Topics in Spatial Structures in "Fifty years of progress for shell and spatial Structures"

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Chapter 12: Topics in Spatial Structures

Section 12.1: Structural Morphology

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The coupling between forms and forces became, at the end of the previous century, one of the major issues for shells and spatial structures, namely for those that are pre-stressed. The denomination "Structural Morphology" covers a field of investigation and research that was increasing in the recent years. It was implicitly implied in design processes of pioneers, it was obviously a major concern for famous shell designers. Founders of the Structural Morphology Working Group of the IASS contributed to its definition and progress inside the association. Our time is characterized by an increasing number of numeric tools devoted to morphology; and the actual actors of this discipline have to face new challenges like simplicity of realization of complex morphologies, or monitoring of transformable shapes. This section aims to provide some features of this fascinating discipline: structural morphology.

12.1.1. Structural Morphology: the first stages.

Pioneers

Structural morphology is not a new discipline born with the eponym working group 15 of the IASS. We may only tell that its importance appeared crucial during the last part of the previous century, when, thanks to new design tools and new possibilities for their realization, shell and spatial structures could have a wider scope of forms. It is a matter of fact that since the founding of the association the coupling between forms and forces was a one of the major issues to be solved by designers like E. Torroja, F. Candela, and P.L. Nervi among others. And they did.

One historical landmark in the field is the work achieved by d'Arcy Wentworth Thompson ([12.1.1]); many of us were fascinated, for example, by his explanations on honeycombs that revealed geometry related to the partitioning of space by rhombic dodecahedra. Naturalist drawings by Haeckel on radiolarian were inspiring for many structural designers, like Robert Le Ricolais. There is no doubt that a study of Leonardo da Vinci's works would provide many examples linked to structural morphology, and precisely to bionics as design support.

The so called "reverse hanging method" has a privilege place in the field of shell and spatial structures; one of the required major objectives in terms of material economy, is to avoid bending, and to find morphologies of structures in pure state of tension and/or compression, considered as optimum for reducing materials.

The "reverse hanging method" solves this question for a given set of loads, becoming an emblematic method; it was used with success for instance by Antoni Gaudi, in case of Colonia Güell, close to Barcelona, before being the key method of design for the nave of Sagrada Familia. But this method was also used before him by many other people: C. Wren for St. Paul's Cathedral in London, G.

Poleni in the rehabilitation model for St. Peter's in Rome, Rondelet for the dome of the French Pantheon in Paris (E. Ramm [12.1.2]).

The origin of this reverse method is described in [12.1.3]:

> It was Robert Hooke who discovered that the line of an arch, for supporting any weight assigned, should be the inversion of the shape of a catenary, or hanging chain, which is bearing that weight. He apparently announced that he had made the discovery to the Royal Society of London around 1671, but he did not provide any details until 1675, and then the details were encrypted. In an appendix to his *Description of Helioscopes*, he stated that he had found "a true mathematical and mechanical form of all manner of Arches for Building," and the solution was:
>
> "abcccddeeeeeefggiiiiiiiiillmmmmnnnnnooprrsssttttttuuuuuuuuux."
>
> Unlike Hooke's law of the spring, which he announced with a similar anagram, Hooke did not provide a translation in his lifetime, but it was provided by his executor in 1705: "Ut pendet continuum flexile, sic stabit contiguum rigidum inversum--As hangs a flexible cable, so inverted, stand the touching pieces of an arch."

<u>Contributions for a definition</u>

In his application for a new IASS working group Ture Wester wrote in 1991 ([12.1.4]):

> Form-finding is rooted in the search for optimum use of materials and/or energy. It is also inspired by ideologies influenced by one or more of the following fields of study: biology, ecology, philosophy, ethnology, crystallography, fractals, geometry, visualization and other areas.

During the SMG seminar in Nottingham the discussion is again opened (Huybers [12.1.5]):

> S. Medwadowski started during the opening of this conference in Nottingham again a discussion on the meaning of Structural Morphology. T. Wester emphasizes that this discussion has been vivid since the conference in Montpellier, five years ago. We generally mean by this: The study of the interaction between form and structure. However, everybody has his personal vision.
>
> M. Burt comments: 30 years ago, in 1967, he had organized at Technion University a course on "Structural Morphology". 6 years later, H. Crapo of Toronto University started the journal "Structural Topology". The term "Structural Morphology" is more appropriate to our working area. It means: Morphology of Structures. It has not just a physical meaning, but 'structural' has a wider concept: a set of entities with certain relations between them. Any structure has a geometrical representation.

It is a matter of fact that form and structure are two closely related concepts and their history displays inverse evolution (Motro [12.1.6] pages 15-32). But 'structural' implies also the concept of a design process ending in the construction itself, and is consequently an 'active' denomination, and not only descriptive one.

The link between Structural Morphology and Structural Optimization is evoked by Ramm and Bletzinger ([12.1.7]), arguing:

> In a confined sense structure means here construction, i.e. the load carrying element. This in turn means that both areas (structural morphology and structural optimization) deal with the same subject and supplement each other. Structural Morphology as the discipline of forms in general; structural optimization describes the genesis of optimal forms.

and concluding:

Structural morphology and structural optimization are the two sides of the same medal.

Ramm and Bletzinger introduce three terms in the Design Model: sizing, shape and topology. At this point topology is not prescribed and can be modified during the process providing a new dimension to the form finding process.

It can be said very simply that in the triad “Firmitas, Utilitas, Venustas”, (Vitruve [12.1.8]) is the link between “Firmitas” and “Venustas”.

12.1.2.The roots

Concrete shells

The first two chapters of this “jubilee book” demonstrate the importance of shell forms. In the first chapter D.P. Billington underlined the work achieved by Eduardo Torroja, “who had become the major organizing force for the two great mid-century innovations in structural concrete: thin shells and prestressing”. Eduardo Torroja, Nicolas Esquillan, Anton Tedesko, Pier Luigi Nervi, Felix Candela, Mircea Mihailescu and Heinz Isler are the main shell designers. Most of the significant concrete shells of the 20^{th} century were built prior 1968. Shape finding was a key point of shell design; analytical shapes, experimental models (including reverse hanging method), and then numerical models were all investigated. Heinz Isler ([12.1.9]) submitted a classification of morphology of shells keeping the analytical and the experimental models (and including in this part several possibilities such as “Spanning, Stamp, Pneumatic flow, Hanging Reversed, Hanging Positive, Combined”). If Heinz Isler did not pay attention to numerical models that came afterward, he introduced another class “other methods” opening the way to forthcoming models, but also Nature Inspired shapes which constitute a rich domain for designers. An interesting approach of the shape finding has been published by Ekkehard Ramm ([12.1.2]), giving information about the different goals in these approaches, and putting the accent on optimization procedures.

Spatial structures

After the era of shells, new trends appeared around the sixties: space structures and tension structures. They are both included now in so-called “Spatial Structures” naming; it is not the place in this section to provide a precise definition and to understand the difference between “Spatial” and “Space” structures. The later was popularized by Z.S. Makowski since 1966 and the first International Conference held in Guildford (UK) and the four following ones. The change of name, introducing the word “Spatial” is evoked in chapter 3 of this book by Ekkehard Ramm.

As far as structural morphology is concerned, it is more interesting to pay attention to morphology and structural behavior. For all cases, shells, space structures, tension structures, designers try to end with pure tension and/or compression solicitation. The “membrane behavior” of shells refer to pure compression, and results sometimes from a reverse-hanging design method. Members of space structures are either in compression or in tension. Tension structures, like cable nets and textile membranes, are pre-stressed so as to be under tension whatever can be the applied loads.

Space Structures

In the early times of space structures, designers based their projects on polyhedral geometries, trying to keep as low as possible the number of different member’s lengths; double layer grids, barrel vaults, geodesic domes were largely developed taking simultaneously advantage of new numerical methods like the displacement method, and of the increasing power of computers. Simultaneously new configuration processes, like “Formex algebra” were developed so as to simplify the generation of morphologic data (Nooshin [12.1.10]).

Tension Structures

Only three years after its founding by Torroja, the IASS organized, in Paris a symposium devoted to tension structures ([12.1.11]); this symposium was organized by Nicolas Esquillan, who achieved the well known concrete shell of CNIT five years before. It is worthy to notice that the first lecture that appears in the proceedings was given by Frei Otto opening the way to new tension structures, and quoting at the very beginning of his talk the work achieved by another French engineer Bernard Laffaille who was a pioneer of tension structures. These structures are mainly characterized by a tension state ensured by prestressing. Simultaneously a very crucial topic appeared in term of structural morphology, since the so-called form finding processes where developed to meet the coupled constraints linking forms and forces. As usual designers began to develop physical models; soap films, which are least area and energy surfaces, constituted the first bases of form finding. Numerical methods, like force density method, and dynamic relaxation allowed increasing the range of equilibrated surfaces. It was then possible to use finite element methods in order to model their mechanical behavior under the combined effect of prestressing and external loads, taking also into account the non linear effects.

<u>Morgantown “The development of Form”</u>

The 1978 IASS symposium was devoted to Form, and, even if the related proceedings were never published, it was a very important event in the history of the Association. A special issue of the bulletin was edited and in its introduction, Stefan J. Medwadowski expressed clearly the importance of form with respect to structural analysis:

> Such considerations led to a proposal that an IASS Symposium should be held devoted to as general as possible a study of the development of form of shells and spatial structures. It was hoped that such Symposium might be helpful for designers in improving the quality of design, just as a symposium devoted to the study of numerical methods, say, might aid in the development of techniques of analysis. It was realized, of courses that the design process differs qualitatively from the process of analysis- it involves making choices based in part not only on the rational parts of the task, but also on the unquantifiable emotional response of the individual designer (Medwadowski [12.1.12] 3-4).

Many important topics were the object of six technical sessions chaired by famous leaders: shells and spatial structures in the environment (A. Paduart), shell structures (F. Levi), tension Structures (P. Rice), spatial structures (M. Kawaguchi), unusual structural forms (J. Schlaich), the individual as form giver (S.J. Medwadowski). Needless to enumerate all the speakers, some of them were the main actors of the study of form during the last three decades; many of them have significantly contributed to the association’s goals.

12.1.3.The Structural Morphology Working Group

Thirteen years after the Morgantown Symposium, the Executive Council of the IASS decided to create a new working group, which was not devoted to specific kinds of shell and spatial structures, nor to analysis, but to a field where designers, and namely architects involved since the beginning in the association, could develop a wide range of researches and proposals tightly related to morphology.

<u>The „Gang of four“</u>

The decision of the IASS Executive Council

Following the application for a new working group devoted to Structural Morphology, sent by Ture Wester just before the 1991 IASS Symposium in Copenhagen, Stefan J. Medwadowski wrote (Motro [12.1.4]):

It is a great pleasure for me to confirm that, at its meeting in Copenhagen held on September, 1, 1991, the Executive Council of the IASS approved the formation of a new Working Group N° 15, Structural Morphology, with yourself as Chairman.

The application was motivated by Ture Wester in the following terms:

> The activities of IASS include the determination of the form of spatial structures. This area has been one of the most stimulating for us, whether through individual contributions to various symposia or as the central theme of the 1978 IASS Conference. A number of members of IASS are engaged in research in this area and a special session is planned for the Copenhagen symposium in 1991.

Photo: Ture Wester
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Ture Wester
1941-2008
Born in Randers, Ture Wester was graduated in 1963 , at the Danish Engineering Academy, Dept. for Building Structures. After some years in consulting offices, he joined the Royal Danish Academy of Fine Arts, School of Architecture (1966), where he taught basic structural behavior, morphology and patterns in Nature. He developed pioneers researches on the "plate-lattice dualism", was head of the "Plate" laboratory in Copenhagen. He worked on more than twenty structural projects, and was the author of 3 books, 7 scientific reports, 9 chapters in books, 10 compendia, 55 technical papers. Several universities received him for research and teaching purposes, and namely in Japan.

Joining IASS in 1988, he organized the symposium in Copenhagen in 1991, and chaired the Structural Morphology Working Group until 2004. He was member of the executive council, of the Advisory Board and participated to several committees of the association.

He received posthumously the Torroja medal in 2009, during the Valencia Symposium.

Some of his most notable projects and innovations are described in this chapter as well as in Chapters [additional chapter numbers to be inserted by Editors].

It is worthy to notice importance of the IASS 1978 Symposium soon described in a previous paragraph.

The first information meeting was held on September 5, in a local Danish pub called "Kanal Caffeen". During the following week end (September 7-8) the "Gang of four" gathered at Wester's holiday-farmhouse at the small island of Moen in order to discuss strategies, methods and future activities. The Gang of four refers to Ture Wester, Pieter Huybers, Jean François Gabriel and René Motro who established an action group during the IASS 1989 Symposium in Madrid. The specific name Structural Morphology was proposed by Michael Burt. (Motro [12.1.6] pages 2-3)

Figure 12.1.1 “The gang of four in Moen”: in front P.Huybers, T. Wester, J.F. Gabriel, behind R. Motro

International seminars on Structural Morphology – Newsletters-Books

Two main decisions were taken: the working group will organize international seminars, and publish newsletters. The first international seminar was held the following year in Montpellier, France (1992), five others were organized until 2008 (Acapulco). In his chapter “The first 13 Years of Structural Morphology Group”, Ture Wester described these seminars; interested readers can learn more on the fifteen newsletters published by the working group (Motro [12.1.6]). Ture Wester resigned from chairmanship in 2004, because of his health problems, and I took the baton until 2008 organizing the sixtieth seminar in Acapulco, and editing a special Issue of the Journal of the IASS titled “Morphogenesis” ([12.1.13])

Many members of the working group made a specific effort to spread the knowledge in the field. (Michael Burt [12.1.14], Tony Robbin [12.1.15], Jean François Gabriel [12.1.16], René Motro [12.1.17], Hugo Verheyen [12.1.18], Ariel Hanaor [12.1.19], John Chilton [12.1.20], Haresh Lalvani [12.1.21]).

12.1.4. A new era for the Structural Morphology Working Group

The international seminar in Acapulco provided the opportunity to define characteristics of some of the forthcoming researches. It is useful to quote some sentences of the preface written for the special Issue on Morphogenesis:

> “Morphogenesis” was adopted as unifying concept, and as usual for every concept it is very difficult to define it; perhaps we can agree with Rivka Oxman when she writes “Morphogenesis…is a set of morphogenetic processes that are related to the phenomenon of form emergence”. “Emergence” is of course a key word. Six topics were chosen according to our willingness to work on this concept: nature, cognitive aspects, design methods and strategies, design tools (software for morphogenesis), design tools (software environments for computational morphogenesis), new materials and new structural systems.

… The development of contemporary free form architecture requires appropriate morphogenetic tools: "Pascalian forms …" proposed by M. Bagneris et al., is one of them.

Andrew Borgart became the new chairman in Acapulco, and it is not surprising to have in this special issue a description of the "New challenges for the Structural Morphology Group" describing the possible research fields. Always on the theme of a continuous process of conceptual design between past and present, K. Bollinger et al. describe in their contribution some historic Truss Structures, before developing actual conceptual design in "Truss Structures-from Typology to Adaptation". Rivka Oxman undertakes a more theoretical approach of the form emergence in her "Morphogenesis in the Theory and Methodology of Digital Tectonics", taking into account the actual contribution of digital methods. But whatever can be the forms and their associate morphogenetic tools, the conceptual design is governed by the skills of human people, and it is worth to ask "Who is the designer?", a double question if we think on the one hand of its identification for a given architecture, and on the other hand of the mental processes specific to design activities. E. Stach establishes a parallel between "Structural Morphology and Self-Organization", taking advantage of natural forms that are structurally efficient. Closing this special issue, J. Stratil offers some examples of the forthcoming design processes in this era characterized by an increasing amount of information. Her paper puts the accent on "Digital Master Builders (and) Evolutionary form-finding in the Information Age".

We are effectively in the "information age".

Taking advantage of the on-going progress of numerical tools, designers began since more than fifteen years to built projects that are characterized by free morphologies. Blob architecture, free forms are now actual issues. Since 1995 a new subgroup was integrated under the denomination "Free Form Design" under the impulsion of Andrew Borgart and Manfred Grohmann. This subgroup was merged in the original working group two years after.

Becoming chairman of the Structural Morphology Group in Acapulco (2008), Andrew Borgart and his co chairmen Bernard Maurin and Jeroen Coenders have defined several research foci, and five study groups (see [12.1.22]):

- Transformable Structures:
- Adaptive Formworks
- Computation and Geometry
- Origami
- Curved Surface Structures

This new team organizes its first International Seminar, just before the 2011 IASS symposium in London. Imagination being one of the necessary skills of the actors for Structural Morphology, there is no doubt that new developments will appear there.

12.1.5. Conclusion

Structural morphology is very helpful during the process between the idea for designing a spatial structure, and its realization. Designers have to be aware of the successive stages of this process beginning with conceptual design aspects. Numerical tools devoted to mechanical analysis are available and the designer can focus on the other stages. But it is absolutely necessary to avoid the confusion between the conceptual design tools and their objectives. Movies tools, or car industry tools, are not adapted to architecture and civil engineering, and sometimes wrong tools, or misused tools can lead to an useless complexity: the dreams of designers become the nightmares of engineers an builders. The performance is appreciated by the simplicity of the result of the design process, not in its complexity: master builders made this evidence since many centuries.

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