Some Paradoxical Aspects of the Use of Computers for Architectural and Structural Design

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Abstract. The architectural form determines visual perception of the building and its social acceptance. From it depends also fulfillment of functional and utilitarian assumptions, adopted at the project beginning. The aim of architectural modeling is primarily to create a geometric model of the future facility. It has also influence on the ability of modeling of the structural system which is a carrier of architectural form. All limitations of the structural system translate into limitations of architectural form. As long as only straight lines and planes were readily available, and any curves and non-planar surfaces were extremely difficult to model – architectural form was characterized by preference of orthogonality. If one looks at the restrictions in both architectural and structural modeling, resulted from the shortcomings of the underlying theory, and the impact that introduction of modeling with use of numerical tools had on change of that situation – it can lead to surprising conclusions.

Keywords: Building modeling · Numerical models · Shaping of form

1 The Complexity of the Form and the Complexity of Means of Expression

While admiring the beauty of classical forms of ancient buildings, we not always remember through how simple means of expression it has been achieved. We do not always remember that it was largely the result of the consistency of the architectural form and construction system.

In terms of static we are dealing with only a few very simple elements: single- and multi-span beams, cantilever bar. Joined together in various combinations they allowed developing well known elements: column, architrave, cornice, frieze, triglyph, metopes, pediments, which became the main components of the style, later supplemented by numerous details, Fig. 1. Thanks to them, we can admire the distinction between Doric, Ionic and Corinthian styles, each of which has been materialized in many, often greatly differing, objects [1]. The same was true in ancient Egypt and other great civilizations, in which their own original architectural forms emerged on the basis of available material and technological solutions. Indirectly, the objects thus manifested their reliability and durability, allowing their users to break away from a purely

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utilitarian function – protection against environmental conditions, and focus on the symbolic function – temple, palace etc.

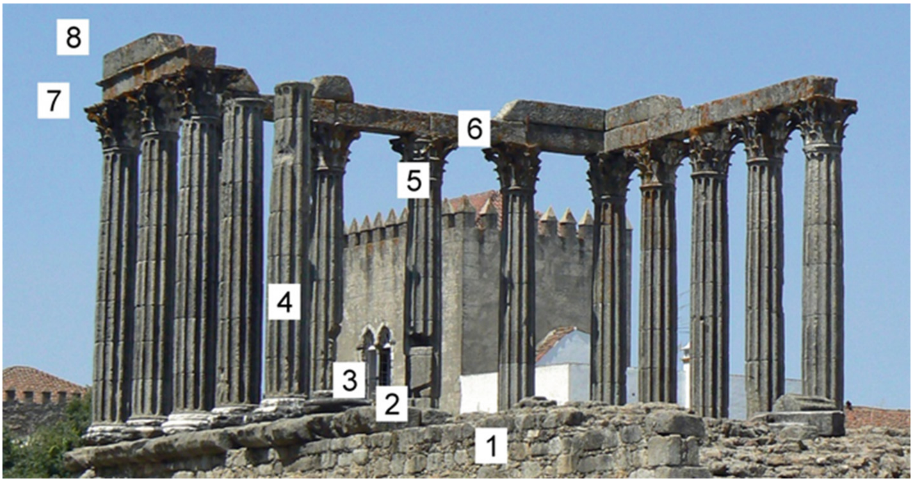

Fig. 1. Basic components of form and structure in the ancient Roman temple in Ebora (Portugal): 1 – stereobate, 2 – stylobate, 3 – column base, 4 – column shaft, 5 – column capital, 6 – architrave, 7 – frieze, 8 – cornice

The complexity of the architectural form was therefore not directly related to the complexity of the structural system. Homogeneous understanding of technology enabled precise communication between the participants of the investment process with use of relatively simple tools.

1.1 Communication in the Investment Process

Every building object emerges first as an abstract idea related to the needs of investor. This idea is translated onto architectural language and converted to the architectural concept. The initial concept is developed up to the stage of detailed design, which must be then communicated to the contactor, craftsmen etc. Information is produced and exchanged at every stage of the investment process. The amount of information and number of connections between the participants in the process, for its exchange increases rapidly with the transition to the successive phases of investment. Since the exchanged information covers a variety of specialized fields and are produced and stored in various forms, their exchange requires the use of appropriate tools, such as classification, coding, graphic conventions, textual descriptions, etc. The ability to exchange information is a precondition for design and construction of a building. Information is exchanged through the model of building, specific to a particular task, which can be used with different agents.

Model of the building, created in the investment process, exhausts contemporary definition of the interface: it denotes a *"point of interaction between a number of* *participants in the process [...], coordination and interaction between several work groups, is used to communicate plans and control production activity. This interaction can be a human interaction, computer systems, or any other medium of communication"* – as stated by the popular definition in Wikipedia. Building models are created to allow the exchange of information between all those involved in their realization – from the investor, through designers up to the craftsmen working on the construction site.

Any limitations on the possibilities of creating models of buildings, as well as the exchange of the information contained therein, in a direct way limits the range of solutions available for the designer. If the architect cannot build a geometric model that describes the required spatial form, he is not able to transmit information about this form to the other participants of the investment process, and thus such a form cannot be constructed. If the structural engineer is not able to build a calculation model of a complex system, he will use the simpler systems, which he is able to consciously use.

1.2 Impact of Building Modeling on Architectural Form – Observations from Antiquity to the Beginnings of the 20th Century

Models of buildings reflect both the needs for which they are created, and the technical determinants of the period in which it originates. All available media were used as an information carrier. In ancient Mesopotamia these were the clay tablets with drawings and cuneiform descriptions. A little later, in ancient Greece, textual description was sufficient as a complete building mode, however physical models were also created. This was due to a common understanding of the general patterns and samples used in construction, called *paradeigmata* [2–4]. Have been also preserved Egyptian drawings used in contract documents, and there are information (e.g. Vitruvius) about drawings used by designers in ancient Rome. It's amazing how much these ancient drawings are close to the modern graphic conventions [5].

This situation remained broadly to the beginning of the twentieth century. Progress in the building modeling was related mainly to media and way to write on these media. In the field of media, it was a shift from a very expensive (and therefore spared) papyrus, parchment and vellum, to the cotton- and linen-based paper and ultimately to the wood-based paper. New recording technologies included printing press with movable type, graphite pencils, color pencils, modern drawing instruments, typewriter, blueprints etc. [3].

In a relatively small extent this development affected theoretical concepts underlying the modeling of buildings. As important steps can only be mentioned: the introduction of "Arabic" numerals, perspective drawing and standardized measurement system. All of these improvements, however, relate only to the technology of presentation in the building modeling and do not have a significant impact on its form. They do not change the scope of shaping forms available for designers. Penchant for orthogonality, strongly disclosed in this period results both from the limitations in the transfer of information about more complex geometry, as well as the inability of its structural analysis.

2 Contemporary Revolution in the Methods of Building Modeling

Visionary work "As We May Think" by Vannevar Bush in 1945, and Memex system described in it, created the ideological basis for development of computer graphics. Another important step in its development was made in PhD thesis of Ivan Sutherland, defended in 1963 at MIT, in which he presented his revolutionary program Sketchpad. This pioneering program changed the way of human-computer interaction, among others things by introducing a light pen as a universal interface. This idea was taken up and creatively developed by Douglas Engelbart, who, in his presentation at the Fall Joint Computer Conference in San Francisco in 1968, later called "The Mother of All Demos", presented fully mature, comprehensive way of working with a computer – the one we know today. The doors to the use of computers in modeling of buildings have been opened.

Currently, the primary carrier of information is a digital recording in computer memory. However, more important than the type of media, aspect of the model is the way in which it represents a modeled object. It is always dependent on the degree of advancement of knowledge in the specific field.

Hitherto, building modeling technology was only a consumer of general scientific knowledge, especially in the field of geometry and applied mechanics, developed independently of the needs of the investment process, so to speak. This situation changed when the graphic computer programs have ceased to be merely intelligent drawing board, but allowed easy handling of complex geometric objects that have emerged along with new theoretical solutions, such as B-splines, biquadratic flexible surfaces, sponges (labyrinths) and many others, e.g. Fig. 2. It is obvious that the emergence of such forms influenced also the forming of the modern aesthetic paradigm.

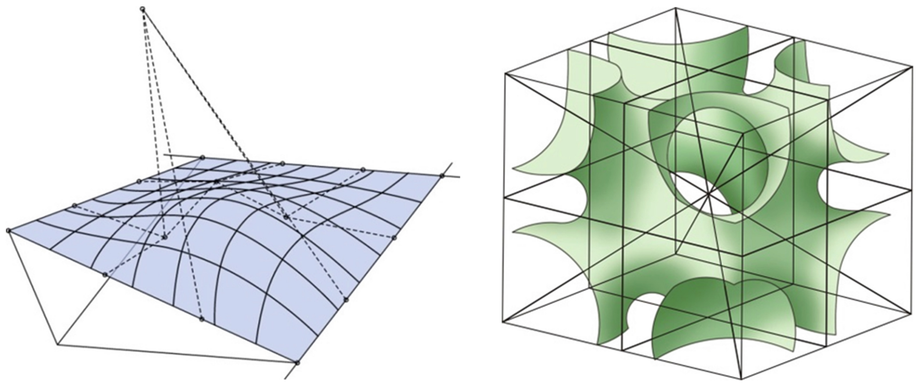

Fig. 2. Two examples of new geometric structures that have been discovered thanks to the possibilities offered by computer graphics: on the left – NURBS surface with visible control vertices (CV) [6]; on the right – single repeatable frame of sponge i.e. a system of saddle surfaces connected with a single polyhedron (the edges of the frames pass through the tunnels of labyrinth) [7]

In structural modeling, the geometric model is just a starting point for the formulation of a model describing the static, dynamic and strength properties of the system. Historically, for a very long time this modeling was based mainly on the accumulated experience and intuition of designers. Since the emergence of the science of structural mechanics and strength of materials, structural models were based on analytical solutions, describing the relationship between the load, internal forces and deformations in different types of construction. The catalog of these types of structures is, however, limited, and any attempt to go beyond it can cause a loss of mathematical support for modeling. Numerical methods, particularly finite elements method, enabled the digitization of structural systems, and thereby description of very complex structures, for which previously did not exist analytical solutions, Fig. 3.

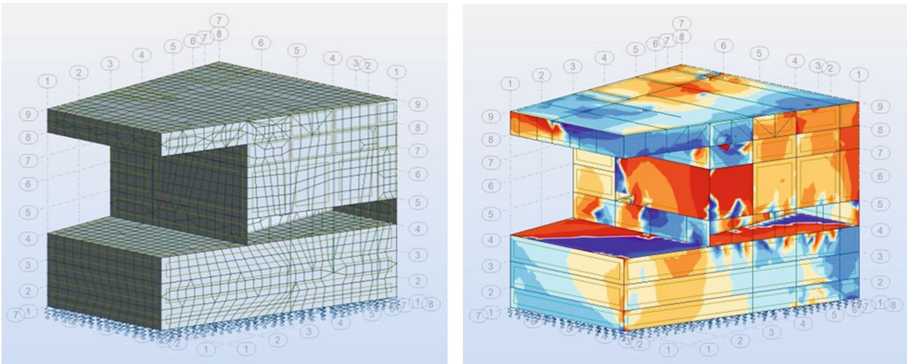

Fig. 3. An example of the analysis of the Opera House in Wroclaw (Poland) using the Finite Element Method (FEM): on the left – division of the building structure into finite elements; on the right – distribution of extreme stresses in the form of maps on the walls of the building

All this has had a significant impact on the modeling in architecture and design. In architecture, it enabled provide any complex spatial forms, manipulate and visualize them, evaluate the impact of climatic factors – a departure from the orthogonal preferences in shaping. In structural engineering, numerical modeling supplanted earlier methods of analyze, such as physical modeling and closed analytical solutions).

3 "Fantastic Development of Possibilities and Lack of Guidelines"

Radical change – increase of modeling capabilities in architecture and structural engineering, occurred almost simultaneously, allowing that modeling of structural systems can keep up with the modeling of architectural form. This led to the widespread belief that "anything is possible". The mere fact that the form is feasible is often sufficient reason for designing it.

Usually unnoticed limitation of structural modeling by means of the finite element method is the need for accurate geometric data, as input to build the model. It is possible to analyze any number of variants of the object model, but they all must be pre-defined. So, can be analyzed only objects whose form has already been geometrically defined earlier, in the stage of architectural modeling, which – as mentioned above – gained almost total freedom to create forms.

In such a process, disappeared – developed over the centuries – common search for forms by architect and structural engineer. And the latter one lost the tools to creatively support architect.

Thus appeared a belief that everything that is possible is reasonable and should be constructed. Sometimes this view is supported by a quote from G.W. Leibniz – *"Omne possibile exigit existere"* – Everything that is possible demands existence (De veritatibus primis, 1686).

In architecture, this became the conviction that there are no ugly or inappropriate forms. More important is originality, understood as otherness and astonishment – sometimes even shocking – of recipient by the visual effect.

In structural design, became possible modeling of "everything". Designers began to create complex computational models, fleeing from the intellectual effort related to the deep understanding of the essence of the problem. This phenomenon constantly increases with entering into working life successive generations of engineers. Mathematics becomes a kind of alibi to justify the lack of their own creative invention.

This situation has led to the emergence of a whole series of forms that can be boldly called pathological. On the one hand, their visual attractiveness attracts the attention of the public opinion, they are widely reported and commented, on the other hand, it is difficult to find for them any (except perhaps for prestige) functional or economic justification. One of the most famous such examples in recent years is undoubtedly the Olympic Stadium in Beijing, constructed in 2008, Fig. 4.

Fig. 4. Olympic Stadium in Beijing (arch. J. Herzog and P. de Meuron)

A huge amount of steel consumed for the construction this object, the structural elements of a very complex geometry and large dimensions, as well as the determination of the investor in the pursuit of the project (during construction were a number of fatal accidents) – were repeatedly subjected to criticism and even condemnation.

Another example of an object whose form is based on a fairly random inspiration (pappardelle pasta) is a new building at the Fair in Milan, Fig. 5. Witty, in the early stages of design, inspiration, has led to the need to design a structural system that is difficult to define other than “forced by the architectural form”. The author of this project, a prominent structural engineer, M. Majowiecki, pointed out on this occasion that indiscriminate “adding” of the structural system, to the arbitrary given architectural form, carries a lot of risks that did not exist before, in the traditional design process [8]. This includes such issues as: a lot more complex configuration of loadings (particularly wind load), unclear scheme for verification of the spatial stability, complicated diagram of exhaustion of cross-section capacity, dynamic problems, etc. Thus, thoughtless pursuit of originality may, in extreme cases, even lead to failure threatening the safety of users of the object.

Fig. 5. “Cometa” Milano Portello Fair in Milan (arch. M. Bellini, struct. eng. M. Majowiecki)

The title of this paragraph, which is a quotation of A. Einstein’s statement, is a brilliant punchline of that situation: we can design and analyze (almost) everything – but do we know what we should design and analyze?

4 Intuition Rediscovered

The reaction to this situation is an attempt to restore, in numerical version, formerly used tools which allow designer not only to control the calculations of the given form, but also allow to actively shaping it. These are e.g. advanced development of long known graphical static methods, reverse catenary modelling, flow of forces method and the use of prototypes of structural forms found in Nature.

On this occasion one can observe a paradox. New possibilities for shaping the geometry led designers to focus on the visual effect of their work, leading up to a "showiness". Today, however, just methods associated with visual perception give hope for healing situation.

An example would be the latest trend in the development of methods for the calculation of structural systems. In the above-mentioned Finite Element Method (FEM) first and very important step is to divide the analyzed area (surface, space) onto sufficiently small parts. Current methods of division are based on algorithms originally developed for other purposes, e.g. rendering in movie animation (e.g. Coons patches). What's more, they referred to the division of the "traditional" surfaces rather than today's popular free-form surfaces. Thus, very often they are based on triangularisation. The isolation of these algorithms from geometric description with use of e.g. NURBS, is obvious.

Intensively developed for last ten years, area called the "Isogeometric Analysis" is focused on working out such algorithms of division, and then calculation procedures in FEM, to obtain homogeneous, using the same geometric tools, description of both the geometry and mechanical properties [9]. The aim of this approach is to bring unity in the geometrical and mechanical description of the modeled object.

Another very interesting and promising trend is to restore to use methods that were once widely used, and then almost forgotten. By combining them with numerical modeling, appeared entirely new capabilities of creating the form.

An example of such a "revitalization" of design methods is intensively renewed interest in graphical statics methods. These methods, which peak development was in the second half of the nineteenth century, have subsequently been almost completely supplanted – initially by iterative calculation method, e.g. the H. Cross's method, and then by the above mentioned finite elements method. Now, in last few years, appear publications in which authors not only highlight the reasonableness of the use of these methods in design practice, but also propose new, very interesting extensions and generalizations of these methods [10].

Physical modeling for a long time was the only available method to analyze complex structural systems. Spectacular examples of this approach for the formation of the whole object can be found in the works of Antoni Gaudí, especially the famous Sagrada Familia in Barcelona. Appearance of numerical methods caused that the scope of the physical modeling is currently limited to testing the individual components, while this approach is not applied as a comprehensive tool to shape the form.

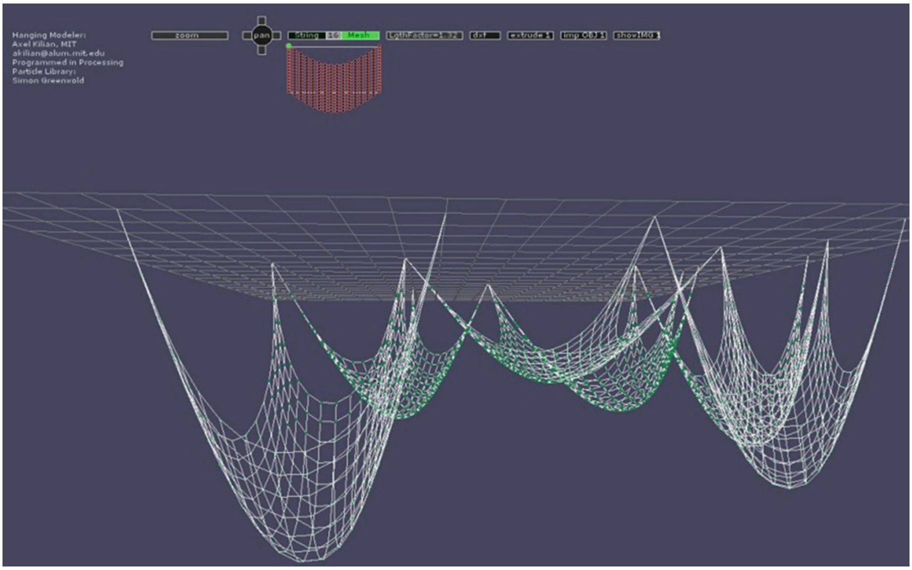

Fig. 6. Interface screen in the Hanging Modeler program, developed by Axel Kilian

A. Gaudí used a special form of physical modeling by building catenary models in which flexible strings likely to transmit only tensile forces, represented arches and vaults of designed structure. After reversing the model upside down, the designer receives a structure which, for the dominant loading schemes, is only in compression. This allowed, for example, constructing impressive structures of stone blocks. Currently, has been developed software based on particle-spring systems, which allows construction of virtual catenary models [11]. This software allows easy creation, through an intuitive graphical interface, Fig. 6, of complex catenary models, which can then be further processed in other programs until the full value structural model is achieved, Fig. 7.

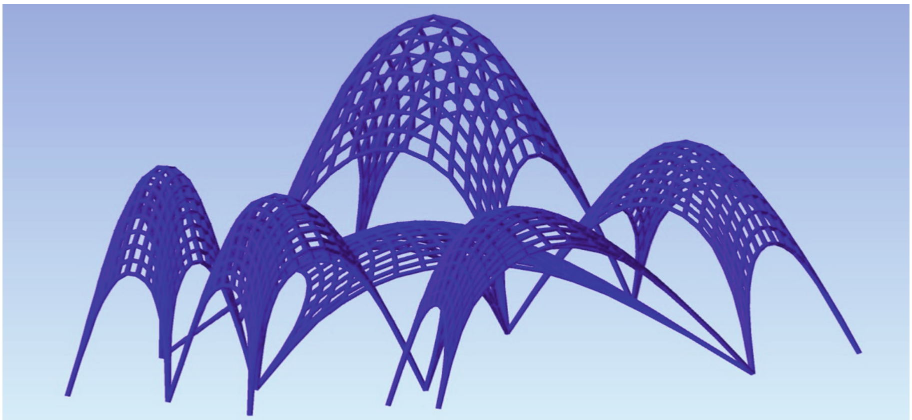

Fig. 7. An exemplary structure shaped in the Hanging Modeler program

Another very interesting example of the numerical implementation of the physical modeling is a software that allows a virtual representation of the process of creating origami structures. This traditional Japanese art of paper folding has been used for the design of deplayable structures of different applications – from construction industry to the space antennas [12]. Freeform Origami software [13] allows to perform and test virtual models based on this concept.

An example of the modeling of the structure of the roof covering of the building shaped as folded shear beam structure is presented below [7]. A simple initial pattern, Fig. 8 left, has been deformed by origami method, Fig. 8 center and right, until the desired geometry was achieved. The resultant model of roof covering, Fig. 9 left, was then transferred to the finite element method the program, in order to determine the values of internal forces caused by snow load, Fig. 9 right. Easy and clearly legible, visual binding of the obtained geometrical form and static structural behavior is a great advantage for the designer in the initial stage of shaping the form.

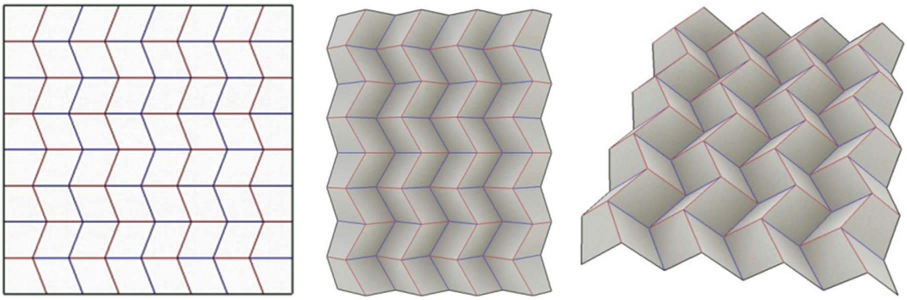

Fig. 8. Successive stages of shaping form of roof covering by means of origami method

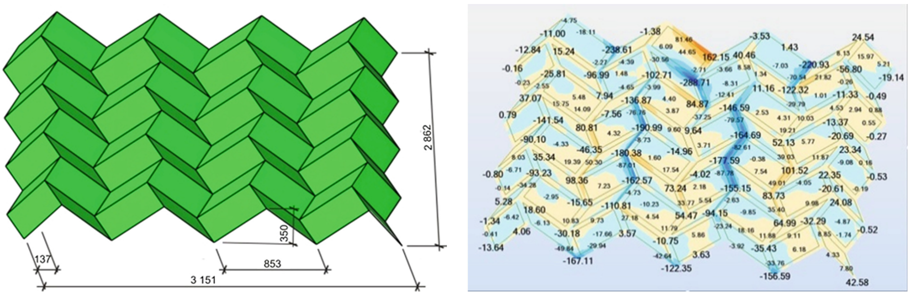

Fig. 9. Analysis of the structure of Fig. 8, by using the FEM program

Still other possibilities results from the use of natural prototypes of structural forms. Using patterns found in the Nature, one can reconstruct them in a scale of the building, while maintaining their interesting structural properties. Interestingly, sources of inspiration are not necessarily obvious and may be based on purely visual associations. Below is an example of using the pattern formed on cracked ice cap, Fig. 10, to design a roof structure of the building, Fig. 11 [7, 14].

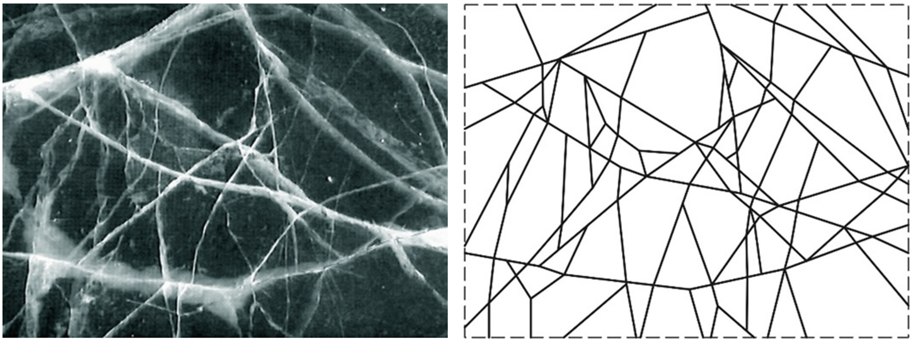

Fig. 10. A pattern formed on cracked ice cap

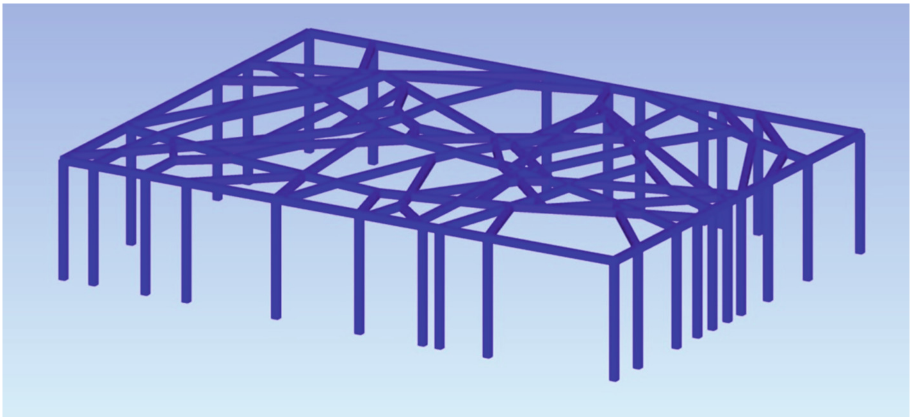

Fig. 11. Roof structure shaped on the base of pattern from Fig. 10

5 Conclusions

After several years of intensive development of design methods with the use of computers, both for modelingin the geometrical form and structural system, one can observe a tendency to return to the intuitive tools for shaping objects. It turned out that the tools for detailed analysis, even of very complex structures, do not facilitate work at the initial stage of work, when it is necessary to define the model. Therefore in recent years emerged the methods and tools to fill in this gap. They allow using computers in the traditional pre-design process.

Traditional, experience based methods of structural design must be replaced by designing based on mathematics, which combines static and aesthetic problems. Lightness (freedom) of architectural form does not automatically translate into a lightness and freedom of structural form.

Artur Loeb’s remark, that *“Space is not a passive vacuum; it has properties which constrain as well as enhance the structure which inhabit it”* [15] is confirmed once again.

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