INNOVATIVE MORPHOLOGICAL DESIGN OF GLASS PLATE STRUCTURES

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INTRODUCTION

Buildings using plane glass elements in the load carrying structure is not a new idea. The large and elegant Victorian palm houses from the time of the industrial revolution often used glass sheets as a bracing element for the steel structure (figure 1). This very appropriate way of using glass has unfortunately almost vanished. Glass has again recently been introduced as a structural element for beams, walls, columns, as an active member in steel trusses, etc. However, very few projects seem to use glass according to its particular properties. The present paper will discuss these properties and express morphological ideas for appropriate shaping, faceting and detailing of structures which are made from glass and similar materials.

GLASS IN NATURE

Glass (SiO_2 being the main component) is widely used in nature as a material for skeletal force-resistant structures. Organisms like, e.g., Radiolaria[1] and Glass Sponges (figure 2) are examples of morphologically highly sophisticated structural configurations. However, these structures do not use glass sheets. They are built from clusters of spicules in such a way that they are comparable to fiber-glass. Nature discovered a long time before we did, that fiber-glass in every way (strength, elasticity, reliability, fragility, etc.) is a far better building material than plane glass. The best option for the structural use of glass seems therefore to be as fibres, and it would be of great interest to try to use glass fibre in structures far more extensively than today where it normally appears as reinforcement for plastics and cements. But when we talk about the use of glass in building structures we usually mean plane glass, this fascinating material with the quality of being highly transparent. However, in nature we find structures built from calcite plates which have almost similar general mechanical properties as glass e.g. coccolithophores[2] and sea-urchins[3], see figure 3. Among these we might find inspiration for efficient use of plane glass for structural purposes.

MATERIAL PROPERTIES OF PLANE GLASS

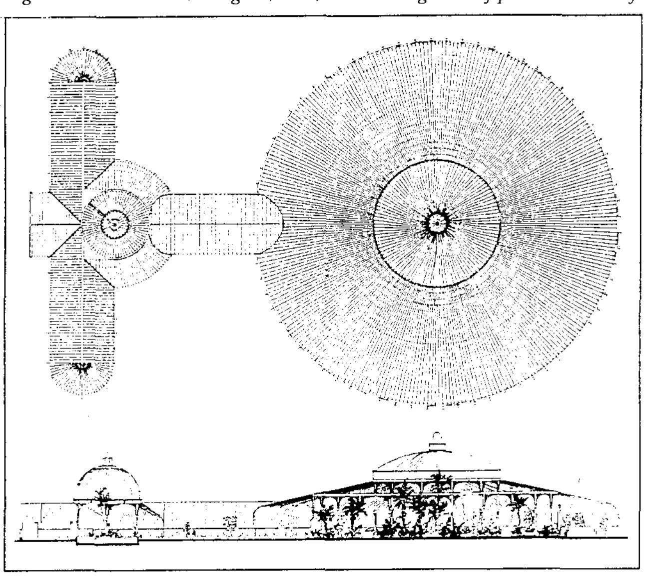
For structural use it is evident to consider tempered or hardened glass as this has much better properties than plain untreated glass. In order to discuss the morphological possibilities for glass structures, it is not necessary to go into details in the field of Material Science. In order to get a rough idea of the properties of plane hardened glass, we can compare it to some well known structural materials:

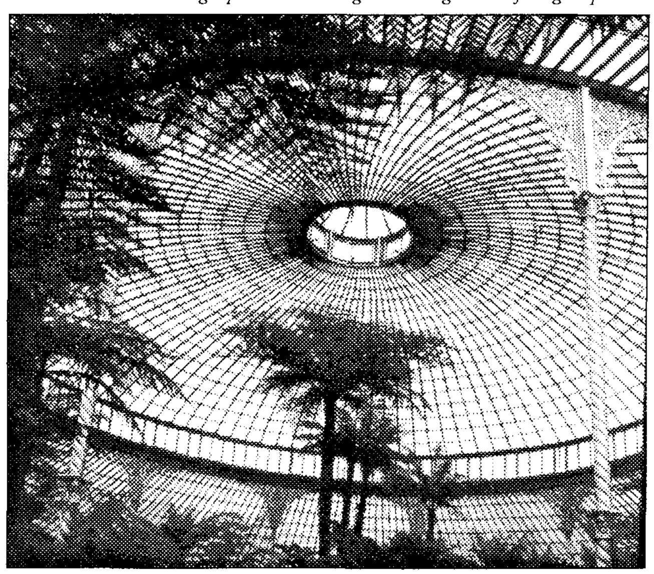
—It has double the strength of mild steel for compression, but half the strength for tension.

—Its rigidity (E-value) is one third of that of steel, or approximately as aluminum, or 5 times higher than that of wood.

—Thermal expansion, which is important in relation to the transfer of forces between glass and, e.g., the casement, is 75%

Figure 1: Kibble Palace, Glasgow (1873). Note the slight out-of-plane curvature of the vertical iron arches on the right photo, indicating the bracing action of the glass panels.



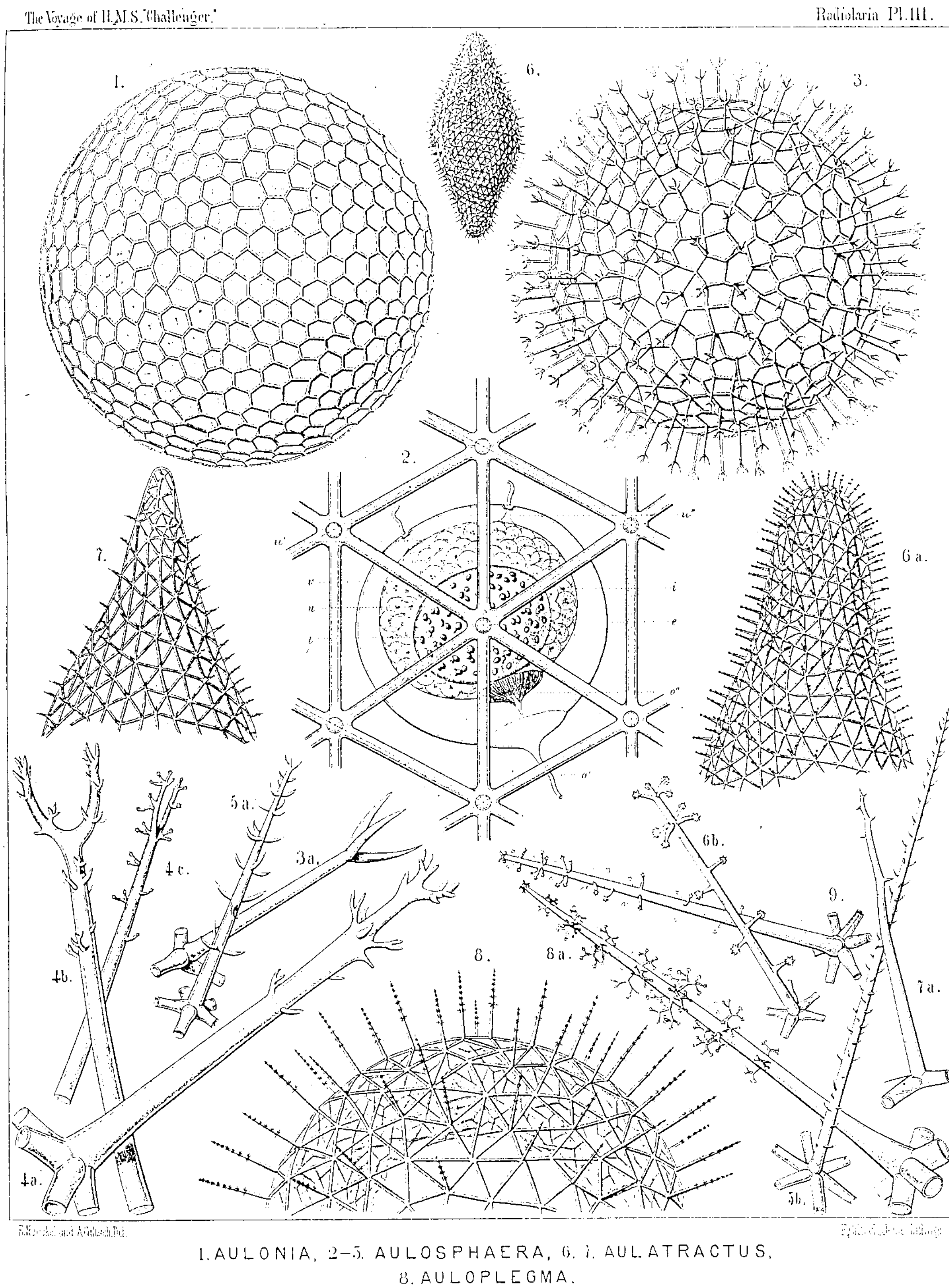


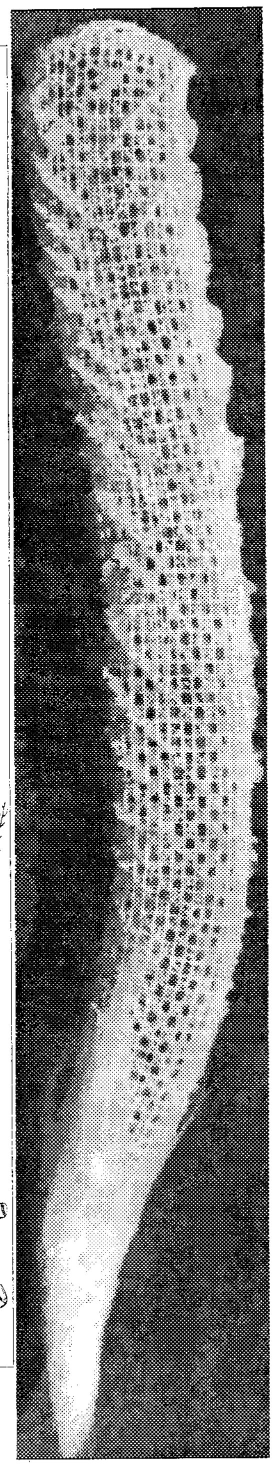
of steel or one-third of aluminum, i.e. closest to steel.
—The specific gravity is one-third of steel, or approximately the same as aluminum, or 4 times the value for timber.
—The maximum working temperature, i.e., without losing much strength is as for aluminum or half of that of steel.
—The "Achilles' heel" of glass is its brittleness. One of the most appropriate ways to reduce this problem is to laminate two or more glass sheets together. As failure will normally only affect one layer, the other layer(s) must hold enough carrying capacity to prevent failure—or the forces must be able to rearrange in the structure until the glass element is replaced.

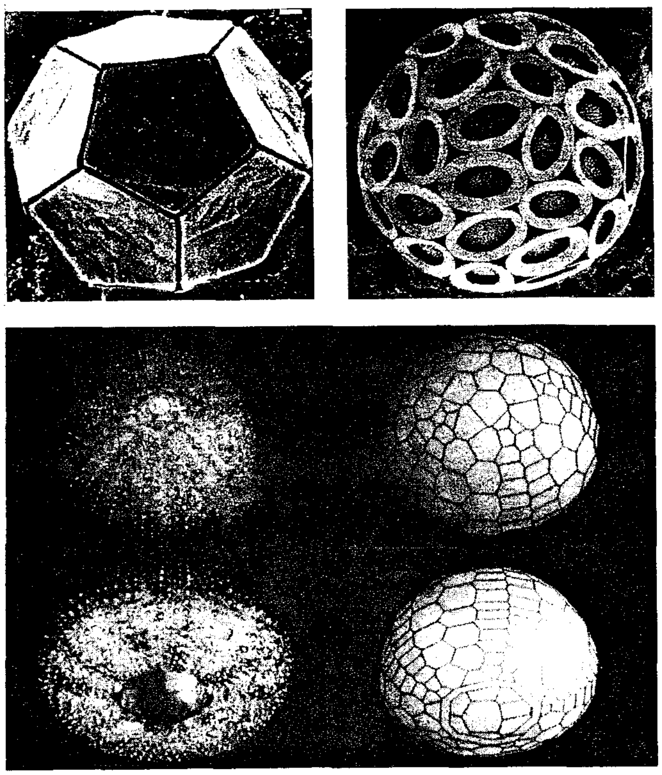
CONVENTIONAL USE OF PLANE GLASS

Under conventional circumstances the self-weight of the glass elements and wind load results in simple tension, compression and/or bending moments. Of these structural actions the bending moments are by far the most dominant

Figure 2: The siliceous marine plankton called Radiolaria (left) and deep sea Glass Sponges (right) show examples of Nature's way of using fibre-glass for its skeletal structure.







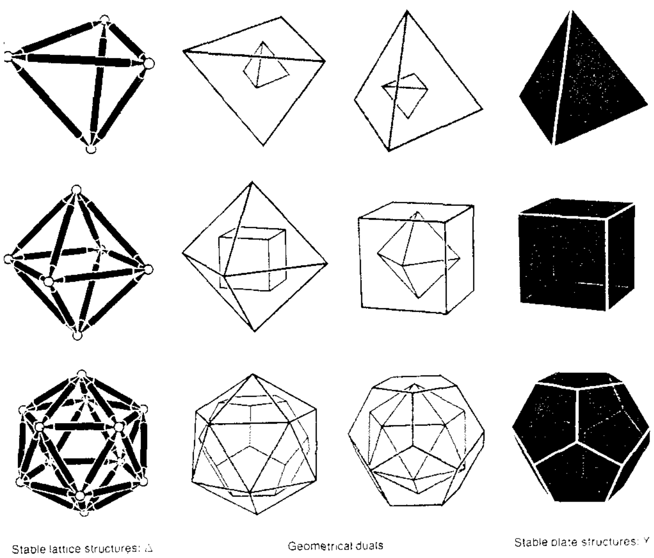


Figure 3: Upper row: microscopic Coccolithophores (Nishida) and macroscopic sea-urchins (lower) in a natural and computer version, showing 3-branched vertex pattern which is significant for pure plate action.

Figure 4: Structural duality follows the well-known geometrical duality. The triangulated polyhedra (tetra-, Octa- and Icosahedra) are stable by pure lattice action (axial forces in the bars), while the 3-branched (tetra-, Hexa, and Dodecahedron) are stable by pure plate action (shear forces across the intersection lines) action.

design load. However, a plane glass sheet which is designed according to the usual bending moments, still contains a lot of bearing capacity for the transfer of forces—preferably distributed forces—in its own plane. This paper deals with the possibilities embedded in this fact—or in other words—investigating the morphology of structures stabilized by plate action.

PURE PLATE ACTION

In a similar way of stabilizing a pure lattice (bar-and-node) structure by tension and compression, a pure plate structure (plane plates hinged together along intersecting shear lines) can be stabilized by the transfer shear forces over the shear lines. The well known characteristic expression for lattice action is the triangle while it is a 3-branched vertex for plate action (figure 4). These two configurations are geometrical duals in our three dimensional world, i.e., if interconnected vertices are substituted with equally intersecting planes a triangle becomes a 3-branched vertex and vice-versa. This duality can be extended to the level of statical properties as rigidity, forces and elasticity [3].

As it is not the purpose of this paper to go into detail about this we must refer to the end notes regarding further reading, but some of the relevant general results are as follows:

A single-layer triangulated structural configuration can only be rigid as a pure lattice structure, and it is rigid if it is closed (like a ball), even that there are some very special non-convex exceptions. The facets are not structurally active and may be removed. Only nodes and bars are needed.

A single-layer structural configuration with only 3-branched vertices can only be rigid as a pure plate structure, and it is rigid if it is closed (here are also some special non-convex exceptions).

A single-layer configuration which is neither fully triangulated nor fully 3-branched cannot be rigid as a pure plate nor as a pure lattice structure, but is rigid (with similar exceptions as above) as a combined lattice and plate structure.

Pure lattice structures are characterized by having concentrated internal forces in bars and nodes, hence well suitable for the use of strong materials as e.g. steel. Pure plate structures distribute the internal forces along the whole length of the shear lines and the total surface of the plates. Distributed forces are of course much better for the use of glass and other similar two-dimensional structural elements than concentrated forces.

This knowledge, embedded in the structural duality, enables plate structures to be generated just as complex as lattice structures are today—in a very simple way. The geometrical transformation, which has the quality to preserve all structural data, is called Polar Reciprocation, and is thoroughly explained in [4] while the structural transformation is explained in [5]. In order to handle the geometrical and structural duality, a computer program has been developed, see [6].

This method of dual transformations has been used in a number of projects made by the author in collaboration with architects, artists and students, as discussed below.

BELLA DOME

Originally the dome in figure 5 was suspended from a roof in Bella Centre in Copenhagen for a building exhibition, and later placed on the ground as shown. This 12m diameter and 6m high dome is a class II, frequency 4 of the Cube (or Octahedron) family and is designed by the author in collaboration with architect T.Ebert, Copenhagen. The plate units are rigid closed frames and made from 68*68 mm timber, bevelled on one side to fit the adjacent frame. The triangular frame-knees are made from 19 mm plywood, depressed and glued.

The intention was to open up the plates as much as possible. The open rigid frame structure is strong enough for the original indoor use, but not strong enough as an outdoor structure. The idea was therefore to strengthen the open wooden frames by adding glass plates. In this situation the wooden bars would act as the casement for the glass, and the glass would, as it is much stiffer than the frame, overtake the plate action almost completely.

MUSEUM LOUNGE

The very regular polyhedral shapes as the above are often considered "too mathematical" and not fit for good architecture. However, these polyhedral shapes may easily be altered to something more appropriate and interesting from an architectural as well as a structural point of view.

By geometrical manipulations, CADual can produce a number of different shapes and facets. At the same time it can evaluate the actual configuration from a statical point of view. For a certain load it is able to determine the efficiency of the structure, i.e. how close the shape is to the equally loaded kinetic net. This enables an interactive design process, dealing with shapes, facetting and structural behavior. Fig.6 shows a procedure for generating structurally and architecturally improved configurations.

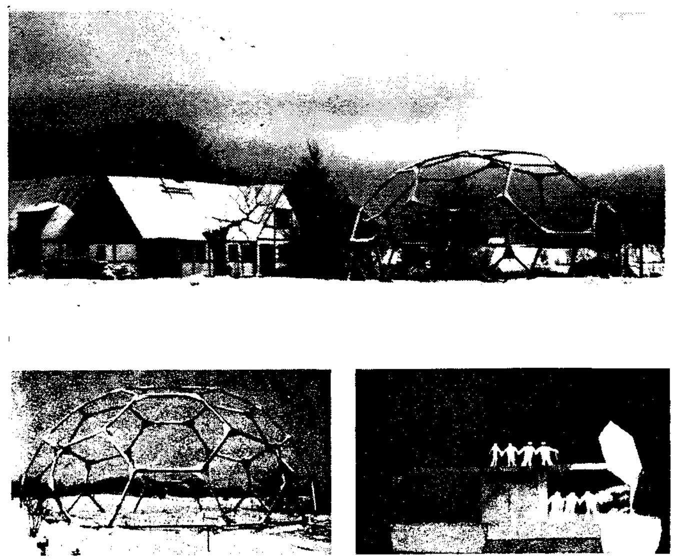
The final project was designed in collaboration with the Danish sculptors M.Joergensen and G.Steenberg for an architectural competition. It was considered whether the glass covering should be structurally active or not, but even if it was absolutely possible, it was chosen to brace the plates by steel rods. Still it gives an appropriate configuration for plane glass used as structural elements.

PENTAGONIA CERAMIC DOME

This project is based on plane ceramic tiles, which have qualitatively the same properties as glass, but is much weaker.

Pentagonia (figure 7) is a single-layer-plate dome-shaped sculpture, 2.8m high and made from 10-to-15mm-thick ceramic tiles, its name is derived from the regular pentagonal top tile and ground plan. The thickness of the tiles is greater than needed from a structural point of view but is necessary to prevent warping of the tiles during firing of the clay. To produce the sculpture, clay slabs of the required thickness were cut directly to the "fold-out" pattern generated by CADual. A sand/cement mortar was used to connect the ceramic tile plates together. Ceramic artists Esben Madsen and Gunhild Rudjord created the form—a paraboloid of revolution—in collaboration with the author. CADual indicated that this form is ideal to resist uniform vertical load—as is, nearly, the self-weight of the structure. Pentagonia is at present being exhibited at the Jorn Museum in Silkeborg in Denmark.

As a ceramic tile is in every way much weaker than glass, it shows at the same time an almost ideal shape and



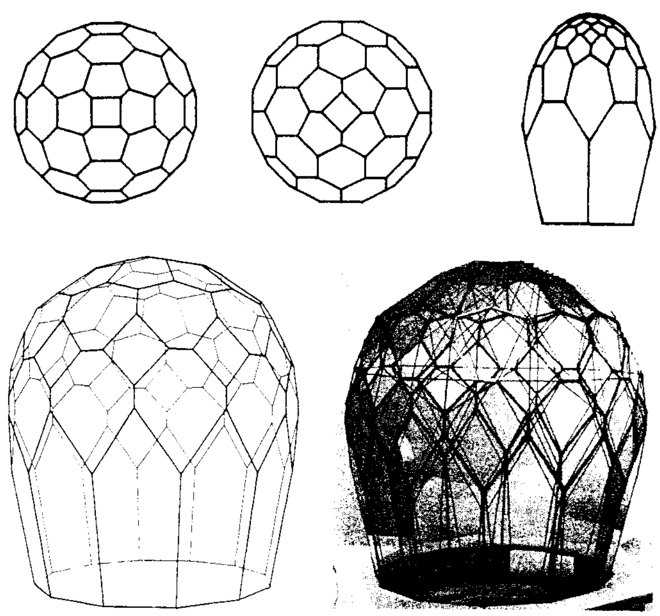
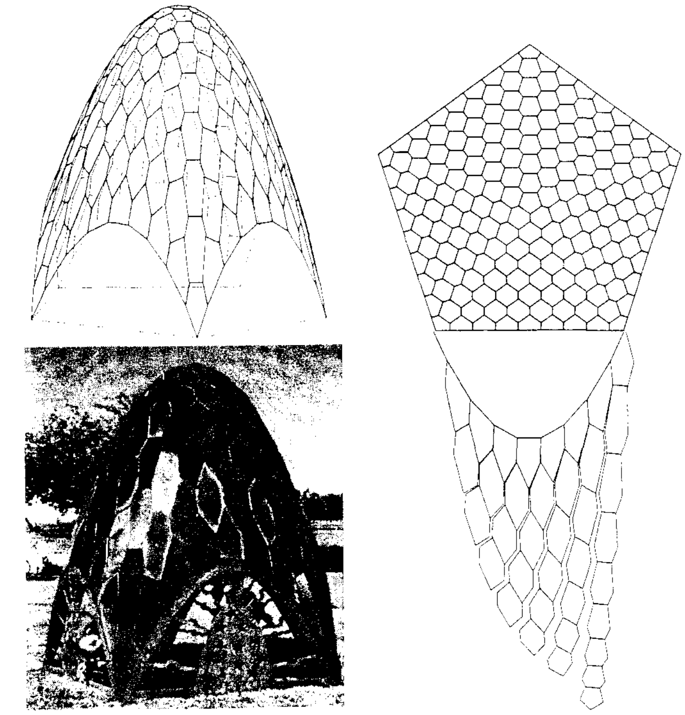


Figure 5: The Bella Dome is a polyhedral pure plate structure with plates as open rigid frames. The openings might be adequately closed by plane glass, which then will overtake the plate action. In fact the wooden frames could then be eliminated, leaving a pure glass plate dome as indicated at the lower right. This seems to be the ultimate solution for glass structures.

Figure 6a: A class I, frequency 4 cube breakdown has for self-weight of the plates an efficiency of 38% (100% is perfect shape for the load). b: The same polyhedron rotated 45 degrees shows an increase of the efficiency to 50%. It is interesting to notice that a spherical polyhedron has different efficiencies when it is rotated. c: Now, the polyhedron is manipulated by CADual into a much more interesting configuration and, at the same time, the efficiency has increased to 75%. d: Further manipulation led to the final shape, and finally the physical model.



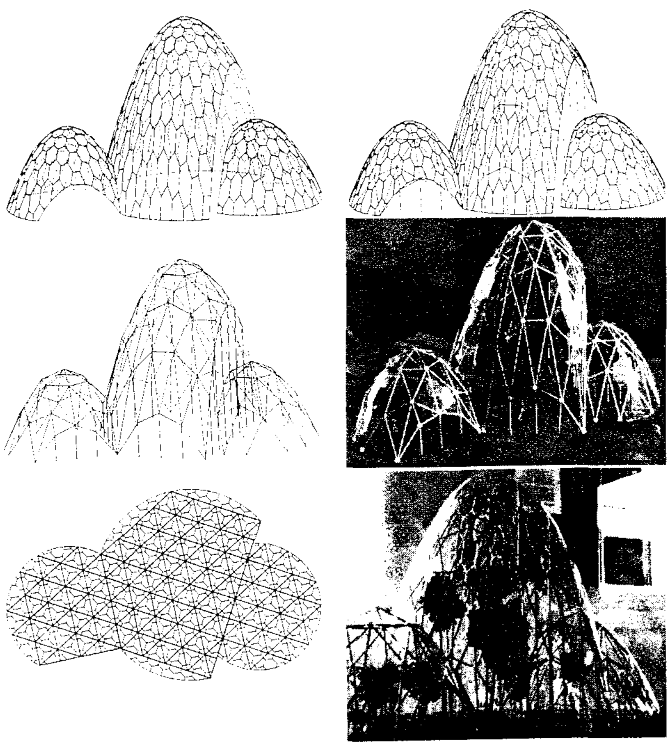


Figure 7: The ceramic dome Pentagonia, the computer model and the cutting pattern for the clay.

Figure 8: Palm House project. Note the perfect regular pattern for the horizontal projection of the structure.

facetting for a pure plate pure glass structure. The investigations by CADual show that shape, faceting and structural properties of Pentagonia makes this configuration quite unique and very appropriate for glass structures. It seems to be the first time that this configuration has been suggested and statically documented. The closest seems to be Gaudi's visionary work with kinetic nets and ceramic tiles [7], even Gaudi used reversed chain curves and did not use the tiles as structural elements.

PALM HOUSE PROJECT

The Pentagonia concept for an ideally shaped glass structure was used as a basis for the final examination project by two B.Sc.(eng.) students[8]. The project was a 30 m high botanical glass house (fig.8). In order to secure the glass plate structure from progressive collapse in case of breakage of a single glass sheet, the 3-branched fine-meshed glass structure was complemented by a triangulated coarse-meshed steel lattice structure. Both the steel nodes and the glass planes follow the same theoretical paraboloid of revolution with the steel nodes on the surface and the bars inside, whilst the glass plates are all external intersecting tangential planes to the same surface. The apparently quite complicated geometry is generated extremely easily by the Dual Method on CADual.

A well-known problem when combining facetted spherical forms is matching boundaries but, as the projection of the glass plates onto the ground plan create regular and equal hexagons, the combination of equivalent paraboloids fit perfectly together. As the glass is a part of the structure and as it is relatively heavy, it is important that the shape is ideal for its self-weight, hence the parabolic form. In the case of modest wind load on the smooth and aero-dynamic shape combined with the fairly large self-weight, the total efficiency of the shape will only slightly decrease.

As the lattice structure is only introduced for emergency reasons, it can be constructed quite slender.

The structural design showed that all the glass plates could be cut from long glass strips of 2 m width, while the lengths were different, which is very relevant for glass production. The static analysis resulted in 12mm hardened glass which was laminated on 3 mm soft glass.

The connection between the glass plates was suggested as toothed which is directly inspired by the toothed join between the plates of the sea-urchin.

MARKET HALL PROJECT

The same two students continued their studies and finished their M.Sc. with a project[9] which was a continuation of the palm house. This time they chose a 16 m tall and 45 m long market hall roof as another type of combined glass plate and steel lattice structure (figure 9). The main parabolic shape is the same as before, but in this structure, the steel and glass structure works intimately together as one structural envelope. The geometry shows quadrilateral plane plates, four-branched nodes which give a projection of perfect squares. The hardened glass plates, cut from a 2 m wide glass strip, was calculated to be of 8 mm thickness, laminated with 3 mm ordinary glass. Because of the necessary transfer of forces between glass and steel bars, and because of the different thermal expansion of these two materials, a friction connection as a steel plate fitting with an elastomer

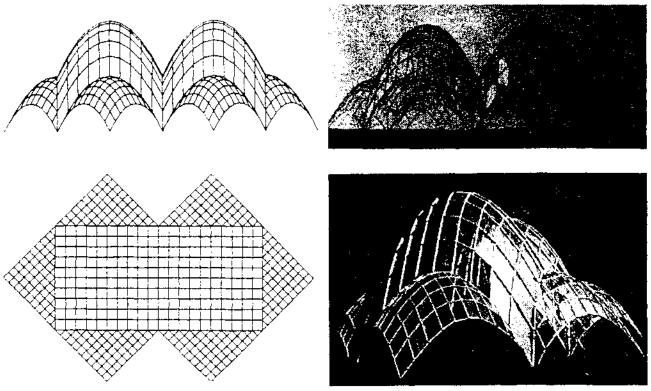


Figure 9: Market Hall project. Note that the horizontal projection creates perfect squares. This project has structural similarities to Kibbles Palace as shown in figure 1.

as lining and fastened by a prestressed bolt was suggested as a realistic possibility.

CONCLUSION

The projects described in this paper are a side-effect of the author's research on the concept of structural duality. It has been fascinating to see that this overlooked concept has led to a deeper insight into Nature's structures as well as suggestions for new and appropriate morphological design and computation of structures made by plane glass sheets.

REFERENCES

1. *Report on the Radiolaria collected by H.M.S. Challenger expedition during the years 1873-1876*, by Ernst Haeckel. 1887, Vol. XVIII
2. *Coccolithophores.* Edited by Winter & Siesser. Cambridge University Press 1994.
3. Wester,T. *Structural Order in Space* (1983). Royal Danish Academy of Fine Arts. Copenhagen, Denmark.
4. Cundy,H.M. and Rollet,A.P.: *Mathematical Models*, Tarquin Publications, Oxford University Press, 1961.
5. Wester,T. *The Plate-Lattice Dualism.* Paper in the Proceedings of the IASS Colloquium on Space Structures for Sports Buildings, edited By Lan & Zhilian. Elsevier Applied Science, London, 1987.
6. Wester,T. *CADual:* Computer Aided Duality. Royal Academy of Fine Arts, Copenhagen. Please contact the author for further information.
7. Zerbst.R. *Antoni Gaudi.* pp.80-81. Taschen Verlag Köln 1987.
8. P.Ohannessian and N.Grunnet: *Projektering af en Glasskivekuppel* (The Design of a Glass Plate Dome). Final examination project (B.Sc.eng.) at the Danish Engineering Academy, Lyngby, Denmark. In Danish.
9. P.Ohannessian and N.Grunnet: *Samvirkning mellem Gitter- og Skivekonstruktioner* (Co-operation between Plate and Lattice Structures). Final examination project (M.Sc.eng.) at the Danish Technical University, Lyngby, Denmark. In Danish.

FURTHER READING, PUBLISHED BY THE AUTHOR:

-*A Geodesic Dome-Type Based on Pure Plate Action* (1990). Paper in the International Journal of Space Structures, Vol.5 Nos 3 & 4. Special Issue on Geodesic Forms, edited by T.Tarnai.

-*Structural Morphology and Natural Structures* (1994). Paper in Evolution of Natural Structures, Part 9. Edited by M.Hilliges. SFB 230, University of Stuttgart and Tübingen, Germany.

-*The Fabulous Paraboloid:* Dual Transformation as a Design Method. Paper in Katachi U Symmetry, Springer Verlag Tokyo 1996.