The Contemporary Trend of Perforation: Case of Exoskeleton Concrete Shells

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Abstract: ***This text is oriented to and is part of the research topic with title "A study of the potential for using perforated RC perimeter walls in high rise buildings considering Architectural and Structural aspects". In brief, the research aims to address the potential in using advanced building structural systems, here presented as innovative Perforated Load-bearing Reinforced Concrete Shear Walls and in addition the process of investigation of sustainable aspects such as design for new architecture image. The proposed methodology it is intended to cover generalizing theories-literature review followed by an analytical, technical and practical study. Many tall buildings champion technology, exploration or innovation by embodying certain physical forms. Therefore it is intended to present a new way of using the vertical structural element of shear wall, that with different arrangements of opening systems. The main focus will be high rise buildings since they cover both aspects of visual and rationality in design, giving the opportunity at the same time to enrich the aesthetic vocabulary of tall buildings via perforated shear wall panels. Several innovative sustainable tall buildings using perforated concrete exterior shell such as O-14 Tower in Dubai, COR Building in Miami and Mikimoto Ginza 2 in Tokyo, are being subjected to analysis. They do confirm a better understanding with regard to the performance of Exoskeleton Concrete Shell Element. Some of them representing technology as extract and achievement of the new era, some representing building process and others transparence and layering of the building. By the beginnings of the 21st century, perforated building envelope set a global contemporary architectural trend, by a significant change of techniques, technologies, functions and materials. Nowadays the contemporary perforated buildings, partially or fully perforated, represent an increasing phenomena. The new trend can be perceived to some extent as an architectural leap of perforation as it has emerged in conjunction with digital technologies or as an increased collaboration among professionals in a co-design. Accordingly, the contemporary trend gives the opportunities to rethink of the future advancements in building envelope in terms of shape, form and performance. Although careful not to advocate the necessity of incorporating exposed structure into a building, it presents a vision of structure as a potentially exciting architectural element, and one that should always be integral with the design concept. Precedents in the research aims in trigger designer's imaginations and suggest ways for them to further develop their individual ideas.***

Keywords: exoskeleton, perforation, building envelope, architecture image

1. Introduction

Many tall buildings evoke technology, exploration or innovation by embodying certain physical forms. In this line, it is intended to present a new way of using the vertical structural element of the concrete wall, with different opening systems. The main focus will be the tall buildings, as they cover both aspects, architectural and structural, aesthetic and rational in design, while at the same time enriching the aesthetic vocabulary of tall buildings through their building skin.

Now a days, tall buildings are far from being as usually prismatic in shape, but even the most conservative architects are designing buildings with several forms and shapes, as well as round buildings. Some buildings express bold structures, and others express smooth architectural curtain walls. Some consist of a single tower; others of two and sometimes identical twins.

The current trend in architecture has stimulated the profession to give almost total freedom in the architecture of tall buildings. Today, with the use of computers, new structural systems are conceived and applied. Computers have made once difficult calculations easy, allowing the engineer to experiment with new configurations in an overall effort to reduce the structural cost.

The goal is to try to figure out the pro and cons of different systems and specifically to look at their stiffness so which of them is stiffer, which deflected less as you try to push on them. The three main structural systems are a braced frame, a shear wall and a moment resisting frame. So every building really needs to have some type of, one of those three systems and sometimes they have multiple systems and designers are looking out how stiff, how they resist the applied load coming from earthquakes or from wind. So you probably found that braced frame was pretty stiff so use a truss system, tends to be very stiff also very efficient. Shear walls can also be very stiff but they tend to use more material so there are pro and cons in this regard. From a single degree of freedom if it experimented with a single degree of freedom model, stiffness is not always better but there are pro and cons. Sometimes designers need stiffness when they get buildings that are very tall and they are not stiff enough, there are too much motions and they are not comfortable especially at the top of the building. And if the beams are not stiff enough they deflect too much. So it has to balance. Stiffness is one piece of the puzzle but there are other reasons. A moment-resisting frame tends to be the choice for a lot of buildings because it allows visual the exterior, it allows windows, so it permits a lot more open space from windows, it is one of the least stiff options but it provides other things that are useful. Shear walls are the opposite, no options for windows in shear wall but they are often used in the core of a building so around elevators and staircases and they are very stiff. But engineering is all about these competing criteria so it is not just stiffness, is also strength but is aesthetics, functionality and cost which is a big factor.

So how you pick different systems would depend on all these criteria. So putting all these pieces together, it will be perceived how structure is changed over the history. So talking a little bit about early structures in stone which are very strong in compression who does a great job with arches, vault domes but is very weak in tension, people did use them for buildings but the span tend to be very small, very short again because it doesn't have very much tension capacity and those beams rely on both tension and compression. So considering a plan view of ancient buildings so an example would be the Parthenon, the temple of Zeus, one of large stone structure, if you look at the plan view you see lot of columns very closely spaced through the building, that is because stone, if it used for the beams, can't span very far. It span little bit farther when they started using arches and vaults in many of cathedral so the span get little more greater and the height got more higher but still it was limited by the material. It was until 1700 with the advent of steel and iron so it started to get more open spaces, the designers started to get taller buildings. So one of the first examples of a steel moment-resisting frame which are more common systems used in early buildings, was the Wainwright Building in St Louis. If you remove the outer skin of the building, you see steel columns and beams. It was designed by Louis Sullivan and Dankmar Adler. Around 1900s, an unofficial skyscraper competition began that was mainly New York and Chicago competing, trying to get the tallest structure. So the Woolworth Building is an example of that. It was commissioned by Franklin Woolworth, the entire goal was to build the tallest building so he paid 13.5 million dollar in cash for the building, it was completed in 1913, it was 241.4 m tall and it was the tallest building in the world until 1930. It was designed by engineers Gunvald Aus and Kort Berle. Again as early buildings it was used a steel moment-resisting frame and it was gained to get a lot of windows. It also was the first building that include an elevator which is the key for making buildings got taller. So if you want to get building taller you will started to have to think about fires and possibility in getting people in and out. The next building which was completed in 1931 was Empire State Building which was the tallest building in the world until 1972, was designed by the architect William F. Lamb and the engineer Homer G. Balcom. One of the key points about this building is the speed which it was built. It was designed and built in 20 months, so it began the phase for construction to use a sampling line approach. It is an iconic building and it was designed in an art-deco style, probably began the famous skyscraper around the world. Internally is using a steel moment-resisting frame to resist those lateral loads. Next building is the John Hancock Tower it introduced a new type of frame infrastructures that actually helped structures in general become taller. So it is introduced the tube structure, so up until then, buildings were traditionally very regular, all the volumes were spaced regularly, the John Hancock Tower uses a truss tube so if you look at the exterior, you will see axes on outside. It was designed by the engineer Fazlur R. Khan with the help of the architect Bruce Graham. It was completed in 1969 and is 344 m tall. Fazlur R. Khan is a famous engineer, he is known as the father of the tube structure. He is a Bangladesh - American engineer. So started from the traditional grid of columns placed very regularly throughout the building, he moved everything to the outside of the building, not everything most the columns and lateral forces resisting system was moved to the outside. This tends to be more efficient and economical, it has to do with the stiffness if it is compared with beams, moving a beams mass away from its center increases its moment of inertia, that why the I beams are mostly used, forms that have everything moved away from the central axes. It is the same in buildings. Tube framed approach increases overall buildings moment of inertia. Fazlur Khan also designed the Willis Tower (formerly now is the Sears Tower) is again a tubed frame system, not with the truss but still tube frame everything in the outside. It was completed in 1973 and it was the tallest for almost 25 years so the Burj Khalifa in Dubai is currently the tallest building in the world. It goes a height of almost 830 meters which is huge, it is 3 times the height of Eiffel Tower to give a perspective. Another way to give a perspective is the weight of the concrete that was used. The weight of the concrete in the building is equal to weight of 100.000 elephants. Another interesting statistics was 12.000 people worked on Burj Khalifa during the construction. The Burj Khalifa was designed by the engineer Bill Baker and the architect Adrian Smith. It is interesting to read about the design which is based on a flower and it is also using a bundle tube construction but it got this three arms so it got very strong core and as it goes up less and less it tappers somewhat like the Willis Tower. The reason it has those three arms is that it can resist the wind in any direction, so it has these three arms of a nice moment of inertia at the base, so it has this strong core and this three arms that extend out to give it some stiffness. So as it tries to bend it got stiffness in any direction, in similarity with beam theory and the moment of inertia. It is an extensive wind tunnel testing that was done, models of the Burj Khalifa and all the details in computer analysis. It is just an amazing feature that brings all the systems together.

2. Building Aesthetic Vocabulary

The building aesthetic vocabulary varies a lot from the compositional parameters of architect. The compositional parameters seem on the other hand that often govern the architectural form. The compositional parameters control the scale of the compositional elements, visual depth of the panel, thickness of the panel's cross section, and overall openness or degree of screening. The scale of the compositional elements refers to the relative size of the elements in relation to the size of the full panel. The compositional scale can be varied from fine to intermediate to monumental. Monumental scale walls, which have few very large rings, can create a focal point in an atrium or a lobby. Fine or intermediate scale walls can be used to delineate spaces while allowing visual communication between spaces, and allowing light to penetrate deeper into a space from exterior windows. The visual depth of the panel can be modified by using compositional elements with varying depths or by laying out a uniform depth panel to create the optical illusion of depth.

Throughout history, there are examples of architectural form and structural integrity intersecting. These intersections are described by architecture professor and author Andrew

Charlesson [1]:
"as places, where structure is given a voice, and it contributes architectural meaning and richness"

Roman structures present an early example of structural innovation influencing and defining architectural form by using stone arches and masonry columns. One of the most iconic structures known to human kind such as the Colosseum, used the arch. Additionally, the Romans expanded the theoretical foundation of arches in order to pioneer barrel vaults and groin vaults, which appeared in many Roman basilicas. Professor Remo Pedreschi describes the idea of structural function being correlated with architectural form by stating [20]:

"The disciplines of structural art are efficiency and economy, and the freedom lies in the potential it offers for the expression of a personal style motivated by a conscious aesthetic search for engineering elegance".

Architect, structural engineer, sculptor and painter Santiago Calatrava effectively combines his knowledge of structural and aesthetic principles to create form that is a graceful creative expression of structure. His designs take on unique architectural form while also embodying the lines of the structural system that are used to carry the loads. One of his buildings that showcases his unique method for design is the Turning Torso in Sweden. This form of the building symbolizes a twisted human torso. Exposed concentric steel bracing constitutes the primary structural system, which represents the "spine" of the torso. He does not use the steel frame as a reinforcing framework but rather celebrates its contribution to the sweeping lines of the structure.

In general a façade refers to one side, usually the front, of a building. It is an integral piece to the overall design of a building. It provides the opportunity to create a personality and character to a building. Facades can come in many shapes and sizes, and it is really a chance for the architect to showcase their talent by bringing a building to life. Although a façade is often associated with older buildings and prestigious buildings, any building can create a recognizable façade.

A curtain wall is a type of façade that has no structural impact. It is a separate structure attached to the building. This is particularly common in modern architecture where the architect simply utilizes a design but doesn't bring it into the structural support of a building. A building façade is important because it is a chance to put the emphasis on design. To many buildings settle for standard designs that meet structural regulations but lack any sort of character. This has a detrimental effect on the places we live in with buildings all lacking something special.

The construction industry sees facade engineering growing in importance. Over the last couple of decades more and more building projects have incorporated a cladding system into their design. Couple this with the green issues and the fact that the building will need to be able to blend into its surroundings and you can see why façade engineering poses so many challenges. Nevertheless, there are these challenges that make the job of a façade engineer one of the most interesting and creative within the modern building industry today.

A properly designed façade can help reduce the building's energy consumption, too. Improving natural lighting and offering better airflow makes a façade-clad building both functional and easy on the eye.

The word 'Facade' literally means Face in French, and a building's facade is actually the front of a building and its face. While structural stability, space utilization, energy consumption etc. are some facts that go into designing a good building, facade design patterns are the face and give personality to the building. An improper facade can also mean the whole building might not display the purpose for which it was built. In this article we will explore some key aspects to be considered for designing perforated facades.

3. Elaboration of Structural schemes by Architectural styles of 20th century

Many tall buildings champion technology, exploration or innovation by embodying certain physical forms. The proliferation of new structural systems and advanced technologies, combined with Modernism's principles of structural clarity, helped to give birth to the movement of Structural Expressionism (Beedle et al., 2007) [5].

This movement began in the 1960s and flourished throughout in the 1970s, and tailed off in the 1980s, during the architectural period known as Late Modernism. Many Modernist high-rises have been bestowed with an explicit trait of structural expression, given that they were vigorously attempting to "honestly" display their structural systems. However, in Structural Expressionism, aesthetic quality has been redefined to emphasize the role of new structural systems and innovative building materials (Ali and Armstrong, 1995; Curtis, 1996). [2]

In this way, structural expression dominates the design of facades, becoming synonymous with the architectural expression of the building as a whole. Such expression was also fully compatible with the International Style and its formalism, another movement that arose during the Modern era.

The notion of structural expressionism, is rooted in bridges employing concrete as the structural material - a material that has the potential to the creation of unique forms, particularly in regards to bridges, which are essentially utilitarian structures that have traditionally been devoid of aesthetic quality.

Some aesthetically sensitive engineers in the past like Robert Maillart and Christian Menn felt that bridges should have aesthetic quality in their natural settings conforming to the landscape. They design bridges that were remarkably attuned to their surroundings, displaying their structural functions in an aesthetically intriguing way.

Architects Felix Candela and Heinz Isler have been inspired by the aesthetics of seashells and the structural logic that they follow, manifesting both elegance and strength.

Pier Luigi Nervi has designed many interesting structures including vaulted structural forms that display a building's load paths and stress flows to create distinct, large-spanning design.

Such expression in tall buildings has its roots in the work of William Le Baron Jenney and John Wellborn Root in the late nineteenth century. Both had engineering backgrounds, but they practiced as architects in Chicago. Jenney used the skeleton frame in the Home Insurance Building but did not express it since it was clad with masonry facade in Romanesque revival style.

In 1960s and 1970s Fazlur R. Khan and Bruce Graham designed a number of buildings in steel and concrete that were structurally expressive. Chicago architect Mies van der Rohe had a profound influence on them, in the same way as Viollet-le-Duc had on Jenney and Root.

Khan's exposure to the architectural/engineering practices at SOM, helped shape him for a remarkable career path in the 1960s and 1970s. He quickly realized that with the increasing heights of buildings, the status quo of structural systems was no longer acceptable. This means that "function follows form" (Billington, 1983) [8] since "form control the forces".

Khan recognized that placing the lateral-force-resisting supports away from the building's center would create a large moment arm to resist overturning of the building. Additionally, it would allow the structure to respond to lateral loads, providing the most efficient performance while consuming the least amount of physical materials.

Khan also recognized that when a tall building's structural system is scaled vertically, the loads created by its heavier weight and the increased wind forces of higher altitudes are magnified exponentially. So he elaborate studies on the scale effect and eventually articulated his findings as the "premium for height", a notion that led to revolutionary developments in height-based structural system charts for the use of steel and concrete in tall buildings (Khan, 1969, 1972, 1973; Ali, 2001). [3]

There have been also distinguished three main architectural styles from the modern thought in architecture that do enhance structure expressionism. Talking about Folding Architecture which is also known as Origami [6], High-Tech Architecture and Deconstruvizm which have all in common the same elements. They do refer to a total building mass reduction, more attention to interior spaces by creating at the same time visible structure. So at the end, a giving building represents technology as extract and achievement of the new era, represent the building process and manifest also transparence, layering by displaying the movement of the building itself.

So in this sequence, is also important to mention and refer to main architects and actioners of each style. As above beginning with the first style, it should be mention the main architect of Origami who is M. Chatani. And then referring to High-Tech architects who are B. Graham, F. Khan, N. Foster, M. Hopkins, R. Piano, S. Calatrava and R. Rogers. And for Deconstructivizm style the main actioners are P. Eisenman, F. Gehry, Zaha Hadid, R. Koolhaas, D. Libeskind, B. Tschumi etc.

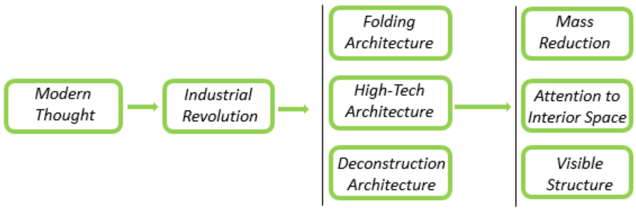


Figure 1: Main architectural styles that expose structure systems at the facades of buildings

The current state of high-rise architecture is characterized by the use of articulated sculptured forms. Owners and developers are demanding, and the public has come to expect these daring shapes. Buildings are designed not to express the pure form of the structural elements but to express the technological progress by creating façades that appear to be structural feats. The goal is the expression of the architectural envelope, not the structure. Today's bracing design required to limit the sway or wind drift of the building calls for ingenuity not in terms of visualizing a single pure structural system but in combining several systems to make the dramatic design concepts of the architect an economic reality. The work of the structural engineer comes in refinements to proven structural schemes with particular attention to details.

Logical structural solutions which could be used in the earlier versions are no longer sufficient to take into account the structural discontinuities. In fact, there no longer is a single system applicable for the entire height. In keeping up with the architectural slicing and dicing, engineers have to follow suit. In a manner of speaking, they cut a brace here, introduce a partial tube there, and so on. In other words, dissimilar structural systems are used around the building façade without undue regard to the one next to, above, or below it. The challenge is in interconnecting different systems to achieve overall continuity. For example, the building configuration may permit the use of perimeter bracing for the bottom 10 floors, the next 10 floors could accommodate a framed-tube solution, and so on.

In spite of the cacophony of external forms currently accepted as architectural styles, large, many-sided prismatic shapes with hints of flamboyance are still dominating the architectural vocabulary because they have the backing of large corporations seeking prestigious symbols. As stated earlier, the tube is still the workhorse of the structural systems, as demonstrated by its use in a large number of buildings. With these practical displays of the tube characteristics, is it not conceivable that this is the most logical solution for all high-rises? Should not the proven economy of this system put an end forever to the search by engineers for a suitable system on each project? The questions are perhaps deceptively simple. To be sure, the tube system is very economical, but even with its adaptability, it requires a certain amount of structural discipline that restricts the use of free-form architecture. The current flamboyance in architecture has necessitated that several schemes be studied and comparatively priced before the adoption of a final scheme. There are several reasons for this. First, every building is a unique response to a particular set of conflicting demands [12]. For example, architecturally it may be desired to have a sculptured profile without structural bracing at the perimeter. And because of the desired size of vision panels, depth of spandrels may have to be limited. Interior beams and girders working efficiently for gravity loads may require expensive penetrations for passages or air conditioning ducts or may require an increase in the floor-to-floor height.

Suboptimizing of the structure without due regard to the opposing demands of other disciplines may eventually result in an increase in the total cost of building. Therefore, less efficient structural systems often need to be studied in the interest of bringing in the total project cost within the allotted budget.

4. Case Studies

Here are described several case studies quite interesting for perforated concrete exterior shell used in high rise buildings with different arrangements of openings in the concrete shell façade of the buildings which do confirm a better understanding with regard to the performance of shear walls/shell elements in this study in terms of perforated shear wall.

Figure 1: O-14 Tower Dubai, COR Building Miami and Mikimoto Ginza 2 Tokyo

In order to better explain the topic of this study eight innovative sustainable tall buildings are taken in consideration. The aim is perceiving through this cases the potential of perforated shell elements in enriching the aesthetic vocabulary of such buildings. With these tower typologies the structure and skin have flipped to new area of tectonics and space. The concrete shell provides an efficient structural exoskeleton as in case of O-14 that frees the core from the burden of lateral forces and creates highly efficient, column-free open spaces in building's interior.

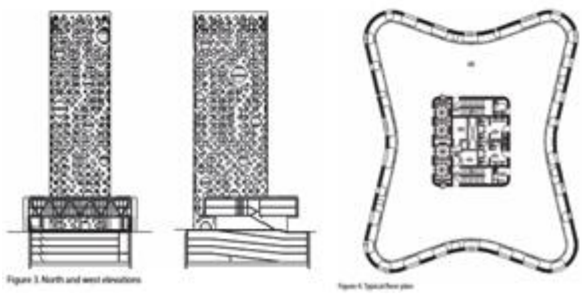
The perforation of shell seeks to attenuate the monotony, while still preserving a sense of the sublime. Modulation of pattern works like camouflage, becoming disruptive and de-materializing the tower block. The shell's pattern changes referring to viewer location and in conjunction with additional patterns of light and shadow which produces a sort of virtual form (Jesse Reiser, 2010) [14]. Because of the effects of his virtual form, the actual form of the building can be simplified and become subject to logics of designing methods of structural analysis and calculation.

Some case studies are analyzed using the reinforced concrete element, which is: the exoskeleton shell element that covers the entire outer surface of the building, such as the O-14 Tower in Dubai, the COR Building in Miami, Mikimoto Ginza 2 and TOD's Omotesando in Tokyo. Some of them represent technology as an extract and achievement of the new era, some representing the construction process and others the transparency of the building. Since the beginning of the 21st century, a new growing trend of perforation has emerged around the world, with a significant shift in techniques, technologies, functions and materials. This clothing typology created a global architectural trend.

Nowadays, modern or partially modern buildings are a growing phenomenon. The new trend can be perceived to some extent as an architectural leap of performance as it has emerged in relation to digital technologies [9]. Consequently, the contemporary trend creates the possibility of future advancements in facade construction in terms of form and performance.

O-14 Tower in Dubai

With the key design idea, that of reflecting the technological advancement of the time, where each facade element is not decorative but functional, Tower O-14 introduces a perforated exoskeleton tubular system that serves both as a structural and architectural element. Panel design, a combination of vertical articulation, encompassing a wide range of visual effects, varying from individual viewing angles to producing a kind of virtual form that mitigates the monotony of a common but also an environmental facade.



Figur e 2: O-14 Tower in Dubai, elevation view and typical floor plan

COR Building in Miami

Inspired by the environment, with the key design idea of building a new green tower in Miami, COR integrates green technologies including wind turbines, photovoltaic panels and hot water generation from solar panels. A hyper-efficient structure consisting of polka dots on the exoskeleton that provides thermal insulation, shade for residents and architectural elements such as terraces and fittings supporting the turbines. COR represents a dynamic synergy between architecture, structural engineering and ecology.

COR Building in Miami represents a dynamic synergy between architecture, structural engineering and ecology. The building structure is composed of polka dotted of exoskeleton shell that provides thermal mass for insulation, shading for natural cooling and enclosure for terraces. (www.archdaily.com, 2010) [16].

Figure 3: COR Building, the parking level and the elevation view of perforated shell

Mikimoto Ginza 2 in Tokyo

With the main idea of the design, that of identifying the structure as the basis of the design, the openings, colors and lights alternating across the facade dictate the conventional shape of the box. Build mass that creates a unique and attractive skin is another way to utilize digital tools for creative construction. Some features are a 20-centimeter-thick shell structure and amorphous windows are irregular polygons with rounded corners.

"Mikimoto Ginza 2" is wrapped in four thin walls which create a tube structural system. There are no internal columns and the floor slabs are a stack of nine homogeneous layers. The façade planes are divided in seven triangle shapes which derive the geometry of the openings of the building. This design follow a structural expressionist approach, becoming possible for the first time through the use of structural analysis technology known as the "finite element analysis method". (openbuildings.com/buildings/mikimoto-ginza-2-profile) [7]

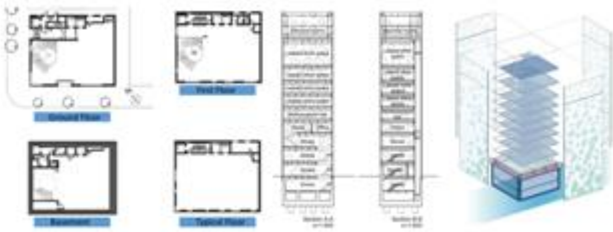


Figure 4: Mikimoto Ginza 2, the basement, ground floor, first floor, typical floor and the elevation view

5. Conclusions

These cases are not intended in themselves to convey the necessity of their application to a building, but to reflect a vision of the structure more centrally this structural but also potentially architectural element with a focus that must always be integral to the concept of design. The main objective of the thesis is to stimulate the imagination of designers and suggest ways to further develop their ideas individually.

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