, the intermediate joints between x and y rods were treated like points (particles), thus transforming the resulting mesh in a double curved surface. Therefore, to simulate the real structural behavior of the deformed mesh, we have chosen to draw the four laths as four superimposed layers, to be connected with a joint. In this way, x and y rods are placed at their real distance, corresponding to the chosen lath section.

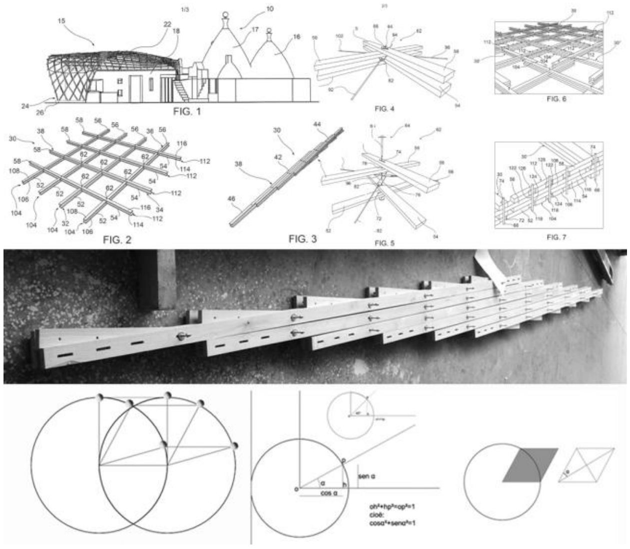

Fig. 8. The patented connection technology

4.1.3. Material properties

Suitable wood species to make timber laths for post-formed gridshells have to present a good decay resistence against external/environmental factors and high bending-strength/elastic-modulus ratio as well (fm/E): so far we experimented conifer (with spruce, larch, pine) and broadleaf (chestnut) species. Experimental tests were carried out time to time on the timber species used in order to characterize the strength and stiffness values (bending strength, elastic modulus parallel to the gain). Wood is a non-homogeneous material, in addition, the laths cross section is relatively small (if compared to sizes usually used for “common” timber structures). For this reason, the presence of defects (knots, slope grain, etc) increase the deviation between mean and characteristic strength values for a given lumber population to be graded.

Material properties definition into the Gfft:

Objective for future improvements of the Gfft tool is the inclusion of a material library to take into account the mechanical properties of the chosen wood species. Currently, these data (Elastic modulus parallel to the gain, Shear modulus) are manually inputted into the tool control panel together with the inertia cross section.

4.1.4. Rotation of the flat grid starting from the boundary constraints

The rotation of the mesh, relative to the boundary, is a topical issue to be managed through the software to reach an optimized structural solution.

For any chosen rotation, all the layers have to reach the boundary lines to guarantee an uniform reaction to strains of the whole gridshell.

The same model, in fact, with the same free edges and constraints, reacts in a completely different way depending on the rotation (45°-90 °) between the lattice and the boundary. The definition of boundary constraint configuration on the ground (shape and position) is, at the same time, a central issue of the tool, given their important function in gridshell global resistance and for the overall resulting shape.

Rotation of the flatten grid relatively to the boundary constraints in the Gfft:

In the Gff tool, the user selects the sides of the perimeter corresponding to the boundaries on the ground. These lines, during the shaping generation, are attracted to the pre-defined boundary curves. Depending on the rotation of the boundaries constraints (45°-90°), this strain (of attraction or repulsion) allows to modify the rhombus shape nearby the ground constraints as well as the boundary curve length. These boundaries can be drawn as polylines, splines or arcs; modifying their geometry and position, the user can evaluate in real time the architectonic and structural effect of these modifications on the overall shape., see fig. 9-10.

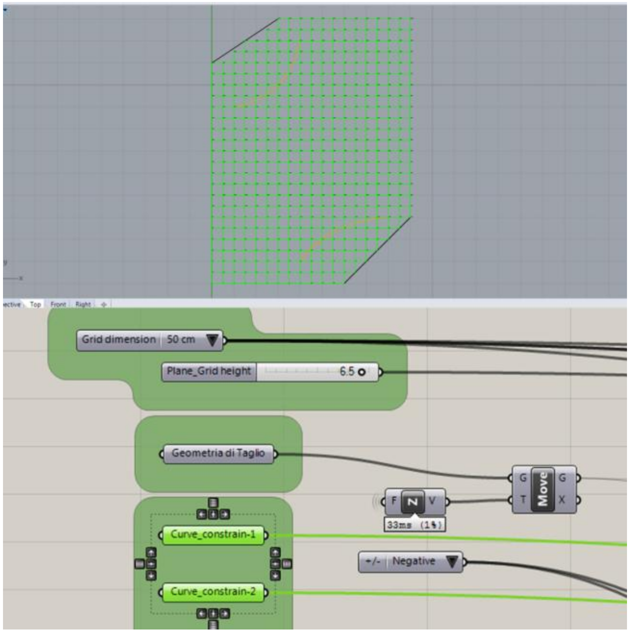

Fig. 9. Example of curve constrain

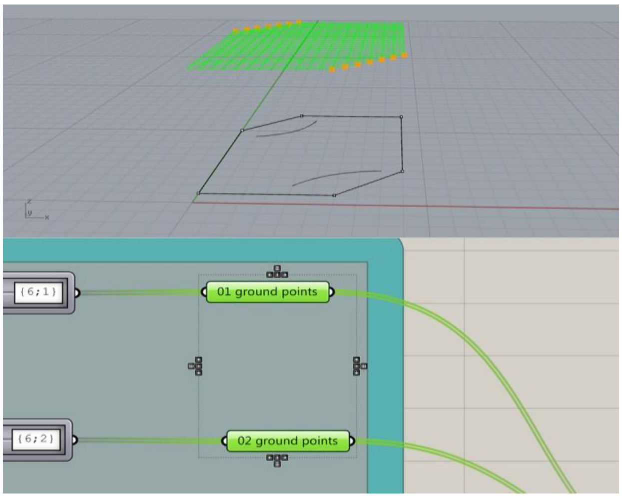

Fig. 10. Example of boundary points

4.1.5. Bracings

The diagonal bracing position can be chosen in the control panel inputs before starting the tool simulation engine, and it can be visualized during the form-finding process without stopping it. The bracing design is an essential parameter in this kind of structure: as Franco Laner clarifies, wood «due to its elevate mechanical properties compared to its weight, needs an absolutely peculiar structural conception that briefly recalls to "bracing", or rather should be spatially, three-dimensionally conceived, out of the plane, so as to join stiffness and lightness, strength and slenderness (…) All the construction codex about wood show that need of a three-dimensional conception.» [16]

The direction and position of bracings can substantially modify, also in our case, the internal stress distribution; for this reason the tool can give a real-time feedback of different bracing combinations without shape modification.

Bracing design in Gfft:

The tool is provided with a dropdown menu where is possible to pick one among the four bracing presets, each one corresponding to a different bracing placement. With this precious "speed dial" we were able to compare different structural behaviour corresponding to different bracing design.

4.2. Gfft beyond inputs: Kangaroo [18], the physical engine

Our early geometrical approach, achievable with the basic *Grasshopper* components, wasn't able to render and simulate the complex structural behaviour inherit in the gridshell material system. A physical approach was needed; that was realized with a specific *Grasshopper* add-on: *Kangaroo Physics*. With its features we could simulate flat lattice behaviour forced to bend and translate.

Kangaroo is a *Particle spring system*, that can simulate the behaviour of a wide range of elements. The springs can introduce a handy simplification: any material, as stiffer it is, can stretch and shorten. [17]

The resulting spring model, which defines rod stiffness as a function of section and **Young's modulus**, is also provided with forces able to simulate the gridshell rods bending stiffness. Through other Kangaroo features, a system of acting constrains force the plane mesh to reach a bent configuration, pulling selected side points to correspondent ground lines.

This formed configuration could be still modified with the variation of rhombus diagonal ratio (leaved still labile): so the use of localized forces, that extend or shorten the diagonal length of an area, allows to "move" the resistant mass in a direction or in its perpendicular, see fig.11.

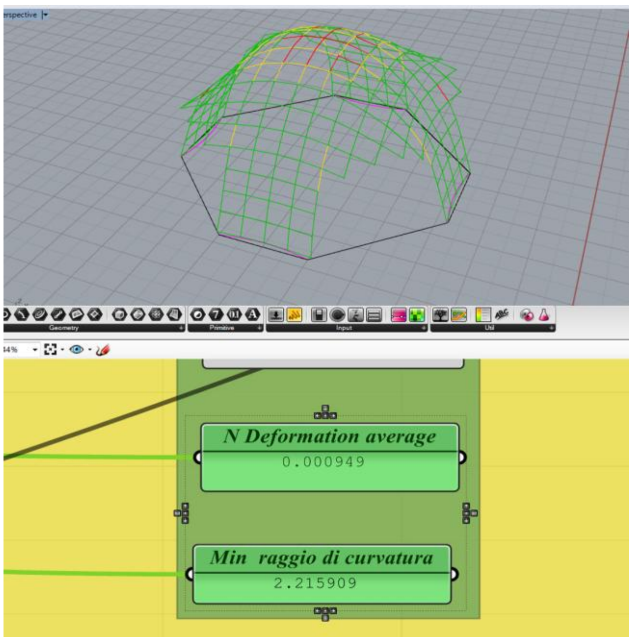

Fig. 11. Analysis of curvature and axial deformation in real time

4.3. Experimental application of a module Fem on the tool: Karamba [19]

We introduced in the Gff tool the add-on *Karamba* (an interactive, parametric finite element program) to try a kind of structural pre-analysis.

With the use of *Karamba* we were able to implement a section of the algorithm that allows us to test, real time, the structural response of a designed shape, through graphical output (efforts graphics, colors of the elements) and numeric output (stress, strain, strain energy, etc..).

During the experimentation of Toledo Gridshell, [13] we assumed an accidental load of 150kg/sqm. The add-on allowed us, with the shaping engine still on, a typical view of a structural analysis program output (bending moment and curvature graphs). It was therefore possible, real time, changing the structure shape (through the modification of form parameters) to minimize the stress concentration detected with *Karamba* at first steps.

Reached a "qualitatively" feasible shape, we finally analyzed the last CAD model in *SAP2000* for further form-improving to be carried out after a few iterations of the structural analysis. This structural analysis also gave us all the information about forces reaction on the ground and, above all, allows a comparison of outpts previously found with the *Karamba* module.

5. CONCLUSIONS

This digital application proves that the developing of an experimental software couldn't be done without an appropriate knowledge of theoretical issue and without an proper skill [20] in gridshell construction (see fig. 12): the deep understanding of how gridshell design arises from an expressive will, a structural requirement and a constructive process, which together tend to Frei Otto's *Form-finding*: the research for a shape that reciprocally merges architectural design, structural behavior and worksite organization already at the heuristic stage.

The outcomes achieved so far through the Gfft are:

- Correct architectural design through a form-finding process that, already from the first design steps, shows the overstressed areas of the mesh and allows to modify the inputs (mesh dimensions, ground lines) in order to optimize the shape.
- Real time output data useful to the design specifications for the suppliers (quantity, sizes) and the contractor (assembly instruction, fabrication graphics, etc.).
- Wireframe model ready to be exported in any 3D modelling and structural analysis software.
- Drawing automation: there's no need to draw each grid element (laths, pivots, bracings, ground lines) because they're just defined by the algorithm.
- Reversibility and flexibility of the design process: it's very easy to make minor changes to all the inputs (i. e. flat grid shape and spacing) or to the final shape with a real time outcome without the need to start over the entire design process.

Outcomes expected during the next few months are:

- User friendly interface: in order to be used even though the user is not a computer expert.
- Tool integration with a large database of material mechanics features.
- Automatic structural optimization: when a satisfied global form is reached the Gfft should improve its structural performance (*form-improvement*) thorough local automatic variations.

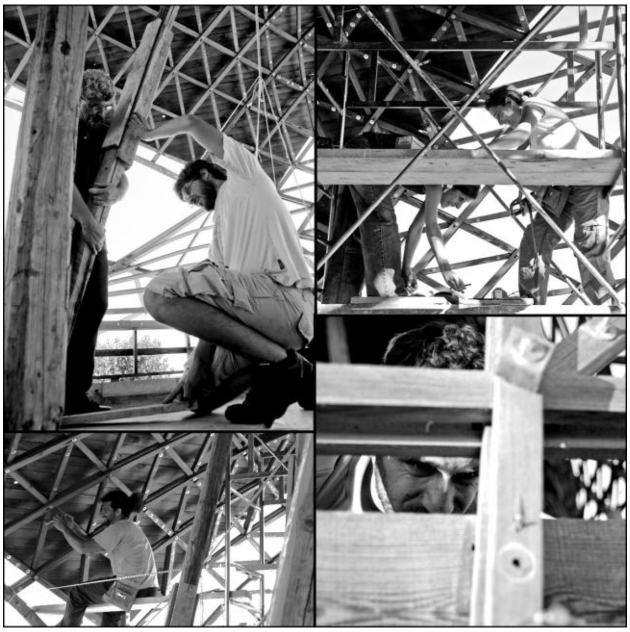

Fig.12. Research team at work: www.gridshell.it

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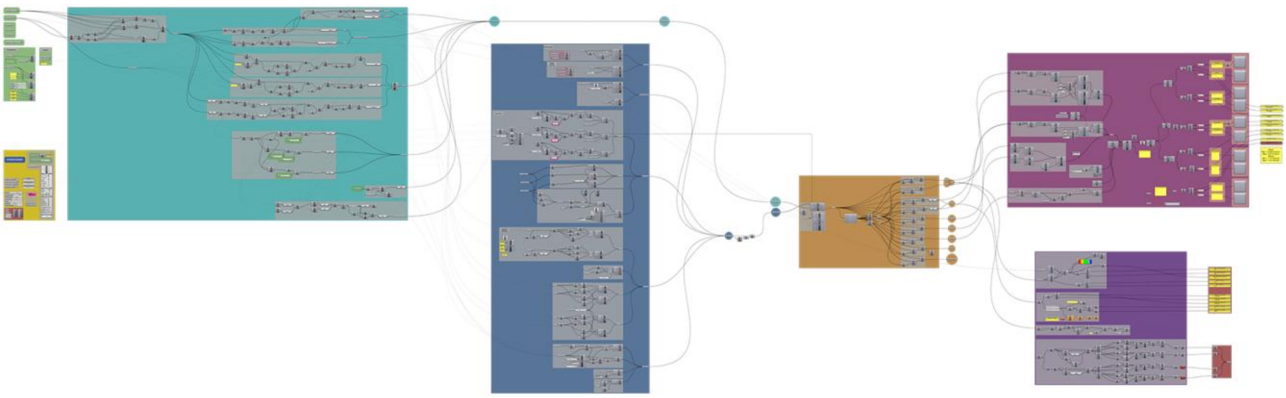

Fig.13. Gridshell Form-Finding Tool (GFFT