Past and Future of Grid Shell Structures

By

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Diplôme d'ingénieur
Ecole Spéciale des Travaux Publics, Paris, 2007

Submitted to the department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING
IN CIVIL AND ENVIRONMENTAL ENGINEERING

At the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2007

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Civil and Environmental Engineering

ABSTRACT

Because of their original organic shape and the column free space that they provide, the design of grid shell structures challenges architects and structural engineers in more than one way. Very few grid shell building exist around the world. This scarcity may be explained by the level of innovation required in such fields as design technique; construction scheme, use of material... The goal of this paper is to unify the design work done on grid shells, to understand the evolution of the designs and to provide the reader with a sense of what awaits grid shell structures in the future.

The construction of a timber grid shell starts from a flat, two dimensional wooden net, the three dimensional shell type structure is then achieved by pushing on the edges of this mat and gradually releasing the internal stresses at the joints to enable the shape to live and the structure to take its most adequate form. Only three wooden grid-shell structures exist world wide, by studying the way they work and behave, as well as the process that lead to the choice of such a structure, we'll understand how grid shell were born in the mind of architects and structural engineers. Even if the mechanism of grid shells is a very clever and well thought system, as wood remains a lively material, it can be subjected to degradation and deformation which as a result will damage the structure and attend to its integrity. Timber construction is also limited in terms of load carrying capacity. As grid shells have become more popular new solutions have been developed in terms of choice of material. Steel has already replaced timber in large span glass grid shell and the use of composite materials to benefit of the original construction scheme of timber grid shell is currently being investigated.

Thesis Supervisor: Jerome J. Connor

Title : Professor of Civil and Environmental Engineering

Acknowledgments

I would like though this page to have a special thought for

Maman

Papa

Eric

Thomas

Mathilde

Géraldine

Cyrielle

Guillaume

Amandine

Bénédicte

Yannick

Guillaume

Nina

Paul

Hervé

Véronique

Benjamin

Yaëlle

Elise

Pauline

Anja

Papi et Mamie

Pépé et Mémé

Arlette

John

And Professor Connor

...Thank You

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Introduction

Despite the different use Man can make of a building, its main purpose remains to provide shelter to human activities. The consequent role of a building is to protect the interior space from exterior aggressions. Therefore it has to be able to carry forces due to exterior solicitations around the enclosed space and to the ground. The structural system chosen for a building is driven by both the geometry sought for the interior space and the external applied loading to which the building will be subjected. The most common structural system is one that counts both horizontal and vertical elements like a column and beam scheme or a portal frame, the horizontal loads are collected by the facades, the vertical ones by the slabs and they are both transferred through the slabs and the beams to the columns which then carry them down to the ground through the foundations. This scheme is the one used in all the usual and ordinary buildings, but structural systems that do not separate horizontal elements from vertical elements also exist, those are shell or membrane structures. Shell structures have become popular with the development of concrete construction. The use of special scaffolding combined with the use of very thick concrete (with low water content) enabled these forms to be achieved. Timber grid shells are another sort of building that explore the characteristics and advantages of shells.

Very few grid shell buildings exist around the world. This scarcity may be explained by the complexity of the forms and thus of the design of such structures. Therefore the study of the actual grid shells is more related to individual case studies than to a building theory. The goal of this paper is to unify the design work done on grid shells, to understand the evolution of the designs and to provide the reader with a sense of what awaits grid shell structures in the future. Starting with the understanding of what grid shells are, the possible future development of grid shell will be addressed after having explained the past evolution of these structures, which is crucial to be able to make any development predictions.

Grid shells are shell structures discretized by means of a grid pattern. The first chapter of this paper aims at describing grid shells as structural systems. Grid shells greatly resemble shells in that that they have the same structural behavior and gain their stability from their geometric shape. The grid pattern that distinguishes the structures that are addressed here enables the overall structure to benefit from the combined action of shell and arches and thus to achieve unique shapes. In addition to form specificity, grid shells benefit from a highly remarkable construction scheme that will also be addressed.

Throughout the second chapter insight on the past development of grid shell construction around the world will be given. Through the analysis of the three principal grid shells that have been constructed, namely: the Multihalle of the Garden exposition in Mannheim (Germany, 1975), the Japan Pavilion for the 2000 Universal Exposition in Hanover (Germany) and the Weald and Downland Museum in West Sussex (United Kingdom, 2002), the evolution of the different phases of the project will be studied. Starting with the design process and ending with the erection scheme of the buildings, this section will explain the reasons behind the scarceness of such structures and the evolution paths that this structural system has followed until now.

After having explored the evolution of grid shells, the focus of this paper in the last chapter is to give future perspectives regarding the development of these highly efficient and architecturally pleasing structures. First the need of developing more grid shell specific computer tools in order to ease the design process and thus spread the grid shell expertise amongst the engineering practices is addressed. Then after showing the structural limitations of timber in grid shell construction, the possibilities of using alternative materials such as steel or Fiber Glass Reinforced Polymers are explored.

1 Grid shell description

1.1 Shells and grid shells structure

1.1.1 Shell structure

Shell structures are tri-dimensional surfaces that resist loads through their geometry. The necessary stiffness to carry the external loads is provided to the shell by its natural three dimensional form. The most common example of such structures are domes. In a dome one cannot make any distinction between the roof and the walls. Every part of the dome is structural and structurally acts the same way. All elements of a dome behave in pure compression and a ring action holding the dome together also develops in the thickness of the wall. It is also clear that domes are self supported structures, during the construction process as well as once they are completed, in the sense that no additional columns or frames are needed to maintain the dome.

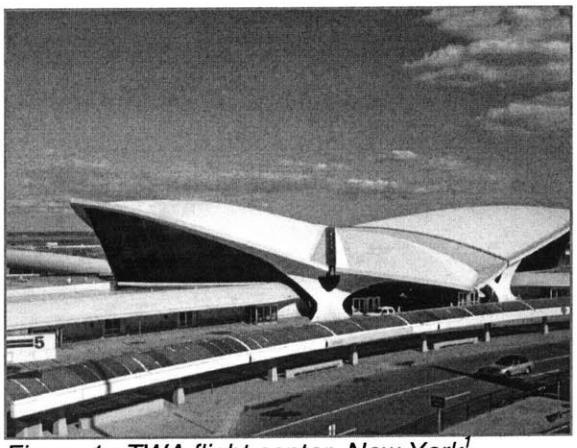

Figure 1 : TWA flight center, New York[1]

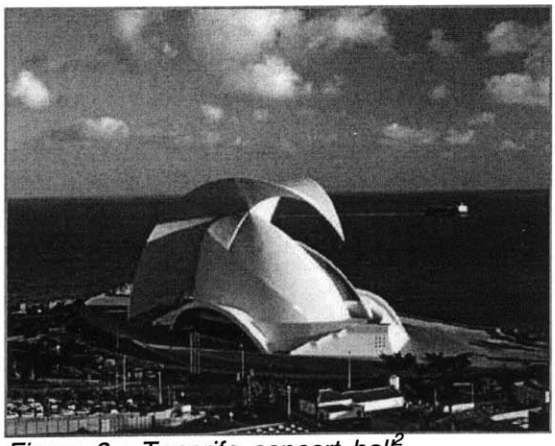

Figure 2 : Tenerife concert hall[2]

[1] http://en.wikipedia.org/wiki/TWA_Flight_Center
[2] Photograph Allan Karchmer

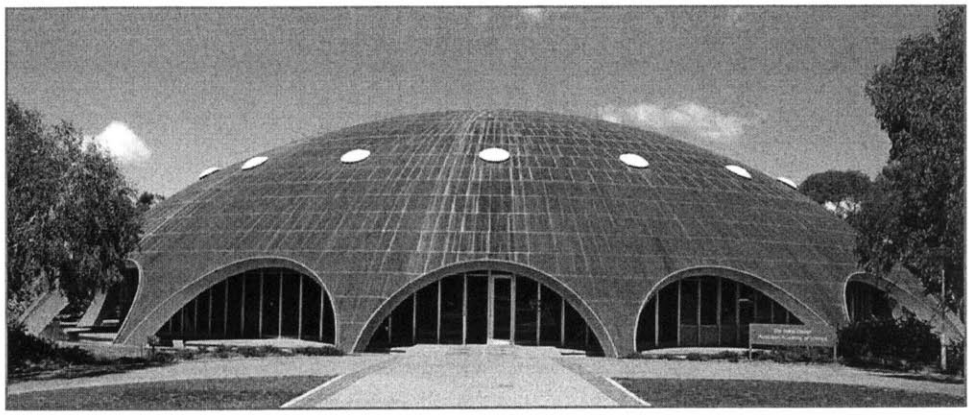

Figure 3 : Shine Dome, Australia[3]

Shells carry the loads mainly through membrane forces: tension compression and shear forces that are developed in the plane of the shell to resist applied loads. As tension compression and shear are the only forces that appear in the shell, that is to say that loads are not resisted by bending resistance, (except at the edges of the shell and at the supports) there is no need for thick surfaces nor high moments of inertia. Slender sections are therefore possible.

However with the use of thin shells, out of plane buckling now becomes the greatest concern regarding the integrity of the structure. Doubly curved surfaces is the most suitable choice of geometry for shell structures since in this case only tension or compression stresses are created in the thickness of the shell. The shell therefore cannot buckle in plane and only out of plane bucking, which is function of the proportion of compression in the shell, stays an issue.

1.1.2 Description of a grid shell

The structures that will now be described are inspired from shell structure as they have the same geometry and the same kind of structural behavior. Grid shells are basically shells where material has been removed to create a grid pattern. Where in a plain shell an infinite number of load paths were available, in a grid shell the internal forces are carried by members and therefore have to follow a restricted number of paths.

Apart from only being discrete shell structures that advantageously benefit from their geometry to become self standing, the grid shells discussed in this paper are characterized by their innovative erection scheme. By tacking only the exact definition of a grid shell, any

[3] http://www.science.org.au/dome/story.htm

geodesic dome or reticulated surface could be called a grid shell. The powerful concept that lies behind structures referred to as grid shells, is that the construction starts from a flat surface. All the members of the structure can be assembled flat on the ground so as to form a two-dimension articulated mat. The final structure will then be obtained by pushing, pulling and deforming the mat, and this being done without introducing any additional connection or structural member. Once in place, the surface having quite a small radius of curvature, the continuous members will act as arches. The final structure will thus benefit from the efficiency of both shell and arch scheme.

In the same way as in a shell, the members of the grid shell experience only tension or compression, shear stiffness is provided by adding diagonal members to triangulated the cells of the grid as will be discussed later.

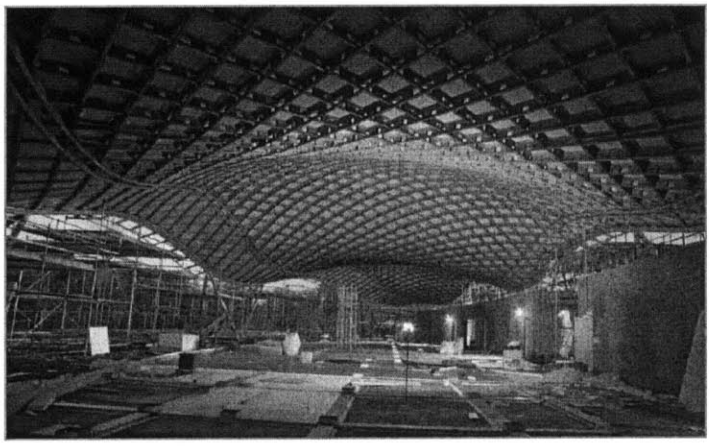

Figure 4 : Interior view of the Savill building during construction[4]

Presently below are examples of grid shells that must not be confused with reticulated shell structures. When laid flat and before any geometric transformation the mat of a grid shell is composed of long members crossing the surface form one end to another, the surface is basically a rectangle with parallel lines drawn in two directions that figure the members. The roof of the Savill Building in Windsor Garden is a good example, it can clearly be seen that by flattening the surface the members span from on side to the other. At another extreme the observatory in the Helsinki Zoo which is also a grid shell has a much smaller curvature than the roof of the Savill building. By getting a close look at this structure that looks much more like a sculpture than like a building, one can notice that the lines drawn by the members on the surface go from one side to another and are fixed at both ends. Structures that look like grid shell but

[4] The structural Engineer, 5 September 2006

that do not have members fixed at both ends are reticulated structures (or surfaces). The domes of the Eden Project are examples of such structures. In this case the structure of the complex are geodesic domes, domes that have had their surface discretized using a pattern based on the repetition of a unique geometrical form, in this case the hexahedron has been chose. In the case of the Eden Project it is easy not to mistake the domes with grid shells but this mistake can be easily made with structures like the Great Court roof of the British Museum below. In fact even if the roof is a double curvature surface and has members spanning from one edge to another, the cells of the grid are triangles, they are therefore non deformable and the surface cannot be flatten to a two dimensional mat. In fact what enables the grid mat to be deformed into place is that quadrilaters are deformable whereas triangles are stable figures.

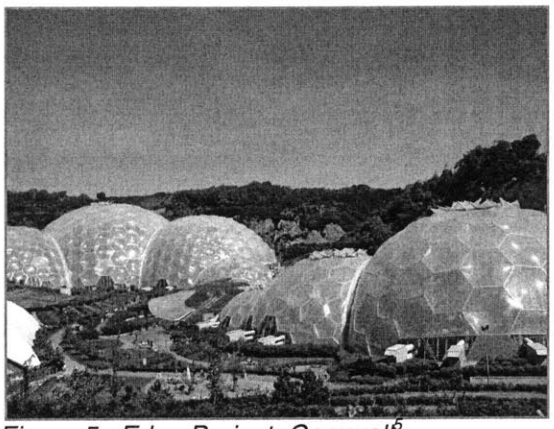

Figure 5 : Eden Project, Cornwall[5]
Geodesic dome

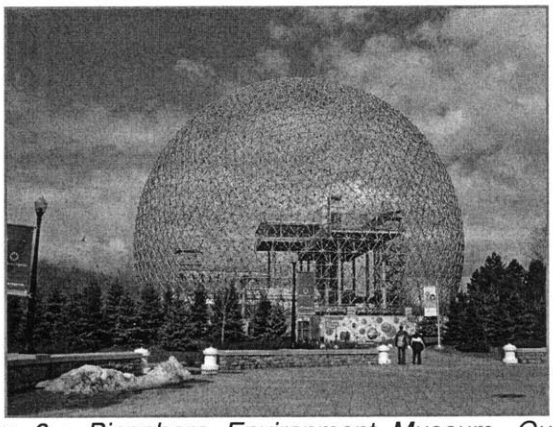

Figure 6 : Biosphere Environment Museum, Quebec[6]
Geodesic Dome

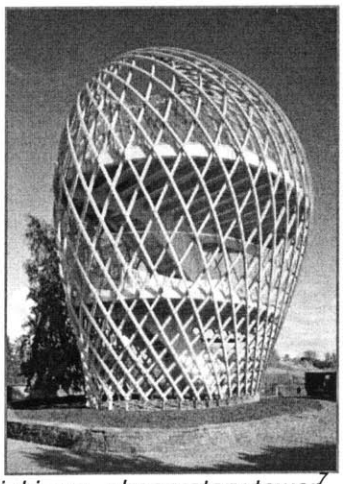

Figure 7 : Helsinki zoo, observatory tower[7]
Grid shell

Figure 8 : British Museum Great Court roof[8]
London, Reticulated surface

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[5] www.eden-project.net
[6] http://biosphere.ec.gc.ca/
[7] PUU4 magazine, 2002
[8] http://www.thebritishmuseum.ac.uk/compass/resources/image/large/com9024c.jpg

1.2 Design of a grid shell

1.2.1 Innovative construction scheme

The particularity of the grid shells is that they are not erected in their final shape, the structure is first assembled as a two dimension grid mat on the ground and it is only during the construction process that it is pushed into the desired shape. The principle of the erection process is to exert forces on the mat so to deform it into the final shape. The same way as when one pushes on the edges of a sheet of paper to give it a tunnel or a hill like shape, the edges of the grid are basically pushed towards each other in order to match the predicted curve of the building. Then once the boundary conditions are set the structure is pulled and pushed at certain points to give its mountainous form to the structure.

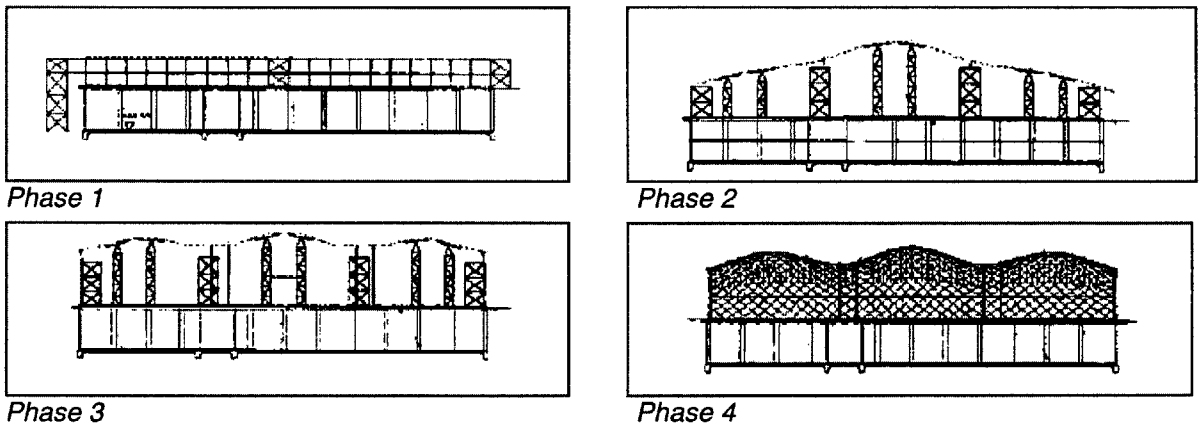

Figure 9 : Example of the construction sequence of the Downland grid shell[9]

To allow this transformation to take place, the grid surface has to be deformable. First assembled on the ground the lattice members are pinned to each other to allow relative motion from one with respect to another. It is clear that starting with a certain square shape, if a force is applied to a node of the lattice, this will cause the members to rotate, deforming the cells into parallelograms, those deformations cause the length of the diagonal of each cell to change, thus allowing the shell to be formed into a doubly-curved surface. Once the shell has been erected into its final shape (by means of pushing and pulling that depend on the technique chosen by the design team and that will be developed later), it has settled into the form that most ideally resists its self weight. This shape is solely assured by the boundary conditions and as no external forces are applied to the structure no bending forces result. But this ideal situation where a structure is only subjected to its own dead load never occurs in real life, the shell will be

[9] Design and construction of the Downland Gridshell', Building Research &Information,

subjected to exterior solicitations such as wind or snow loads which are never uniformly distributed at the nodes and never constant over time.

The grid shell is formed of a multitude of small elements, of cells, each of which is constituted of four laths pinned in a parallelogram shape. Contrary to a full plain shell which can carry loads in every direction, a grid shell can carry loads only axially in the direction of the laths, i.e. for a cell in the two directions of the sides of the parallelogram. A cell can also resist out of plane bending, but it cannot resist any diagonal action, therefore, because of its pinned connections it cannot transfer loads to the adjacent cells. Under self weight only the grid takes a shape such that the strain energy is minimal. In such conditions a grid shell resists additional external point loads by the bending of the laths. This bending induces movement of the laths and therefore can create large deformations of the grid that will readjust in order to once more assure minimal strain energy. With only pin connection a grid shell is not a stable structure and it is clear from now on that diagonal stiffness has to be introduced in this structure. This diagonal stiffness will assure the non deformability of the cells, the transfer of forces from one cell to another and thus the integrity of the shape of the surface.

Diagonal stiffness can be introduced by different ways in the grid shell. First this can be done by restraining the rotation of the laths and transforming the pin connections into moment connections. Shear will then be transmitted through the nodes by bending of the beam. Another solution is to provide bracing to the shell. Diagonal members are introduced in the cells, acting in the same way as traditional bracing in braced frames, they will, by means of compression and tension, prevent the movement of the nodes and thus the deformation of the cells. The bracing members can be chosen to be either very stiff so that they can take both tension and compression, or less stiff so that, as a cables, they can only act in tension.

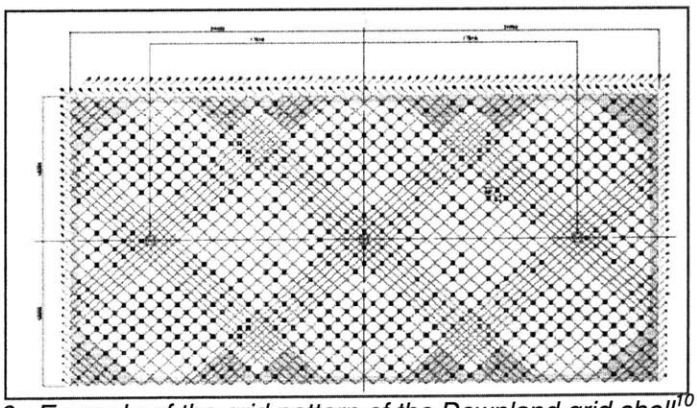

Figure 10 : Example of the grid pattern of the Downland grid shell[10]

[10] The Structural Engineer, vol 79 N°17 4 September 2001

1.3 A material of choice: timber

At first view a grid shell could be made of any construction material from concrete to steel or timber. But the specificity of the construction scheme requires members to be flexible enough so that they can deform during the construction phase and in the end take the shape designed by the architect. Concrete or steel even if they behave very well axially cannot bend easily. A concrete grid shell would have to be cast on site whereas the members of a steel grid shell would have to be formed in a plant before the beginning of the erection. Timber thus appears to be the most indicated construction material for these structures. The low Young's Modulus of timber allows the members to be easily bent into shape. Moreover during the construction phase the members might be subjected to tighter radii of curvature than the ones they will have in their final state, the capacity of timber to bend without braking and to remain elastic makes timber a material of choice.

Timber laths naturally come in limited length, limited by the size of the log they have been made out of, but techniques exist to join two members in order to obtain the desired length. The most commonly used joints are scarf and finger joints.

Scarf joints consist on splicing the end of the two members that are to be connected and then to join them using the appropriate glue. Scarf joints are not ideal to transfer loads, because contrary to steel welding for example the two members do not blend into one another and still behave as two members hold together by a glue interface. However by reducing the joint angle, so as to have more surface involved on both sides of the joint, the bending strength increases. Tests have shown that plain scarf joints with a low slope develop the highest strength but it requires extreme care regarding the matching and the gluing of the two members. Actually for this kind of joints, the manufacturing of the connection and the quality of the glue are of equal importance. The quality depends on the kind of wood and the preparation process it was subjected to, the type and the quality of the adhesive, and most of all of the compatibility of the gluing process and the wood itself.

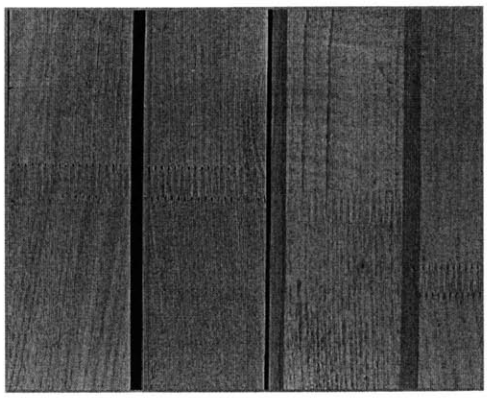

Figure 11 : Example of finger joint[13]

The joining process starts with the production of fingers et the ends of the two wood laths that are meant to be joint together, as can be seen in XXX the angles of these finger can be very variable. The carving stage will have produced a male and a female profile that will match each other and will then be glued. The finger process joining is closer to steel welding than scarf joining timber, in the sense that the gluing surface is much bigger. Moreover the crisscrossing of material from both members leads to a better interaction and a better load transfer between the members. However stress concentration zones also develop due to the sharp angles which make finger joints a weak zone of the timber member.

These joining processes enable wood members to have whatever length that is needed, which in addition to the high flexibility of timber laths, makes wood to be the most efficient material for grid shell construction.

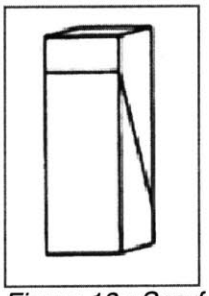

Figure 12 : Scarf joint[11]

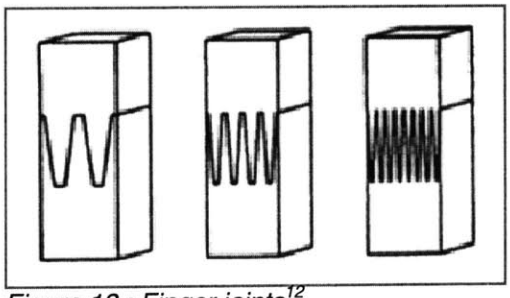

Figure 13 : Finger joints[12]

[11] Courtesy of Céline Paoli
[12] Courtesy of Céline Paoli
[12] www.woodnet.org.uk

1.4 conclusion

A grid shell is a particular and interesting structure from several points of view. First similarly to the conventional shell structures previously described, very architecturally interesting building shapes can be achieved. Grid shell are also interesting construction wise, since less material is used, a grid shell is a less expensive structure but also gives many possibilities regarding the operation of the building, the gaps between the members are many options for lighting or building penetration. But the most specific point of grid shell is the technique used for the erection of these buildings. In this process connections are all done at once, which is an efficient and time saving technique. The erection of the building is extremely rapid since no additions need to be done to the primary structure. Finally what takes the greatest time in the erection process is the cladding of the grid shell and the interior work.[13]

2 Past evolution, understanding of the design evolution

2.1 Introduction

There are very few grid shell buildings around the world, the three main structures that can be found and that really improved the grid shell design process are:

- The Manheim Multihalle building in Mannheim, Germany (1975)
- The Japan Pavilion build for the universal exposition in Honnover, Germany (2000)
- The Downland and Wound Museum in Sussex, United Kingdom (2002)

Deciding to use a grid shell scheme as shape as well as a structural system for a building is neither an easy choice to make nor the first idea that comes in mind.

The design process of a grid shell is first driven by the shape that the architect wants to give to the building. Since the grid shell is both the structural system and the architectural skin of the building, this shape, chosen by the architect has then to be made structural. Architect and structural engineers have to work closely together to make the shape of the building evolve in the two directions at the same time. This key process is called form finding. Once the shape has been agreed upon, the construction scheme has to be defined, this step might bring changes to the shape of the building since the load cases to which the structure will be exposed during construction will be different from the ones the shell will have to handle in its permanent state. In fact, those temporary construction loadings might be even greater. The structure has thus to be designed in order to be stable during all the construction phases.

Architecture, structural design and construction being for this type of building so tightly related, grid shell design requires all the different teams to really work hand in hand during the entire process. In fact it appeared during the design of the different grid shells that one of

the main interests of the architect was to solve structural issues through the exploration of new shapes, this close collaboration thus appeared natural and was even initiated by the architect him self.

The study of theses three examples will focus on four main points which are the reason behind the architectural choice of a grid shell scheme, the evolution of the engineering form finding process and the different technical solutions adopted in the construction stages.

2.2 Grid shells case studies

2.2.1 The Mannheim Multihalle

Every two years a national flower and plant fair is held in Germany. Lasting six months and aiming to welcome over four million visitors, the fair is composed of a big park where growers exhibit their special plants and new species. Organizing the Garden fair gives the opportunity to the town to redevelop and re-landscape forgotten and unused open areas of the town, this fair has therefore become very popular amongst the different German cities.

In 1970 the city of Mannheim was selected to host the 1975 garden show. The architectural program of the project included the actual landscaping of the exhibition park along with a multi purpose hall (Multihalle) housing indoor exposition spots, restaurants and diverse facilities. A local architecture practice, Mutshler & Partners won the architectural competition and was in charge of the design of the Multihalle. His initial design was to have a membrane roof supported by helium filled balloons. This concept was unacceptable for the German building authorities for safety concerns and another structural scheme had to be found. Professor Frei Otto was then asked to join the design team. He had already participated to the design of other Garden Expositions and also had previous experience with membrane structures. After having explored membrane and pneumatic solutions the lattice shell structure seemed to be the most appropriated structure that could both achieve the desired shape and comply with the local building regulations.

The approved design included two principal domes; the Multihalle itself and the restaurant. These two spaces would be linked by a walkway covered by a membrane tunnel. The grid shell would be covered with a PVC membrane reinforced with an open-meshed polyester fabric. The foot print of the building is highly irregular, as can be seen in Figure 16 below, the main dimensions of the structure are summarized in the following table.

Length (m)	Width (m)	Height (m)	Total area (m²)
72	35	15.5	3,600

Table 1 : Mannheim Multihalle, summarized dimensions

Due to the lack of previous engineering experience in this kind of project the design team suffered changes during the conception phase and this up to an advance point. The structural engineers where first a Mannheim engineering practice, Bräuer Spaech assisted by Professor Linkwitz of Stuggart University, who was in charge of expressing the geometry of the structure. Three months before the scheduled start of the construction the structural engineer team resigned from its position assuming that they could not deal with the complexity of this building and the contract was handed over to Ove Arup & Partners. At the stage Arup came into play there was only three weeks left before the tender of the roofs were due and there was little time left before the first members had to be sized. The engineering team had therefore to quickly take crucial design decisions. But despite this unexpected event and the difficulties the design team was put through, the building has been very successful and regardless of its initial two-year design life it is still in place and still accommodates expositions and congresses.

Here the main driving force for the choice of a grid shell as a structural scheme is the desire to follow the initial shape wanted by the architect and the lack of a more performing structural system.

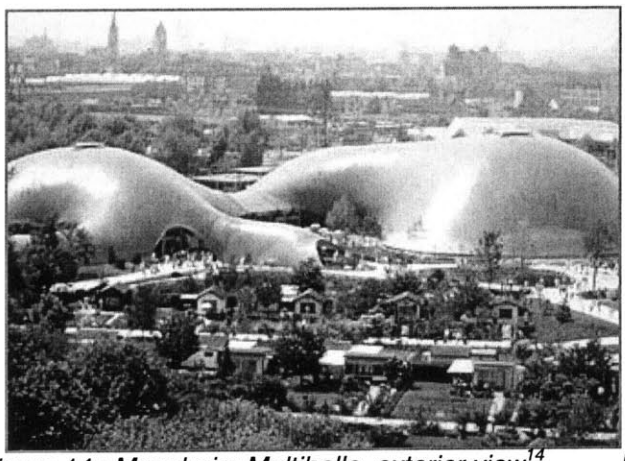

Figure 14 : Mannheim Multihalle, exterior view[14]

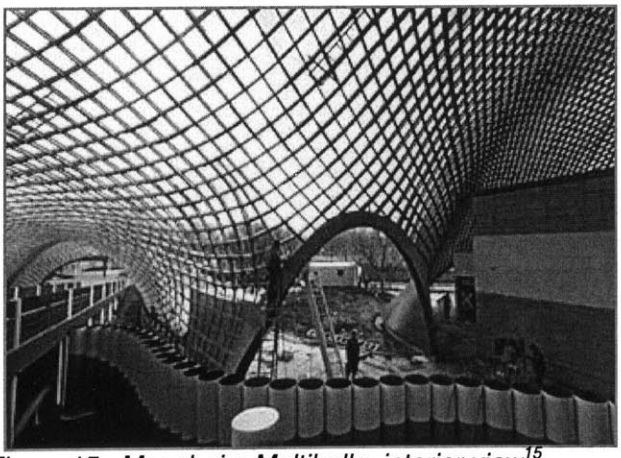

Figure 15 : Mannheim Multihalle, interior view[15]

[14] http://www.proholz.at/zuschnitt/19/gitterschale-mannheim.htm
[15] http://www.proholz.at/zuschnitt/19/gitterschale-mannheim.htm

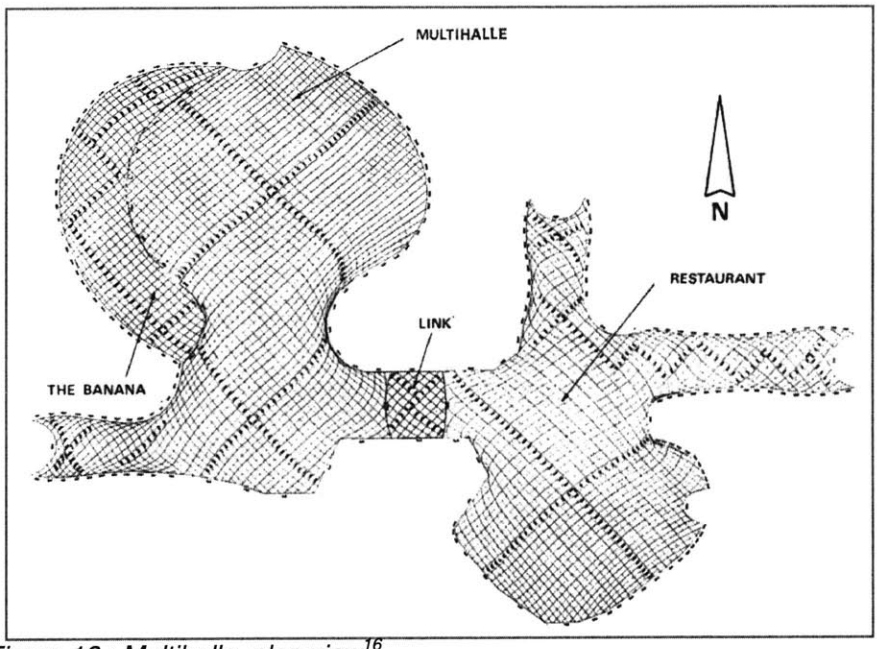

Figure 16 : Multihalle, plan view[16]

2.2.2 The Japan pavilion

Designed by the architect Shigeru Ban, known world wide for his work with paper to design both buildings and furniture, the Japan Pavilion for the "Exposition 2000 Trade Fair" in Hanover, this grid shell has the particularity of not being a timber grid shell but a paper grid shell. The theme of the Expo 2000 was "Humankind, Nature and Technology". Contrary to the Expositions of the beginning of the 19th century the main goal of the Expo was not to showcase the latest technical discoveries but to "show how humans and technology can exist with, and help improve the natural world", according to Expo 2000 director Birgit Breuel. Sticking to this spirit the Japan External Trade Organization selected this design that provide a column free exhibition space and that would entirely be made out of recycled and recyclable material. The design team for the Japanese Pavilion was composed of the architect Schigeru Ban, Professor Frei Otto as a project consultant, Buro Happold who was responsible for the structural design, along with Stefan Polonyi, a structural engineering professor.

The final design counted three elements: an entry zone, the exhibition space itself, and auxiliary office accommodation. The 35,000m² exhibition space displayed exhibits based on the

[16] The structural engineer 1975 N°3 vol 53

theme of making more efficient use of resources and reducing CO_2 gas emissions. The grid shell dimensions are summarized in Table 2 below.

The principle structure of the grid shell was made of paper-covered cardboard tubes. To abide by the German laws that forbade the use of paper only for the structure of a building, a secondary wooden structure had to be added. The paper structure, which was held together by a steel and fabric tape, was therefore connected to a series of timber arches stiffened by cables. The grid shell was assembled flat, and the erection process, taking a big advantage of the bending properties of cardboard tubes, took only three weeks. Once the structure was in place it was covered with a membrane fabricated from glass and fiber reinforced fire proof paper.

Length (m)	Width (m)	Height (m)	Total area (m^2)
72	35	15.5	3,600

Table 2 : Japan Pavilion summarized dimensions

The driving intentions for the conception of this building were sustainability and both technical and technological show casing.

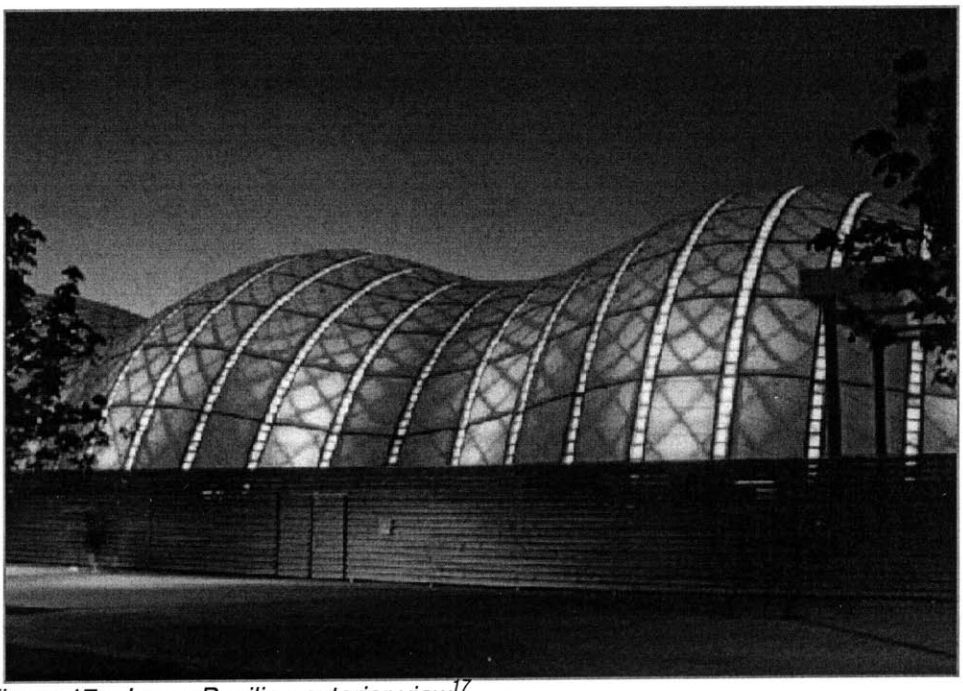

Figure 17 : Japan Pavilion exterior view[17]

[17] http://www.fboller.de/expo2000/

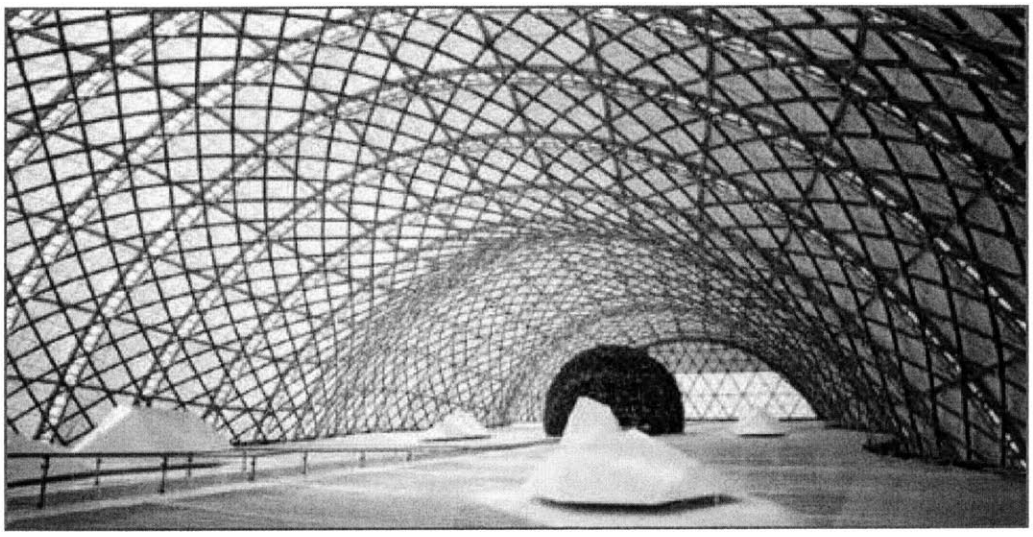

Figure 18 : Japan Pavilion, interior view[18]

2.2.3 The Weald and Downland Museum

Located in West Sussex, southern England, the Weald and Downland Open Air Museum is a leading international centre for the study and the conservation of historic timber frame buildings. The main concern of the museum is to preserve historic buildings from damage and demolition. Therefore the museum dismantles jeopardized buildings, collects them and restores them in its workshops. They are then reassembled and displayed on the museum's grounds. The project of a new building for the museum was driven by the need of a bigger workshop but also by the will of giving the opportunity to the public to assist to the restoration process. A space where artifacts could be stored and displayed to the public had also become a necessity. The architectural imperatives for the design of this building were that it had to reflect crafts and wood work but in an innovative and modern way.

Grid shell and more particularly timber grid shells were not unknown at this point as the Mulihalle and the Japan Pavilion already existed. The choice of a timber grid shell building seemed very adequate since the structure could clearly be seen from the interior – and to a certain point from the exterior as well – and since the innovative constraint was clearly part of this design. Moreover a grid shell enabled the architect to achieve very organic shapes, thus mirroring the valleys and mounts of the museum's grounds and integrating the building perfectly in the surrounding landscape.

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[18] http://www.designboom.com/history/ban_expo.html

The final shape of the grid shell is that of an "organic triple-bulb hourglass", whose properties are summarized in Table 3 below. The workshop area is located right underneath the grid shell, whereas the storage area is dug directly in the hill side thus providing natural stability and better conservation condition to the artifact collection. The grid shell is covered with a loose system of hanging wood plates (western red cedar) and glazing which provides natural lighting.

The design team was lead on this project by a British architectural practice, Edward Cullinan Architects, the structural engineering team was composed of members of Buro Happold that were thus able to benefit from the experience they had gained in the design of the Japan Pavilion. The grid shell design was clearly adopted here because of the political decision made by the directiors of the museum

Length (m)	Width (m)	Height (m)	Total area (m^2)
50	12.5 – 16	7.35 – 9.5	1800

Table 3 : Downland Museum, summarized dimensions

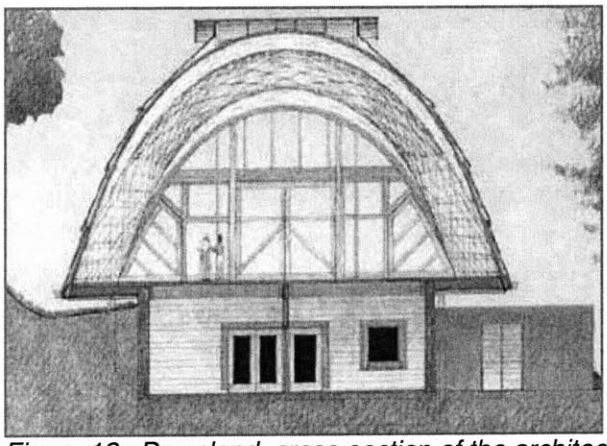

Figure 19 : Downland, cross section of the architect[19]

Figure 20 : Downland, interior view[20]

[19] The Royal Academy of Engineering publications, Ingenia, issue 18 February/ March 2004
[20] http://staff.bath.ac.uk/abscjkw/OrganicForms/HistoryPictures/

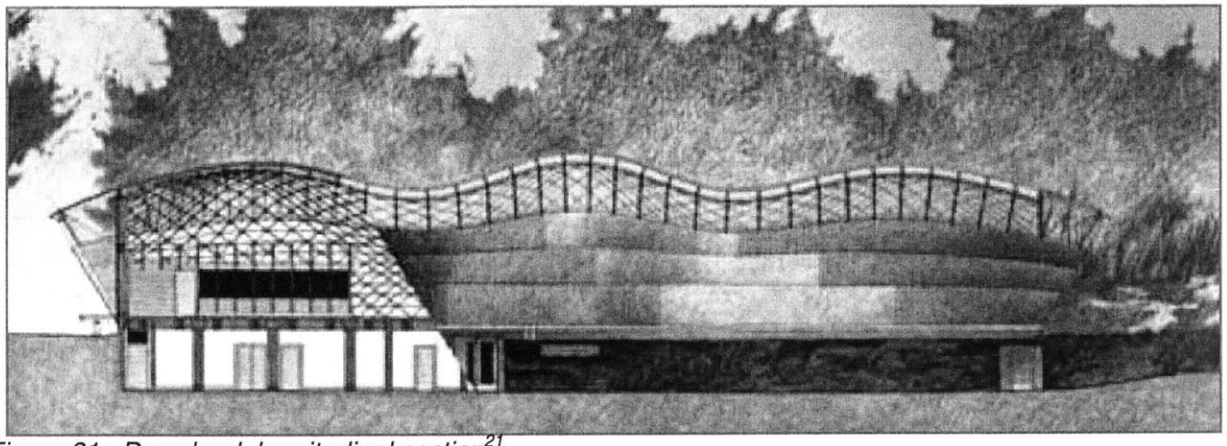

Figure 21 : Downland, longitudinal section[21]

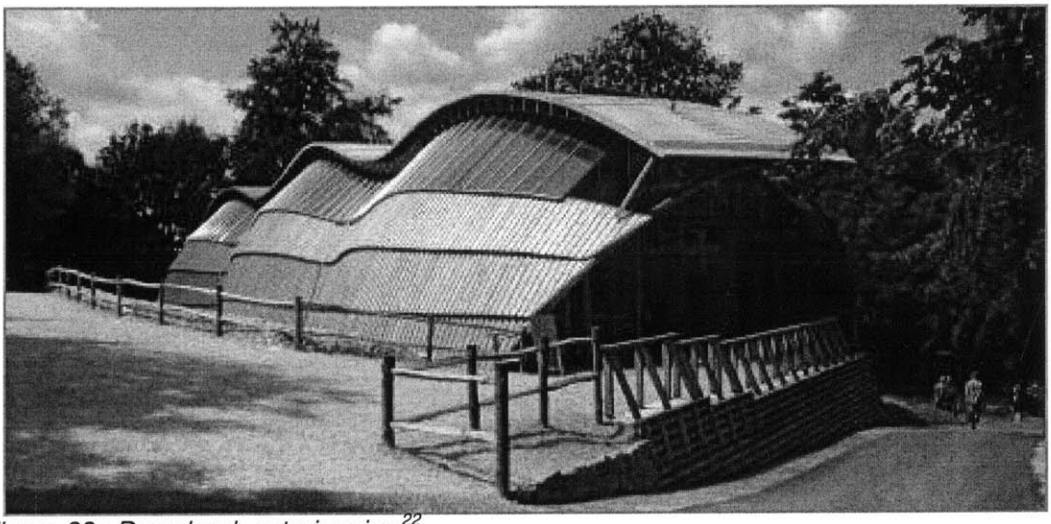

Figure 22 : Downland, exterior view[22]

2.3 The reason behind the choice of a grid shell structure

Tacking the example of the biggest and most famous grid shells described above, it appears that the choice of using a grid shell as a structural scheme can have various origins but is still based on a case by case decision making scheme. Contrary to typical building where the structural system is mostly driven by performance, efficiency and most of all by cost, in the case of grid shell it first begins with the architectural choice of a shape. In the three cases described previously the architects were interested most of all in the shape of the building, those buildings were one of a kind and were meant to be recognizable and characteristic of the city or the project they were designed for. In the case of the Mannheim Multihalle the timber grid shell

[21] The Royal Academy of Engineering publications, Ingenia, issue 18 February/ March 2004
[22] The Royal Academy of Engineering publications, Ingenia, issue 18 February/ March 2004

appeared to be the only feasible structure to achieve the chosen shape, the grid shell was a technical solution to an architectural problem.

Being a self supporting structure, a shell offers lots of possibilities and freedom regarding the design of the interior spaces of the building. The fact that no interior columns are needed is a real advantage for exposition and assembly spaces. The choice of a shell building has therefore to do with the intended use of the building, and this is a second choice factor.

The architectural pleasing and the practical efficiency of the form are inherent to shell structures. Deciding to choose a grid shell over a plain shell relies on several aspects. Weight is a determining criterion. Obviously being a discrete structure the weight of a grid shell is far less than the one of a plain structure. Moreover the openings completed in the shell to discretize the surface also provide daylight sources. The particularity of the erection of grid shells is also a reason of choosing a grid shell more than a plain shell.

The choice of a grid shell structure appears also to be a very political decision for the design team. The Downland Museum as well as the Japan Pavilion are very good examples where the choice of construction materials was as important as the structure itself. For the Museum, it was requested that the building be a sustainable one and that wood was the ideal material. The client thus did not only want a wooden structure but he also wanted to expose the wood. The grid shell was the ideal compromise between a show off structure and a sustainable building. For the Japan Pavilion sustainability was also an issue as it was the main focus of the exposition, the wish of using and therefore publicizing Shigeru Ban's discovery of paper tubes was also determinant. Once more a grid shell was a structure that permitted not only to use those tubes but also to display and broadcast their use.

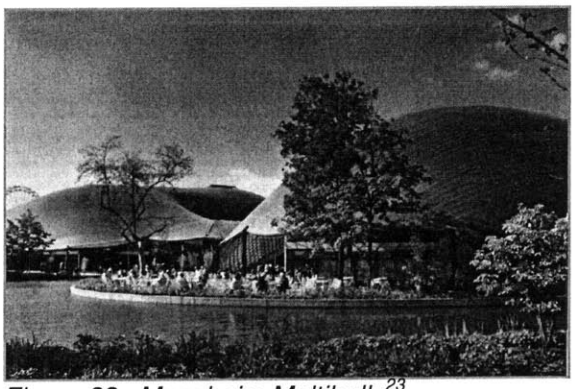

Figure 23 : Mannheim Multihalle[23]

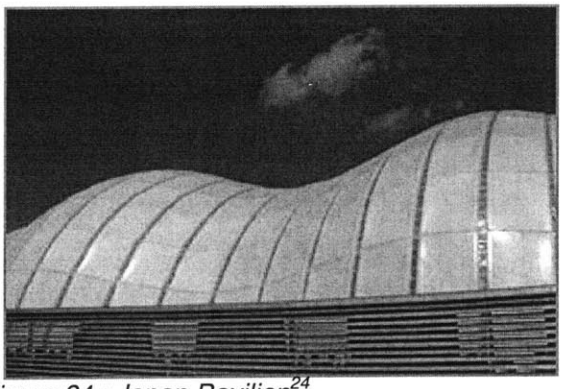

Figure 24 : Japan Pavilion[24]

[23] http://www.kunst.uni-stuttgart.de/wendland/progetti/mannheim/
[24] http://www.ashkeling.com/eu2000/hannover.html

Figure 25 : Downland grid shell[25]

2.4 Form finding process

After the choice of the overall shape of the building, form finding is the most important step in the design process. In the case of grid shell buildings, the structure and the skin (the global external shape and the appearance) of the building cannot be thought as separate entities, they are one and only element. In a typical design process, the shape of the building is optimized according to architectural considerations and only then is designed a structure capable of supporting this shape. In the case of grid shell both architecture and structure have to be optimized at the same time. The form finding method corresponds to this process. This step consists on finding the most efficient geometry that can both resist the external loading and meet the architect's requirements. This phase is crucial since the better material is used the better the structure performs which obviously leads to economical savings. Technical innovation and development can therefore be, during this phase, very meaningful and significantly impact the efficiency of the design.

2.4.1 An empiric method: Hanging chain model

2.4.1.1 Structural properties of hanging chains

Price is a determining factor to assess the constructability of a structure. Typically, price is closely related to the size of the members used, and the choice of the section of the members is related to the stresses in the members and the loads they have to resist. Bending moment is therefore an important quantity that has to be minimized in order to have the smallest section

[25] http://staff.bath.ac.uk/abscjkw/OrganicForms/HistoryPictures

possible. In fact for a given yield stress we have :

$$\sigma = \frac{M}{\frac{I}{v}} \quad \text{or} \quad I = \frac{M.v}{\sigma}$$

Moreover the inertia of a section is related to its size and shape, and therefore to the amount of material and the cost of the profile.

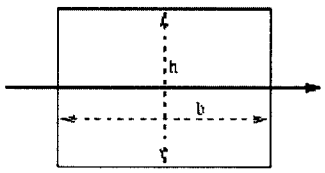	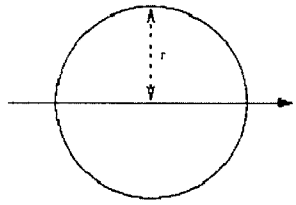	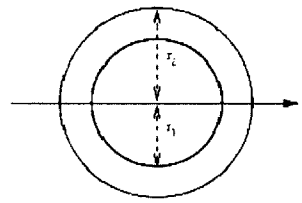
$I = \frac{B.h^3}{12}$	$I = \frac{\Pi.R^4}{4}$	$I = \frac{\Pi.}{4}.\left(r_2^{\,4} - r_1^{\,4}\right)$

Table 4 : Examples of moment of inertia for particular sections

Therefore the ideal shape to give to a member to optimize costs is one such as the bending moment in the member is zero. Given this, the ideal equation of an arch is : $y = \frac{M_0}{H}$, where M_0 is the Bending moment in the equivalent simply supported beam, and H is the horizontal thrust at the bases of the arch.

A way of easily determining the optimistic shape of a member is using a physical chain model. A chain, as a string, has no bending or shear rigidity, it therefore cannot carry bending moment. Pinned at both ends a chain thus takes a shape such as the bending moment along it is zero. This property of chains is very useful to determine easily the adequate shape of arches and even of surfaces.

2.4.1.2 The use of chain models to describe structures and surfaces

A chain, pinned or fixed at its end, takes naturally the most efficient form to carry the vertical loads applied to it. Submitted only to gravity loads, it takes a catenary shape, if additional loading is applied to it, it will deform and take the most adequate shape so that the bending moment is zero. To determine the most effective shape that has to be given to an arch the easiest method is to, knowing the loading the arch will have to resist, apply a scale version of this loading to a chain and flip the chain upside down. Adopting this shape the arch will resist loads only through geometric stiffness. As the arch acts in compression whereas the chain acts in tension buckling

issues that didn't exist in the chain model might appear in the arch model. Additional calculations shall therefore be lead to get the required rigidity and inertia needed to prevent buckling.

Using this method it is easy to get the right shape for a specific loading, but as can be guessed using the chain analogy, a given shape will certainly work only for a unique loading. And the fact is that a structure will never be subjected to a unique constant loading, the engineer has therefore to find a shape that would work for every loading the structure will be confronted to over its life time. This is to say that the final shape of the arch has to include all the chain curves corresponding to all the different loadings. In other words the thrust line has to stay inside the material repartition of the arch regardless of the loading state. The final shape of the arch will therefore be the envelope of the thrust lines corresponding to the different load cases.

The hanging chain technique can also be applied to the design of domes. A dome behaves in compression, it basically can be seen as a set of arches crossing at a unique point. Considering this, a physical dome model can be done by joining a set of chains at their middle point. Boundary conditions corresponding to the real life situation are given to the physical model and it is then studied under the possible loadings. This technique has long been used for the conception of the gothic cathedrals and more recently by the Spanish architect Antonio Gaudi in the design of the Segrada Famila in Barcelona.

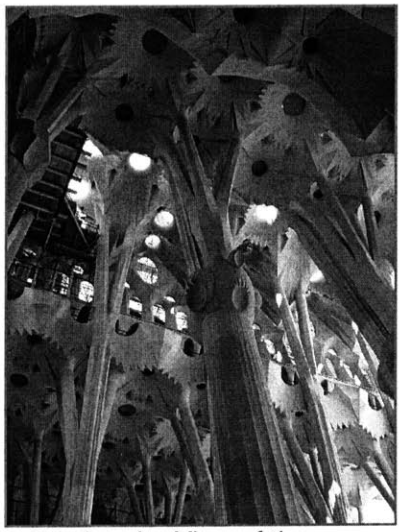

Figure 26 : Interior View of the Segrada Familia[26]

Figure 27 : Hanging chain model of the Segrada Familia[27]

[26] Photograph : Vali Nicaise
[27] www.lookingaround.free.fr

This technique can easily be extended to three dimensional surfaces. To achieve such a surface, a chain net is done by criss-crossing chains and hanging them at their extremities as well as at intermediate points. This way the architect/designer can study the behavior of the surface under different loadings, he can tune the surface by adapting the lengths of the members for example, so that it best adapts to the different load combinations. This physical approach enabled the designers to quite accurately study complex structures without using finite element programs that at the time this technique was used were not advanced enough to deal with such complicated geometry. Moreover this technique gives the chance to the architect who designs a building based on its structural behavior to make changes in the structure so that it both behaves well and suits his architectural tastes.

This technique is the one that was used to study and to define the structural shape of the first significant grid shell building which is the Manheim Multihalle. As no design tool powerful enough to study such a complex shape was available in the market, the choice of the chain model appeared to be the most adequate. The grid shell roof was modeled by a chain net and was hung in different places to match as accurately as possible the shape Frei Otto expected the building to have. Then, once the boundary conditions at the edge of the roof were set, the shape of the double curvature surface was optimized for all the possible load cases. As the building was meant to be a shell structure, no significant thickness could be given to the surface, the envelope thrust surfaces could not be selected as the final shape of the building. Therefore the shape selected was the one that could best handle all the possible load cases. This form selection process still implies that the structure has to be checked for buckling and also for the withstanding of non funicular loads.

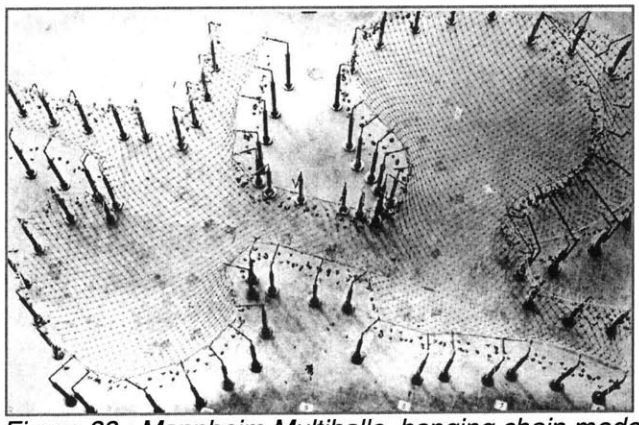

Figure 28 : Mannheim Multihalle, hanging chain model[28]

[28] The Structural Engineer, March 1975, N°3, Volume 53

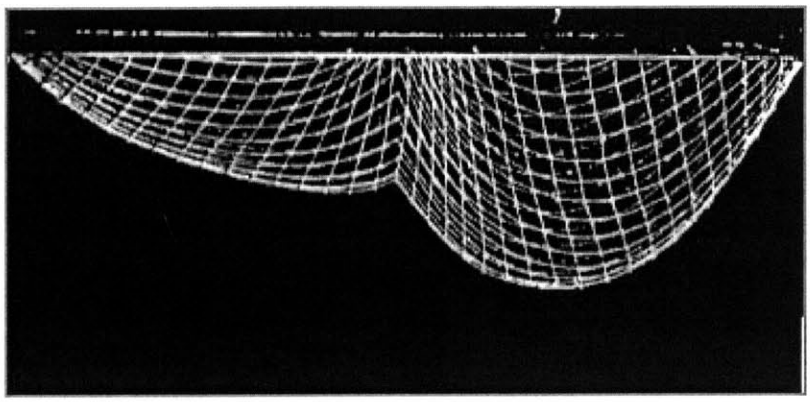

Figure 29 : Mannheim Multihalle, computer version of the hanging chain model[29]

2.4.1.3 From the hanging model to the actual building

Converting a hanging chain model to an actual building raises several issues. The first one is the way of communicating the information retained in the model to structural engineers and then to construction labors so that they can actually erect the building. The second challenge relies in the flipping process. It seems unavoidable that some adjustments have to be made to change an all tension structure (the chain model) into an all compression building which is the grid shell.

In the case of the Multihalle grid shell, stereo pictures of the model were taken by the architect. These pictures were then used as input data to a three dimensions computer model. Due to inherent inaccuracy in the taking of the pictures, this initial set of coordinates had to be modified and adjusted so that it could be used to perform a non liner analysis. For example, the members of the grid were not of constant length and some members appeared to be in compression (the photographs were taken of the suspended model before reversing it, so every member should be in tension). The computer model was therefore adjusted so that the members were of constant length and so that the structure was in equilibrium under its self weight.

This task was performed by the architect's practice and the numerical model was then passed over to the structural engineers so that they could size and check the members.

The hanging chain model still remains an uncompleted model, and building a shell with the exact same geometrical and member properties as the chain model would not ensure the

[29] The Structural Engineer, March 1975, N°3, Volume 53

stability of the building. This remains in the fact that on the inverted model, the gravity loads create tension forces in the members that increase the stiffness of the structure. The only remaining concern in such a tensioned structure is that the joints are of sufficient quality so that they can resist those forces. Contrary to the model, in the inverted grid shell, the gravity loads create compressive stresses in the structure, which instead of enhancing the stability of the shape, create instability and buckling concerns. The following step is thus to size the members so that they resist compressive loads and don't buckle.

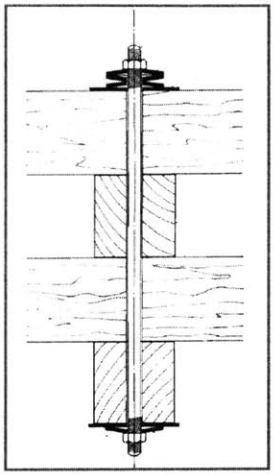

Figure 30 : connection detail of a double layer grid shell[30]

The calculated inertia needed for the structure to be stable appeared for all three grid shells examples, due to large spans and significant loadings, to be too big. In fact the members had to have dimensions that could still enable the member to be bent into place. The calculated inertias were yet too big to enable the bending process to happen. The structural engineers thus resorted to the use of double layer grid shell instead of single layer grid. Instead of being one deep lath, the members of the grid would be composed of two more slender laths placed one above another. Acting as the two flanges of a W shaped steel beam, the two laths would give the right moment of inertia to the member but would still be slender enough to be bent properly. In order for this concept to work properly, the two laths have to work together. In an W beam the flanges are connected by the web, even if shear stresses are not that big of a concern (the use of a full web is not required) shear has still to be shared between the two laths. The solution to this problem was given through the use of shear connecting blocks at the level of the connections, as will be discussed later. Those shear transferring elements are crucial since without them the situation would be similar to having two single layer grid shells on top of each other, neither of them being able to withstand its own self weight.

Once shear transfer is effective between the different layers, the last concern regarding the stability of the structure concern diagonal stiffness and the deformability of the cells. Even when the connections between the members have been turned into moment connections, which theoretically should ensure the stability of the shell, the cells are not guarantied to be

[30] The Structural Engineer, March 1975, N°3, Volume 53

undeformable. In fact triangulating the cells with braces is a necessity to ensure the stability of the grid, not under self weight, but under the asymmetric loading, such as wind loads for example.

2.4.2 The development of computer assisted techniques

Once the form of the building has been agreed upon, the following step is to give structural specifications to the members composing the structure. In other words the structure has to be studied under the different types of loading it will be subjected to and all the structural components have to be sized. This design phase implies a large set of calculations that cannot be done by hand and require the assistance of the computation power of computers.

At first the use of finite elements programs was restricted to the actual design of the members, the determination of their inertia and the checking of the structure first under its self weight then under external loading. In the case of the Mannheim grid shell and the Japan Pavilion, the selected shape was funicular and a chain model was very appropriate to define their geometry. However funicular shapes are appropriated for structure where the dominating load is self weight. This was the case of the Mannheim grid shell or the Japan Pavilion that had big spans. The design of the Downland grid shell was not governed by self weight (small span and light weight wood wladding) but by exterior solicitations such as wind and snow loads. The funicular model was not the most suitable scheme for the Downland Grid Shell, and a non funicular scheme was therefore adopted. Such a scheme could not use hanging chain model as a form finding technique, computer models were then the only technique that could be used to design the profile of the building. The use of softewares evolved and they became a form finding tool as well as a structural analysis instrument.

The computer program used to perform the analysis is based on the dynamique relaxation technique. This technique first approximates the shape of the structure then modifies this shape by monitoring the kinetic energy of the structure when making it oscillate. This technique commonly used in the design of tension structures. As the chosen design for the Doawnland grid shell was not a purely funicular structure the program had to be modified to allow the memebers to take compression and shear forces in addition to tension. The same program was also used to model the structure at different stage of formation during the erection process so as to determine the supports that were needed to ensure the stability of the grid at all times. The jacking supports were modelled by springs to account for the impact of the rising of the surface on the dynamic model.

Using a computer model to find the suitable form does not give immediately the right distribution of the members. During the analytical study a certain density of members is needed in order to accurately describe the surface, the grid pattern obtain to suit those needs might not necessarily correspond to an efficient repartition of material regarding the loads that have to be carried. A structural analysis, with the according computer model still needs to be performed. In fact it appeared in the case of the Mannheim Multihalle that in certain areas the final grid matched the form finding one, but that in others where stresses were less concentrated, every other line of the form finding grid was an actual member. The determination of the member location was done through an iterative process, several grids were tested and modified until all the members behaved well under loading. Several iterations lead to a lattice having 0.5m spacing in highly stressed strips and 1.0m spacing in more lightly loaded areas.

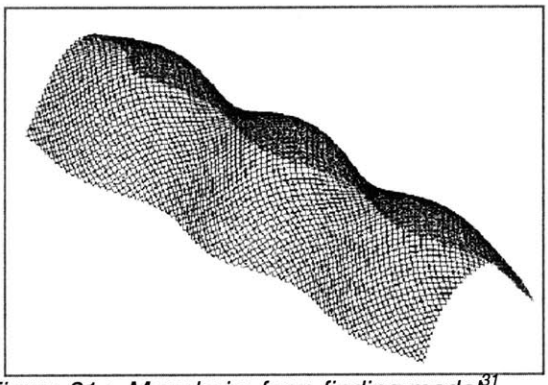

Figure 31 : Mannheim form finding model[31]

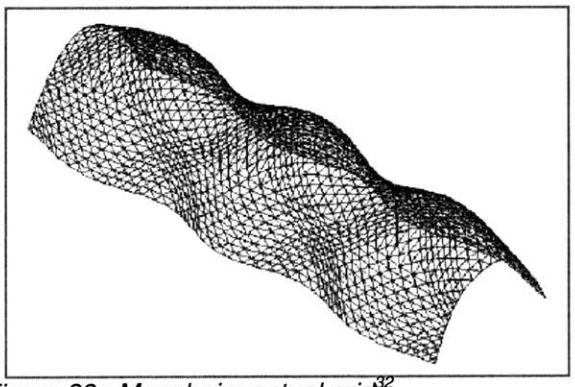

Figure 32 : Mannheim actual grid[32]

The computer model behaved well, however a physical model appeared to be a necessity in order to test the connections, the joints between the laths and to check how the timber members could be bent and how they actually react under tight radius of curvature. A 10m² grid was built to scale and tested. this step appeared to be very meaningful as it enabled to determine a joint failure rated and verify is the assumptions taken concerning the behaviour of the timber during the erection phase were correct.

Computer form finding is the only solution when the structure is not funicular. Even though the results appeared to be relevant and close to the actual grid pattern of the grid shell, this computer assisted process does not give results immediately like a suspended chain model and the use of such a tool also appears not to be as intuitive as the use of a chain model

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[31] Building Research & Information, Design and construction of the Downland Gridshell
[32] Building Research & Information, Design and construction of the Downland Gridshell

2.5 Construction techniques evolution

2.5.1 First method "upward" construction

The power of the grid shell as a design, and what makes it a very interesting structure is its erection scheme. As has been described previously, not only can a grid shell be erected quickly but the fact that the main connections are done on the ground and not up in the air is also a huge advantage.

The first method that has been used to "fold" the lattice mat into the final shape of the grid shell is one where exterior machinery (i.e. external forces) are used to push and lift the mat into its final form. This method follows the same scheme as the form finding process using hanging chains. The laths that have been laid flat on the ground and are lifted into shape, then boundary are set by fixing or hinging the edge members and then the connection between all the other members are tightened to give to the created surface its stiffness.

In the case of single layer lattice, the stiffness of the structure during erection is close to the expected one of the final structure, the grid shell is thus assumed to stay in place without any additional support as soon as the boundaries are set. Only minor modifications or adjustments might be needed in order to arrange the overall shape of the surface or slightly redistribute loads in order to minimize strain energy.

Now considering a multiple layer grid shell it cannot be assumed that once the edge of the shell are attached the structure will stand and will need only slight shape adjustments. In fact the reason why multiple layers are used is because the collapse load of the grid shell was close to, or even less than the self weight of a single lattice, additional layers are needed to provided the additional stiffness a unique layer was lacking. The temporary supports cannot therefore be removed before the connections between all layers are secured and that the composite action effectively occurs.

Different techniques can be adopted to pull the lattice from flat to doubly curved. The first one would be to pull the lattice at certain nodes from above, using cranes. The second one would be to push the lattice from underneath using cleverly located jacks and scaffolding. Those two procedures imply acting against the gravity forces and require additional checking of the structure. During the temporary state when the grid is being lifted and the boundary connections are not yet tighten, the members may be submitted to greater stress than the ones they have been designed for. Those additional stresses are due to intermediate stages where the radii of curvature of certain members are greater than the final ones but also to the extra bending

induced in the members between two lifting points. The choice of one scheme over the other needs to take into account parameters such as the size of the shell, the number of lifting points that would be needed in each scheme and the predicted duration of the erection (in order to quantify the price of the rent of the equipment). In the case of the Multihalle both schemes where studied.

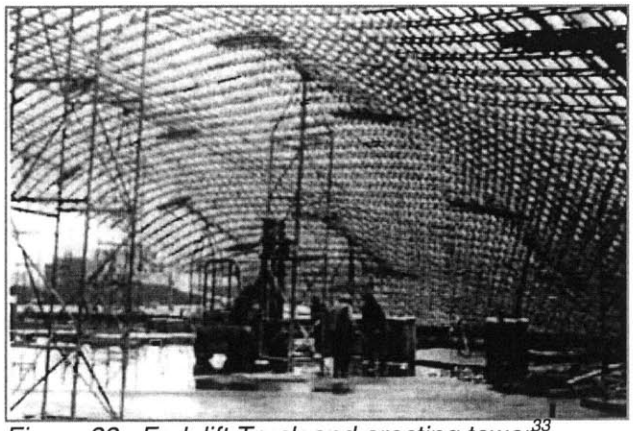

Figure 33 : Fork lift Truck and erecting tower[33]

Figure 34 : Detail of a H shaped spreader[34]

At first the erection was planed to use cranes. It appeared that for this proposal four 200 tons cranes capable of carrying 16 tons at a 40 meters radius would be necessary, as well as additional support at the edges of the grid. This scheme appeared to be extremely expensive since the cranes would have to be in place for at least three weeks. The second option was then investigated, and chosen. Having now lifting towers under the surface of the grid shell reduced the size of the needed equipment, but raised an additional issue. The grid shell acting on the tower brought up stability concerns for the scaffolding towers. The solution was found in the addition of a H-shaped spreader to the scaffolding tower that would distribute the lifting force to more than one node and stabilize the tower. The towers were mechanically jacked up while another vertical element was added to the tower. As the towers were lifted, some of them had to be slightly moved to allow for the changes of shape of the lattice. Combining both lifting and lateral movement, fork lift trucks were chosen to jack up the towers as these pieces of equipment would also be heavy enough to control the movement at the base of the towers. Figure 33 above shows a view of the erecting tower supported by a fork lift truck, while Figure 34 shows a detail of the H spreader. The connection between the top of the tower and the spreader is a ball joints that allows the rotation of the spreader according to the orientation of the

[33] The Structural Engineer, March 1975, N°3, Volume 53
[34] The Structural Engineer, March 1975, N°3, Volume 53

surface. The tower therefore provides only the vertical support needed and does not constraint the forming of the double curvature surface.

2.5.2 Second method, "downward" construction

With the construction of the Downland grid shell a significant innovation in the construction process of the structure was made. The big difficulty in the typical construction sequence was to push the shell into form. Energy had to be put in the erection process to act against gravity loads. The bigger the grid shell, the larger are the forces needed to counteract the self weight of the grid shell. Moreover the process of pushing up on discrete nodes concentrated stresses in particular areas which resulted in a number of connection breakage. Rather than acting against gravity it was decided to take advantage of this force. The solution was to start the erection process at heights rather than from ground level and to use gravity as the forming forces.

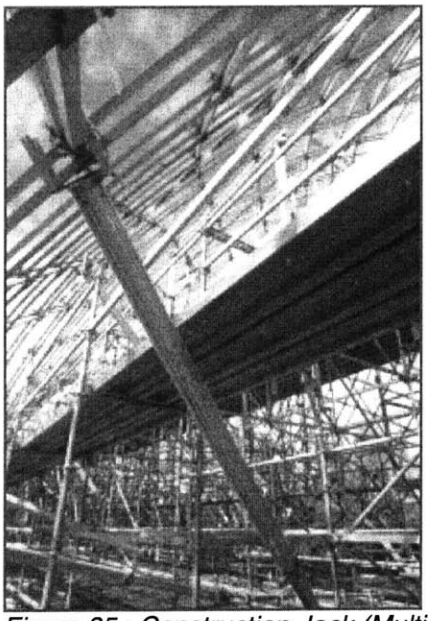

Figure 35 : Construction Jack (Multi prop)[35]

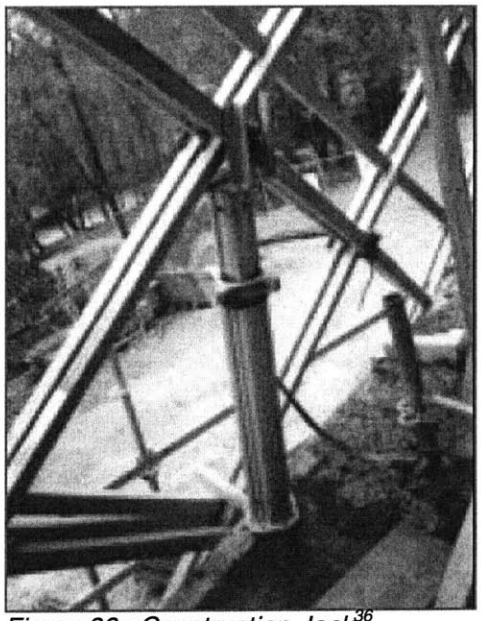

Figure 36 : Construction Jack[36]

The surface of the Downland grid shell counts three crowns and two valleys; it was decided that the domes would be formed by letting the grid simply fall into position, and that external forces would be used only to form the three tops. The laying-out platform would thus be elevated at the height of the valleys and instead of being pulled in position the grid shell would be lowered into place. In order to put as less stress as possible into the members during the forming process it was decided to have the forming of both valleys and tops occur at the same time, this

[35] The Structural Engineer, Volume 79, No 17, 4 September 2001
[36] The Structural Engineer, Volume 79, No 17, 4 September 2001

would be more effecting than for example forming the shell into a cylinder and then squeezing it where the valleys were meant to be.

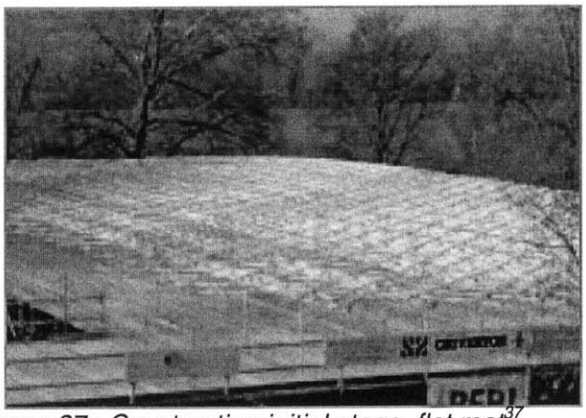

Figure 37 : Construction initial stage, flat mat[37]

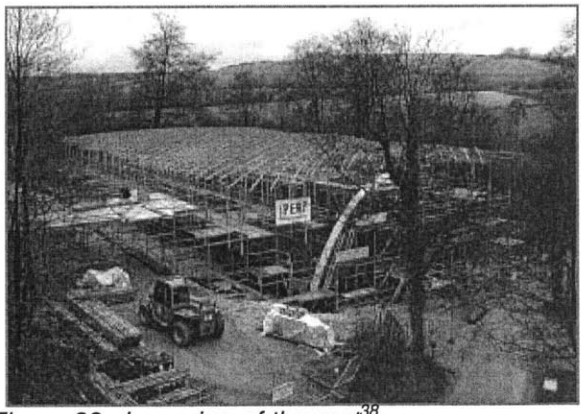

Figure 38 : Lowering of the mat[38]

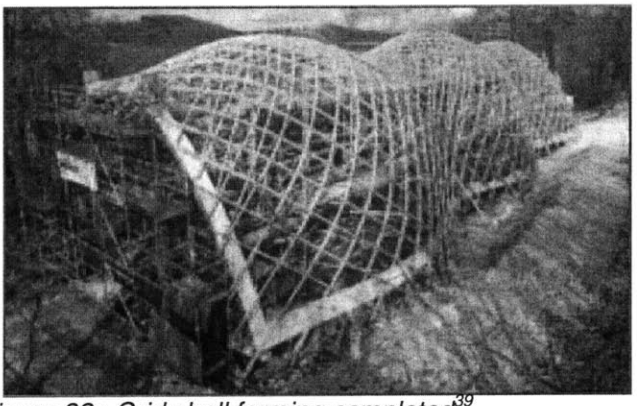

Figure 39 : Grid shell forming completed[39]

2.5.3 Evolution of the design of the connections

The erection process of the grid shell entirely relies on the quality of the nodes. The nodes must, during the erection process, be able to allow rotation in all directions while staying in a specific position along the member, and at the final stage be transformed into moment connections.

While designing such connections is quite straight forward for a single layer grid shell, a single bolt, let loose during the construction and tighten "snug tight" at the final stage is enough, it is not as easy for a multi layer grid shell such as the ones that have become more widely used.

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[37] The Structural Engineer, Volume 79, No 17, 4 September 2001
[38] The Royal Academy of Engineering publications, Ingenia, issue 18 February/ March 2004
[39] The Structural Engineer, Volume 79, No 17, 4 September 2001

In the case of a double layer grid shell, four members end up crossing each other at a given node. In addition to having to join those four members, the connections must also allow the two layers to slide one on top of another since inner and outer layers do not have the same radius of curvature. In addition to these constraints, the connections must also enable vertical shear to be transferred between the two layers, the two layers would be acting separately. In fact not being able to transfer this shear renders the use of a multi layer scheme useless. Shear is thus transfer through connecting blocks that are added between the members of the different layers. Those wooden blocks enable to have a continuity of material at the level of the connections and thus a path for the stresses to follow.

The first connection scheme that was proposed was for the Mannheim Multihalle. This connection featured slotted holes in the two outermost layers, the two inner layers having only a simple hole through them and a bolt would go through the two holes and the two slots. The holes in the inner layer would ensure that the node is at the right place along the member, while the slots would allow the sliding of the outer layer to happen. This connection performed pretty well during the erection, but they were not ideal considering load resistance. In fact as the structure is designed to take axial loads, the cross section area is a critical dimension, so not only is carving slots in the members a time consuming process but is also diminishes the resistance of the members and of the structure.

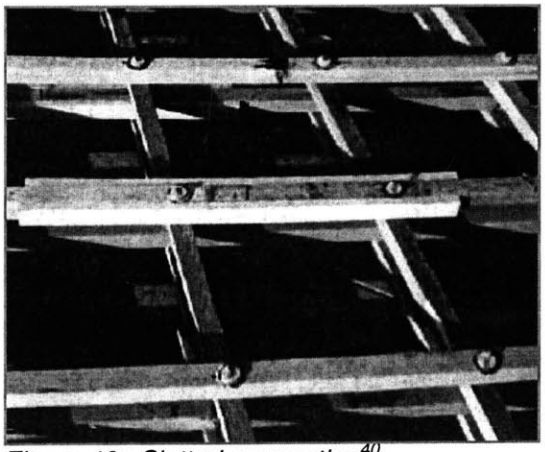

Figure 40 : Slotted connection[40]

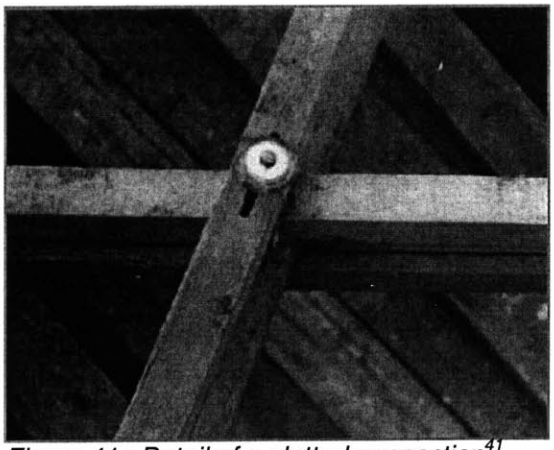

Figure 41 : Detail of a slotted connection[41]

And alternative to this loss of axial strength was proposed with the Downland grid shell, the principle was to have a connection that would not penetrate the members. This was achieved

[40] The Structural Engineer, March 1975, N°3, Volume 53
[41] The Structural Engineer, March 1975, N°3, Volume 53

with the use of three steel plates that clamped the members together. Two plates would be placed respectively below and on top of the joint, four bolts –one at each corner of the plate- would be kept loose to allow for the rotation and the slidding of the members and would then be fastened to create a moment connection. This scheme could work perfectly excepted that there is no way to assure that the node will stay in place and won't slide along the member, this is why a third plate is inserted between the two layers. A pin would be placed through the third plate with its only goal being to fix the location of the joint. This scheme was developed and patterned by Buro Happold .

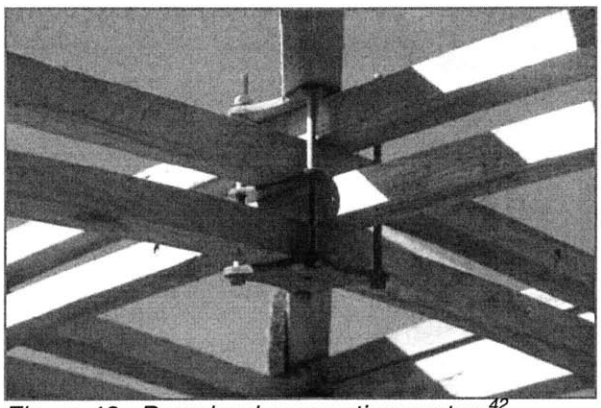

Figure 42 : Downland connection system[42]

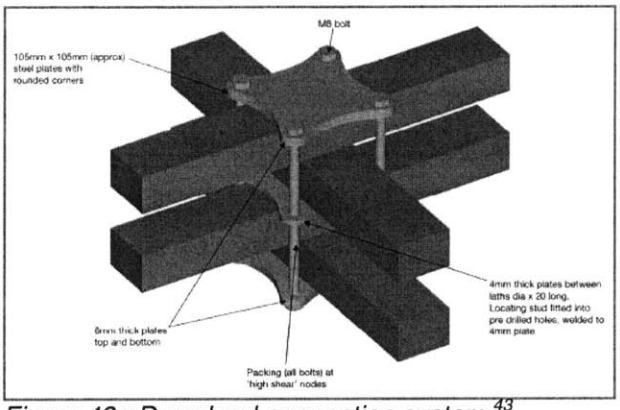

Figure 43 : Downland connection system [43]

The connection scheme chosen for the Japan Pavilion are also worth mentioning. Matching the uniqueness of this paper tube structure, the connections are very unusual and specific to this design. The connection were made of metal reinforced fabric tape, and inspired of traditional bamboo construction.

Figure 44 :Japan Pavilion temporary connection [44]

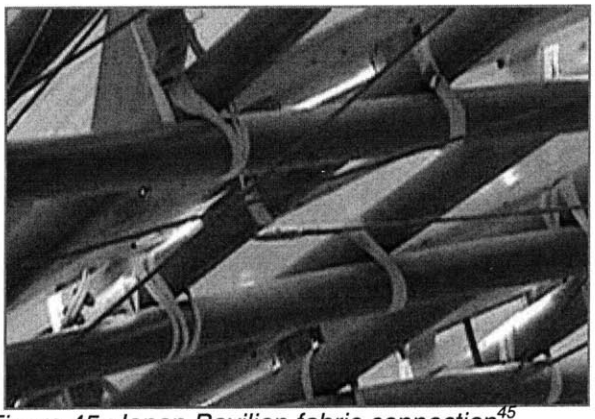

Figure 45 :Japan Pavilion fabric connection[45]

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[42] Building Research & Information, Design and construction of the Downland Gridshell
[43] Building Research & Information, Design and construction of the Downland Gridshell
[44] http://www.ashkeling.com/eu2000/hannover.html
[45] http://www.ashkeling.com/eu2000/hannover.html

2.5.4 Conclusion : A structure not widely used

The design of grid shells structures both in the form finding process and in the prediction behavior of the building under operation appears to be a complex process. Contrary to other more common structural systems no design guide lines exist and no tools have been developed specially for their study. As has been developed the design method used greatly depends on the project itself and until now the structural engineers have resorted to home made design techniques such as chain form finding and the construction of scale models to test in real condition the behavior of their design.

The fact is, that the lack of expertise in this field is a hindrance to the further development of grid shells. In fact one of the common points between the major grid shells is that the structural engineer company on the design team was either Buro Happold or Arup Ove Partners. The boldness of structural engineers has its limit concerning innovation. Since grid shells are very unique and since no guides or no design and construction recommendation exist regarding these buildings, only big practices with the knowledge and research back up available have agreed to take part in this adventure. Designing a grid shell really requires more than design ability, it also requires for example the financial security to launch research or tests. The development of the new connection patent for the Downland Grid Shell was a costly decision to take from Buro Happold. Not all structural companies can afford spending so much time money and effort in one project, and not all companies are confident enough to start a project with no technical back up.

It may be the lack of wide spread expertise, the fact that all the knowledge is gathered in the hands of only two engineering firms, the fact that for this construction, wood is the favored material and that it doesn't suits the tastes of the client, but the fact is that in the last fifty years as few as only three significant grid shell have been built world wide.

3 The future of grid shells

Intro very efficient structure, architecturally pleasing architects have got a taste for these structures. is there a reason why we would like to have the design evolve?

Perennity of wood?

Wood cannot carry as big a load as metal for example, and as these structures are really getting to be liked by architect there are becoming more and more popular so more widely used and they might require bigger spans, become also very popular to enclose court yards.

3.1 Development of more performing software

3.1.1 From a design stand point

The main element that prevents the construction of grid shell to develop and to expand worldwide is the lack of adequate tools that confine the design expertise into very few hands. Current finite element design software, even though they can be very powerful, are not appropriate enough to the design of grid shell. The crucial step in grid shell design is the form finding process. Actual programs are not designed to incorporate this stage. An ideal program would be one in which there was no need to remodel the structure to test for a different shape. Pushing this a little further, an ideal program would be one that could in the same way a physical model does, adapt the shape of the model to the loading it is subjected to. Current finite element programs do not have this artificial intelligence to propose solutions to the structural problem they high light, and the form finding process reduces to iterative testing of hand input models. Moreover the calculation performances of very efficient programs can sometime not fully be used because of the lack of user friendly interface. In actual programs, inputting data is a lengthy and uninteresting process. In the same way retrieving results information from the program can be long and confusing. Improving the user interface of finite element programs will, even if they

are not at first place adapted to the structural particularities of grid shells, provide structural engineers with a more handy tool where the results will be easily available. This would enhance the confidence of small companies which would then spread the grid shell knowledge amongst the practices. There is no doubt that for grid shell buildings to develop, the number of engineer capable of designing them has to increase first and this is tightly linked to the performance of their tools.

But the design team being not only restricted to the structural engineering part of the process, the design softwares have to become multidisciplinary and enable the different parts of the design (from architectural design to member sizing) to happen using the same computer program. Having all the parties using the same tool will allow a much better understanding between the different teams, and will also enable to spare time and mistakes in information communication, as will be developed in the following section.

3.1.2 From a construction point of view

The ultimate goal of a building is to be constructed. Even if a building is completely well defined architecturally and structurally, the work of the designers has to be past on to the contractor so that the building can actually take life. In a typical building the way information is past from the design team to the contractor is by the use of two dimension plans. A grid shell is in essence a three dimensional structure, it cannot be reduced to a two dimension space without loosing accuracy. Even by multiplying the number of plan views, of elevation, of cuts, the information will always be incompletely transferred. In the case of the Multihalle, all the design of the structure, from the specification of the overall geometry to the investigation of member properties and connection details, was done by the structural engineers, owing to the complexity of the structure the contractor was not at all involved in the detailing as it is often the case in typical buildings. All these specifications were done using the computer model they had developed. The first task was thus to try to find the most efficient way to convert a three dimension model into a two dimension plan without losing too much information. The engineers found themselves having to write geometric computer codes to produce the fabrication drawings. But as the contractor was not involved in this process he did not fully understand the system used to define geometry which led to some errors.

To deal with such complex structure it is essential to develop a communication scheme that would enable both designers (architects, engineers) and contractors to communicate and understand each other easily. Frank O. Gehry, American architect of the Guggenheim museum in Bilbao, the Disney Concert Hall in Los Angeles or the Stata Center at MIT, has been for

several decades using the software Catia to model his buildings. Catia is a program developed by the aerospace industry that enables the description and the study of three dimensional surfaces. Even though this program suits well the need of an architect looking for complicated shapes and curves, this program has been optimized for the aircraft industry not for structural engineering and construction. Developing a sort of "Catia-Construction" program would be of great help for the design of typical three dimensional buildings and most specifically therefore of grid shells.

To be powerful such a program should have several levels of use according to the phase of the design it is used for. There should be at least three levels:

- architect level, where the main focus is on geometry and shape
- engineer level, where the behavior of the shape selected by the architect is studied, adjusted, changed
- contractor level, focused on the production and the construction of the structure it would be more concerned on dimensions and details

In the case where every design step can be thought in three dimensions, the design process has clearly become more efficient, first because no information is lost inbetween the phases and secondly because the three main entities think in the same way, the communication barrier will thus have been erased.

However an issue still remains. Once the information has gone all the way to the contractor it still has to be transferred on site to the workers, and a job site is obviously not the right place to have a computer station and it is even less conceivable to imagine each workers with his laptop moving around the job site. However if, thanks to the new grid shell oriented program, the members have been well defined, well produced the assembly work needed to be done by the construction worker will be simplified. Surely an information cession at the beginning of each day will be enough to clarify how the structure is assembled and give much more sense to normal two dimensional construction drawings.

3.2 The use of new materials

3.2.1 Structural problem related to wood construction

Until now the material dedicated to the construction of grid shells has been timber. Because of its light weight, because it is a natural and sustainable material and most of all because of its

bending capacity that allowed a very efficient erection scheme to be developed, wood has been the material on which designers have been focusing. With the development of grid shell structures the interest in these structural systems has been growing amongst the architect community. Not only are they structurally very efficient, but they also provide a great flexibility to interior design by providing a column free space and they also are without any doubt from an architectural stand point very aesthetically pleasing structures. The will of bringing grid shells one step further in their use has pushed timber to the edge of its capacities.

Wood is an organic material, and if it can have significantly different properties depending on the specie considered, its characteristics can also change and be degraded throughout its life time. The deterioration that wood can undergo can be divided in two main categories, moisture related degradation and mechanical degradations, or in other words degradation due to their use as a structural material.

3.2.1.1 Wood degradation, lose of structural integrity

Wood is a hygroscopic material which means that it naturally takes water from the exterior or releases water in order to balance the moisture level with the surrounding environment. This ability to store and release water conducts wood to shrink or expand according to its moisture level, moreover wood being able to store large quantities of water is also subjected to fungi infection and related decay. Many species of fungi exist amongst which we can find most of the mushrooms, the fungi that are discussed here are wood parasites since they develop in wood and feed upon it.

The level of moisture in timber is characterized by two indicators the moisture content and the fiber saturation. Moisture content characterizes the quantity of water retained in the wood as a ratio between the weight of the enclosed water and the total weight of the wood. Typically a timber member is considered to be dry when it has a moisture content of 19%. The fiber saturation characterizes a moisture content above which any additional water is stored in wood as in a reservoir, wood fibers act as water tanks.

Fibers are long hollow cells. When water is absorbed in wood it is first stored in the walls of the fibers, then when the walls have reached their saturation level, which is the fiber saturation, water is stored in the cavities of the fiber cells. The water contained in the walls is called bounded water, and the one stored in the cavity is free water. The development of fungi bacteria cannot be started without accessible water. Since the only available water for those bacteria is free water, the fungi induced decay cannot be initialized below fiber saturation. On the other

hand the shrinkage and swelling of wood is related only to bound water. Once the walls of the cells are saturated they cannot expand anymore and the wood structure is not affected.

Below fiber saturation the main concern regarding the preservation of wood is expansion and shrinkage. This natural behavior of wood may lead to crack formation. When wood dries a moisture gradient is developed across the section and induces stress. The outer shell tends to shrink as it dries below fiber saturation whereas the inner core, still wet, prevents this movement. This causes cracks to occur on the wood surface. At the time the inner core starts to dry, the perimeter shell has already settled in dimensions and now constraints the shrinkage of the core which causes the cracks to propagate from the surface to the core. Cracks can also be created in the same way by changes in temperature. The cracks do not propagate from the surface to the interior but from one side of the member to the other. The side where the temperature is higher tends to shrink whereas the cooler side provides constraints to this shortening.

Above fiber saturation expansion of wood is less of an issue, now the main problem is fungi decay. The wood-inhabiting fungi can be separated into moulds, stainers, soft-rot fungi and wood-rotting basidiomycetes. Molds grow on the surface of wood with little effect and can be easily removed; staining fungi penetrate the cellular structure damaging cell contents and walls, reducing strength and stiffness; and decaying fungi can significantly reduce wood's strength by penetrating its cellular structure, and can destroy its chemical composition by consuming cell contents. Wood affected by some decaying fungi will lose structural strength before the decay is even visibly evident. Moreover certain fungi also attract some insect species (termite, carpenter ants, beetles...). The females lay their eggs in the wood, once the eggs have hatched the larvae feed on wood creating voids and significantly reducing the strength of the material.

A number of treatments exist to medicate the degradation processes of wood described. These treatments include coating, chemical treatment, special drying techniques, but still these possibilities of damage cannot be totally eradicated and a high level of maintenance is required to ensure the perenity of the structure.

3.2.1.2 Structural issue related to the use if wood

In addition to natural degradation wood has also mechanical limitations to its use in construction. First of all the yield strength of wood is far lower than that of materials such as steel or concrete. Therefore wood cannot carry heavy loads. However the bigger the spans become the larger the self weight of the structure is. Dead load is also increased by the type of cladding chosen, the loads of a grid shell entirely cladded with glass will be much too large for

timber construction, whereas steel for example might be much more suitable. Load is the first limitation, the second one concerns the connection details. Connecting to pieces of wood necessarily involve an additional component. In construction steel connections or glue type connections are the most commonly used. Whatever technique is chosen, connecting points are the weakest areas in a wooden structure. Loads will never be transferred through composite connections as well as through the equivalent timber member made out of a unique piece as can be achieved in steel construction by welding the two pieces together. The last concern regarding wood construction is the great heterogeneity of mechanical properties between different species, different trees of the same specie and also along the same log. Imperfections like knots, splits or shakes result in zones of concentration of stresses and in the impossibility of fully using the wood capacity. Managing to obtain the required amount of wood laths of same (and high) quality is a troublesome process and has the risk of seeing weaker elements installed.

3.2.1.3 Timber replacement in future grid shells

Possible long term degradation, load carrying limitation, weakness of joint manufacture, hassle of finding wood of even quality, are as many reasons to look for other materials that could be used to medicate these issues in grid shell construction.

Two different development paths will be described in the following section, the first one leading to heavier structures, the second one investigating the possibility of even lighter structures than timber grid shells. Being a heavier material and one capable of supporting larger loads than timber, steel can become an appropriate material to create larger and more heavily cladded grid shell buildings. On the second hand the use of composite material to create very light grid shells seems very feasible. In fact, composite materials have a large elastic deformation capacity before yielding they can thus easily be bent and be used in the construction process so specific to timber grid shells.

3.2.2 The use of steel for high weight grid shell

3.2.2.1 The use of mechanical properties of steel

Compared to wood, steel has a much higher yielding strength, it can therefore once installed carry much larger loads. Glass is ten times heavier than wood and hundred time heavier than the fabric that was used to cover the Mannheim Multihalle, it is obvious that timber members could not carry these loads, this combined with greater spans or smaller radii of curvature (thus reducing the geometric stiffness of the grid shell) makes steel an excellent

candidate to replacing wood in higher weight grid shells. However in terms of flexural behavior, steel cannot be bend as easily as wood. To achieve a radius of curvature typically found in timber grid shells with a steel member, the necessary energy for this process would be enormous. In addition to the great force that will be involved in this bending process, when timber would relax in a less bended shape when its radius of curvature is greater during the construction process, a steel member would in the same situation be definitively deformed.

3.2.2.2 A different erection scheme

The higher rigidity of steel, though it is this characteristic that would enable steel grid shells to carry loads prevents grid shells to be erected in the same manner timber grid shells were. It would be impossible to deform a mat made of big steel members to give it the shape of an equivalent steel Downland grid shell for example. Steel members will thus have to be prefabricated in steel plants before being brought to the construction site. This huge difference of erection scheme brings both advantages and drawbacks.

First if members need to be prefabricated, their size and geometry must be perfectly defined, which needed not be the case in timber construction. In fact once the model was set and verified the only geometrical parameters that were needed for the construction were the total length of the members and the location of the connections. The final deformed shape of the timber laths was not a concern because it was sure that once the two extremities were at the required location the member in between would take the adequate shape. Moreover in grid shell fabrication, standardization is impossible. Every member would have to be bent and shaped as a unique piece. For the forming of the steel members to be an easy process a design software enabling easy information transfer between the design team and the steel contractor, as described previously, would be of great help. Once the design is set the program would be able to give all the geometric properties of a member joining two connection points. By connecting such a program to the automated member forming chain, the issues related to the uniqueness of each member will be very much attenuated. On the other hand, having predefined members will assure that, during construction, there is no deviation between the actual location of the connections and their desired sets of coordinates. In addition to providing a shape guarantee, steel construction enables to make easier connections. First, steel to steel connections are much safer than timber to timber connections since the two pieces blend into each other rather than being maintain in place by an exterior device. Secondly the connections can also be according to the adopted scheme prefabricated in the steel plant. A possible connection scheme would be to have a quadruple socket in which the steel members would be inserted. The socket would

then be secured by the use of bolts or welding. This construction scheme, in addition to being easily achieved on site, will also assure that the members are well oriented.

3.2.2.3 Norwich Union Headquarters grid shell

The refurbishment of Norwich Union Headquarters, completed in 2006, explores the concept of grid shell structure using steel as the structural material. This project features a doubly curved steel and glass grid shell spanning forty meters in the main direction, thirty meters in the shortest one and covering the courtyard between four existing buildings. An interesting feature of this design is due to the fact that the four existing buildings being historical buildings they couldn't serve as supports for this additional steel roof. The grid shell is meant to serve only as a roof, not as the envelope of an entire building. The radius of curvature of this grid shell is therefore much larger than the one of the Downland grid shell for example. The grid shell not reaching down to the ground additional supports were needed to hold the grid roof at the desired height. Those supports were provided by four tree like columns and a truss beam running all around the shell at its perimeter. The role of this outer beam is to restrain the forces developed by the grid shell wanting to push back into a flat mat shape. As the support is in this case not provided by the ground, additional care had to be given to the design of the supports of the roof. The tree columns are, as can be seen in Figure 47, composed of two main parts, the vertical "trunk" is made of a vertical steel truss on which are fixed the three steel branches of the tree. Those inclined tube columns support three structurally week points of the gutter beam, the first one supports the corner of the grid, while the second and third columns support respectively the middle point of the shortest span and a point on the long side of the roof where the bending moment is important. Those columns are each placed near the corner of the roof.

The spread of the grid shell is resisted both by the moment connections between the members of the grid shell and the belt action of the outer gutter truss. Lateral stability is provided by the belt beam as well as by two existing buildings. Even if those two buildings couldn't be used as a base (ie foundation support) to the grid shell they could be used as lateral constraints (ie acting as a wall against which the grid could lean).

The grid shell itself is composed of circular hollow steel sections the thickness of which ranges from six millimeters at the crown of the grid to thirty millimeters in the corners. To insure the closing of the building and the sealing of the glass skin, relative motion between steel frame and the glass cladding was limited by not fixing the glass panels directly to the steel skeleton but to an aluminum pattern placed on top of and attached to the steel grid shell. The aluminum framing was calculated in order to ensure that the glass panels would perfectly match. Having

the glass supports independent from the structural steel enables eventual deformations or inaccuracies of the steel grid shell to be absorbed in the design.

Figure 46 : Norwich court yard Interior view[46]

Figure 47 :Norwich Court yard roof[47]

3.2.3 Using composite materials for extremely light grid shells

3.2.3.1 Composite material

A composite material is by definition any material obtained by the physical assembly of two components of different mechanical properties. In the resulting product the two (or more) components can still be identified, no melting or blending between the components has occurred,

[46] Structural Engineer, February 2007 issue 17, volume 84
[47] http://www.fabermaunsell.com/NewsMedia/46/71/index.jsp

but the composite displays physical properties that are a combination of the mechanical properties of each component. Typically materials have a preferred working mode. They cannot behave as well under all kind of stresses, for example pure concrete behaves very well in compression but is a very week material in tension. Composite materials have been developed in order to medicate this load specificity of material behavior. Two or more materials are combined to take advantage of the mechanical properties of each of them. This is how reinforced concrete was invented.

The same concept has been adapted to the plastic industry. Because of their very efficient weight to strength ratio, the big variety of appearance they can have (transparent, opaque, colored) and the fact that they can be very easily formed into a great variety of shapes without any size or length restriction, Glass Fiber Reinforced Polyester (GFRP) has become the most popular reinforced plastic material in the construction industry.

Usually composite plastics will consist of two separate components, the matrix (continuous phase) and the filler (typically the reinforcing fibers). The matrix does not provide strength to the material but it serves to hold the fibers together to form the bulk of the material and to transfer the loads to the reinforcing phase. Typically formed of various epoxy type polymer (and also counting several additives to prevent the early curing and to give to the composite its final aspect), the raw material of the matrix comes in as a viscous syrupy liquid. The fiber reinforcement and an initiator (to get the chemical bonding reaction between the two phases started) are then added to the matrix and the desired shape is achieved. The curing process results in cross linking of the polyester chains of the matrix and the formation of the final material. The rigid solid material in which matrix and filler have bonded both mechanically and chemically displays mechanical properties far different and also far superior to the ones of either component taken alone.

In a GFRP, strength comes from the glass reinforcement. Reinforcement is provided in bundles of fibers or filaments combined in strands. Reinforcement can be laid in different manners in the matrix, which will greatly impact the behavior and the strength of the composite. The most common technique is to spread the reinforcement randomly in the matrix, the material thus obtained has fairly equal properties in every directions, the second technique is to lay out the fibers in favored directions. The mechanical properties of the material now really depend on the direction considered as well as on the directions of the fibers. This method is typically used for long reinforcing fibers and leads to generally uniaxial or biaxial material.

The final properties of GFRP elements depend as much on the specified composition as on fabrication factors, some of the most important factors are:

- resin formulation
- filler specification
- curing conditions
- type and amount of reinforcement (size and lay out of the fibres)
- nature of the bounds between the matrix and the glass
- fabrication process
- quality of the work

Figure 48 :Fiber glass mat[48]

Figure 49 :Uniaxial fiber glass cloth[49]

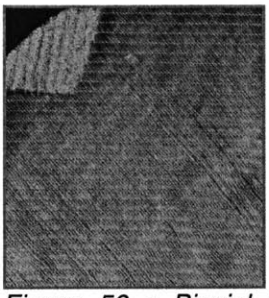

Figure 50 : Biaxial fiber glass cloth[50]

Because of all these parameters, the FGRP composites can have a big variety of characteristics and cannot be reduced to a unique set of numerical values. Following is an example of the ranges of typical characteristic parameters.

	Chopped Strand Mat	Parallel Roving	Parallel Laminated
Glass content, %	25-45	50-70	62-67
Tensile Strength, MPa	76-160	550-900	540-600
Tensile Modulus, Mpa	5.6-12	-	31
Flexural Strength, MPa	140-260	690-1400	590-720
Flexural Modulus, MPa	6.9-14	34-49	31-38
Compressive Strength, Mpa	120-180	340-480	280-340

[48] http://www.lbicorp.com/navsea.html
[49] http://www.lbicorp.com/navsea.html
[50] http://www.lbicorp.com/navsea.html

3.2.3.2 Application to the fabrication of grid shells

In the existing grid shells wood has been chosen as a favorite material because of its low weight and its great deformation capacity before failure. In any case has timber been chosen because of its resistance. Glass Fiber Reinforced Polymer has a limit deformation of about 1.5% (versus 2% for wood) and a weight of only 1.9kg/m3. This type of material has therefore a much higher strength (from 20GPa to 40GPA) than wood (10 GPa). Thus for a given type and a given geometry of grid shell, the carrying capacity before failure will be much bigger for a composite grid shell than for a timber grid shell.

Construction wise thinking of using GFRP also makes a lot of sense. As has been discussed previously, grid shells are designed so that loads are carried quasi exclusively in an axial manner through the members. The composite members therefore need only have fibers in one direction. Using uniaxial members also reduces the possible risks in the use of composites. The use of randomly spread reinforcement leaves a chance of uneven capacity in different directions, and creates the risk of using the material in its weakest direction without noticing, choosing to use uniaxial composites takes out such risks. Unidirectional profiles can be easily fabricated using already available industrial processes such as pultrusion. This technique enables the production of big length of tubes in a fast and economical manner. Moreover having big lengths of members available also avoids linkage and connection problems (when a longer member is made out of smaller pieces) that exist in timber grid shells.

The rapidity of the erection scheme of grid shells, combined with the extreme light weight of Fibre Glass Reinforced Plastics could lead to the development of fast installable shelters. In the way of deployable structures, once the connections between the members of the mat are done the structure takes form very easily. Furthermore as the structure itself will be very light (the main load being probably the weight of the fabric cladding put on top of the GFRP structure) its installation would require very few equipment as well as very few manpower. This kind of structure would be ideal in extreme situations when emergency shelter is needed in case of natural disasters for example. Also, the grid shell capacity of spanning big distances would be a huge advantage.

Temporary composite grid shell could also be used for the various expositions and festivasl organized world wide, this field of application probably being more favorable to the development of such structures. In fact before it becomes relevant to use GFRP grid shell as

emergency shelters, the concept has to be further improved so that their production is optimized and becomes truly cost efficient. The "emergency shelter industry" not having lots of founds to spend on form development, it is more likely that GFRP grid shells would be developed for big occasion purposes. As a matter of fact theses kind of gatherings are typically exceptional events during which the organizers want to leave a nice impression on the attendees (spectators, exhibitionists, personalities...) grid shell structures have clearly very interesting architectural features that could only enhance the unforgettable feeling the organizers would be looking for.

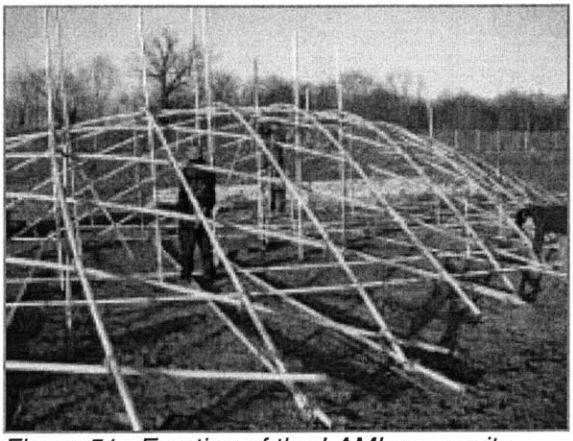

Figure 51 : Erection of the LAMI composite shell[52]

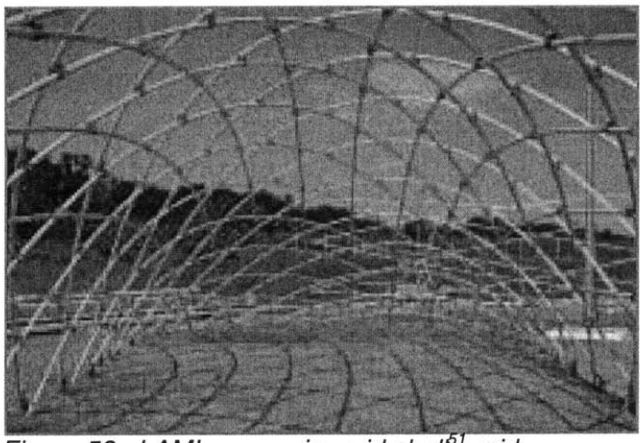

Figure 52 : LAMI composire grid shell[51] *grid*

Recently the LAMI (laboratory for material analysis and identification at the Ecole des ponts et chaussée, Paris) lead a study on the feasibility of composite grid shells. The first step of their investigation was the development of a software capable of accurately predicting the behavior under loading of a composite grid shell. Based on the dynamic relaxation algorithm this program has been optimized for the special mechanical properties of GFRP, it also takes into account the relative eccentricities of the members at their connecting points and aims at predicting the structural deformation of a grid shell. The implementation of the software has been successful and a model, the size of a typical house, has been built to test the performances of a composite grid shell as well as the accuracy of the results. Proving the effectiveness of composite grid shells, the test grid shell has been completely installed in eight hours by three men alone without any special equipment. Once erected and braced the shell was loaded and it appeared that the developed software was quite accurate. The discrepancies between the calculated and

[51] www.enpc.fr/fr/enpc/ecole_mouvement/pdf/lettre_**lami**.pdf, brochure 2006
[52] www.enpc.fr/fr/enpc/ecole_mouvement/pdf/lettre_**lami**.pdf, brochure 2006

measured deflections were of the order of the tube diameter, and it was found that the introduction of the bracing multiplied by six the maximal allowable load.

3.2.3.3 Material degradation

Glass Fiber Reinforced Plastic can be a very performing material since it can be tuned and adapted to the structural needs, the only issue related to their use concerns their possible degradation.

All types of material may be damaged so that use cannot be maid of their full strength anymore. Usual construction materials benefit from experience. As they have been in place since decades structural engineers know how to deal with the long term diminution of their load carrying capacities. Regarding composite material the research and their use in construction has not come yet to a point where enough data are available to build a theory on the long term assessment of GFRP structures.

The mechanical properties of fiber reinforced composites depend on the one of the matrix, the filler and on the quality of their interface. This latter component is critical since it is at this level that loads are transferred from the matrix to the fibers. Any damage on any of these three component levels will lead to the ruin of the composite and thus of the structure.

The first part to be affected by deterioration is generally the outer surface of the member, the rate of the propagation of this deterioration depending on various parameters such as:

- the composition of the material
- the manufacturing method
- the degree of cure
- the nature of the surface finish
- the environment the composite is used in

Studies proved that the deterioration of the surface has two main causes which are the failure of the interface between the resin and the reinforcing fibers and the cracking of the resin itself. The typical deterioration process starts by the weakening of the interface. Under the influence of environmentally induced aggression such as atmospheric moisture or solar radiations, the interface is weakened which leads to the out popping of glass fibers. The fact that all the fibers are now not totally engaged in the load resistance, clearly reduces the carrying capacity of the members. The second breakdown that might occur is the micro cracking of the surface, which is typically induced by solar radiation. The surface is subjected to fatigue due to the out popping fibers, and to tensile stresses produced by the gamma or ultra-violet radiations.

Those to stresses lead to the ultimate strength of the plastic composite material to increase and the fracture toughness on the other hand to decrease. After a certain amount of received radiation the damage is irreversible and the big number of cracks that appeared in the matrix renders the latter to be inefficient and useless.

It appears that GFRP are much more sensitive to environmental aggressions such as moisture and sun radiations. Protective coatings have thus been developed so as to improve the life time of these materials. The typical coatings are lacquers based on acrylic resin. This kind of protection prevents the fibers from protruding as the resin acts like an additional bonder and also protects the resin to be hit by the ultra violet radiations thus preventing the matrix cracking. Long term behavior of composite members and thus even more of composite structures cannot be accurately predicted but seems to be less than for typical construction materials, however this disadvantage does not apply much to the temporary structures described previously. Shelters or outdoor tents are not aimed to stay in one place for a long time. This is a big advantage since, first, the member will not be subjected to long time exposure and second because if a member is damaged in can be easily replaces as the structure has been designed to be built and un-built.

Conclusion

Many architects have been interested in organic shapes as well as in structural challenges. Frei Otto is one of these designers that have always sought to push the design technology further beyond its barriers. Frei Otto is the one architect who has created interest in grid shell structures and who has brought structural engineers to explore this innovative scheme along his side.

With the Mannheim Multihalle the first step towards grid shell theory was made. Being the first significant grid shell and the first double layer grid shell to be constructed, the design of the Multihalle did witness a very experimental design process. Architect and structural engineers closely worked together to generate the effective geometry of a self standing surface. This first design was done using a traditional chain model to determine the geometry and a modern computer program to study the behavior of the structure. The design of the Japan Pavilion for the Hanover exposition featured the same design techniques. The main innovation being the use of cardboard members, this enabled the structural engineers to focus on the efficiency of the structure and thus to gain experience. The Downland Museum represents a further significant step in the design evolution of grid shells. The first difference is that Frei Otto is not the architect for this project but Buro Happold is still the structural engineering company in charge of the design. The second distinction that can be made is that physical models have been abandoned and computer models have been preferred for their ability to deal with non funicular structures. Construction technique have also changed and turned to a more effective, less energy demanding scheme.

The development of more performing computer programs, the growing interest of architects in these structures are as many needed elements to encourage the development of grid shell construction and the creation of grid shell design guide lines, if not of a structural theory. The design of a grid shell has a double level of complexity. The column free feature of these

buildings, very much enjoyed by architects, can only be earned through an initial complex geometrical stability investigation, followed invariably by a load stability study. For now only Buro Happold has the technical expertise as well as the experience to design large timber grid shells but this cannot remain. With the evolution towards more friendly-user computer programs, structural engineers novice in the grid shell design field will be able to overcome their fears and be reached by the global enthusiasm for grid shell buildings.

In parallel to the structural and technical evolution of grid shell structures, their significance has also changed. From being an architectural and structural statement in the context of renowned expositions, grid shells have evolved into more commercial products. Proof is that the replacement of timber by more durable and performing materials is currently under study or actually being experienced. On one hand the outstanding aesthetics of grid shell have attracted developers and influenced the development of steel grid shells. The necessity of replacing timber by a more effective material in terms of load capacity and durability has arisen through this interest. On the other hand the innovative construction scheme of timber grid shell has generated the curiosity of the composite material industry. The study of the use of Fiber Glass Reinforced Polymer in grid shell construction is currently at a less advanced stage that the one on steel, but promises to be very fruitful.

It is remarkable to notice how one structural concept can lead to so many innovations in terms of design methods, construction technology, material use, design collaboration... After over forty years of under representation in the building environment, the development of grid shell structures has taken a swift pace and is now reaching for all the spheres of the construction world.

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