A New Frontier in Modern Architecture: Optimal Structural Topologies

Alessandro BEGHINI
Associate
Skidmore, Owings & Merrill, LLP
Chicago, IL, USA
alessandro.beghini@som.com

Lauren L. STROMBERG
PhD Candidate
University of Illinois
Urbana, IL, USA
lstromb2@illinois.edu

William F. BAKER
Partner
Skidmore, Owings & Merrill, LLP
Chicago, IL, USA
william.baker@som.com

Glaucio H. PAULINO
Professor
University of Illinois
Urbana, IL, USA
paulino@illinois.edu

Arkadiusz MAZUREK
Structural Engineer
Skidmore, Owings & Merrill, LLP
Chicago, IL, USA
arkadiusz.mazurek@som.com

Summary

Optimal structural topologies set a new frontier in modern architecture and provide a benchmark to evaluate the performance of existing and future structures. Several methodologies for the optimization of structural shapes and systems have been explored by engineers and architects at SOM (Skidmore, Owings & Merrill, LLP) in collaboration with universities and nearby academic institutions. These new technologies have consequently been integrated into the design process.

The optimization is conducted with a combination of commercially available codes and custom written programs that interface with the commercial codes via the API (Advanced Programmer Interface). This paper highlights some of the optimization techniques and their applications to the conceptual design of high-rise projects.

Keywords: *Topology optimization, high-rise buildings, shape optimization, Michell frames, Genetic Algorithms*.

1. Introduction

Inspired by the seminal paper by Michell, structural engineers and architects at Skidmore, Owings & Merrill, LLP (SOM) have been using several tools for the optimization of structural shapes and systems to develop structural/architectural topologies during the conceptual phase of the design process.

The optimization problem is characterized by a given design domain, loadings and boundary conditions. Within the topological space several structures capable of carrying the loads from the points of application to the supports could be outlined. However, given a certain objective function (minimum compliance, minimum tip deflection, target frequency, maximum buckling capacity, etc.), the optimization process leads to the best structural system for the problem considered.

Michell trusses represent a valuable starting point in defining optimal layouts, and several analytical solutions have been derived over the years for relatively simple load conditions (e.g.: cantilevers, simply supported beams, etc.). The work of Michell and later contributors on the continuum theory of optimal frames of least weight have been recently expanded to optimal discrete system of interest in high-rise design as described in [1].

Efficient numerical methods have been developed to derive optimal structural shapes for various problems, such as topology optimization using SIMP or homogenization, Evolutionary Structural Optimization (ESO), Bidirectional ESO, etc. These optimization methods are currently employed extensively, for example, in industrial design and in the automotive and aeronautical industry [2]-[3]. The utilization of advanced topology optimization in the structural/architectural world represents an additional tool in the design process. Structural engineers at SOM have applied some of these structural optimization techniques in the concept design of several long span structures and high-rise buildings. The results provided new, unique topologies and helped the designers characterize the structural/architectural system.

2. Optimal Geometry of Braced Frames

At its inception, the SOM research group was inspired by the work of Australian mathematician A.G.M. Michell and his seminal paper "The Limits of Economy of Material in Frames-structures" (see [4]). Michell trusses represent a theoretical solution for optimal truss member layouts with minimum structural material.

SOM engineers derived the mathematics behind Michell frames and explored the literature for the most recent developments on the analytical theory of optimal frames. Among the major contributions, a custom "Michell frame generator" tool has been developed (see Figure 1), which enables the engineer to calculate and draw the cantilever Michell frame for a variety of parametric conditions, including boundedness of the frame, overall height, grid density, and base angles.

Michell frames are optimal solutions which are derived mathematically in a continuum. However, structural frame systems are, by nature, discrete, being made of columns, beams and braces. Therefore, the optimal solution deviates from the solution in the continuum as described in [1]. The paper describes the graphical rules to construct optimal discrete frames for the three point problem (i.e. frames with two points of support and one point of loading). Such rules are described in Figure 2 below.

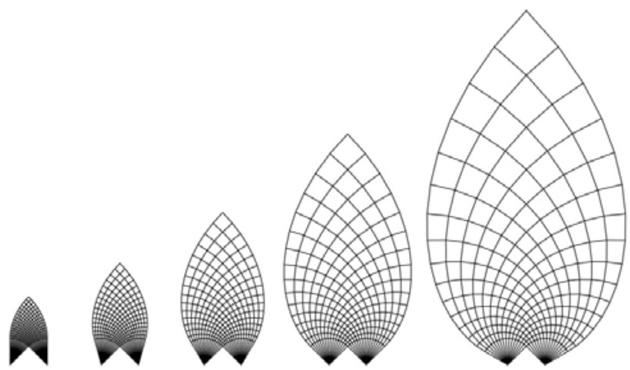

Fig. 1: Michell truss generator

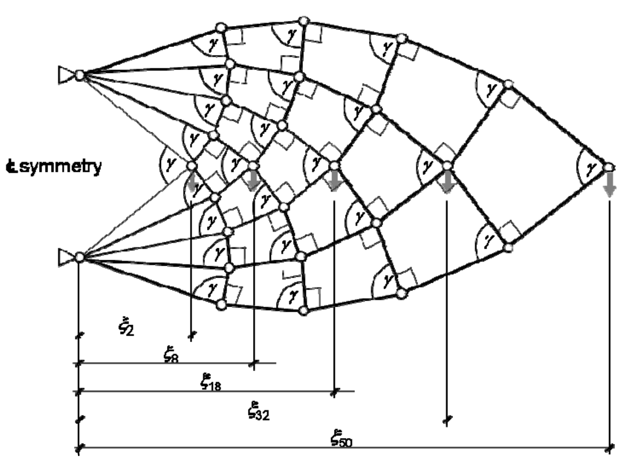

Fig. 2: Optimal discrete Michell frame for a point load (taken from [1])

3. Topology Optimization

Theoretical methods [4] for the layout of optimal members are limited to simple topologies and load conditions. Numerical methods for topology optimization provide a more general framework for optimal solutions. In this approach, the material is iteratively re-distributed in the design space to optimize for the structural target (e.g. maximize structural stiffness or minimize compliance).

Topology optimization has been applied extensively for the conceptual design of structural systems and substructures. Shown here is the result for the optimal steel braced frame layout for a gravity loading in a bridge structure connecting three mid-rise buildings in Shanghai, China. The target of the optimization was to maximize the overall stiffness (minimum compliance) with constraints on the overall volume of material.

Fig. 3: Topology optimization of a building

The topology optimization was carried out with a custom written program developed in collaboration with L.L. Stromberg from the topology optimization group lead by Professor Glaucio H. Paulino at the University of Illinois at Urbana Champaign (UIUC).

In the design of a high-rise building subject to wind loads, the shear behaviour typically dominates at the top of the structure, whereas both shear forces and overturning moments are present in the lower portions as described in [5]. Therefore, the optimal bracing angle is around 45° at the top and closer to a “high-waisted” cross brace near the base. Additionally, under typical loading conditions, the columns at the base of a building are larger in size than at the top. Thus, a study using topology optimization with *pattern gradation*, or the geometric stretching and shrinking of patterns along the height, was performed for the design of the high-rise building shown below [5]. This technique, developed in collaboration between UIUC and SOM, allows for the design to smoothly transition from the bottom to the top of the building.

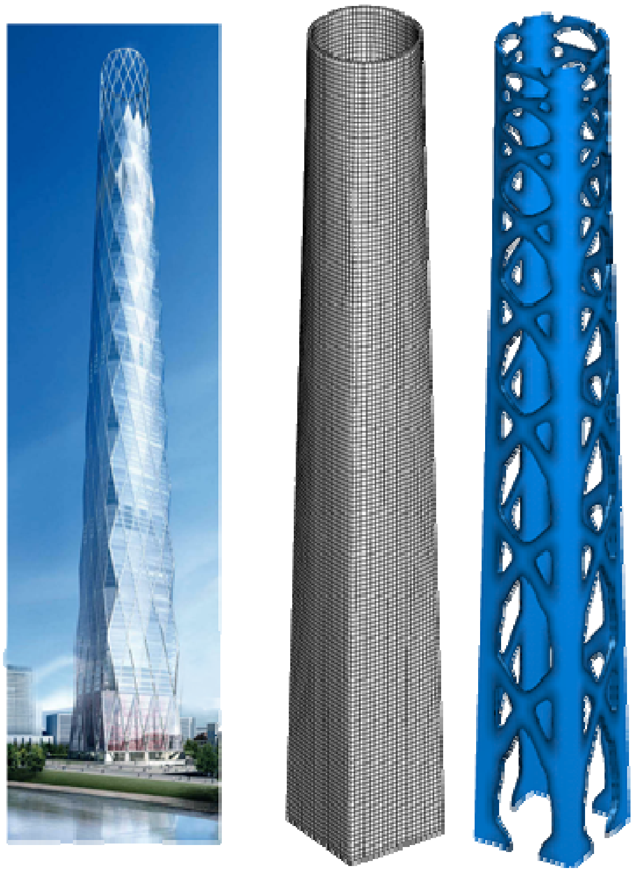

Fig. 4: Topology optimization of a high-rise building (taken from [5])

Other results of the on-going collaboration with UIUC on topology optimization for high-rise buildings are documented in [6].

4. Surface Optimization

The shape of a building can be optimized using topographical surface optimization based on a variety of objective functions, such as minimum compliance, minimum tip deflection, optimal frequencies, etc. The constraints for the problems include structural aesthetics, site geometry, massing, optimal view angles, minimum member size, etc. The optimization is conducted with a combination of commercially available codes and custom written programs.

The software starts from a generic initial (arbitrary) shape which is iteratively modified through the optimization process until the best shape for the objective considered is found. In the example shown in the figure below, the geometry is parametrically controlled by the radii of the floor plates at various elevations. The height of the building, the base diameter and the overall internal volume are constrained to set values, dictated by local code provisions for height limits, site constraints, etc. A uniform wind load is applied on the initial shape and the building surface is iteratively modified to minimize the top displacement (structural objective).

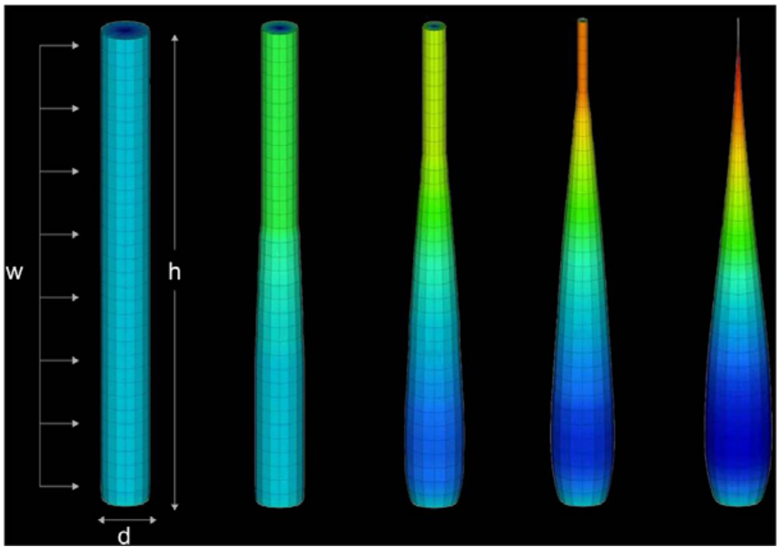

Fig. 5: Surface optimization of a high-rise building

5. Genetic algorithms

Genetic algorithms are searching procedures mimicking the process of natural selection (survival of the fittest) [7]. In structural engineering terms, the best, or 'fittest', solution is the one which satisfies a target structural goal (maximum stiffness, for instance) for a certain volume of material (as a constraint). The analysis is based on a parametric model of the structure where the controlling parameters are grouped together to form a 'genome'. An initial random population of genomes is evaluated for structural 'fitness'. The best performing genomes move to the next generation while the poor performing genomes are replaced by new ones. The new genomes are partly generated randomly and partly by a variety of basic operations on the previous generation of genomes, which includes combining two well performing parent genomes (crossover) and slightly modifying a well performing genome (mutation). The optimum solution is the one which results from the evolutions of several generations of genomes. The process ends when additional iterations bring minor changes to the structural performance.

The computational procedure used in the example shown here is a combination of a genetic algorithm search engine and commercial finite element software. The genetic algorithm code, written in visual basic .NET, has a very flexible architecture, thus allowing interfacing with several types of software to solve a variety of problems. The genetic algorithm communicates with the finite element software via custom-written codes in the Application Programming Interface (API). At each iteration of the analysis, the finite element model is modified according to the parameters determined by the genetic algorithm, and a structural analysis is run. The calculated structural response based on the structural objective is then returned to the genetic algorithm for genome fitness evaluation. Depending upon its performance, a genome may or may not survive at the next generation.

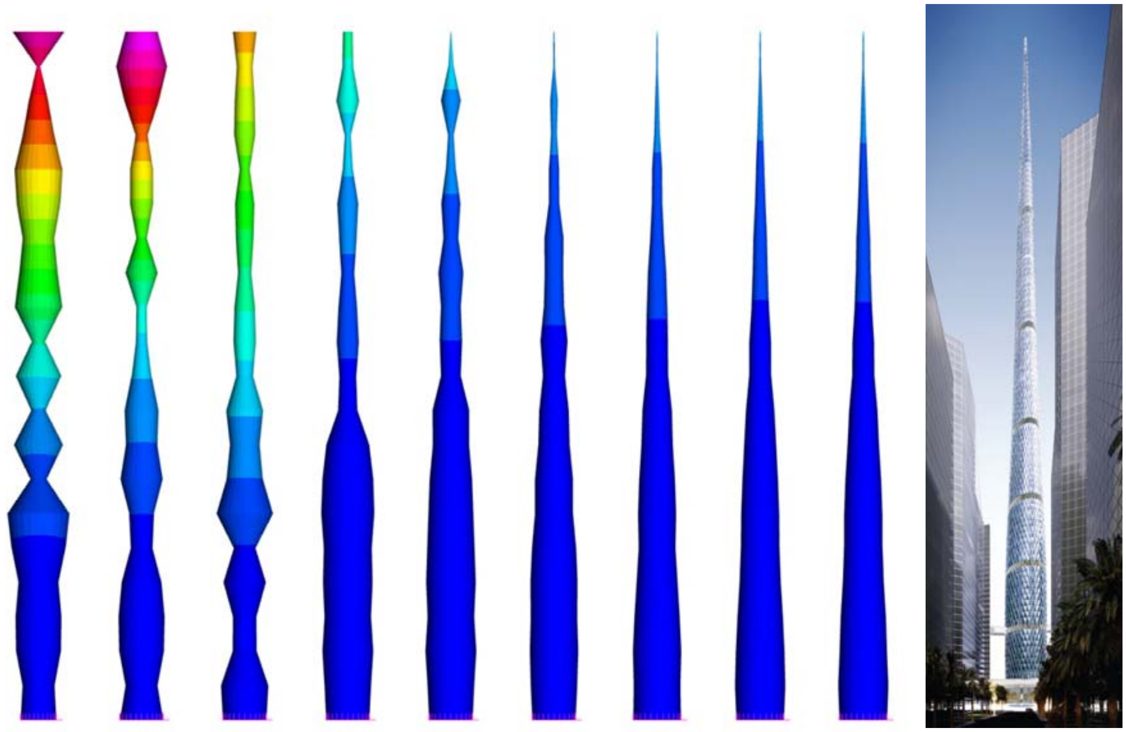

Fig. 6: Surface optimization of a high-rise building using genetic algorithms (left) and architectural rendering of the building (right)

5.1 Conclusions

Several techniques for the optimization of high-rise buildings and long span structures have been described with applications to the conceptual design of a variety of structures.

5.2 References

[1] A. Mazurek, W.F. Baker, C. Tort (2011) "Geometrical aspects of optimum truss like structures." *Structural and Multidisciplenary Optimization,* 43(2): 231-242.

[2] Sigmund, O. (2000). "Topology optimization: a tool for the tailoring of structures and materials" *Philosohpical Transactions of The Royal Society: Mathematical, Physical & Engineering Sciences,* 358(1765): 211-227.

[3] Zhou, M., Fleury, R., Shyy, YK, Thomas, H.L., Brennan, J. (2002) "Progress in topology optimization with manufacturing constraints." *Proceedings of the 9th AIAA MDO Conference*.

[4] Michell, A.G.M. (1904) "The Limits of Economy of Material in Frames-structures" *Philosophical Magazine*, 8(47): 589-595.

[5] Stromberg, L.L.., Beghini, A., Baker, W.F., Paulino, G.H. (2011) "Application of layout and topology optimization using pattern gradation for the conceptual design of buildings." *Structural and Multidisciplinary Optimization*, 43(2): 165-180.

[6] Stromberg, L.L.., Beghini, A., Baker, W.F., Paulino, G.H. (2011) "Topology optimization for braced frames: combining continuum and discrete elements," submitted to *Engineering Structures.*

[7] D.E. Goldberg, (1989), *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison Wesley Longman, Inc, Indiana, U.S.A.