# EXPLORING STRUCTURAL MORPHOLOGY USING CAD

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**Abstract**

Often in the design process the student's imagination is restricted by their inability to visualise, model or accurately sketch ideas for innovative structural systems, By using CAD as a design tool it is possible to explore the morphology of complex structures and to be able to produce perspective drawings of them with relative ease. Within AutoCAD there is a small library of standard three-dimensional objects and surfaces that can be called upon to generate more complex forms. However, to further facilitate the architectural design process, an extended library of innovative structural forms would allow the professional designer, or student, greater design freedom and any increase in the palette of structural forms available should stimulate creativity. As practical examples, the paper describes how students have been encouraged to experiment with the use of structures which can only be physically modelled with difficulty and which are also difficult to represent on the two-dimensional surface of the drawing board unless the geometry has previously been determined by the methods described. These are (i) Reciprocal Frame three-dimensional beam grillage structures and (ii) plate domes created from lattice structures by point-to-plane duality. The problem, of representation of these structures has been overcome, in the first case, by generating AutoLISP procedures to draw the complex three-dimensional geometrical form automatically in AutoCAD and, in the second case, by the development of the computer program CADual.

## 1. Introduction

CAD is a powerful tool in the process of architectural design and may be used to explore more freely the morphology of non-conventional structures that may be difficult to conceive either by physical modelling or on the drawing board. In the field of education it can often be a challenging exercise to ask the students to generate designs using some innovative or non-conventional structure. The students, however, are often discouraged from investigating a number of alternative solutions if the structural form demands an inordinate amount of time to draw, even with the aid of standard CAD methods on a computer, It is advantageous, therefore, if the basic structural geometry can be generated, quickly, in alternative shapes and sizes and then modified, if necessary, to suit the student's own design concepts.

The innovative structural forms described below are introduced to the students at the University of Nottingham and the Royal Danish Academy of Fine Arts in lecture courses. As a result, several of them are tempted to experiment with them in the studio design projects, which are generally limited to buildings with small to medium spans at this stage of the course. However, although simple in concept, the three-dimensional structures are difficult to draw in two dimensions and it was found that, when the students discovered this difficulty, they were reluctant to try and use the particular systems after all.

It was felt that the students were, therefore, missing many interesting opportunities to design buildings with non-conventional geometry and form, and the authors are currently trying to make their task easier by enabling them to experiment with the complex geometry through the medium of CAD.

## 2. Examples of the three-dimensional structural systems

There are, of course, many exciting three-dimensional structural systems but two particular innovative systems (firstly, the Reciprocal Frame and secondly, facetted plate domes) are used here to illustrate the advantages of using CAD to explore their complex geometry.

### 2.1 The Reciprocal Frame

At Nottingham, research is currently being carried out into the morphology of a particular structure known in the United Kingdom as the Reciprocal Frame and in Germany as the Mandala Dach (see Figure 1).

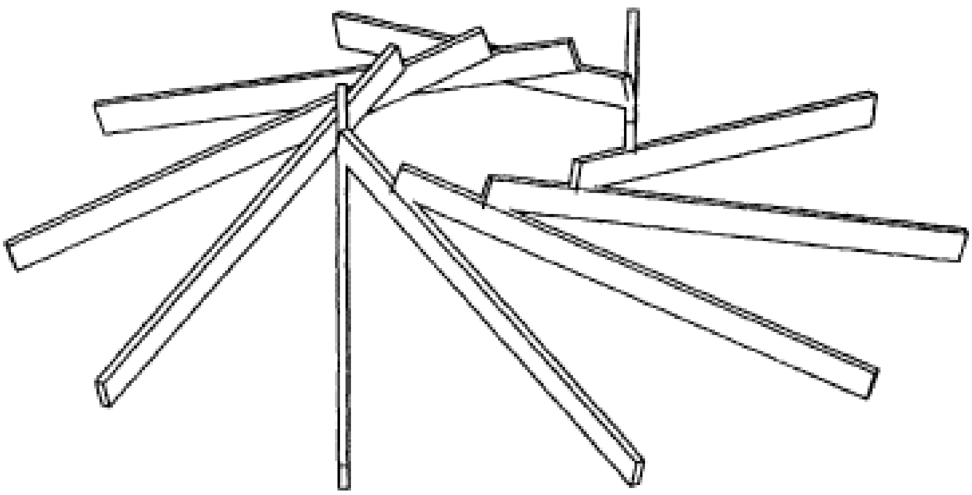


Figure 1. A typical Reciprocal Frame 3-dimensional beam grillage.

This is a structure, used mainly for roofs, where a closed, circuit of beams is formed in which the outer end of each beam rests on a perimeter support, and the inner end rests at some point on the following adjacent beam whilst in turn supporting the inner end of the preceding adjacent beam. In this way a three-dimensional structure is produced where all beams are mutually supporting. When viewed from below, this can be visually very dynamic as the primary beam structure appears to be rotating about an axis in empty space at the centre of the roof. Additionally, there is no apparent means of support for the inner ends of the beams which generates a certain visual tension to the structural form.

Full scale structures of up to 11 metres in diameter have been built by the U.K. patentee Graham Brown. A similar structure, of approximately 7 metres diameter, has been used recently for the Seiwa Bunraku Puppet Theatre, on the island of Kyushu in southern Japan [1] and in Lausanne in Switzerland a salt storage building of 26 metre span was constructed with 11 beams, using an analogous planar grillage [2]. In the past examples have also been constructed by the Spanish architect Jujol who worked with Gaudi [3].

### 2.1.1 Reciprocal Frame geometry

The simplest buildings using the reciprocal frame are generally polygonal or circular in form but even in these cases there are several variables to be considered, some of which are mutually dependent. These are: -

- the number of beams - which does not necessarily have to equal the number of sides of a polygonal building
- the length of beams
- the size of the outer polygon or circle
- the size of the central polygon or circle
- the rise of the roof from the outer supports to the central polygon
- the direction of rotation (clockwise or anti-clockwise).

Within these parameters there is considerable scope for design flexibility and it is advantageous to be able to rapidly draw and view these alternative configurations in three dimensions. Additional exciting architectural possibilities can be obtained if some of the conditions of regularity are relaxed. For example, alternative plan forms (either regular or irregular) may be considered for the perimeter supports and central polygon, the angles in plan between adjacent beams may be varied around the circuit, the point of contact between adjacent beams may be varied (and, consequently, the slope, length and rise of each beam) etc. However, with each reduction in regularity the structure becomes more difficult to visualise or model.

### 2.1.2 Visualisation of the Reciprocal Frame form

It would appear reasonably straightforward to visualise simple versions of the grillage in three-dimensional space with a physical model using, for example, small timber beams of the correct scale. However, due to the inter-dependent relationship between the rise of the roof from the outer supports to the central polygon and the number of beams, there is only one depth of beam that can be used for any given configuration. This means that a new model must be made for each alternative roof configuration, otherwise, either additional packing is required between the beams it their intersections, or the beams must be suitably notched on their underside at the inner end. It must be noted that the geometry of the required notch is quite complex. Further, to obtain some idea of the impact of the structural form as seen from inside the building, by the user, a modelscope or miniature video camera must be used.

Although the Reciprocal Frame grillage is relatively difficult to model accurately or to sketch freehand, it can be drawn easily by computer, especially if the geometry is regular, as it is in this is the ease, its simplest form. Hence, this is a good example of a situation where the use of CAD as a design tool can directly facilitate the design process, as it enables the designer to experiment freely where otherwise they may be reluctant to do so.

To overcome the problem of easy visualisation of the grillage assembly, the first and third authors have written a short computer routine in AutoLISP to draw the structure three-dimensionally in AutoCAD and this is described below.

### 2.1.3 AutoLISP routines

Initially, an AutoLISP routine was produced to draw the beam centrelines in three-dimensional space for the simplest form of Reciprocal Frame with beams of equal length and slope, supported at the outer ends at the corners of a regular polygon and forming a regular inner polygon. From the simple input of roof dimensions, the number of beams and the direction of rotation, the configuration of beam centrelines can be drawn automatically. Subsequently, a series of AutoLISP procedures, have been developed to draw the full beams. Some examples of the results are shown in Figure 2. Currently, alternative more complex configurations are being investigated and these will be added to the AutoCAD pull-down menu bar, so that students will be free to select a variety of roof forms.

Once the basic three-dimensional beam grillage has been drawn, it is then possible to investigate alternative roof forms for the areas between the beams (see Figure 3). At any stage the student can produce internal perspective views with ease by using the "perceive" command in AutoCAD having placed a suitable viewer beneath the structure. An examples of an interior perspective of a house with a Reciprocal frame roof is shown in Figure 4.

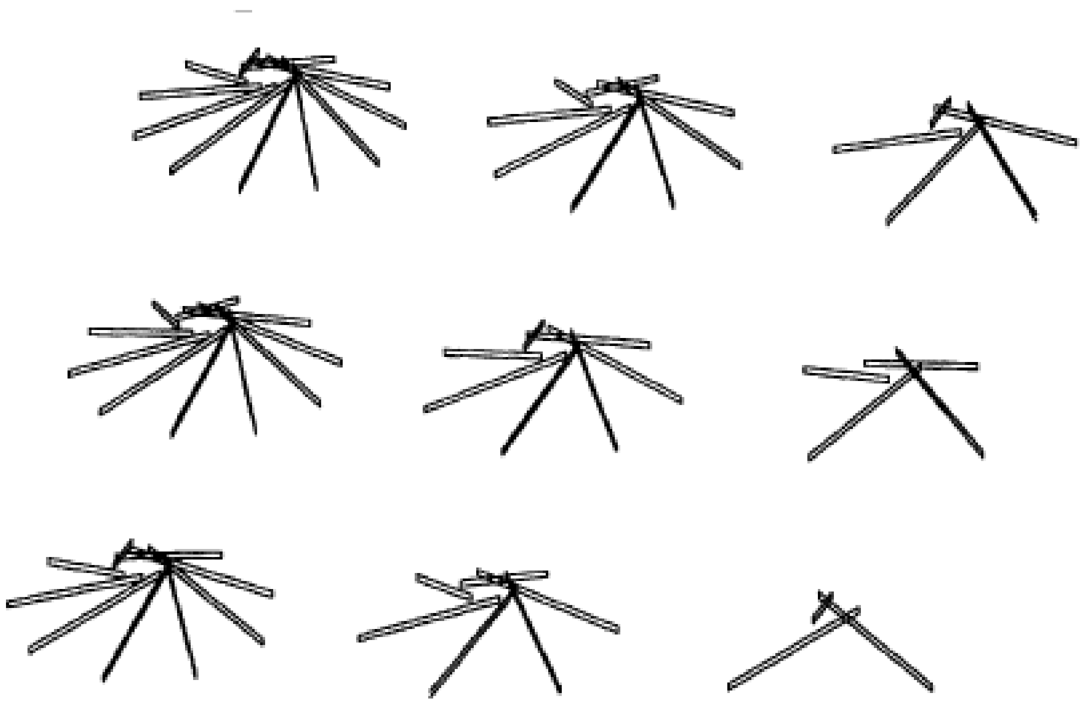


Figure 2. Examples of computer generated Reciprocal Frame configurations

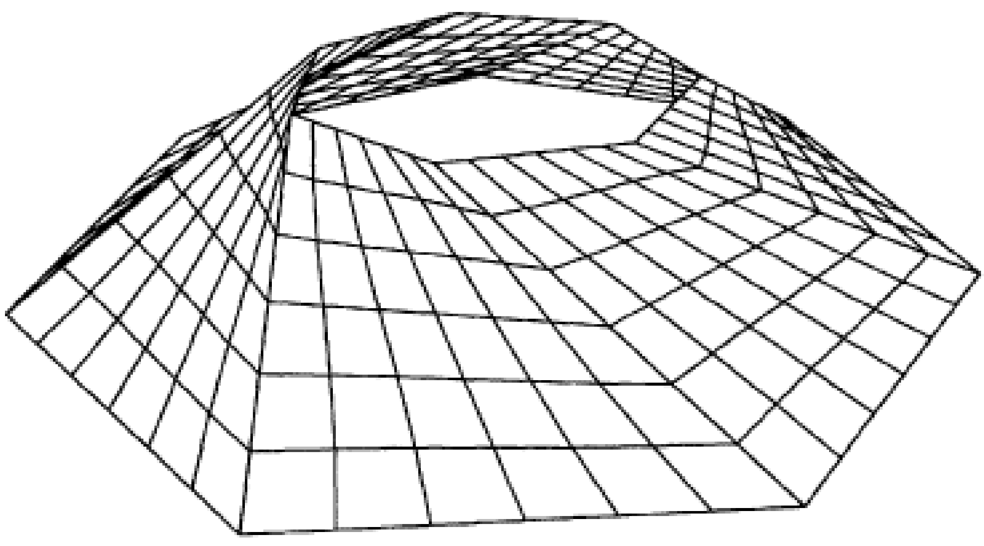


Figure 3. Warped surface generated between beams of Reciprocal Frame

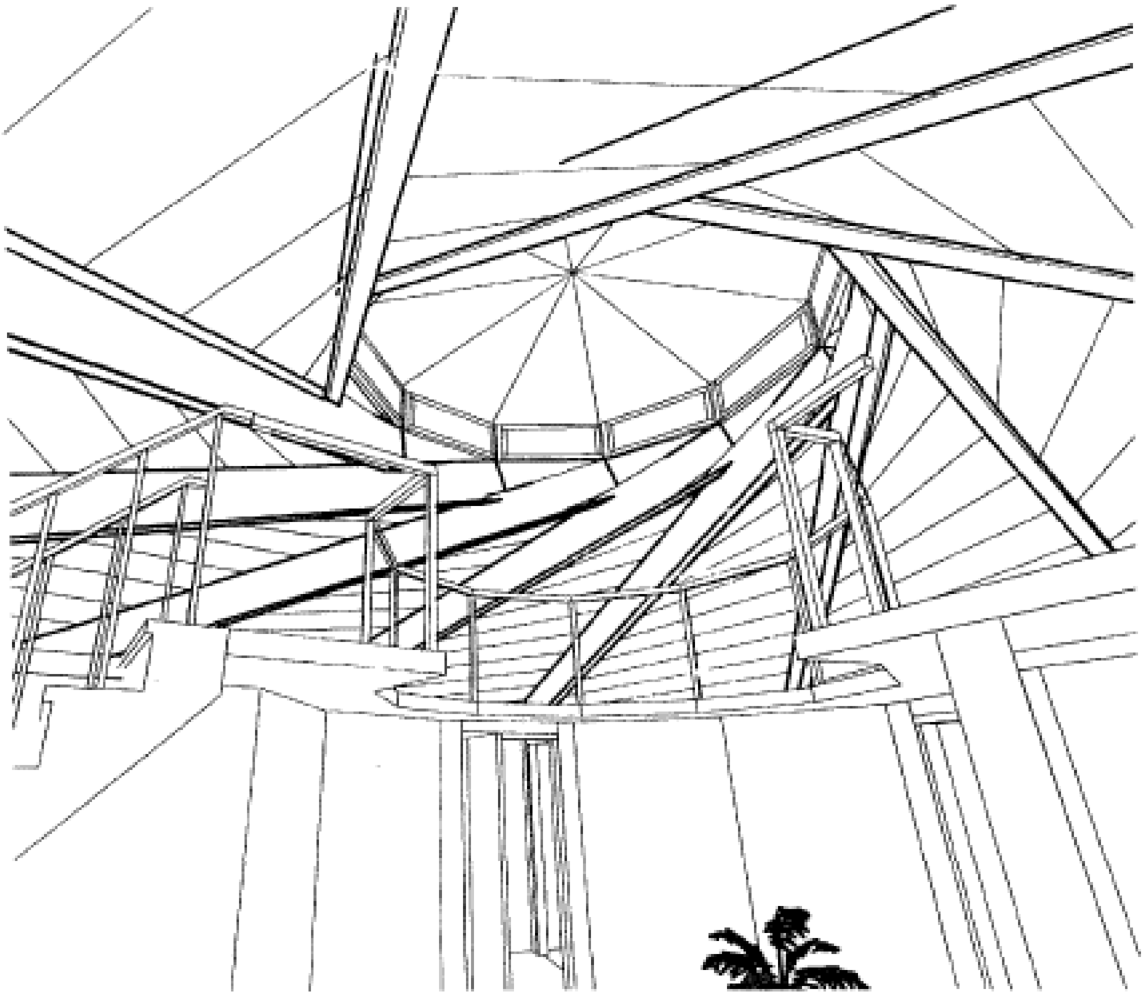


Figure 4. Interior view of Reciprocal Frame roof for a house

**2.2 Facetted Plate Domes**

The Dual Method is based on the well-known point-to-plane dualism which connects the regular polyhedra into pairs as shown in Figure 5. As stated in Wester [4] this method also has a structural content, as a triangulated octahedron or icosahedron stable as a bar and node structure is transformed into a cube or dodecahedron stable as pure plate structures. The mechanical behaviour is described in Wester [5] and will not be dealt with here.

The Dual Method is a tool for shaping structures with plates and their intersections and this differs from the "normal" bar and node form of description. This description of the structure allows a "fold-out" cutting pattern of the three-dimensional form to be produced with ease.

Examples of the application of this method using the program CADual [6] are described below. In each case the program was used to design the dome form and to generate the cutting pattern of the individual plates.

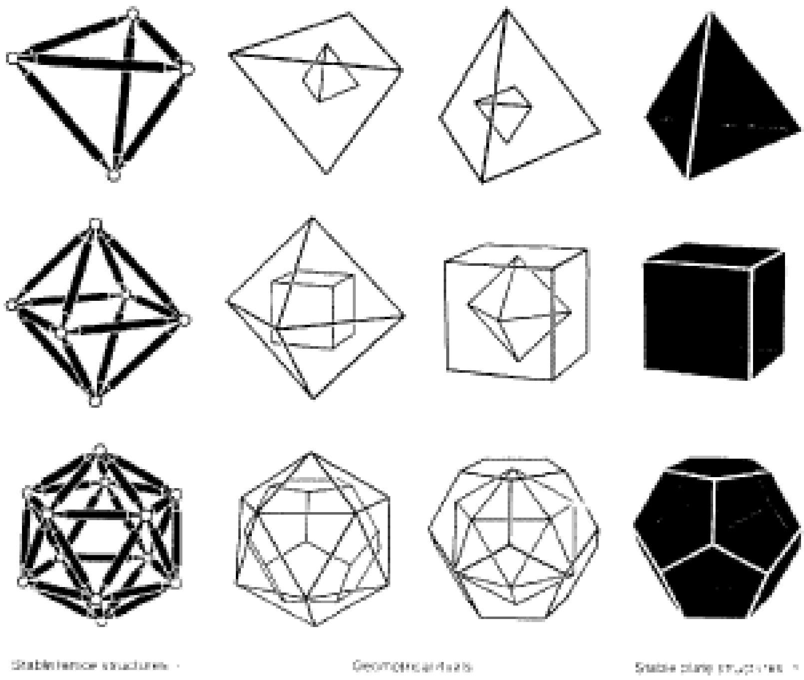


Figure 5. Geometric duals of regular polyhedra

**2.2.1 Pentagonia ceramic dome**

Pentagonia is a single layer plate dome-shaped sculpture, 2.8m high and made from glazed ceramic tiles approximately 15mm thick, its name deriving from the fact that both the top tile and the ground plan are regular pentagons. The thickness of the tiles is greater than that needed from the 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 the computer and after firing and glazing a sand/cement mortar was used to connect the ceramic tile plates together. Ceramic artists Esben Madsen and Gunhild Rudjord created the form which is a paraboloid of revolution; this being an ideal shape to resist uniform vertical load - as is, nearly, the self-weight of the structure. Pentagonia is exhibited at the Silkeborg Museum in Denmark. The computer model, the computer generated "fold-out" pattern and the final sculpture are shown in Figures 6(a) to (c) respectively.

**2.2.2 Palm house structure**

A palm house project created by engineering students Paul Ohannessian and Nicolas Grunnet is a combination of a coarse-meshed, bar-and-node, steel structure and a fine-meshed glass plate structure. Both the steel structure and the glass structure follow the same theoretical paraboloid of revolution with the steel nodes on the surface whilst the glass plates are tangential planes to the same surface. The complicated geometry of the structure is generated extremely easily by the Dual Method.

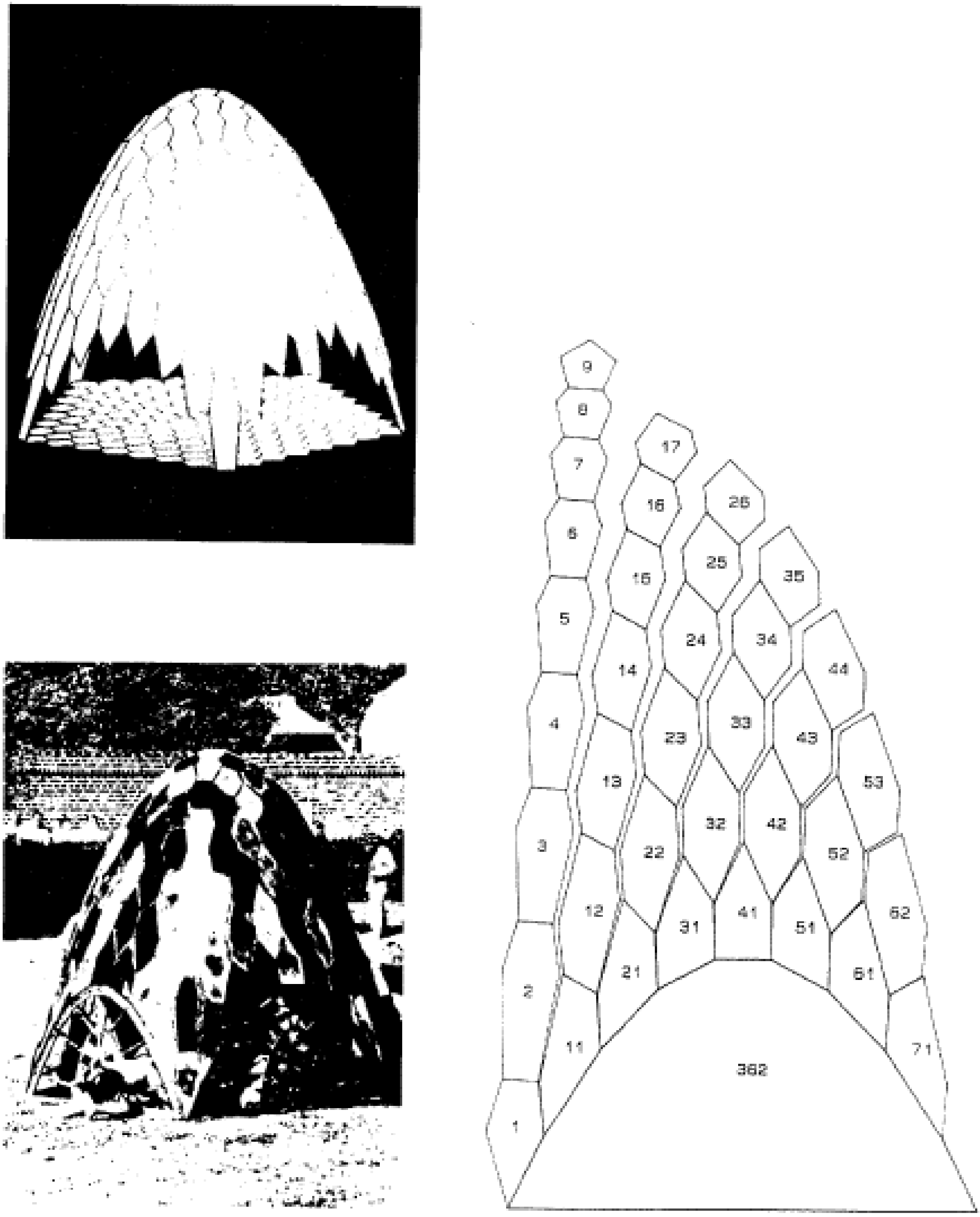



Figure 6. Pentagonia - (a) computer model, (b) "fold-out" pattern and (c) final sculpture.

A well-known problem when combining facetted spherical forms is matching boundaries but, as the projection of the glass plates onto the ground plan creates regular and equal hexagons, the combination of equivalent paraboloids fit smoothly together (as shown in Figure 7). As the glass is a part of the structure, it is important that the shape is ideal for its self-weight, hence the paraboloid form. However, in the case of, for example, lateral wind load, the steel structure will ensure the stability of the combined system. Separate computer models for the two structures, glass (upper) and steel (lower), are shown in Figure 8(a) and the physical model in Figure 8(b).

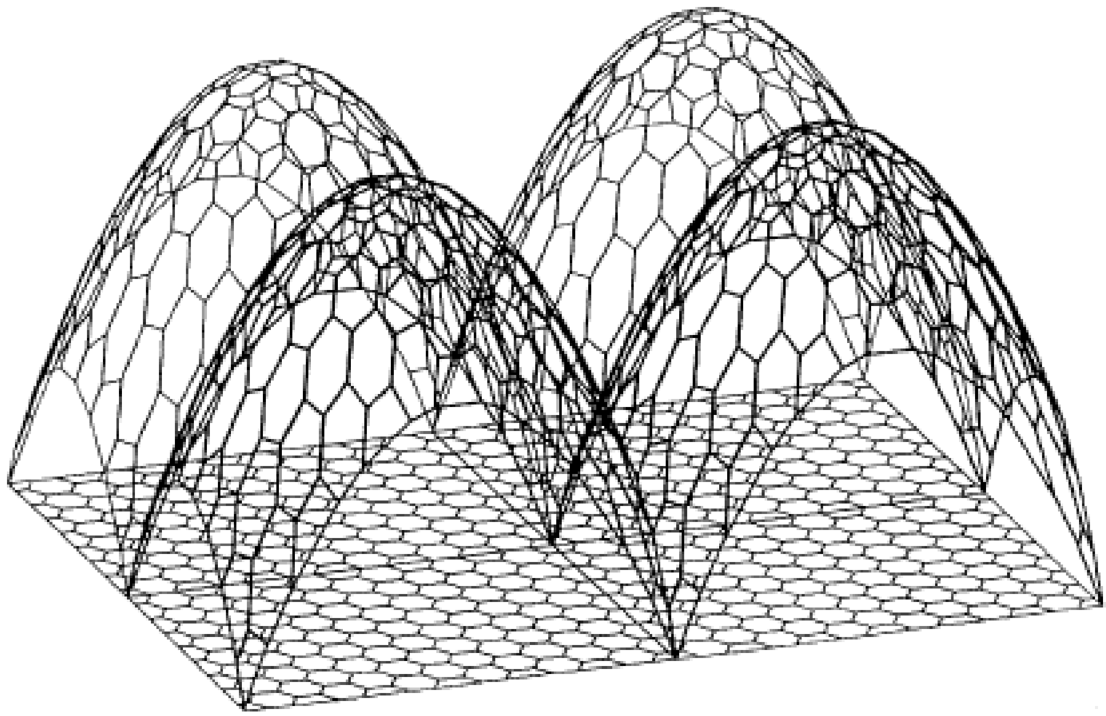


Figure 7. Example of the "clean" connection line between facetted paraboloids with a regular hexagonal pattern on the horizontal projection plane.

### 2.2.3 Market hall roof

Another type of combination between a steel bar-and-node structure and a glass plate structure is illustrated by a market hall glass roof (Figure 9). The main shape is the same as the project described above and was produced by the same students for an MSc examination project. In this combination, the steel and glass structures work intimately together as one structural envelope. The concept is similar to the previous project but, in this case, the plan projection is a grid of perfect squares.

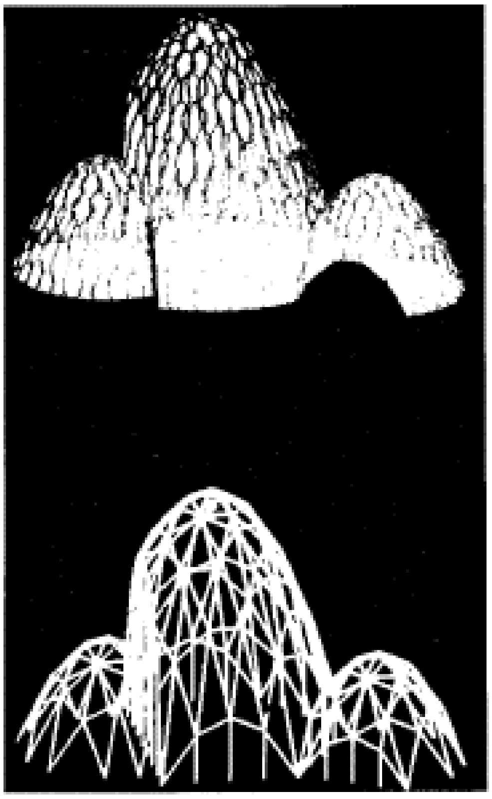


Figure 8. Palm house - (a) computer model of glass structure (upper) and steel structure (lower) and (b) physical model.

**2.2.4 Assembly Hall**

The final example is a project for an assembly hall at a museum, designed by the artists Mogens Jorgensen and Gudrun Steenberg, which uses a steel and glass plate structure. In this case the shape is based on a "free-facetting" of an ellipsoid of revolution about a horizontal axis. The computer generated form is shown in Figure 10(a) and the physical model in Figure 10(b).

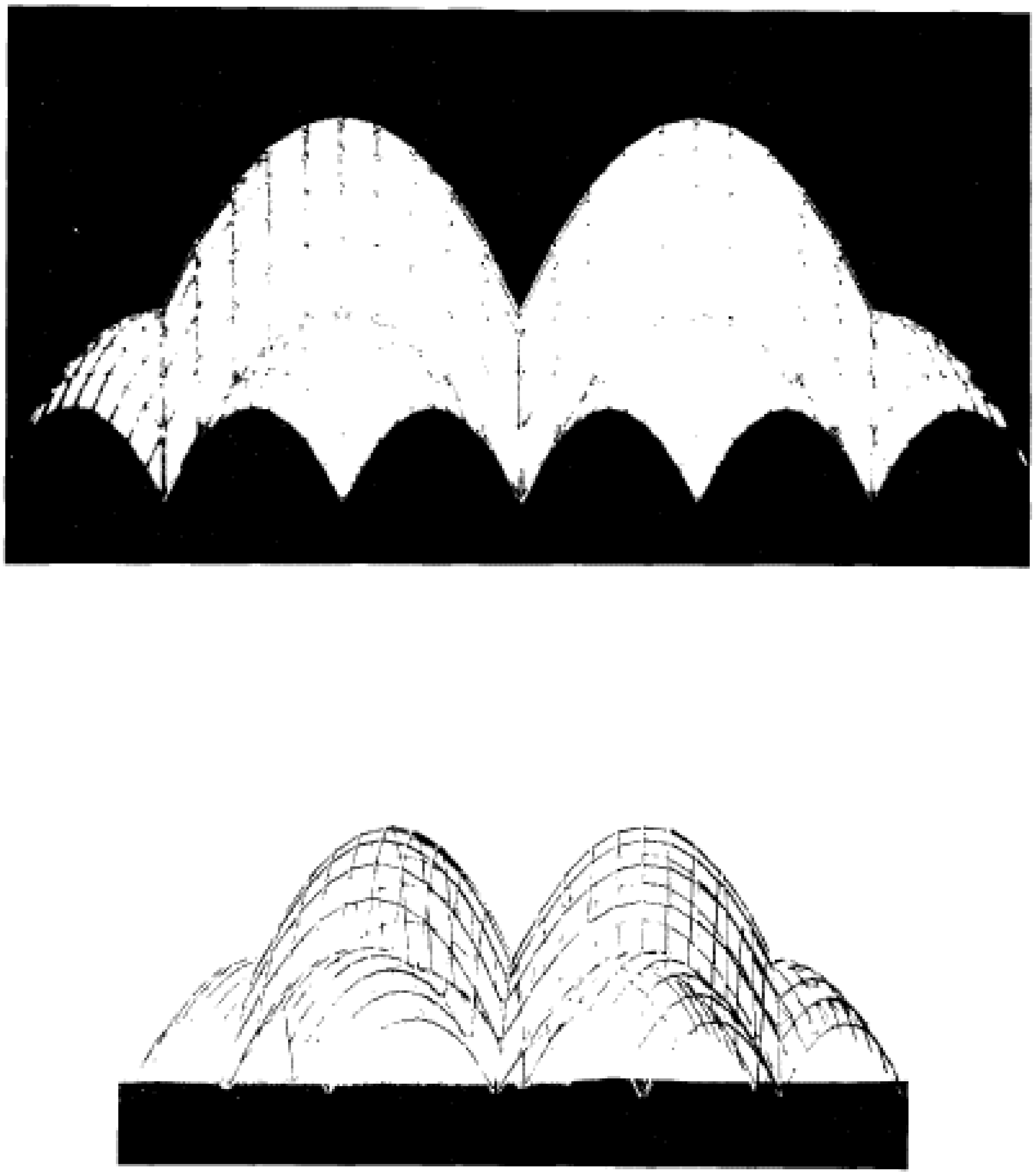
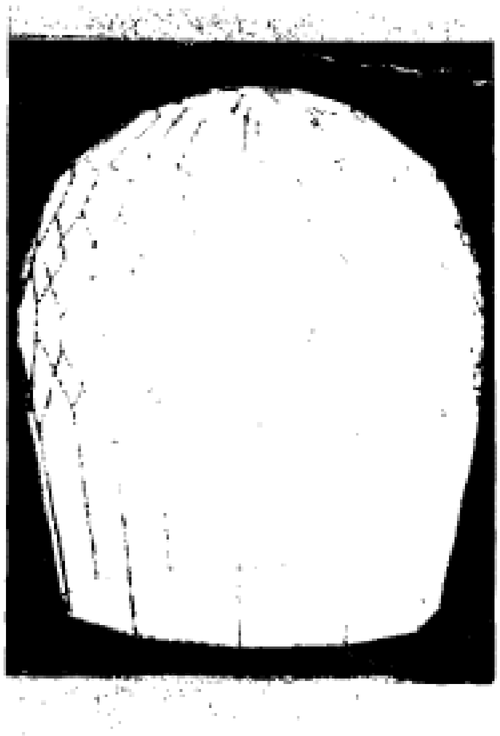


Figure 9. Market hall - (a) computer model and (b) physical model outside view

**3. Conclusions**

In the field of design of architectural structures there has been a steady progression from the "trial and error" methods that produced the magnificent Gothic cathedrals through prediction of forces by graphic statics techniques, calculation by slide rule and electronic calculator until the present day where complex three-dimensional structures can be analysed with relative ease by computer. Similarly, in architectural design there has been an equivalent progression from freehand sketching through accurate generation of details and perspectives on the drawing board, simple two-dimensional CAD to



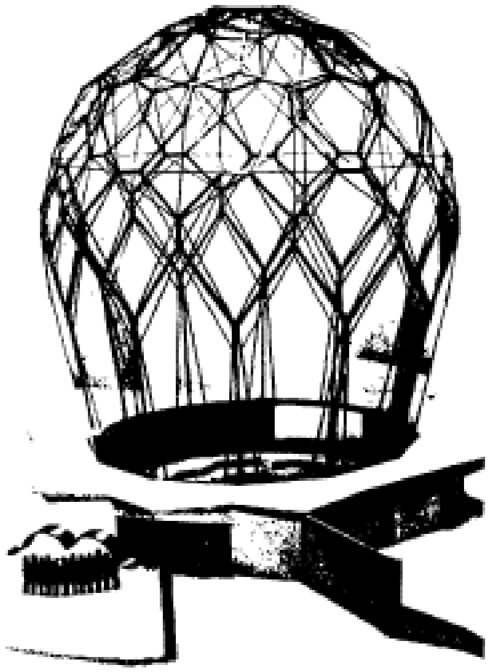


Figure 10. Assembly Hall - (a) computer model and (b) physical model (Photo Viggo Rivad)

culminate in the colour rendered images and virtual reality representations that are available to architects today. In both cases the speed of processing data has been greatly increased. However, the authors feel that the imagination of designers has not necessarily kept pace and that there are considerable opportunities for exploration of structural morphology using computer aided techniques.

The examples given in this paper have demonstrated how CAD can be used as a tool to investigate a variety of alternatives of innovative structural forms. In both cases described the forms are difficult to draw or model without the assistance of computer generated three-dimensional representations and dimensional information. Therefore, CAD has facilitated the design process and added to the diversity of structural forms available to the designer.

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