TIMBER SHELL STRUCTURES AND THEIR SHAPES - RECENT DEVELOPMENTS AND DESIGN APPROACH

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The aim of this paper is to outline recent developments in shape design and application of lightweight timber shells, to highlight the possibilities for their use in architecture and building and to emphasise the conceptual approach to integrated shape design by interrelating architectural, engineering, material and construction aspects.
Examples of executed timber shells are given and are complemented by exploratory investigations into structural shape including suspension shells, ribbed shells and modified grid shells which illustrate some new possibilities of lightweight structures in timber.

INTRODUCTION

Internationally timber construction is in a phase of strong development: major research programmes are supported by the governments of Switzerland (since 1985) and by the Federal Republic of Germany (1989) and stronger interest in timber structures has been shown by architects and engineers in European countries and in the United States, Japan, Canada. A substantial increase in interest has been noted in Australia and has been supported by the local timber industry.

An important group of structural systems is now receiving considerable interest
lightweight surface structures in timber.

Their economy, which had already been proven during the 1960's and 1970's, and their capacity to provide new and architecturally attractive solutions for hall structures of medium to large spans is being recognised. The stumbling block for increased utilization of timber shells in building at that time had been the relatively high effort required at the design stage combined with the difficulty to analyse and to document complex three dimensional structures economically.
In the 1990's this situation is completely changed as suitable computer aided design, analysis and documentation methods have been developed that allow complex design and manufacturing processes to be conducted economically.

Research into an interdisciplinary design methodology of these structures has commenced in Europe with the involvement of the author and in Australia:
The Lightweight Structures Research Unit (LSRU) at the University of New South Wales has participated in pilot studies with European partners:

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1988/89 with the Chair for Timber Structures (IBois) at the Federal Technological University of Lausanne jointly with the Institute for Application of Geodesy in Building (IAGB) at Stuttgart University and currently (1990/91) with the Forschungsgruppe Membranbespannte Holzkonstruktionen (Research Group 'Timber Structures with Stressed Membranes') at the Universities of Innsbruck and Vienna in Austria.

The particular, innovative aspect of these research programmes is their interdisciplinary nature: structural shape is taken as the central and common aspect for simultaneous investigations in architecture (architectural design, building shape and function, environmental design, detailing and costing), structural engineering (structural shape and analysis, material, construction, manufacture, assembly) and in shapegeneration and shapeanalysis (CAD shapefinding, optimization).

From a construction-oriented viewpoint integrated design approaches enable even relatively large and complex structures to be constructed economically by smaller timber construction contractors. Intelligent shape design considers the particular nature and properties of timber. Combined with economical jointing methods such as nailing and dowelling it aims to use economical timbers such as softwood boarding or smaller sawn sections in preference to laminated sections.

The following sections introduce the field of investigation in timber shells, illustrate possible approaches to structural shape finding and give executed examples of structures.

1. SURFACE STRUCTURES IN TIMBER

The primary aim of the study has been to develop design methods for medium to wide-span shell structures that can be constructed economically from layers of boarding. Consequently we emphasised those structural systems that can use the chosen material type (boarding) and connection method (nailing/dowelling with or without lamination) to their best advantage. From the range of surface structures, which include plate, folded plate and single and double curvature shells we concentrated therefore our investigations on ribbed and gridded shells. Either suspension or compression shells are possible:

Ribbed and Gridded Shells:
Elements: curved/ rigid linear and surface element/ surface structures
Stiffness: compression, in-plane shear, secondary bending

Suspension Shells:
Elements: curved/ "flexible" linear and rigid surface element/ surface structures
Stiffness: tension/compression, in-plane shear, secondary bending (wind suction).

(Compression) Shells:
Elements: curved/curved rigid surface element/surface structures
Stiffness: compression/tension, in-plane shear, secondary bending (buckling)

Table 2 Ribbed and gridded timber shell structures identified according to structural elements and stiffness properties

The range of available structural and cladding systems ranging from the fully loadbearing stressed flexible membrane to the built-up roof on a continuous surface formed from layers of boarding is shown for suspension shells:

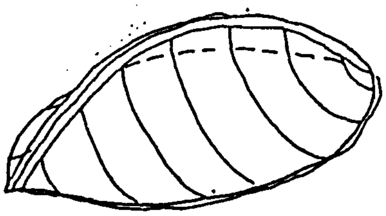
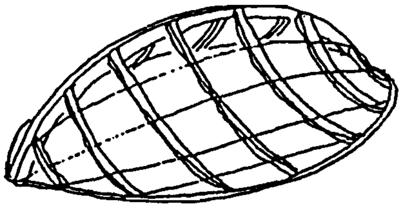
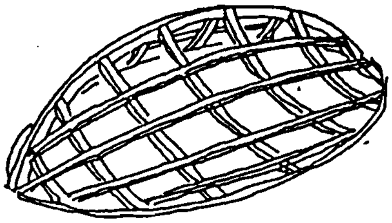
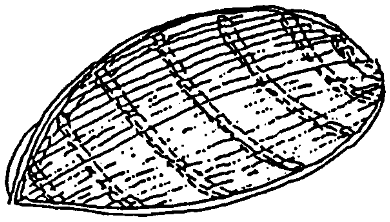
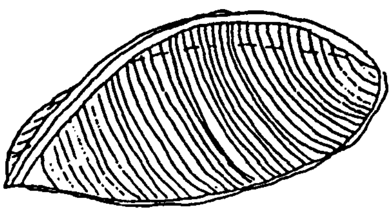
1		**Primary Structure:** Laminated Arch **Secondary Structure:** Stressed Membrane
2		**Primary Structure:** Laminated Arch **Secondary Structure:** Suspended Ribs with Stabilising Cables and Stressed Membrane
3		**Primary Structure:** Laminated Arch **Secondary Structure:** Lattice Grid with Stressed Membrane
4		**Primary Structure:** Laminated Arch **Secondary Structure:** Suspended Ribs with 2-3 layer Nailed Boarding **Tertiary Structure:** Slightly Stressed Membrane Cladding on Built-up Roofing
5		**Primary Structure:** Laminated Arch **Secondary Structure:** Membrane Shell f.i. from Nailed and Laminated Layers of Boarding **Tertiary Structure:** Slightly Stressed Cladding Membrane on Built-up Roofing

Table 2: Figures 1-5 show examples of principle timber suspension shells with different methods of structural, semi-structural and non-structural cladding with stressed membranes. The primary structure is always a laminated arch.

2. SHAPE-THE FOCALPOINT FOR ARCHITECTURAL/STRUCTURAL DESIGN

The next stage was to investigate possible shapes and shape-finding methods. Approaches to shapefinding for surface structures can be through 4 groups of structural shapes:

form-determined shapes	(e.g.geometric shapes)
load-determined shapes	(e.g.funicular shapes)
material-determined shapes	(e.g. bending stiffness)
optimal shapes	(shapes determined by multifunctional shape-optimisation processes

Principal parameters for the manipulation of structural shape are:

dimensional extension	
curvature	(at element-unit-aggregate levels)
boundary	
support	(type and position)

Timber shell structures can utilize all of the above shape types.

Executed examples of geometrically determined form-derived shapes are the Tacoma dome (1982) (Fig.1) which utilizes a triangulated grid layout from laminated elements in the shape of a spherical cap and the ribbed shells for the Faulerbad in Freiburg (1983) (Fig.2) in the shape of hyperbolic paraboloids. In comparison, the geometry of the spherical dome shown in Fig. 3 is made from a grid which is formed from largest circles which are retrained between an upper compression and a lower tension ring (all illustrations from Natterer Herzog Volz (1990)).

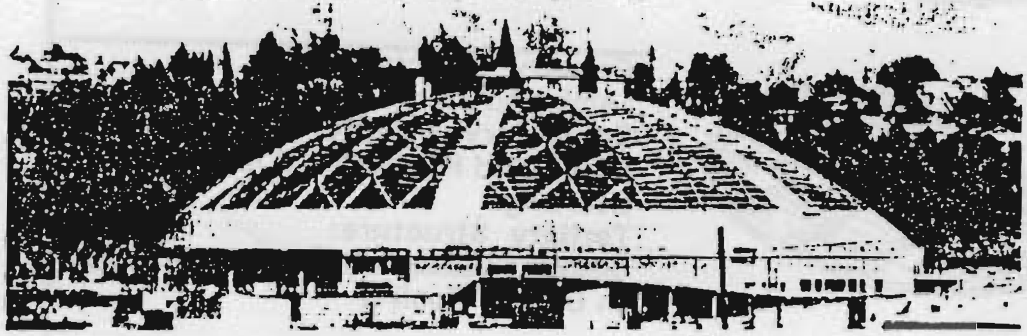


Fig. 1

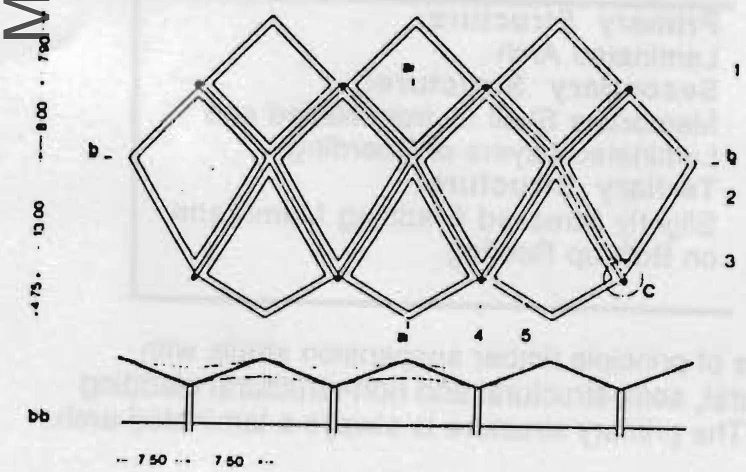


Fig. 2

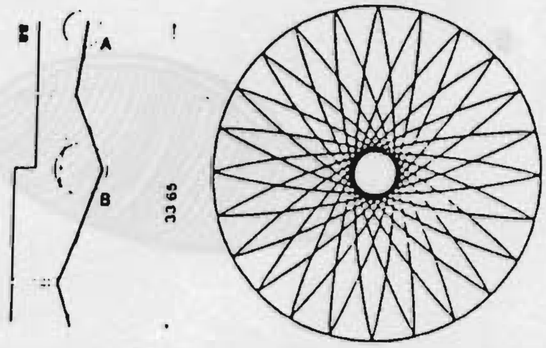


Fig. 3

Load- and material-determined shapes are especially useful as these shapes are already optimized from either aspect: loading or material property (bending stiffness) . These shapes lend themselves readily to further optimisation by considering additional optimisation criteria such as architectural, material-specific and constructional aspects.

At LSRU we have been working on load-determined and on material-determined shapes (timber) leading to a shape vocabulary for suspension shapes using both, physical and computer modelling (Figs.4, 5 & 6, Table 3). Investigations into the suitability of such shapes for particular building applications are in progress and we expect them to lead to a set of guidelines for designers.

Fig. 4

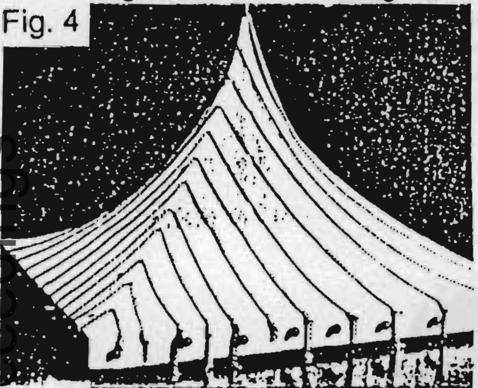


Fig. 5

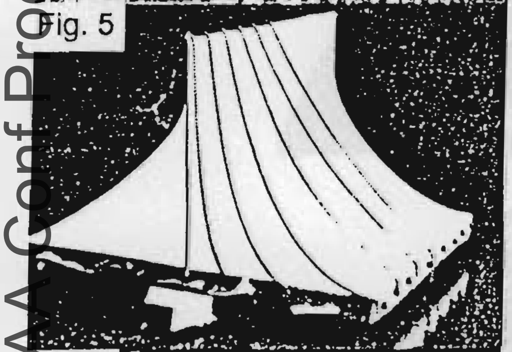
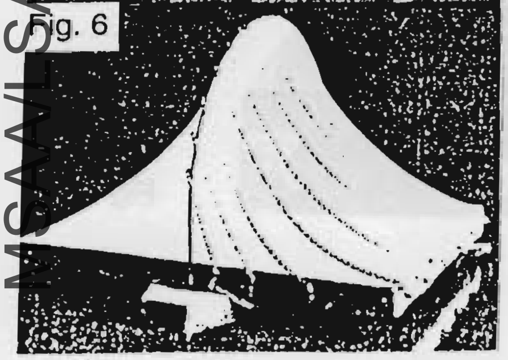


Fig. 6



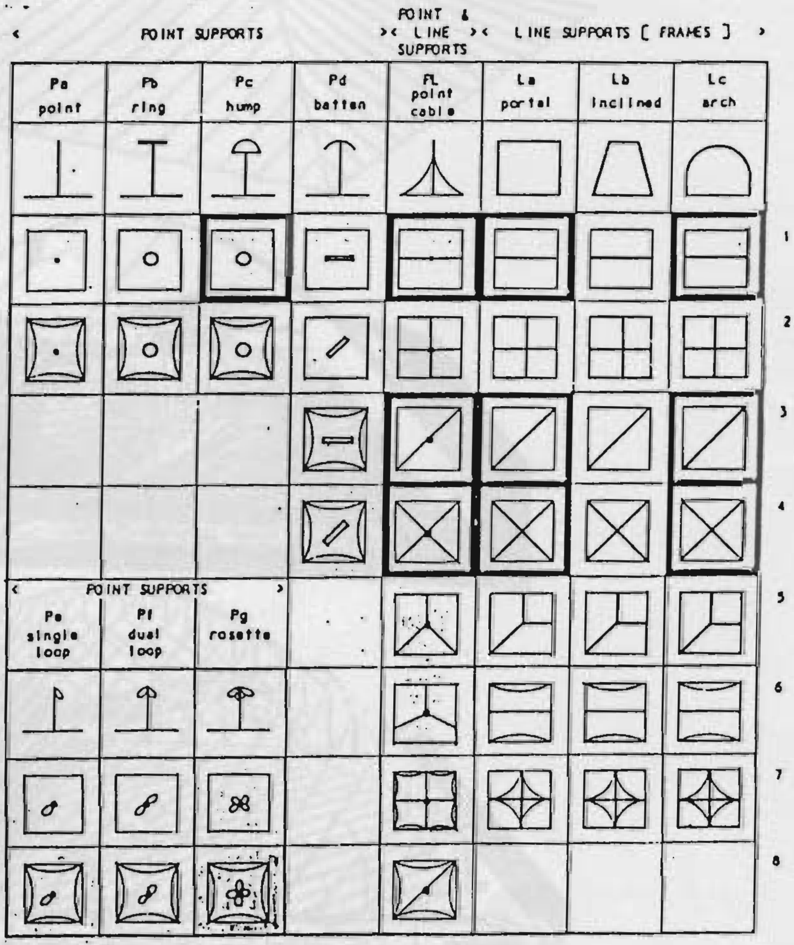


Table 3

Table 3 shows a matrix of possible suspension shapes over square plan with different primary support systems and boundary types.

Figures 4-6 show models for suspension shells over square plan and different primary support systems: mast and suspended beam (4), frame (5), arch (6).

One of these shapes, a suspension ribbed shell over square plan and supported by an arch positioned across the diagonal was developed as a test model for a study of the Forschungsgruppe Membranbespannte Holzkonstruktionen in Austria (Figures 7-10). The project involves a comparison of shapes found by three different methods:

1. geometrically by suspending parabolic curves from a parabolic arch
2. using CAD shape-finding for prestressed cable-nets (FASNET: IAGB Stuttgart)
3. by physical modelling on a 1:40 scale model.

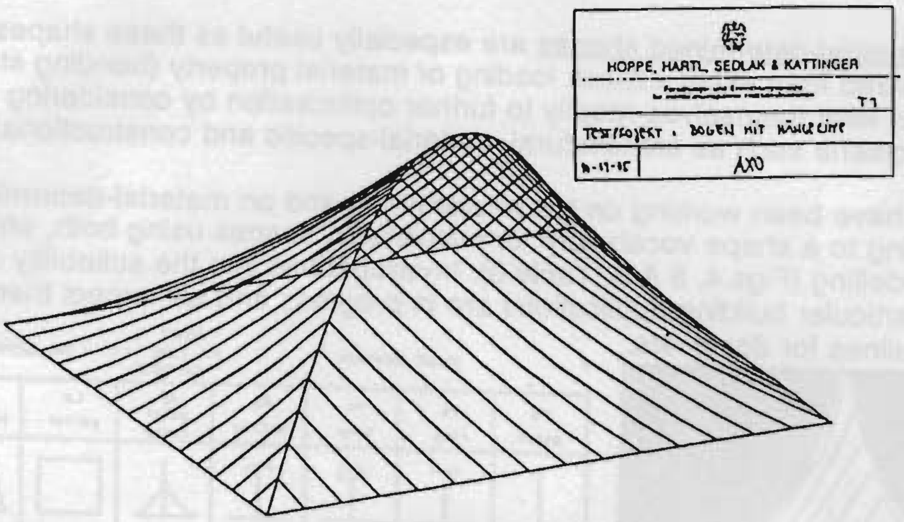


Fig. 7

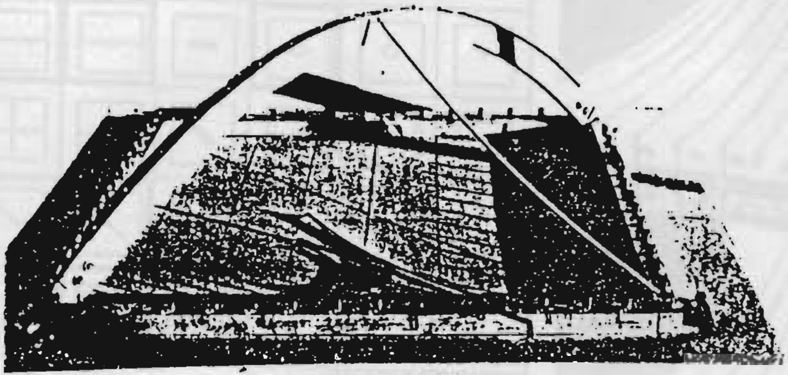


Fig. 8

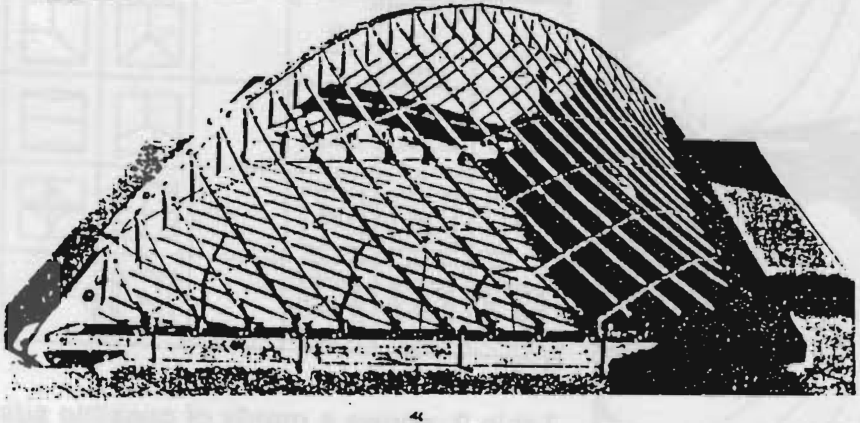


Fig. 9

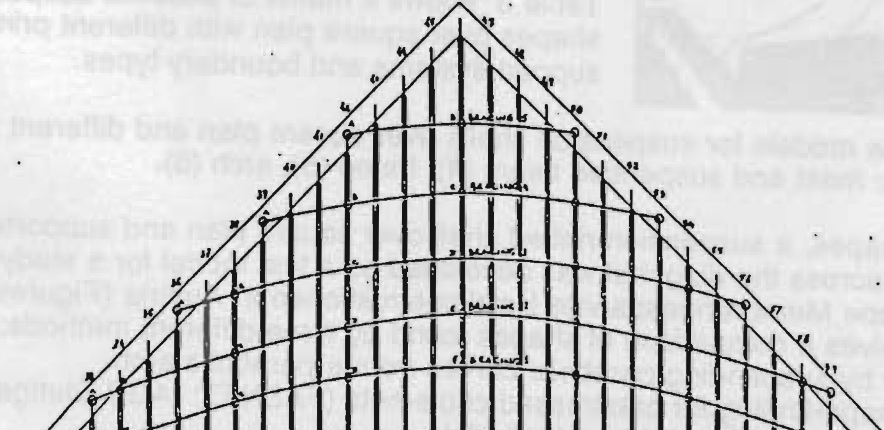


Fig. 10

Presently, the CAD and model shapes are being compared and modifications are introduced to the programme that allow the bending stiffness of net elements to be considered during the shape-finding process.

The CAD package TSHELL which has been developed by Dr.Peter Kneen at the University of New South Wales based on a CAD programme for cable-net and membrane structures (FABDES and POSTLISA) can model beam elements and equal-mesh grids with small modifications (Figures 11 and 12). It must be modified to allow large enough adjustments in the net-geometry to be made to form unequal mesh grids in response to the actual position of restraining elements ("cables").

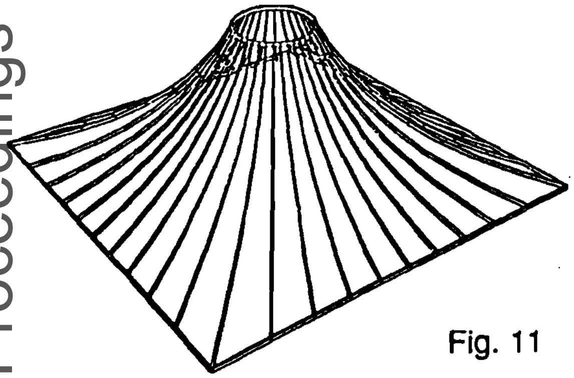


Fig. 11

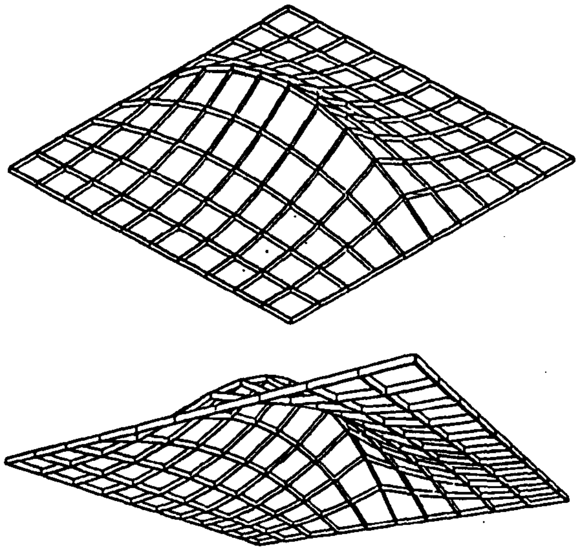


Fig. 12

The significance of developments of material-determined shapes for timber shells is that the structural/architectural shape is found by taking the particular characteristics of the material into account (e.g.bending stiffness, maximum bending radius, connections, type of timber e.g. nailed or laminated boards) rather than forcing the material into a given shape as is the case for purely load-determined or form-determined shapes.

As timber boards and sawn timbers preferably bend in one direction with a degree of twisting possible the layout of the mesh is governed by placing ribs onto a surface in such a way that only bending along one axis occurs. An un-equal mesh results which is essentially free from bi-axial bending as experienced in equal-mesh grids.

Similar investigations into domical compression shells were done based on previous work into equal-mesh grid shells (Fig. 25-26 LSRU Gridshell) and into material-determined shapes for un-equal mesh lattice shells (Figs.13-17) jointly with IBOIS Lausanne and IAGB Stuttgart:
Based on FASNET, a programme was written that allows unequal mesh nets to be generated. The figures 13-15 show the shape development of an unequal mesh gridded shell over square plan with inclined boundary arches. Figure 16 gives the plan and 17 a shape developed from 15 by simulation of an internal pressure load.
In order to find the material-determined shape we constructed a 1:40 scale model of the shape (15) with vertical arch boundaries at LSRU. Figures 18-21 show the construction (18, 19) and the completed model (20, 21). The shape was recorded by 3D-co-ordinate measurement and compared with the CAD shape (see next page).

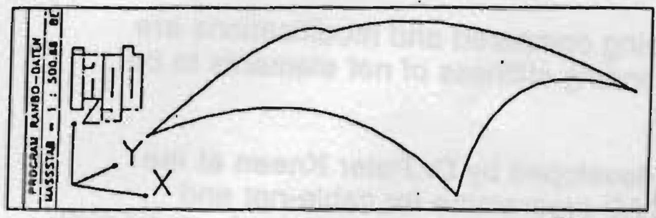


Fig. 13

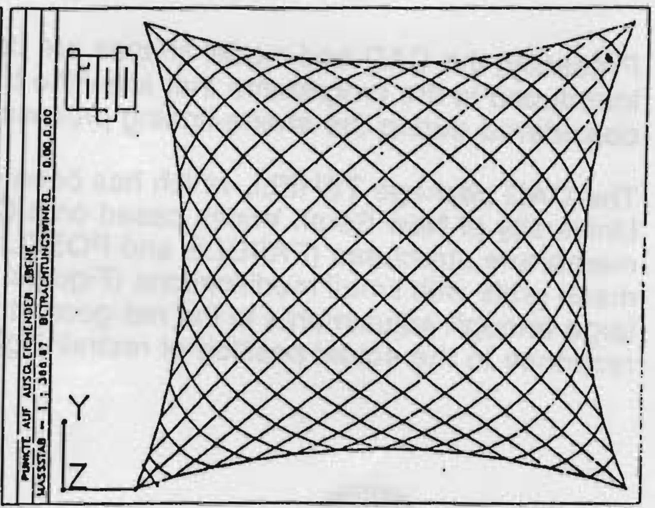


Fig. 16

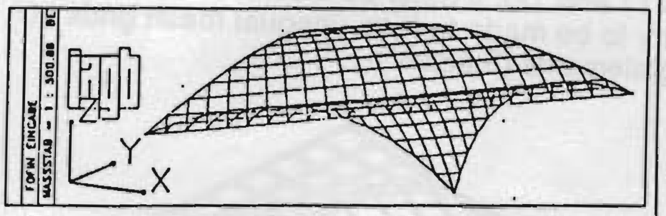


Fig. 14

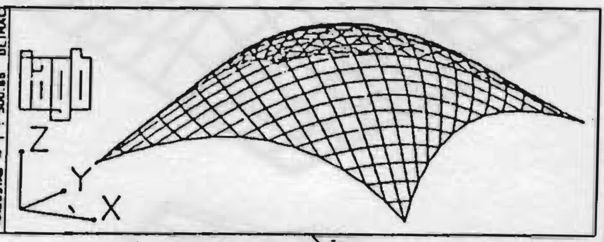


Fig. 15

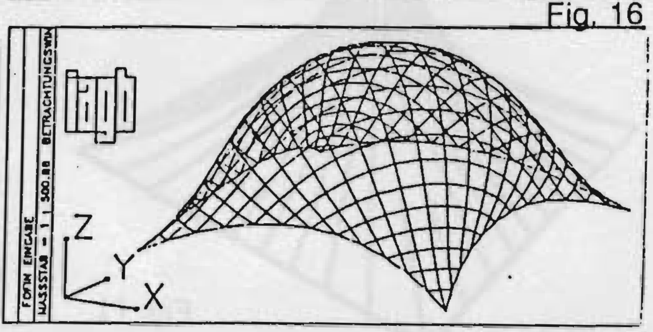


Fig. 17

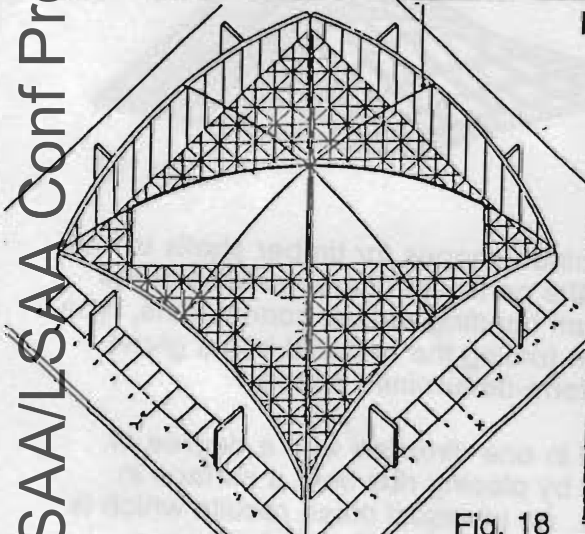


Fig. 18

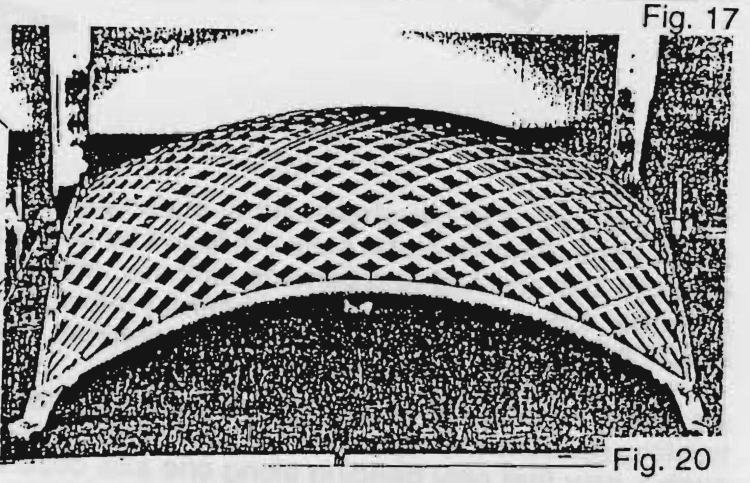


Fig. 20

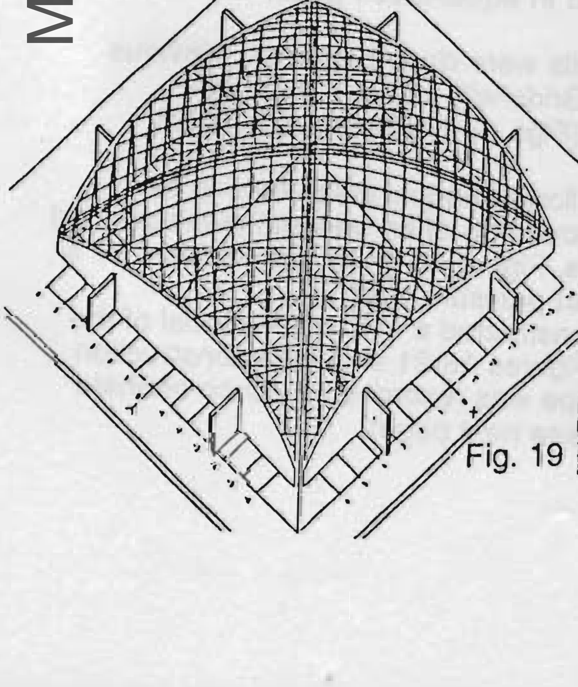


Fig. 19

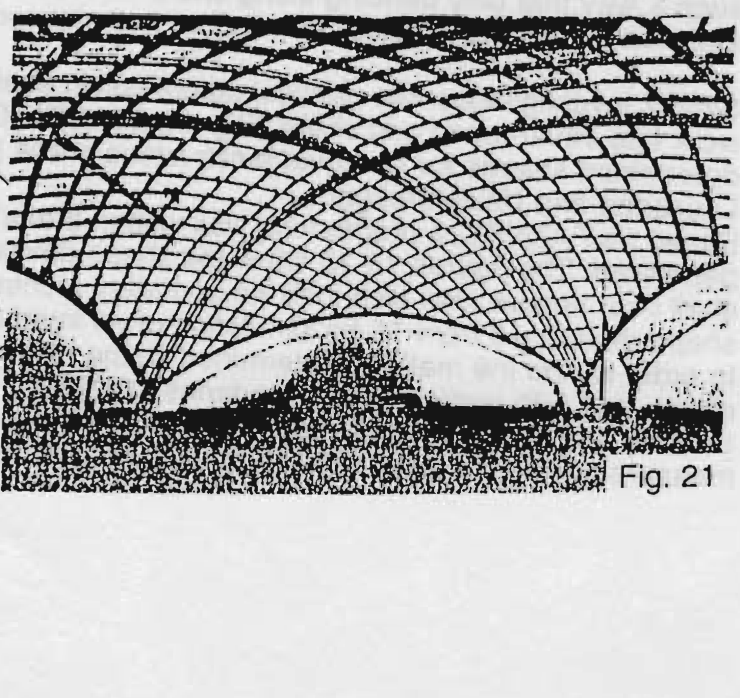


Fig. 21

Figures 22 and 23 give shapes of gridded shells over square plan with horizontal and vertical arch boundaries and with the grid parallel to the boundaries (TSHELL)

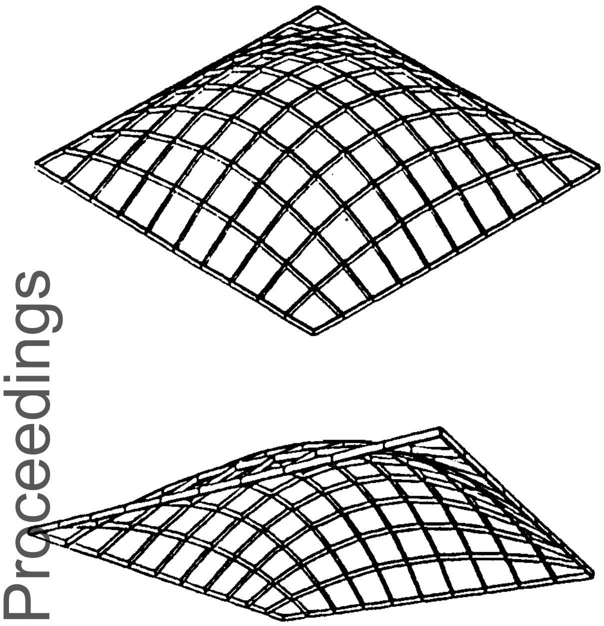


Fig. 22

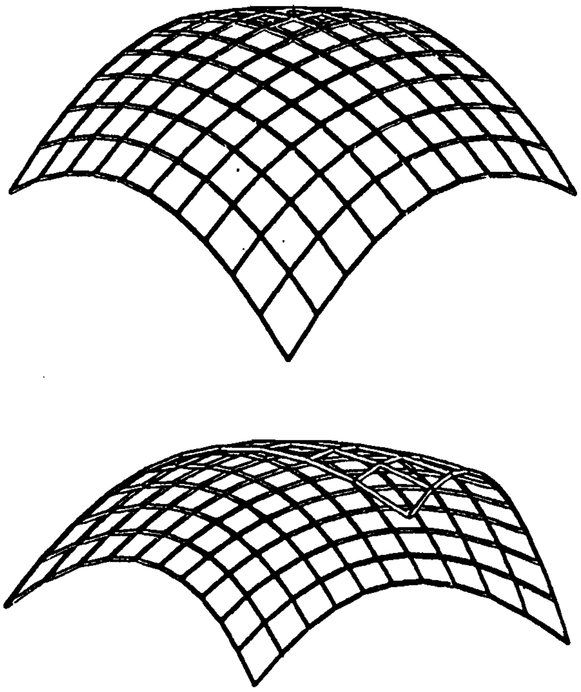


Fig. 23

The Institute of Lightweight Structures (IL) at Stuttgart has conducted model studies into load-determined shapes. Since the early 1970's: suspension shapes based on hanging chains from masts, cables, arches and rigid frames Fig.24 shows a number of different variations for point-supported surfaces with free edges illustrating the effects of shape manipulation by systematic exploration of support placement.

The majority of grid shells constructed todate utilise load-determined shapes with equal-mesh grids. Examples are the Multihall at Mannheim (1975), the LSRU Gridshell (1981) shown in Figs.25 (plan/elevation) and 26 (developed grid) and recently the Exhibition Pavilions for Nara Silk Road (1987). Figs 27- and 28 illustrate CAD shapes of two pavilions (from Natterer Herzog Volz (1990)).

It must be re-emphasised that while load-determined shapes are a suitable starting points for timber shells the rib/grid layout must be optimised for the particular timber material to be employed in order to avoid costly prefabrication of three-dimensionally curved laminated ribs.

For grid shells this optimisation process is not compatible with maintaining equal mesh grids and leads invariably to changes in mesh layout.

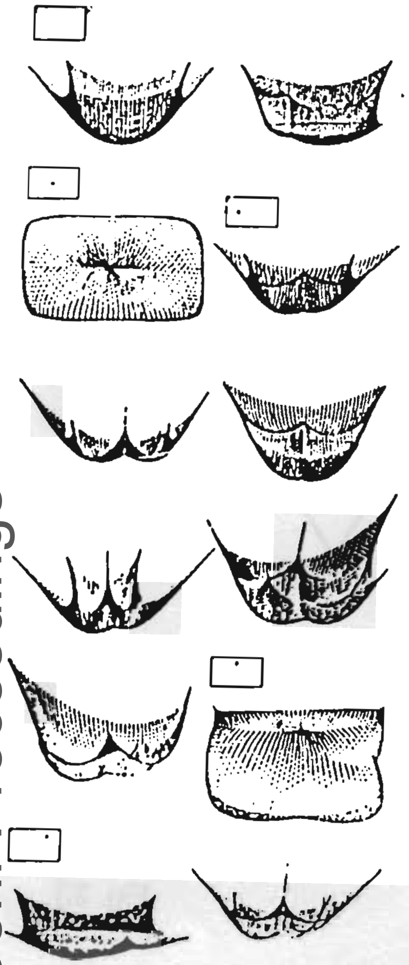


Fig. 24

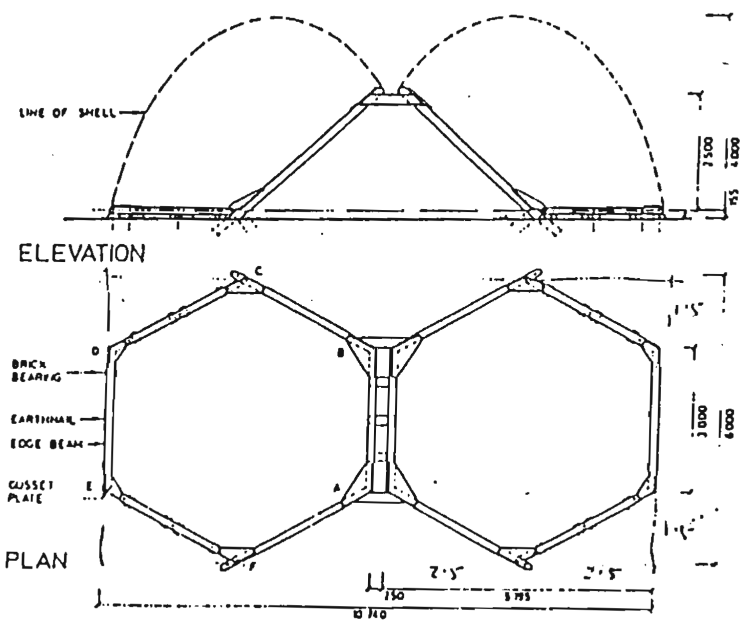


Fig. 25

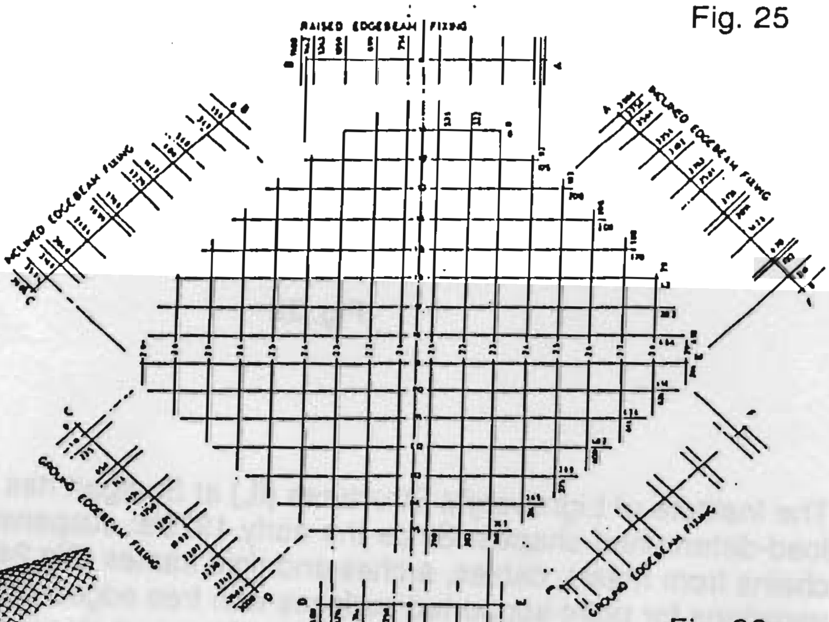
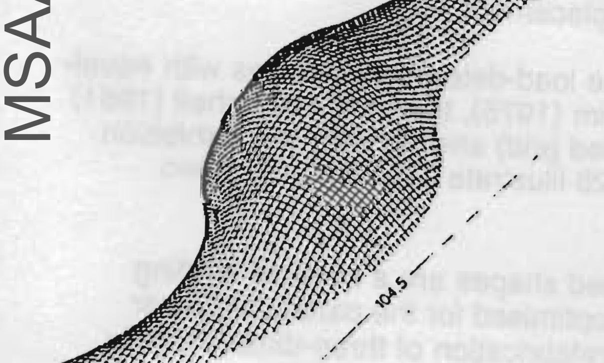
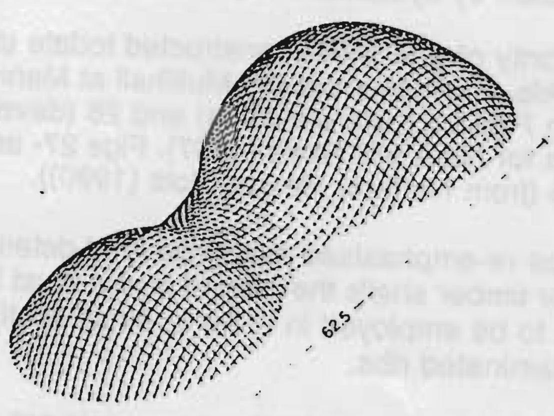


Fig. 26



Theme Pavilion

Fig. 27



Nara Pavilion

Fig. 28

The following table lists available shape-finding methods:

SHAPE-FINDING METHODS:

Form-derived shapes:

Curved surfaces:
translational, rotational and ruled surfaces
for shells, grid(network)shells, ribbed shells

Load-derived shapes ("funicular shapes"):

Suspended Cable/Arch-Frame:
chain
CAD/Shapefinding programme
for suspended beam-, suspended (ribbed) shell structures
Suspended Nets:
chainnet
CAD/Shapefinding programme
for cable-nets, grids, gridshells, shells
Suspended Flexible Membranes:
rubber skin and plaster (selfweight)
CAD/Shapefinding programme
for membrane shells, shells
Inflated Flexible Membranes:
rubber skin and plaster (under pressure)
CAD/Shapefinding programme
for airstructures, membrane shells, shells
Prestressed Flexible Membranes:
soap film, stretch-fabric, rubber-skin
CAD/Shapefinding programme
for anticlastic membrane- and (ribbed) shells, tents, cable-nets

Material-derived shapes:

Bending rods:
spring steel wire, glassfibre or timber rods or strips
for bent-arch -,and shell structures

Optimal shapes:

Interactive multifunctional mathematical optimisation by computer for all types of structures

Table 4 Shape-finding techniques, including physical model and computer-based methods, available for conceptual design of surface structures. The listing identifies type of shape, shapefinding technique and type of structure.

CONCLUSION

In summary, a variety of shape-finding methods are possible and must be chosen in response to the type of shape and material chosen for construction.
Material-determined shapes that respond to the dominant loading case have emerged as the best compromise . for economical structures.
The shape thus becomes the starting point to integrated design development involving architectural, structural, constructional and environmental aspects.
Structure and structural shape are subjected to a multitude of influences from other parameters. Depending on the building type these are often of higher priority for the overall building and must therefore be considered by all involved in the design process.

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