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Grid shell for the next generation: *Shape of how to build*

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Abstract

This paper presents general concepts for the kinematic method for the gird shell construction and basic criteria for the meshing method suited for the kinematics of the structures. The objectives of this study are to reduce the temporary support work, which often costs as much as grid shell itself, and give a shape to 'how to build'. Through the case studies demonstrated herein, the authors propose, from more general aspect, structurally and architecturally, to add another quality component to the classically defined three qualities of an architecture; firmitas, utilitas, venustas. The forth one shall be the *construction process*. A structure shall present more integrity, which is to be sound and efficient in terms of the entire design and construction processes.

Keywords: grid shell, kinematics, gird meshing, construction, scaffold, barn raising

1. Introduction

Recent years have seen a growth in the number of grid shells in various types of architectural projects, such as atrium spaces, court yard roofs and indoor botanic gardens. Lightness, use of glass, and natural forms are behind the popularity of this contemporary roof structural system. In contrast with their simple and elegant looks, the design of the grid shells requires in-depth understanding of the form and stability of structures. These grid shells are materialized by the innovation in structural engineering, development of material science (Schober [1]) and advancement of numerical analysis techniques. The innovation in structural engineering includes invention of well thought out details for member joints often incorporated with bracing cables since stiffness and stability of the grid shell structures are very sensitive to such detail engineering. Thus, the designs of grid shell projects were controlled by more engineering principle than architectural reasons. However, while the determination of grid shell forms are still driven by structural optimization, we have witnessed emergence of new phenomenal grid shell forms, although structurally not optimal, created from successful collaborations of visionary architects and ingenious structural engineers. For example, the envelope structure of the YAS island marina hotel and the roof structure of Fiera Milano are the iconic projects that present the three major trends that characterize such contemporary gird shells.

The three trends are 1) free form, 2) increase of scale, and 3) release from rigid boundary. The engineering issues caused by these contemporary trends are respectively, difficulty in optimizing structural efficiency, economy of temporary supports, and lack of thrust. Although the free form and absence of rigid boundary are often adverse to the original engineering principle in their extreme cases, these three trends should be seen as the evolution of the grid shell. And such evolution should be further cultivated by both architectural and structural innovations.

The grid shells have been always built on temporary support structures. Some grid shells were fully assembled on the scaffold. Other ones were preassembled in a yard with jigs up to the size that a crane can lift up and those regional shell pieces are connected together on the scaffold. In either way, a temporary support needs to be built as high as a grid shell itself. This is not only because high accuracy is required for grid shell constructions but also because the structure is very unstable until the shell form is completed. And, it can cost as much as the gird shell itself when the scale of the structure becomes larger since the temporary support structure increases by volume.

On the other hand, in the modern construction in the field of space frame structures with much larger spans, such as roofs for stadiums or indoor sport facilities, the construction methods to reduce that can significantly reduce temporary support work and shorten construction terms while increasing the construction accuracy have been developed and demonstrated in practice. The push-up and lift-up methods are the two major ones. Among push-up methods, the pantadome system patented by Kawaguchi [2], [3] employs kinematics of a structure in which the structure is unstable only in the direction of the reaction of push-up support. In most cases divided space frame pieces were preassembled in the yards and brought together in the initial position for the push-up procedure. The initial positions for preassembled pieces are not as flat as those in lift-up methods. In the lift-up methods, the assembly of a roof structure can be completed on the flat platform near ground independently of the substructure. But, in case the substructure does not contribute to the stability during the lift-up process, other measures must be taken to ensure it.

In the grid shell design practice of the recent years, engineers are occasionally requested to fit the grid shell as much as possible to the free forms designed from architectural reasons. Computational grid mesh optimization methods have been proposed by some that take the planarity for quadrilateral grid into account and modify a free form surface (Sassone [4]). Nevertheless, the triangulated grid is often chosen for free forms in order to fit the mesh with minimum change of geometry although it makes joint detail more complex and the grid structure less transparent. To distribute a nearly uniform gird shapes on the free form surface of today requires certain criteria and iterative computation.

Based on the above observation of the current grid shell construction practice and being inspired by the other roof structure construction, the authors are developing the kinematic construction methods for the grid shell and meshing technology suited for the kinematics. The objectives of this study are to propose alternative approaches to the problems associated with 1) free form and 2) increase of scale by combining kinematics of the grid shell construction, grid meshing suited to the kinematics. And, with that, the authors attempt to propose a direction for the further evolution of the grid shell. The rigorous structural optimization is outside of the scope at this point of research development.

This paper presents current research status with some case studies of the grid shell kinematics. For the conceptual study for kinematics, first, prototypes of grid shell application and the corresponding push-up or lift-up strategy are illustrated. Second, analysis method is described, and finally three kinematic concepts are presented in the case studies. Stress analysis is not the main focus in this paper. For the grid meshing method, the general ideas of the algorithm is first described and followed by the criteria to suite it to the kinematics of the structure. Full integration of the meshing technology to kinematics is still under development at this point. This paper is concluded by remarking on the outlooks of establishing the new criterion to evaluate the shape of a structure.

2. Conceptual study for the kinematics of the grid shell

2.1. Prototypes of the grid shell application

Typical building prototypes to which the grid shell has been applied can be categorized as follows; 1) an envelope structure supported on the ground level (Figure 1a, b); 2) a roof structure on a flat building (Figure 1c, d); 3) a roof for a court yard space (Figure 1e, f); 4) a linear vault for rail way platform (Figure 1g); and 5) a canopy with columns, which can be also cylindrical grid shell system (Figure 1h). In many cases, the shorter span is up to about 20 meters. In addition, the grid shell is often applied to a renovation of existing buildings. In such cases, a space for assembling yard may be very limited, and devices for push-up of lift-up need to be small enough to be installed in the court yard or the roof top. For the conceptual study of the kinematics, the grid shell geometry has only single curvature. But, the concept shown in the following sections will be applicable to double curvature structures by arranging the division lines. This issue is discussed in the section for meshing criteria. The cases of the application prototype (4) and (5) are not discussed in the following section of this paper.

2.2. Methodologies for push-up or lift-up with kinematic joints

The basic procedure of the kinematic construction methods takes three steps. First, a grid shell is assembled as much as possible with kinematic joints on the ground or a platform close to the ground. In this state, structure should be ideally flatly layout on the platform or folded in a compact shape. (Figure 2 a, b, d, f, h)

Second, the structure preassembled with kinematic joints needs to be positioned on the supports. In cases of the prototype (1) or (2), this step may not be necessary. The perimeter gird shell members can be directly installed on the support. In the case of the prototype (3), the preassembled structure needs to be moved on to the supports (Figure 2 f, i). To utilize cables and winches may be preferred to jacks if the building roof top is available for winches. During the lift-up, the preassembled structure will either stay folded or sagged by gravity (Figure 2 i).

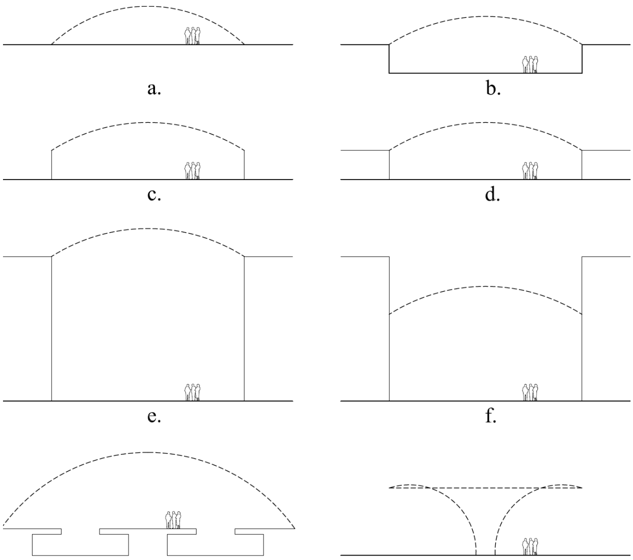


Figure 1: Prototypes of the grid shell application

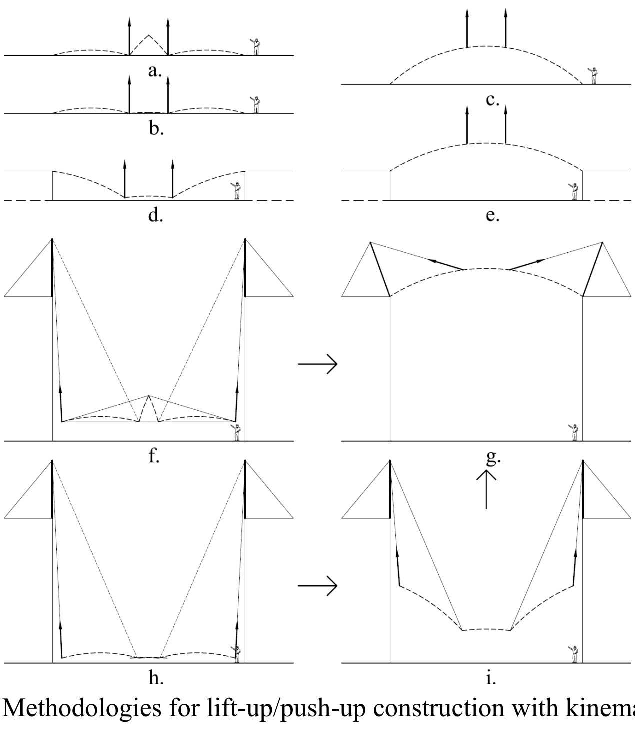


Figure 2: Methodologies for lift-up/push-up construction with kinematic joints

Third, the preassembled loosen structure is set to the final position. Then, the kinematic joints are fixed. For the prototype (1) and (2), either jack-up or winch-up measure will be possible. For the prototype (3), the measure utilized in the second step will be continuously utilized in this step (Figure 2 g).

2.3. Analysis methodology

For conceptual analysis of the kinematic construction, geometrically nonlinear time-history dynamic analysis technique is utilized. In order to simplify the definitions of kinematic joints in the simulation, beam members in the grid shell were modeled with triangulated plane trusses about major axis. In fact, this approach offers some advantages in kinematic simulation as follows. The top and bottom flanges of a beam as deferent elements, so that the eccentricity of the kinematic hinge bottom flanges are defined as different members. The contact problem of such eccentrically defined hinge connection can be easily defined since the beam joints are not defined with single node (Figure 3 sets of two nodes linked with red line). Torsional stiffness of beam members in this modeling approach are caused only by the three dimensional relation to the adjacent members at the joints. This, in turn, clearly visualize the effects of the three dimensional configurations of the adjacent members to the kinematics of the structure. This visibility and the reduced degree of freedom are useful in assigning one degree of freedom to each joint as desired.

In order to simulate jack or winch up, a special bar element is defined (Figure 3 green line). The special element changes its slack length in the dynamic calculation loop, and the corresponding internal force is virtually developed in the next dynamic time step puling up the structure. Other than this special feature, this element works as truss or cables with certain mechanical properties assigned. If the rate to change the length is set to be very slow and if viscous damping is properly set to cause energy dissipation, this approach can virtually simulate lift-up or push-up procedure. In order to simulate lift-up by cables, more than one element is assigned to each cable so that they do not carry compression.

The contact behavior is modeled by defining another special bar element (Figure 3 red line). This stiffness of this bar element is activated only when it becomes shorter than contact tolerance distance or directional cosine to its original vector becomes negative.

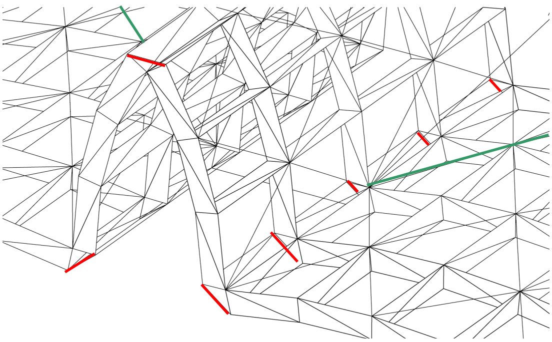


Figure 3: Grid shell dynamic analysis model for kinematic study

In this study, the beam section is assumed to be relatively deep, so that each gird shell parts connected with kinematic joint behave nearly rigid. When a grid shell form is optimized, the beam section can be so small that a part of such grid shell divided for kinematics can be actually very flexible. However, in such case, the part can be temporally braced to make it behave nearly rigid if necessary. Also, this study assumed relatively large scale free form. Therefore, the section is assumed arbitrarily deep.

2.4. Kinematics case studies

Three different kinematic concepts are presented in this section. In this paper, they are called Stretch-and-snap method, Unfolding method, and Two DOF pantograph method and shown in Figure 4, respectively (a), (b) and (c).

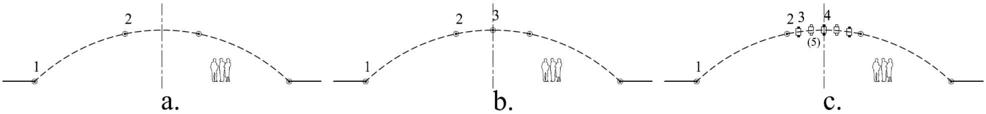


Figure 4: Grid shell dynamic analysis model for kinematic study

2.4.1. Stretch-and-snap method

This concept is the simplest as it is made of only two hinges in a half of the symmetric portion. Instead, this requires methodical plan and special care to control of the length of the two winch wires. The lift-up is not only executed asymmetrically, but also one wire needs to be released while maintaining a certain stress at some point of lift-up erection process. This can be described by using the analogy of snap through of a structure. But in the actual step for lift-up erection, the wire lengths need to be controlled to prevent any unstable state that can be caused, if not well controlled, by the fact the wires do not carry compression. One way to minimize such unstable states is to stretch this four hinge arch about one kinematic hinge before the other kinematic hinge is pulled up. This system will be suitable to the application prototype of the grid shell (1) and (2) since the preassembled potions can be initially set on the supports. If it is laid out on the ground with kinematic hinges, it needs larger space than covering area. Geometry of a low rise-to-span ratio is preferred.

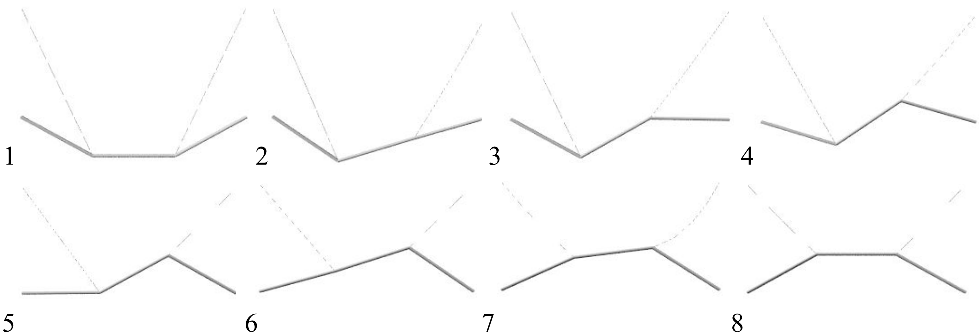


Figure 5: The kinematic erection sequence of the stretch and snap method

2.4.2. Unfolding method

In this concept, a grid shell in the initial position is folded out of its own plane and is unfolded to form a vault structure in the final position. This requires only the hinges in a half symmetric portion, but the folded preassembled portions need to be set nearly vertical, which require a crane or a small temporary support. This sequence is illustrated in figure 6. During the lift-up from the ground to the roof level, the folded initial geometry should be braced not to expand by itself as it tends to expand wider than the final span. This will be suitable for the application prototype (1) and (3), and applicable to a wide rage of rise-to-span ratio.

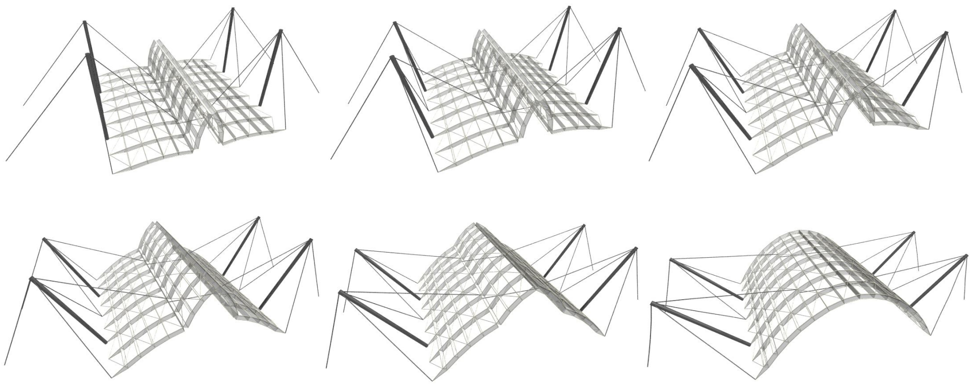


Figure 6: The kinematic erection sequence of the unfolding method

2.4.3. Two-DOF pantograph method

This applies the concept of pantograph with one more degree of freedom than ordinary pantograph or pantadome system. If the kinematic structure is lift up by cables, and as far as equilibrium can be found in a stable state, it will not be a major problem to have two DOF for the nodes at which lift-up force is applied. This concept uses at least four hinges in a half symmetric portion, counting from the one at the support to the one at the crown (Figure 7). The third and the fourth one are orientated in the perpendicular, i.e. horizontal rotation, to the first and second vertical ones. This pantograph system can be folded nearly flat in the plane of the grid shell itself, and the required area for ground assembling can be smaller than the projected area of the final grid shell geometry. During the lift up from the ground level to a roof position, this kinematic structure can be sagged by gravity as it can deform in both directions within the final span length of the vault geometry. This system will be applicable to all the application prototypes of the grid shell, (1), (2) and (3). But, rise-to-span ration near to optimal is preferred. Two alternatives of this concept are shown below. The second one uses five hinges. By this means, kinematic joints at the crown (hinge No4 in Figure 4.c) move only in the vertical direction (Figure 8).

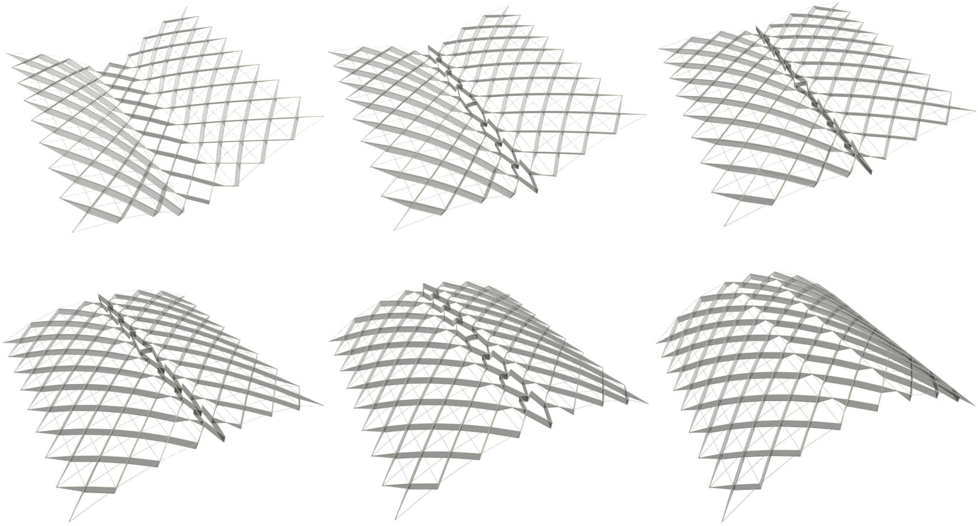


Figure 7: The kinematic erection sequence of the two-dof pantograph method I

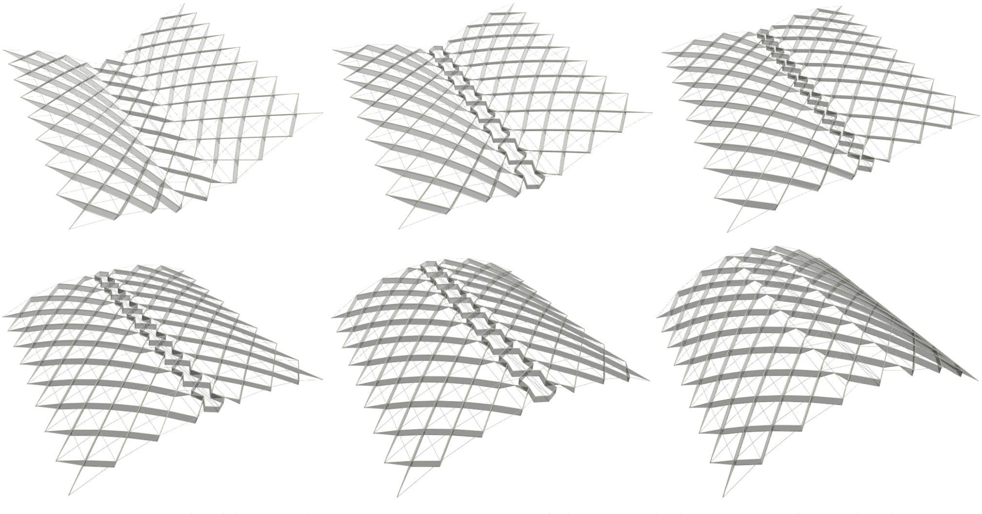
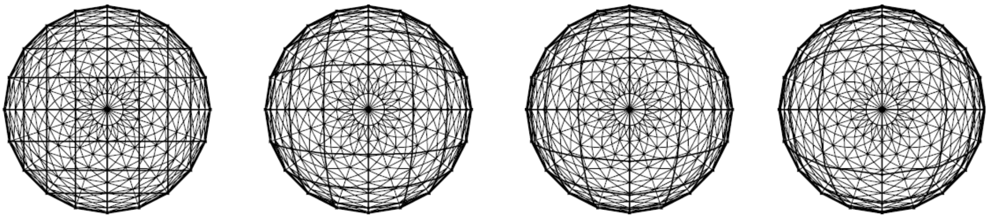


Figure 8: The kinematic erection sequence of the two-dof pantograph method II

3. Grid meshing methodology for kinematics of the grid shell

3.1. Algorithm

To use the mesh algorithm introduced in this section, a faceted surface geometry approximate the designer's free form must be prepared. Many commercial modeling software tools can generate such geometry. Users decide the topology of mesh with in the projected plane (Figure 9a). Each node of the user given 2D grid is projected to the facets perpendicularly to the original grid plane. Then, iterative calculation starts to minimize variation of length or angles. These variables are measured directly by the global nodal coordinates, but a new position for a node is searched in a geodesic sense within the facet on which the node is defined until it moves to one of the edges. By this means, coordinate variables are reduced from three to two. The variations of the lengths or angles are evaluated node by node about the adjacent grid elements. The sequential update is repeated until criteria are met. Figure 9 shows demonstration with a half sphere model. Figure 9 (b), (c), (d) respectively show the results of this optimal mesh technique in terms of minimum variation of grid lengths, grid angles and their combination. This meshing technique has demonstrated its practical applicability in some project.



a. b c. d.

Figure 9: The grid mesh technique principles

3.2. Criteria for kinematics

The implementation of the criteria in order to suite the grid to the kinematics is still under development. Here, only criteria to accommodate kinematic system in the mesh are outlined below.

1) A three dimensionally curved surface has to be divided into preassemble regions. The boundary of such divided regions should be smooth curves that are compatible with kinematics.

2) Since the kinematic hinges need to be lines up, a certain number of grid nodes or hinges, which are not necessarily on the rigid nodes, need to be coordinated in a straight line.

3) If uniform beam sizes are preferred, many hinges need to be assigned to prevent force concentration during erection. In this case, the grid on which these hinges are assigned, need to be straight in the plan and the same elevation.

4) If a fewer hinges are assigned, mesh density needs to be varied to support the force concentration during the erection.

4. Conclusive remarks

Although the accomplishment is still little in terms of the integration, the authors offered an outlook of integrating the kinematics and grid meshing technique into form determination process of the grid shell by presenting general concepts for kinematic construction and by outlining the approach to mesh the grid accommodate the constraints required for the kinematics. Kinematic constructions, as have been demonstrated by the lift-up or push-up practice, provide opportunities for us to share the contemporary barn raising, which we rarely do despite having many constructions of larger scales. This will in turn remind us that building process, i.e. design and construction, is as important as the performance and beauty of architecture after it is completed.

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