PLAUSIBILITY IN ARCHITECTURAL DESIGN

DOMEdesign – Software Support for the formal shaping and architect-oriented design of shell structures

Christian Tonn (christian.tonn@archit.uni-weimar.de, www.c-tonn.de),

Christian Wolkowicz, Alexander Stahr, Thorsten Thurow, Jürgen Ruth, Dirk Donath

Chair for Structural Engineering, Prof. Dr.-Ing. Jürgen Ruth

Computer Science in Architecture, Prof. Dr.-Ing. Dirk Donath

Summary

Complex gridshell structures used in architecturally ambitious constructions remain as appealing as ever in the public realm. This paper describes the theory and approach behind the software realisation of a tool which helps in finding the affine self-weight geometry of gridshell structures.

The software tool DOMEdesign supports the formal design process of lattice and grid shell structures based upon the laws of physics. The computer-aided simulation of suspension models is used to derive structurally favourable forms for domes and arches subject to compression load, based upon the input of simple architectonic parameters.

Irregular plans, three-dimensional topography, a choice different kinds of shell lattice structures and the desired height of the dome are examples of design parameters which can be used to modify the architectural design. The provision of data export formats for structural dimensioning and visualisation software enables engineers and planners to use the data in future planning and to communicate the design to the client.

1 Introduction

The design of aesthetically pleasing dome and shell structures is a demanding task for architects and planners. The design of such constructions is associated with high-technology, apparent weightlessness and innovation. The formal design of complex curved shell structures enclosed by rule-prescribed enveloping surfaces present architects with challenging design and construction problems. Through the use of complex suspension models and complicated drawn representations the architect attempts to describe the complexity of the surface envisaged. Typically a model is pulled, distorted and varied until the desired form is achieved. The problem is not only how to communicate this form; it must also be feasible as a structural construction. Continual project adjustments and building restrictions, such as those presented by a pre-existing built contexts, complicate the matter still further. The task is to provide the planner with a tool in which architectural parameters can be modified. Redundancy is minimised in the design of the object-oriented model. The resulting shell structure profits from the interface and interaction possibilities with many other available tools, improving the quality and efficiency of the result through maximised interoperability.

2 DOMEdesign - Basics

2.1 The Server

DOMEdesign is based upon a server concept developed by Dipl.-Inf. Thorsten Thurow. This can be visualised as a data brain (the server), and working platforms (the various clients). Several clients can connect to a server via TCP/IP and are constantly in communication when active. DOMEdesign, developed at the Bauhaus-Universität Weimar, is one of these clients. The server stores, administers and serves all application data such as geometry, parameters and target values, whereas the client is responsible for operation, calculation and control. This system makes it possible to work as a team on a design using the same data, to consult with one another online or to perform time-intensive calculations on a remote computer.

2.2 Theoretical foundation

For the form generation procedure DOMEdesign uses an algorithm based upon dynamic relaxation methods. These were originally developed by A. S. Day in the 1960s for the computer-aided study of flow behaviour. The Dynamic Relaxation Method centres around the movement of individual nodes using deflection vectors. The method involves applying movement to each node of a structure and waiting until each node achieves a structural equilibrium with all other nodes in the system, influenced by a user-definable damping value. Movement is applied through the application of pre-tensile or compressive loads which deflect the initial form and then, through a process of iteration, lead to the final balanced shape. The dynamic movement of the system does not include any stiffness variables or material properties. (Source: Ralf Höller)

DOMEdesign simulates simple suspension models (e.g. string-nets or suspended wet fabrics), a system widely used for determining the form of such structures. DOMEdesign bridges the gap between the experimental and the analytical formal exploration without sacrificing the playful and intuitive element of design.

The following section presents a short overview of the algorithms used in DOMEdesign. They are applied to all nodes of a space-frame structure with the exception of the bearing nodes at the edges of the shell. The following four steps are repeated iteratively until an equilibrium is achieved.

1. The applied load is broken down into bar forces.
2. The sum of the bar forces in each rod is added to produce resulting forces. The resulting forces from each rod attached to a node combine to produce a deflection vector for that node.
3. The nodes shift position by the amount of the deflection vector according to a time-increment, a mass and velocity value.
4. As a result of the node's movement the distance between the nodes has changed. This is then corrected using a balancing algorithm which restores the current rod-length.

The balancing algorithm involves an iterative, node-for-node consideration of the entire space-frame structure. The individual nodes are moved along the lines of their connecting rods until the ideal rod-length is achieved within a defined tolerance.

2.3 Working method

The formal design can be approached in two fundamentally different ways. The first approach involves defining the perimeter base nodes and the global definition of a rod-length. The rod-length is increased until the desired height of the dome structure is reached. This allows a dome-net to be constructed that is anchored at particular edge points (see Fig. 4). The second approach starts with a flat net with a constant rod-length and mobile bearing base nodes. The start plan is therefore larger than the final plan. As the net arches upwards the base points move towards each other until the defined span-width, height or covered area is reached. This is the method discussed in our example.

2.4 Parameters

DOMEdesign is specially oriented towards the initial phase of the planning process with the emphasis on straightforward operation using only a few starting parameters. The architect envisages a particular idea, a concept which needs to be explored experimentally and designed in terms of geometry. The approach must consider the architectonic intentions as well as the planning context. With this in mind, DOMEdesign is grouped into three areas, geometry (Fig. 1), calculation (Fig. 2) and target values (Fig. 3).

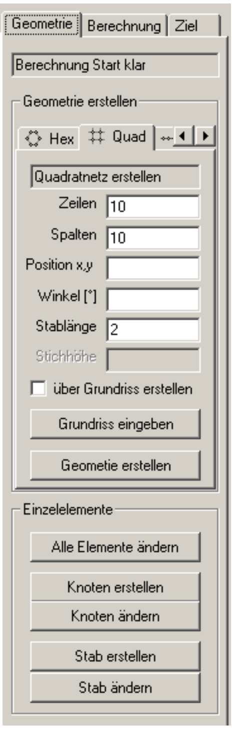

Fig. 1 Define geometry

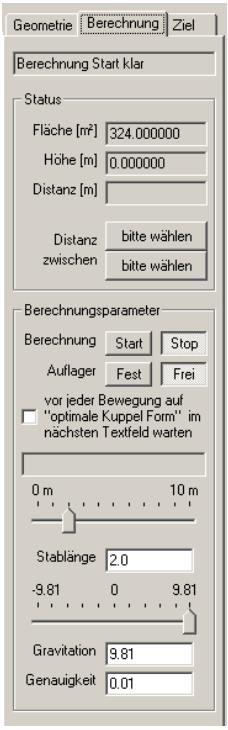

Fig. 2 Perform calculations

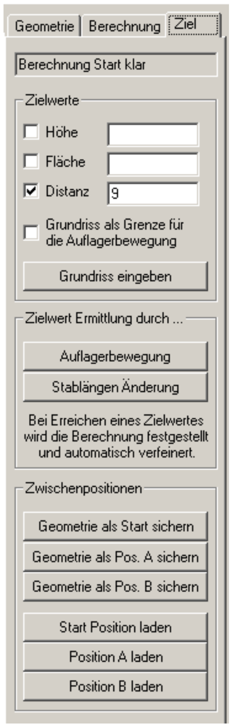

Fig. 3 Define target values

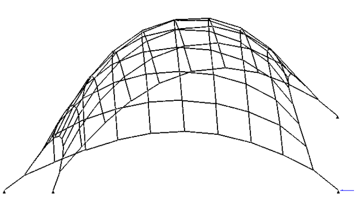

Fig. 4 quadratic net

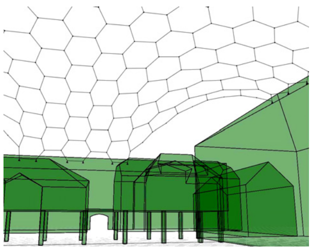

Fig. 5 hexagonal net

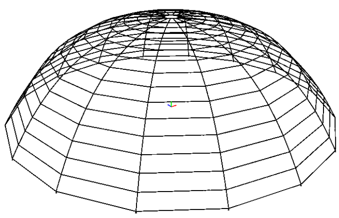

Fig. 6 radial net dome

DOMEdesign offers the planner different kinds of net and grid types. Quadratic (Fig. 4), hexagonal (Fig. 5), and radial networks (Fig. 6) can be automatically generated on the basis of particular floor plans or a desired radius. The geometry at the beginning of the process is flat and arches during the simulation to the dome forms shown above (Fig. 4-6).

The following section discusses some of the parameters which can be applied and experimented with during the design explorations.

3 Examples of application

The reference object used for this example is the Goethe Gartenhaus and garden in the park on the Ilm in Weimar (Fig. 7 and 8). The planner's task here is to provide an enclosing roof to secure and protect the historic monument. The roof should be independent of the building and be both attractive and contemporary in form.

Fig. 7 Goethe Gartenhaus in Weimar

Fig. 8 Park on the Ilm, with arrow for Fig. 7

In this case it is not possible to remodel the ground significantly. As a result the topography of the site is a determining design factor. The planner therefore creates a landscape model with which he or she can work. The landscape model here was created using different 3D and CAD programs. The topographic object is then imported using a 3D STL-import function in DOMEdesign (Fig 11).

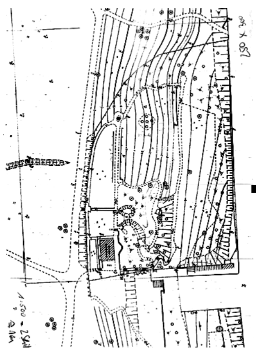

Fig. 9 Contour map

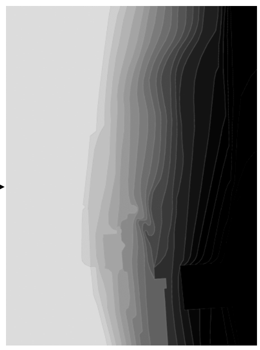

Fig. 10 Contour slices

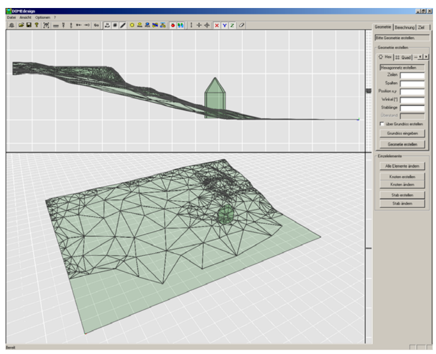

Fig. 11 Imported topography with Gartenhaus

The next stage is to determine a start net using the parameter "plan". Using the mouse or through the input of specific coordinates, a polygon in plan is generated (Fig. 12) which is then automatically filled with a parametric net type. This start net can be generated so that the edges of the net represent the bearing nodes. In this example (Fig. 13) a hexagonal net type has been chosen. A quadratic net would also be possible here.

In addition freely formed DXF starting nets can be defined e.g. in AutoCAD and can be imported and manipulated in DOMEdesign. In the following stages the topography object layer is hidden for the sake of clarity.

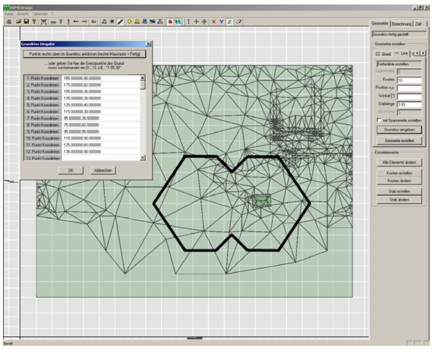

Fig. 12 Plan: Input via mouse and/or coordinates

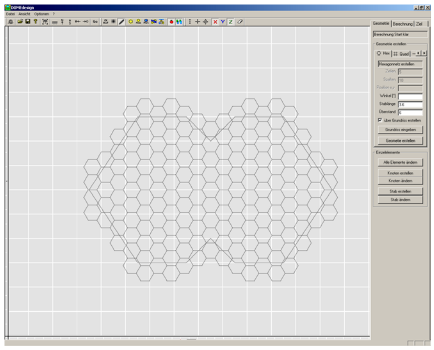

Fig. 13 automatically generated starting net

The bearing points at the edge of the net are movable within a specific geometric plane. By linking the starting net to the topographic object, all bearing points of the frame structure can be set to rest on the topography. The movement plane for the bearing points is perpendicular to the normal vector of the 3D surface on which the point rests.

The movement of the bearing points across the edges of ground-facets within the topography model is an important aspect. As a bearing point shifts across the edge of a ground-facet, it is automatically realigned perpendicularly to the next 3D ground-facet and its movement vector correspondingly adjusted. If there is no further ground-facet beyond the edge of the existing facet, then the bearing point remains on this edge. This is simulated by the projection of the movement vector on the virtual edge plane of the facet. This virtual plane is formed out of the respective edge (as cut by the movement vector) and the normal vector of the current facet. This ensures that position of the bearing point is calculated correctly should it happen to fall on the edge of a facet.

Once the start parameter topography, plan, rod length and net type have been defined, the calculation can be initiated. It is possible to set certain target values to help define the end form, e.g. the height of the dome, the area to be covered or a particular span. In the example shown, the base polygon in plan which was used to generate the starting net is also defined as the target plan (Fig. 14). This means that the movable bearing points can only be shifted up to this boundary. Again, this is calculated mathematically through a projection of the movement vector of the bearing point into the virtual edge of the plan polygon. This plane is then formed through the respective plan boundary and the normal vector of the plan (0 | 0 | 1).

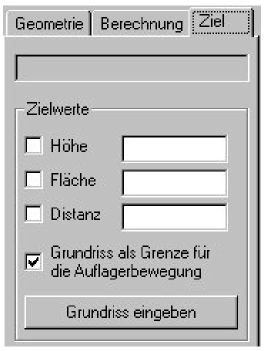

Fig. 14 Dialogue target values

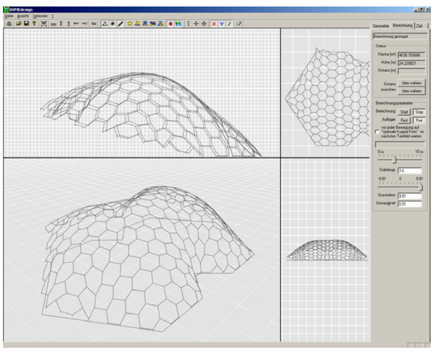

Fig. 15 calculated dome form

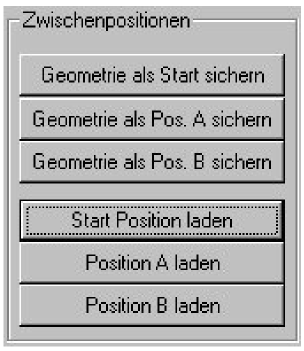

Fig. 16 Saving different variants

Fig. 15 shows the results of the formal exploration. By saving settings for different dome design variants, it is easy to explore alternatives (Fig. 16).

The geometries can also be exported as 3D DXF files and can therefore be used with other software. Figs. 17 and 18 show visualisations of the example made with 3D Studio. The architect and client can assess the design and aesthetic aspects of different design variants and identify possible areas of improvement or the need for further design variants.

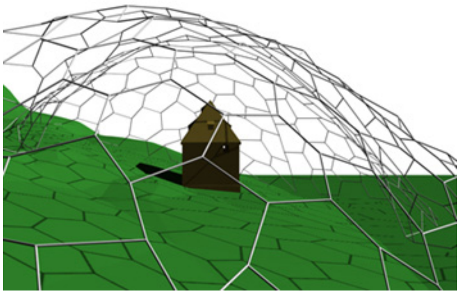

Fig. 17 Perspective of Goethe Gartenhaus

Fig. 18 Interior perspective view northwards

The DXF export also enables geometric data from the chosen variant to be imported into structural engineering software. The design and cross-section of individual structural members can then be calculated. The use of DOMEdesign ensures that the entire space frame arrangement has an optimal structural form and gives the architect added design plausibility.

4 Optimising the construction

Does it make sense to separate formal design aspects from the constructive principle in the development of domed constructions?

Form the point of view of the technical realisation of such free form structures in conjunction with cost-efficiency, further problematic aspects also need to be considered. At present, the program produces forms where the area enclosed by the nodes and rods is not planar. However, when using a roofing material consisting of planar glazing elements or pneumatically filled membrane cushions, this is of paramount importance.

Free space frame geometries also exhibit the characteristic that the nodes to which the fixed-length rods are connected each have their individual character. The industrial production of appropriate nodal points can only be achieved using computer-aided CNC manufacturing methods and results in highly-complex geometries within a small amount of space. One possible solution, already investigated in some real projects (see Schlaich), involves the elementarisation of a free-form surface into many smaller facets which can be standardised. The difference in between the roofing facets and the free-form structure is small enough that it can be compensated for through tolerances in the sealing joints.

Another possible solution is the manufacture of pneumatically-filled membrane cushions with a freeform edge geometry, a similar approach to that used in the manufacture of textile roofs. In this case, the need for planar surfaces is no longer relevant.

5 Conclusion

The DOMEdesign program presented here is a tool for exploring the form of space-frame and grid-shell structures in the early design phase. It unites an experimental explorative design tool, analogue to working with suspension models, with a digital design tool. This has a series of advantages:

- The user interface allows an intuitive and creative approach to designing. This differs considerably from the parameter-based, technical engineer-oriented tools already available. The overall form can be influenced more-or-less freely by shifting individual nodes.
- The ability to import a 3D landscape model caters for a primary aspect of architectural design: relation to the context. This means that a design is anchored to its future context, its edges and topological characteristics from the outset.
- Free forms can be developed upon the basis of freely definable plans. The repertoire of architectural forms is extended considerably.
- The form determination is prescribed by mathematical and physical rules and leads to structurally optimal forms. The result is highly efficient, light structures which improve the design possibilities for otherwise strongly structurally-based buildings and give the architect added plausibility and design-assuredness.
- The designed geometry is saved in digital data form and can be exported via different interfaces for further use in other software.

DOMEdesign is a tool for determining the design form of complex structures. It can already be used and a free version is available from www.c-tonn.de. Further developments and optimisation possibilities for form determination have been described in this paper. The form finding and generation process is an important planning aspect that will increasingly become a focus of software support.

6 Literature

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