University of Bath

Alternative formats
If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

PATCHWORK GRIDSHELLS: USING MODULARITY TO FACILITATE PREFABRICATION AND SIMPLIFY CONSTRUCTION

Philippe CHAREST[1], Paul SHEPHERD[2], Richard HARRIS[2], André POTVIN[1], Claude DEMERS[1] and Sylvain MÉNARD[3]

[1] *School of Architecture, Laval University, 1 Cote de la Fabrique, bureau 3210, Quebec City, Canada. G1R 3V6*
[2] Department of Architecture and Civil Engineering, University of Bath, North Road, Bath, UK. BA2 7AY
[3] Department of Applied Sciences, University of Quebec in Chicoutimi (UQAC), 555 Boulevard de l'Université, Saguenay, Canada. G7H 2B1
philippe.charest.1@ulaval.ca, p.shepherd@bath.ac.uk, r.harris@bath.ac.uk, andre.potvin@arc.ulaval.ca, claude.demers@arc.ulaval.ca, sylvain_menard@uqac.ca

ABSTRACT

Modern architectural design has seen a shift towards iconic doubly-curved envelopes enclosing large column-free spaces. Gridshells have long been considered an efficient solution to such designs, but their actual use in practice has not spread worldwide. For elastic gridshells, their advantages in terms of substantial material savings can often be overshadowed by the significant challenges associated with their construction. Similarly, for rigid gridshells, the manufacture of a large number of different members and nodal connections is often a barrier to their implementation.

This paper proposes an effective way of designing, fabricating and erecting gridshells. The "Patchwork Gridshell" consists of a number of efficient elastic gridshell patches assembled using rigid gridshell frames. It can easily generate a number of different configurations, use a wide range of materials, and allows more architectural expression of practical long-span forms. The benefits of combining the ingenuously simple efficiency of elastic lattices and the power of digital fabrication are demonstrated by digitally rebuilding four alternative configurations of the Japan Pavilion of the Hanover Expo 2000 as a case study. The result is a flexible digital workflow which creates large column-free spaces that are capable of being constructed efficiently by non-specialist contractors.

Keywords: Gridshells, Construction Methods, Computer Aided Design, Structural Design

1. INTRODUCTION

Since the emergence of gridshells in the early 70s, structural analysis has been a major issue for designers [1]. However, the introduction of dynamic relaxation and finite element analyses into the digital environment seems to have shifted the challenge into the fabrication and construction phases. For elastic gridshells, which are characterized by the deformation of a flat grid of members, the erection process presents major issues such as occupying a lot of space on the construction site, reducing control over the final geometry, and requiring the calculation of a new load case scenario for crane lifting [2]. For rigid gridshells, which are assembled from shorter, straight or curved members, the large number of diverse components leads to complexity in connection manufacture and the erection process [3]. There is, therefore, a need to develop a new way of building gridshells that will allow them to be practically realized. The method proposed below divides an initial surface into sub-surfaces, with each resulting patch fabricated from rigid frames filled with an elastically deformed lattice. In this way, it is possible to combine the advantages of both rigid- and elastic-gridshells, leading to efficient construction of curved geometries. To demonstrate the approach in a realistic setting, the construction and structural behaviour of different options for the Japan Pavilion at the Expo 2000 in Hanover, which two of the authors worked on, is used as a case study project.

2. MOTIVATION

2.1. Renewed interest in gridshells

In the late 90s, the computer shifted from simply being used as a tool to accelerate the production of technical drawings to become a form generator in its own right [4]. Therefore, the restrictions of traditional post & beam construction slowly evaporated, and the quest for architectural fluidity and the immaterial nature of surfaces became dominant. In this new digital context, several constructed projects illustrated a contradiction between their apparent fluidity and the predominance of their structure [5]. Traditional construction methods were inappropriately applied to the realization of complex geometries, which increased construction time [6, 7] and the quantity of materials used [8]. This inadequacy led to renewed interest in developing more permissive systems to materialize contemporary organic shapes.

An interesting combination of aesthetic and structural systems for this kind of purpose is the gridshell, which creates a dramatic ambience by articulating the space with its topology [9]. The gridshell is defined by Harris, Romer, Kelly and Johnson, who worked on the Weald and Downland Gridshell: "A gridshell is a shell with large openings in it in a manner that allows the remaining strips or grids to behave, structurally, as a shell" [10]. Rather than being transferred in an infinite number of directions, the compression and shear forces are redirected along the longitudinal axis of the members and this feature allows forces to flow efficiently to their supports [11]. Gridshells require a relatively small amount of material to cover large-span spaces, without the need for intermediate columns [3, 12]. The minimization of material reduces the embodied energy and leads to more sustainable designs. Despite these major benefits, very few gridshells have actually been constructed. The reason was mainly associated with the difficulties of performing the required non-linear structural analysis on such complex shapes. However, with modern computational tools this no longer became a challenge for suitably skilled engineers and architects, and the limiting factors moved to the construction process itself. With modern digital fabrication tools, construction is also becoming less of a challenge and the benefits of gridshells should now be reassessed.
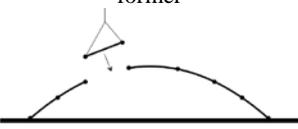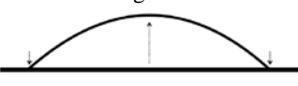
2.2. Construction Issues

There are two main categories of gridshells, one with long, continuous members crossing each other at nodes, and another with relatively short members forming a discrete grid connected at the nodes [13]. The first category consist of an active-bending system in which a structural shape is obtained by bending a grillage of members (Figure 1) [14]. The term « elastic gridshell » is usually used since the erection process is reversible [15]. Although there are some inventive exceptions, such as the Silk Road Exposition in Nara Park [16], in general, long, continuous straight members are fabricated off-site, assembled on-site into a flat grid and deformed into shape. Thus, the grid definition corresponds to a network of equidistant points on a surface, known as a Tchebychev network [17].

Figure 1: *The Savill Garden elastic gridshell, Englefield Green, UK, 2005*

In the past, the motivation for elastic gridshells lay in the difficulty of manufacturing curved elements, so straight elements were bent into curved shapes [14]. The constructive simplicity of producing identical elements and simple bolted/screwed connections led to this system becoming well recognized and relatively widespread [3]. It is also easier to transport straight elements to the construction site and to assemble them on the ground. Research suggests that active-bending systems facilitate the erection process [18] and elastic gridshells can be raised in very little time [19]. Nonetheless, as shown in Table 1, which details five installation techniques of erecting elastic gridshells, such advantages are sometimes paired with limitations. In fact, when time comes to manipulate a large scale flat mat, the crane lifting, scaffolding and the manipulations of long laths can become a huge challenge.

Table 1: *Gridshell installation techniques*

Installation technique	Pros	Cons
Crane lifting of a grid assembled on the ground	• Ease to assemble a flat grid at ground level • Simple connectors • Transportation of straight elements	• Large site needed • Grid size limited by the crane's capacity • Lifting is a separate load case scenario • Determination of lifting points • Distribution of suspension forces • Insufficient or excessive deformation • Difficulty to control process, which needs careful manipulation of shell at individual points • Cost for crane lifting
Crane lifting of a full or part grid assembled on profiled former	• Possibility of prefabrication • Use digital fabrication tools • Total control of the final geometry • Integration of traditional skylights	• More material due to glulam frames • Cost for crane lifting • Transportation of curved surfaces • Complex connectors • Difficulty to construct smooth shell with accurate geometry
Push-up of a grid assembled on the ground	• Ease to assemble a flat grid at ground level • Numerous push-up points for deformation • Possibility to add push-up points during the process • New possibilities with inflated membrane • Simple connectors • Transportation of straight elements	• Heavy weight of the grid • Site safety issues (work under heavy moving structure) • Determination of lifting points • Grid slides on the ground during the erection • Slow site phase of construction
Gravity/pull-down of a grid assembled at high levels	• Ease to assemble a flat grid with straight members • Transportation of straight elements • Simple connectors	• Temporary scaffolding • Difficulty to remove scaffolding with a moving structure • Restricted site access • Insufficient deformation with gravity • Slow site phase of construction
Direct installation of a grid using pre-drilled and dimensioned laths	• More control on the final geometry • Transportation of straight elements • Use digital fabrication tools • Fast site phase of construction	• More material due to glulam arches • Temporary scaffolding

The difficulty of erecting large elastic lattices may be responsible for the interest in rigid gridshells, the second category described by Naicu, Harris and Williams [13]. To build a doubly-curved surface, short members are fabricated off-site and transported to the construction site where they are assembled like a giant jigsaw puzzle. In addition to being a more traditional way of erecting a building, this strategy allows exploration of complex geometric configurations (Figure 2), which can be optimized according to the load distribution. However, such freedom comes with its disadvantages. Every structural member generally meets at a node with a different angle, requiring a large number of different and non-standard connections [3]. This situation can be partially ignored by using digital fabrication techniques, but still presents complexities for both the manufacturer and constructor.

Figure 2: *Crossrail Place, Canary Wharf, London, UK, 2015*

In recent years, manufacturing technology in the construction industry has greatly improved, inheriting some of the advances developed in other industries such as automotive and product design. Off-site fabrication tools have shifted from mass-producing identical objects to high-tech control systems capable of producing unique objects with very little extra effort [20]. Mass customization overcomes the obstacles of standard construction capabilities and building designers are no longer concerned with whether or not forms can be built, but rather need simply to decide which tool should be used to build them [21]. However, there is no unanimous consensus on this affirmation. Even if the realization of highly complex structures is possible, other constraints, such as budgets, technical knowhow and risk, limit this great constructive freedom. Such methods seem to be reserved for buildings where complex form is justified over other budgetary concerns, or limited to specific elements of a building [5]. There are also major risks concerning the assembly of such a huge number of similar-but-different components on site.

Elastic gridshells facilitate the fabrication process of doubly-curved buildings, but present serious challenges in terms of erection of the whole structure. Conversely, rigid gridshells can facilitate the erection process itself, but present challenges in terms of fabrication.

2.3. Materiality

Since the early development of elastic gridshells, timber has proven to be an ideal material to materialize doubly-curved envelopes. It is the only traditional material that can bend sufficiently without breaking [22] and the low torsional stiffness of timber allows the deformation of a flat grid of identical straight laths into a doubly curved shape [23]. An elastic gridshell necessitates a high elastic limit strain (f_m), to allow sufficient deformation, and a high Young's modulus (E) to provide stiffness for the grid in its final position [24]. However, to achieve the required bending strength, the dimensions of the cross-section may then limit the deformation of the members, making timber unsuitable for active-bending systems [3]. This aspect justifies double-layer lattices, which allow tighter curvatures with smaller cross-sectional areas by providing the ability for the upper and lower laths to slide along each other during erection.

An alternative approach by some researchers has been to investigate the use of other materials with high ratios of high elastic limit to Young's modulus (f_m/E), such as Fibre Reinforced Polymers (FRP). With f_m/E ratios around five times higher than most wood species [14], Glass Fiber Reinforced Polymer (GFRP) is a relatively affordable material which has the potential to allow pronounced deformations whilst being less prone to buckling [24]. Thus, the dimensions of the cross-sections can be reduced, which decreases the amount of material involved and leads to more economic structures. Bamboo is also an interesting material with an f_m/E ratio comparable to FRP and is more environmentally sustainable. Due to its rapid growth, bamboo forests can have a carbon density four times higher than a spruce forest. And since it grows close to emerging world economies where forest resources are often limited [25], this material becomes an interesting alternative for gridshells.

Historically, other materials have also been used for gridshell construction, such as paper tubes. Despite a lower stiffness than wood, a depreciation of its mechanical properties over long periods of time and a high sensitivity to humidity, paper is still an economic and ecological alternative, entirely recyclable and widely available which can be manufactured in tubes of a wide range of diameters, thicknesses and lengths [26].

The approach to gridshell construction proposed in this paper is flexible and could be used with all these materials, and combinations of them, depending on the designer's requirements, priorities and access to fabrication tools.

3. METHODOLOGY

Over the past few years, an increasing number of experimental elastic gridshell pavilions [3] have shown that modern active-bending systems still have benefits in terms of transportation, assembly, performance and adaptability [14]. Nevertheless, these pavilions were relatively small and there is no modern example of large-scale elastic gridshell construction since the Savill Building in 2005. This suggests that the deformation of a grid on the construction site is manageable up to a certain limit, beyond which it introduces multiple challenges which are hard to overcome. Thus, in this paper, the authors propose a hybrid system, which combines large-scale, rigid, curved elements for the

superstructure with patches of surface made from elastically deformed grids. The division of an initial form-founded surface into a number of smaller sub-surfaces can foster prefabrication and facilitate transportation. Each superstructure member is manufactured off-site according to its required geometry and the stiff structure then acts as a frame to support a patchwork of smaller, locally constructed elastic gridshells. With this strategy, it is possible to materialize doubly-curved surfaces from many identical straight elements and reproduce complex configurations to provide efficient structural behaviour.

The method involves three principal steps, design, fabrication and erection, and the objective is to provide an efficient way to design and build contemporary organic shapes. Parametric modelling software, in this instance *Grasshopper*, allows designers to perform form-finding and structural analysis in a single digital environment to facilitate communication between architects and engineers, and can integrate a wide range of materials. The fabrication phase involves digitally controlled machines for rigid elements and standard hand tools for the elastic lattice, and leads to flat pre-assembled lattices and singly-curved pre-fabricated elements for easy transportation from factory to site. Lastly, the erection process involves assembly of the components and crane lifting. It breaks the erection process into a series of steps, limiting the size of each crane lift and allowing for faster construction by having multiple teams working in parallel

3.1. Design

To implement this method, a parametric workflow was created in *Grasshopper*, an algorithmic modelling software that uses the *Rhinoceros3D* interface as a visualization platform. It has many strengths, including the support of a growing community of users, compatibility with many other software packages and, above all, a plug-in ecosystem which multiplies its simulation and analysis potential [27]. For the form-finding process described below, the plugin *Kangaroo2* [28] is used, mainly because it is intuitive for designers and fully integrated with the Grasshopper interface. It is a particle-spring system, which simulates the physical hanging-chain method in a digital environment by modelling the behaviour of malleable bodies [29]. The amplitude of the deformation depends on the initial geometry of the surface, the intensity of the forces applied and the properties of the springs, which are carefully chosen to replicate realistic properties of the materials being simulated.

After form-finding the surface, designers define the configuration of the primary structural members and the finite element plugin *Karamba [30]* analyzes their structural behaviour. *Karamba* provides a comprehensive analysis of spatial structures, lattices and shells, and by considering the material properties and cross-section geometry, it determines the maximum displacements and forces in each member. Since the initial surface can be divided in many different ways, there is freedom to use the structural analysis results to help decide on an efficient discretisation, for example decreasing the spacing of members where forces are higher. The aim is to minimize the number of rigid elements (which can be more difficult to fabricate) and to control the size of the elastic lattice patches to maximise the use of timber laths with standard lengths.

3.2. Fabrication

As mentioned in section 2.2, the main advantage of elastic gridshells is the materialization of curved shapes with identical straight components, which means that they can be fabricated with simple techniques and standard tools. For natural materials like wood, every member must be inspected to avoid imperfections, especially knots, which can dramatically decrease mechanical performances and result in fracture during the erection process. Optical inspections and mechanical tests can be performed to cut out imperfect or weak laths [2]. For materials produced industrially, such as FRPs and paper tubes, their uniform composition ensures consistency in their mechanical properties and such tests are not as relevant. In all cases, since the grid is assembled flat before being deformed, it is important that node connections can cope with the movements involved, such as rotation, torsion and, for double-layer gridshells, sliding [2]. For the rigid part of the gridshell, the choice of tools depends on the material, connectors and complexity of the grid. For example, a complex configuration of timber components attached to one another by dovetail joints would require multi-axis milling machines, whilst paper tubes can be connected with multi-directional steel connectors or simple lashings. Ideally, the rigid frame members would be singly curved, and the lattices scissored closed, to ease their transportation to site.
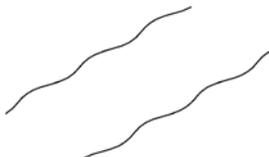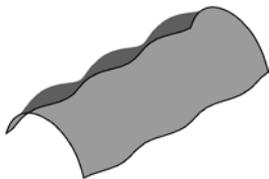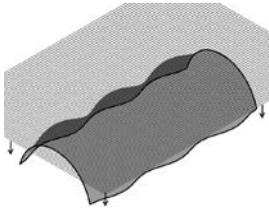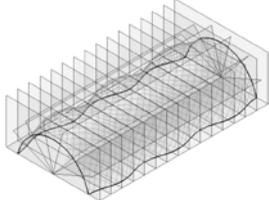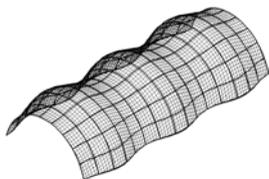
3.3. Erection

The erection phase starts with the assembly of each individual superstructure frame followed by the elastic lattices being unfolded and fit to their respective frames. After the use of temporary scaffolding installation to provide support during the process, a crane moves every frame to its final position, and connects them together. Depending on the geometry 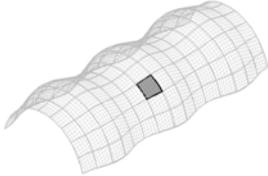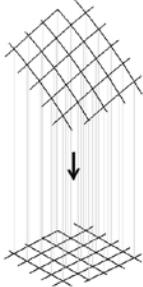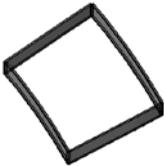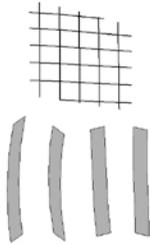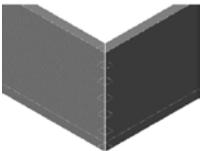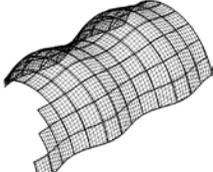and the division of the overall surface, it may be possible to firstly install all the lower patches, then the upper ones, minimising scaffold and crane time. It may also be possible to proceed with the installation of successive arches from one side of the building to the other, potentially removing the need for scaffolding completely.

3.4. Summary

Table 2 summarises all the steps in the three phases with illustrations and corresponding descriptions.

Table 2: *Methodology table*

	Step	Figure	Description
Design	1. Boundary conditions		In this case, the boundary conditions represent two curves drawn in *Rhinoceros3D*. The boundary conditions depend on the design constraints such as environmental analysis or architectural program.
	2. Funicular Shape		After having defined a mesh between the two curves in *Grasshopper*, the particle-spring system of *Kangaroo* produces a funicular shape. The curvature of the resulting mesh can be evaluated to make sure it doesn't exceed the maximal curvature allowed by the members.
	3. Elastic lattice		The definition of the elastic lattice is obtained by draping a network of regular quadrangles on the funicular shape using *Kangaroo*. This strategy creates a Tchebychev net on the surface without any external script.
	4. Rigid elements		The rigid structure corresponds to the intersection between two sets of planes and the elastic lattice defined in step 3. Those planes can be drawn in many different ways depending on the design constraints.
	5. Structural Analysis		The structural analysis is performed with *Karamba*. The goal is to visualize the shear forces and the bending moments in every member. If the results satisfy the design criteria, the designers can continue with the fabrication phase. Otherwise, they can change the elastic grid spacing, the configuration of the rigid elements, the cross-sections of the members or the material properties.

Fabrication	6. Cell extraction for fabrication		Every patch created by the division must be extracted separately for fabrication.
	7. Grid		The elastic lattices are digitally unrolled using *Kangaroo*. The members are projected on the ground plane, and the solver rebuild the configuration with the desired lengths afterwards. All laths can be manufactured using traditional tools and simple standard connectors. They can be mono or multi-layered according to the structural analysis.
	8. Edge elements		The edge elements are used to build frames that will support the elastic lattices. An inward extrusion gives the thickness while a downward extrusion gives the height. These components, can be fabricated using digital milling machines for more complex geometries. Similarly, connectors can be manufactured using digital manufacturing tools in more complex cases, or standard connectors for simpler configurations.
	9. Transportation		To facilitate the transportation, the elastic lattices can be folded since the bolt/screw connections provide rotation. For the edge elements, their unidirectional curvature eases transportation as well.
Erection	10. Frame assembly		On the construction site, the edge elements are assembled into stand-alone frames. They could be placed on a series of jacks set to specific heights to hold them roughly in place whilst their corners were joined together using standard connector brackets or carpentry-style joints.
	11. Deformation		Elastic lattices are deformed according to each frame geometry.
	12. Crane lifting		Each patch is crane lifted to be positioned on the final geometry. During this operation, wires can introduce undesirable stresses to the frame. Therefore, the structural behaviour of each patch should be evaluated before erection.
	13. Gridshell construction		Starting from the bottom to the top, each patch is assembled to each other using mechanical assemblies such as bolts and nuts on the edge beams at regular intervals. The cell assembly requires temporary scaffolding. When every patch is in place and the structure erection is completed, the scaffold can be removed before the cladding is installed.

4. CASE STUDY

This section uses the Japan Pavilion of the World Expo 2000 in Hanover as a case study to demonstrate the effectiveness and flexibility of the proposed method. The Japan Pavilion itself was erected as a single layer elastic gridshell, with a flat grid of paper tubes assembled on temporary scaffolding. The finished shell measured 75m long by 35m wide and 15.5m high at its highest point. The paper tubes were 12 cm in diameter and 2.2 cm thick. The stiffness of the lattice was increased by wooden arches at regular intervals at the request of the German authorities, although the calculations showed that they were not necessary [26]. Figure 3 illustrates a plan and a cross section of the shell. Since this is an existing design, steps 1 and 2 of Table 2 are not relevant and the grid configuration becomes crucial for structural analysis.
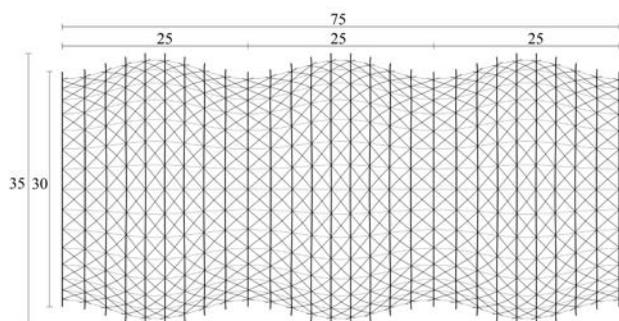

Figure 3: Plan view, Japan Pavilion, World Expo, Hanover, Germany, 2000

For the purpose of this study, the grid will be sub-divided into a number of panels. The edge elements of each panel are all the same material (glulam) and the same cross-sectional geometry (30cm high by 5cm thick rectangle). For the elastic lattices located inside these panels, the Tchebychev net stays the same in every simulation with hollow circular cross-section (12cm diameter and 2.2cm thickness) and the material (paper tubes) reflecting the tubes used in Hanover. The objective is to study the division pattern as the only variable and assess its impact on the maximum displacement of the resulting gridshell, therefore only self-weight load is considered.

To understand the effect of the grid division on the general structural behaviour, a hierarchy of four division patterns are introduced. Level 1 uses only orthogonal and equidistant members, Level 2 maintains an orthogonal layout but allows members to be translated, Level 3 allows members to be rotated without crossing each other, and Level 4 shows the least restrictive arrangement where members are translated, rotated and can cross each other.

To represent Level 1, a regular orthogonal 5x5m grid has been chosen, which would facilitate the fabrication and transport of both the elastic lattices and the edge elements to site. For Levels 2, 3 & 4, the shell is divided into panels suggested by a Genetic Algorithm, in this case *Galapagos* in *Rhino-Grasshopper*. The optimisation strategy is defined by placing 14 points on each boundary curve and 6 points on the arches to define the high-points of the grid. They are then connected by a series of vertical planes which intercept the Tchebychev net. The genotype for the optimization is the amplitude of the translation or the angle of the rotation of each plane and the fitness function is the maximum displacement under self-weight. The Figure 4 illustrates the workflow of the simulations.
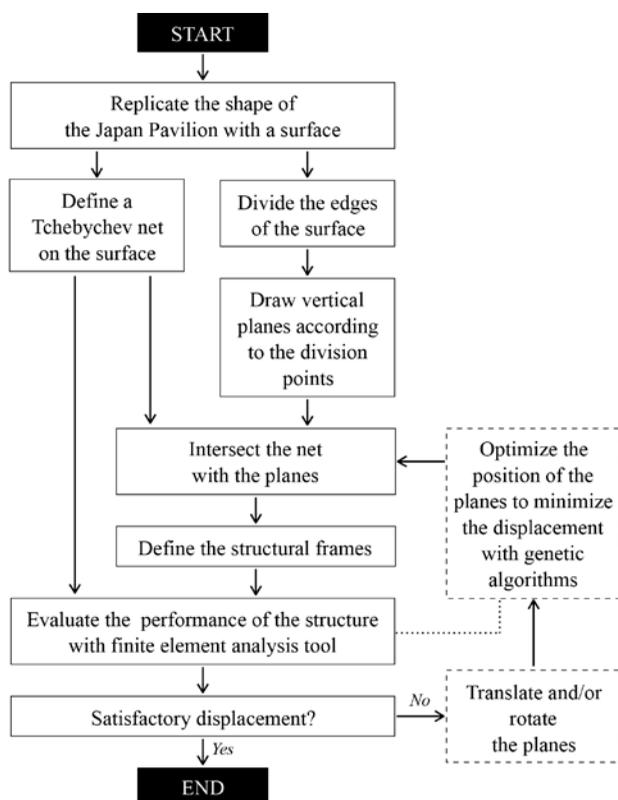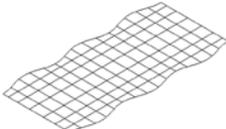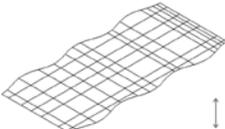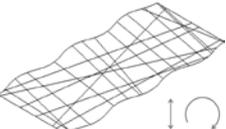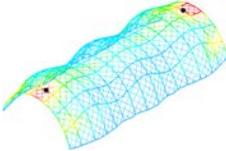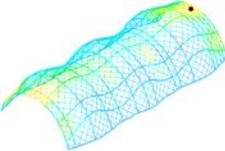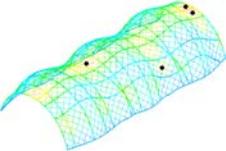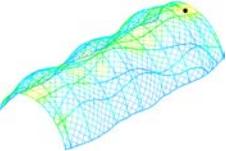

Figure 4: Workflow of the simulations

The results of the structural analyses are shown in Table 3, with the position of the maximum displacements marked with black dots. The best result corresponds to the Level 4 which has a maximum displacement approximately 40% lower

*Table 3: Characteristics of the structures in function of the division pattern*

Level	1	2	3	4
Division Pattern				
Structural Analysis				
Max. Dis. (mm)	53	38	41	32
Number of connections	128	128	126	120

than the Level 1. As the level of complexity increases, the degree of freedom of each member also increases, thus the solver has the opportunity to find even better configurations at Level 4 even if the computational time increases. It is also possible to notice that the Level 2 has a lower displacement than the Level 3. A possible explanation for this result might be the relative simplicity of the shape under consideration. The uniform distribution seems to be more appropriate for a better structural behaviour in this specific case, but it might be different when the form grows in complexity. In all cases, the method allows the exploration of different configurations corresponding to the designer's needs.

The complexity provided by Levels 3 and 4 also provides structural stability, especially important during the erection process. Usually, rotational attachments to the foundations or support systems are insufficient to avoid excessive deformations under heavy load [2]. Thus, the triangulation of the grid is a well-known strategy to provide some shear stiffness. For example, diagonal bracing elements or cables can be added at the end of the erection to lock the shape in its final position [12]. Alternatively, by using this system of Level 3 or 4 patches, the primary structure of non-orthogonal patches adds stability. Even if the constructability of non-regular grids is rarely studied [31], this complexity comes at a cost, since the members meet at different angles. On the other hand, the results show a lower number of connections at Level 4, which represents time saving at the fabrication phase. Whilst the design of the

connectors is outside the scope of this paper, it is suggested that these connectors could integrate anchors to facilitate crane lifting during erection, so the cost of making them bespoke is somewhat mitigated.

To make sure that the frames respond well to the erection phase, a finite element analysis was performed using the same cross-section, material and load case as described above. Figure 5 shows the displacement of a typical 5x5m patch under self-weight, with the maximum displacement of approximately 5mm seen near the centre of the patch and the maximum stress not exceeding the allowable compression (4.4 N/mm^2) and bending (6.6 N/mm^2) values for paper tubes [26].
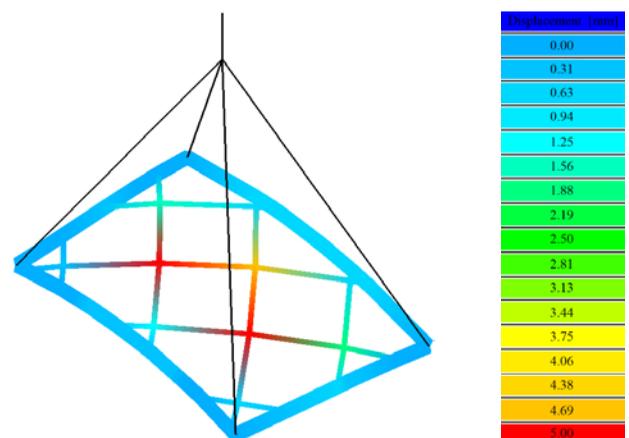
Figure 5: Structural simulation of crane lifting with displacement

5. CONCLUSION

This paper has suggested a new method for the design, fabrication and construction of a Patchwork Gridshell, which facilitates prefabrication, allows efficient transportation and simplifies erection. Modern modelling software has led to increasing complexity of architectural forms, which suggests that gridshells might once again become a popular solution for constructing curved geometries using straight elements. Elastic gridshells are efficient, but present major construction issues on site. Rigid gridshells can be constructed using more traditional methods, but require the manufacture of a large number of different members and complex connections. The method proposed in this paper is a hybrid solution of the two, since it combines the practical and poetic characteristics of vernacular early gridshells with the constructive simplicity of discrete surface grids. Whilst some gridshells have been constructed in a modular fashion in the past [32], they have not combined elastic and rigid systems in this manner, and particularly not as a holistic construction system.

The concept of modularity fosters prefabrication, and since the elements are curved in only one direction, the members can easily be stacked for storage and transportation. On the construction site, the erection scheme differs from most conventional rigid gridshells, since it consists of connecting surface patches to each other, rather than connecting individual members to each other until the final shape appears. There is no need to manage the deformation of the entire gridshell lattice at the same time, and even if temporary scaffolding is necessary, it doesn't need to occupy the entire site and limit access. The rigid elements offer more control of the final geometry and avoid excessive deformation.

Not only does this method foster prefabrication and simplifies the erection process, it can moreover facilitate deconstruction of the gridshell. At the end of the building's life, the erection process can be simply reversed to dismantle the shell and recycle its components. By using a crane, it is possible to remove all the patches one-by-one, disconnect the edge elements and remove their elastic lattices. The gridshell could even be transported to a different site and re-erected. The method also introduces the opportunity to integrate other envelope elements, such as insulation, cladding or even windows/skylights, before the erection process, which can be a major advantage to construction time,

quality control and allows parallel on-site works. This step could also be performed in an off-site factory, with carefully monitored quality and environmental control and not susceptible to external weather, but it is expected that the extra challenges and space required to transport finished, doubly curved patches would mean that an on-site approach to services integration would be preferable.

This preliminary study has explored the potential benefits of Patchwork Gridshells, but more research is under way to develop the ideas into a construction system ready for site. The *Grasshopper* script that generates the patches needs to more carefully consider a minimum and maximum length for the edge elements to avoid really small or really large patches, which would be impractical for fabrication and transportation. Similarly, nodes of the elastic lattice sometimes occur very close to an edge element, which makes its inclusion unpractical. In such instances, the node could be moved to fit exactly on the edge element, but the impact on both the complexity of the construction and the structural performance of the patch would need to be checked.

Since the method involves two very different kinds of members with different stiffness (rigid edge elements and elastic lattice members), it is important to note that any original funicular form-found surface is no longer funicular. The method has the ability, but not requirement, of having continuity (in terms of both in-plane curvature and orientation) across patches. Thus, it is possible to have different orientations, and even end-positions, for the elastic lattices on either side of a rigid element. This would be simpler to build, as there would be no need for additional, head-to-head connections between consecutive elastic laths, and membrane or shear forces could be transferred via suitably designed connections between the rigidly formed frames. An additional benefit would be the possibility of eliminating in-plane curvature, and therefore in-plane bending, in the elastic mesh. However, the resulting form would lose the architectural fluidity characteristic of a continuous gridshell as a consequence.

FURTHER WORK

This paper focuses mainly on the design aspects of the proposed patchwork gridshell, and on the generation of the structural geometry in particular. The construction of a large-scale physical mock-up

to demonstrate the practical viability of the method is the subject of future work by the authors. The prototype will also identify an ideal connection system to join elastic members to the rigid edge beams, how best to trim the elastic members and place them in the rigid frames, as well as the best way to attach the cells to each other. Options for exterior cladding will also be investigated. Once the theory and analysis presented in this paper is combined with full-scale physical demonstrations, it is hoped that Patchwork Gridshells will be more widely adopted by practice, realising their material savings, relative ease of construction and architectural elegance.

ACKNOWLEDGMENTS

REFERENCES

[1]   C. Williams, "What is a shell?," in *Shell structures for architecture : form finding and optimization*, S. Adriaenssens, P. Block, D. Veenendaal, and C. Williams, Eds. London: Routledge, Taylor & Francis Group, 2014, pp. 21-31.

[2]   J. Chilton and G. Tang, *Timber gridshells : architecture, structure and craft*. London: Routledge, 2017, pp. xxii, 258 pages.

[3]   B. D'Amico, "Timber grid-shell structures: form-finding, analysis and optimisation," Doctor of Philosophy, Napier University, Edinburgh, 2015.

[4]   G. Teyssot and S. Bernier-Lavigne, "Forme et information. Chronique de l'architecture numérique," in *Action architecture*, A. Guiheux, Ed. Paris: Éditions de la Vilette, 2011.

[5]   A. Picon, *Digital culture in architecture : an Introduction for the design professions*. Basel: Birkhäuser, 2010, p. 223 p.

[6]   G. Lee, "Construction issues of irregular-shaped buildings," *Journal of Architectural Institute of Korea,* vol. 52, no. 4, pp. 63-65, 2008.

[7]   K. Kim, K. Son, E. D. Kim, and S. Kim, "Current trends and future directions of free-form building technology," *Architectural Science Review,* vol. 58, no. 3, pp. 230-243, 2015.
(DOI: 10.1080/00038628.2014.927751)

[8]   L. Ney and S. Adriaenssens, "Shaping forces," in *Shell structures for architecture : form finding and optimization*, S. Adriaenssens, P. Block, D. Veenendaal, and C. Williams, Eds. London: Routledge, Taylor & Francis Group, 2014, pp. 15-20.
(DOI: 10.4324/9781315849270)

[9]   S. R. Malek, "The effect of geometry and topology on the mechanics of grid shells," Doctor of Philosophy, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Boston, 2012.

[10]   R. Harris, J. Romer, O. Kelly, and S. Johnson, "Design and construction of the Downland Gridshell," *Building Research & Information,* vol. 31, no. 6, pp. 427-454, 2003.
(DOI: 10.1080/0961321032000088007)

[11]   S. Adriaenssens, M. Barnes, R. Harris, and C. Williams, "Dynamic relaxation," in *Shell structures for architecture : form finding and optimization*, S. Adriaenssens, P. Block, D. Veenendaal, and C. Williams, Eds. London: Routledge, Taylor & Francis Group, 2014, pp. 89-101.
(DOI: 10.4324/9781315849270)

[12]   P. Cuvilliers, C. Douthe, L. d. Peloux, and R. L. Roy, "Hybrid Structural Skin: Prototype of a Gfrp Elastic Gridshell Braced by a Fiber-reinforced Concrete Envelope," *Journal of the International Association for Shell and Spatial Structures,* vol. 58, no. 1, pp. 65-78, 2017.
(DOI: 10.20898/j.iass.2017.191.853)

[13] D. Naicu, R. Harris, and C. Williams, "Timber gridshells: Design methods and their application to a temporary pavilion," in *World Conference on Timber Engineering (WCTE) 2014*, Quebec city, Canada, 2014: University of Bath.

[14] 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. (DOI: 10.1260/0266-3511.28.3-4.187)

[15] E. Lafuente Hernández, S. Sechelmann, T. Rörig, and C. Gengnagel, "Topology Optimisation of Regular and Irregular Elastic Gridshells by Means of a Non-linear Variational Method," Vienna, 2013, pp. 147-160: Springer Vienna. (DOI: 10.1007/978-3-7091-1251-9_11)

[16] I. Liddell, "Frei Otto and the development of gridshells," *Case Studies in Structural Engineering,* vol. 4, pp. 39-49, 2015. (DOI: 10.1016/j.csse.2015.08.001)

[17] B. Lefevre, C. Douthe, and O. Baverel, "Buckling of Elastic Gridshells," *Journal of the International Association for Shell and Spatial Structures,* vol. 56, no. 3, pp. 153-171, 2015.

[18] C. Gengnagel, E. L. Hernández, and R. Bäumer, "Natural-fibre-reinforced plastics in actively bent structures," *Proceedings of the Institution of Civil Engineers-Construction Materials,* vol. 166, no. 6, pp. 365-377, 2013. (DOI: 10.1680/coma.12.00026)

[19] M. Kuijvenhoven and P. C. J. Hoogenboom, "Particle-spring Method for Form Finding Grid Shell Structures Consisting of Flexible Members," *Journal of the International Association for Shell and Spatial Structures,* vol. 53, no. 1, pp. 31-38, 2012.

[20] F. Scheurer, "Materialising Complexity," in *Theories of the digital in architecture*, R. Oxman and R. Oxman, Eds. New York: Routledge, 2014, pp. 287-291.

[21] F. Gramazio and M. Kohler, *Digital materiality in architecture*. Baden: Lars Müller, 2008, p. 111 p. (certaines pliées).

[22] C. Paoli, "Past and Future of Grid Shell Structures," PhD, Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, 2007.

[23] R. Harris and J. Roynon, "The Savill Garden Gridshell Design and Construction," *Structural Engineer,* vol. 86, no. 17, pp. 27-34, 2008.

[24] F. Tayeb, B. Lefevre, O. Baverel, J.-F. Caron, and L. Du Peloux, "Design and Realisation of Composite Gridshell Structures," *Journal of the International Association for Shell and Spatial Structures,* vol. 56, no. 1, pp. 49-59, 2015.

[25] B. Sharma, A. Gatóo, M. Bock, and M. Ramage, "Engineered bamboo for structural applications," *Construction and Building Materials,* vol. 81, pp. 66-73, 2015.(DOI: 10.1016/j.conbuildmat.2015.01.077)

[26] C. Correa, "Designing with paper tubes," *Structural engineering international,* vol. 14, no. 4, pp. 277-281, 2004. (DOI: 10.2749/101686604777963496)

[27] A. Tedeschi, *AAD_ : algorithms-aided design : parametric strategies using Grasshopper®*, First edition ed. Brienza (Potenza): Le Penseur, 2014, p. 495 pages.

[28] D. Piker. (2017). *Kangaroo3d*. Available: http://kangaroo3d.com

[29] S. Bhooshan, D. Veenendaal, and P. Block, "Particle-spring systems," in *Shell structures for architecture : form finding and optimization*, S. Adriaenssens, P. Block, D. Veenendaal, and C. Williams, Eds. London: Routledge, Taylor & Francis Group, 2014, pp. xiii, 323 pages.

[30]   M. Heimrath, A. Orlinski, C. Preisinger, M. Tam, R. Vierlinger, and C. Zimmel. (2017). *Karamba*. Available: http://www.karamba3d.com

[31]   R. Mesnil, C. Douthe, and O. Baverel, "Non-Standard Patterns for Gridshell Structures: Fabrication and Structural Optimization," *Journal of the International Association for Shell and Spatial Structures,* vol. 58, no. 4, pp. 277-286, 2017. (DOI: 10.20898/j.iass.2017.194.893)

[32]   J. Natterer, N. Burger, and A. Müller, "The roof structure "Expodach" at the World Exhibition Hanover 2000," in *Space Structures 5*, G. A. R. Parke and P. Disney, Eds. London: Thomas Telford, 2002. (DOI: 10.1680/ss5v1.31739.0020)