New Optimization Techniques

Session Organizers: Andrew BORGART, Edgar STACH

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Andrew BORGART (TU Delft), Edgar STACH (University of Tennessee)*

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Computational structural form finding and optimization of pneumatic structures

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Abstract

In the last few years a number of computational methods have been developed for structural optimization, methods for structural shape optimization (Bletzinger and Ramm [1]) or for topology optimization like evolutionary structural optimization methods (ESO / Extended ESO) (Cui, Ohmori and Saski [2]) etc. Most of these methods are based on dissecting the element into numerous parts for the optimization process and by deleting or adding parts after individually being tested against the design objective, which is achieved by variation of the design variables who are subjected to the design constraints in a process of multiple iterations. The results of this type of optimization used in mechanical engineering are usually satisfactory, for example car components, or in the building industry for nodes of structures. For spatial structures, such as shells, the result is not always aesthetically satisfying and is the geometry sometimes the result of an arbitrary chosen ending of the optimization process. An other problem is that the results are in most cases academic and rarely constructible. This can also apply to pneumatic structures. An alternative approach of form finding and optimization could be a more holistic way of optimizing, like the "Thrust Network Analysis" (Block and Ochsendorf [3]). Methods like this do not involve a lengthy process of iterations and they give as result a shape which forms an integral whole and is not an (arbitrary) assemblage of parts. The results are architecturally more satisfying. If holistic methods like this can be combined with the chosen production techniques for the structure formulated as geometric mathematical descriptions, which act as on of the design constraints for computation (form finding) together with for example physical loads and / or geometric constraints, elegant and constructible structures could be the result. The big advantage of this combined approach would be that the form fined (sometimes structural optimized) shape satisfies the constraints of the required production method and will result in cost effective structural systems for the realization of complex geometry structures but without limiting the freedom of form generation. In our research we aim to develop computational methods for form finding, optimization and production of complex geometry (spatial) structures, which should be elegant and constructible and that are easy to use for designers. The other important aim of this research is to give insight into the difficult structural behavior of complex geometry structures. An illustrative way of achieving this is by using visual parametric computational models (Fig. 1).

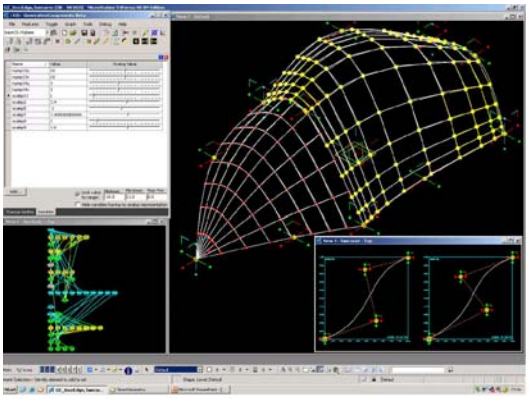

Fig.1: Visual parametric computational model.

1. Introduction

Bubble clusters (Borgart and Stach [4]) can be used as a way to design structures with air inflated cushions, like the Eden Project of Grimshaw (Fig. 6). In this case to the bubble cluster method was used to determine on the global scale the shape of the intersecting domes which make up the structure and on the local scale per sphere the geometry of the grid of the dome surfaces (the domes skeleton structure, Fig. 2 and 5). In the case of Eden Project the interaction between these two scales did not result in a satisfactory geometry of the surface grid at the intersection of the domes, resulting in awkward truncated air cushions (Fig. 6). A grid optimization, like was performed with the roof of the British Museum, could have resulted in a more satisfying result.
By using the characteristics of bubbles clusters structures could be optimized for form (like the truncation problem of the Eden Project) and force flow, like for example in the case op Radiolarians (Fig. 2).

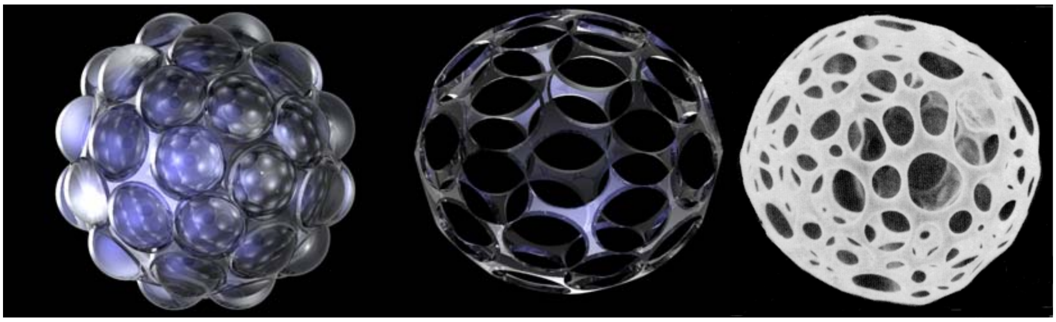

Fig.2: Bubble clusters (spheres) in closest packing, Intersection of bubbles with sphere, Radiolarians.

2. Force Optimization

Radiolarians (single-celled marine organisms, Fig. 2) condense their structure according to the flow of forces; by controlling the diameter of the individual bubbles intersecting the global sphere which in the radiolarian. Bubble clusters with a high amount of small diameter bubbles have a large amount of membrane surface, which finally results in a denser skeleton structure. The density of the skeleton structure reflects the amount of stress that can be carried within the structure. In this way radiolarians optimize the geometry of the grid of the skeleton structure according to the magnitude and the direction of the applied loads.
This principle can be used for an optimization algorithm. As the first step the surface of the structure, which is unloaded, is divided into equal sized spheres in their closest packing (with six spheres round each sphere in a hexagonal grid). Each sphere is in a membrane stress situation like a soap bubble, for which the Laplace-Young equation (Isenberg [5] holds: $p = 2*\sigma/r$ (p = internal pressure, σ = stress, r = radius). By assuming the stress in each bubble as constant throughout the optimization procedure the internal pressure in the bubbles will represent as a measure the internal stress in the structure. When the structure is loaded the internal stress in the structure will not be equal anymore in all places. Because we take the membrane stress as a constant with the Laplace-Young equation we can see that radius of each bubble will change according to its pressure. This will result in an optimized configuration of bubbles (Fig. 3), in which the stress in each bubble is the same.

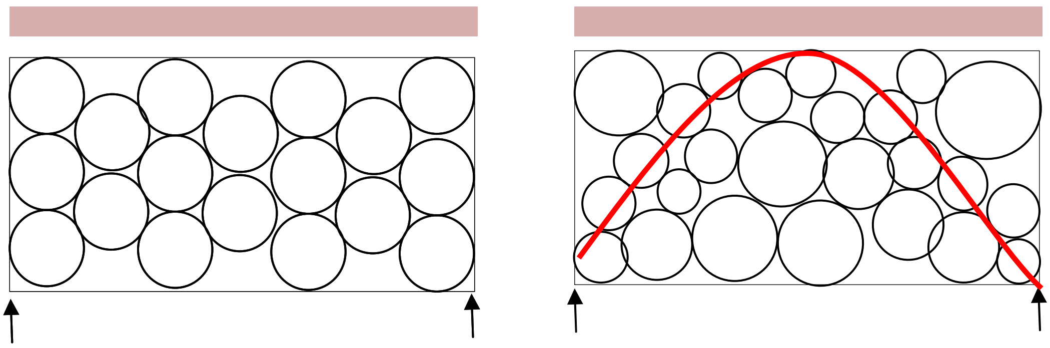

Fig.3: First step op optimization, final step optimization.

For the way to solve this optimization process a lineair optimization formulation has been used as is applied in the “Thrust Network Analysis”, in this way a more holistic way of optimization is achieved without an endless process of iterations with vary little variations in the numerous solutions.
Ways of extending the proposed optimization routine is to take into account the deformations of the spheres during optimization without volume and pressure change or with volume and pressure change (Fig. 4) by using Boyle’s Law ($P_0*V_0 = P_1*V_1$ (P = pressure, V = volume, o = before change, 1 = after change). The benefit of the first extension is that the bubbles don not have to remain as spheres during the optimization, which gives an added design variable. The second extension would also give the added possibility of, besides form change, varying the membrane stresses and allowing the air inflated cushions (bubbles) to structurally behave differently.

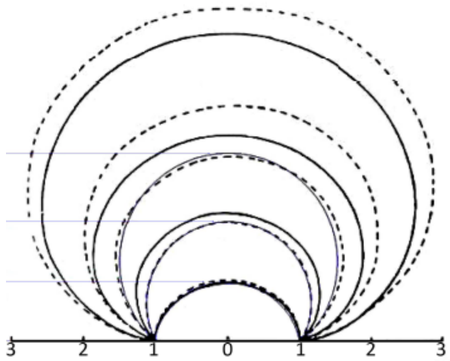

Fig.4: Deformation of different sized membranes.

3. Form Optimization

By using the above proposed methods of optimization it would be possible to solve the geometric problem of the Eden Project of the truncated air cushions at the intersection of the domes and retaining an efficient and elegant structure. An efficient way of optimizing bubble clusters is to simulate foam. Lord Kelvin in 1887 suggested that foam could be represented as a space partitioned into cells of equal volume with the least area of surface between them by a 14-sided space-filling tetrakaidecahedron (a truncated octahedron with 6 square sides and 8 hexagonal sides). Later it was discovered in 1993 by Weaire and Phelan that there is a more optimum solution the foam bubble cluster, the Weaire-Phelan structure which was used as the basis for the design of structure of the Water Cube in Beijing (Fig. 5 and 6).
By using the possibilities of deformations and volume and pressure change of the bubbles during optimization and constraining these to the geometric mathematical descriptions relating to production techniques it is possible to design constructible pneumatic structures.

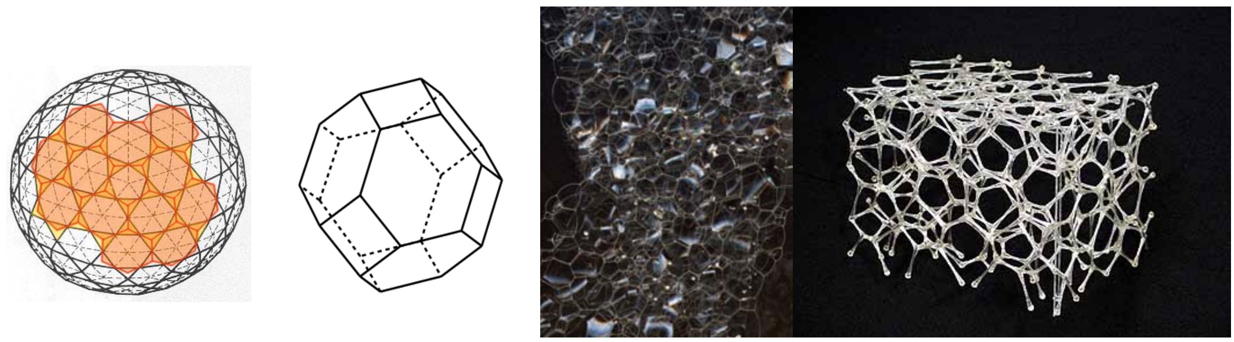

Fig.5: Configuration of grid Eden Project, Truncated octahedron, Foam, Weaire-Phelan structure.

If we compare the geometric solutions of the Water Cube and the Eden Project (Fig. 6), we can see that the first gives a more satisfying solution also at the intersection of the planes, this is mainly because of the intrinsic beauty of the foam bubble cluster.

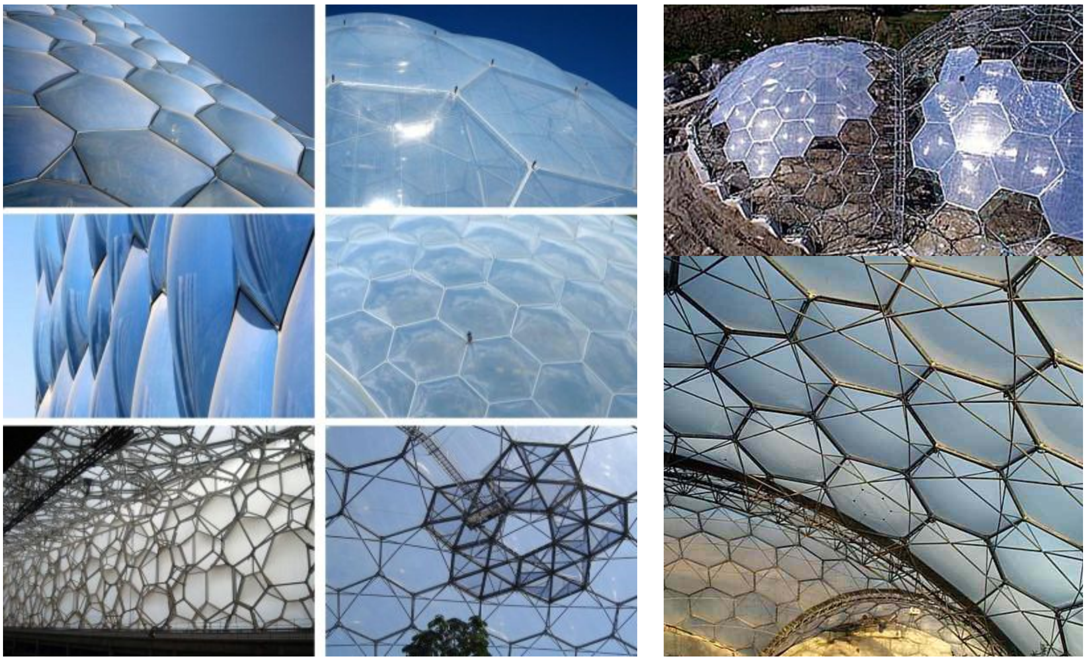

Fig.6: Water Cube in Beijing, Eden Project

4. Conclusions

Using new methods of optimization with a holistic approach gives the designer a range of design possibilities as well allows for insight into the structural behavior and the geometrical properties of the structure.
Results will be shown at the conference.

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Responsive building envelopes: Optimization for environmental impact

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Abstract

In recent years the impact of various environmental conditions, either global aspects, such as climate change, or resulting local aspects, such as floodings, played an increasingly decisive role in the design of new buildings and structures. Understanding the interrelation between these impacts and the built environment is a major public and scientific interest. The increasing costs of energy, which are required for construction and maintaining the buildings (around 50% of UK’s overall consumption, ARUP [2]), require optimized solutions: the interface between the inside and outside environment becomes more relevant, in order to control the flow of heat, light, noise, information and other media. Although these impacts are not static most artificial products are static and they do not have the ability to react to changes in their environment.

1. Introduction

One important aspect in this field is the introduction of adaptive systems into architectural and structural engineering projects, which allows a new approach to design: apart from traditional concepts, such as “form follows function” or “form follows force” the amount of energy brought into the system can influence the optimum solution of the overall system: “form follows energy”.

"We have shifted from the mechanical age to a "solid state" era. The world of the 21st century will be a "solid state" world. "Solid state" techniques are based upon materials which can alter their properties or transmit information merely due to electronic or molecular proceedings. Hence we can dispense with mechanical systems in many cases." - Mike Davies, 1990

Mike Davies’ proposal of the “polyvalent wall”, Davies [3], is still a challenging concept to control the transmission of energy (light and heat) through building skins and was a consequence of the energy crisis of the 70s. The idea is to have multiple layers of different active functions as on compound material, which can regulate the properties of the building envelope.

Much work has been related to his ideas, but mainly stayed at a theoretical level. Recent developments in material research now allow coming to real-world practical, commercial applications. Nowadays materials such as phase-change-materials, electro-chromic glasses and coatings, based on nano-technology, are available and the task is to span the gap between this material level to large scale building or civil engineering applications. Apart from that another challenge is to leave the idea of “static systems” behind and develop systems, which possess dynamic properties to react to external changes in the environment.

Within this paper the interface between inside and outside shall be discussed using 4 case studies using different design drivers, namely noise, wind, light and (heat) energy.

2. Case studies

2.1 Noise

Apart from specific design tasks, such as music or theatre halls, the consideration of NOISE is not an overwhelming design driver for most architectural projects, although buildings such as the elevated tube for the McCormick Tribune Campus Centre at IIT show that this can be a key design element as well. In future alternative solutions will be found using concepts, such as active noise control, and applying smart devices, i. e. layers of piezoceramic films, in the purpose to optimize in this regards.

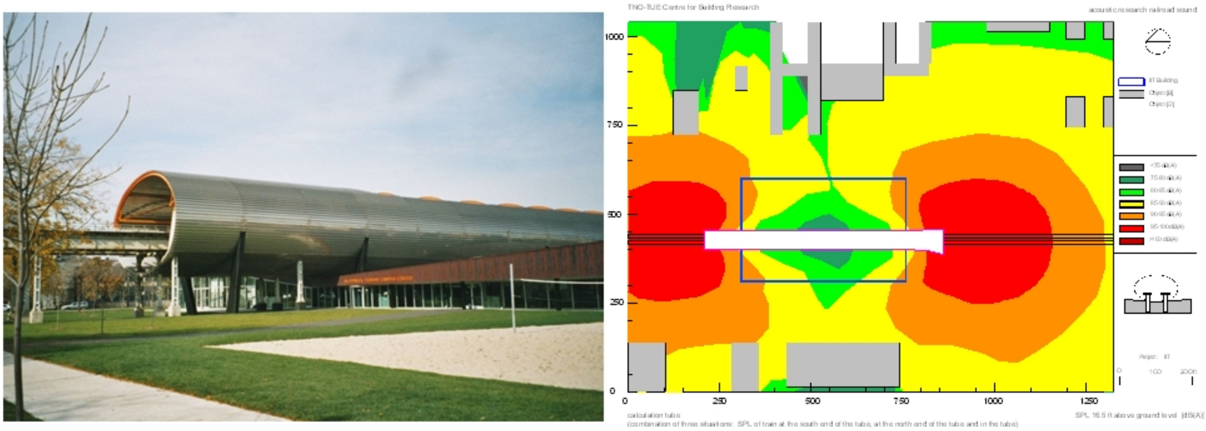

Figure 1: IIT McCormick Student Campus, Arch.: OMA, Eng.: ARUP, Acoustics: TNO

In Figure 1 (right) some principal results of acoustic studies are shown: during the design process the overall dimensions and the end geometry of the tube were strongly influenced by these studies.

2.2 Wind

A typical example where the interaction between external environment, building skin and main structural system plays a major role is the field of WIND engineering. Obviously wind is nothing static, therefore the question arises why the building skin or structure is static and is not able to respond to different conditions: This idea has been studied at the 1080m high Evolo tower, which is wind responsive, i. e. the overall structural geometry can respond to external conditions at three levels: global shape morphing, local manipulation of wind effects and the consideration of active surfaces.

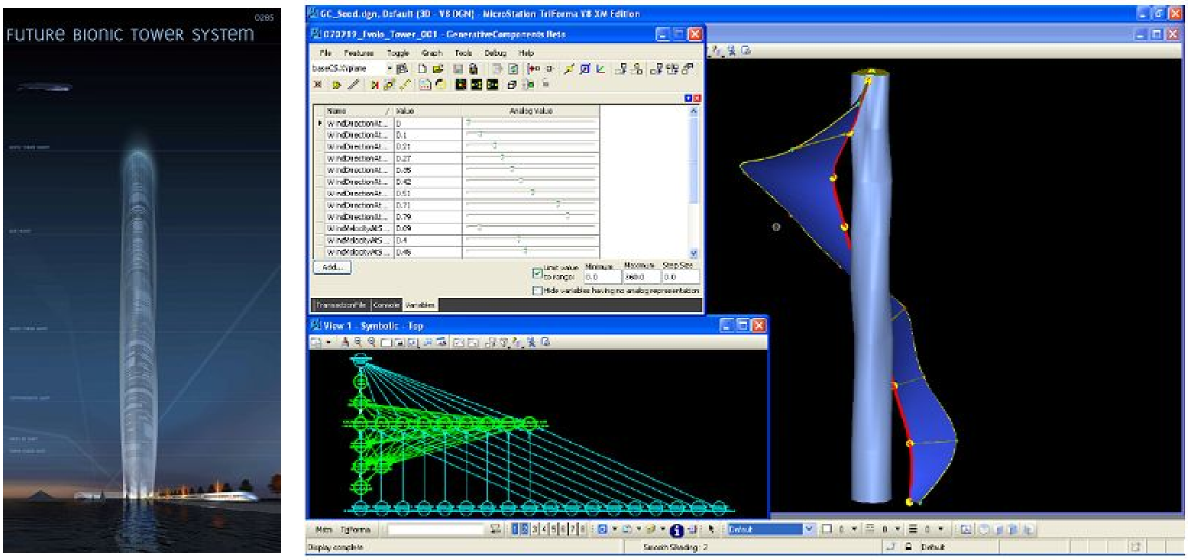

Figure 2: Evolo Tower, Arch.: Braun Associates, Eng.: TEC, Parametric modeling Ajdarpasic [1]

Shape morphing structures are designed to displace surfaces while resisted by large pressure loads. They can change their shape, configuration or other properties to improve the way they carry different types of load, making them a kind of smart structure. One way of addressing this challenge is to seek structures that have a unique combination of low actuation resistance and high passive strength. One example is the Kagome structure (Fig 3), which can be actuated into relatively complex surface shapes (Hutchinson [5). The following examples are the first investigation and modeling stage on a Kagome truss which can be applied as facade for the envelope of the tower. By moving the points, the shape of the structure with its components adapts automatically. The Kagome truss created below can be exported from GC to a wide range of computer-aided design and analysis programs to look at other specific features, Ajdarpasic [1].

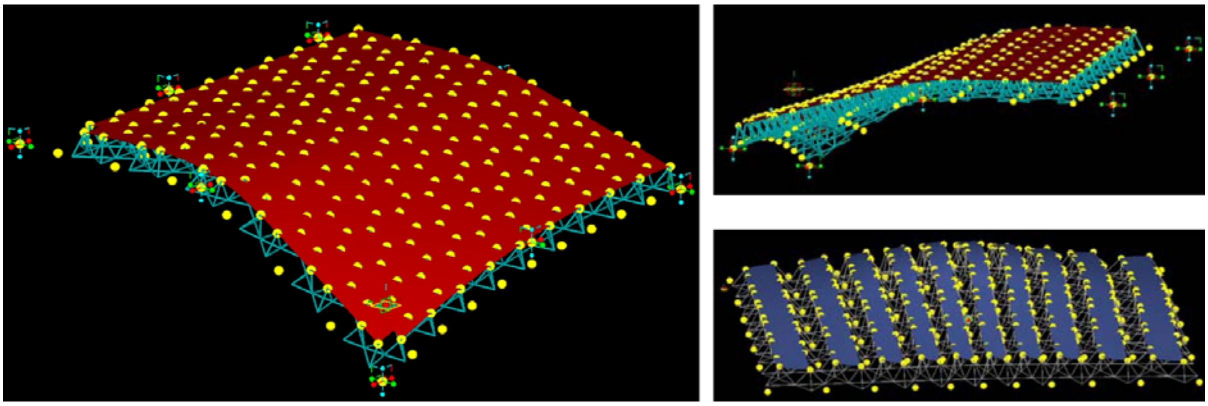

Figure 3: GenerativeComponents model of a shape morphing façade as a Kagome truss, Ajdarpasic [1]

2.3 Light

Another important design driver in architectural engineering can be the aspect of LIGHT: Initial studies, carried out for a feasibility study for the environmentally driven refurbishment of the Triton office building in Frankfurt. In that case a variable complex geometry for the facade was developed in order to maximize natural lighting and to minimize heat gain in summer for different sun conditions. Although this façade is still static further considerations will involve dynamic elements as well.

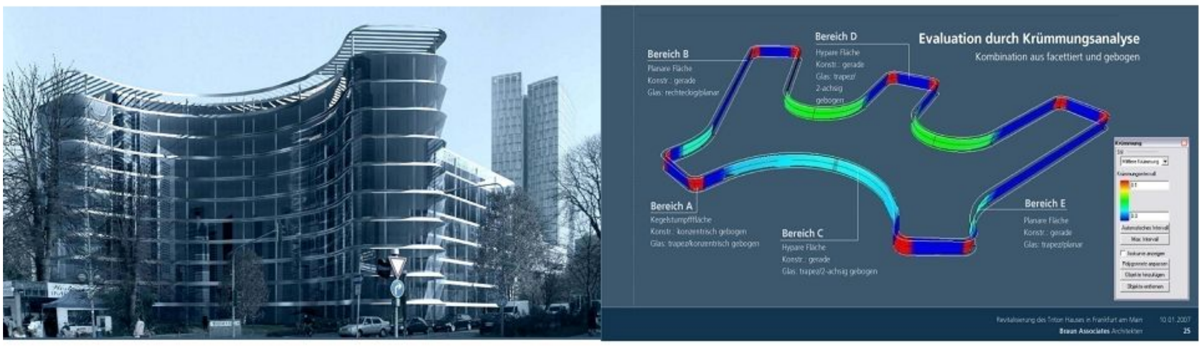

Figure 4: Triton office building Frankfurt, Arch.: Braun Associates, Eng.: TEC/ Transsolar

Detailed curvature analysis of the envelope surface has been carried out in order to find an optimum solution in terms of performance and economic aspects as well, i. e. maximizing the area of flat, or at least single curved elements, without compromising with the lighting performance.

2.4 (Heat) Energy

Further on the flow of ENERGY through the envelope needs careful considerations: Corpform’s adaptive behaviour is the main focus of the experimental object in order to show an integrative system with adaptive building envelope and a structural system with variable chemical and physical properties with the main goal to control the internal environment: Phase change material (PCM) is embedded into the textile facade system in order to control the heat flow between inside and outside.

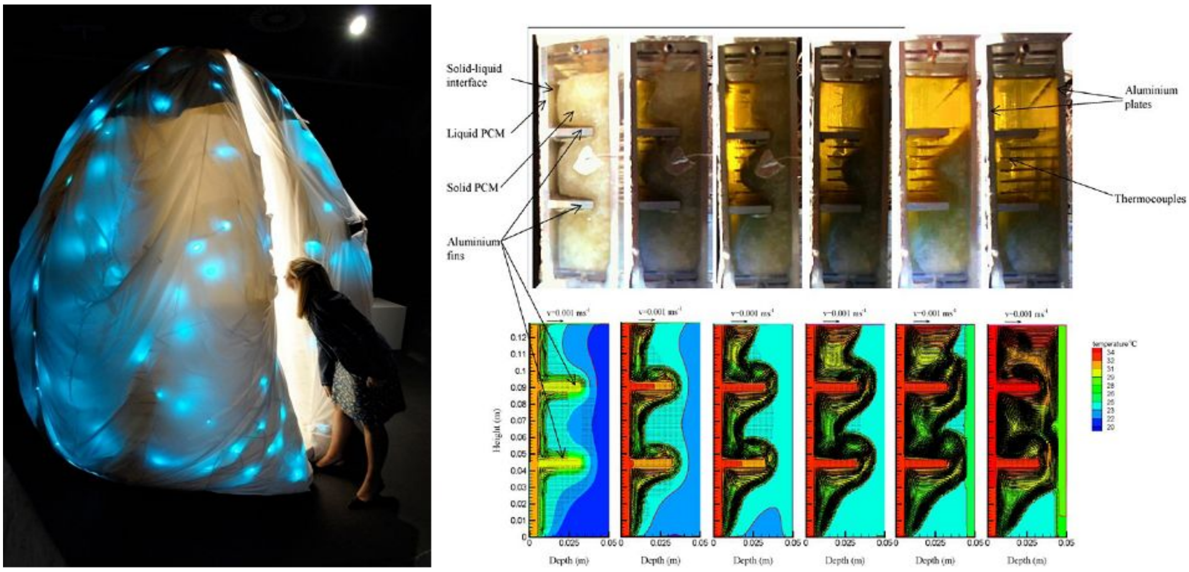

Figure 5: Adaptive pavilion Corpform, Arch.: formorf, Eng. : TEC ; PC-PCM system (Huang [4])

Future studies focus on embedding functional materials within a cellular or multi-layer system. This allows new concepts and applications of textile building envelopes in order to improve its (currently) poor building physic properties. The combined integration of photovoltaic (PV) with phase change materials (PCM) creates synergetic effects (Fig. 5): on the one hand side the PCM can cool down the PV cells in order to increase its efficiency and on the other side the PCM can store the energy and release over night time.

3. New design tools and materials

Different optimization techniques are nowadays available (such cross-section optimization of truss structures), but there is still a lack when the practicing designer wants to consider various criteria as it is common and required in the architectural engineering design process. Advanced optimization methods offer this possibility and are widely used in other industries. The above mentioned projects study how these tools can be transferred and applied in construction industry, e. g. multi-criteria optimization for ecological and economical considerations, in order to maximize sustainability benefits.

Apart from that new materials play a major role in architectural practice and research: Smart materials are able to adapt their physical or chemical properties, in order to optimize the mechanical or thermal response of a structure or building. This in combination with innovative manufacturing processes will lead to new concepts in architecture, which require ongoing research.

4. Conclusion

In all these areas new materials, which might be inspired by nature, and new tools, such as parametric and associative software, play a substantial role in enhancing the performance of new concepts in architecture and engineering. Spanning the gap from Nano to Mega will yield to new optimization techniques.

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Using Evolutionary Computation to explore geometry and topology without ground structures

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Abstract

Over the past two decades there has been an increasing interest in using what has come to be called Evolutionary Computation (EC) in the analysis and optimization of structural systems. These methods include Genetic Algorithms (GA), Evolution Strategies (ES), Simulated Annealing and other stochastic based numerical methods. Each of these methods shares the drawback that they are very computationally intensive compared to deterministic methods. Furthermore, the computational burden can rapidly increase as the size of the analyzed structure increases. This paper suggests that the level of computation can be significantly reduced by avoiding the common practice of using ground structures in coding the topology. Additionally, comparative examples show that a broader range of good solutions can be reached when the use of ground structures is avoided.

1. Introduction

The problem of topology and geometry optimization of discrete structures like trusses using EC is often hindered by conditions associated with the use of a ground structure. Ground structures are used to define both topology and geometry by providing a raster of admissible nodes between which members can either be present or not present. This on-off character of ground structures makes them well suited for description as binary strings used by conventional EC methods like Genetic Algorithms. But the use of ground structures produces a computational hindrance in that the length of the binary string (chromosome) impacts the level of computational intensity needed for the EC. This is because the size of the EC population is related to the length of the chromosome string used to describe the solutions. Since each individual in the population needs to be analyzed and breed with other individuals, the level of computation quickly escalates as the size of the ground structure, and thereby the population, increases, even though the total number of members present may not be so high.

In addition, a coarse ground structure can negatively impact the quality of the solutions found. The dilemma is that to find better solutions a finer ground structure is needed, but by using a finer ground structure the computational intensity makes the method impractical for larger systems. This paper hopes to offer some suggestions to code the topology and geometry without the use of ground structures, and thereby reduce the computational intensity of the problem and enhance the quality of the solution.

2. Ground structures

Ground structures have been used since Dorn et al. [1] proposed their use for topology optimization of plane trusses. Dorn describes a ground structure as the set of all admissible bars which can be considered to connect a set of admissible joints. Ground structures were first applied in direct computational methods like Linear Programming. Figure 1 shows an example by Klarbring et al. [2] of a ground structure used with a Linear Programming solver to design a bridging structure. Klarbring selected 8767 members in the 210 node ground structure shown on the left in Figure 1. All possible members for a 210 node ground structure would total 21945. On the right side only the members selected for the solution are depicted. There are of course many more members on the left of Figure 1, than actually selected in the solution shown on the right.

EC applications use coded (usually binary) strings, analogous to chromosomes, to describe individual solutions. In this paper the solutions are structures or trusses. The "genetic" description of the structure is represented by the binary string. When ground structures are used, this coded string takes the form of an on-off list of all admissible members. In this binary string, member connectivity is represented by 1's and no connectivity (no member between nodes) is represented by 0's. So in the Klarbring example, the string would need to be 21945 bits long in order to include all possible members of the 210 node ground structure. In fact it makes no difference whether all of the members are present as on the left or just selected members as on the right. In either case the binary string would have the same length or 21945. Only the ratio of 1's to 0's would change.

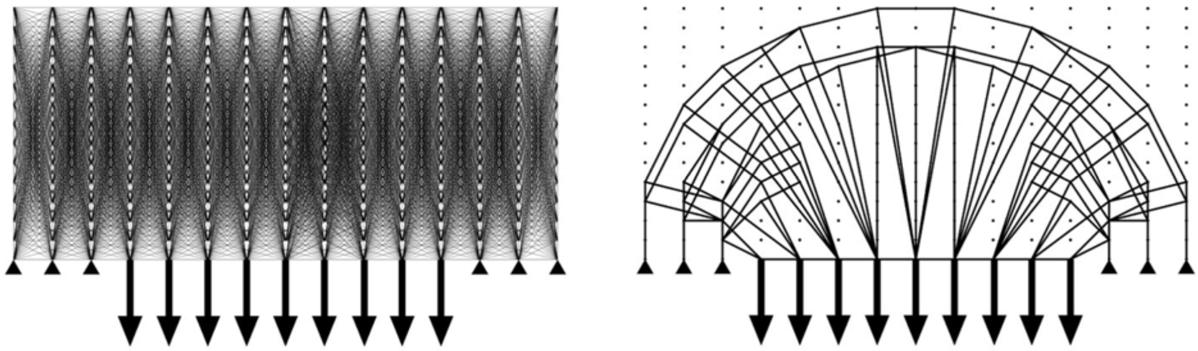


Figure 1: Left - Ground structure from Klarbring (1995) showing 8767 of 21945 possible members.
Right - Ground structure nodes and optimized topology from Klarbring (1995).

Unfortunately, in EC, the longer the length of the genetic string, the larger will be the population needed to evolve towards better solutions, see Goldberg [3]. And the larger the population size, the more generations will be needed to move the population towards convergence. The size of the population and the number of generations are what make EC so computationally demanding. Each solution must be bred, new solutions generated and then each new solution evaluated. So the coding efficiency of the genetic string becomes critical to the performance of the EC.

2.1 An example using a ground structure

The example shown in Figure 2 is by Deb & Gulati [4] and uses a Genetic Algorithm to produce optimal geometry and topology for a bridge truss based on a ground structure. Deb comments that most examples of truss topology optimization which use GA's find first a topology while holding all member cross sections constant, then once a topology is chosen the members are sized. Of course, in using a ground structure, the selection of topology and geometry are linked. That is, when a topology is chosen from the ground structure, the geometry is not altered from that ground structure. These two points certainly limit the quality of the results one can obtain. Deb corrects the short coming of the first point by optimizing each stable topology found in order to determine each member size. In this way the fitness can be based on actual member sizes. But like all methods based on ground structures, it is still limited by the second problem of linked topology and geometry.

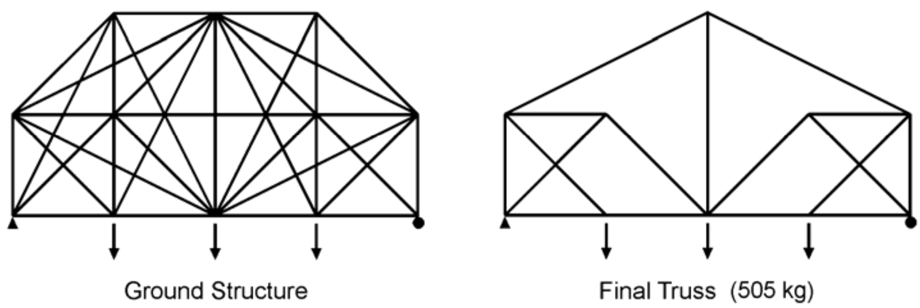


Figure 2: The ground structure (left) and the optimized truss (right) used by Deb & Gulati (1999)

The effect of linking topology with geometry is made apparent in comparing Figure 2 with Figure 3. Figure 3 uses the same topology and load conditions as used in Figure 2, but selects a geometry without the constraints of Deb's ground structure.

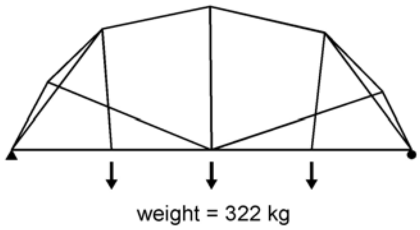


Figure 3: A lighter weight geometry based on the same topology as the one found by Deb & Gulati (1999) in Figure 2. This solution was found without using the ground structure.

Furthermore, Figure 4 shows three other topology/geometry combinations for the same problem, each of which performs better than the solution found in Figure 2. The solutions in Figure 4 were all found without the use of ground structures. It might be added that although buckling is considered in the sizing of the members, each member is assumed to be braced at the joints. This makes the evolution toward many short compression members, as can be seen in the in the arch in the Topo ID 18 of Figure 4, and the longer tension members readily understandable.

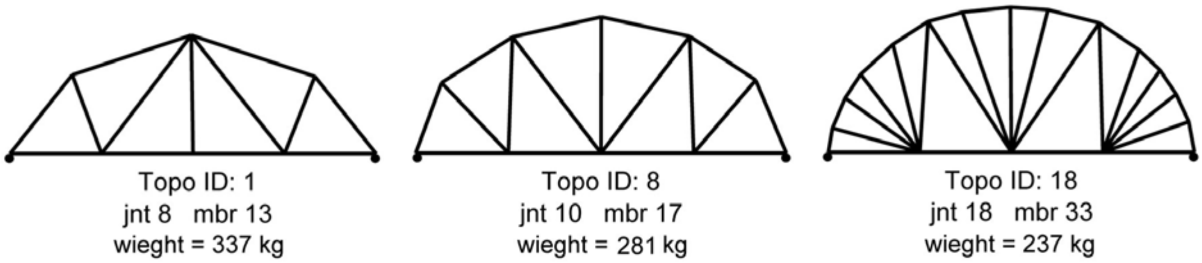


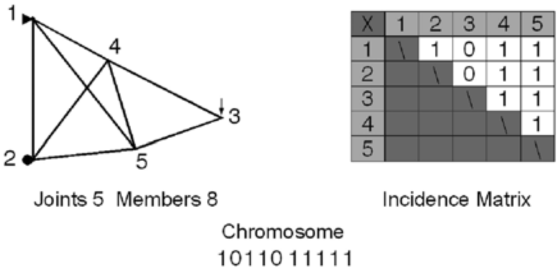
Figure 4: A selection of three other topologies based on the same criteria as used in Figure 2, but without the constraints of a ground structure. A larger set of solutions is shown in reference [5] by von Buelow.

2.2 The computational cost of ground structures in EC

Another aspect of ground structures is the effect the resolution has on the solution. Compare Deb's result using low resolution (12 nodes) with that of Klarbring in Figure 1, which uses the much higher resolution of 210 nodes. Then compare this with the results shown in Figure 4 that do not use a ground structure at all. As the resolution of the ground structure increases, the solutions become more similar to those without a ground structure. Of course the reason Deb chose such a low resolution has to do with the GA coding. The length of the chromosome is based on the total number of admissible members in the ground structure. In Deb's ground structure this number is 39 as counted from the ground structure in Figure 2. The chromosome coding used by the author is based on the upper triangular portion of the incidence matrix. That number equals nodes(nodes-1)/2, or in this case 10(10-1)/2=45. If Deb were to increase the resolution of the ground structure to something on the order of Klarbring's 210, the number of admissible members in his ground structure would go way up to 210(210-1)/2 = 21945. Since the population size in a GA is linked to the chromosome length, an increase from 39 to 21945 would require a significant increase in the population size as well. Both the longer chromosome and the larger population size would slow the computation of the GA to an unacceptable level, and the size of the problem quickly becomes unmanageable. However, since the chromosome coding method used by the author is determined by the actual incidence matrix size, and not the ground structure size, the chromosome remains 45 even when using real numbers for joint locations. In other words, by not using ground structures as a basis for chromosome coding, it is possible to get much higher resolution than Klarbring's example, at about the same cost computationally as Deb's unsatisfactorily low resolution GA.

3 EC chromosome coding without ground structures

Figure 5 shows how the chromosome can be coded based on the incidence matrix. Joints are sorted by location before the chromosome string is extracted, with fixed and loaded joints numbered first. See von Buelow [6].



X	1	2	3	4	5
1	\	1	0	1	1
2		\	0	1	1
3			\	1	1
4				\	1
5					\

Figure 5: Extraction of the EC chromosome from the incidence matrix

Of course by this method the chromosome lengths for different topologies are often different. In traditional GA crossover breeding this would be a problem. It is easily overcome, however, by simply choosing a cut and crossover point taken from the shorter chromosome string. Figure 6 shows this procedure.

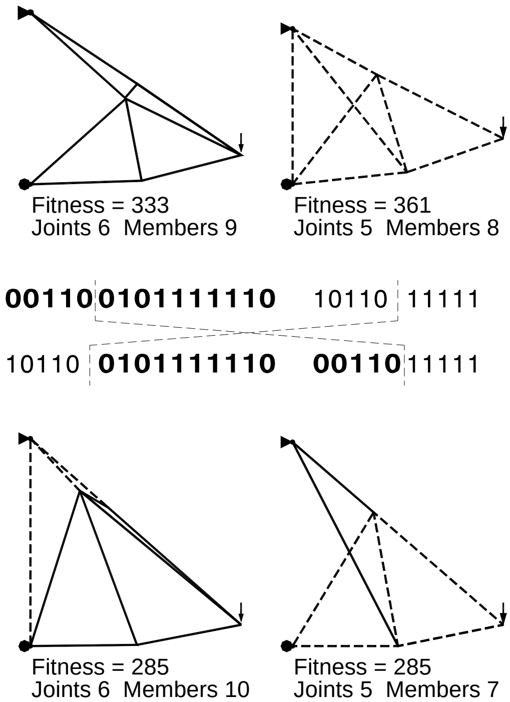


Figure 6: Breeding of two truss topologies using the chromosomes from the incidence matrices

Summary

This paper has shown two major advantages which can be achieved by basing EC chromosome structure on the member incidence matrix rather than a traditional ground structure. These are:

- Refinement and quality of the solution
- Reduction of chromosome length leading to reduction of computation

Further details can be found in the recently published dissertation by the author [7] under the direction of Prof. Werner Sobek (ILEK, Universität Stuttgart). See:
http://elib.uni-stuttgart.de/opus/volltexte/2007/3160/pdf/PvB_diss.pdf

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Structural Morphology and Self-organization

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Abstract

This paper is an investigation into some fundamental principles concerning the logic of form optimization in nature in relation to special and physical constraints. One of the chief aims of this study is to make a contribution towards a true and complete understanding of optimization processes in nature by dealing with these processes according to their origins, principles, processes, essential features and scope. It has been attempted to establish, both by argument and evidence that the same optimization processes used in nature can be used in architecture.

1. Introduction

The objective of structural optimization is to maximize the performance of a structure or structural component. It is driven by limited resources, environmental impact, and technological competition which demand lightweight, low cost and height-performance structures. Optimal design means the best feasible design that satisfies the prescribed performance criteria.

It is of great importance to find the best possible structural topology or layout for given design objectives and constraints at a very early stage of the design process (the conceptual and project definition phase). Thus, over the last decade, substantial and fundamental research efforts have been devoted to the development of efficient and reliable computational methods for structural optimization like structural shape optimization[1] and topology optimization[2] (evolutionary structural optimization methods, ESO). These computational tools are in general not being used by architects or designers who would need simplified computational methods for form and structural optimization in the critical early stage of the design process. “Lightweight principles in nature” introduces methods to bridge the gap between structural optimization theory and its practical application to structural design. It shows simplified methods and programs for form finding and typology optimization based on processes in nature.

Form
↑
Structure ← → Material   Form → Structure → Materials

Nature   *Architecture*

Fig.1 Integrated and linear design process in nature and technology

The integration of structural morphology (form-finding of structure) would simplify the architectural form- and typology finding process considerably. Then structural optimization and structural morphology can also serve the process of architectural form-finding. Structural morphology in this sense is to be understood as the integration of form-generating methods, structural shape-optimizing methods and the design principles of a structure and its structural elements. In this regard, the production of component parts (CNC production), optimization in design- and production-procedures (generative design tolls for associative and parametric modeling) and assembly (automated assembly) play a crucial role. These variables can enter the morphological form-finding process as mathematical variables and constraints. In the design of free form buildings with complex geometrical structures, the goal is to define the form geometrically as early as possible. Instead of post-rationalizing double curved geometry the goal is to "pre-rationalize" the design method.

2. What is structural optimization?

Structural morphology occurs on three different levels: on the global scale (structural system), the local scale (structural component) and the micro scale (material). The basic ingredients for Performance-Based Optimization of Structures are the optimal 'layout', the interplay between the form-finding or morphology, the structure and the structural material. In this context the "layout" of the structure includes information on the topology, shape and sizing of the structural components and the materiality. The abstraction of the essence of optimization techniques in nature and their categorization gives an overview of general strategies for optimization processes addressing multiple problems simultaneously. It also is the starting point for simplified computational estimation strategies. The goal is not to develop a unified new optimization method, but rather to develop simplified specific methods coordinated with the structure or the form-finding process.

Structural Morphology: Structure Optimization + Typology Optimization + Material Optimization

2.1 Structural optimization categories

Types of structural optimization can be classified into sizing, shape and topology optimization.[3]

Sizing, shape and topology optimization address different aspects of structural design problems. Typically sizing problems deal with the optimal thickness of individual members for example in a truss structure. The optimal thickness distribution in the individual member is reached in terms of peak stress or deflection etc., while equilibrium and other constraints on the state (deflection) and design variables (thickness) are satisfied. The main feature of the sizing problem is that the domain of the design model and state variables is known a priori and is fixed throughout the optimization process. In a shape optimization problem the goal is to find the optimum shape of this domain. Typology optimization finds the optimal lay-out of the structure within a specified design space. The only known quantities in this problem are the applied loads, the possible support conditions, the volume of the structure to be constructed and the additional design restrictions. In this case the physical size and the shape and connectivity of the structural elements are unknown. The topology, shape and size of the structure are not represented by standard parametric functions but by a fixed design domain (design space). Typology optimization of solid structures involves the determination of features such as the number, location and shapes of holes and the connectivity of the domain.

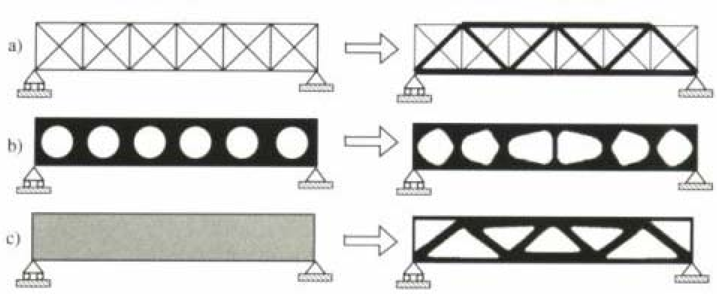

Fig.2 Three categories of structural optimization. a) Sizing optimization of a truss structure, b) shape optimization and c) topology optimization. The initial problems are shown at the left hand side and the optimal solutions are shown at the right. [4]

2.1.1 Typology optimization

The topology optimization method solves the basic engineering problem of distributing a limited amount of material in a design space. Optimal design is concerned with the optimization of structural topology, shape and material. It also encompasses a comprehensive and unified description of the state of the art of the so-called material distribution method, based on the use of mathematical programming and finite elements. Applications treated include not only structures but also MEMS and materials.

3. Morphology

The term morphology in biology refers to the outward appearance (shape, structure, color, and pattern) of an organism and its component parts. This is in contrast to physiology, which deals primarily with function. In engineering, the term morphology could be replaced with the term structural form finding.

3.1 "Structural Morphology - Bridge between Civil Engineering and Architecture"

Structural morphology, or the 'science of form of structures,' is one of the most active research areas in architecture, aiming to bridge the gap between the fields of civil engineering and architecture, and will lead to a better understanding between the two disciplines. Structural morphology deals with the study of the relationship between the geometric form and structural behavior. Fig. xxx compares the structural configuration of a natural organism with a man made structure. The geodesic dome and the ridged radiolarian shell adopt a spherical form approximated by a polyhedron with triangular or polyhedral faces. This arrangement minimizes the amount of material in the structure as well as its weight.. Both structures have no dominant bi-dimensional stress-resistant element and stresses are transmitted along the whole surface, in the case of the radiolarian as a lattice shell mash and, in Buckminster Fuller's geodesic dome, a plate shell mesh.

Structural morphology as a relatively new field of engineering is becoming more and more the centre of interest for many different and diverse disciplines. Architecture (form), structural engineering (structure), material science (new materials and properties) and mechanical engineering (thermal dynamics and building environment) are all interrelated in the form finding process. Combining structural design, morphology and materials in an integrated design approach will open up new perspectives in designing complex geometric structures.[5]

Structural morphology plays an integral role in digital design and fabrication. In the last decade the increasing use of computer aided design and manufacturing has enabled the construction of buildings with complex geometries and has changed and challenged the building industry of the twenty-first century. Such projects require an integrated 3D approach with CAD, FEM (Finite Element Method), CAMP (Modeling and Prototyping) and CAB (Computer-Aided Building).

Structural morphology in architecture addresses the following key issues*:*

- Spatial arrangement of standing structures at static equilibrium.
- The complex relationship between force, form and material in 3D Forms: form-finding, structural morphology and optimization.
- The streamlining of interactive processes between design, engineering, analysis and manufacturing.
- The development of new materials and production methods for integrated building components.
- Engineering and prototyping of production, and the completion of construction processes.
- Influence of production methods on design / engineering components.
- Design methodology for component design and product development.

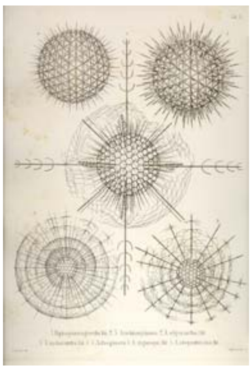

Fig.3 The skeleton of radiolarian can be made by triangles or other type of polygons, Ernst Haeckel: Die Radiolarien (RHIZOPODA RADIARIA) Berlin, 1862, Tafel 10 Fig.4 Geodesic dome by Buckminster Fuller

3.2 Smart geometry

Architecture is fundamentally about relationships. Many of these relationships are geometric in nature or find a geometric expression. Structural engineering often relies on the ability to decompose the form into clear and independent subsystems, where the precondition to 'design' the structure is premised on the clarity of such arrangements. Contemporary architecture often escapes this and subsystems have to morph as much as the architectural form. New analysis tools are essential to avoid the severing and isolation of systems, to handle complex geometries, to harness the efficiency of interconnected subsystems, and for manufacturing.

Nature uses simple numerical rules. Shells for example use the Fibonacci numbers to generate complex geometries and structural forms and soap bubbles form bubble clusters based on the equilibrium of surface tension within the membrane.

4. Load case-adapted bio-mimetic constructing – a standard technique in mechanical engineering

Nature typically uses not additive, but highly integrated systems, which optimize several necessary features in one component. Energy acquired by photosynthesis or heterotrophic processes has to be diverted between growth and reproduction, and protective measures. The fundament of biological constructions is the axiom of constant stress principle, which results in minimal investment and maximal performance of biogenic lightweight structures. The basis for a transfer of biological lightweight systems into technical systems (bionics/biomimetics) requires detailed studies concerning architecture and material properties of structural components in combination with the crucial functional aspects within the ecological context.

Nature typically uses not additive, but highly integrated systems, which optimize several necessary features in one component. Energy acquired by photosynthesis or heterotrophic processes has to be diverted between growth and reproduction, and protective measures. Thereby, the efficient use of energy is critical for survival. This resulted in the evolution of strong materials and stable lightweight constructions, which present an attractive design pool for advanced technical applications.

The fundament of biological constructions is the axiom of constant stress principle, which results in minimal investment and maximal performance of biogenic lightweight structures. These characteristics are also key properties for optimized technical constructions, regarding both ecological and economical aspects. It is therefore evident, that loadcase-adapted biomimetic constructing should become a standard technique in mechanical engineering.

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Feasibility of Free-Forms

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Abstract

Emerging new technologies enriched the exploration of architectural designs and testing of architectural ideas. New tools such as parametric modeling software enabled architects to investigate designs of “free forms” and shapes of unseen complexity in the past. Rapid prototype models offer new means to examine tectonics and spatial qualities. Yet, these “free-forms” must recognize constrains of structural and constructional realities.

This conceptual investigation assess free-forms with respect to structural performance, construction efficiency and fabrication feasibility. The structural performance is assessed by finite element analyses showing stress distribution under typical loads and assigned support conditions. Decrease of the critical stress field is related to structural efficacy. Evaluation of construction and fabrication feasibility is associated with mass-customization of the elements and connections.

Examples of recently constructed free-forms offer tectonics of volume with astonishing spatial conditions. Current built examples, e.g. Guggenheim Museum in Bilbao, reveal separation of the language of surface and the language of supporting structure. In this investigation an attempt is made to bring the harmony and blend the two different articulations. It is intended to contribute to growing needs of “meaningful” explorations of digitally generated forms in conceptual stage of architectural designs.

The concept is tested in architectural curricula on a real case design of a canopy for Yungang Grottoes in Datong, Shanxi Province, China, that is recently declared the UNESCO world heritage site.

1. Introduction

Powerful digital tools provide new ground for generating and exploring architectural designs. They contribute to the common methods to enrich the means of contemporary architectonics. We see more and more of their presence not only in designs of signature buildings but also in architectural curricula.

Parametric modeling software allowed creation forms of unseen complexity before. 3-D printers are able to produce new physical models for visualization of ideas, exploration of tectonic and spatial qualities. Some forms are fully free-forms. Any complex form to be build-able need to be evaluated for the structural efficiency and constructional efficacy.

Figure 1 shows a gesture of Japanese architect Shigeru Ban to create impression of weaves. Ban was inspired by a hat to create a roof that is supported from above. ARUP’s office used in house developed form finding software to fine tune the form in a process that took several months and about 1000 iterations. The double curvature was assembled from large number of small timber elements yet the elements themselves were of double curvature. It was a challenging task to make the hat form feasible.

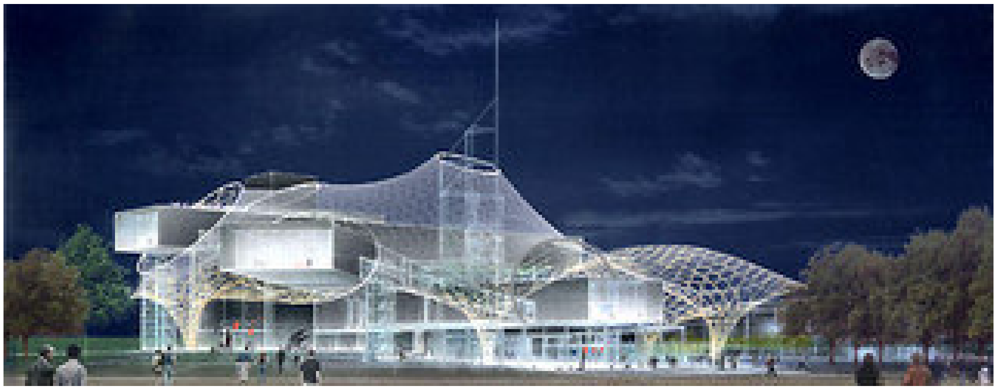

Figure 1: New Center Pompidou at Matz

This conceptual investigation is focused on structural performance and constructional feasibility of free-forms. It is an attempt to test a concept for mass-customization of free-forms. The search of the form is driven by spatial and structural effectiveness. Parametric modeling and structural analyses software were compound to balance creativity with efficiency. The investigation is rooted to the Chinese context. It is first tested in teaching environment and later explored in research studies.

2. Free-Form Canopy

Tectonics of a large volume is explored by articulation of free form to create remarkable spatial condition. Design of the form beside spatial considerations need to include technical consideration such as: structural performance, construction feasibility, and manufacturing efficiency. Larger the scale larger is the importance of these considerations.

A free form investigation is tested in a real case design of a canopy for Yungang Grottoes in Datong, Shanxi Province, China, that is recently declared the UNESCO world heritage site. The Grottoes were built around 450. They stretch along about one kilometer of a mountain ridge and include fifty-three grottoes with approximately 51,000 statues varying in size from 2cm up to 17m. The tallest Buddha surrounded by many small Buddhas in Grotto No. 5 was the focus of this exploration.

For the last 1500 years the statues were exposed to human destruction and environmental forces of water, wind, erosion, resulting in sever damages. Recently the Government of China initiated effort to protect the Yungang Grottoes with a shelter.

Graduate students at the Chinese University of Hong Kong, Department of Architecture visited the site and entertained design alternatives of a shelter in the technics design studio. The mountain ridge is twenty meter high and the requirements was for a shelter not to rest on it. It is a reasonable requirement since the edge of the ridge has questionable support resistance. Moreover, the shelter itself should not read as a part of the historic site. The proposition shown in Figure 2 was selected for further investigation

Figure 1. Yungang Grottoe with Canopy Exploration

Intent to maintain the site unattached and to add a shelter is contradictory. Any new structure would substantially alter the site. Therefore, response of a structure to the site conditions was set as a primary goal in architectural design. A shelter would have to allow people to sense the uniqueness of the site, culture of the place, religion and imaginative values. Six "mushroom" columns different in size and height were designed to support the canopy roof and preserve spatial perception of five caves. The plane of the roof mirror the form of the ridge and the columns create the form of pointed arch to stress and direct visual observation of Buda.

Structure of the canopy is basically steel truss. It provides light and transparent yet strong enough support to large snow loads and cover large spatial volume. Computer simulations were used to adjust the canopy plane curvatures and shape of parametrically design "mushroom" columns and to improve performance of the whole canopy assembly. Figure 2 shows the process of adjustment of the canopy plane curvatures. Four areas: A;B;C; and D were distinguished with highest stress concentration. The plane curvatures were iteratively distorted to monitor the change in the stress level for better or worse. The best geometry not to alter the architectural intent was sleeted as the final solution.

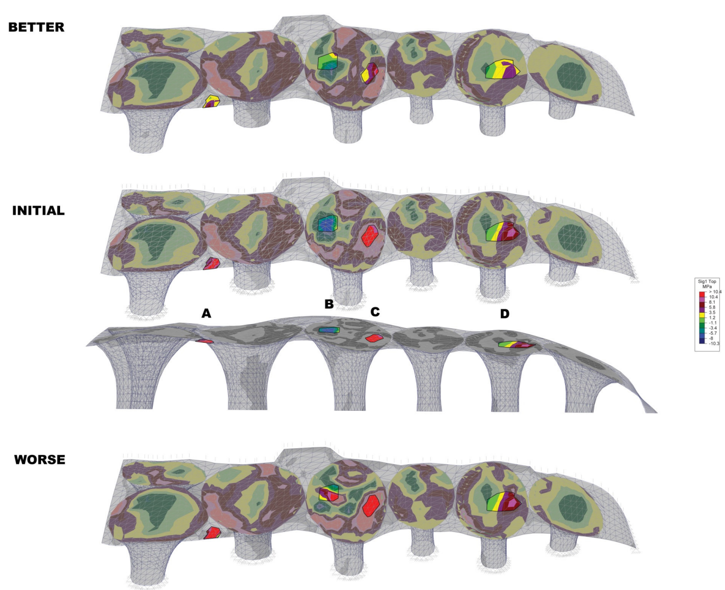

Figure 2. Adjusting of Form of the Canopy

Curvatures in the columns and the canopy are constantly changing as it was the case of the Center Pompidou at Metz earlier mentioned. To accommodate the constant curvature change a large number of small length aluminum steel hollow bars were used. Contrary to the Pompidou Center the elements here are straight stressing a need for joints to accommodate various angels in different planes. The number of individual joints and members is large and a mass customization process had to be conceptually resolved. The number of dissimilar members was reduced by custom design of members with adjustable length. Mass customization of the joints with flexible angles was resolved in collaboration with industrial center design at POLYU in Hong Kong. A new concept of members and joints was developed for which a patent is pending. The joins are design as frictional with flexible angels. Statically they are fixed or partially fixed connections. A model in scale 1:12 was developed to test the concept. Model of the end "mushroom" column with corresponding canopy is shown in Figure 3.

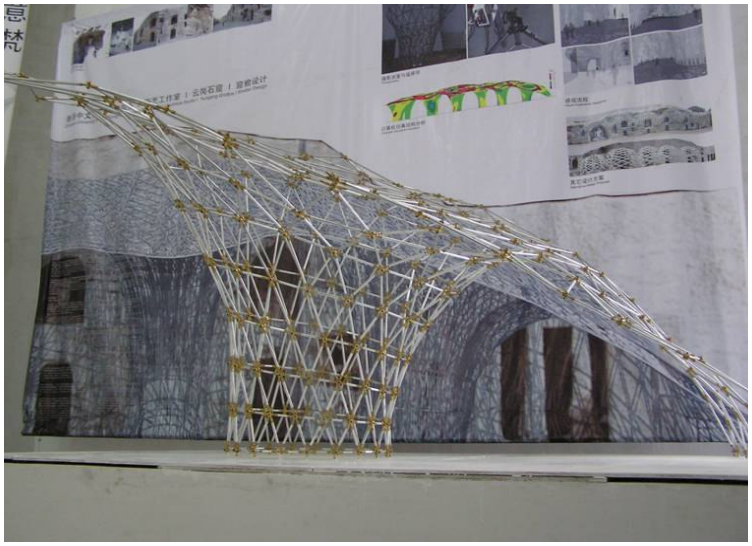

Figure 3. Concept Model for Mass-Customization of Free-Forms

The model is assemblage of triangular modules in scale 1:12 and was displayed at the Shenzhen Architecture Biennale in China. The aluminum elements are of adjustable length yet the bras joints were in not in the same scale thus visual expression is not fully achieved. The envelop is implicit of a transparent plastic surface that can also contribute to the stability of the whole canopy assemblage. Maintains of the geometry of this flexible assemblage is controlled by optical laser device.

3. Conclusion

Feasibility of free-form tectonics of large volume was explored. Presence of large number of elements and joints in a weaving surfaces required resolution of a mass customization of members with adjustable length and joints with flexible angels. Parametric modeling, innovative concept of mass-production and structural performance analyses were merged to enable creativity structure with efficient performance and feasible construction. The free-form concept was tested in a real case design scenario of the canopy for Yungang Grottoes in China.

Acknowledgement

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From nano structure to mega stadiums

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Abstract

As one of the emerging design tools, computational morphogenesis opened up new areas of investigations in the field of architecture giving new and interesting geometric typologies. This design tool, abstracts rules of natural morphogenesis in order to establish local and organizing principles and build systems that display a robust and flexible structural performance.

Although, these new design strategies generate various interesting three-dimensional forms, in most cases they are referred as "just patterns" without any structural potential. On other hand, extensive research done on the structure of crystals, cellular structure and soap bubbles shows that no matter how random their atomic arrangements look like, the specific condition of how the atoms join determents the stabile structure in larger scale.

This paper will present geometrical strategies and methods that use simple components that carry over their structural logic into a complex system; in this case into mega stadium structures. In order to think about form and structure all together, the components, therewith the overall system, use the principles of natural constructions to guarantee variation, flexibility and structural stability.

1. Introduction

In the recent years, with advance in computer-aided design, digital fabrication and advance performance analysis methods, new design strategies have emerged. With the arrival of parametric modeling the importance of geometry in design was reassert and new ways of architectural expressions were created. Nowadays, the architectural vocabulary is about complex geometrical relationships and principles, parametric equations, variables and conditional statements (Figure1).

Some of the emerged design approaches and structures are based on methods by which natural forms are generated. Critical feature of biological systems is the interdependence between lower simple components, in molecular level, and higher levels of structure. These large 3d spatial structures are generated in a simple process of self-assemble of the small modules characterized by high level of differentiation, redundancy and complex hierarchy. Translated in a scale of large architectural projects, the integration of form, material and structure into a single process represents a significant design strategy which reduces the building elements into modules with inherent characteristics. Unlike the conventional top-down engineering where the materiality and the structure are specified after defining the shape of the structure, the morphogenetic approach uses them as design drivers. These design methods were implemented in research of flexible stadium design.

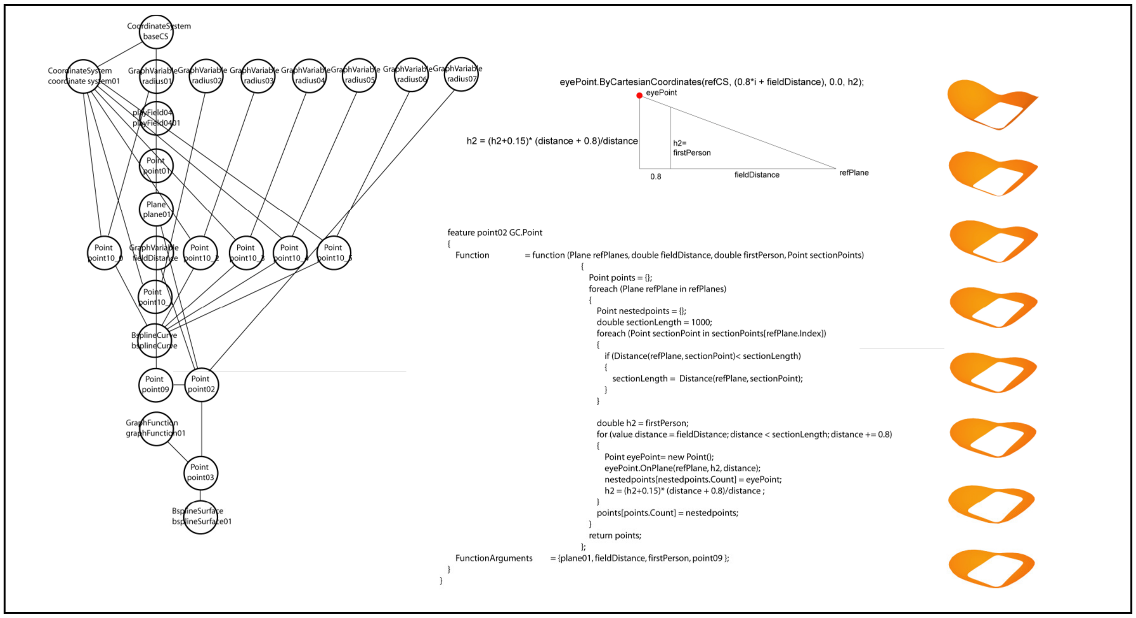

Figure 1: Parametric model of the global geometry of stadium. Driving parameters are the view lines and distance from the play field.

The research pursuits the idea of creating new typology of stadiums for Olympic Games triggered by the many modern cases of conventional stadium design which failed to provide a “second” post-event life to the building. Olympic stadiums have a life cycle that for a short period serves a function which calls for specific size and form. After the games, the Olympic stadiums need to accommodate to different daily scenarios. Therefore, from the early stages of design most important facts is how to incorporate a maximum flexibility into the design and structure, which will enable flexibility in size and function.

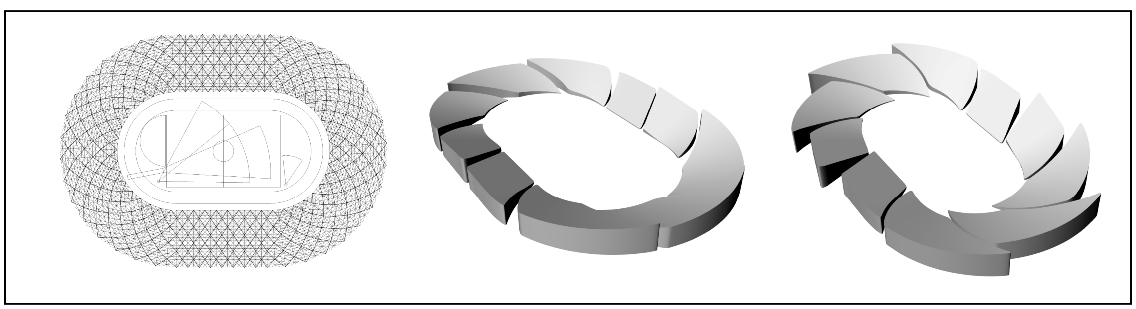

Figure 2: The lenses-like geometry allows the stadium to change from athletic to soccer stadium configuration

On a system scale the global geometry is defined by different external parameters, such as, the playfield size, orientation, optimal view lines and number of seats. On the local scale, the parametrically defined components populate the global geometry by adopting their geometric information to it. On other hand, the global geometry, as higher level of structure, contains the geometric articulations of the lower simple components; hence, this approach is neither top-down nor bottom-up, but the different components on local and global level are generated simultaneously.

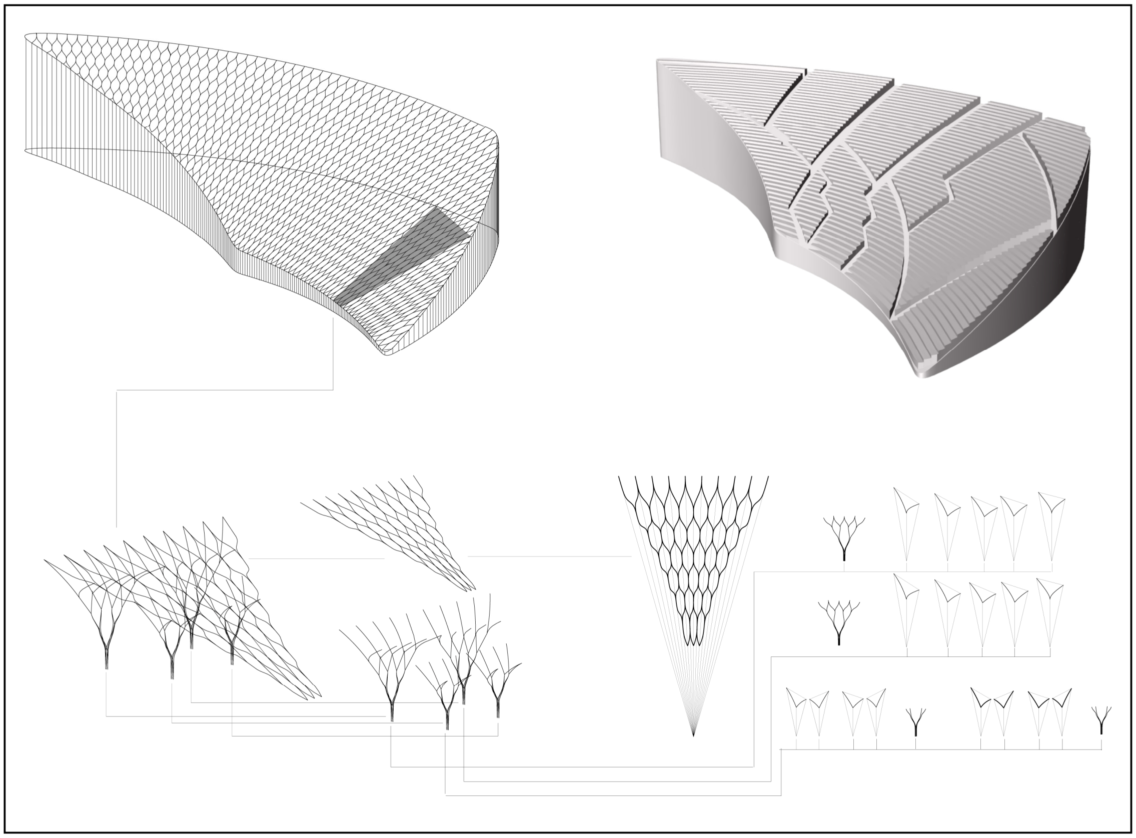

Figure 3: Flow diagram of the assemblage and manufacturing of structural components

Creating such a system, as geometric network on a global and local scale, delivers various levels of control over the design and enables introduction of control constrains. Embedding geometrical behaviors, manufacturing constrains and assembly logic allows for developing a design with build-in performative and structural capacities. The manufacturing constrains, which includes geometric associations that remain unchanged throughout the system, ensuring that any element can be directly fabricated from planar cutting sheets and assembled.

Finally, the three-like structure, generated from hexagonal components, is based on the pattern formed by a crack moving in a crystal. The process of cracking is characterized by successive joining of many small cracks into bigger formation following the direction of stress. Each new crack joins perpendicularly an old one. The same logic and process was followed in the creation of the stadium structure. Analyzed by the method of graphic statics, these structures shows that the force polygon similar like the crystal cracks forms a pattern that has bearing capability.

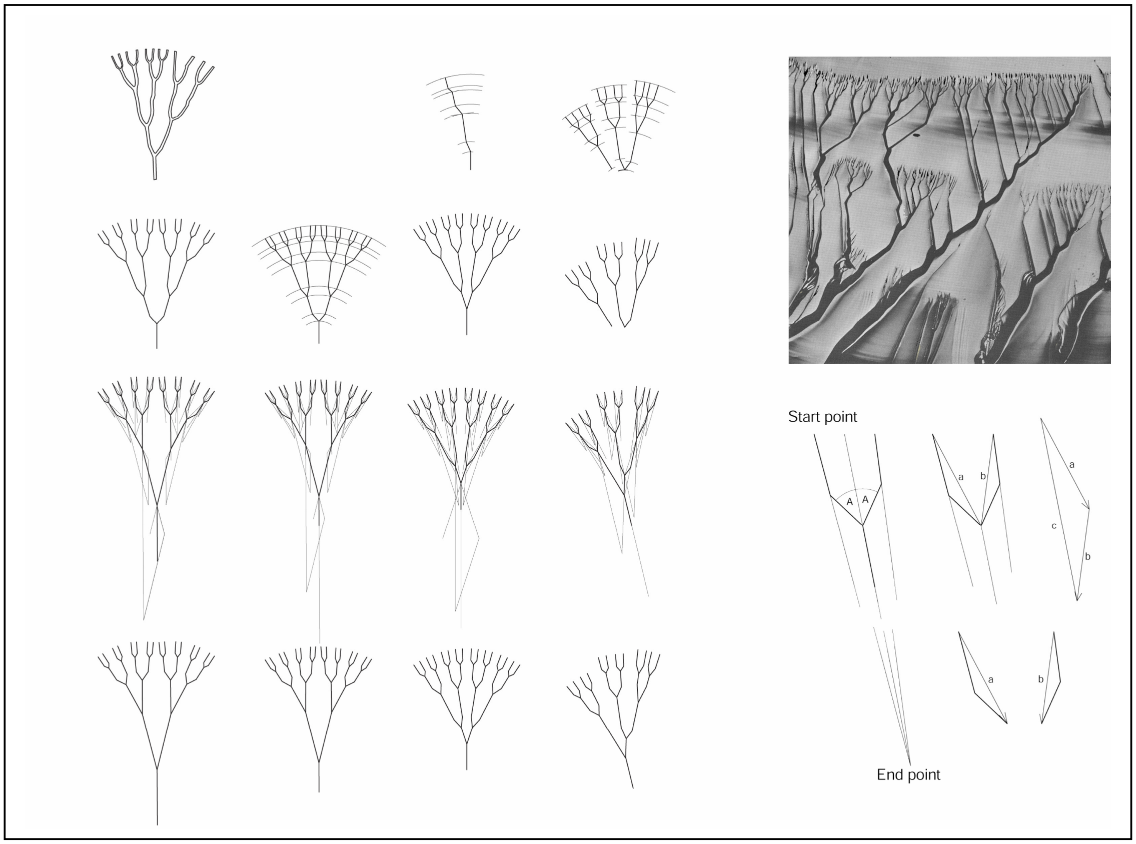

Figure 4: Three-like structure based on the crack pattern in cristals

These studies will establish a base for my further efforts in developing a concept for sustainable Olympic Game venues. By using light-weight structures and sustainable building materials, the stadium structure can be assembled, dismantled, transported and reassembled in various locations.

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