# Numerical modeling and simulation of lightweight structures - using the example of the Olympic Stadium in Munich on its 50th anniversary

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**Abstract:** We present various aspects of numerical modeling and simulation arising from the main focus areas of the Chair of Structural Analysis at the Technical University of Munich. These include several considerations on the load-bearing behavior of lightweight structures, which are best associated with and demonstrated on the Olympic Stadium in Munich. This landmark has been an architectural and engineering challenge and a source of inspiration from its inception until now, in 2022, on its 50th anniversary. Therefore, we intend to provide a technological overview of the approaches used to model and evaluate these types of structures, clearly identifying the numerical advances and highlighting particular contributions from our institute.

*Keywords:* Lightweight Structures, Numerical Wind Tunnel, CAD-Integration, IBRA, CWE

## 1 Introduction

In structural design and analysis, lightweight constructions represent a combination of architectural aspiration and engineering challenge. Such designs allow open spaces to be covered by complex shapes, typically double-curved surfaces. They are characterized by their geometric stiffness rather than an inherent robustness from large cross sections. Due to the low thickness of the structural elements, these shapes tend to exhibit large deformations at small strains, for which geometric nonlinearities must be accounted for. Adequate stiffness is achieved through geometry (with curvature) and prestressing of certain parts or elements. Lightweight structures may be susceptible to transient effects because of their low inertia. Wind in particular, which is not only a time-dependent but also a shape-dependent load, requires careful investigation. The balance between form and force is key to the proper consideration of the effects on the structural behavior.

The study of freeform shapes and minimal surfaces using soap bubbles and fabric models represents the early and exploratory approach to lightweight design. Further experiments are measurements made in wind tunnels for appropriate load effects on the complex shapes. Lately, the appearance of numerical methods combined with improvements in hardware enabled new possibilities for the design and analysis process. This area is the focus of our contribution, with the Olympic Stadium in Munich serving as a motivator for many further developments. We cover aspects ranging from basic mechanical prerequisites over specifics of CAD-integrated analysis and a unified workflow for the detailed simulation of coupled wind-structure behavior using the numerical wind tunnel.

Figure 1: The Olympic Stadium and its numerical structural model [1].

Fig. 1 shows the Olympic Stadium in Munich with its surroundings. A sketch of the numerical structural model is overlaid. In times of highly demanded digital twins, such models are the key to providing answers to questions directed at the actual built structure. It serves design as well as predictive analysis purposes (i.e. structural/mechanical twin) and can easily be enhanced by more properties (monitoring data, cost estimates, etc.). This idea is captured in the description of the AiCAD-concept [2].

The pioneering work on the original structure could not have been possible without many protagonists (architecture and engineering: Behnisch, Leonhardt, Otto, Schlaich; numerics: Argyris, Biguenet, Haug, Linkwitz, Schek) [3], [4]. Their contribution is further detailed in [5], as a tribute to the simulation methodology for textile lightweight structures. We build upon this knowledge base with further advances in numerical developments.

## 2 Design and Analysis of Lightweight Structures

We focus on the peculiarities of designing and analysing lightweight structures, where form and force are inseparable. In the case of the Olympic Stadium Roof, one can observe the series of double-curved surfaces arising from a cable net and its plexiglass cladding.

The typical design cycle is depicted in fig. 2. In the early design process, the starting point is identifying the target equilibrium shape for given prestress and boundary conditions by a formfinding analysis. However, this shape is bound to change during the iterative process of considering all design steps. This is followed by the structural analysis under relevant external loads. Other steps are related to specifics in the manufacturing and construction staging. Cutting patterns need careful consideration, as membranes will have to be joined from flat pieces and prestressed to arrive in their designated position.

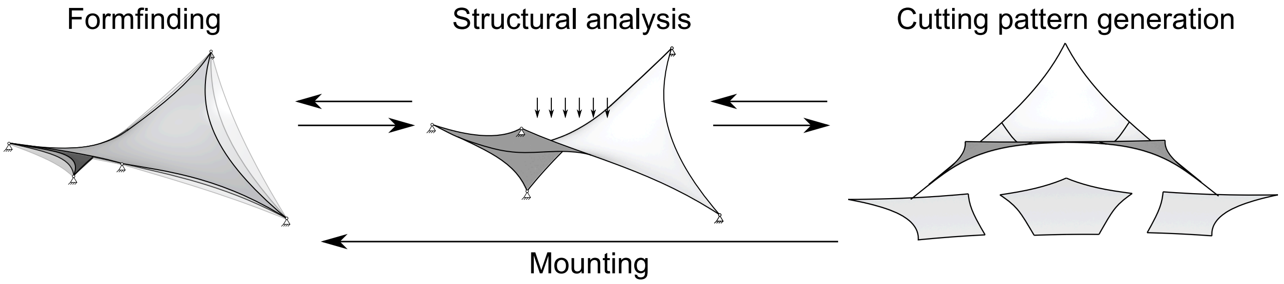

Figure 2: The design cycle of membrane structures [6].

## 2.1 Nonlinear Structural Analysis

Lightweight design typically considers large displacements of the structural components. Geometrically nonlinear analysis is thus needed to capture the mechanical behaviour appropriately, thoroughly motivated in [7]. This section discusses the necessary preliminaries for such considerations and points out the challenges inherent to flexible structures.

The Finite Element Method (FEM) is used to simulate the structural response to external forces and internal prestresses. The method is based on the equilibrium of virtual work. Derivation of the relations highlights two critical aspects relevant for analysis:

- There exists a non-negligible contribution of the geometry to the stiffness matrix, which implies an update and assembly of it at each iteration of a numerical process.
- For cables and membranes we need to ensure proper prestress, otherwise such elements are mechanically non-viable, leading to critical errors in a computational context.

This is in contrast with the linear theory of first order analysis, which is only valid for small deformations. For most use cases in lightweight analysis, it is a must to account for the change of shape during deformation. This is not only critical for updating the stiffness matrix, but also can be a key component in case of follower loads, such as wind. Additionally, prestress ensures proper behaviour, both from an engineering point of view as well as for numerical consideration, as respective elements lack inherent out of plane stiffness. It is evident that the formulation as well as the numerical models need to be suitable to ensure such aspects.

Thin fabrics and materials stretch considerably under such actions. How the structure is planned to behave once mounted, can be considerably different to how it is produced, transported and mounted. Consequently, the aspect of cutting pattern generation has high importance. A numerical approach enables reverse-engineering to lead from the target geometry to the cutting patterns necessary to achieve this. Figure 3 highlights this concept.

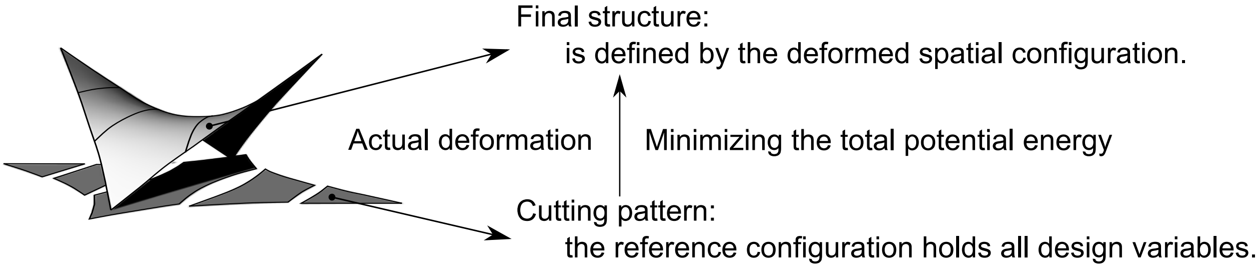

Figure 3: Cutting patterns for a hypar structure [6].

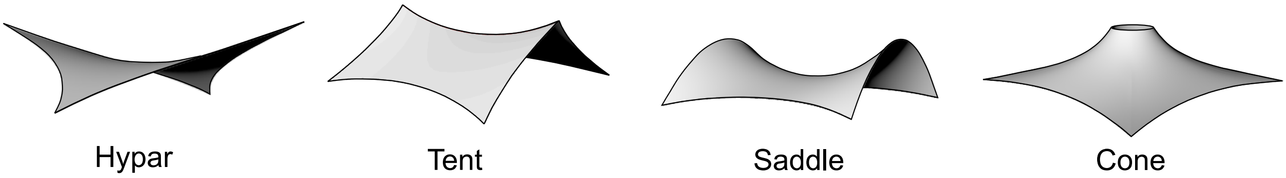

Figure 4: A selection of representative geometries for membrane structures [6].

For engineering purposes, there are certain recurring shapes, which are of utmost relevance. Figure 4 shows a collection of geometries, which will either occur alone or in certain arrays or formations. Specific modifications will lead to particular structures, such as the Olympic Stadium Roof in Munich.

## 2.2 The CAD-Integrated Design Cycle

The design and analysis of lightweight structures calls for a close cooperation between architects and engineers, as shown by the exemplary structures in the Olympic Park. However, the computational models are often separate and transferring data from one discipline to the other can be cumbersome. CAD-integrated analysis skips this gap by allowing all participants to work on one model for most of the design and engineering tasks. This is well in line with the topic of Building Information Modelling (BIM). However, the main link is not only to have a common format for the geometry and structural properties, but first and foremost to ensure a functional structural model, serving both computation design and analysis. This implies stringent requirements on how the model needs to be created and used.

The proposal is to use an isogeometric discretization based on Non-uniform Rational B-Splines (NURBS) instead of linear shape functions, using the inherent parametrization available in the CAD workflow. The geometry is enhanced by mechanical properties to build the structural model. As such, the Isogeometric B-Rep Analysis (IBRA, as described in [8]) combines CAD and FEM, permitting a strongly linked workflow between architects and engineers. It is also very appropriate for delicate considerations related to shape, iteration loops and exploring multiple design scenarios by utilizing parametric CAD environments, see [6] for detailed explanations and examples.

# 3 Wind-Structure Interaction of Lightweight Structures

Due to the interaction of form and force, the consideration of surface loads is challenging while it is especially important to capture them appropriately. The direction and intensity of wind effects (pressure and friction) will adapt to deformation, rendering them follower loads. Moreover, if lightweight structures span over large distances, potentially non-negligible amounts of air (or snow) have to be considered. Physically this leads to added mass at levels which require the detailed analysis of interaction between the construction and loading force. Such effects happening on the interface between various physical domains (in our case wind and structure) constitute a specific research area within multiphysics, in particular Fluid-Structure Interaction (FSI). We present our contributions to and recent investigations with the so-called *numerical wind tunnel*, the representative tool in Computational Wind Engineering (CWE). In [9] the potentials and challenges of this analysis tool are briefly outlined, with work since then further consolidating the research efforts. We specifically focus on enhancing the load-bearing and response behaviour of structures in wind.

## 3.1 Modelling Requirements of the Numerical Wind Tunnel

Investigations using the numerical wind tunnel imply multiple assumptions and have to obey various requirements. Similarly to the "traditional" (i.e. "analog") equipment, the analysis needs the definition of the relevant flow domain, generation of realistic wind conditions, the latter including various neighbouring elements and obstacles. An appropriate structural model has to be constructed as well, following the considerations presented in section 2.

Typical inflow conditions for general Computational Fluid Dynamics (CFD) investigation are well known. Additional requirements arise for wind engineering. These refer the proper metrics for the flow conditions in order to be considered realistic: the streamwise velocity component, particularly the time-averaged mean and turbulence intensity over height, supplemented by the turbulence length scale and power spectral density of the spectrum at characteristic points. This inflow condition can be created with a synthetic wind generator. Further consideration are linked to other nearby objects or terrain, which could have significant impact on the local flow conditions.

We aim to investigate the transient loading of wind on deformable structures. Consequently, both numerical models need to obey appropriate modeling best practices. A segregated approach permits applying known properties and strategies, optimal for the two domains - fluid and structure - separately. The wind flow around the target construction is recreated with the Large Eddie Simulation (LES) technology, whereas the structure is supported by a model suitable for geometrically nonlinear structural analysis.

## 3.2 Investigating the Olympic Stadium Roof

We focus on showcasing recent developments on the Olympic Stadium Roof. This is an ideal example of a large span lightweight construction. It is numerically modeled with plates in membrane action. The original design process in the 1960s' and 70s' used various experimental methods and analytical

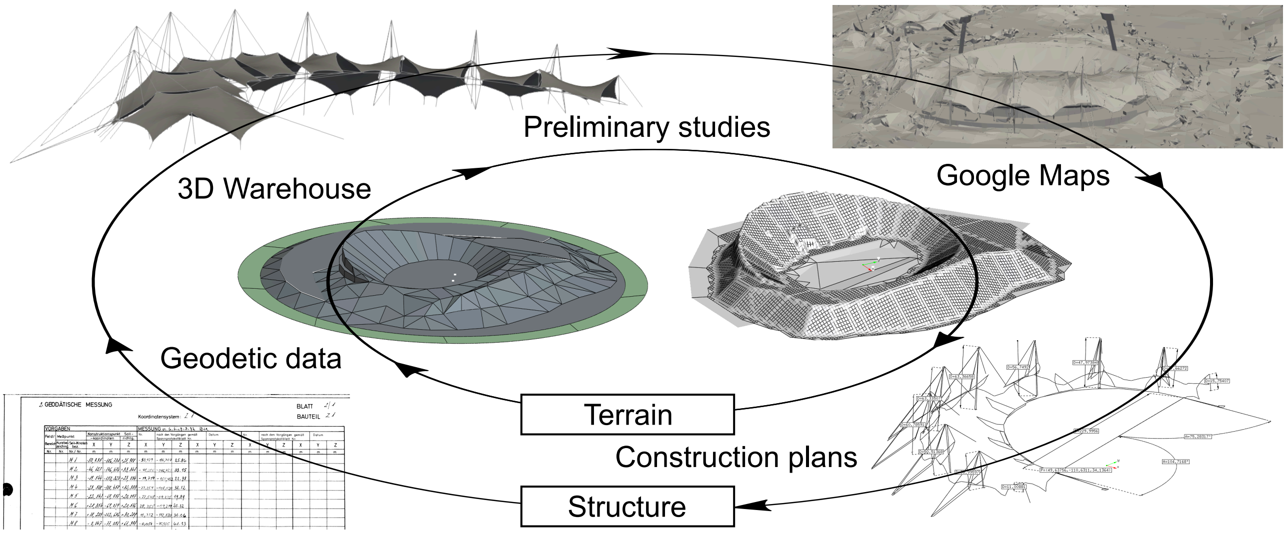

Figure 5: Model-update workflow.

considerations to arrive at this shape and respective prestress state. Due to the lack of extensive computational methods at that time, the structure is the result of ingenious engineering and is supported by the experience of all involved. Our current shows recent advances, in particular creating a viable computational model and simulation environment for the wind flow as well as structural investigations.

Apart from building appropriate numerical models for the structure of the Olympic Stadium, relevant parts of the surroundings have to be considered. For the construction we used data from building archives (based upon on-site measurements) as well as digital resources (Google Maps and 3D Warehouse). In contrast to an initial design process (such as in section 2.2) with the shape resulting from formfinding, here the shape was given. As such, We iteratively optimized the prestress state to achieve this target, under the consideration of self weight. This implies the iterative process of updating the model, as presented in fig. 5, by carefully investigating various sources.

Fig. 6 depicts the setup for the CWE-analysis used to investigate the wind-structure interaction of the stadium. The study includes the turbulent wind around the stadium and its surroundings. Not only the flow field and the aerodynamic loads are assessed, but the effect of the flexible structure in captured as well. This complexity renders such numerical simulation to be carried out on High-Performance Computing (HPC) machines. These exploit parallelism on distributed memory units based on the Message Parsing Interface (MPI).

## 4 Conclusion and Outlook

We showcased various developments relevant to the numerical analysis of lightweight structures. In particular, we linked multiple aspects to the example of the Olympic Stadium Roof in Munich. The necessity of considering geometrical nonlinearity was highlighted. A CAD-integrated workflow enables architects and engineers to work on one common geometric model, which is also mechanically

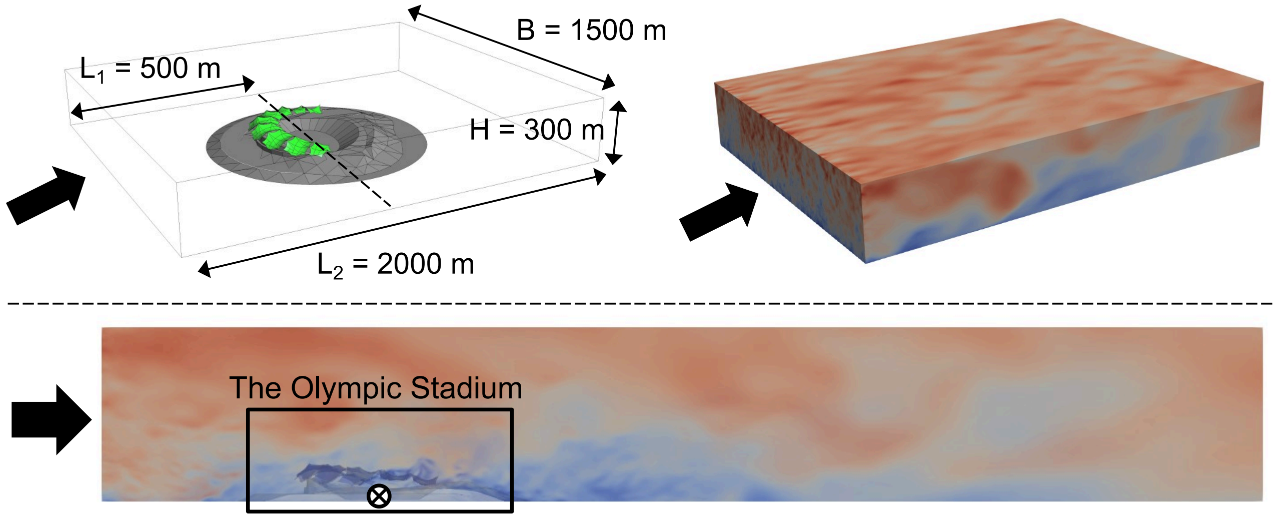

Figure 6: The CWE-model of the Olympic Stadium.

correct and ready to be used for analysis purposes. We additionally demonstrated recent capabilities in multiphysics simulations, where coupled phenomena need to be investigated. Herein the wind-structure interaction of the Olympic Stadium Roof with its surrounding was modeled and simulated. This heavily relies on adequate computational models for the simulation capabilities of the numerical wind tunnel being properly leveraged on a high performance computing environment. The outcome is a detailed flow field, the wind loads as well as their effect on the flexible structure.

The workflow can be viewed as a whole, starting with finding the appropriate shape of lightweight structures and ending with the usage of these for advanced analysis purposes, such as the action of wind. This fully-digital workflow can go well along with various advances in BIM. Yet it not only needs a common format and shared data, but requires the proper links to be made for simulation needs. Detailed and realistic numerical models are also the bases for an outlook towards digital twins. In such a context validated replicas can be paired with existing structures, where the updating of the parameters is based on monitoring data.

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