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Lightweight Tensile Structures towards an Architectural-Engineering Integration

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Introduction

Lightweight tensile structures outstand as an exemplary field that revolutionized architectural technology and engineering in the early 70´s, while having established new frame conditions and methodologies regarding cooperation between architectural and engineering disciplines in practice and research [1]. Cable-net and membrane structures' form-finding process is directly related to aesthetic, functional, structural and construction aspects from early stages of the design. The structure's geometry is revised in an iterative process of form finding until an equilibrium form under the imposed stress requirements of the members and boundary conditions has been reached. The origin of lightweight tensile structures and the initiation of numerical methods of analysis that enabled the realization of the roof structure of Munich 1972 Olympics-Arenas frames three phases of developments in the area: design and computational analysis, design optimization and automated manufacture, and open loop multivariable systems performance based design. The specific project's succession of technology driven design processes are reviewed from the perspective of an interrelated syntax of architectural and structural design.

The Olympic Stadium of Munich

When the first prize of the architectural competition for the sporting premises of the 20th Olympic Games in 1972 in Munich was awarded to the Stuttgart architects Behnisch and Partners with Juergen Joedicke on Friday the 13th of October 1967, the advantages of the design were obvious, arising from the main architectural idea for a transparent, unusual and innovative tent roof. At the same time no one from the jury actually believed that the proposed design of the lightweight structure, covering an area of 75.000 m^2, could be realized. Frei Otto and Fritz Leonhardt, both Professors at the Faculty of Civil Engineering at the University of Stuttgart, while not having participated in the design, insisted on the contrary. The competition results were documented in the German architectural press as follows: "The realisation and conviction are important, that not the tent roof structure à la Montréal was awarded, as a fashion of architecture, but it was the overall concept of the work of Behnisch that convinced the jury. The built form is not the primary, but the aim conception for a task, which exactly is not derived from a formal aspect but from the nature of the problem. And for this the technological construction possibilities ought to be found" [2].

On the 1st of March 1968 Behnisch and Partners were commissioned with the construction of the sport premises on the southern area of the Olympic park. The prestressed cable-net roof was set to further planning. Soon after a timber and a perlite concrete covering of the net were abandoned, as well as a timber shell solution; all systems were too stiff for the selected roof shape. Frei Otto and his team then found a preliminary tensile solution through model studies. Owing to the lack of other possibilities, initially tulle models were measured photogrammetrically to ascertain the required cutting pattern. At that time, only model techniques, geometrical expedients and idealised calculation methods that were adequate for relatively simple forms, were used. To that, construction possibilities would compensate the insufficiencies of the design, the construction planning and the erection on site. Nevertheless, such traditional methods of design, practiced already by Frei Otto with Rolf Gutbrod and Fritz Leonhardt for the preceded German pavilion of the Expo 1967 in Montréal could not satisfy any more the requirements for precision, safety and calculability of the particular structure; in detail, the requirements with regard to geometrical precision, as well as determination of the exact length of all cables under the planned prestress, material related issues, as for example cable anchorages and fittings, as well as prefabrication demanded completely new solutions. As a matter of fact the lightweight tensile structure of Munich showed that to that point there was no experience with the scale and measures of the particular project. With the task of its construction the breakthrough into a different, new quantitative dimension was needed, as this project went to the borders of structural engineering of its time in numerous fields: Structural design, computer applications, material science and technology, structural detailing, prefabrication, welding and erection.

One of the most influential collaborators of the architectural team and Frei Otto was John H. Argyris, an exceptional specialist in the field of computers, aeronautics and fluid mechanics and one of the inventors and creators of the finite-element analysis method that revolutionised engineering sciences [3]. The finite-element method was expanded and applied for the first time internationally for the design, development and analysis of the long-span structure of the Olympic Stadium of Munich 1972, making the realization of the original "architectural vision" feasible.

Computational analysis of lightweight structures encompasses each individual element with a unified calculation process. Initially a direct application to the stated problem formulation for such structures was nevertheless not possible. New developments regarding the theory and calculation programs became necessary and had to be worked out in very limited time by Argyris and his team at the Institute of Statics and Dynamics of Aerospace Structures at the University of Stuttgart. The static equilibrium of the prestressed net was investigated through iterative loops of geometrical nonlinear elastostatic analysis. The investigated form of the structure was at first approximated and then numerically improved interactively, until equilibrium at the required prestress level was achieved.

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An in-depth study for evaluation of the gained experience in terms of integration and consolidation of the disciplines involved succeeded the project realization. With the suspended cable roof of the Olympic Stadium of Munich, a period was initiated dedicated to automatic form generation. The conclusion of the research on the form finding, the statics and dynamics of long-span net structures formed the basis for the subsequent development of modern software programs for nonlinear analysis of such structures. The developed calculation procedures were expanded and applied in further studies, as for example for the Stadium of Niedersachsen in Hanover and the Olympic Stadium of Montréal.

At the same time, the development and application of the finite-element method in structural engineering shifted the field into a science of creation of a variety of simulations distanced from the actual construction and structure of the building. The gap between architecture and structural engineering became even more prominent within different concentration areas of the disciplines; in the processes of creation of form, primarily derived from abstract aesthetic and functional reasoning on one side and numerical calculation and optimization on the other side.

Towards interdisciplinary iterative design processes

Contemporary advances of digital design technology enable at first place closed loops of linear design developments ranging from the conceptual phase to the realization of the initial concepts, to the analysis, production and fabrication. Based on such linear, sequential developments of form, planning and construction any optimization process is most often undertaken consecutively through improvement of discrete intermediate design results within respective multidisciplinary teams of operation. Since the early 90's, aspects of prefabrication, standardization and consequent industrial production and erection are of minor relevance for modern computer-aided manufacturing techniques; this applies for example to the milling geometry of any joint and the implicated production process [4]. In recent years for example numerous cable-net shells have been constructed of steel rods and glass plates, taking over an important model role in the steel construction industry in terms of developing digital design and production chains. In such less interactive linear process of design the originally smooth free-form surfaces of the overall shape generated through a three-dimensional modelling program are transformed into a viable structural system. In most cases the shape is modified to act like a shell structure, while the geometric optimization provides a smooth curvature. In a second step the three-dimensional geometry is transformed into a structural grid, i.e. into a triangular net that forms the grid shell. An automatic transformation into triangular net results in faceted edges, irregularity of the meshes and various node connections. The final step consists of the structural analysis of the net. The same data file that is used for the dimensioning of the members is also used for the definition of all parameters of the geometry for fabrication purposes.

Non-linear design processes based on interdisciplinary performance optimization criteria are considered to be crucial for the future of the engineering disciplines. The example of the international lightweight roof structure at the central entrance area of the Expo 2010 in Shanghai, designed almost 40 years after the precedent Olympic Stadium of Munich, by the architectural office SBA, Stuttgart/Shanghai, in collaboration with Knippers Helbig Advanced Engineering, Stuttgart/New York, comprises the largest contemporary membrane structure worldwide. The project is undoubtedly exemplary for its comprehensive design that was primarily directed by functional and extreme environmental conditions at the site, as well as structural constraints of the geometrically refined overall design form and automated fabrication processes [5]. The project reveals broader characteristics of discrete non-linear iterative performance based design developments with regard to the original form conception, optimization and realisation.

Research based design processes

Computational platforms of operation and real-time performance simulators provide meanwhile robust visualization and feedback features that can be associated with geometrical digital design models. In this frame design developments at various stages may encompass further parametric investigations with regard to the form, material and structure. Such iterative analysis steps of design verification and optimization shift the focus of the design teams to developing processes, from which specific results then come about through the definition of an emphasis on influencing values and parameters. In this way recent advances of disciplines, specialization, materials, system science and computational design enable a radical change in the contextual frameworks in which architectural and structural design, analysis and production are placed. Further collaboration, cross disciplinary communication, experimentation and research at all stages of the design process become feasible through a collective bottom-up approach, in order to achieve efficiency, sustainability and technological innovation [6]. Beyond non-linear approaches within the design process realized through certain cyclic interdisciplinary design steps, also interactivity within the decisions making processes may provide promising modes of operation for a bottom-up approach, enabling an iterative feedback loop of integrated physical, computational and construction design. Thus an aptitude for open loop developments in multivariable systems may also be achieved from early conceptual designs until fabrication through respective research based architectural-engineering design processes.

Integration in the design process

The brief review of processes of design of lightweight tensile structures proves that the future of structural engineering in particular cannot be perceived as static, but variable and therefore interactive. In this frame, the syntax of design and any related implicated developments from the conceptual to the realization phase that are followed in practice and require not only cross-disciplinary-, but also cross-national cooperation's for expertise, are of major significance. Such integrated activities promise to generate substantially new, innovative and transformative solutions to buildings and their designs, as well as to the associations, the industry and methods employed to realize them. At the same time, digital technology opened many possibilities for an integration and shift from mass-production to mass-customization in an effort to relate the principles of the former with the advantages of individual fabrication. Related processes are based on the coupling of computer-aided design and analysis, manufacturing and rapid prototyping through virtual engineering in favour of performance.

Integration of the architectural and structural engineering disciplines is undoubtedly acknowledged in practice and research, due to its potential to apply a heterogeneous set of discourses and types of knowledge, through cyclical and comprehensive processes of development. In addition it enables further interdisciplinary advancements in terms of advanced performance based research or technology transfer within the built environment.

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