





STRUCTURAL EMERGENCE

ARCHITECTURAL AND STRUCTURAL DESIGN COLLABORATION AT SOM

KEITH BESSERUD, NEIL KATZ AND ALESSANDRO BEGHINI

At Skidmore, Owings & Merrill (SOM) there is a strong culture of collaboration between architects and engineers, and innovation in computational technologies – the firm fervently embraced the computer over 50 years ago. Here a cross-disciplinary team from SOM, architects **Keith Besserud and Neil Katz** and structural engineer **Alessandro Beghini**, describe their current work on FE algorithms and how this has informed recent projects.

SOM, Convention Center, Tanggu, China, 2009

The final shape of the roof was generated using a genetic algorithm (GA), providing a more efficient structural solution while accommodating specific programmatic requirements.

A unique tradition of multidisciplinary innovation has flourished at Skidmore, Owings & Merrill (SOM) since the firm's inception, perhaps most notably between the architects and structural engineers. The firm's aggressive adoption of computational technologies in the 1960s further reinforced this collaboration, facilitating the creative marriage of novel structural concepts and architectural expression on projects like the John Hancock Center (late 1960s) and the Sears Tower (1973) in Chicago by architect Bruce Graham and structural engineer Fazlur Khan. This spirit of architectural and engineering collaboration feeds the development of conceptual and technical invention to this day at SOM, leading to new structural and architectural paradigms.

Of course, computation continues to play a key role in these speculative collaborations. Compared to the 1960s, we now have the benefit of computers that are much more powerful, analytical algorithms that are much more sophisticated, and visualisation techniques that render the analytical data in ways that make it much more immediately understandable. The net result is that on a given project, with typical time constraints, it is now possible to evaluate many more design proposals and gain much deeper insights into theoretical concepts.

With visual mappings of the flows of the forces and coloured heat maps that depict the distribution of stresses and magnitudes of displacements, architects can immediately develop a powerful intuitive understanding of how the overall shape of a building affects its structural nature.

From a structural engineering perspective, the ability to explore these types of theoretical concepts is due in large measure to the emergence of finite element (FE) algorithms over the past several decades. Although the key FE concepts were originally developed in the 1940s and formalised into algorithms in the 1960s (for the aerospace and nautical industries), it is only more recently that they have become commercialised and more readily useable on architectural engineering projects.¹

Like most firms, SOM frequently uses commercially developed finite element analysis (FEA) software programs to assess structural performance. However, in addition to developing expertise as users of these types of software programs, there is also deep interest in contributing at a more fundamental level to the ongoing evolution and advancements of FE algorithms.

For example, SOM engineers are actively collaborating with Professor Glaucio Paulino and his students at the University of Illinois at Urbana-Champaign, focusing specifically on the definition of FE mesh elements. Traditionally, 2-D FE meshes have been idealised as regular rectangular or triangular elements, delineated as close to identical as possible. However, the researchers at the University of Illinois have found that irregular (instead of regular) 2-D meshes offer interesting potential benefits. By utilising irregular hexagonal² and polygonal elements generated from Voronoi algorithms,³ these meshes can improve the mathematical stability of the optimisation algorithms and eliminate the 'chequerboarding' effect often generated with regular quadrilateral and triangular meshes. In developing this research, the University of Illinois team has created custom meshing algorithms and FE solvers in MathWorks® MATLAB® that have been used experimentally by both the university researchers and SOM engineers on various of the firm's projects as a means of validating the research. Most recently, research into this Voronoi approach to meshing is being extended from 2-D domains into 3-D domains.

In addition to the meshing and solving capabilities of commercial FE programs, the visualisation of data is another valuable capability, especially with regard to reinforcing transdisciplinary collaborations between architects and engineers. With visual mappings of the flows of the forces and coloured heat maps that depict the distribution of stresses and magnitudes of displacements, architects can immediately develop a powerful intuitive understanding of how the overall shape of a building affects its structural nature, even without a solid understanding of the mathematics or algorithms.

This ability to get a clear window into the structural performance of a given design scheme allows designers to speculate more intelligently and more immediately about possible modifications to improve the design. SOM designers and engineers have found that, like the graphic statics analytical methods conceived decades earlier, the visualisation of the structural forces in FEA can often lead designers to possible design solutions which can be directly inferred from the visualisations.

The efficiencies of FE algorithms and power of computers mean that it is possible to evaluate a very large number of designs in a relatively short amount of time. One way of navigating through this potentially vast solution space to find better-performing designs would be to intuitively attempt to determine each iteration after evaluating each round of structural analysis. However, such a process would likely be inefficient if the goal is to identify a set of globally best-performing designs.

Alternatively, automated search algorithms can be used to identify a set of optimal solutions, usually with much greater efficiency. In practice, these optimisation techniques are a valuable means of helping designers to not only identify best-performing designs, but also to develop an understanding of why the best solutions perform so well. Whether the optimal solutions are actually adopted by the design team is usually a matter of additional non-structural criteria, such as programmatic requirements or budgetary constraints, or aesthetic considerations; however, even if the optimal solutions are not adopted explicitly, the knowledge gained in the process is usually still of great value.

Two of the primary search techniques that SOM architects and engineers have been using are based on genetic algorithms (GAs) and gradient-based algorithms (for example, density methods). With both techniques, FE algorithms provide the means of establishing structural performance. Typically, GAs are used for shape-optimisation exercises and use FEA in the fitness function, while gradient-based methods are used for topology-optimisation exercises and use FEA to determine the most efficient distribution patterns for the structural material within a given design domain.

The GA used by SOM was developed in-house. Written as a stand-alone application in Visual Basic .NET (VB.NET), it can be connected to any type of simulation program that has an application programming interface (API) that can interface with VB.NET. The simulation software (for example, FEA, radiation analysis or cost analysis) determines the fitness of each design; the GA determines the parametric values for each design in a given population (taking the fitness of each design in the previous population); and a specially developed additional code automates processes of moving inputs and outputs between the GA, the simulation software and the geometry modeling software.

SOM's custom GA works very well for single-objective design problems, but for multiple-objective explorations the firm is also experimenting with commercial optimisation engines such as Red Cedar Technology's HEEDS® MDO and Esteco's modeFRONTIER®. It is also aligned with academic efforts to explore 'human in the loop' optimisation techniques which allow designers to intervene with the optimisation process during execution, and also with optimisation strategies that incorporate definitions of 'novelty' as a driver of the search process.⁴

SOM, John Hancock Center, Chicago, Illinois, late 1960s

Structural engineer Fazlur Khan (left) and architect Bruce Graham with a design model of the John Hancock Center, featuring the braced-frame structural system that was devised for the project.



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Professor Glaucio Paulino, Cameron Talischi and Chau H Le, Centroidal Voronoi Tessellation (CVT) mesh, University of Illinois at Urbana-Champaign, Urbana, Illinois, 2009 Compared with quadrilateral meshes (upper mesh), the CVTs provide greater mathematical stability for finite element (FE) algorithms and lower compliance values in optimisation applications.

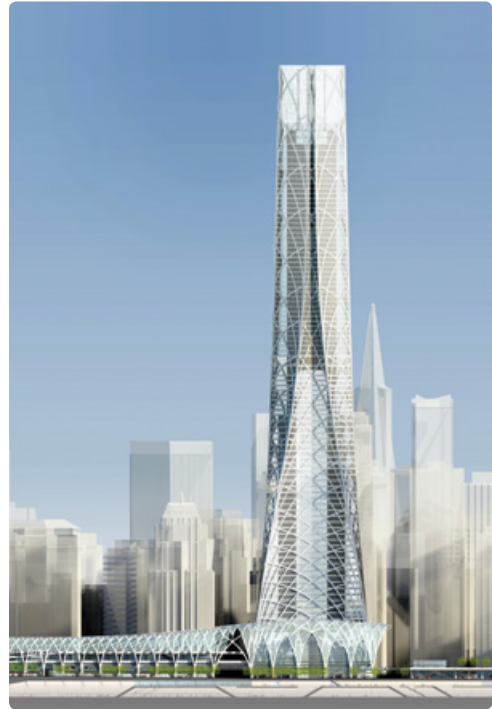


GAs have been used at SOM for shape-optimisation searches for both towers and long-span roof structures, such as that for a large convention centre in Tanggu, China (2009). Here, the designers had defined a series of undulations that correlated to the varying ceiling heights required for the performance spaces and circulation spaces beneath. Although it was generally understood that the undulating form had certain stiffness characteristics that would work well from a structural perspective, the designers were still interested to know what an optimal structural solution would look like, with deviations from the original surface constrained to specific upper and lower limits. The result presented by the GA was a shape that was a recognisable descendant of the original, but exhibited a much more efficient distribution of stresses across its surface.

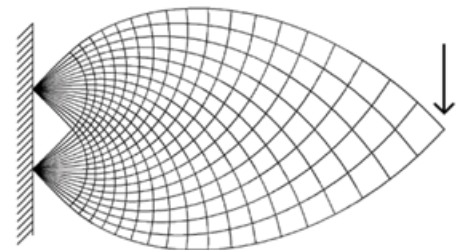
The GA was also used for the Yongsan office tower competition in Seoul, South Korea (2009). In this case, the logic of the building form was parametrically predefined as a set of circular concentric floor-plate profiles whose radii were allowed to fluctuate in the optimisation process according to maximum and minimum thresholds that would allow for marketable lease spans. In other words, the economic criteria were managed as constraints that had upper and lower boundaries, while the structural performance criteria were configured as the fitness function (minimising deflection at the top of the tower). The GA ultimately presented a building form reminiscent of a teardrop with a profile that curved outwards as it went up from the ground, and then retreated inwards, tapering to a point at the very top.

The teardrop shape came as a surprise to the designers who were intuitively expecting a more conically tapered shape to emerge as the optimal form. The structural engineers, however, recognised the profile as having similarities with the Michell frame concept they had been actively researching. Michell frames are a family of minimum material solutions for a variety of load and support conditions composed of orthogonal fields of lines. In other words, they represent an optimal structural frame solution for a cantilever or, more relevantly, a tall tower.

On subsequent tower projects – the TransBay Transit Center in San Francisco and Shanghai Center in Shanghai (both 2010) – the knowledge developed in the Michell frame research work became even more directly manifested. Here, the architects and structural engineers chose to make a formal expression of the lateral bracing members on the exterior of the buildings by tracking the lines of principal stress, similar to the geometric arrangements exhibited in the Michell frame.



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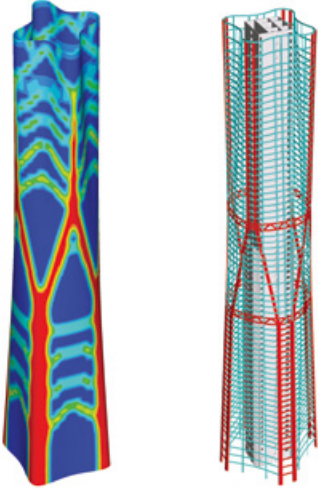
top: SOM, TransBay Transit Center competition, San Francisco, California, 2010
 opposite: SOM, Shanghai Center, Shanghai, China, 2010

For these two tower proposals, the lines of principal stress as revealed in finite element analysis (FEA) models and echoed in Michell frame diagrams were expressed architecturally on the exteriors of the buildings.

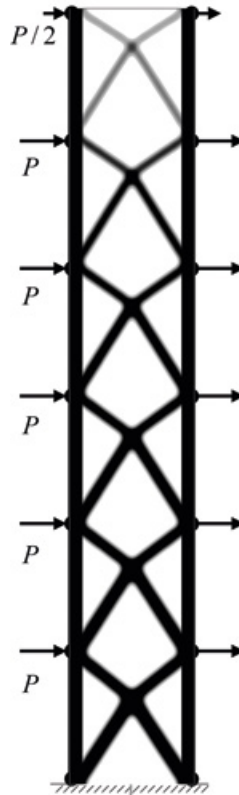
Michell frame

The Michell frame represents an optimal topology for a cantilever structure.

SOM, Yongsan office tower competition, Seoul, Korea, 2009
 The structurally efficient teardrop shape for the building was revealed through the use of a genetic algorithm.



SOM, White Magnolia office tower, Shanghai, China, 2010
 A gradient-based optimisation algorithm was used to identify the most efficient arrangement for a structural system for a pre-established complex building shape.



above left: Lauren L Stromberg, Analysis of cantilever cross-bracing, University of Illinois at Urbana-Champaign, Urbana, Illinois, 2012
above right: SOM, Office building, Sydney, Australia, 2012
 In the diagram on the left, researchers at the University of Illinois, in collaboration with engineers at SOM, demonstrated that the optimal location for the intersection point of a cross-brace was not the midpoint, but instead a position somewhat above the midpoint, again confirming the relevance of the Michell frame. The rendering on the right shows the application of the optimal brace design on an office building.

The lateral bracing schemes for the San Francisco and Shanghai projects are also revealed in topology-optimisation exercises using gradient-based search algorithms. These types of algorithms operate on a design domain that contains a fixed amount of structural material that is initially distributed evenly across the domain, but then iteratively redistributed in order to realise the most efficient use of that material. For two additional projects in Shanghai, topology optimisation revealed very novel proposals for the expression of optimised structural systems; one for the White Magnolia office tower (2010) and another for a commercial development (2011) in which the multi-span bridge element connects three towers. The latter study was conducted in collaboration with Professor Paulino's research group at the University of Illinois.

Finally, to come full circle, the iconic cross-bracing of the John Hancock Center was revisited in a sense for an office building in Sydney, Australia (2010). For this project, a series of diagonal cross-braces are again expressed on the exterior of the building, but the optimal topology for a structural braced frame is one in which the diagonals intersect at locations higher than their midpoints.⁵ The optimal solution for the shear bracing, as revealed in the gradient-based search algorithm, again shared some similarities with the Michell frame solution.

Architects and structural engineers at SOM work together in a long-established spirit of research-driven collaboration that has yielded many important designs in which the architectural and structural concepts evolve in synchronicity. Today, these collaborations are facilitated through the use of computational algorithms that draw the two groups even closer in processes that require them to jointly define performative goals and constraints, to define geometric forms in terms of their parametric relationships, and to speculate about the likely performative qualities of different formal strategies. Algorithmic tools such as FEA programs and GAs are critical to expediting processes of searching vast solution spaces for well-performing designs, and are facilitating the exploration of new, previously inaccessible theoretical paradigms and emergent formal typologies. ▽



SOM, Commercial development project, Shanghai, China, 2011
A gradient-based optimisation algorithm revealed an irregular pattern for an optimal structural system for the bridge component of this project, which was incorporated as part of the architectural tectonics.

Notes

1. Kenneth H Huebner, Donald L Dewhirst, Douglas E Smith and Ted G Byrom, *The Finite Element Method for Engineers*, Wiley-Interscience (Chichester), 4th edn, 2001, p 12.
2. Cameron Talischi, Glaucio H Paulino and Chau H Le, 'Honeycomb Wachspress Finite Elements for Structural Topology Optimization', *Structural and Multidisciplinary Optimization*, Vol 37, No 6, 2009, pp 569–83.
3. Cameron Talischi, Glaucio H Paulino, Anderson Pereira and Ivan FM Menezes, 'Polygonal Finite Elements for Topology Optimization: A Unifying Paradigm', *International Journal for Numerical Methods in Engineering*, Vol 82, No 6, 2010, pp 671–98.
4. Joel Lehman and Kenneth O Stanley, 'Abandoning Objectives: Evolution through the Search for Novelty Alone', *Evolutionary Computation*, Vol 19, No 2, 2011, pp 189–223.
5. Lauren L Stromberg, Alessandro Beghini, William F Baker and Glaucio H Paulino, 'Topology Optimization for Braced Frames: Combining Continuum and Discrete Elements', *Engineering Structures*, Vol 37, 2012, pp 106–24.

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