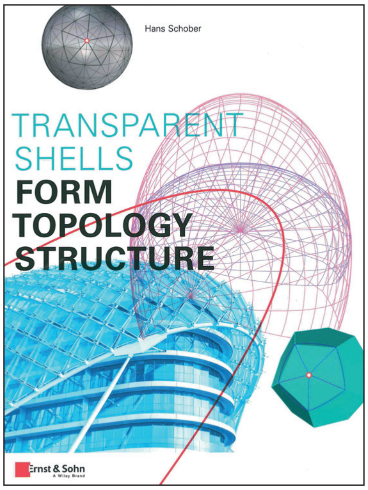
Review

This book will prove useful to engineers and architects in the concept design stage of a transparent shell, concludes Ian Liddell, although it is not technical enough to be used for detail design and construction purposes.

Transparent shells: Form, topology, structure



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Publisher: Ernst & Sohn
Price: £60.00 (hardcover); £49.99 (E-book)
ISBN: 978-3-433-03121-6

Dr Hans Schober worked in the offices of Schlaich Bergermann und Partner (SBP) from 1982 until his retirement in 2009, becoming a partner in 1992. This book contains a lot of examples of remarkable glazed roofs supported on reticulated shell structures from the SBP portfolio.

The book is divided into eight chapters. The first three entitled: "Introduction to shells", "History" and "Design principles of grid shells" are of an introductory nature. The first chapter on shell behaviour I found particularly limited since it just covered spherical shells with membrane forces in the radial (meridional) and hoop directions, while the reality is much more complicated. Chapter 2 includes some historical examples of Victorian iron and glass structures from Paris and Milan, as well as quite a bit on the subdivisions of a sphere based on the platonic solids and the example of the structure of the Zeiss Planetarium (Jena, Germany) by Bauersfeld and Dischinger.

The story doesn't really begin until Chapter 3. This starts with a few earlier examples of Jörg Schlaich's work with cable nets plus a reference to the Mannheim grid shell by Frei Otto for the 1974 Bundesgartenschau. In 1988, SBP was selected to design a glass dome for a pool in Neckarsulm. It was to be as transparent as possible; hence, they adopted a quadrilateral grid on a spherical surface and, trying to standardise the elements, went for equal length members and an adaptable node that could rotate to accommodate all the mesh angles. The result was that the glass panes did not lie

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in planes and had to be formed as parts of a sphere, and then the grid elements had to be curved as well. Because the nodes were basically pinned, they also had to add diagonal cables across the meshes to stiffen the grid so it would act like a shell. The construction of this structure is well illustrated and there is a comment that the spherically curved insulating glass cost more than double the price of flat glass.

For their next project, a covered courtyard in Hamburg, SBP adopted barrel vault geometry for most of it, with a small area of double curvature in which the quadrilateral glass panels could be twisted on site, or where the twist was too great they were divided diagonally. Similar construction details to the Neckarsulm pool were used. After this, the author realised that it would be a better idea to devise geometries for making doubly curved grid structures where the mesh quadrilaterals were planar.

Chapter 4, which occupies 40% of the book, is titled "Graphic design principles for grid shells with flat quadrilateral meshes". It covers various geometric methods for producing singly and doubly curved surfaces that can be covered with flat glass panes. The methods described include translational surfaces where a curve, the generatrix, lying in a plane is translated, possibly in three dimensions (3D), keeping the planes parallel (if two of the edges of a quadrilateral are parallel then its surface will be planar) and rotational, where the plane of the curve is rotated about an axis that lies in the plane so that the quadrilaterals are planar by symmetry. Additional shapes can be generated by a combination of scaling the generatrix and rotating or translating its plane. It is also demonstrated how shapes can be joined into arrays to make extended canopies covering large areas using flat quadrilateral panels.

All the geometries discussed in Chapter 4 cannot be fitted onto a random boundary. The generated surface would have to be stopped off close to the desired boundary and infill panels added. In Chapter 5, so-called free-form grid shells are discussed. These can be fitted onto different boundaries not defined specifically by the shell geometry. Any doubly curved surface can be covered with a triangular net that will have flat panels, and examples of this are included. However, quadrilateral panels have a better appearance and can reduce costs. The author shows how the glass industry now accepts that a small amount of warping can be acceptable. He also shows some methods of mixing triangular panes with quadrilaterals or stepping quadrilateral panes to accommodate a curved surface.

In Chapter 6, methods of form-finding and optimisation are presented. The methods include NURBS-based surface generation using the software Rhino, and a method using Sofistik to model a rubber sheet, presumably under pressure or gravity loading. There is a brief mention of dynamic relaxation, a solution process for physical modelling that allows large deflections and more information on the force-density method. This last is widely used in Germany since its development by Professor Linkwitz's Institut für Ingenieurgeodäsie at Stuttgart and has the advantage of distributing the triangles evenly over the surface.

Chapter 7 has two pages on the structural design of grid shells. The intention is to highlight the special features that apply to the structural analysis of grid shells. These include the stiffness of node connections in the case of bolted nodes, the stiffness of cable ties and the effect of offsets at the nodes and the estimation of buckling loads. For this last, which is the most likely mode of failure, the use of non-linear software with built-in initial imperfections is advised. Finally, it is noted that the calculations involve high-performance software and should be used by engineers who are familiar with such analyses. In my view, they should also be checked by a "proof-engineer".

Chapter 8 has a list of the glazed grid shells engineered by SBP, some 40 in total. There is also a presentation of all the different node types (22) that they have used over the years. Nodes, of course, are a part of the construction process, as well as structure and architecture, and the contractors have a major input into their development, so it is interesting to see the number of different solutions to the problems. Generally, the attachment of the glass and its sealing is not shown or is just indicated in a photo or a section. However, the problem of twist along the member lines between the nodes is discussed. The members are not twisted themselves and this results in discontinuities at the nodes unless circular sections are used. Even with the flat-panel quadrilateral grid, there will be discontinuities in angles over the members and the problem of four lines of seals meeting at a node. The seals are probably the elements with the shortest anticipated life and costly to replace.

The final chapter is a philosophical discussion of the design process and who does what, etc. The discussion is mainly about selection of form, a process between the architect and the engineer which is largely the topic of this book. The necessary input from a specialist contractor is not included.

Summary

I think this book is intended primarily for architects and engineers who may work with them. It's quite technical in a patchy way – there is some maths to introduce the ideas of how shells carry load, but this is not carried through to 3D. There is also some

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maths for defining the geometric curves used in the form generation examples that I would say is A-level stuff.

These days CAD software will generate surfaces using NURBS functions to generate very complex forms. As the author points out, similar forms can be generated using conventional geometry: circles and other conic sections can be translated, rotated or scaled to generate predictable forms that can be built using quadrilateral grids that have flat panes of glass. This is not a new idea, but one that has been forgotten in the excitement of the on-screen development of 3D surfaces in the computer age. A benefit of this process is that the resulting form is under the control of the designers and the glazing costs are greatly reduced.

The other section that will be of great help to designers is where examples of node connections are presented. Although there is a large range of different structures presented, I think it is unfortunate that examples by other design teams are omitted. The use of the book will be mainly in the concept design stage since, as noted, highly experienced engineers and contractors will be required for the detail design and construction.

Ian Liddell

Ian Liddell is a Fellow and Gold Medallist of the Institution of Structural Engineers and a Fellow of the Royal Academy of Engineering. He was a founding partner of BuroHappold and was the engineer in charge of the work on the huge timber grid shell for the Mannheim Bundesgartenschau in 1973–74.