Scripting for a New Architecture: Studies in Structural Optimization

William Baker
Skidmore, Owings & Merrill LLP

Alessandro Beghini
Skidmore, Owings & Merrill LLP

Juan Carrion
Skidmore, Owings & Merrill LLP

Cenk Tort
Skidmore, Owings & Merrill LLP

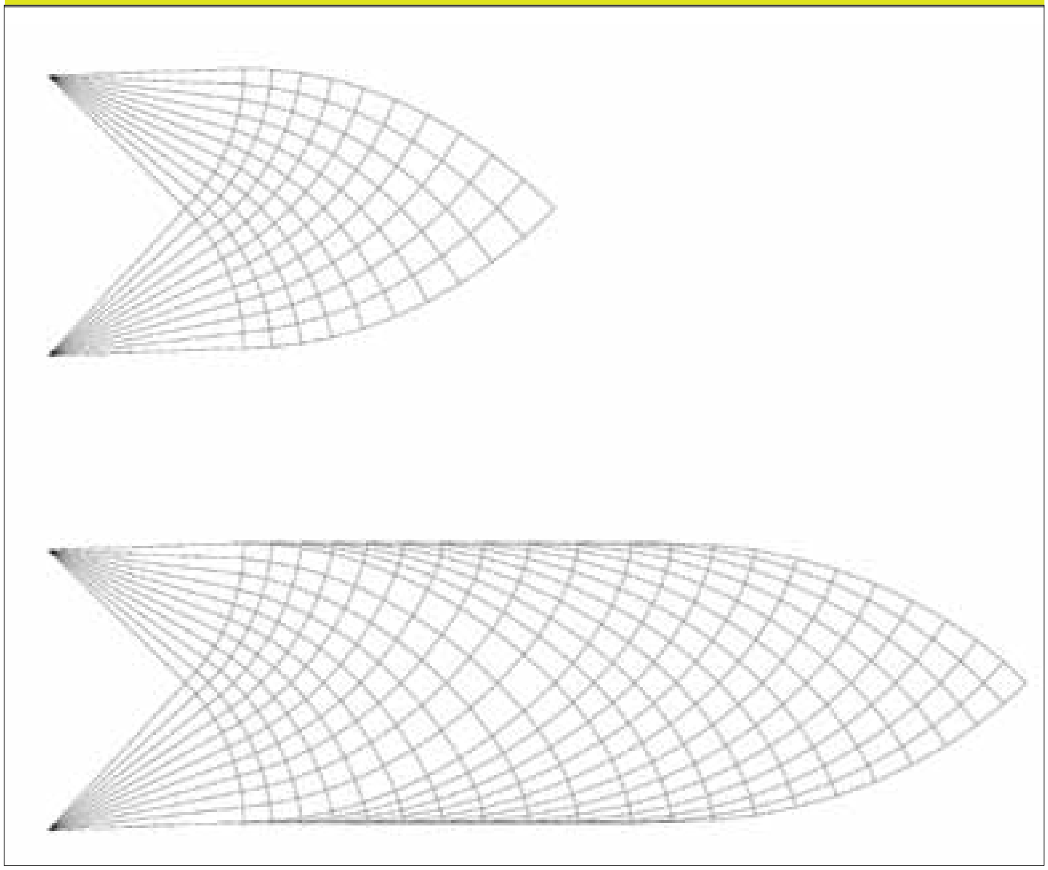

Figure 1 Michell truss layouts based on Graczykowski and Lewinski (2006)

ABSTRACT

This paper describes how scripting has been successfully used by structural engineers at Skidmore, Owings & Merrill, LLP (SOM) to rediscover, apply, and develop several tools for structural optimization. Some of these methods are described in this paper for applications to high-rise buildings and long-span roof structures.

1 INTRODUCTION

Optimal structural topologies represent a new frontier in architecture and set a new standard against which we can compare the performance of existing and future structures. Inspired by the seminal paper by A. G. M. Michell (1904), structural engineers at SOM have been using several tools for optimization of structural shapes and systems for developing efficient structural/architectural topologies. Among these tools are Michell frames, principal stress trajectories, evolutionary structural optimization, genetic algorithms, and force density.

Scripting plays a major role in enabling access to the programming interface of commercial software and the use of several of their built-in functions to code optimization algorithms. Commercial, in-house, and university-developed software that employs various types of optimization techniques (based on gradient methods, genetic algorithms, hybrid procedures) have also all been successfully applied for topology and shape optimization of several potential high-rise projects and long-span structures.

2 MICHELL FRAMES

In 1904, A. G. M. Michell published his seminal paper on frame structures of least weight, where he identified the optimal solution for several structural systems, including a cantilever beam that transfers a tip point load to a circular support. This solution is composed of two sets of logarithmic spirals intersecting at right angles. In a logarithmic spiral, the angle between the tangent and the radius always remains constant.

The continuous circular support of Michell's optimal solution is an aspect that needs to be addressed in a real frame. If we utilize the geometric solutions by Hill (1950) for tracing the slip lines field in perfectly plastic materials (i.e., Hencky Nets), we can find the solution for a truss supported at two points with a script. The next step in the optimal cantilever problem is to introduce a constraint for the width of the frame. Figure 1 illustrates the truss layouts based on the formulation by Graczykowski and Lewinski (2006) for a truss bounded by a rectangular region. The aspect ratio for the solution in figure 1 at the top is similar to the one proposed by Hemp (1973). On the other hand, the solution in figure 1 at the bottom is more slender with an aspect ratio of 3.5.

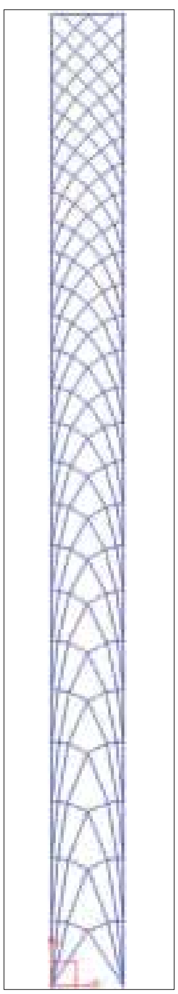

Figure 2 Principal stress trajectories for a tube building

3 PRINCIPAL STRESS TRAJECTORIES

The flow of lateral forces in a high-rise building can be studied analytically using basic principles of mechanics like the concept of principal stress trajectories. The equations governing the problem are solved numerically in a CAD script, and then the lines of force are traced. Assumptions concerning the load distribution and the plan geometry of the building have to be simplified. Typically, for a first concept design, a uniform load is considered and the cross section is assimilated to a tube or an 'I' shape. The results of the analysis for the case of a tube and uniform lateral load are shown in figure 2 on the left. Notice that when the wind is blowing in a certain direction, the longitudinal walls of the tube are working as a web, while the transverse walls are working as flanges.

Since the design has to cover the entire range of possible wind directions, the actual optimal stress trajectories are a combination of the flange solution and the web solution.

Principal stress trajectories have been used to inform the layout of the outer diagonal bracing system in several conceptual designs for high-rise buildings (fig. 2)

4 SHAPE OPTIMIZATION

Shape optimization was recently employed to determine the most efficient form of a large roof structure for a design competition. The roof was approximately 216 m in length by 90 m in width, and it was constrained to have enough clear height at specific locations to fit the interior structure. The roof curvature was optimized for self-weight as well as for imposed loads using several software components linked via their respective Application Programming Interfaces (API's):

- Optimization algorithm: HEEDS (Hierarchical Evolutionary Engineering Design System) from Red Cedar Technology (www.redcedartech.com)
- Parametric Geometry Modeling: Digital Project (www.gehrytechnologies.com)
- Structural Analysis Strand7 (www.strand7.com)

At each iteration of the optimization process, the optimization engine (HEEDS) sends updated values of the design variables to the geometry modeling software (Digital Project). This software modifies the model accordingly and creates an IGES file with the new geometry. This file with the updated geometry is imported into the finite element software (Strand7). A finite element mesh is created, and loads and boundary conditions are applied to the model. The structural analysis solver is run, and the required response quantity (i.e., the objective of the optimization, which is compliance for this case) is then calculated and sent to the optimization engine to complete the iteration. This optimization framework presents a rather flexible architecture, applicable to a large number of problems. The results from the shape optimization process are presented in figure 3. As the optimization process advances, the shape of the structure changes and produces smaller values of the deflection, maximizing its overall stiffness. The optimized structure is both structurally efficient and aesthetically pleasant

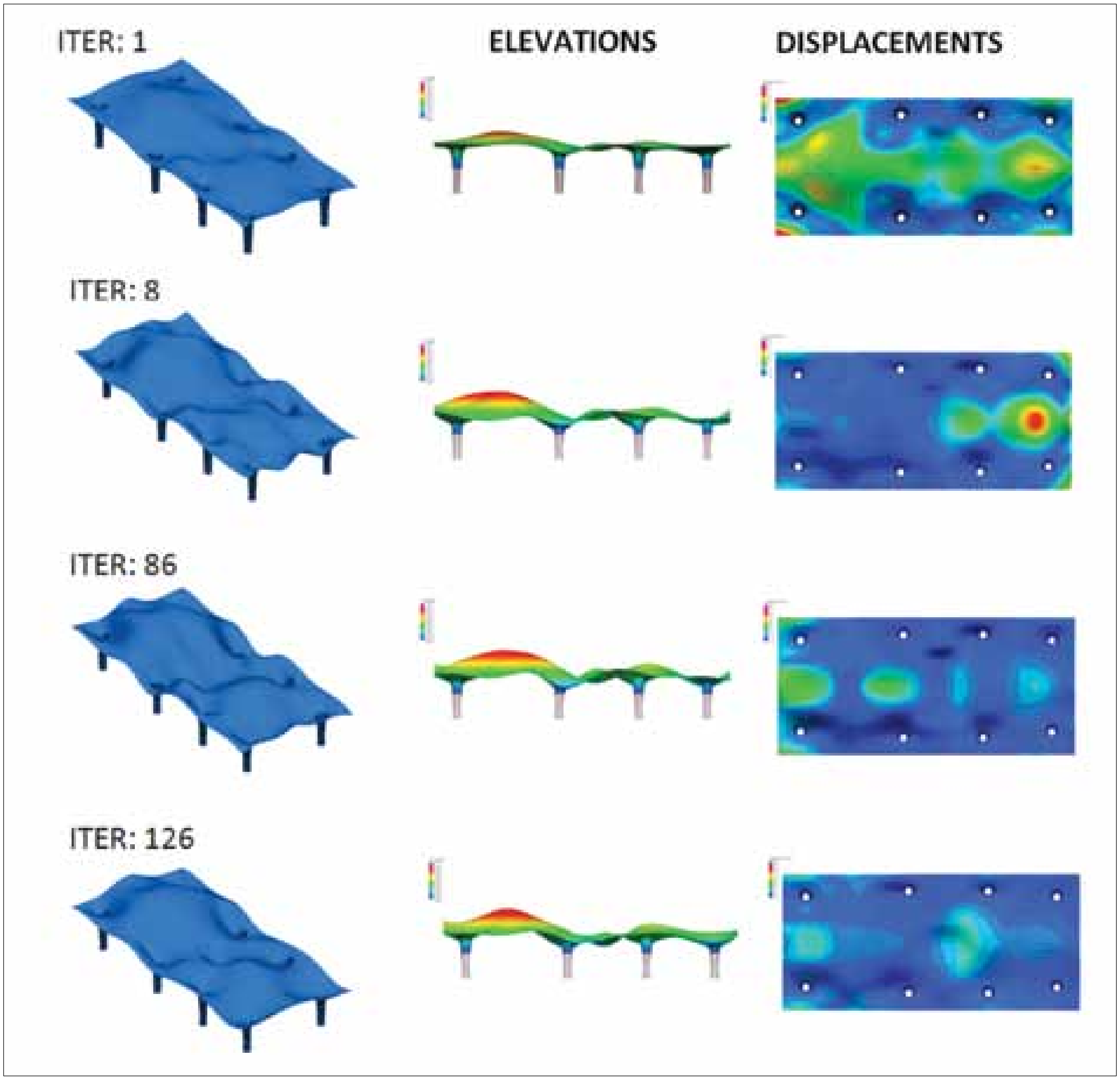

Figure 3 Shape optimization results

CONCLUSION

Several optimization methodologies and scripting tools are available to architects and engineers. The interdisciplinary collaboration between them leads to new forms and geometries that are at the same time structurally efficient, aesthetically appealing, and very functional.

REFERENCES

MICHELL A. G. M, (1904). THE LIMITS OF ECONOMY OF MATERIAL IN FRAME-STRUCTURES. IN PHIL. MAG., SERIES 6, VOL. 8.

HEMP, W. S. (1973). OPTIMUM STRUCTURES. CLARENDON PRESS, OXFORD.

GRACZYKOWSKI, C., AND T. LEWINSKI (2006). "MICHELL CANTILEVERS CONSTRUCTED WITHIN TRAPEZOIDAL DOMAINS-PART I: GEOMETRY OF HENCKY NETS." IN STRUC. MULTIDISC OPTIM, VOL. 32, P. 347–368.

HILL, R. (1950). THE MATHEMATICAL THEORY OF PLASTICITY. CLARENDON PRESS, OXFORD.