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Parametric Modeling of Flat Rod Structures

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Abstract. Thanks to the use of advanced digital tools and the achievements of knowledge encompassing numerous fields of science including mathematics, computer science, and even genetics, architects now have the means to create multi-variant design solutions. The quantifiable benefits of interdisciplinary design are increasingly recognized within the field of architecture. As a result, a surprising variety of new ideas and designs emerge. These are often the result of advanced material and structural optimization, and their technological qualities become as important as their visual reception. The subject of this research paper is presenting the results of modeling various configurations of flat rod trusses. The aim of the analysis was comparing the efficiency of the use of materials in differently configured trusses, including trusses created *via* parametric modeling.

1. Introduction

Contemporary architectural design is influenced not only by the developing technologies of construction materials and fabrication processes. The achievements of the first industrial revolution led to the standardization of design elements. Such efforts developed mainly in industrial settings, according to the Fordist idea of standardizing the final product that lead to mass-scale production of unified components. The "think globally, act locally" [1] concept brought on a greater awareness among designers and collaborations in the field of interdisciplinary design. Changes taking place today include "tailor-made"[2] solutions and better opportunities for manufacturing individualized, optimized components. This process can be observed in the increased use of advanced calculation programs. Thanks to such software, it is possible to create mathematical models and algorithms recreating, among others, natural behaviors brought to life *via* biomimetic design processes[3]. The search for optimization of both material and manufacturing technology is also manifest in the selection of efficient structures, materials, etc.

2. Interdisciplinary and topological optimization design

The search for the geometric shape of structures and the construction of rod structures are both important elements in the design of architectural forms, which consists in reflecting the intended visual effect, but also the rationalization of technical and material solutions[4]. From the point of view of tectonics, another important element beyond the shape of the structure is determining the grid distribution[5]. Obtaining effective structural divisions of grids is a task that should be solved as an interdisciplinary issue through analyzing paradigms from two disciplines: architecture and construction. Local compaction and expansion of the grid is an attempt to optimize the structure – too many elements cause the deadweight and then greater deformations. For the most part, the analyses are concerned with determining the metrics of the distribution, which in the case of free-form architecture is crucial for the realization of curves describing the form. Large-scale structures, such as bridge and roofing girders, were traditionally designed as relatively straightforward rod structures. The progress in construction took place as a result of changes to geometrical and static models, optimization was usually limited to the use of possibly many repetitive elements. The changes that occur in the manufacturing process of construction elements allow the erection of load-bearing structures from prefabricates that are assembled directly and automatically on the construction site thanks to the use of parametric code(Figure. 1, Figure. 2). The research carried out in this area indicates the possibility of achieving significant efficiency, particularly in regards to the optimization of materials, as evidenced by a significant number of ongoing studies. Thanks to the algorithmization of tools used in the design process it becomes increasingly straightforward to follow the more eco-efficient models derived from research on the evolution of morphogenetic processes occurring in nature. Most of this research, however, is based on material optimization – or the analysis of the flow of forces within structural elements – and the removal of surplus material. When examining grid structures, it is important to find the optimal distribution of rods and nodes so that only those elements that are necessary and do not place additional load on the structure remain in place[6].

Figure 1. An example of generative optimization of material through the use of digital production. Tests conducted by scientists from Imperial College, London in cooperation with ARUP

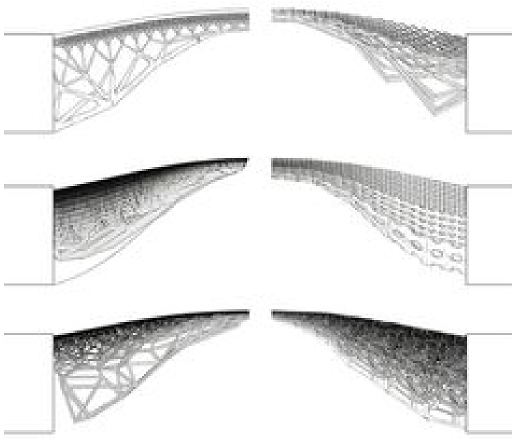

Figure 2. Phases of optimisation of the bridge conducted by scientists from Imperial College, London in cooperation with ARUP

3. Optimization of structural elements

Because they are relatively light, flat trusses are not always adapted to boundary conditions in the optimization process – only their load-bearing capacity is tested[7]. Due to the ease of execution, these constructions are used as girders in bridges, footbridges, or roofs structures. In traditional layouts, it is possible to separate main elements such as top and bottom chords, diagonals, and posts. In majority of projects architects did not attempt to form their structure, instead leaving their visual quality to the engineers. Developed in the 21st century, new software for computer-aided design has amplified the need to alter this way of thinking. The use of generative design methods and the growing awareness of the need to imitate patterns found in nature allow designers to optimize not only the entire shape of the structure, but also the shape of all its components[8]. For example, thanks to Architectural Design Optimization (ADO) analyses, architectural and construction simulations can be conducted, allowing architects to minimize, for example, the use of materials or the energy necessary to produce a support structure. The impact of the development of contemporary analytical methods is particularly evident in the method of shaping structural details. One example of this type of optimization is the research focusing on the elements of connections in membrane structures, conducted in the AGU – the Advanced Geometry Unit, founded in 2000 within the Arup design studio(Figure. 3). Thanks to the current accessibility of additive technologies manufacturing construction elements only on a small scale, it was decided to use FEM to optimize the mass of connectors in one of the objects designed by the studio. The designers faced the task of not only computational material optimization, but also the technological practice of manufacturing the given elements, whose height is the result of applied materials and manufacturing technologies. The final form not only weighed less, but was also significantly different from the original. The optimization allowed saving 75% of the weight of the connectors, resulting in the reduction of the mass of the entire structure by over 40%.

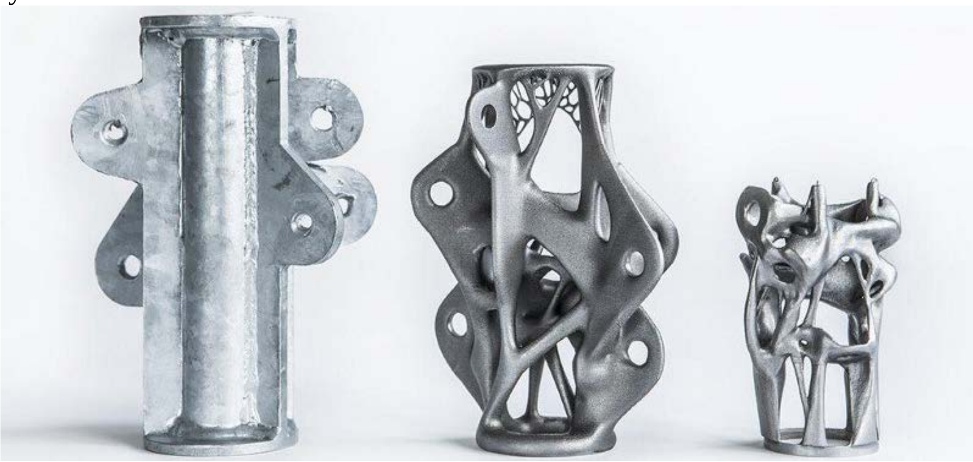

Figure 3. 2 Phases of material optimization of load/weigh, conducted in the interdisciplinary AGU cell within the Arup design studio

4. Development of architectural design optimization (ADO)

A. Gaudi, F. Otto, and S. de Chateau have already carried out optimization activities, however, the inability to calculate geometrically advanced forms has proven to be a serious difficulty. The development of computer-aided design visible at the turn of the 21st century has enabled the introduction of a number of tools that have streamlined computer-aided calculations. In a way, the successive generations of new software force users to search for new aspects of optimization. Presently, it is possible to use advanced mathematical algorithms and improve the technical qualities of materials, including in the nanoscale. The surrounding natural environment affects man's creative intuitiveness – it is a source of inspiration, a guide. Contemporary shaping of structural forms of architecture consciously draws on bionic patterns. These actions appear to be dictated, on the one hand, by the search for a new visual quality in architecture, and on the other – the rationalization of technical and material solutions. One should also remember that the structure is subject to the laws of physics, construction and building materials age with the passage of time, while the form and function are adapted to the environment, as well as assessed on the basis of subjective impressions – and all this stems from Nature(Tarczewski 2011). Digitized design’s capabilities for creating new architectural forms depend on the perceptive and cognitive abilities of architects. Meanwhile, the parametric and generative design process is a dynamic process characterized by discovering new possibilities in comparing numerous variants. In architectural searches, particular attention is paid to form finding and topology.

The role of the designer in using generative tools is to interpret countless results by creating parametric models or genetic algorithms, analyzed in static calculations while creating topologically variable surfaces, isomorphic skeletons, the emergence of new forms, and self-similarity processes, etc. The significant geometric complexity of structural forms is a big challenge in contemporary architecture. More and more often, unique objects in innovative shapes drawn from nature are being implemented. Having gained access to ever more powerful computer-based calculation capabilities and improved methods and methods of fabrication, architects are able to design increasingly sophisticated objects.

5.In the search of optimal rod structures-case studies

The search for effective engineering solutions in keeping with architectural values prompted the authors to analyze non-standard flat trusses. The research presents various ways of topological optimization. Obtaining the minimal mass in each of the considered variants was adopted as the most important parameter. Differences in the number of nodes and the length of rods have been disregarded due to the fact that flat rod structures are fairly simple elements to fabricate. Conclusions from the research conducted in the context of design of load-bearing structures with some degree of geometric complexity can become a useful tool in the hands of an architect. The scripts prepared during the research were designed to universally adapt to boundary conditions, depending on the adopted configuration of rods. The assumed task was to develop basic assumptions and preliminary guidelines for the design of trusses with a free-form rod structure. Different geometries were a part of authors case studies Figure 4. presents standardized types of traditional trusses, Figure 5. presents configurations of parametric designed trusses.

The longest truss has a smaller mass with a height/span ratio of 1/11L. These small differences, however, are insignificant and therefore are disregarded in further analysis. As the next step, the profile cross-section was optimized using Robot Structural Analysis software: 4 groups of rods were generated for each solution. Due to dividing rods into groups and the assumption of different closed cross-sections, each of the solutions achieved a significant reduction in the mass of the truss (between 9% and 50%).

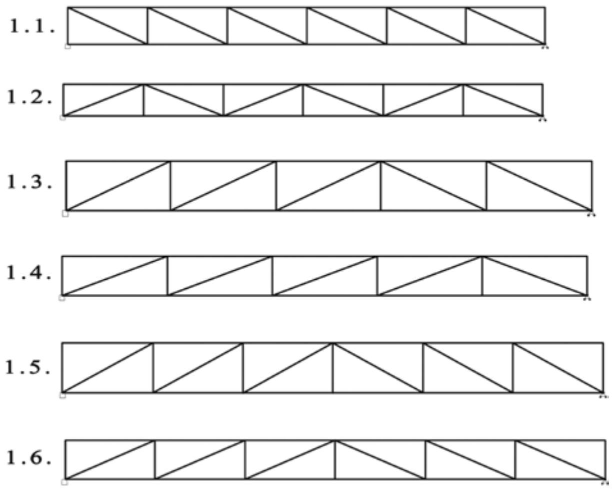

Figure 4. Case studies
- shape of models in Analysis 1

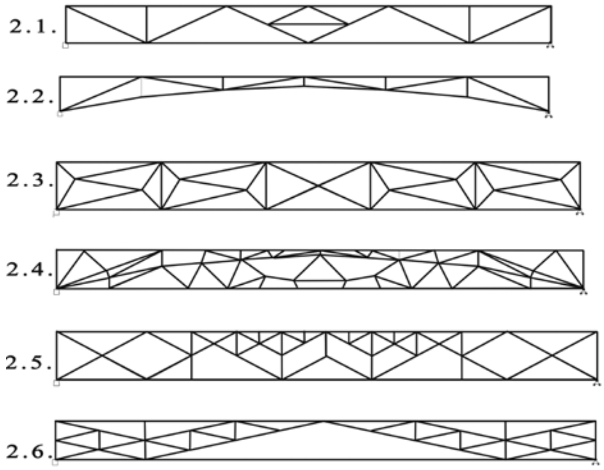

Figure 5. Case studies
- shape of models in Analysis 2

Table 1. Analysis 1 – Summary of truss patterns and total combined mass for each individual variant

#	Truss/ Lattice construction structure length [m]	Truss height Proportions h = 1/11L or h +1/14L	Weight [kg] for 1 group of rods	Weight [kg] for multiple groups of rods	Optimization effect resulting from changing the profiles of rods
1.1.	13,5	1.22	351	319	-9,11%
1.2.	13,5	0,96	348	174	-50,00%
1.3.	16,25	1,47	400	263	-34,25%
1.4.	16,25	1,16	386	243	-37,04%
1.5.	16,5	1,5	421	323	-23,28%
1.6.	16,5	1,17	460	316	-31,30%

The modifications undertaken in Analysis 2 consisted in changing the internal structure of the trusses, while maintaining the location of the supports, the external shape and the point of application of external forces (the requirement to keep these truss nodes in these positions). The adopted variants are free-form interpretations of the geometric truss developed on the basis of an algorithm. The results described already include the material optimization described in Analysis 1. Variants 2.1 and 2.5 show a significant reduction in the mass of the entire structure – 37,93% and 28,79% respectively – when compared to the optimized variants from Analysis 1. This results from the distribution of truss nodes and rods in relation to the distribution of forces. In addition, example 2.1 does not have a different geometry than standard trusses, which suggests that the optimization process does not require excessive increase in the total length of rods or the total number of nodes in order to achieve satisfactory results. In example 2.2, despite a significant transformation of the geometry and the reduction of the total length of rods, the mass of the truss did not change. In example 2.4, despite a slight increase in weight, the tendency of the nodes adapting to the forces involved can be observed. In the next steps, in order to optimize, it would be necessary to eliminate rods within the bottom chord, which add extra load to the structure. Variants 2.3 and 2.6, which were generated in the process of symmetrical truss divisions, are not designed in accordance with the flow of forces, and therefore the entire structure must bear the load of the excessive number of ineffective rods.

In traditional truss design(Table 1), one of the most important parameters is to determine the height of the truss in relation to its span. However, as it can be seen in the analyses, the search for a more favorable rod structure in the construction of the truss is also important. Shaping the form with the use of generative design tools allows obtaining many solutions that can determine the quality of the architectural message(Table 2). Striving for optimization of, among others, the minimal use of material, does not limit architects to the design of classic geometric forms.

Table 2. Analysis 2 – Summary of truss patterns and total combined mass for each individual variant

#	Truss/ Lattice construction structure length [m]	Truss height Proportions h = 1/11L or h +1/14L	Weight [kg] for multiple groups of rods	Optimization effect resulting from changing the profiles of rods
2.1.	13,5	1.22	198	-37,93%
2.2.	13,5	0,96	173	0,00%
2.3.	16,25	1,47	378	+43,72%
2.4.	16,25	1,16	255	+4,93%
2.5.	16,5	1,5	230	-28,79%
2.6.	16,5	1,17	398	+25,94%

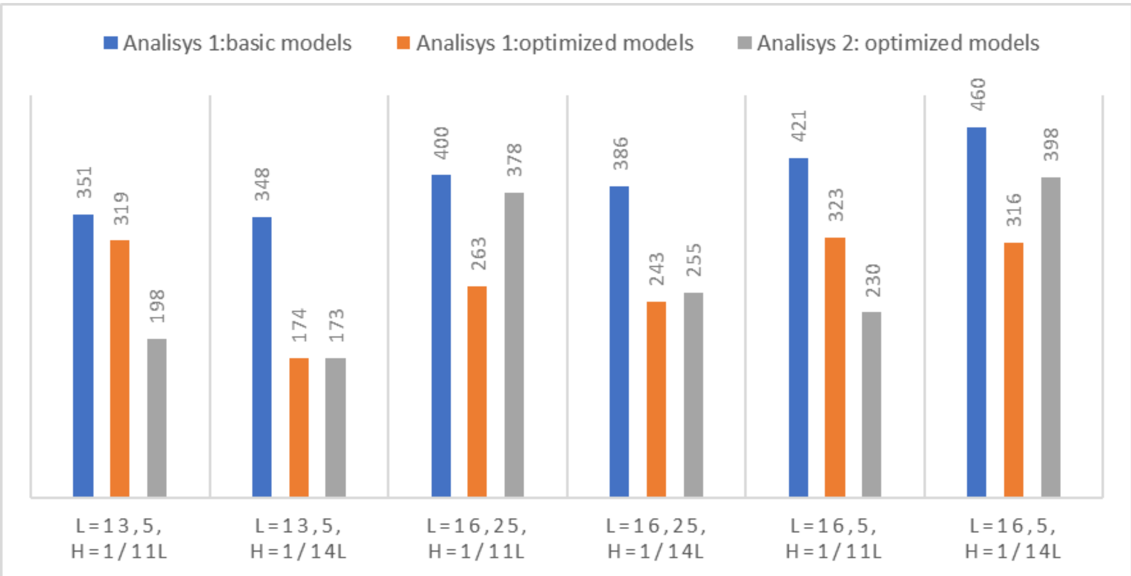

Figure 6. Comparison of all variants

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6. Conclusions

Reflections on how to optimize rod structures have been developing since the 19th century, but it was access to contemporary computer-aided programs has advanced these efforts. Differentiation, but also the creation of free form and geometrically complex structures is a feature of contemporary architecture. The original, bionic shapes of buildings erected in the 21st century are the result of explorations in avant-garde architecture – surprising in terms of art, and increasingly rational due to the technical and material solutions they employ. Computational calculation methods lead to the improvement of modeling tools, as well as the fabrication of construction elements, and architects are able to design unconventional forms with increasingly complex structures. The algorithmization of tools supporting the design process provides new opportunities in the search for innovative and effective load-bearing structures. The results presented above indicate that there are many possibilities in the search for optimized material solutions in architectural and construction design, which is particularly important in the context of more economical management of resources available on the global scale.

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