Form Matters

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ABSTRACT
Master builders throughout history have made significant strides in exploiting forms to enclose three-dimensional spaces, to provide shelter and protection or to bridge voids, such as water and roadways. In the absence of numerical prediction methods, they resorted to trial and error construction practices or structural theory to establish a good enough structural form. Today, we experience a renaissance of free forms as an architectural expression. Yet, structural performance as the main design driver is often excluded from the initial design process. The scholarship at the Form Finding Lab (Princeton University, USA) can be placed in a force-modelled tradition by pioneering novel numerical structural form generation approaches and unique structural performative forms. Three studies are presented that showcase the development of such techniques, which when craftfully manipulated, result in surprising shapes for structurally efficient footbridges, roofs and barriers.

Master builders throughout history have made significant strides in exploiting forms to enclose three-dimensional spaces, to provide shelter and protection (e.g. the Pantheon dome in Rome, Italy, 126 CE), or to bridge two-dimensional voids (e.g. the footbridges by Robert Maillart in Toss, Switzerland, 1932). In absence of numerical prediction methods, they resorted to trial and error construction practices or structural theory to establish a good enough structural form (see Figure 2, p. 79). Today, structural engineers are often excluded from the initial building or bridge design process and are introduced into the picture only once the form has been fixed. Pier Luigi Nervi, structural engineer and designer of the exquisite Little Sports Palace (Rome, Italy, 1958), stated:

> *Resistance due to form, although the most efficient and the most common type of resistance to be found in nature, has not yet built in our minds those subconscious intuitions which are the basis for our structural schemes and realizations (1955: 96).*

The objective of this paper is to categorize different structural curved forms in modern and contemporary architecture, and to place the scholarship of our Form Finding Lab (at Department of Civil and Environmental Engineering, Princeton University, USA) in the force-modelled form tradition by showcasing novel numerical form finding approaches and unique structural forms.

1. CONTEXT AND RELEVANCE

When evaluating curved forms in modern and contemporary architecture at our Lab, we distinguish three distinct categories: sculptural, geometric and force-modelled forms.

1.1 Sculptural forms

With the available geometrical digital modeling tools, some architects develop forms based on esthetic considerations with the sole aim of achieve scenographic effects. This design approach raises questions from a structural point of view with respect to the resulting lack of structural efficiency. The design development of such a sculptural shape needs a team of architects, engineers and contractors to find the right synergy between esthetics, context, structural performance and constructability. The shell of the Nuovo Polo Fiera Milano (Milan, Italy, 2012) developed by the architect Massimiliano Fuksas (1944) in collaboration with the engineering consultancy Schlaich Bergermann and Partner and the contractor Mero & Co. illustrates this design approach.

1.2 Geometric forms

Geometry is a tool that has been used since antiquity for the development of architectural shapes. These forms are thus limited by the rules imposed by analytical geometry and the designer's imagination. Through the centuries smart architecture has developed around 'simple' geometries chosen for their constructive or structural qualities. Examples can be found in the thin reinforced concrete hyperbolic paraboloid shells by Félix Candela (1910 – 1997) and the masonry sinusoidal masonry walls and roofs by Eladio Dieste (1917 – 2000).

1.3 Force-modelled forms

Of all traditional structural design elements (ranging from material choice, profile sections, node type, global geometry and support conditions), the global shape mostly decides whether a curved form will be stable, safe and stiff enough to span a space or void without intermediate supports. This is the most important challenge for a designer of a curved surface when aiming for economic, environmental and structural efficiency. By pioneering novel numerical form finding approaches and unique structural forms, the scholarship of the Form Finding Lab at Princeton University (USA) is placed in this force-modelled form tradition.

The origin of this tradition lies within the works of Robert Hooke, the 17th century English natural philosopher, architect and polymath. In 1675, Hooke resolved the riddle posed in the Royal Society as to what the ideal shape of an arch is. "As hangs the flexible line, so but inverted will stand the rigid arch" (Hooke, 1676).

In the 20th century both architects and engineers – Antonio Gaudí (1852-1926), Sergio Musmeci (1926-1981), Heinz Isler (1926-2009) and Frei Otto (1925-2015) – have experimented with physical form-finding techniques based on Hooke-inspired hanging chain models to arrive at force-modelled shapes. For an extensive review of the history of physical form finding techniques and pioneers, we refer the reader to Adriaenssens, Block, Veenendaal, & Williams, 2014.

In collaboration with the School of Architecture at Rome Tre University, we studied the research and projects of the lesser known Sergio Musmeci (Adriaenssens, Gabriele, Magrone, & Varano, 2016). Once an apprentice to Pier Luigi Nervi (1892-1979) and Riccardo Morandi (1902-1989), Musmeci is noteworthy for his ability to design and construct continuous shells with unprecedented shapes well ahead of his time. In this quote, he captured the essence and benefits of force-modelled forms:

> *"There is no reason why the unknown factors should always be the internal stresses and not, for example, the geometric parameters which define the form itself of the structures, since in this latter case a uniformity of stresses and a much more complete and efficient use of material may be obtained. With this method, it is possible to arrive at a synthesis of new forms rich in expressive strength" (Musmeci, 1980).*

He understood the importance of minimizing area while maximizing structural function in shells as early as the 1960's when he developed the design for the Basento Bridge (Potenza, Italy, 1967). What is most intriguing about Musmeci is his understanding and manipulation of physical, numerical and analytical methods of form finding to achieve his design intent.

2. NOVEL FORM GENERATION TECHNIQUES AND STRUCTURAL SHAPES

Having established what force-modelled shapes are, and how practitioners have embraced both physical and digital form finding techniques, we showcase three other studies carried out at our Lab. The studies are chosen to illustrate the variety of techniques we develop as well as the wide realm of forms and novel structural systems that emerge using these techniques.

2.1. Walkable trussed arch

In this first study, we return to the question 'What is the perfect shape of an arch?' or, more precisely, of a trussed walkable arch. The maximum slope of a trussed arch footbridge that allows pedestrians to cross a void, is set by accessibility slope guidelines and thus needs to be shallow. As a result, the arch is prone to in-plane snap-through buckling. This means that the arch can assume an inverted equilibrium position (see Figure 3 left, p. 79). Since the arch bridge is also lightweight, its natural vibration can coincide with the pedestrian-induced vibration (see Figure 3 right, p. 79), a phenomenon experienced by the visitors to the Millenium Bridge in London (designed by Norman Foster) on the day of its opening in year 2000. When that happens, resonance occurs which can lead to severe structural damage. So what happens when we try to optimize the buckling or dynamic behavior (resonance) of a walkeable trussed bridge by allowing the nodes of the arch's truss top chord to displace? (see Figure 4, p. 79). The resulting truss forms, optimized in 2D (nodes only allowed to move in x, y vertical plane) and 3D (nodes allowed to move in all 3 directions) are given in the Table 1. The resulting truss shapes adhere to the slope guidelines and show a wide variety of forms including non-standard top chord topologies, global bow string topologies, tapered deck profiles and bowtie profiles in plan. When we evaluate these optimized forms for other structural criteria such as maximum axial member load and global deflection, we were surprised to find out that all obtained optimized forms outperform the initial form. When we start optimizing the base form for different boundary conditions, a whole new realm of forms is revealed to us (see Figure 5, p. 81) (Halpern & Adriaenssens, 2014, 2015). This study showed us that even for a simple structural system like a walkable trussed arch, there is a whole wealth of superiorly behaving unexplored forms waiting to be discovered.

2.2. Bending-active elastic forms

What form does an elastic strip take when bent? Jacob Bernoulli addressed this question first in 1694. To describe that shape, we worked out an algorithm that establishes the shape of an elastic rod under axial load and in-plane bending. This algorithm, which was then implemented by Daniel Piker in Kangaroo (Rhino), has allowed for the form generation of elastic rods and active-bending systems including in-plane elastica and a wide exploration of three dimensional grid shell forms. These complex shapes, shown in Figure 6 as an example, cannot be described by using analytical expressions. We are very grateful to Daniel for making that algorithm, which was buried in a research paper available to the digital design community (Adriaenssens & Barnes, 2001; Barnes, Adriaenssens, & Krupka, 2013; Richardson, Adriaenssens, Coelho, & Bouillard, 2013; Tysmans, Adriaenssens, & Wastiels, 2011), and the resulting increased interest in the design of bending active grid shells.

2.3. Pneumatic storm surge barrier

In 2012 we witnessed the destructive force of Hurricane Sandy in New Jersey, USA. This natural phenomena resulted in large economic and social losses, especially at the New Jersey shore. We began envisioning a stowable, air-supported barrier that could be deployed along the coast line to block abrupt water elevation change and inundation (see Figure 1 , p. 76). Pneumatic barriers have been used for smaller dams, but not for large barriers subjected to extreme hurricane loads. A pneumatic barrier is a flexible closed membrane that is pre-stressed by internal air pressure and loaded by external forces. Such a barrier can deform extensively while retaining its functionality. As the magnitude of external loads increases, the flexible barrier changes its shape. As it changes shape, the orientation of loads is altered, which in turn has an effect on the barrier's shape. This interdependence of force and form requires a fluid structure interaction modeling approach. Thus, the analysis and design of such a barrier is not straightforward. We resolved the coupling between force and the flexible form in a novel algorithm (Streeter, Rhode-Barbarigos, & Adriaenssens, 2015) and developed an internal pressure update procedure that accounts for the air tightness of the system. Our results revealed that the constant pressure assumption, commonly employed in scientific literature, should not be employed in an analysis under storm surge loads; it underestimates the membrane tension which might result in catastrophic rupture of the barrier. Very little research has been done on the form finding of rigid or flexible forms subjected to extreme loads resulting from hurricanes, earthquakes or tsunamis. We are very excited to have started working in this societally relevant field.

3. CONCLUSION

The pursuit of better structural urban forms runs as a Leitmotif through our research. Our contributions have been in developing novel numerical form-finding algorithms and design methodologies that enable unique large span bridge, building and barrier forms for a resilient and sustainable built environment. These forms are dictated by the flow of forces. Therefore, the forms can be very thin, cost-effective, and have low carbon footprint while maintaining strength, stability, and be aesthetically pleasing and comfortable for users. In our recent research we started addressing new challenges such as non-structural design drivers and extreme loads leading to the same goal. In doing so, we hope to advance the structural design profession by solving resilience challenges that urban societies face globally. m

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