JOURNAL OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES

Prof. D. h-C Eng .E. TORROJA, founder

Vol. 57 (2016) No. 2

June n. 188

ISSN: 1028-365X

Journal

VOL. 57 (2016) No. 2
n. 188 June

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Technical Papers

COVER: *Figure from paper by Y. Anastas, L. Rhode-Barbarigos and S. Adriaenssens*

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Printed by SODEGRAF ISSN:1028-365X Depósito legal: M. 1444-1960

JOURNAL OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES: **J. IASS**

HOW TO UNDERSTAND 'STRUCTURAL MORPHOLOGY'?

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Editor's Note: Manuscript submitted 26 January 2015; revisions received 30 June 2015 and 27 August; accepted 2 September 2015. This paper is open for written discussion, which should be submitted to the IASS Secretariat no later than December 2016.

DOI: http://dx.doi.org/10.20898/j.iass.2016.188.765

ABSTRACT

Due to its wide range of related research contents and diversified research approaches, the term 'Structural Morphology' has not been clearly defined by the Structural Morphology Group (SMG) of the International Association for Shells and Spatial Structures (IASS), founded in 1991, although some scholars have given their own viewpoints. This paper presents a different way to understand the meaning of "Structural Morphology" and its connotations. Nowadays, numerical techniques have become the most important means to do research in the field of structural engineering, and they can assist in the design, analysis and optimization of structures by handling a large number of parameters. In this paper, we present a common conceptual scheme for these numerical analysis methods. The scheme classifies the parameters of the initial structural system into five categories and, with the aid of numerical analysis methods, leads to the structural performance of the final structure. Two simple numerical examples are shown to verify the rationality of the scheme. On this basis, a conceptual formula to describe 'Structural Morphology' is proposed, which contains the whole numerical analysis process, shows the goal of structural morphology and also suggests a suitable methodology. Moreover, since numerical form-finding and computational morphogenesis have become two main research foci of structural morphology, a basic introduction, methodology and some achievements related to each research focus are presented in this paper.

Keywords: *structural morphology, parameters, structural performance, structural form, mechanical behavior, numerical form-finding, computational morphogenesis*

1. INTRODUCTION

During the IASS (International Association for Shell and Spatial Structures) Copenhagen Symposium in 1991, the IASS Working Group NO.15 SMG (Structural Morphology Group) was founded by the 'gang of four' - Ture Wester, Pieter Huybers, Jean-François Gabriel and René Motro [1, 2]. Since then, related researches have been one of the main focus points in the field of structural engineering, especially for shell and spatial structures. However, structural morphology is not a new discipline born with the SMG working group. Many scholars, designers or engineers over many years have taken the relationship between forms and forces as one of the major issues to be elaborated upon [2]. The term Structural Morphology was proposed by Michael Burt [1, 2]. While due to its wide range of related research contents and diversified research approaches, the term 'Structural Morphology' has not gained a clear definition from the SMG since 1991. Many scholars made their contribution for a definition of this term, but everybody keeps his personal version [2]. The following gives two viewpoints from different perspectives.

Motro gave a parametric approach to Structural Morphology in his papers [3, 4, 5]. Any design process for a system proposed has to deal with multi-parametric problems, and it could identify the main parameters and then classify them in four categories: forms, forces, material and structure, shown in Figure 1. The position of 'Structural

Morphology' in this system is at the interface between the parameters ‘form’ and ‘structure’, it is the direct relation between the study of form and structure extended to cover the relational sense. This relation is affected by the behavior of the material and by the need to ensure the static (and sometimes dynamic) equilibrium of the system ***S*** being designed.

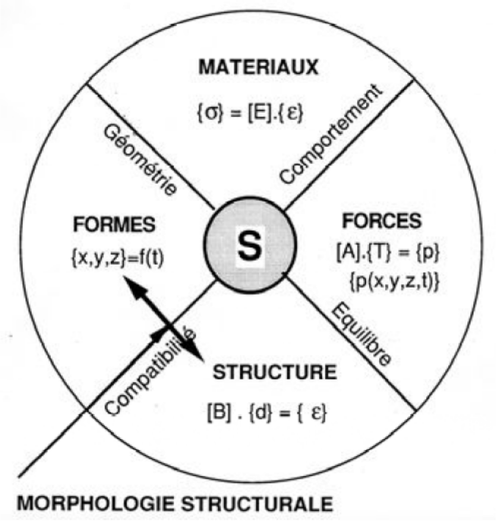


Figure 1: *The conceptual scheme of Motro [5]*

Shen and Wu suggested a preliminary definition of 'Structural Morphology' [6], that it is a discipline which studies the interaction between the structural form and its mechanical behavior from an integral prospective, aiming to realize the rationality and efficiency of the structures.

It can be seen that the former viewpoint from Motro is on the basis of the analysis parameters of the structural system, and presents an appropriate position of the 'Structural Morphology'. The latter one from Shen and Wu seems a bit abstract, but it can clearly show the orientation, goal and main content of the research on structural morphology. However, both of the two viewpoints based on their own understandings are the crystallization of their research and practice.

Nowadays, 'geometry', 'form-force relationship', 'form-mobility relationship', 'technology transfer', 'computation' and 'prototyping' become the research focus of structural morphology [7, 8], and some new challenges are emerging continually. With the development of computer technology, numerical technique has become the most important means for research in the field of structural engineering, which can design, analyze or optimize structures by handling a large number of parameters. On this basis, many numerical analysis methods have been gradually developed and played an important role in modern research for 'form-finding' [8, 9] and 'morphogenesis (based on structural optimization)' [8, 9, 10], which are the two main means and aspects of the research on Structural Morphology in the authors' view.

Against this background, this paper proposes a common conceptual scheme for numerical analysis methods, which would cover the whole analysis process from the initial structural system to the final structure. Then a new way to understand 'Structural Morphology' is proposed, and the methodologies of the numerical form-finding and the computational morphogenesis are discussed afterwards. Moreover, some numerical examples and achievements (mainly from the authors and members in their research team) are shown to verify the rationality of the conclusions in this paper.

2. THE CONCEPTUAL SCHEME OF NUMERICAL ANALYSIS METHODS

In the last few decades, many numerical analysis methods have been developed for structural design, analysis or optimization. Almost all of them handle the parameters which can be used to describe the initial structural system by numerical methods, and after the analysis, they can obtain the parameters which can be used to describe the final structural performance, including the final structural form after complete deformation and its mechanical behavior under certain loads.

Based on the above context, a common conceptual scheme of numerical analysis methods is raised in this section, shown in Figure 2.

2.1. Specific information in the conceptual scheme

In order to explain the information in the conceptual scheme more specifically, it is divided into three parts as follows:

1) The initial structural system

In numerical analysis methods, one defines and describes the initial structural system by using necessary parameters, and these parameters can be divided into the following five categories:

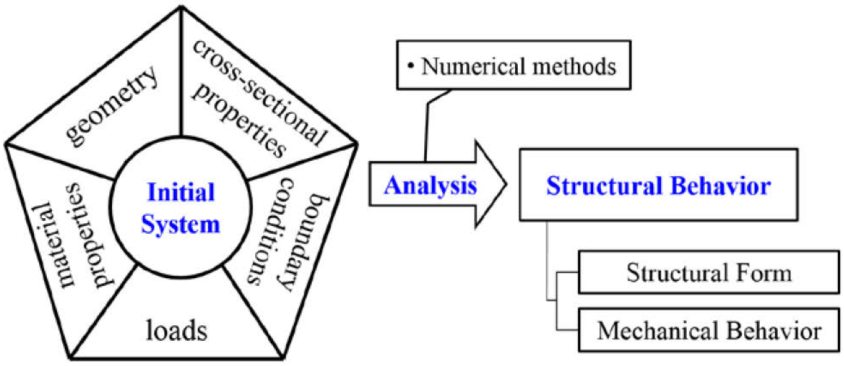


***Figure 2:** The conceptual scheme of the numerical analysis methods*

- The parameters of geometry, which are used to define the initial shape and space of the initial structural system.

- The parameters of cross-sectional properties, which are used to define the mass distribution of the initial structural system.

- The parameters of material properties, which are used to define the constitutive models of all building materials in the initial structural system.

- The parameters of boundary conditions, which are used to define the mechanical features for both the supports and joints in the initial structural system.

- The parameters of loads, which are used to define all the loads that applied to the initial structural system.

2) The numerical methods

From the first part, it can be observed that we can totally define and describe an initial structural system with the five categories of parameters. Then a new problem occurs - how to handle the five categories of parameters?

Nowadays, many numerical methods have been developed or are still developing, and here we just give a simple introduction of two sophisticated numerical analysis methods.

For a structural system such as a common concrete or steel structure, it is possible to analyze it with equilibrium conditions, or also with additional equations if it is an indeterminate one. The Finite Element Method (FEM, for short) [11] is one of the most sophisticated numerical analysis methods to handle the five categories of parameters of the initial structural system by generating mesh, developing element stiffness equations and recombining all the element equations into a global system of equations for final calculation. On this basis, Nonlinear Finite element method was developed to solve nonlinear questions in which the deformation cannot be neglected.

For a structural system such as a piece of cable or membrane, it cannot develop the equilibrium equations for the current position of the initial structural system. The basic and critical step to analyze this system is to find its state of equilibrium under certain loads and constrain conditions, which is a strongly nonlinear problem, and after some dispose to keep stable it can be used as a structure. Dynamic Relaxation (DR, for short) [12] method is one relatively mature numerical analysis method to solve those problems, in which the system oscillates about the equilibrium position by an iterative process with each iteration based on an update of the geometry.

3) The structural performance

After the numerical analysis, it can get the final equilibrium structure with complete deformation under certain loads and constrain conditions. It can also describe the structural performance of the final equilibrium structure by using parameters, and these parameters can be divided into the following two groups:

- The external structural performance - structural form, which refers to the final equilibrium structural form after complete deformation under certain loads and constrain conditions. It equals to the difference between the initial form and displacement, and each of the five categories of parameters may have influence on it. For most of the building structures, under the action of the loads, the system should still maintain its shape and remain its location. While for some structures with nonlinear characters, the final equilibrium form may be totally different with the initial one.

- The internal structural performance - mechanical behavior, which refers to the mechanical behavior of the final structure under certain loads and constrain conditions. It includes the internal force, stress, strain, strain energy or other parameters. And it can design the structure or evaluate its mechanical property by using different kinds of the mechanical behavior. The rationality of the mechanical property of the structure is of crucial importance which would help to ensure safety and to conserve materials for the building, and it may have an influence on the final equilibrium structural form.

In addition, in order to determine that if the final system can be used as a structure, here, it points out the four following properties of the mechanical behavior of a structure:

- Equilibrium, which is the most basic property of the structure and provides the basic equations for structural analysis.

- Strength, which is an important indicator of the limit states of ultimate bearing capacity.

- Stiffness, which is an important indicator of the limit states of serviceability of a construction.

- Stability, which is an important indicator of the design process for columns, beams, plates and shells.

From above introduction, it can be seen that both the two aspects of the structural performance are obtained from the analysis of the five categories of parameters of the initial system. They would exist simultaneously and interdependently. In this case, each of the five categories of the parameter would have an influence on the structural performance.

In conclusion, the information of the conceptual scheme is introduced in detail in this part. It can be seen clearly that parameters play an important role in the whole analysis process from the initial structural system to the final equilibrium structure. Therefore, rational classification, disposal and analysis for those parameters become one of the most important works needed in the process of structural design, analysis or optimization.

2.2. Numerical examples

In this part, two simple examples are shown in order to verify the rationality of the former context, and either of the whole process of the numerical analysis would follow the conceptual scheme.

1) Simple beam under distributed load

In this example, we would like to get the bending moment diagram and deformation diagram of the simple beam under distributed load, and known conditions are shown in Figure 3.(a).

Firstly, it shows the five categories of the initial system as follows:

- The parameters of geometry --- ***L***, which refers to the span of the beam.

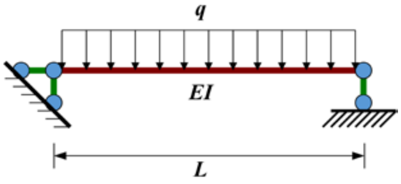
- The parameters of cross-sectional properties --- ***I***, which refers to the section inertia of the cross-section.

- The parameters of material properties --- ***E***, which refers to the elastic modulus of the material.

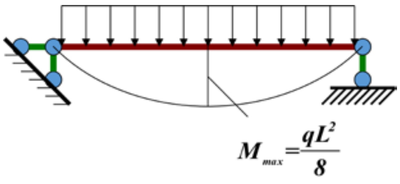
- The parameters of the boundary conditions --- the left support is a fixed hinge bearing and the right one is a sliding bearing.

- The parameters of loads --- ***q***, which refers to the distributed load.

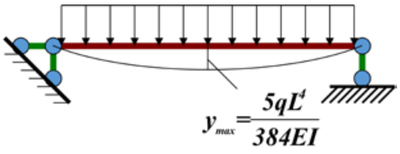
Secondly, we analyze the former five categories of parameters by using the equations of static equilibrium and the method of sections, which is one of the most basic methods in Structural Mechanics and would not be covered here, to get the structural behavior. It should be noted that the bending rigidity ***EI*** of this beam is sufficiently large in this problem which obeys the small deformation assumption.



(a) The initial structure



(b) The bending moment diagram



(c) The deformation diagram

Figure 3: *Example 1*

After the analysis, we gain the bending moment diagram shown in Figure 3.(b) and the deformation diagram shown in Figure 3.(c), and it can also be seen that both the value of the bending moment and the deformation are expressed by some of the five categories of parameters.

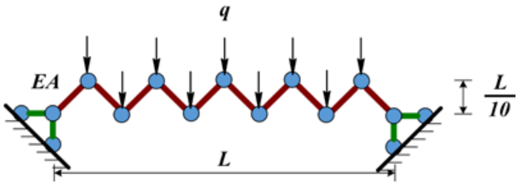
2) Equilibrium form of 10-link mechanism

In this example, we would like to get the final equilibrium shape of the 10-link mechanism with two bearings in the ends, in which all the masses are focused on the joints with the value of ***q***. The links have no weight and cannot be stretched, and known conditions are shown in Figure 4.(a).

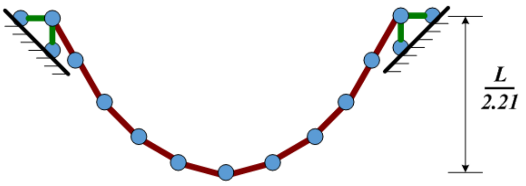
Firstly, it shows the five categories of the initial system as follows:

- The parameters of geometry --- ***L***, which refers to the span of the mechanism; ***L/10***, which refers to the coordinates of some joints.
- The parameters of cross-sectional properties --- ***A***, which refers to the section area of the cross-section.
- The parameters of material properties --- ***E***, which refers to the elastic modulus of the material; in this example, the value of it is very large to ensure the very small elongation of the links.
- The parameters of the boundary conditions --- all the two supports are fixed hinge bearings. All joints are articulated which cannot bear the bending moments.
- The parameters of loads --- ***q***, which refers to the mass in each joint.

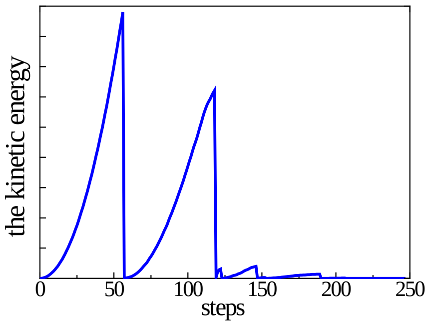
Secondly, we analyze the former five categories of parameters by using the Dynamic Relaxation method to get the structural performance. In this example, in order to ensure the constant length of the links, some special sets are done in the analysis process: 1) the link can only be stretched with a negligible deformation by setting a very large elastic modulus; 2) the axial force of the link is set to zero when it is in a compressible state.



(a) The initial mechanism



(b) The equilibrium shape



(c) The evolution curve

Figure 4: *Example 2*

After the analysis, we obtain the final equilibrium shape of the 10-link mechanism shown in Figure

4.(b) and the evolution curve of the kinetic energy by steps shown in Figure 4.(c). We can also attain the distribution of internal force or other behavior of the equilibrium mechanism, which are not covered here.

From the former two simple numerical examples, it can be seen that the classification of the parameters for the initial structural system is reasonable. After numerical analysis, it is also reasonable to divide the parameters of structural performance into two categories, which would be considered in different degrees based on the requirements in the design or analysis process. In this case, the conceptual scheme in Figure 2 has shown its rationality and applicability for the numerical analysis process, which can apply to either initial structural system.

3. STRUCTURAL MORPHOLOGY

Since a very early age, people prefer to build buildings with novel forms to meet their increasing requirements and with optimal mechanical behavior to save costs or keep safety.

Meanwhile, the coordination between the structural form and its mechanical behavior has been taken as a research focus in the field of structural engineering, especially for shell and space structures, which always have novel structural forms and use their shape to bear loads.

Recently, with the development of economics and society, more novel structural forms are emerging to meet people's visual enjoyment and spiritual needs. Due to the growing power of the computer function and structural construction technology, it seems that 'anything can be carried out as long as you want to' has become the key characteristic of the modern structural technique, and the rationality of the mechanical behavior has been placed in a relatively minor position. Therefore, new methods, techniques or structural system innovations to coordinate the relationship between structural form and its mechanical behavior are imperative needed. In this case, related research on Structural Morphology shows its greater significance than before. However, 'Structural Morphology' has not gotten a clear definition from the SMG group since its foundation in 1991.

Everyone keeps his own understanding of Structural Morphology, but this paper tries to present a new way to understand this very term on the basis of the conceptual scheme presented in Figure 2. A basic formula to describe 'Structural Morphology' is proposed in this part, and afterwards, the basic methodology of related researches on structural morphology is pointed out.

Shown in Figure 5, it can be clearly seen that the parameters of the structural performance are obtained from the numerical analysis of the five categories of parameters of the initial structural system, and therefore each category of parameters would have influence on the structural form and its mechanical behavior. Based on this, 'Structural Morphology' can be described as follows:

$$\mathbf{B} = \boldsymbol{f}\,(\mathbf{A}) \tag{1}$$

which means that: in order to obtain the structure with novel form and optimal mechanical behavior, we can adjust some of the five categories of parameters of the initial structural system under certain constraint conditions by some analysis means. Here,

B -- refers to the final structural performance, which always requires both optimal structural form (the external expression) and rational mechanical behavior(the internal expression). Specifically, the structural form should meet the architectural requirements, and its mechanical behavior should be rational and efficient.

A -- refers to the initial system, which can be described by the five categories of parameters.

f -- refers to the analysis methods to handle the five categories of parameters of the initial system, in order to get optimal structural performance. Among those methods, form-finding (which may need a one-time analysis process or a cyclic analysis one) and structural optimization (which is always a cycle analysis process) are the two important means.

In conclusion, it can be observed clearly that the above conceptual scheme and the conceptual formula can cover the whole process of numerical analysis, and show that the research goal of Structural Morphology is to balance the two aspects of structural performance - the structural form and its mechanical behavior. And moreover, they can also suggest the suitable methodology of research on Structural Morphology.

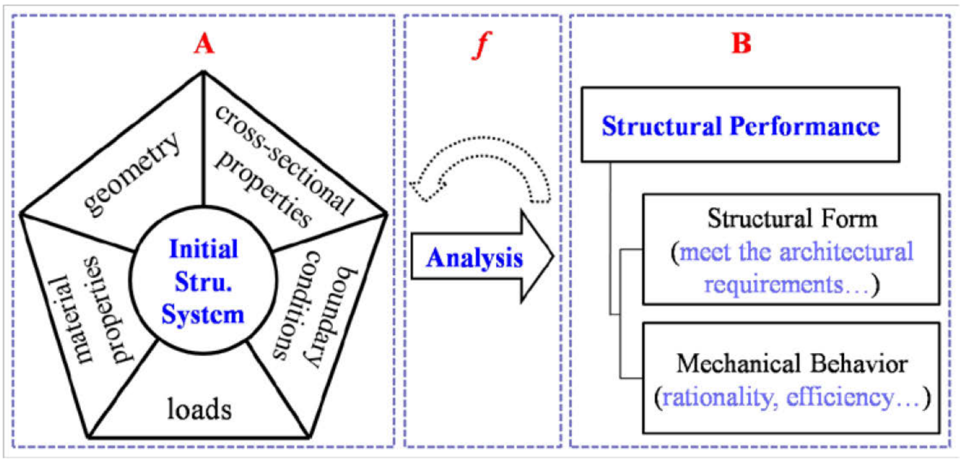


Figure 5: *The conceptual scheme of the Structural Morphology*

4. NUMERICAL FORM-FINDING AND COMPUTATIONAL MORPHOGENESIS

Nowadays, many research focuses and challenges are exhibiting in front of scholars [7, 8], and among those, numerical form-finding and computational morphogenesis are the two main ones. In the authors' view, they can also be considered as the two main means to get novel structural forms with optimal mechanical behaviors. Based on the above conclusions, this paper concludes the methodology of each research focus and some research achievements would be discussed in this section.

4.1. Numerical form-finding

Form-finding is a forward process in which parameters are explicitly/directly controlled to find an 'optimal' geometry of a structure which is in static equilibrium with a design loading [13]. It is always used to express the process of determining the equilibrium shape of lightweight structures. In the pre-computer-age, architects and engineers used physical model experiments to conduct the form-finding process, among which the hanging model experiment and the soap film experiment are very famous. With the development of computational techniques, most of the form-finding processes are carried out by numerical methods. In the last decades, the term 'form-finding' has been used in a more special context, It has been related to mechanical methods which are applied to find the shape of structures subjected to the action of forces in equilibrium [9].

For this kind of problems, the final equilibrium structural form always has a very close relationship with the mechanical behavior. For instance, in tension structures, the equilibrium structural form provides the structure with geometric stiffness to withstand loads. It is acceptable for most people that the mechanical behavior is reasonable after the process of form-finding, and what they concern most is to find the structural form under certain constraint conditions.

Figure 6 shows the conceptual scheme of the numerical form-finding: for most of these problems, after giving the five categories the parameters of the initial system, the equilibrium structural form can be obtained by the analysis at one time. While in order to get the form with some other constraint conditions, it also needs some adjustment of the initial system. However, the adjusting process does not have systematic methods, and it depends mostly on designers' subjective approach. Moreover, it should be noted that the initial structural system always performs as a geometrically unstable system, and the analysis for the initial structural system has strong geometric nonlinearity.

Motro divided the equilibrium form systems into two categories, one is the 'funicular' systems (in the broad sense of the term) in which form depends on the external system of actions applied, and the other is 'self-stressing' systems in which stiffening results from a system of internal stresses in static equilibrium [5]. The form-finding problems can also be divided into these two categories (tension structure and relevant structural systems belong to the 'self-stressing' system, hanging structure and pneumatic structure belong to the 'funicular' system). Many scholars' achievements are discussed in the following the two categories.

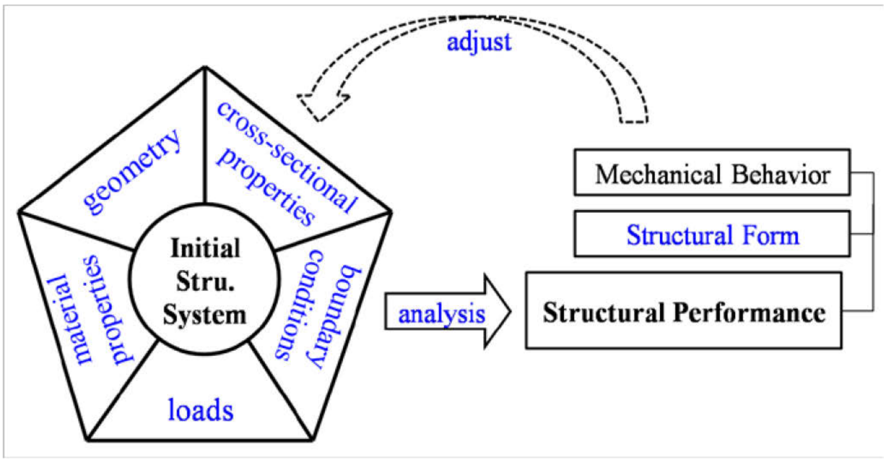
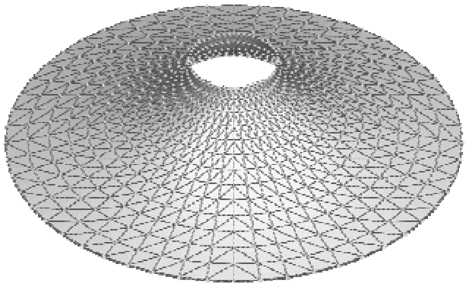


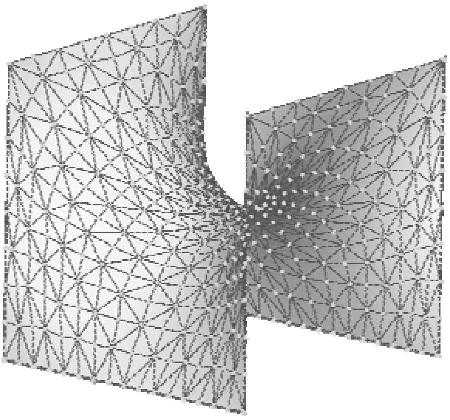
Figure 6: *The conceptual scheme of numerical form-finding*

1) The 'self-stress' systems

This is a relatively mature area, many numerical methods have been put into practice for many years, and many are even developed for the form-finding of tension structures.



(a) The tension membrane in the form of catenoid



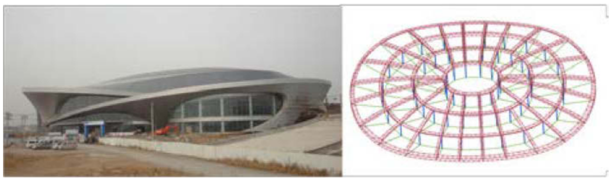
(b) The tension membrane with minimal surface

Figure 7: *Tension membranes generated by FPM*

The analysis methods can be normally categorized into three main families: stiffness matrix methods, geometric stiffness methods, and dynamic equilibrium methods [14]. The non-linear finite element method, the force density method [15] and the dynamic relaxation method are the typical example of each category, which would not be covered here.

Based on the mechanical concept of the vector form intrinsic finite element [16], Yang et al. [17] presented a general finite particle method (FPM) framework for investigating the shape analysis of tension membrane structures under given boundary conditions. If this method is applied iteratively with constant and isotropic stress prescribed at any given point on the surface, it can lead to a stable minimal surface. Figure 7 shows two classical tension membranes are generated by this method.

(a) EasyLanding



(b) The Dalian Center Gymnasium

Figure 8: *Examples of innovation of structural system*

This is also a research focus which can bring innovation of structural systems. For example, tensegrity structures, cable dome, suspen-dome and etc. are invented and form-found by scholars or engineers. And some innovative structural systems have been put into practice. Figure 8 shows a sculpture of tensegrity structure made by Snelson [18] and the Dalian Center Gymnasium with a suspen-dome designed by Cao et al. [19].

2) The 'funicular' systems

This kind of problems is also a research focus of structural morphology. Almost all the numerical form-finding methods for 'self-stressing' systems can apply to this kind of problems, but with some different sets. In this article, two relatively new numerical methods and the research on some further problems of the hanging model experiments are discussed.

Block and Ochsendorf [20] presented a methodology for generating compression-only vaulted surfaces and networks, which is called Thrust Network Analysis. The method uses projective geometry, duality theory and linear optimization, which is a graphical and intuitive method. This method is applicable for the analysis of vaulted historical structures, specifically in unreinforced masonry, as well as the design of new vaulted structures. Figure 9 shows the conceptual scheme of this method.

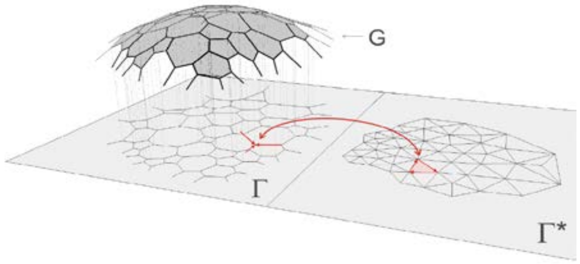


Figure 9: *The conceptual scheme of the Thrust Network Analysis method*

Borgart [21] introduced and developed an approximate calculation method for air inflated cushion structures for design purposes. In this method, the complicated geometric non-linear behavior of deformations of membranes has been solved by relatively simple analytical formulas. By using these and the method of optimization for form and force, designers are offered a range of design possibilities as well as insights into the structural behavior and the geometrical properties of air inflated cushion structures. Figure 10 shows a numeric simulation air cushion.

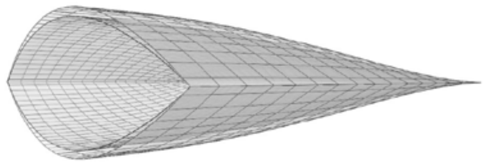


Figure 10: *The numeric simulation air cushion*

Wu et al. [22] used the nonlinear finite element method to simulate the hanging model experiment. By using the bisection method to adjust the elastic modulus, the shape of the inverted structure with certain control points is obtained. Moreover, the problem of form diversity for the inverted structures is discussed by using the methodology of the conceptual scheme proposed in Figure 2. Figure 11 shows some diverse numerical models changed from the same initial model.

Figure 11: *The diverse numerical structural models*

3) Some new issues

The numerical form-finding research for structures is an undisputable promising area in the field of structural morphology. Some new issues need to be resolved are presented here.

- More realistic situations need to be considered. Similarly to the computational morphogenesis research, the numerical form-finding methods should also consider the complex load combinations, more complex constraint conditions or others. And in this case, its mechanical behavior under live loads also need to be researched.
- The combination of the numerical form-finding method and the structural optimization method is needed. Some constraint conditions may bring difficulties to the form-finding process, and

subjective adjustments by designers will no longer apply. And then, some structural optimization methods should be introduced. For instance, the bisection method was used to get the shape of the inverted structure with certain control points [22].

4.2. Computational morphogenesis

Computational morphogenesis is realized on the firm foundation of both FEM as a tool of numerical analysis and various methods based on relatively newly-developed algorithms for structural optimization to generate the configuration or the system of structures [10]. For most of these problems, the structures would not allow excessive deformation after their construction, the parameters of geometry and cross-sectional properties can almost determine or equal the final equilibrium structural form, and what it concerns most is the mechanical rationality of the structure. Therefore, most researches today focus on generating optimal mechanical behavior by adjusting the parameters of geometry or cross-sectional properties.

Figure 12 shows the conceptual scheme of the computational morphogenesis. The mechanical behavior of the structure (strength, rigidity, stability or their combination) would act as the optimization objective. Each category of the parameters of the initial structural system can act as the optimization variables (most are the parameters of geometry or cross-sectional properties). Moreover, the objective function would be founded to link the objective with the variables. Subsequently, one suitable optimization algorithms would be selected to conduct the optimization process by adjusting the optimization variables under certain constraint conditions. With each change of the optimization variables, one computational analysis would be processed. Clearly, it would be a cyclical process.

Among these so many achievements obtained by scholars in this area [9, 10], those the authors and members of their research team gained are introduced as the following two groups:

1) Computational morphogenesis based on the optimization of geometry

This area is also called 'shape optimization for structures', and two examples done by the authors' research team are shown here. One is about free-form shells, and the other one is about free-form reticulated shells.

Li et al. [23] presented a method of computational structural morphogenesis for free-form shells, named as NURBS-GM method. This method uses the NURBS technique to describe the geometry of the initial structure. It takes the structure stain energy (the smaller the value, the better the mechanical behavior) as the objective function. Additionally, it takes the FEM as the structural analysis method, and uses the gradient method to adjust the control points and the weights of the numerical function of NURBS surface. By using this method, the structural form can be modified to obtain an optimal mechanical behavior. Figure 13 shows the evolution of one surface and the strain energy of one free-form shell using this method.

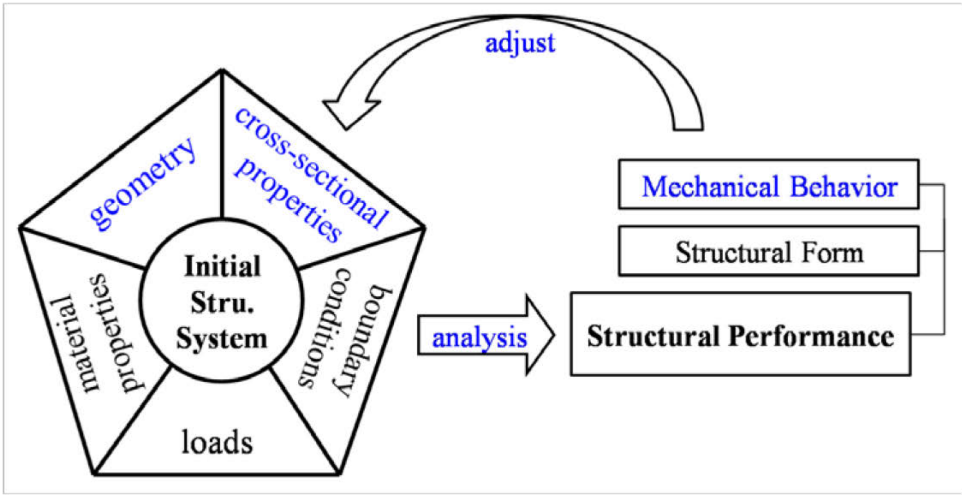
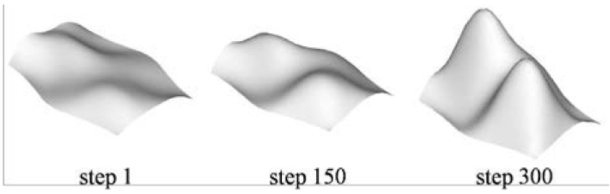
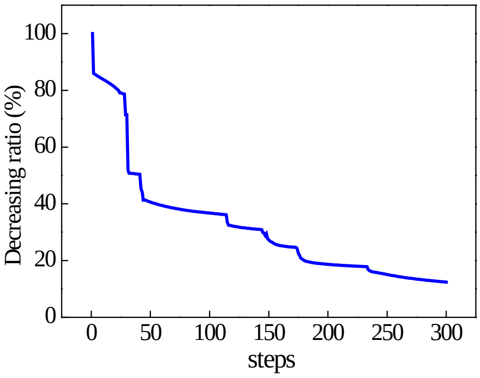


Figure 12: *The conceptual scheme of the computational morphogenesis*



(a) The evolution of structural form



(b) The evolution of strain energy

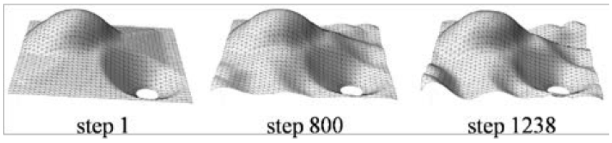
Figure 13: *Example of free-form shells*

Cui et al. [24] presented a method of computational structural morphogenesis for free-form reticulated shells. This method also takes the structure stain energy as the objective function, also takes the FEM as the structural analysis method, and uses different geometric methods to describe the geometry of the initial structure. Based on the strain energy sensitivity of its nodal coordinates, the method adjusts the nodal coordinates to achieve the reasonable structural form with minimum structural strain energy. Figure 14 shows the evolution of the surface and the strain energy of one free-form reticulated shell using this method.

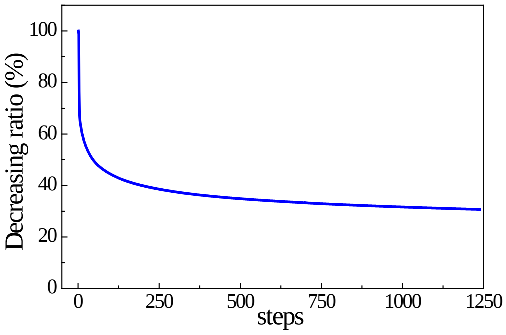
2) Computational morphogenesis based on the optimization of cross-sectional properties

This is an area also called 'topology optimization for structures'. This article shows two examples done by the authors' research team. The first is about continuum structures, and the second is about discrete structures - framed structure.

Chang et al. [25] presented a structural topology optimization algorithm using the direct gradient projection method with a transformation of variables technique, which is an efficient and reliable topology optimization method for continuum structures. This method takes the compliance of the structure as the optimization objective, takes the FEM as the structural analysis method, and uses the method presented to adjust the parameters of cross-sectional properties. Figure 15 shows one numerical example of this method.

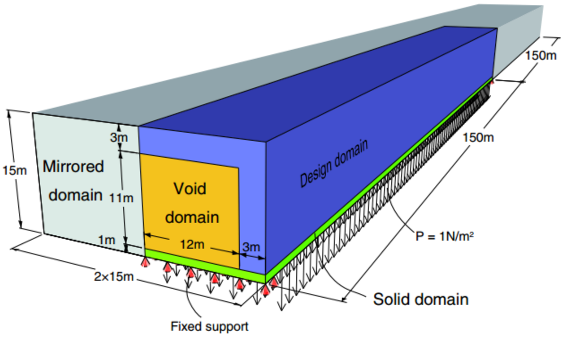


(a) The evolution of structural form

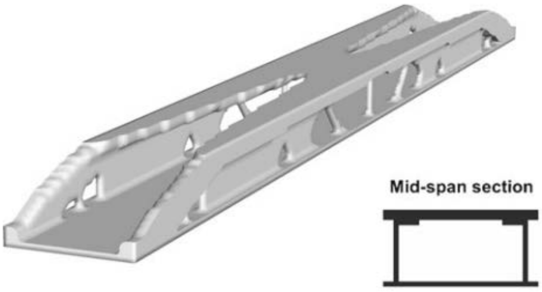


(b) The evolution of strain energy

Figure 14: *Example of free-form reticulated shells*



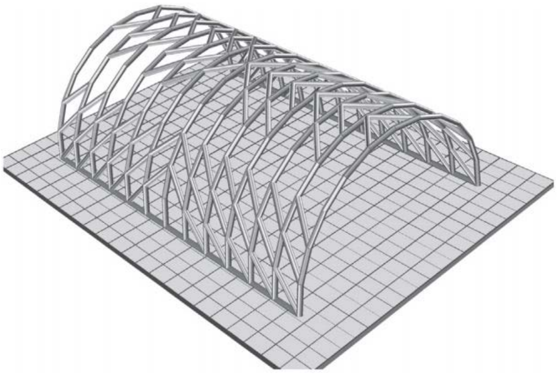
(a) The initial structure



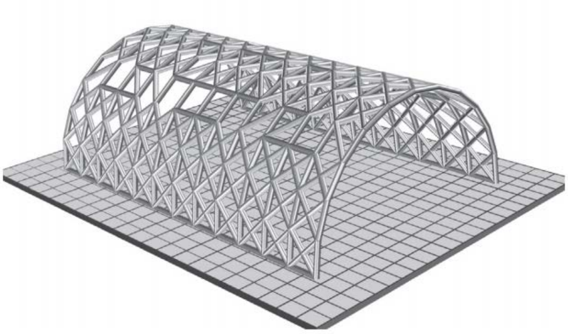
(b) The final structure

Figure 15: *Example of continuum structure*

Cui and Jiang [26] presented a morphogenesis method for the topology optimization of framed structures subject to spatial constraints, also for shape optimization simultaneously. This method is based on the elemental and nodal sensitivity information to generate or amend the structural topology. It adjusts the nodal positions to achieve a structural form with minimum strain energy. This method combines direct elemental addition or elimination, free nodal shift, or restricted nodal shift related to the structural geometry. Figure 16 shows a numerical example about the optimization of one single-layer cylinder reticulated shell.



(a) The initial structure



(b) The final structure

Figure 16: *Example of discrete structure*

3) Some new issues

The computational morphogenesis has shown its great value in research, and some cases have adopt it in practice. However, there are still some new issues need to be resolved.

- More optimization variables need to be considered. Each of the five categories of parameters of the initial system can be seen as the optimization variables, and so can their combination. For example, taking the parameters of material properties as optimization variables, it may generate a more efficient structure by replacing the tensile members with cables in a truss structure.

- More realistic situations need to be considered. On one hand, the optimization should be processed under certain constraint conditions which should meet the designers' requirements rather than without any limit. On the other hand, the optimization for complex load combinations should be developed instead of just for specific load conditions.

- New construction technique needs to be developed. The results of the computational morphogenesis always have very complex shapes and cross-sections, and it would bring great difficulties and new challenges to the construction. In this case, new tasks about the practice of the computational morphogenesis methods are lying ahead of scholars, architects and engineers.

This part states the methodologies of the numerical form-finding and the computational morphogenesis, as well as discusses the advances of each research focus. It clearly shows the rationality of the way to understand 'Structural Morphology' and some other conclusions in this paper.

5. CONCLUSIONS

This paper recommends a conceptual scheme of the numerical analysis methods for structural systems. On this basis, a different way to understand 'Structural Morphology' and methodology of it are presented. Afterwards, two main research focuses of 'Structural Morphology' are discussed. The main conclusions are:

- It proposes a conceptual scheme of the numerical analysis process, which consists of three parts: the initial system described by the five categories of parameters, the numerical analysis methods and the structural performance including the structural form as well as its mechanical behavior. In order to verify the rationality of the conceptual scheme, two simple numerical examples are introduced.

- Based the conceptual scheme of numerical analysis methods, a conceptual formula to describe 'Structural Morphology' is proposed.

Compared with Motro's viewpoint [5], this way to understand 'Structural Morphology' is from a perspective of conducting the research. It covers the whole analysis process, shows that the goal of 'Structural Morphology', which is to balance the structural form and its mechanical behavior, and also shows the methodology of it. However, compared with Shen and Wu's viewpoint [6], the way to understand 'Structural Morphology' in this paper is more concrete and can be seen as a succession and development of it.

- The two main research focuses of 'Structural Morphology' - numerical form-finding and computational morphogenesis - are discussed in this paper. On the basis of the way to understand 'Structural Morphology', the methodology of each focus is presented. In addition, some scholars' achievements and some new issues are also discussed.

The conceptual scheme presented in this paper, which consists of various branches of knowledge, can also help to develop the discipline system of civil engineering or engineering mechanics to some extent. However, this must not be an impeccable one. Basically for instance, it does not cover the context of structural construction. However, for the understanding of 'Structural Morphology' and the methodology to do related researches, the authors hope to arouse a more in-depth thinking and discussion from the scholars.

ACKNOWLEDGMENTS

This work is funded by the NSFC (National Natural Science Foundation of China, a General Program) Project NO.51378150, named 'Key problems of structural morphology and new-form space structures'. The authors would like to thank Prof. Shizhao Shen from Harbin Institute of Technology and Prof.dr.ir. J.G. Rots from Delft University of Technology for their support and guidance during the generation of the main ideas of this paper. We are also very grateful to the editors and referees for their valuable comments.

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