Computation and geometry in structural design and analysis: proposal for the Computation and Geometry WG15 study group

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Summary

Through three examples from practice spanning decades, this paper demonstrates the evolution of the geometric definition and structural analysis of complex geometry buildings. Gaps in current knowledge relating to computation and geometry are then discussed, and the case is then made for the birth of the new Computation and Geometry study group as part of the IASS SMG.

The study group aims to support research in computational geometry in structural engineering by bringing expert researchers and practitioners together in order to increase and share knowledge. Research themes relate to digital design and the description of structural geometry based on computational methods and techniques. The use of computational methods and software tools in the creation of structural geometry will also be explored.

Keywords: *Study Group, Structural Morphology, Geometry, Computation*.

1. Introduction

As the design, analysis and construction of structures heavily relies on shape definitions, the field of structural geometry is an important intermediary between design and realisation. This is most evident for monocoque structures, where the structural behaviour is determined by their shape. Over the years, a number of pioneering architects and engineers have devised various techniques for defining structural geometry, resulting in innovative and iconic structures. Consider for instance the work of Heinz Isler, Eduardo Torroja, Felix Candela and Antoni Gaudí, and their ability to define structural shapes based on physical form-finding using various methods.

However, due to the recent ease by which the geometry of complex surfaces and elements can be digitally generated, modern building designs show an increasing complexity in form and layout in relation to engineering and construction. As a result, in many cases the symbiosis between geometric form and structural behaviour is under pressure. At the same time however, computational methods and technologies are being developed to deal with structural complexity, giving the computer a more prominent role in engineering practices.

Successful and efficient implementation of such methods and technologies is becoming more reliant on coherent research in this field. This is especially due to the rapid development of new software packages and the increase in computational power. However, these new tools require an in-depth knowledge of (structural) geometry, for instance with respect to meshing strategies or rationalisation of surfaces, and of the mathematical properties of curves and surfaces.

This paper presents three examples in which structural geometry definitions are the main focus of the design, and describes the computational design methods used. As such, they exemplify different relationships between structural geometry and advanced computational methods. Subsequently, the paper presents gaps in the current knowledge relating to computation and geometry, and discusses the need for a new Computation and Geometry study group as part of the IASS Working Group 15: Structural Morphology.

2. Computation and Geometry in Example Projects

2.1 Mannheim Multihalle Gridshell

The Mannheim Multihalle gridshell [1] is a classical example where a physical form-finding method was used to define the structural geometry for a large pavilion [Figure 1].

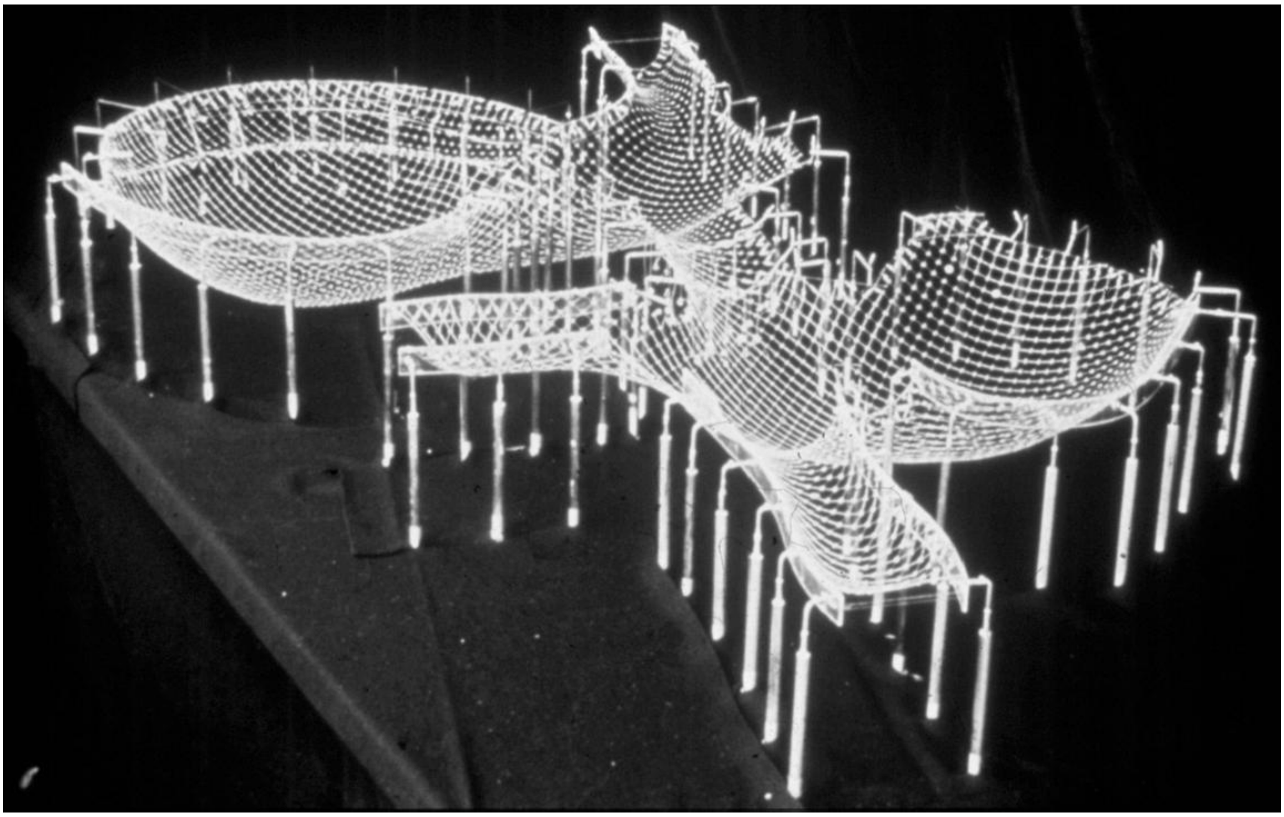

Fig. 1: Mannheim gridshell hanging chain model by Frei Otto

Although the hanging chain model gave rise to the overall geometric configuration through a combination of photographic and mathematical techniques, more detailed calculations were required to define the precise and local geometry, such as the definition of structural behaviour under various loading conditions and the analysis of possible buckling failure of individual elements.

Since digital computing was in its infancy at the time, the choice and capabilities of the available analysis software was much more limited than we would recognise today. Therefore computer analyses were used sparingly. Instead, hand calculations based on measured curvatures were carried out and validated with scale model tests, using both applied loads and in wind-tunnel tests. Even then, a full-scale load test on the finished structure was deemed necessary by the proof engineer.

This shows that the physical form-finding methods were in tune with the mathematical and physical analysis tools available, even if some laborious measurements (stereo-photography and contour-plots) of the model were required to generate the input necessary for these calculations.

2.2 Stuttgart21 Rail Station

In the early stages (circa 2002) of the design of the Stuttgart21 rail station [2], a physical model was the only 3D representation available [Figure 2]. In order to facilitate engineering design and optimisation of the shell, a digital 3D model was required, particularly to investigate the levels of stress in the shell, which could not readily be deduced from the physical model.

Fig. 2: Stuttgart21 hanging fabric mode by Frei Otto

Using a combination of a robot-arm type 3D position measurer and high level of manual labour, 15,000 3D coordinates were logged and then meshed in CAD software to give a 3D design surface [Figure 3]. This surface could then be used as the basis for subsequent form-finding and structural finite element analysis models.

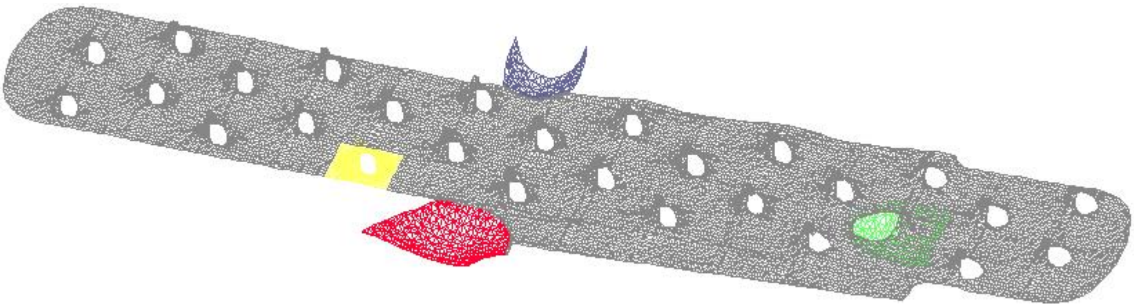

Fig. 3: Stuttgart21 digitised point cloud by Buro Happold

This example highlights the fact that whilst physical form-finding methods are extremely useful for defining an efficient and elegant design solution, they are no-longer compatible with the way modern practices design such buildings. The rapid development and widespread adoption of computational methods in engineering now mean that we must look to new ways of generating, manipulating and optimising geometry, that do not inhibit the creativity of the designer, but nor do they inhibit the efficiency of the modern design process itself.

2.3 Aviva Stadium

In the summer of 2010 the new Aviva Stadium, the new National Stadium of Ireland, was opened to the public [Figure 4]. The roof and facade system for this stadium was designed entirely parametrically, with a single parametric model being shared between architects and engineers [Figure 5].

Fig. 4: Aviva Stadium near to completion

Additionally, this parametric model was extended to link directly to structural finite element analysis software by the engineers, defining section sizes, connections, supports and a full description of the load cases and combinations. The software was also linked directly to the bespoke CAM software used by the facade fabricators, allowing each of the 4000 individual facade louver elements to be specified and manufactured individually. This led to a completely parametric work-flow from the design of the overall doubly-curved building form through to structural design, optimisation and manufacture. More information on the design of this project can be found in the literature [3, 4].

Whilst the project was build on a solid work-flow of parametric geometry and integrated analysis, there was still room for improvement. The hierarchical nature of the parametric model meant that any changes requested by the engineers or fabricators had to be communicated back to the originators of the model (architects), the change implemented at this top-level, and then cascaded down through the parametric model to the rest of the design team. A bi-directional model based on constraint-modelling would have sped up this process and made it truly collaborative. In addition, the link between parametric model and structural analysis had to be coded in software from scratch by the engineers and was rather specific to this particular project. A more general and integrated link between modelling and analysis will be required if these tools are to be used more generally.

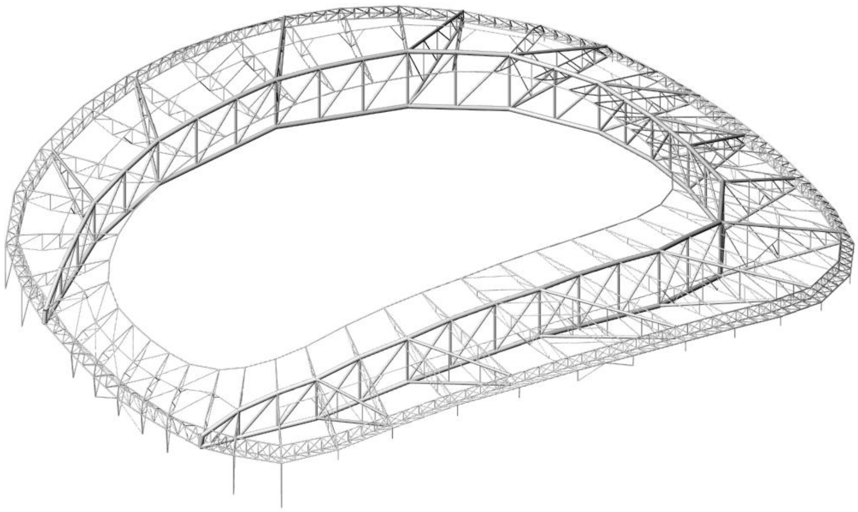

Fig. 5: Roof steelwork of the Aviva Stadium, defined parametrically easily modified and optimised

3. Innovative Research in Computational Geometry

The examples presented in the previous section coarsely show how different levels of computational geometric definitions support the design process and how computational analysis methods used in structural engineering have developed. The first two cases show how the principles of the inverted hanging chain model are used for building design, and how the methods used to capture their shape for use in structural analysis have had to keep up with the rapid development of computing techniques. Digitising these physical models for computational analysis poses difficulties and this suggests that the geometrical form-finding process needs to move from the physical to the digital in order to facilitate the efficient flow of data.

The last example demonstrates one way of achieving this. Geometric definition based on parametric and associative modelling is fast becoming the norm, and we are now beginning to see seamless interoperability with structural design and analysis software. However, this interoperability is not being used to its full potential. Most parametric modelling concerns itself with describing complex geometry through equations and relationships and pays little attention to physics and how the structure is actually behaving.

There are examples where digital parametric modelling is directly related with structural form-finding. Reference is made to a research project at the Massachusetts Institute of Technology in which particle-spring systems are proposed for finding structural forms composing only axial forces [5]. The goal of the research was to increase intuitive understanding of the structural behaviour of complex forms at the early stages of design. This method allows for real-time discovery of structural form, rather than analysis or optimisation of an existing form. Form finding processes early-on make the designer aware of structural responses and give just the insights into structural behaviour that the early physical models of Otto and his contemporaries gave.

Nevertheless, whilst some research has been conducted in the field of computational geometry, it is usually performed on an ad-hoc, project-by-project basis within industry. The results are therefore not always disseminated, either for commercial reasons or because they are only thought to be applicable to one specific project. This culture is not beneficial to the construction industry as a whole, since it ensures valuable research time is wasted on “reinventing the wheel” and makes it difficult for the industry as a whole to make progress. Structured research, bringing together expert knowledge of geometric structural design from practice, and the theory and positive attitude towards dissemination seen in academia, is essential in order to make a step-change in progress for the building industry.

Additionally, with the emergence of new digital tools available to architects and engineers, whilst a range of new possibilities arise, this also means that new processes in structural design need to be adopted. One example is the relationship between parametric structural models and the definition of loads and load cases for the analysis of the structural behaviour. Although parametric modelling allows for quick and frequent geometry updates, analysis software is generally incapable of automatically reacting to the updated geometry and interpreting the implications in terms of updating load definitions. Current developments along these lines are driven mainly from practice, especially since modelling and analysis software differs between different companies. However, the industry would greatly benefit from a joint effort in research related to problems like these.

The authors believe therefore, that a new study group within the IASS is needed, to support coherent research in the field of computation and geometry, and to provide a platform for researchers, engineers and designers to communicate and share knowledge. The study group will focus on research themes which explore the use of computational methods and tools in the creation of structural geometry. Therefore, the group will develop a wide range of study topics, all of which will have an underlying theme of performance-driven structural design. Its aim will be to support research in computational geometry in structural engineering, by bringing expert researchers and practitioners together in a spirit of collaboration in order to share and increase knowledge.

The formation of the study group is supported by Working Group 15, Structural Morphology (SMG) of the International Association for Shell and Spatial Structures (IASS), with the aim of focusing and driving forward research fields linked to structural morphology. As such, there is a strong link with the research conducted by other study groups of the SMG, such as “Curved surface structures”, “Adaptive formwork”, “Transformable structures” and “Origami”.

4. Conclusions

It has been shown that whilst the current digital methods employed in the modern design office are no longer compatible with physical models for shape generation, something has been lost along the way. Parametric models facilitate the easy manipulation of complex geometry forms, but do not necessarily lead to more efficient designs and the user learns nothing about how the proposed design will behave structurally. Whilst some software has been developed to enable to combine parametric modelling with structural design and analysis within the computer, and can respond to physical and structural drivers as well as encompass constructability, such tools are rare and often not shared across the industry.

For the construction industry to make full use of the potential that modern technology can offer, what is needed is a “one-stop-shop”, where like-minded designers and engineers can collaborate on research projects and share their findings with the wider professional community. This will promote a dialogue amongst experts, sharing knowledge and avoiding wasted efforts and reinventing the wheel.

With this in mind, the authors propose to start a new Computation and Geometry study group within the IASS SMG and invite interested people from practice and education to get in touch and get involved.

Help change the way the industry goes about developing and researching new computational geometry modelling tools. Come and join us!

5. References

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