Innovative Developments in the Design and Construction of Timber Shells; Potential and Practical Examples

By Klaus Linkwitz, Stuttgart

Abstract

Generally „shell“-structures are associated mentally rather with the materials of reinforced concrete and steel, and many fine examples of this type can be found throughout. In comparison, the the number of timber shells executed appears to be small, the more so, if we take into consideration the potential of this material. Especially the technique of combining glued-laminated timber elements with a cover of thin planks has the potential of challenging designs with artistic qualities. They may be realised in an extraordinary variety of shapes, combining slenderness with wide span. Wood as construction material has the additional advantage of being natural and caressing eye and hand when perceived.

Their conceptual design starts with the finding of an adequate shape, permitting loads to be taken down within their surface thus minimising bending and yielding thin shells.Here today's advanced techniques and tools of complex formfinding may be applied fully, as are : Computer aided design using geometrical form elements, computer aided design based on elastomechanical derived shapes of equilibrium, and computerised geometrical reverse engineering. Also physical models - especially in the beginning of the design phase - play an important role.

The shapes thus found then have to be „translated“ to their materialisation by structural elements. In wooden shells this means a translation into - mostly double-curved - ribs, beams, and assembly units permitting premanufacturing in the factory and easy and fast assembly on site. This includes the complete finish of the individual elements unto their shift-planes for all joints and intersections. This is achieved by a computer aided numerical description of all elements and numerical monitoring of the manufacturing process.

After transportation of the complete set of premanufactured timber elements to the construction site, even most complicated structures can be assembled on site in short construction times. However, as a prerequisite for this kind of execution high professional standing of the timber craftsmen involved and an accuracy in constructions as normally only found in mechanical engineering are demanded. Application of the principles outlined above are demonstrated at some timber shells erected in recent years in Germany in recent years.

1. The Potential of Timber for Shell Structures

Up until 30 years ago cupolas and shells could only be imagined as a skull-cap cut our of a sphere. The famous Saarinen shell at the Massachusetts Institute of Technology (MIT) is an example of this. Wood still widely is recognised as a stiff, non bending material used in the form of straight beams - if the dimensions of the cross section are large - or thin planks allowing limited bending. Used in this combination we find since more than thousand years extraordinary structures as large roofs in churches and monasteries, as observation platforms in astronomy and, a more profane application, structures using the „Fachwerk“ type to build houses in large quantities in Europe’s towns in the middle-ages.

However, examples of beautiful as well as practical forms of wood construction can be found in ship building, especially in sailing ships since a long time. In some of the world's wharves where yachts are built this art is still alive today, although to a great extent plastics have replaced wood as the material for hull construction. In ship building we find an application of one of the characteristic qualities of wood, namely its great flexibility, especially when the boards or layers of timber are thin. Thick timber, on the other hand, is prized for its enormous resistance to strain. The masts of a sailing ship, as high as 70 or 80 metres, were expected to remain absolutely straight even in a tempest.

Besides, as a building material wood possesses another advantage: when looking at or touching it people feel it is natural and pleasant. Proper chemical preparation makes it almost completely fire-resistant. Even its natural enemies, wood worms and termites, can today be successfully prevented by chemical means.

Looking at the majority of the wooden buildings put up today, one must regrettably see that they make only partial use or none at all of the potential of wood as a building material. This is especially true of the almost limitless potential of glued laminated timber structures.

2. Grid Shells and GluLam Timber Shells

True shells made of timber occurred as grid shells. Here the shell’s hull is constituted by a layered, meshed grid of long timber beams with very small cross section dimensions. In the intersection points the beams are pin jointed permitting arbitrary angle changes when the grid is assembled and still laying on the ground. When, to erect the shell. the nodes are pushed up by scaffolding into their final spatial positions, the grid takes different intermediate assembly shells made possible by the continuous change of the mesh angles in the grid. Indeed, as long as their bending capacity is not overstrained, the grid net can assume almost any spatial form only by changing its mesh angles. However, when the angles are kept permanently fixed also the appertaining shape becomes fixed. Thus, if the meshed grid is pushed from the ground into a spatial shell form and then the angles are fixed - by constructural means whatsoever - it becomes a grid shell.

A well known example of this technique simultaneously displaying a beautiful design is the grid shell of the Garden Exhibition, Mannheim, Germany 1974.

The great flexibility of a single thin board, combined with the strength of a solid, thick beam is found in so-called ‘glued laminated’ (**GluLam**) timber structures. Such beams and trusses, consisting of up to several thousand glued lamellae, may be manufactured with almost any curvatures or torsions. Complicated, doubly curved shell-like supporting frameworks, or parts thereof, can be produced. Today glue and composite methods of construction are so highly developed that, when the suitable types of wood are chosen, large-span constructional elements of extraordinary slenderness and strength can be produced, making it possible to design and build wide-span free forms.

If we want to apply the GluLam technique to design and construct a timber shell we have to distinguish our approach clearly from the above mentioned grid shells. There the load bearing structure is the space-grid itself acting as a shell after the mesh angles have been fixed. Thus the laths constituting the lattice work can be - compared to span - extremely thin. This may be seen in an exemplary manner at the grid shell of the Gardenshow in Mannheim. Naturally, this principle functions only if the shape of the grid shell is a perfect „figure of equilibrium“ accomodating all forces in the thin layer of the shell itself.

With GluLam constructed shells we use a different principle. The primary, load bearing structure is a skeleton of GluLam beams - „meridian ribs“ and „ring ribs“ - intersecting each other in solidly fixed „shifting joints“ and considerably wider spaced than the laths in a grid shell. Already the beam skeleton acts as a shell type, but the true shell type is only achieved after the beam skeleton has been covered and finally fixed with a double layer of thin planks.

Compared to the grid shell we get two distinct additional advances. First, all parts constituting the shell - the ribs and edgebeams - can be premanufactured unto the last detail, including the shifting joints. Second, the assembly on site is much easier and also safer than the assembly of a large grid shell. The pole- or mast-like high points are set up, the edge beam is put into its place and thereafter the skeleton of the ribs is assembled between the higher points and the edge beams. After the assembly of all premanufactured ribs on site the final shape is automatically there ! Contrary, in the assembly of a grid shell, the lattice grid laid out on site on the ground has to be pushed up into space by vertically movable scaffolding attacking at many selected nodes, which, after having been pushed into their final spatial position simultaneously create the final shape of the shell.

As the GluLam beams can be manufactured in rather arbitrary large cross section dimensions, also the constraints - again compared to the grid shell - governing feasible forms are much reduced: We can build the these shells in shapes unattainable by grid shells.

3. Some Fundamental Aspects regarding Formfinding and Subsequent Design

However, for each individual design one must choose from the virtually endless wealth of possible forms the one which matches the purpose of the building, gives it a characteristic expression and also takes advantage of the specific qualities of the wood. Of particular importance here is a design making good use of the curving and torsional qualities of the individual elements as well as the possibility of their economic prefabrication in the factory

Mainly we have three types of shape creation: „Free forms“, corresponding basically to the catalogue of forms supplied by (geometrical) CAD-Systems, „Figures of Equilibrium“ derived from physical models of figures from equilibrium figure generating analytical-mathematical methods, and finally shapes created by „geometrical reverse engineering“ permitting the creation of shapes resembling sculptoral works.

We will discuss either type and outline it in a typical example.

3.1 Free Forms; Computer Aided Design (CAD)

3.1.1 Characteristics

As is the case with reinforced concrete, in also in timber structures many shapes are designed and built from surfaces or surface elements that can be fully described mathematically. Up until 30 years ago cupolas and shells could only be imagined as a skull-cap cut out of a sphere. The famous Saarinen shell at the Massachusetts Institute of Technology (MIT) is an example of this. If one proceeds from the plain curve to the mirror-image double curve, one obtains hyperbolic surfaces. These too fall into the category of mathematically describable surfaces. Applying differential geometry we may generate them from moving straight lines.

Using this principle, the Spanish-Mexican architect and engineer Candela designed and built many hyperbolic shells in a large variety of forms and in great aesthetic perfection.
The art of skilfully applying a generatrix of differential geometry can already be found in the work of the great Russian architect and engineer Suchov. He designed according to these principles the first spatial structures, although only as iron or steel constructions. In them he was also able to use -- in accordance with the generatrix for the hyperboloid -- straight, uncurved elements.

In Barcelona Gaudi used the principle of the meandering sliding surface in order to generate the intricate roofs over the school near the Church of the Sagrada Familia. In a further step he generated equilibrium figures as hanging physical models, which he then turned upside down, finding natural forms for arches and vaults.

The appearance of CAD has significantly expanded the variety of free forms compared to the sections taken from spheres and paraboloids that were usual in former times. In the sixties the mathematician Coon created at the MIT the so-called Coon-surfaces with which spatial surfaces - - defined only by their edges -- can be reproduced mathematically. The Coon-surfaces were used in particular in designing car bodies. In the third example I show the use of Coon-surfaces in a wood structure.

A further result of CAD was the appearance of developments of the quadratic or cubic parabolas either as two-dimensional spline lines or as three-dimensional spline surfaces. In combination with sliding elements splines can be used to generate complex spatial forms whose origin in relatively simple mathematical laws is no longer apparent. The "Ahrtherme" example is intended to illustrate this.

The field of automobile construction is also the origin of the last, modern, expanded free form, namely the Bezier-surfaces. They were discovered by the French mathematician Bezier and applied by the Renault Company in Paris in the mathematical modelling of car bodies. Compared to the Coon-forms and spline forms, which approximate given lines and points, Bezier-lines and surfaces have the undeniable advantage of being able to approximate not only the points but at the same time also the tangents defined with them. This makes Bezier-surfaces a powerful tool particularly in the hands of the "mathematical sculptor".

"Sliding surfaces" attained particular importance as used for large glass roofs made from homogenous elements. They too can be fairly easily formulated mathematically and thus also generated in a computer.

3.1 2 Example: Timber-shell Health-Spa Bad Neuenahr (1992)

a.) Conceptual Design and Formfinding

The principle shape of this shell was conceived as a big lampshade, first developed and studied on models made of textiles. This already allowed the first rough calculations which gave the necessary cross sections of the ribs, the shell and the tree. In numerous calculations the form of the meridian curve, the cross sections of the construction elements, the endurance of the glue kept being varied and adjusted to one another until an optimal flow of forces was obtained and the amount of wood and glue needed could be reduced to a minimum. After these preliminary studies the geometric determination of the shell-form as a free-form was carried out.

Constructed on the basis of a GluLam rib skeleton it stands on a sixteen-metre high wooden column which like a tree branches out toward the top and is there connected to the upper ring-rib. The shell-like skeleton itself consists of fifty meridian ribs with a cross section of only 12 x 18 cm -- with a length of over thirty metres -- and 17 ring-ribs that have cross sections between 11 and 16 cm and diameters of 5 to 18 metres. The extreme end of the meridian ribs is marked -- when seen from the outside -- by a concave, circular edge beam which, matching the doubly curved surface of the shell, is also doubly curved.

The final shape is intirely defined mathematically as a rotational form. A vertical elevation through the roof (figures 6,7) shows the axis of rotation and the generating meridian line which indicates the shape of the roof by rotation around the vertical axis. The roof is then intersected at the edges by vertical cylinders. creating the shape of the edge beam bringing the shell to its end at the bottom.

In detail a significant part of the form-finding process consisted in the determination of the form generating meridian line. It is composed of three cubic parabolas as a spline in such a way that in the vertical elevation of the shell-roof necessary initial and final inclinations as well as a number of further constraints are be met, concerning distances to observed between the roof and structures lying below it and between the roof and the water level. In a series of experimental computer run-throughs different splines were analysed by differential geometry in their location-dependent curvature behaviour and continually changed systematically by variation of the buttlike joints of elements and the instantaneous curvature until a line was found that obeyed all side constraints, had the most constant changes of curvature possible and also appeared pleasant and consistent to the eye. The technical scientific means used for this were CAD, differential geometry and the method of least squares.

After rotating the cubic spline around the middle axis one obtains the initial forms (figures 6 and 7). At their edges and symmetrically around an axis running from top to bottom are now placed a total of eight small and six large vertical cylinders , intersecting the surface (figures 8,9) The result is the meandering edge cut inwards into the lampshade-like shell.

b.) Materialisation

For the materialisation and construction of the shell (figure 9) fifteen superimposed ring-ribs are used (they have the radius of the shell's corresponding horizontal cross section) and fifty radial meridian ribs (they are the transformation of the two-dimensional generating splines into three-dimensional beams). The individual meridian ribs have different lengths. These lengths result from the intersections with the vertical cylinders. The meandering form of the edge is materialised by a series of superimposed double edge beams. The surface of the ring-ribs and meridian ribs which as constructive elements contact the roof surface and the edge beams are formed in such a way that they represent the cut-out shape of the rotational surface of the roof. The constructive elements either touch each other in common geometric surfaces or penetrate or intersect each other.

The description shows that, seen geometrically, the shell-roof of the Ahrthermal Baths in Bad Neuenahr is a geometric free-form surface. For its final generation only geometric definition were used. Questions of the flow of forces in the roof had already been studied before this final determination.

The actual static calculation was carried out after the final definition of the form both as a spatial framework and as a shell. The calculation and the appearance of the shell and its bedding reveal that the lower ring-ribs together with the edge beams form an encircling pressure ring. The shell gets its stability from support at the corner-points and along the facades.

The computer modelling of the geometry and its constituting elements makes it possible to represent various views of the roof before it has been built. Figure 10 shows a computer-simulated "aerial photograph" of the roof from a distance.

c.) Premanufacturing

In carrying out the details old, proven carpenter’s joints -- pegs, scarfing, plugs and other hardwood devices -- were used wherever possible. In the construction of the tree-supports no metal connections are necessary. The galvanised pin-plugs at the ends of the meridian ribs were shielded by glued knot-hole plugs against the inside air of the baths. The head cap screws and the groove nails for mounting the shell are also galvanised. All together, this construction makes very little use of metal means of joining.

The constructive parts forming the roof -- the ring-ribs, meridian ribs and edge beams as well as the central "tree" -- were all prefabricated in the workshop of Christian Burgbacher & Co, including such details as the shifting planes. The monitoring measurements necessary for positioning and aligning the templates on the marking-off floor were derived from the geometric conditions sketched above in the form of computer lists. For this a special program system named "Ahrtherme" was developed with a number of modules.

The principle of the representations for the fabrication is shown in figure 11, using the example of a meridian rib. Given is the horizontal position of the marking-off floor (figure 11) in the fabrication hall at Christian Burgbacher's. Each meridian rib is mathematically fitted into it by means of two spatial rotations and a translation in such a way that it lies in the "plane of fabrication" at a distance of one metre. Now through the meridian a close sequence of vertical cutting sections is laid on the plane, fig.11.

The monitoring measurements with the edges characteristic of fabrication as well as the position of the cutting plane on the marking=off floor were predetermined and are the basis for the prefabrication.

From the geometry an additional number of independent measurements were calculated in advance as a way of checking the fabricated parts. They permit a thorough geometric check of the prefabricated parts by the master carpenter at the workshop before delivery to the construction site.

The form of the roof, significant in its uniqueness, and the design of the thermal baths lying below it provide the guest, as was the architects' intention, with a special spatial experience. One is led easily and naturally from room to room up to the central climax: the main hall with the pools, the cafeteria and the gallery. There the eye finds its focus and point of rest in the central vertical support that spreads upwards and outwards like a tree, guiding the viewer's attention through the glass roof to the outside.

3.2 Forms and figures of equilibrium: Stuttgart's "FASNET"

3.21 Characteristics

Common to all mathematical geometrically generated forms, is the fact that, they are defined purely mathematically and therefore without regarding the flow of forces occurring within them. If -“incidentally“ - the geometric form of such shells were to follow precisely the flow of forces at work in them, they would be almost free of bending load. (An example of such a structure is the classical Roman arch.) In reality, however, the flow of forces generally does not follow the surfaces generated as free forms. Consequently, under its own weight as well as external loads bending loads occur which must be compensated for by means of greater thickness of the shell and (often considerable) steel reinforcement. If one wants to build very thin, wide-span plane load-bearing structures of steel, other metals, concrete or wood, their form must be adapted to the flow of forces in them so that the bending loads are kept as low as possible.

This brings us to the field of „figures of equilibrium“ and their role in the process of formfinding for timber shells.

The best example of a form that naturally finds its equilibrium is a film of soap suspended within a given rim. The film is extremely thin; there is no occurrence of bending stress in it; we find only tension forces, in isotropic form. If the soap lamellae are transformed into a buildable structure, one obtains a diaphragm or, in other cases, a favourable basic form for a prestressed cable-net. However, we have to keep in mind the very basic fact that a soap- lamella = minimum surface **cannot** be defined by a closed mathematical expression but is instead the solution to a location-dependent differential equation. The forms of prestressed cable-nets or of nets hanging freely under their own weight **cannot** be given by closed mathematical expressions either.

As structural shapes they did not become useful until they were approximated through model making. In concrete shell construction Heinz Isler in Switzerland, gave up the classical geometric free forms and achieved a decisive break-through in form-finding by means of equilibrium forms observed on physical models and derived from measurements made on models. A key experience leading to his new, epoch-making method of form-finding was the reflective, unbiased observation of his sofa cushion. It suddenly became clear to him what physical laws would explain its natural form. He developed a new method of form-finding for doubly curved structures. He subsequently designed and built a large number of extremely thin, beautifully shaped and very stable concrete shells. He later expanded this principle after observing forms taken on by wet towels under the influence of frost. Experiments and mathematical analysis showed Isler that even when using the same amount of material the doubly curved shells could withstand three times as great a load as a flat supporting structure before they broke.

Up until the middle of the sixties it was considered impossible to directly generate equilibrium forms by means of computation.

Challenged by the engineer's tasks of finding forms and determining their cutting pattern for the roof of the Olympic Stadium in Munich new mathematical methods of generating and analysing exact equilibrium figures were discovered in Stuttgart. J. Argyris and his colleagues expanded the method of finite elements to prestressed cable- nets. Independently of this, the present writer and his staff developed new, unconventional methods, of which the **„force-density method“** in particular has proven itself to be a powerful and flexible tool for the computer supported numerical generation of equilibrium figures. These are surface structures, in which the forces -- under the structure's own weight or under a predetermined load -- are exerted only in the plane.

As was already the case with the geometric free forms, the physically determined equilibrium forms provide an inexhaustible variety of shapes. Compared to the geometric free forms they have the further advantage that when later realised in the construction of a building the bending load is drastically reduced, so that as a tensile construction they can be made extremely thin and as structure subject to compression they can be made with very slight thickness. FASNET, developed in the author's Institute, is a powerful tool to computergenerate such forms of equilibrium directly and also under many prescribed constraints.

That the principles of using equilibrium figures can also be applied advantageously to GluLam timber shells is demonstrated in the following example.

3.2.2 Practical Example:Timbershells Health-Spa Bad Duerrheim (1985)

a.) Conceptual Design and formfinding

The predominant principles governing the conceptual design of the shell are here deduced from a compelling environment and the purpose of the building covered by the shell.

Bad Duerrheim, is an old spa and lies on a plateau at a height of about 700 metres. The place is bedded in the mountain landscape of spruce and fir-trees of the Southern Black Forest. The newly built mineral bath was supposed to receive a roof that, through its form and its support, would express the close connection with the surrounding landscape. After a number of experiments with models it was conceived as a multiple timber shell. Here wood was chosen quite unanimously as the appropriate building material.

The shell - again consisting of a skeleton of GluLam beams covered crosswise by planks - rests on five tree-like supports and has a total surface of 2500 sqm. The tree-supports with heights between 11.5 m and 7 m are grouped around a central place. Between them „hangs“ the doubly curved diaphragm- like shell, using the tree-supports as high-points and parts of the edge beams as low-points. From the ring-shaped closing upper edge of each tree-support "meridian ribs" run to the other trees and to the edge beams. They are intersected vertically by horizontally positioned ring-ribs which are held together by finger jointing so that they can withstand both tension and compression forces. The overall length of the ring-ribs is 2900 metres.

Taking as a point of departure the beneficial properties of figures of equilibrium as structural forms, an ideal shape of the grid like structure would be characterised by the fact, that both, meridian- and ringribs, are subjected to normal, axial forces only under deadloads, and bending be as small as possible. Simultaneously, with respect to an economical prefabrication certain symmetries in the forms, allowing multi-use of premanufacturing form tools, would have been appreciated. Other constraints concerned the necessity to have uniform inclinations of the meridians in their points of departure at the tree rings, and many others.

To take into account all these requirements a strategy of formfinding was employed which had been found to be extremely successful with cablenet- and membrane-structures.

The process set out with a „topological description“ of the skeleton like structure yielding essential basic data input for the formfinding process. To potentially create selfmoulding figures of equilibrium the finally rigid skeleton was discretised and modelled as a net of individual bar members pin-jointed to each other. To these slack lengths and "force-densities" were assigned. This virtual net was hung between the high tree supports and the bottom edge beam. To gain a preliminary geometric description of the edge beams they were defined to be the lines of intersection between the net and vertically positioned cylinders around the shell/net. To permit the development of feasible figures of equilibrium the x,y-coordinates along the edge beam, and x,y,z co-ordinates at the anchoring points on tops and bottoms were taken as fixpoints. In a similar way the starting points of the meridians at the tree rings were defined to lie with fixed coordinates x,y,z on horizontal circles. In the subsequent calculation of figures of equilibrium under arbitrary constraints all other points of the net were free to move, depending on the different sets of constraints imposed in the subsequent process of formfinding. This rendered a number of usable figures of equilibrium.

The results of this first phase of formfinding analysis were then further modified to accomodate also those geometrical restrictions resisting direct equilibrium approximation. They, consequently, had to be treated in separate procedures of trial and error and in close team word between engineer and architect. They concerned improvements of meridians to reduce unnecessary torsion, improve ringribs by influencing their differential behaviour of curvature, observing height constraints with respect to the underlying structures of the sole-bath, aesthetical constraints concerning ribs directly connecting trees, etc.

Additionally, finite element analysis was used to control independently the results of formfinding and also to analyse load-deflection behaviour for typical loading cases.

b.) Materialisation and prefabrication

Due to the discretisation of the shell as a spatial net the result of the formfinding process are systemlines representing the net-structure and idealising the meridian- and ringribs corresponding to a "wire-model" of CAD. However, these one-dimensional lines alone and their geometrical representation do not yet allow a unique definition of the three-dimensional beams in space and thus also premanufacturing of the three-dimensional ribs. Additionally also torsion and curvature of the beam like elements have to be known and introduced in the numerical monitoring of manufacturing. As the net-structure is a discrete representation the shell''s surface, the normals of that surface can be derived following each individual rib=sequence of net elements along its path in discrete points. This was possible either by using neighbouring points and calculating the instantaneous tangent plane or using the information of another step, namely the final approximation of the ribs by splines.

Finally the cutting pattern thus derived was transformed into a best fitting plane for each individual element to be manufactured and allowing a convenient setting and layout of the form tools without too large differences in relative heights above the manufacturing floor. Using this information the manufacturer was able to set out the form tools properly and to fabricate each of the 400 different elements of glued laminated timber without any error or double-manufacturing

3.3 Model making and modelling with differential geometry in the computer:

'Geometrical Reverse Engineering'

3.3.1Characteristics

A further, special way of form-finding is the combination of model making and subsequent mathematical modelling. Here the model can take on almost any aesthetically justified form of the sculptor's imagination. Forms created in this way need be neither mathematically describable free forms nor equilibrium forms in the physical sense. When being transferred to a realisable building they must be transformed by means of "patching" or the method of the least squares into elements of free forms or elements of equilibrium forms which are then buildable. In this combination it is possible -- as far as the form is concerned -- to design and make the most complicated structures. I will discuss this in my third example.

3.3.2 Practical Example: Timber Shells of the Hoelderlin-Haus-der-Anthroposophia Maulbronn (1998)

a.) Conceptual Design and Formfinding;

a.) The spiritual process and model building

The shapes of the five roofs of the Hoelderlinhaus Maulbronn cannot be derived from elementary geometrical forms. As edges we find neither straight lines nor circles nor parabolas. Its surfaces may neither be explained as figures of equilibrium nor do they belong to the sources of CAD programs. There are no spheres, spheroids, cylinders or parts thereof and we do not find closed Bezier- or splinesurfaces.
Much more, the shapes of the Hoelderlinhaus' surfaces are to express the anthroposophical ideas of the Austrian born philosopher Rudolf Steiner. Looking at them without prejudgement we may perceive their design to be styled very freely and subjectively but still conveying an uniform and consequent aesthetic language. Also in their realisation by the material wood they are supposed to reflect - unto the smallest detail - Steiner's spirit.

Here, for the conceptual design a most unconventional and unique approach was taken.
The house and its shell-like roofs were created in a spiritual process lasting nearly five years. This process was initiated and then under the leadership of the medical doctor Elisabeth Krauss - a niece of the late famous physicist Werner Heisenberg - and involved from the very beginning the participation of the young members of the "society for the promotion of the anthroposophic idea", and architect and engineers.

After many trials, discussions and errors the collective process of formfinding resulted in a wooden model made by a member of the society expressing as much as possible the vision the group had of house and roofs. It was scaled 1 : 25, showed the principal walls of the house and also the shapes of the roofs. In detail we recognise a big principal roof - consisting of three subroofs - covering the large assembly hall, and a smaller front roof extending perpendicular to the main roof, placed at a lower level, covering a number of service rooms and split into two subroofs. The big main roof and the smaller front roof rest on the crest of the brickwork outside walls, which - in context with the overall idea of the building - also are shaped irregularly in plan and elevation.

By their appearance from out- and inside, the roofs together with the materials constituting them are to procure in the visitor an experience of that space and its expression which was anticipated by the group as the very essential of the building, served as the backbone in their process of formfinding, and materialises their own identification.

However, the unique experience of space of the large assembly hall is not only mediated by the covering roofs but also, and quite essentially, by two substantial, large main beams. They subdivide the main roof in its three subroofs. Their design and shaping in detail - the longitudinal development of variable curvature and torsion had been used, with great instinctive skill, by the group as means of expression - cost much endeavour and time. Also here many experiments, trials and errors accompanied the path to the final design.

Now, the small wooden model had to be "translated" into a real, buildable construction.
This was achieved in four main steps, namely

- measurement of the model using terrestrial photogrammetry,
- mathematical modelling of essential edge-lines and of the roofs' surfaces,
- mathematical translation of the various line- and surface-objects into three-dimensional construction elements,
- Analysis and calculation of all digital information necessary for monitoring premanufacturing, premontage in the factory and final assemblage on site.

b.) Photogrammetric measurements of model

For the close-up survey and measurements of the model a number of photogrammetric baselines - surrounding the model - were established and placed close enough to the model, yielding large image scales and allowing the application of stereophotogrammtric techniques. Natural edges and other significant pointlike features of the model were used as the necessary control points and their coordinates determined by micro-triangulation. The local coordinate systems of individual baselines then were transformed into a uniform local photogrammetric coordinate system. A further transformation of this system finally led to a local "site-coordinate-system" - serving as a basis for all setting out, control, and monitoring measurements. The latter was also tied to the geodetic survey of Baden-Wuerttemberg.

As result of the photogrammetric measurements 3-D coordinates of characteristical points of the roof surfaces, the main beams, and the crests of the brickwork walls were available. However, these are still falsified by substantial errors - due to inaccuracies of the model itself and due to intrinsic inaccuracies of the photogrammetric process - prohibiting their direct use for mathematical modelling.

c.) Mathematical modelling of edge lines and surfaces.

A detailed analysis of the measured data of the model showed, that these needed thorough additional treatment not only due to the above stated errors but also due to reasons of constructural feasibility. The edge lines of the crown surfaces of the walls , for instance, had to be reworked taking into consideration water flow from and along the roof, insulation, and major changes of the front face of the large roof.

As a point of departure, mathematical modelling could not use figures of equilibrium or closed geometrical surfaces as free forms. Each of the five subroofs had to be further subdivided into about fifty small surface patches which then could be approximated - using also least squares techniques - by Coon-surfaces with mutual boundary lines and tangents. The construction elements "ribs" and "beams" were derived from the patched Coon-surfaces by intersecting them with other surfaces and thus generating one edge line of the later rib/beam.

d.) Materialisation;

- - Elements and assembly units

Still, these edge lines are by no means sufficient to define neither the real structure to be build nor the construction elements constituting the structure. A basic and elementary step in this direction consisted in "materialisation" of the Coon-surfaces into individual constructural elements, creating, when assembled, the desired shapes. Again, after many discussions and detailed studies a solution was adopted in which the roofs are dissolved into a number of individual units of assemblage - with dimensions allowing their easy and fast transport by light cranes from their place of storage at site to their final in situ position in the roofs. By doing so not only the individual constructions elements but complete small assembly units became premanufacturable. Naturally, such a method of manufacturing and assembly requires highest accuracies in every step of the building process. Tolerances were therefore set to the millimetre.

In this context another problem - from the team's great experience with the Bad Duerrheim shells - manifested itself. For a long time all involved had believed that - similar to Bad Duerrheim - an adequate guidance in space of ribs and beams automatically and unavoidable would be equivalent to employ double curvature for all shape constituting elements, i.e. simultaneous existence of instantaneous curvature and torsion along each element. It seemed rather unimaginable to only curve the ribs (and beams) in one direction and to compensate the necessary curvature in the second direction by "pseudo-curvatures". However, employing methods of differential geometry and also taking into account imperative details of the actual premanufacturing devices a new concept was developed. In this the rib shapes are adequately defined by vertical and inclined intersections of planes with the roof constituting surfaces in such a way, that manufacturing can be executed in approximately torsion free working planes and thus proceed very economically.

After assembling the elements into construction units and placing them into their final positions in the roof they convey, however, the strong illusion of being double-curved in the classical sense, thus underlining the unique forms of the shells.

- Main beams

From the beginning the two big main beams were regarded to be of great impact on the expressive character of the assembly hall. Therefore a solution as perfect as possible, and without concessions to imperfections or insufficient endeavours became imperative. Inspite of the many trial and error experiments their realisation in the wooden models had succeeded only partially, conveying their basic ideas of design, shape, and expression. From thereon they had to be created newly by mathematical tools which had to be translated in adequate computer programs. However, it was not known at the beginning by what mathematical means this could be achieved and especially how to translate into mathematics the intention to give them exactly that "knack" of shape which the group would judge to be congruent with their imagination.

An impressive number of computer programs had to be developed from scratch allowing sculptural work guided by mathematical laws, applying always differential geometry and empirical judgement of intermediate results. Especially different laws for applying different development techniques of curvature and torsion were investigated. After many trials finally convergence towards a satisfactory form was achieved, creating individual shapes for each of the two beams which were found fully acceptable by the group and which also were manageable for manufacturing under the given constraints - even if the latter had to be stretched to the utmost.

e.) Montage on site

As a prerequisite for the assembly of the roof, the brickwork walls of the underlying building - upon which the roof rests through its edge beams - have to be erected on site with utmost geometrical accuracy. Only then continuous contact between the lower surface of the edge beam and the upper crest surface of the wall can be established. In practice on-site construction invariably shows some inaccuracies. Therefore, to prepare the montage of the edge beams, the actual, executed geometry of the brickwork walls was measured and corrected physically where necessary. Afterwards the edge beams could be positioned on top exactly, joined by wedge like breechblocks , and then thoroughly fixed horizontally and vertically with the walls themselves. This induces their acting as a ringlike anchorage, accomodating also the incoming tension forces caused by the tendency of the loaded roof to widen the anchorage ring. Now, by a crane, the prefabricated assembly units could be entered into the front roof and fixed.

The montage of the main roof demanded after the fixation of the ringlike edge beams the erection of the two main beams starting at the front and ending at the back walls of the great assembly hall. Since the already finished brickwork of the walls prohibited any major adjustments and each of the main beams had arrived on site in five prefabricated elements now to be joined together in wedge like breechblocks accuracy requirements were again high. Thereafter the assembly units of the roofs - starting with subroof Nr.1 - after being picked up by the crane were lowered from above into their final position, fixed at edge- and main beams and created, one after the other , the shell of the main roof in extending dimensions. Exercised high precision in premanufacturing of elements and units, in the position of edge- and main beams and the again demonstrated professionalism of the carpenter-master and his men led to a montage without errors and interruptions. To the great surprise of the curiously watching crowd of spectators the whole coverage of the roof was finished in a couple of days.

The wooden shell gets an additional protection and fixation by one layer more of planks and - on top of that - one layer of thin copper sheets..

. **4. Literature**

Linkwitz, K. [1996]: Holzschalendaecher Hoelderlin-Haus-der-Anthroposophia,Maulbronn; Bautechnik , Heft 4, Ernst & Sohn, Berlin 1996, ISSN 0932-8351

Linkwitz, K. Stroebel, J., Singer, P. [1996]: Die Analytische Formfindung,in "Prozess und Form natuerlicher Konstruktionen"; Ernst & Sohn, Berlin1996, ISBN 3-433-02883-4

Linkwitz, K. [1995]: Two examples of integrated formfinding and numericallycontrolled premanufacturing: the timber shells of Bad Neuenahr 1993 andMaulbronn 1995; Proceedings of the International Symposium 1995 , Milano,organised by the International Association for Shell and Spatial Structures(IASS), SGEDITORIALI Padova/Italy , Via Lagrange, 3 , 1995

Wenzel, F., Frese, B., Bartel, R. [1993]: The timber ribbed shell roofsabove the baths in Bad Duerrheim and Bad Neuenahr, Germany. Proceedings ofthe IASS International Symposium May 1993, Istanbul

Linkwitz, K.[1991]: Formfinding of Lightweight Surface Structures byGeodetic Methods; in Applications of Geodesy to Engineering, IAG-SymposiumNo. 108, Springer Verlag Berlin Heidelberg New York 1993, ISBN 3-540-56233-8

Gruendig, L., Linkwitz, K., Bahndorf, J., Stroebel, J. [1988]: Geodaetische Methoden als Mittel zur Form- und Zuschnittsermittlung von Flaechentragwerken - Beispiel Bad Duerrheim - in Ingenieurvermessung 88 Duemmler-Verlag, Bonn 1988

Wenzel, F., Frese, B., Bartel, R. [1987]: Die Holzrippenschale in Bad Duerrheim; "Bauen mit Holz", Heft 5, 1987

Address of Author :
Prof. Dr.-Ing.Dr.sc.techn.h.c.Dr.h.c. Klaus Linkwitz
University of Stuttgart
c/o Obere Tannenbergstr. 24
D-71229 Leonberg Phone ++49-7152-42155 ; Fax ++49-7152-75387; Email DrLinkwitz@t-online.de