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Dutch Maritime Museum: Form-finding of an irregular faceted skeletal shell – Part a

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Abstract

In the context of the search for an efficient structural shape to cover the Dutch Maritime Museum courtyard in Amsterdam, the authors briefly discuss the driving design factors that influenced the earliest glass roof coverings. The trends that have emerged during the late 20th and beginning 21st century in the design of skeletal steel glass shells are exposed. These design developments range from sculptural to geometrical and physical intentions (part a).

The discussion of the competition design development of the Dutch Maritime Museum Shell roof by Ney and Partners shows the quest for a structurally efficient catenary form based on a poetic geometrical idea. This paper presents a novel methodology that slightly adapts the catenary shape with the objective of achieving planarity in all the triangulated, quad angulated and pent angulated mesh facets. The challenge of facet planarity is gracefully solved and adds to the elegance, structural efficiency and economy of this design (part b).

Keywords: conceptual design, form-finding, steel shell, planarity facets, historic courtyard, Maxwell reciprocal network.

1. Introduction

In the wake of the Industrial Revolution glass/metal structures appeared as a result of two factors: society's desire for green, quiet spaces in overpopulated cities and the scientific emergence of new construction materials: glass and iron.

In the early 19th century the first greenhouses with a glazed roof appeared in Northern Europe as living spaces. Their tall construction and maintenance cost (due to the glass and the required heating system) made them style icons of the elite. Their curved shapes (1. ridge and furrow e.g. Chatsworth 1834, UK and 2. vaulted e.g. Kew 1844, UK [1]) allowed the sparse sunlight to hit the glass panes perpendicularly, into the space and hit the citrus and lime trees (hence the name orangery). Other varieties of tender plants, shrubs and exotic plants also came to be housed in the orangery. The introduction of the palm tree, an impressive and prestigious plant with large religious significance pushed the sculptural shape of the greenhouse further upwards.

In the middle of the 19^{th} century the development of greenhouse typologies is in full swing and results in culture houses, conservatories and winter gardens (e.g. Royal greenhouses Laeken 1875, Belgium shown in figure 1 [2]). The winter garden is of particular interest to this paper as it defines a social meeting place adjacent to a private mansion or public building. With time the plants have lost their importance to the winter garden's social function.

Mass production of affordable iron in the 2^{nd} half of the 19^{th} century further encouraged design and construction of temporary cast and wrought iron and glass tall and large span exhibition halls. Plenty of light entered the exhibition areas of buildings such as the Crystal Palace 1851, UK (shown in figure 1). Its filigree iron structural skeleton was pre-fabricated and it was subsequently dismantled and moved from Hyde Park to Sydenham in South London. Unfortunately it was destroyed by fire in 1936.

The second half of the 20^{th} and the beginning of 21^{st} century experienced a new up-rising of the design and construction of roofs over social gathering places, winter gardens without plants, covering courtyards of historically important public buildings (e.g. courtyard British Museum see figure 1, UK, Deutschen Historischen Museum, Germany, Museum fur Hamburgische Geschichte, Germany [3]). The shapes of these glass covered single layered steel skeletal shells are driven by a combination of sculptural, geometrical, physical and constructional considerations [4]. The recent re-emergence of these structures goes hand in hand with the evolution of digital design tools that enable the designer to develop and analyze more free and daring geometries.

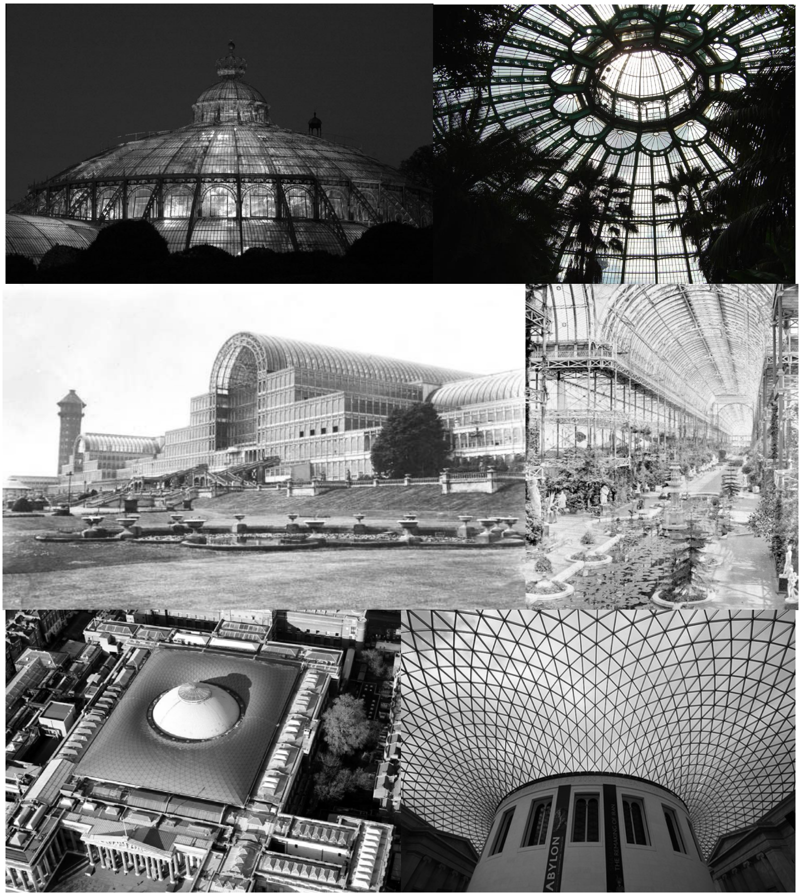

Figure 1: a. The Laeken wintergarden (Belgium 1875) still mainly serves as a social meeting place.b. The pre-fabricated Crystal Palace (UK 1851) was dismantled soon after its intended use. c. The British Museum Courtyard (UK 2000) steel roof, adds value to the Museum by expanding the useable circulation space.

2. Single layered steel skeletal shells covered with glass

Today's designers (either from an architectural or engineering background) of these non botanical winter garden shells seem to be guided by one or more of the following four driving factors: imposed existing situation, sculptural architectural esthetics, geometrical shape, structural efficiency and economy.

2.1. Imposition on an existing situation: the modern winter garden

In the last two decades existing historically relevant public buildings with a central open courtyard have been adapted to extend the useable floor area to an indoor/outdoor climate. These generally narrow buildings count on the courtyard for daylight. Steel and glass shells offer a unique solution to this design challenge. The historic context for these shells imposes a series of design constraints within which the designer has the freedom to develop the shell's form. The boundary conditions often include height restrictions and limits upon the maximum extra load that can be imposed on the existing building, particularly in a horizontal direction. In the reviewing the design of recently realized steel shells, the driving design factor more often seems to have been architectural scenographic esthetics rather than structural performance.

2.2. Sculptural architectural esthetics

With the available geometrical digital modeling tools, more architects base their work on esthetic (and often subjective) considerations to achieve scenographic effects. This particular design approach raises questions from a structural point of view with respect to the resulting lack of structural efficiency.The evolution of a sculptural shape needs a team of architects, engineers and contractors to find the right synergy between esthetics, structural performance and context. The shell of the Nuovo Polo Fiera Milano [5] developed by the architect Fukas in collaboration with Schlaich Bergermann und Partner and Mero & co illustrates this design development. (See figure 2).

Figure 2: The Nuovo Polo Fiera Milano (Italy 2004, architect Fukas in collaboration with Schlaich Bergermann und Partner and Mero & co) illustrates how the architectural shell is discretised in quad angulated and triangulated (at the supports) meshes.

2.3. Geometrical shape

Geometry is a tool that has been used since antiquity for the development of architectural shapes. These forms are thus limited by the rules imposed by analytical geometry and the designer's imagination. Through the centuries smart architecture has developed around 'simple' geometries chosen for their constructive or structural qualities. (Examples can be found in the design of the cupola of the cathedral Santa Maria del Fiore by Brunellesci and more recently the thin concrete shells by Felix Candela [6]). Surfaces of revolution, translational surfaces, scale-trans surfaces lend themselves excellently to shell action and discretization into sub elements. In this context the work of Schlaich and Schober on steel shells is innovative. Schlaich et al. [3] devised a method to find the right translational or scale trans surface that can be divided into quad angulated planar meshes. The Hippo House of the Berlin Zoo designed by architect Grieble and Schlaich Bergermann und Partner [7] exploits this approach in an elegant steel shell as shown in figure 3.

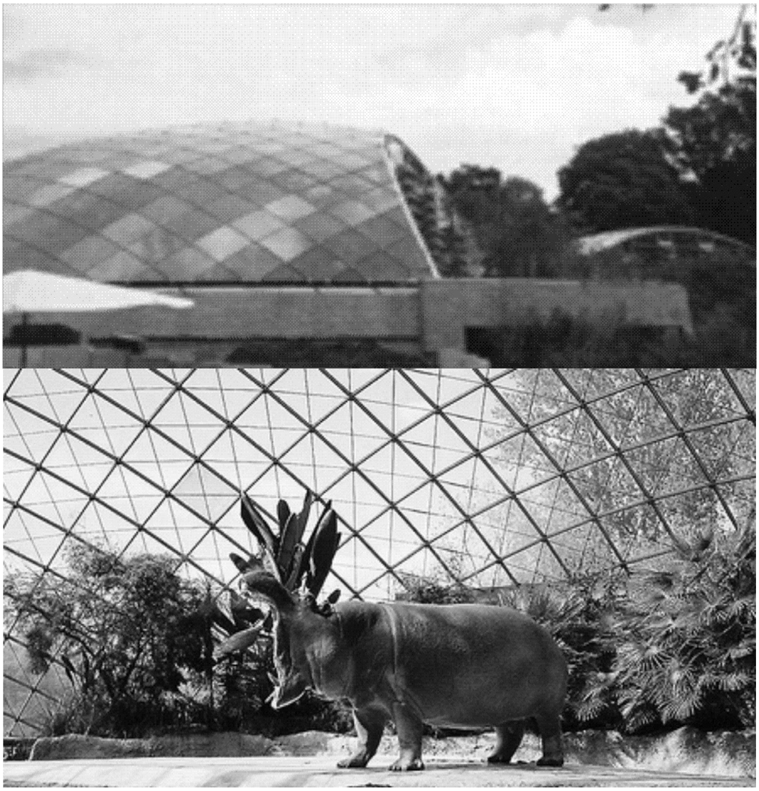

Figure 3: The Hippo House (Germany, 1997) designed by architect Grieble and Schlaich Bergermann und Partner shows the discretisation of a translational surface into planar quadrangular meshes.

2.4. Structural efficiency

Of all traditional structural design elements (ranging from material choice, profile sections, node type, global geometry and support conditions), the global geometry mostly decides whether a shell will be stable, safe and stiff enough. The shell spans large distances with a fine structural network (skeleton) of individual small sub elements. The first design consideration lies in setting the exact boundary conditions within which the shell shape can be developed. The curved shape is of vital importance to achieve stability through membrane stiffness. Shell bending needs to be avoided by finding the 'right' geometry so that under the self weight only membrane action results. Membrane action makes efficient use of material. The important structural design challenge lies in the determination of a three dimensional surface that will hold the skeletal shell. Part b will discuss how this was achieved for the Dutch Maritime Museun shell. The second important consideration lies in the discretisation of the form driven by the planarity of the different meshes covered by glass panes. For this project a specific method based on origami folding was derived and will be discussed in part b. Sometimes planarity of mesh might not be desired e.g. Norman Foster's design for the Smithonian Institute, USA. Due to steel digital fabrication techniques (pioneered in the design of the roof over the courtyard of the British Museum [8]) standardization of meshes and thus elements and nodes is no longer considered crucial, but mesh planarity of non-triangular meshes is still a vital issue.

2.5. Physical Form

In the 20th century both architects and engineers (Gaudi [9], Otto [10] and Isler [11]) experimented with physical form-finding techniques that for a given material, a set of boundary conditions and gravity loading found the efficient 3D structural shape. The importance of finding a funicular shape for steel shells lies in the fact that the self-weight (gravity loads due to steel and glass) contributes largely to the load to be resisted. The sub elements need to be loaded axially to make most efficient use of the section profile.

Numerical form-finding techniques (force density [12], dynamic relaxation [13]) have been successfully applied to weightless systems whose shape is set by the level of internal pre-stress and boundary supports. However when it comes to funicular systems whose shape is not determined by initial pre-stress but by gravity loads (such as the case for masonry, concrete or steel shells) fewer numerical methods have been developed. This is mainly because of the difficulty of finding optimal forms for those shells which rely on both tensile and compressive membrane stresses to resist dead load. Kilian et al. [14] presented a shape-finding tool for statically determinate systems based on particle-spring system solved with a Runge-Kutta solver, used in computer graphics for cloth simulation. Block et al. [15] recently published the thrust network analysis to establish the shape of pure compression systems. For the initial competition design form-finding of this particular NSA roof Project (part b), the dynamic relaxation method usually used for pre-stresses systems, was adapted to deal with 3D funicular systems with tension and compression elements under gravity loads.

2.6. Conclusion

Part a of this paper discussed the development of glass roof shapes from its early appearance in the 19th century to 21st century steel/glass roofs. Recent case studies illustrate the design drivers behind the emergence of these new shell roofs. These drivers have been identified as imposition on an existing situation, sculptural architectural esthetics, geometrical shape and structural efficiency. The development of structurally efficienct complex curved surfaces can be achieved by physical and numerical form-findings methods. Part b of this paper shows the search for a structurally efficient and constructable steel glass skeletal shell over the courtyard of the Dutch Maritime Museum based on a poetic geometrical idea.

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