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Gridshells, Downland Gridshells: A Creative Mechanism in Setting up Structure

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ABSTRACT
Gridshells are one of new structural systems and are suitable for large span coverage. The system consists of a set of elements that make up the network connect to each other and loads are being transferred through the curves to the supports having two or more way behavior. Such a structural system has a low depth to span ratio. This paper attempts to examine and identify the advantages and disadvantages of this type of structure focused on downland gridshells. Downland Gridshells with a unique erect process are among less well known gridshells. In this regard, first the gridshells have been classified from different perspectives and then various dimensions of downland gridshells have been examined and compared with regular gridshells.
Keywords*: shell, gridshell, downland gridshell, structural systems, structural technology*

INTRODUCTION

Perhaps the most common structural system is the one that transfers horizontal and vertical loads separately by its members**.** Frame systems can be noted among these systems that transfer loads through horizontal members such as beams and vertical members such as columns to the foundation and eventually the ground**.** However, there are some structural systems in which horizontal and vertical elements are not separated**.** Membrane structures, such as structures Air-supported structure, and shells are included.

Shell is a thin structure with curved surfaces which transfers loads only by the tension, compression and shear to the supports. Shell is distinguished from traditional arches through their tensile strength. Such a system is very effective where the loads are distribute and the use of curved shapes is appropriate [1]. The shell is a three-dimensional structure to resist loads through their form [2]. The curvature of such a system is a prerequisite for shell behavior. Shells can be used in different curved forms in one or more directions or free-form curves. Thus, this system can be a lot of potential in the field of architecture and formic aesthetic.

If the regular holes are embedded in shells, the resulting structure through a focus of removed material on the remaining stripes is known as a gridshell, a gridshell is actually a shell with large openings, so that the grids and the remaining stripes show similar structural behavior that of shell [4]. In gridshells, where there are countless load transfer paths in shells, internal forces are carried by members and therefore limited routes [2]. Although the shear force cannot be transferred through grids, some Bracing are required to generate shell behavior. Among Bracing are the use of continuous covering layer in the grid or the use of diagonal Bracing which makes grids triangulation (Figure 1 and 2) [5].

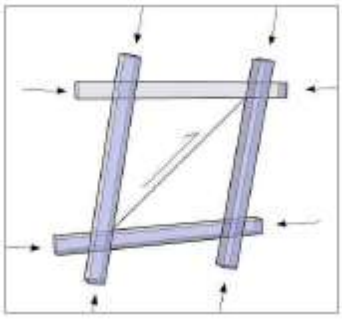


Figure 1. The use of diagonal Bracing to create shell behavior [5]

Figure 2. The use of continuous covering layer to create shell behavior [5]

Gridshells facilitate sustainable development in three directions: 1) reuse of historic buildings with appropriate functions, 2) materials can save up to 50% compared with conventional frame structures and ability to be build structures with different materials and 3) greater amounts of natural light enter the building [3]. It is also one of the ways to meet different architectural and structural expectations. Openings are easily generated by converting the shell into grid and pre-fabrication is possible by the construction of separate stripes. Other advantages are using less materials, structural efficiency, wide span coverage and potential for rapid construction with high economic efficiency [4]. In addition, gridshells beautiful appearance can be used in exterior with providing countless opportunities in the field of interior design and architecture richness.

However, there are a few stability failure on gridshell structures including:

- members buckling means a member buckling without influence on the rest of the structure
- local instability, meaning the failure of one or more nodes
- global instability, meaning the structure buckles as a whole. It is comparable to continuous shells.
- The combination of the above scenarios [6]

Gridshell classification

Gridshells are structural systems with many variations. According to the definition of the gridshell, any curved surface with very low depth to span ratio may be regarded as a gridshell. Gridshells may be classified in terms of the geometry of the grids, load transfer type, form and categorizing based on the establishment of structures.

Grids geometry

A gridshell may be made of different geometric modules. But the most used modules as the basic patterns are included, square, diamond, triangular and hexagonal grid. Triangular format geometry is of the inherent stability. Other patterns can also be achieved by changing the basic patterns (Figure 3).

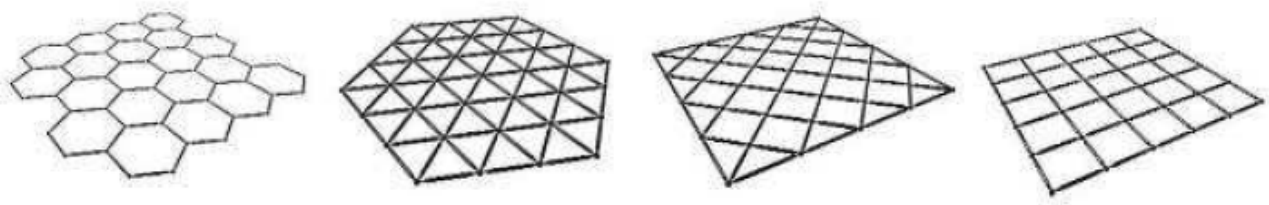


Figure (3) basic patterns for grid geometry, [7]

Type of load transfer

One of the features of grid structures is their ability in two or more way load transfer. This means that unlike the structural that transfer loads in one direction to supports such as a set of beams that cover an span in one direction, the system transfer loads from multiple directions. So in this sense, gridshell can be classified as two- way, three- way and four-direction and four – way grids (Figure 4).

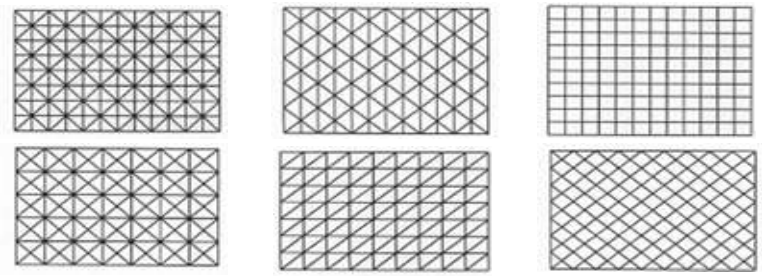


Figure (4) transfer load patterns in the grids, two- way patterns (right figures), three-way patterns (middle figures) and four-way patterns (left figures), [8].

Form

Gridshells, as well as shells can be divided into different categories according to structure mat curvature and form. Gridshells which are curved in one direction, (e.g. cylindrical shells), two- directional shells (all kinds of domes), shells with curvatures in opposite directions and shells with free-form curved surface (Figure 5). It should be noted that such shells can use different geometry patterns with variety of load transfer mechanisms.

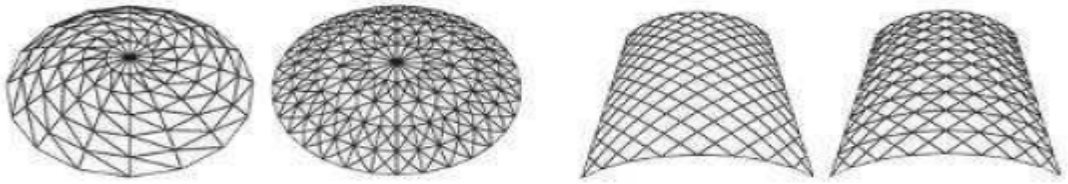


Figure 5. Cylindrical grid (right figures), Dome grid (left figures)

the establishment of structures

The establishment of shell structures can be divided into two categories: downland gridshells and regular gridshells. These two types of shells are similar in appearance but set up in different manner and have different structural behavior.

DOWNLAND GRIDSHELL

construction of such a shell begins of a flat form, then by applying pressure on the edge of the network and the gradual release of internal stresses in the joints, the structure takes on the most appropriate form and thus a three-dimensional structure is achieved (Figures 6 and 7). In the initial assembly on site, network members are attached to each other with relative movement permitted. Force excreted on one of the nodes of the square network causes the other member's rotation and cell shape is changed into a parallelogram. This deformation causes a change in the length and diameter of each cell, thereby allowing the shell to be formed by a two-direction curvature [2]. Figure 7 shows the use of this structural system in Savill building. As is clear, the members of such a system continue from one end to the other end without a break along the span**.** The structure is established in final form by the flat mesh end fixed in support and according to the support condition.

Figure (7) Savill Building, downland gridshell [9]

Figure (6) downland gridshell flat form [9]

A mesh made of elastic rods is limited in a surface takes specific geometric form that has the lowest stress [10]. Similarly, when the gridshell is erected in the final set, takes the form of an ideal weight tolerance with minimum tensile strength. There is not any bending force as long as no external force is applied to the structure. But this ideal state that the structure is only affected by their dead load never happens in real world. Shell is subjected to external forces such as wind and snow that do not uniformly applied on the nodes and is not permanent, as well. Such a system resists external point loads by bending members. The bending moves members and thus can form a mesh change leading to rearranging members and ensure minimum tensile strength [2]. Thus, this is a adaptable system that however, the members and nodes motion (joints) must be kept at an acceptable level.

MATERIAL

As is clear, materials used in the system must have the ability to be deformed. The common structures for gridshell are made of timber, which can be bent elastically without breaking. Also, timber is used due to low-density and high strain range (about 2%) but not for power (30Mpa at best) [11]. Timber gridshells are of spatial structures and combine structural efficiency with a pleasant appearance. In addition, when properly designed leave very little impact on the natural environment. Another feature of this type of structure is the basic flat network building using direct members and then bending them down and reaching the final form in a relatively short time [5]. Thus, their use in temporary buildings such as temporary exhibitions, or when rapid construction is concerned, can be customized

Fiber glass reinforced polymer materials also can be used in the system. These polymers have power of 350Mpa and strain of about 1.5% to just 1.9 kg / m3. Fiber glass reinforced polymer materials have greater stiffness than timber and thus, for a given geometry of the gridshell, shell buckling load for composite is more than that of timber in value [11]. However, such materials can be considered as an alternative to timber members and in addition to structural properties generate the different beauty of the architecture.

Joints

Nodes (Joints in the structure) should not only join the members to each other, but should provide rotations while maintaining the geometry of the grid Due to the special erecting mechanism of downland gridshell. In fact, the ability of the nodes rotations is the unique characteristics of the structure and provides the possibility of building free and complex forms. It is well known that the nodes are of critical points of the structure and their design requires a high level of creativity and innovation. There are very few of these types of structures in the world because it requires high level of creativity. However, two types of nodes that are typically used in these structures are slot node and plate node.

Node using the slot

Since the depth of the grid member is high to cover large spans, it is difficult to establish the curve comes to form the final curve. To overcome this problem the two- layer grids is used. To generate a curved shape of flat two-layer grids, nodes should allow members of the network to rotate, on the other hand, due to the difference in the curvature of the upper and lower members and as a result the differences in the layers length, layers should be possible to slide on each other. In Mannheim, this problem could be overcome through a slot in the two outer layers (Figure 8). The slot between the two outer layers allowing them to slide the inner layers. bolt through the two inner layers keeps a constant distance between the nodes. slotting is expensive and time consuming, in addition causes weakness in the structure [4]. In fact, the existence of slots in the structure concentrates stress in this point and may structures fractures under the loads less than of ultimate stress.

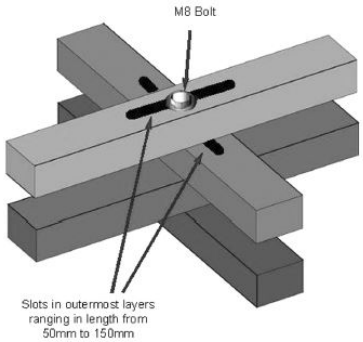
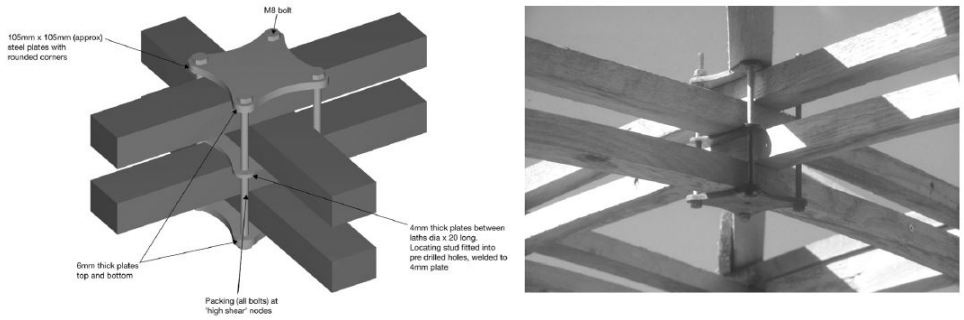


Figure 8. Create nodes through the slot [4]

Nodes using the plate

Another system is the plate system than is preferred to previous systems**.** This node consists of three Layers of plate that to maintain nodes position a plate is used in the middle (Figure 9). A pin is connected to the center plate and enters into the central layers and keeps them in fixed position**.** Thus, nodes are capable of rotation with the same distance from each other**.** The thickness of the Layers is considered so that able to bend [4]. In any case, the nodes design is of the interesting challenges in the system.

Figure 9. Create nodes Using plate [4]



Case study

Examples of the application of this system are Mannheim multi-purpose hall designed by Frei Otto in 1975 (the first large-scale timber gridshell [12]), the Japan Pavilion at Expo 2000 in Hanover and weald and downland open air museum that the last cases have studied in the following.

Weald and downland open air museum (Figure 10): The first two-layer gridshell is made of in Great Britain that was built near Chichester in Sussex as an addition part of the museum**.** Its timber grid shell forms from of a flat network of timber. Building in all its aspects was a dynamic process; first the entire structures as a flat grid was assembled at a height above the ground, and then while the scaffold through a telescopic system was support placed on its position on the lower level by manpower**.** Thus, the structure reached its final shape under the stepwise control and supervision [13]. The building has won 8 awards and took the second place in RIBA 2003 Stirling Prize [14].

Figure (10) the construction of weald and downland open air museum, all figures [15].

The regular gridshells

There are examples of gridshells that should not be confused with the Downland gridshell. Downland gridshells before any geometric change and when are placed as a flat mat, including the members that extend from one side of the mat to the other. This mat is essentially a quadrilateral shape with parallel members. Savill's roof in Windsor garden (Figure 7) is a good example in this regard. You can see very clearly that by flattening the roof mat, members extend from one end to the other. There are some structures similar to downland gridshell structures but their members are not fixed at both ends such as Great Court Roof of The British Museum (Figures 11 and 12) which while curved in two directions and members have been drawn from one end to the other, but consists of triangular mesh and cannot be deformed and two mats cannot generate two-dimensional network. In fact, what makes downland gridshells able to change the form in space is that they are deformable quadrilateral while triangles are stable [2]. Therefore, in addition to different structure establishing mechanism, two other main features

separating downland gridshell system from the ordinary form, are member extending from one end to the other end and the other is the ability to become a two-dimensional mat. These two conditions must be provided simultaneously.

Figure 11. Great Court Roof of The British Museum during construction

Figure 12. Great Court Roof of The British Museum interior view

The materials and joints

New solutions on the choice of materials development were found with the popularity of gridshell, now, steel replaced timber in glass gridshell structures with wide span. The use of composite materials to improve the conventional plans to build a timber gridshell is being investigated [2]. Free forms and irregular gridshells covered with glass panels are usually made of steel. Złote Tarasy in Warsaw and new Milan trade fair are included (Figures 12 and 13).

Figure 12. New Milan trade fair Figure 13. Złote Tarasy building

jointing choice depends on the geometry of the components and jointing techniques since the various systems have different stiffness. Rigid connections are essential to the structures with large span, while the semi-rigid connections are more economical for medium and small span. The semi-rigid joints are usually bolts and are useful due to rapid construction in comparison with welded structures but weld joints stiffness is significantly greater than the bolts joints (Figures 14 and 15) [19]. But, regarding the pinned connection, it must be said that gridshell structures with pin connection are not stable, here are diagonal stiffeners are of value. Diagonal stiffeners ensure lack of deformation in network, transferring forces from one network to another and the integrity of the mat. stiffeners in grids act like braces on

Braced Frames. They can pull or push and prevent moving nodes and thus prevent the deformation of grids. stiffener members can also be selected with high hardness, in which case they can be resistant to tension and pressure, or with less hardness, such as the cable that can only resist tension [2]. Finally it should be noted that the choice of Connections are depends on the project condition, including the Span extent, materials used, labor and so on.

Figure 14. Connect with Bolt

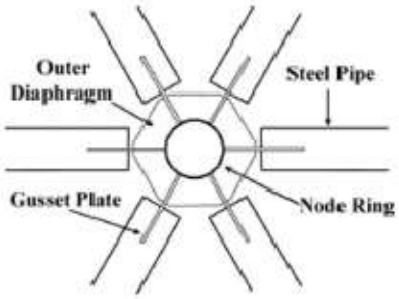


Figure 15. Connect with welding

CONCLUSIONS

Industrial revolution led to dramatic improvements in scientific and technical fields and thus affected many areas. Architecture and construction are not also exempt from these developments. New materials and industrial production, new computational techniques and new applications that require large spaces and thus Large span were among these developments. As a result of such developments, new structural systems were also introduced. Gridshells is one of these new systems. Multi-directional transfer of loads, low weight structures, speed construction and economical construction has made this system one of the suitable options to cover the large span. Gridshells covered with glass provide better access to daylight and moreover, because of the beauty of networks they are often used expose. In this way they can contribute to the architectural expression. Note that in such a system the nodes are critical points. Also, the structure is usually made of wood or steel that is weak against fire, so necessary measures should be considered in this case.

Downland gridshell system with specific erect process distinguishes itself from other gridshells. The system by applying pressure to the edges of a flat elastic network and their involvement with supports takes its form is different from those gridshell with short structural members and located into their places according to designed form. In Indeed members stretches from one side to the other side of the support, and possible expansion of gridshell in the form of a flat mat are of downland gridshell features. When the edges of such a system are fixed in the support, the structure takes a form with the lowest tension and when an external load is applied, the structure is more prone to take a form with less tension due to new condition. This is another special feature of this structure.

Finally, it should be said that in such a system architecture and structure are one and inseparable. It seems essential for architects and students to recognize such structures due to their architectural potential.

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