Title:	**Case Study: O-14 Folded Exoskeleton**
Authors:	Jesse Reiser, Partner, Reiser + Umemoto RUR Architecture Nanako Umemoto, Partner, Reiser + Umemoto RUR Architecture Jaime Ocampo, Senior Vice President, Ysrael A Seinuk PC
Subjects:	Architectural/Design Building Case Study Structural Engineering
Keywords:	Construction Environment Structure
Publication Date:	2010
Original Publication:	CTBUH Journal, 2010 Issue III
Paper Type:	1. Book chapter/Part chapter 2. **Journal paper** 3. Conference proceeding 4. Unpublished conference paper 5. Magazine article 6. Unpublished

Case Study: O-14 Folded Exoskeleton

Jesse Reiser

Nanako Umemoto

Jaime Ocampo

Authors

Jesse Reiser, Partner
Nanako Umemoto, Partner

Reiser + Umemoto RUR Architecture, PC
118 East 59th Street, #402. New York, NY, 10022

t: +1 212 421 8880 f: +1 212 421 8881
www.reiser-umemoto.com

Jaime Ocampo, Senior Vice President

Ysrael A. Seinuk, PC
228 East 45th Street, 2nd Floor. New York, NY 10017

t: +1 212 687 2233 f: +1 646 487 5555
www.yaseinuk.com

Jesse Reiser
Jesse Reiser received his Bachelor of Architecture degree from the Cooper Union in New York and completed his Masters of Architecture at the Cranbrook Academy of Art. He was a fellow of the American Academy in Rome in 1985 and he worked for the offices of John Hejduk and Aldo Rossi prior to forming Reiser + Umemoto with partner, Nanako Umemoto. Jesse is an Associate Professor of Architecture at Princeton University and has previously taught at various schools in the US and Asia, including Columbia University, Yale University, Ohio State University and Hong Kong University.

Nanako Umemoto
Nanako Umemoto received her Bachelor of Architecture from Cooper Union in New York in 1983, following studies at the School of Urban Design and Landscape Architecture at the Osaka University of Art, and formed Reiser + Umemoto with partner, Jesse Reiser in 1986. Nanako currently teaches at the University of Pennsylvania, and has previously taught at various schools in the US and Asia, including Harvard University, Columbia University, Hong Kong University, Kyoto University, Pratt Institute, and the Cooper Union.

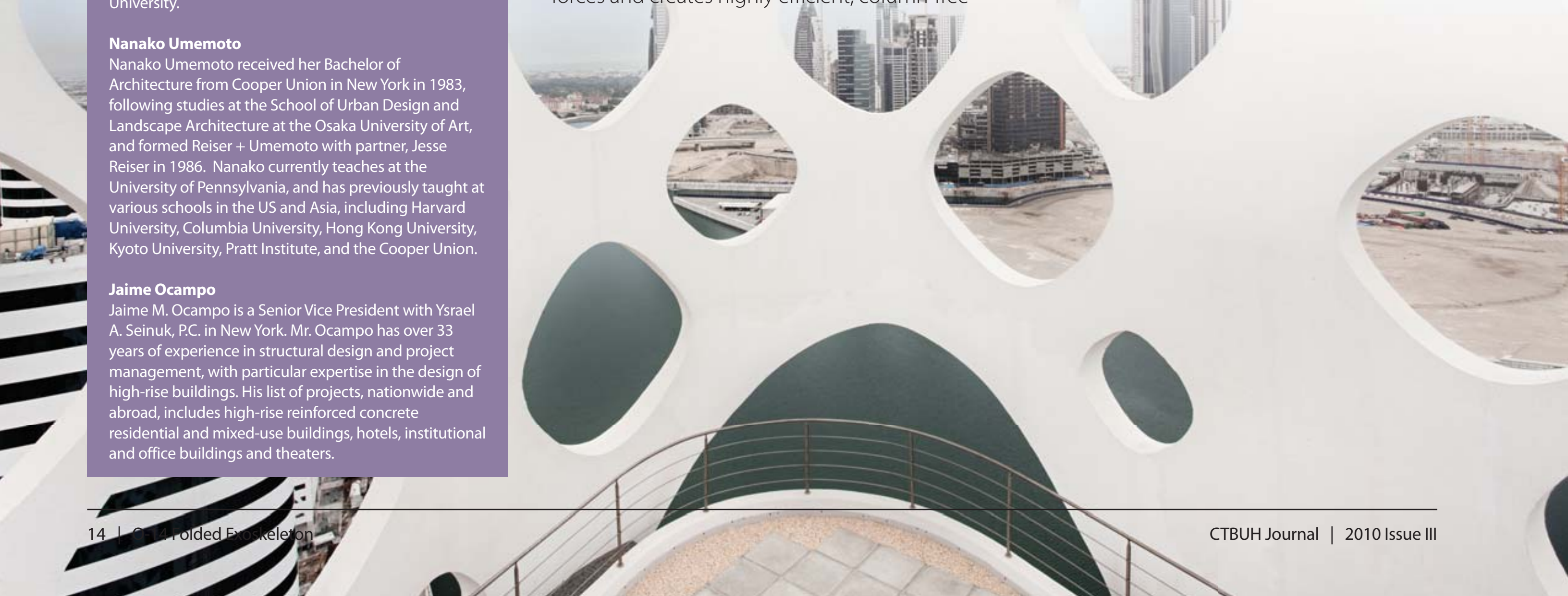
Jaime Ocampo
Jaime M. Ocampo is a Senior Vice President with Ysrael A. Seinuk, P.C. in New York. Mr. Ocampo has over 33 years of experience in structural design and project management, with particular expertise in the design of high-rise buildings. His list of projects, nationwide and abroad, includes high-rise reinforced concrete residential and mixed-use buildings, hotels, institutional and office buildings and theaters.

"With O-14, the office tower typology has been turned inside out – structure and skin have flipped to offer a new economy of tectonics and of space. The concrete shell of O-14 provides an efficient structural exoskeleton that frees the core from the burden of lateral forces and creates highly efficient, column-free open spaces in the building's interior."

O-14 is a 22-story commercial tower characterized by 1,326 openings, randomly located and varying in size, throughout the whole exterior shell. The tower contains over 27,900 square meters (300,000 square feet) of office space and is located along the extension of Dubai Creek in the Business Bay area of Dubai, occupying a prominent location on the waterfront esplanade. O-14, named after its lot designation, broke ground in February 2007, and in May 2009, the tower's concrete structure was completed and the building topped out. It is one of the first towers to appear in the skyline of Business Bay, scheduled to be fully finished and occupied by the fall of 2010. The project has generated extraordinary international interest in the architectural press, as it is among the very first innovative designs to be constructed among a sea of generic office towers, which have come to be the standard in Dubai's current building boom.

Architectural Overview

With O-14, the office tower typology has been turned inside out – structure and skin have flipped to offer a new economy of tectonics and of space. The concrete shell of O-14 provides an efficient structural exoskeleton that frees the core from the burden of lateral forces and creates highly efficient, column-free open spaces in the building's interior (see Figure 1). The exoskeleton of O-14 becomes the primary vertical and lateral structure for the building, allowing the column-free office slabs to span between it and the minimal core. By moving the lateral bracing for the building to the perimeter, the core, which is traditionally enlarged to receive lateral loading in most



curtain wall office towers, can be minimized for only vertical loading, utilities, and transportation. Additionally, the typical curtain-wall tower configuration results in floor plates that must be thickened to carry lateral loads to the core, yet in O-14 these can be minimized to only respond to span and vibration. Consequently, future tenants can arrange the flexible floor space according to their individual needs.

The shell is organized as a diagrid, the efficiency of which is wed to a system of continuous variation of openings, always maintaining a minimum structural member, adding material locally where necessary and taking away where possible. This efficiency and modulation enables the shell to create a wide range of atmospheric and visual effects in the structure without changing the basic structural form, allowing for systematic analysis and construction. As a result, the pattern design is a combination of a capillary branching field, gradients of vertical articulation, opacity, environmental effects, a structural field, and a turbulence field. Yet these moves are not solely programmatic, economic, and environmentally related. In fact, these benefits are by products of a design that preferences pattern in order to distance itself from the generic, break up the now-standard tower stratification in order to emphasize verticality, and to confuse a sense of scale and height.

In O-14, the fenestration, or perforation, is not tied to the overall regulating geometry. In a typical office building, the subdivision of form would locate programs in a predictable way, as in larger windows and offices at corners, etc. Here, rather, the pattern seeks to attenuate the monotony, while still preserving a sense of the sublime and the monumental. Its deliberate lack of coordination with the floorplates engenders a randomized connection – all of this confuses legibility and scale, and defeats easy reading of the building's height and reorganizes the hierarchy of office space. Modulation of pattern works like camouflage, becoming disruptive and de-materializing the tower block. The shell's pattern changes as its relationship to the viewer changes, and in conjunction with additional patterns of

Figure 1. O-14 column-free interior space

Figure 2. O-14 ground lobby

...ratings

"LEED…was to be a set of guidelines for architects, engineers and others who want to make buildings less wasteful. However, developers quickly realized that its ratings – certified, silver, gold or platinum – were great marketing tools, allowing them to charge a premium on rents here."

Alec Appelbaum in a column discussing LEED certification in the New York Times, May 19, 2010. Source: http://www.nytimes.com

light and shadow, produces a sort of "virtual form." Because of the effects of this virtual form, the actual form of the building can be simplified and become subject to logics of production methods, structural analysis, and economy.

Dubai's typical urban condition is one of many emerging economies: the tower is located directly on the street, including a pedestrian arcade and a parking structure at the base of the building, which often creates a dead street behind the building. O-14 attempts to create a better urban condition by using these typologies while questioning their definition within its limited site. Rather than assuming that the podium base would simply have an active front, O-14 subsumes the typical arcade into its shell and produces another layer of activity higher up on the podium top. The parking is moved to four underground levels and the typical ground-level podium is elevated, thus freeing up the ground plane for a continuous elevated pedestrian level (see Figure 2), a new ground that is created above the street level. The promise is that O-14 and its neighbors could produce activity on many levels and engender new kinds of connections from the rear street to the promenade, activating the waterfront block as a kind of infrastructure for the district.

Architectural Expression

When considering the expression of O-14, one must first consider the move from masonry logics of building to those of vector-based construction. The shift from arch-and-wall ideas to column-and-beam signifies a shift in thinking about matter, in which structural logics within building components gradually become freed from the excessive material surrounding them. The logical extension of this idea leads to analysis of ideal structural form – the evolution of the cable and point load, and on to the truss and space frame, etc. – which is the precursor to the machine-aesthetic, the Modern concept of Functionalism, and eventually its degradation into the baleful high-tech.

High modernism has been described as various species of the dialectic between the generic and the accidental: wherein the generic is classical and impersonal, and the accidental is singular and unique. Instead of merely accident, or the accumulation of disparate elements, the process of design produces a singularity, which through its systematic nature, produces singular, yet systematic conditions. Difference is produced by similarity, resulting in ubiquitous difference, or continuous variation.

The design of O-14 compounds these ideas, primarily considering the uses and functions of the office spaces within, yet also primarily considering the appearance, porosity, and affects generated by the façade. Internally, the intention is that the program will locally reorganize itself in relationship to the apertures. This combination is a rejection of the pure separation and codification of parts and components, as in Structural Rationalism or Structural Expressionism, in favor of a "Matter/Force" arrangement, where matter and force are viewed as one.

Structural Design

O-14's unique perforated concrete tubular shell serves as its main architectural feature, its primary structural system, and an environmentally-smart brise-soleil. This exoskeleton-sunscreen wall features more than 1,326 openings of different sizes in an apparently random pattern but actually creating a diagonal grid to enable its use both as gravity and lateral support (see Figure 3). This quality represents concrete at its best.

The shell, being a primary structural element, required close collaboration between the architect and structural engineer in order to arrange the entire façade. The sizes and locations of the openings were carefully coordinated in order to make the wall effective in channeling both gravity and lateral loads down to the base of the building. The size and reinforcements of each solid shell element between the openings resulted from several iterative analyses, involving the varying of the openings' sizes and locations.

The exterior shell of O-14 ends at the ground floor level and is picked up by a continuous 1.20 meter (3'-11") deep ring beam that follows the irregular outline of the wall. Vertical loads are then transferred through four levels of parking, located underground, to allow for a maximum amount of parking space. The ground floor slab acts as a diaphragm slab, transferring lateral forces to the basement core shear walls, foundation walls, and additional shear walls that are adjacent to the parking access ramps. The gravity and lateral support system is also comprised of the core walls surrounding the main stairs and elevators in addition to the primary exterior shell (see Figure 4). The central core acts as a shear wall up to the 5th level, serving as a transition from the foundation walls and lower level shear walls to the exterior wall above grade.

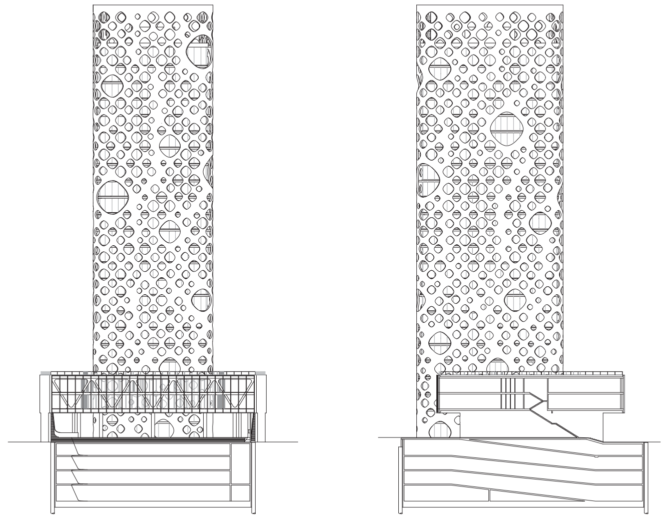


Figure 3. North and west elevations

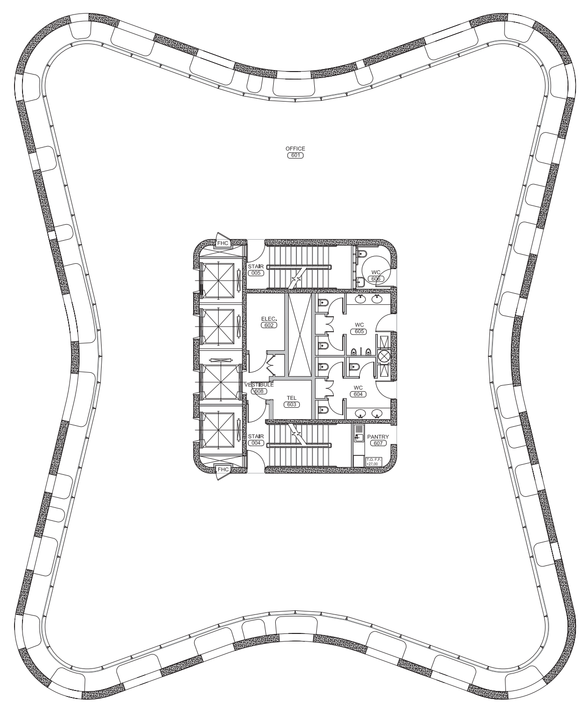


Figure 4. Typical floor plan

In terms of the floor system, O-14 uses a conventional flat plate system, with spans ranging between 7 to 10.5 meters (22'-6" to 34'-6") and thicknesses varying from 20 to 30 centimeters (7.8" – 11.8") for typical office floors. The mechanical floor and other floors designed with heavier loads possess slab thicknesses between 35 and 40 centimeters (13.8" – 15.7"). Slab connections to the exterior wall and a 600-millimeter wide band running along the perimeter of the interior section are 40 centimeters (15.7") thick. Underground parking is also of flat plate construction, with the garage columns spaced approximately 6 to 7.5 meters (19'-8" to 24'-7") apart. With the water level at approximately 3 meters (9'-10") below ground, the 4th basement level acts as a pressure slab, with thicknesses varying from 1 to 1.8 meters (3'-3" to 5'-11"). Building support is comprised of drilled cast-in-place piles.

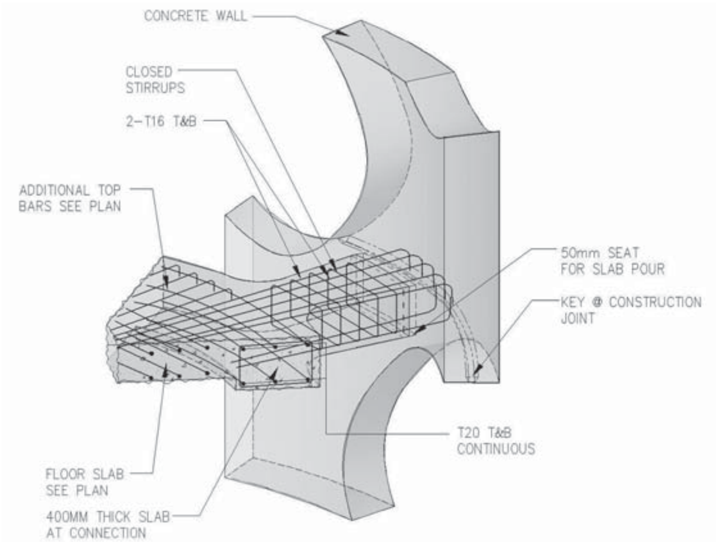


Figure 5. Slab connection to exterior wall

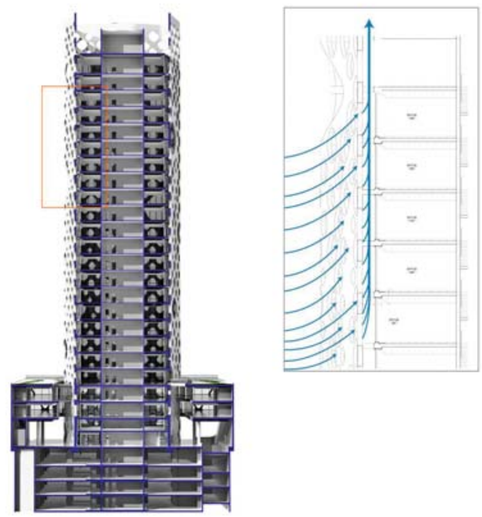


Figure 6. Heat chimney effect

At the base, surrounding three sides of the tower, is a podium three stories high. Structurally independent of the tower, the podium is supported by nine interior circular concrete columns, the east and west property walls, and a 50-meter (164'-1") truss spanning the entire width of the site. This truss configuration has been jointly designed by the architect and engineer to blend in seamlessly with the rest of the structure, while allowing for unrestricted views in the wide open spaces at each podium level.

Environmental Effects

The shell acts not only as the primary structure of the building but as a sunscreen open to light, air, and views. The openings on the shell thus modulate according to structural requirements, views, sun exposure, and luminosity. The overall pattern is not in response to a fixed program (which in the tower typology is inherently variable); rather the pattern, in its modulation of solid and void, will affect the arrangement of whatever program comes to occupy the floor plates.

Between the plane of the floor plate and the exterior wall's vertical opening, each slab edge is set back by one meter from the wall. Since the locations of the openings vary throughout the façade, each floor level is connected differently to the exterior wall at its diagonal grid by tongues extending through the one-meter gap (see Figure 5). Approximately 720 such connections exist between the interior floor slab and the exterior shell (approximately 30 connections per floor).

This one-meter gap between the main enclosure and exterior shell creates a so-called chimney effect, a phenomenon whereby hot air has room to rise and effectively cools the surface of the glass windows behind the perforated shell (see Figure 6). This passive solar technique is a natural component of the cooling system for O-14, reducing energy consumption and costs by more than 30%, which is just one of many innovative aspects of the building's design.

Construction Methodology

O-14 is sheathed in a 40-centimeter (1'-4") thick concrete shell perforated by 1,326 openings that create a lace-like effect on the building's façade. In order to create the perforated exoskeleton, O-14 uses a slip-form construction technique: modular steel concrete forms are used then moved along the building axis, preventing costly dismantling and setup of complex shapes. The holes are achieved by weaving Computer Numerically Cut (CNC) polystyrene void-forms into the reinforcement matrix of the shell, around which are constructed the slip forms of the interior and exterior surfaces of the shell. Super-liquid concrete is then cast around this fine meshwork of reinforcement and void-forms, resulting in an elegant perforated exterior shell. Once the concrete has cured, the forms are loosened and moved up the tower to the next level, where the process begins again. Dubai Contracting Company worked closely with Beijing Aoyu Formwork Company to systematize the production of the foam pills on site, and to streamline the assembly process of the sheathing, steel reinforcement, and foam pills prior to casting.

From the ground floor to the top of the parapet wall, the total height of the exterior shell is 105.7 meters (346'-9"). The shell thickness is 60 centimeters (2') from the ground to the 3rd level, and 40 centimeters (1'-3") from the 3rd to the roof level. A special detail was incorporated into the foam pills at this transition area to accommodate this change on the interior of the façade. Normal weight concrete of 70MPa (10.2 ksi) was used.

In designing the wall, the openings were classified into five different types based on their sizes. The diameter of the largest opening is 8.30 meters (27'-3") and spans across a two-floor height. The smallest opening diameter is 1.40 meters (4'-7"). The overall void ratio created by the openings is approximately 45%.

Modeling and analyzing the shell of O-14 was one of the biggest challenges in the design of

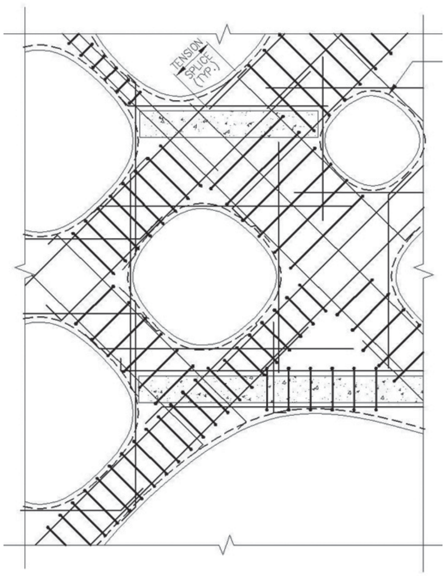


Figure 7. Typical reinforcement layout

the whole building. With careful collaboration between the architect and the engineer, the analysis was conducted in the manner of a feedback system. This process began with Reiser + Umemoto generating a 3D model of the shell with preliminary locations of the openings. Using analysis software, the structural engineer could then apply gravity and lateral forces to the digital model in order to identify stresses in the elements between the openings. Size and location of these openings were adjusted accordingly, resulting in a differing grid pattern. Comments on the model were then sent back to the architect to determine the architectural implications of these changes, after which the architect revised the model to send back to the engineer for more analysis and so on. This system of feedback took several iterations until the final shell's apertures, elements and grid pattern fulfilled both the architectural and structural requirements.

While determining the location and size of the shell's apertures, additional complications arose regarding the connection points between the interior slab and the exterior shell. Thus, the length of the gap between slab and shell, hence the spans of the edges of the interior slab, had to be carefully monitored and controlled for deflection.

The O-14 shell acts almost entirely in compression, and its reinforcement consists of minimal temperature reinforcing bars on each face. Elements between the openings form a quasi-diagonal grid pattern and are reinforced accordingly to address shear stresses. Edges of the openings were ringed with edge reinforcement for crack control, with the largest openings using 25 millimeters (1") diameter bars and the smallest, 16 millimeters (0.6").

Special attention was given to the detailing of the reinforcement so that each individual element's reinforcement could be integrated into the greater system. Overlaps and tie points were determined based on embedment at each "node" location for adequate transfer of element forces while also helping with the concrete placement.

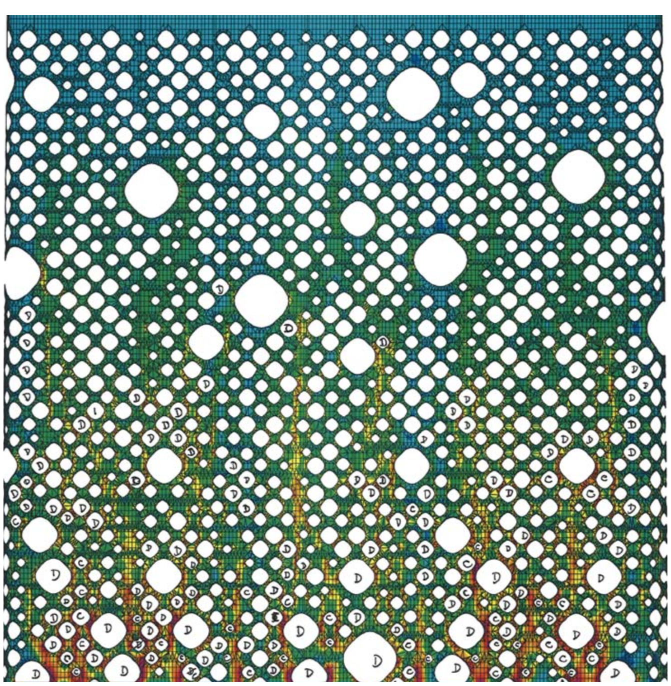


Figure 8. O-14 shell stress diagram

...luminous

> "If the luminous, sky-reflecting steel-and-glass exterior wall of the Trump skyscraper is the best thing about the project, compensating for its subpar spire and riverfront bulk, then the outdoor space runs a close second."
>
> *Blair Kamin on the Trump Tower Plaza on his blog at http://featuresblogs.chicagotribune.com/theskyline/2010/05*

Overall, the reinforcing requirements were both moderate and economical (see Figure 7).

In the World Trade Center in New York City, the alloy compositions of its steel tube structure were intricately modulated to achieve variable strength areas in an effort to maintain the relentless uniformity of its elevations. This accommodated the variable stresses in the tower while allowing the apertures to be larger and of uniform size, yet in the end was governed by the rules of prefabrication and economy. With O-14, the strength of the shell is modulated based on mediation between materiality and aperture (see Figure 8). Variable stresses are accommodated by locally increasing and decreasing material so that a uniform strength concrete can be used, simplifying material preparation. Changes in overall opacity can be accommodated by changing the uniform strength of the concrete mix. The mix is a balance between strength and fluidity, as extreme fluidity is necessary for larger contiguous pour segments and slip forming technology. Herein lies the economy of the system, so that within its constraints, a wide spectrum of forms can be possible with little impact to the overall cost or production time. ■

Editor's Note: For further discussion about this topic, please visit http://discussion.ctbuh.org.