A Review of the State of the Art of Timber Gridshell Design and Construction

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ABSTRACT: Timber gridshells are lightweight doubly curved structures. They are generated by deforming a flat timber grid towards a curved shell-like target shape. The designer can achieve a best fit approximation to a pre-determined target shape by varying the grid, boundary geometry and member stiffness. Thus a wide variety of built forms can be created. Additionally timber is a renewable resource. Despite these advantages, few timber gridshells have been realised. Bending active gridshells are complex to analyse, design and construct. The research presented here is a comparative study of a number of existing timber gridshells in terms of approach to design and analysis, material selection and construction process. The joints, the number of layers, type of bracing and type of covering are also examined. Barriers to the more frequent adoption of timber gridshells in design are identified. Research currently underway at the University of Limerick is aimed at reducing these barriers.

KEY WORDS: Timber; Gridshells; Bending active; Free-Form Architecture; Precedents.

1 INTRODUCTION

Throughout history, building structures have been created using a wide variety of forms. Shell structures are particularly versatile in the variety of forms they can assume. Timber has been used throughout the Middle Ages, Early modern period, 19th century, 20th century and is still a very prominent material in the 21st century as a structural element in buildings. Gridshells are discrete shell structures. A gridshell, like a continuous shell, is a structure that gains its strength and stiffness through its double curvature configuration. Gridshells are made from elements that have one dimension considerably longer than its other two, which makes timber a suitable material. A timber gridshell enables doubly curved structures to be formed from a set of straight, prefabricated, identical components. The development of computer methods in modelling complex three-dimensional structures is a development that will increasingly facilitate designers in using this challenging structural form. Additionally, engineered materials further facilitate designers to achieve complex geometries.

Many types of curved structures exist today. Gridshells can be classified as either bending active or bending inactive. The term bending active means that the structural elements have to be deformed by bending to give the structure its final shape. A type of bending pre-stress is thus generated in the members during forming [1]. Alternatively, bending inactive describes a structure whereby the structural elements do not need to deform to give the structure its shape. A typical bending inactive structure would be a truss, portal frame or a geodesic dome such as the Eden project or the Quebec Biosphere. The majority of bending inactive gridshells have been constructed from steel. These structures are comprised of numerous straight elements each inclined at a different angle to its adjacent element and joined at nodes usually by welding, if the geometry is irregular, to give the structure its curved shape. An example is the roof over the great court in the British Museum [2] and the courtyard roof in the Museum of Hamburg History [3]. In addition, a number of bending inactive timber gridshells have been constructed such as the University of Exeter Forum [4] and Centre Pompidou Metz [3]. The timber members for Centre Pompidou Metz are created by machining smaller curved timber sections out of initially straight glulam timber of large cross section. In contrast, bending active gridshells are not all that common, however a number of them have been constructed such as the Multihalle in Mannheim [5], the Weald and Downland Museum [6], and the Savill Garden centre [7].

In order to advance the knowledge base of gridshells, a detailed account of those gridshells that have already been constructed is required. Many aspects of gridshells can be personalised, giving each gridshell a completely different appeal. Six notable bending active gridshells are described here. The design context, computational modelling and analysis procedures, material selection and production, joint details and construction methods are described. Subsequently having described individually each gridshell, the development of gridshells over time is discussed with a final focus on how this research advances the topic of gridshells.

2 DEFINITION OF A GRIDSHELL

Bending active gridshells are lightweight doubly curved structures, creating open plan spaces that make efficient use of sustainable materials. Only a few of these elegant structures exist today. They are complex structures made by deforming initially straight elements. The analysis and design of these structures is difficult and is centred on the form finding of the gridshell. An initially flat grid must be sufficiently flexible to be able to bend and twist towards a target shape. The exact target shape may not be an equilibrium form for the given materials, sections and geometry. Nonetheless a final shape can be achieved which approximates to the target shape.

A gridshell may be thought of as a shell whose material has been gathered as strips concentrated along lines or laths and intersecting at nodes. This new system is a lattice shell that can transmit forces in the direction of the laths and can also resist some out of plane bending. A lattice shell can be seen as a series of arches that are connected together creating a series of (usually) quadrilateral shapes. For this reason a lattice shell does not entirely conform to shell action by itself [8]. In order for the lattice shell to conform to shell action a means is necessary by which in-plane shear stresses can be distributed through the shell. This is done by applying some form of bracing to triangulate the quadrilaterals of the structure enabling in-plane shear stresses to be developed, resulting in a gridshell. A more detailed description of gridshell bracing systems can be found in section 3.3. By concentrating the shell into strips, openings are easily created. By adjusting the depth of the strips, the stiffness out of plane and thus the buckling capacity can be modified [6].

The benefit of bending active timber gridshells becomes apparent in the construction stage. Complex forms can be shaped relatively easy [6]. The way in which these forms are created is generally by laying a flat grid of continuous timber laths in two directions. The laths are then connected at their intersections (nodes) with a cylindrical joint. The cylindrical joints allow rotation for the individual laths to scissor relative to each other so that deformation can occur [9]. Once the required shape is reached, the perimeter nodes are constrained to the edge boundaries, all the nodes are tightened and the structure is stiffened by some form of bracing system (Figure 1). This construction method is suitable for a material that; is lightweight; can be bent without too much effort; and has sufficient capacity to resist the loads after construction. Timber satisfies these three criteria.

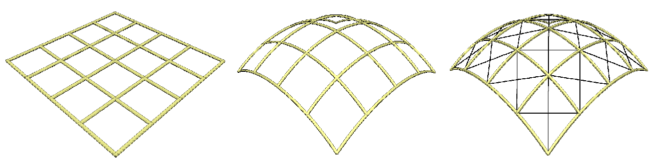

Figure 1: From a flat grid to a lattice shell to a gridshell

The way in which the gridshells in this study were constructed vary considerably from constructing them in-situ piece by piece, laying out the grid above and pulling it down, and laying out the grid on the ground and pushing it up.

3 GRIDSHELL COMPONENTS

3.1 Layers

There are practical and physical limitations on the tightness of curvature to which gridshell members of a particular cross-section can be bent. The depth of member required for a single layer gridshell to achieve relatively large spans may be too deep to permit bending of the flat lattices to a final shape with tight radii of curvature. The solution to this problem is to use multiple layers for the gridshell which have smaller section sizes [6]. The layers are initially un-coupled therefore they deform independently of each other and because of their small section size, they can form tight curvatures. Once the form has been found, the individual layers are connected together to create a composite structure which has greater out-of-plane bending strength enabling the gridshell to span longer distances.

A single layer gridshell (Figure 2a) has a single lath in each direction where as a double layer gridshell (Figure 2b) has two laths in each direction. A double layer gridshell is, in simple terms two single layer gridshells one placed on top of the other but locked together to create the composite action. This develops greater out-of-plane bending strength and stiffness. The parallel members are allowed to slide relative to each other during the formation process so that the flexural stiffness of the members is that of a single layer gridshell. A qualitative stress block for a single layer and a double layer (coupled and uncoupled) is given in Figure 3.

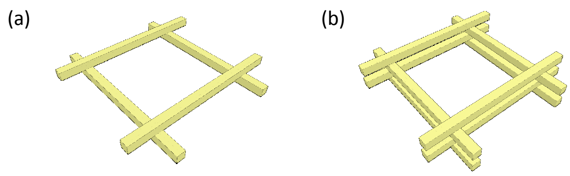

Figure 2: (a) a single layer gridshell and (b) a double layer gridshell

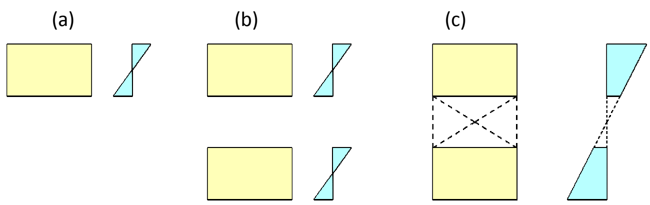

Figure 3: Qualitative allowable stress blocks of different gridshell layers, (a) single layer, (b) double layer (uncoupled), and (c) double layer (coupled).

When the double-layered gridshell approaches the target shape, the nodes are tightened and shear blocks in the form of wedges or solid blocks of timber are inserted between the layers, thereby ensuring composite action between the two layers. A double layer gridshell with a gap between the layers equal to the thickness of the members themselves has a flexural stiffness that is 26 times stiffer than that of a single layer of the same material (assuming full compatibility).

There is potential to further this type of system, multi-layered (>2) gridshells could be utilised to achieve larger spans. By adding more layers or increasing the depth of the shear block the out-of-plane bending strength and stiffness is further increased [10].

In addition, according to linear elastic beam bending theory, the local radius of curvature that a beam can achieve is directly proportional to the thickness. Assuming a constant strength and stiffness, the only difference between the double layer and geometric equivalent single layer is the magnitude of the thickness of the material. A single member in the double layer has a thickness that is at least three times smaller than the thickness of a geometrically equivalent single layer. Therefore, a radius of curvature can be achieved with the double layer that is three times smaller than would be possible with a geometrically equivalent single layer.

3.2 Crossover Joint

Gridshell structures have very large numbers of nodes and so the design of the crossover joint is essential to the success of the overall structure. The formation process of a gridshell has the most influence on the type of nodal joint adopted. During the typical formation of a bending active gridshell, the grid must allow rotation of the laths (scissoring) at the joints (Figure 4). Here, the lengths of the diagonals in (a) are equal but in order to form the lattice into the correct shape scissoring is required. Thus the lengths of diagonals in (b) are not equal ($L_{13} > L_{24}$) [6].

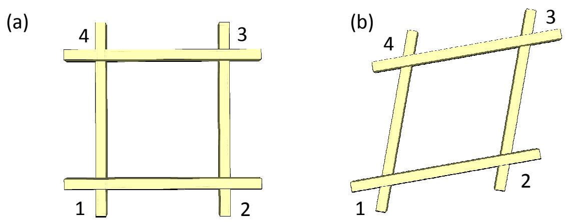

Figure 4: Scissoring of gridshell members, (a) before scissoring, and (b) after scissoring.

A wide variety of crossover joints were designed for different gridshells. For single layer gridshells, the joint detail is not too complex as relative sliding of the layers is not required. However, particular attention is required in a double layer gridshell to detail the joints in such a way as to permit sliding during forming.

Once the gridshell has been formed, the joints are tightened which prevents this independent sliding. The reason for allowing sliding between layers is to prevent the build-up of any unwanted stress in the laths during forming allowing tighter curvatures to be achieved. The required curvatures of the two laths are different due to their geometrical location in space. Thus, the distance between adjacent nodes on each lath is different. This phenomenon is displayed in Figure 5, showing a portion of a double-layered gridshell before and after being deformed. The distance L between Node 1 and Node 2 is the same for both laths before deformation. With sliding allowed, the gridshell is formed and now the distance between both laths is not the same. The angle θ is the same for the arcs created by the neutral axis of both laths. $R_1 > R_2$ and $L = R\theta$. Therefore $L_1 > L_2$.

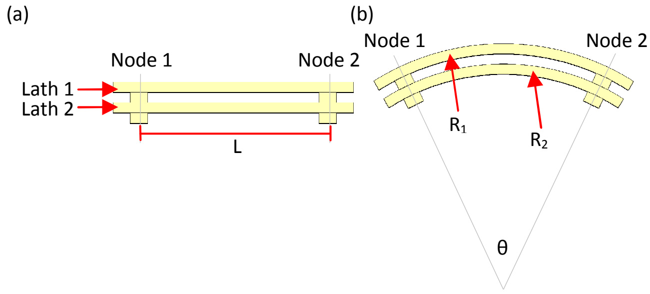

Figure 5: Relative sliding of layers, (a) as a flat grid, and (b) after deforming.

Gridshells are lightweight and undergo significant deformations due to snow and wind loadings as well as fluctuations in moisture content. Therefore, the joints need to be detailed appropriately to facilitate these movements.

3.3 Bracing

For three dimensional structural stability and for shell action [3] to be developed in a gridshell, a means is necessary by which the shear forces can be transmitted from one edge of the gridshell to the other. Therefore, a gridshell must have sufficient in-plane shear strength whereby the laths will efficiently distribute the applied forces and the gridshell will behave similar to a continuous shell. In-plane shear strength can be provided in several ways:

- Rigid joints
- Cross ties (tension only bracing)
- Rigid diagonal bracing
- A continuous membrane layer

The reason for the bracing system is to triangulate the structure to provide in-plane shear strength and stiffness (Figure 6). Quadrilaterals are inherently flexible because their geometry can change without a change in member length. However, this is not true for a triangle whereby the members themselves must deform for the entire structure to deform.

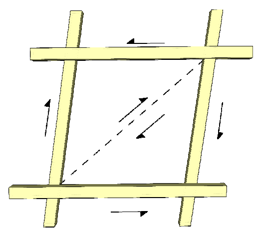

Figure 6: Gridshell element with diagonal bracing

The bracing is typically applied to the gridshell structure once the forming process has been completed and each end node is at its designated boundary. The internal supports remain in place until the bracing has been added. This is to ensure that the completed structure accurately represents the target shape. Without the bracing, the structure would be incomplete and excessive deflections or even failure might result from the self-weight and construction loading.

Each of the bracing types has advantages and disadvantages. The rigid diagonal bracing offers advantages over cross-tie bracing. Steel cables can only act in tension and hence each quadrilateral would require two cables running orthogonally. However, timber can carry both tension and compression, meaning that it is only necessary to run a bracing lath in one direction across a given quadrilateral [6]. Rigid joints are poor at creating a stiff overall structure on their own and must be used in conjunction with another type of bracing. If rigid joints were to be used on their own, the size of the joint required to create full fixity may be too big and obtrusive.

The rigid bracing system can be formed using long lengths similar to the laths themselves (bending active bracing) or by short straight lengths (bending inactive bracing), one for each quadrilateral. For bending active bracing additional bending stress are introduced to the structure. This may cause a change in geometry of the overall structure due to additional out of plane forces being applied at the joints. An additional benefit of rigid bracing is that external facades such as cladding panels can be attached directly to the bracing thereby reducing the complexity of the connections.

Crosstie bracing does not add any additional out-of-plane forces to the structure. However, crosstie bracing is tensioned upon application and if this tensioning is not carried out in a controlled manner, unwanted changes in geometry may occur. In contrast, temporary crosstie bracing can be beneficial during the form finding process to force certain areas of the structure to scissor in a certain direction. Depending on the joint type and façade used, the crosstie bracing does not increase the overall depth of the structure unlike the rigid bracing. Moreover, an alternative to linear bracing elements is to use planer elements such as stressed skin panels [10].

3.4 Materials

Gridshells can be created by using materials such as timber, steel, Fibre Reinforced Plastics (FRPs) and even cardboard tubes. This versatility makes gridshells an ideal structure to design and create very efficient forms. A material with a high f_m/E_m ratio is most suited to gridshells [11]. This material should have a low elastic modulus to enable bending without too much force and a high bending strength to allow tight curvatures to be achieved. High slopes and curvatures are efficient in supporting the accumulation of vertical force that occurs close to a support in compression or tension.

The timber used for the Weald and Downland [6] gridshell and the Savill Garden [10] gridshell was improved by cutting out short grain and other irregularities such as knots and clusters of pin knots. The defects were cut out and the defect free sections of the laths were re-joined using finger joints. For these joints a liquid PUR glue was used which is suited to the gluing of finger joints with green timber. Long uninterrupted laths in a gridshell reduce the number of structural components as well as simplifying the joint detail to a single repeatable joint across the structure.

Timber has an advantage over other materials when it comes to selection of a material for a gridshell, especially when it comes to multiple layers. Waste is reduced, the improved timber is used for the laths and the remaining timber can be used for the shear blocks and other non-critical components. Doubly curved gridshells offer a greater variety of curvatures than with other structures. However, the issues around defects and variability have to be dealt with when it comes to timber due to it being a natural material.

4 EXISTING GRIDSHELLS

The Multihalle gridshell in Mannheim Germany was the first large-scale bending active timber gridshell. Constructed from Western hemlock, it was designed by Frei Otto and built in 1975. The form was developed using physical models. Long lengths of timber were produced by finger jointing but many finger joints broke during the forming process. Lath breakages were repaired on site by adding splice pieces to the sides of the broken member. Steel cable bracing was used; the specific tension force in the cables set the stiffness of the overall gridshell. A fabric membrane was used as a weathering skin. The gridshell was assembled flat on the ground. It was then raised using movable platforms. Spreader beams were used at the tops of the platforms to distribute the forming forces.

Twenty-seven years would pass before the next large scale bending active double layer gridshell would be built, this time at the Weald and Downland Museum in Sussex. This gridshell had many notable improvements from its predecessor. Firstly, computer based form finding and structural analysis was used. Better material selection and processing using finger and scarf joints along with improved monitoring on site during forming significantly reduced the number of breakages. The material selected was green Oak, which had a high moisture content reducing its bending stiffness for form finding. The erection sequence was similar to that used at Mannheim except that the flat grid for the Downland gridshell was raised to a level equal to the finished level of the valleys. Then under gravity it was deformed downwards towards the target position. The formation of the gridshell was sequenced and was rigorously monitored to identify potential breakages and other complications before they became critical [6]. In addition, the bracing was made from the same material and also functioned as a mount for the cladding. The structure was clad in western red cedar boards, polycarbonate glazing to allow in light and a ribbon roof made from flexible polymer concrete. To connect the layers together without drilling slots and holes in the timber sections, a patented nodal connection was developed to clamp the layers together.

A different type of gridshell appeared in Helsinki in 2003. The members were manufactured pre-curved using four laminates of red fir. Additionally, steam bending was utilised to further bend the members into position on site. A simplified nodal connection using a single bolt was easily implemented as the gridshell was erected lath by lath and the boltholes were drilled when the laths were in place. No deforming of a flat grid was carried out, which would have been difficult given the vertical orientation of this gridshell. This gridshell has no external façade so the timber was treated with an oil-based wood preservative with UV protection.

The largest bending active gridshell designed to date was opened as the visitor centre of the Savill Gardens in Windsor Great Park in 2006. This shallow double layer gridshell made from Larch had only two breakages during construction. This is due to the low curvatures and the knowledge that had been gained from previous gridshells. A greater strength and stiffness was achieved for this double layer gridshell by increasing the depth of the shear blocks beyond the depth of the gridshell members. A combination of the erection procedures that has gone before was used. Firstly, a single layer was formed by deforming a flat mat. Then, the shear blocks were screwed to this layer and lath by lath, the second layer was screwed to the shear blocks. The bracing system comprised of two layers of plywood that acted as a stressed skin membrane. Roof insulation and metal roof cladding is fixed to the plywood. Oak laths are then fixed to the cladding to complete the roof structure.

The Chiddingstone Orangery gridshell, although it is considerably smaller than the previously mentioned gridshells still represented an advance on previous Gridshells in some respects. This gridshell was made from locally sourced green chestnut. In addition, it is the first timber gridshell to accommodate a frameless glass roof, proving that these structures can be made stiff enough to support brittle finishes. However, this was only made possible, by further developing the patented node used in the Weald and Downland gridshell to accommodate the glass and cable bracing.

Advances in materials allowed gridshells to be designed using polymer composite materials [12]. The structural behaviours of these manmade materials are more predictable, having uniform linear elastic properties in the case of GFRP. Manufacturing GFRP tubes with standard dimensions allowed use of swivel scaffolding connectors. In addition, advances in computer technology since the Mannheim gridshell in 1975 allowed for the precise finished geometry of the gridshell to be predicted before erection. As a result, the fabric membrane was prefabricated off-site prior to completion of the gridshell structure, saving considerable time and money.

The timber gridshells presented here had high costs associated with them because a high amount of processing was required to obtain suitable defect free lengths of timber. Therefore, to increase the availability of the gridshell form to architects, engineers and clients a lower cost material would be required.

5 BARRIERS

As can be seen one of the most significant barriers to the development of gridshells is the availability of an appropriate material. High material selection and processing costs hinder the availability of gridshells as a viable structure. In addition, the analysis of bending active gridshells is complex given the non-linear geometries and organic shapes. Specialist computer software is required to firstly predict the geometry that a flat grid would take when formed towards a target shape and then predict the deformations and stresses that are developed due to self-weight and applied loads. Stress due to both forming and those throughout the structures design life need to be considered. An accurate prediction of the gridshell geometry is required in order to be able to design other elements of the building such as external finishes and boundary locations.

6 CONCLUSIONS

In summary, under the headings discussed for the six gridshells mentioned, six different materials were used (including five different timber species). Each gridshell took on a unique shape and size. Three different forms of bracing were developed as well as six different external finishes applied. This study shows that gridshells are very versatile to different architectural forms and finishes. A summary of key data on each gridshell is presented in Table 1 and Table 2. The historical timeline of each of these gridshells is presented in Figure 7 beginning with the Shukhov gridshell [13].

Timber gridshells are sustainable structures being constructed from a renewable resource. They are lightweight. They are structurally efficient being of shell-like form. The construction procedures and techniques are now relatively well developed. Current research at UL is investigating the potential of an engineered Irish timber product as an alternative to solid timber in bending active gridshells.

Table 1: Comparison of each gridshell presented in each study

Gridshell	Location	Plan size	Height	General Shape	Layers	Lath size	Material	Bracing
Multihalle Mannheim	Mannheim Germany	60m x 60m 40m x 40m	15.5m	Two principle domes connected with tunnels	2	50mm x 50mm at 0.5m	Western Hemlock	Twin 6mm cables at every 6th node
Helsinki Gridshell	Helsinki Zoo Finland	$82m^2$	10m	Vertical Bubble	1	60mm x 60mm	Laminated red fir	Timber Floor Diaphragm
Weald and Downland	Singleton UK	50m x 16m	7.35m 9.5m	Triple Bulb Hourglass	2	50mm x 35mm at 1m	Green Oak	Green Oak
Savill Garden	Windsor UK	90m x 25m	4m	Sinusoidal shape Three domes	2	80mm x 50mm at 1m	Larch	Plywood membrane
Chiddingstone Orangery	Chiddingstone UK	12m x 5m	~1m	Elliptical dome	2	40mm x 30mm	Green Chestnut	Steel Cables
Solidays' Festival	Paris	26m x 15m	7m	Unsymmetrical two domed	1	42mm Diameter 3.5mm Thickness	GFRP Tubes	GFRP Tubes

Table 2: Role of software for each gridshell presented in this study

Gridshell	Form Generation	Equilibrium Form Finding	Engineering Design (stress checks)
Multihalle, Mannheim	Wire mesh model Physical hanging chain model	Physical hanging chain model Mathematical Model	Experimental tests ARUP (buckling analysis)
Helsinki Gridshell	Scale models 3D Computer Model	None	LUSAS FEA Software
Weald and Downland	1:43 wire mesh model 1:30 wooden strips model	Dynamic Relaxation Physical models	STAAD Pro Dynamic Relaxation
Savill Garden	Mathematical Model	Dynamic Relaxation Physical models	FEA software
Chiddingstone Orangery	Mathematical Model	Buro-Happold Computer Modelling	Buro-Happold Computer Modelling
Solidays' Festival Gridshell	Mathematical Model	Dynamic Relaxation	Dynamic Relaxation

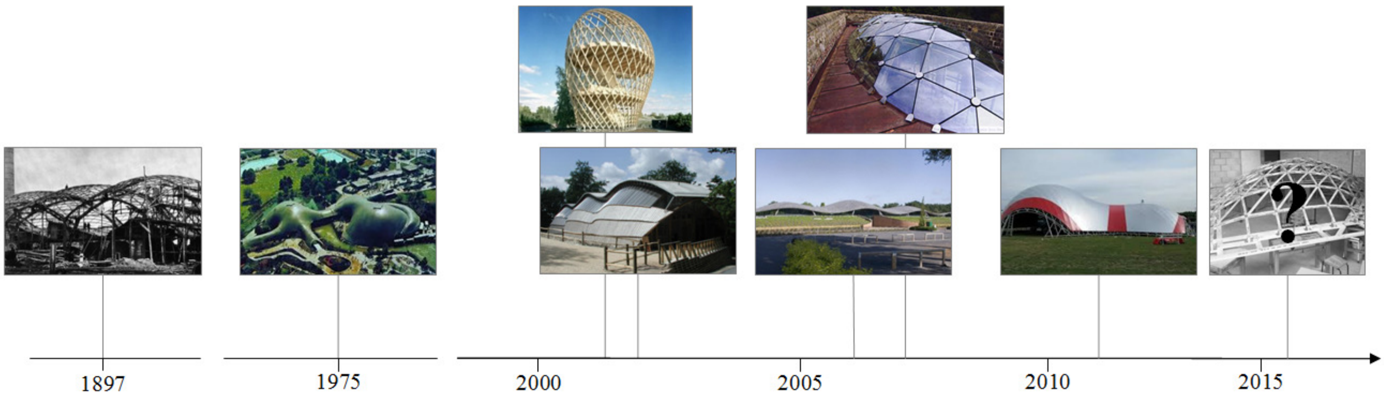

Figure 7: Historical timeline of bending active gridshells presented in this study

ACKNOWLEDGMENTS

This research has been funded by the Irish Research Council (IRC), EMBARK 2012.

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