Sustainable Structures and Architectural Forms of Tall Buildings

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ABSTRACT

The paper is discussing sustainable structures in tall buildings, the concept presented in the recent publication by Elnimeiri and Gupta in (Elnimeiri and Gupta 2008). Energy efficient building design is becoming increasingly important, as we think more about the environment and energy conservation. In this paper, we review examples of sustainable structures illustrating the interaction between architectural form, structural efficiency, and energy efficiency and propose possible design solutions.

KEYWORDS: Sustainable structure, structure, tall buildings, environment, form, efficiency, energy, wind, architecture, aesthetics, and collaboration.

1. INTRODUCTION

As we try to preserve the changing environment, energy conservation turns into a priority. Because buildings account for a large proportion of energy use, architects and engineers must focus on energy efficient design. It is important to design efficient structures and functional architectural forms. Integrating them with energy efficiency strategies is essential to achieve a sustainable structure: a hybrid using the least amount of resources to create a healthy and environmentally friendly building. Such a sustainable structure is only possible with close collaboration across different construction disciplines.

Today, one of the problems in the field is the lack of knowledge of how to achieve a truly sustainable structure. Thus, collaboration across different disciplines becomes essential. While there is often an interaction between architectural and structural forms, architecture and energy efficiency, there is rarely an interaction between structures and energy efficiency strategies. At the same time, a structural system accounts for thirty percent of the total building cost and is of a primary design focus. Thus, it is critical for a structural system to support building energy conservation and for structural engineers to be a part of sustainable design practices by developing new ideas to enhance building energy efficiency.

2. REVIEW OF SUSTAINABLE STRUCTURES

The Chicago Spire, a 150 story tower designed by architect Santiago Calatrava, has an unusual building facade formed by its pointed floor plan which is twisted 360 degrees around its axis towards the top (see Figure 1). In this tower, the exterior skin doesn't express the structural system of the building. It was difficult to integrate an exterior structural system with the twisted building facade because structures tend to lose their stiffness and bearing capacity when excessively twisted. Therefore a conventional internal core structure was designed.

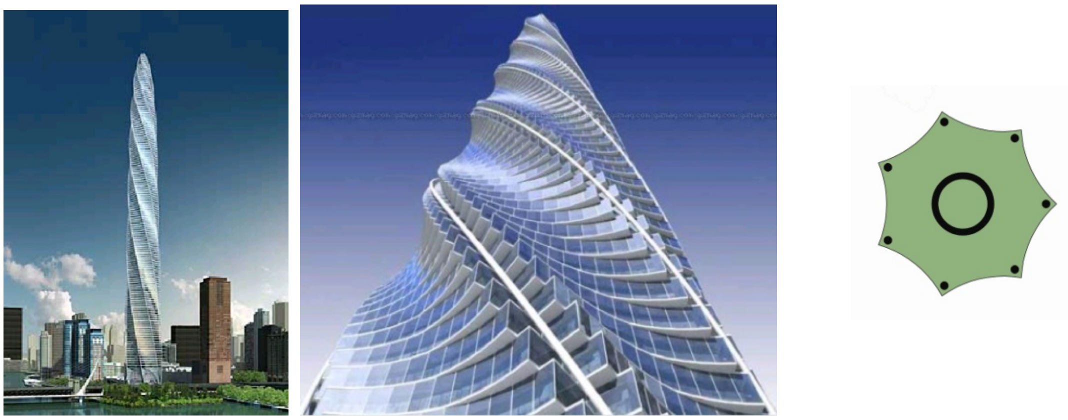


Figure 4. Chicago Spire, Chicago, USA (source: Chicago Spire LLC) and its floor plan

Sustainable structural systems often depend on the architectural forms of the building. Structural and architectural forms may be combined to reduce material use. For example, stiffened architectural forms will have good structural performance as well. This idea was used in a research project at the College of Architecture, Illinois Institute of Technology (IIT) (see Figure 2). The structural validity of this particular form comes from maximizing the moment of inertia at the base of the building. In this project, the architecture and structure work together to reduce the gravity and lateral loads on the building. In addition to great structural performance, this architectural form could be used to enhance building energy performance. Some ideas are proposed later in this paper.

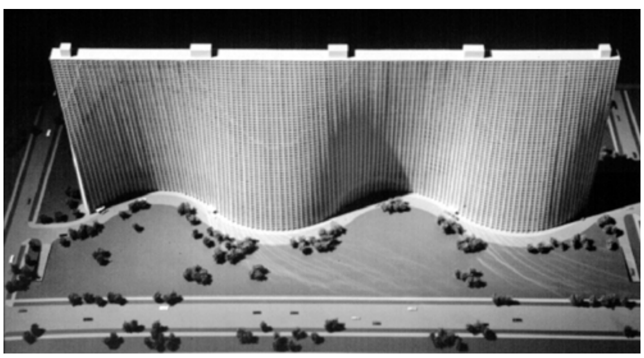


Figure 5. Student thesis project (source: Master's Thesis Program, IIT)

Scale has a great impact on the selection of an architectural form, structure, and energy efficiency. To a great extent, scale determines the choice of a structural system and a form. Frequently, a building form can be perceived as an expression of the structural system. For example, a tall and slender building will require a structural system that responds well to the dynamic nature of wind. These requirements may restrict geometric forms, such as dramatic setbacks or excessive twisting, as they cannot withstand certain dynamic forces.

Some energy technologies in buildings can be very dependent on the structure that houses them. In 1997, the first author introduced an innovative structural system for a 600 meter high tower based on the solar chimney technology developed by Schlaich from Stuttgart, Germany, in the early 1980s (Figure 3). The tower structure was a very tall tube supported by multiple cables anchored to the ground. At the bottom of the tube, the air is heated by the sun in glazed collectors. The tube channels convective hot air from its bottom to the top which generates energy when it passes through small turbines. The taller the chimney, the more electrical energy can be produced. The structure for a solar chimney would have to be extremely tall, which is challenging from economic and construction perspective.

Figure 6. Model of a 600 meter high solar chimney and its cross-sectional plan representing a porous organic form (source: the authors)

Sustainable structures may use nonconventional renewable materials such as bamboo. In the Tjibaou Cultural Centre in New Caledonia, by architect Renzo Piano, bamboo was successfully utilized as a primary structural material (Figure 4). Besides being a naturally renewable construction material, bamboo was an abundant local material, which significantly reduced embodied building energy. This form and structure can also be explored for tall building construction.

Figure 7. Tjibaou Cultural Centre, Nouméa, New Caledonia (source: Renzo Piano Building Workshop)

Today, more efficient structures are being developed. Efficient structures, such as diagrid, have been used recently on two projects by architect Norman Foster: the Hearst Tower in New York (Figure 5) and the Swiss Re Tower in London (Figure 6). In both cases, the structural systems were located near the buildings' exterior and were expressed on the facades.

Figure 8. Hearst Tower, New York, USA (source: Foster and Partners) and its floor plan

Figure 9. Swiss Re Tower, London, UK (source: Foster and Partners) and its floor plan

A good example of the combination of structure and architectural form highly responsive to its environment is The Met, a 69 story residential tower in Bangkok (Arch Daily 2009). The building structure consists of a series of closely spaced parallel shear walls (Figure 7). The shear walls form three clusters of residential units, separated by air gaps. Along the building height, the clusters are connected by sky bridges supporting gardens or community spaces. The air pathways between the three clusters of residences allow free air movement, thus providing the building with natural ventilation. The shear walls' layout also allows cross ventilation inside the residential units. In addition to ventilation, the air pathways between the shear walls reduce wind force impact on the structure. Recessed windows and hanging gardens also provide shade which helps avoid overheating in the hot and humid Bangkok climate.

Another example of sustainable structural and architectural integration is the Cocoon Tower in Tokyo by Tange Associates (Tange and Minami 2009). This 50 story tower is a vertical campus housing Tokyo high education institutions (Figure 8). The building structure consists of an inner core and three elliptical diagrid frames located at the perimeter. The diagrid frames are rigidly connected only at the base and at the top. Each of the three diagrid frames houses a classroom at every floor. The circular space between the exterior structures forms a series of three story atriums stacked on top of each other. The atriums serve as student lounges or enclosed school yards.

Figure 10. The Met, Bangkok, Thailand (source: Arch Daily) and its floor plan

Figure 11. Cocoon Tower, Tokyo, Japan (source: Archicentral) and its floor plan

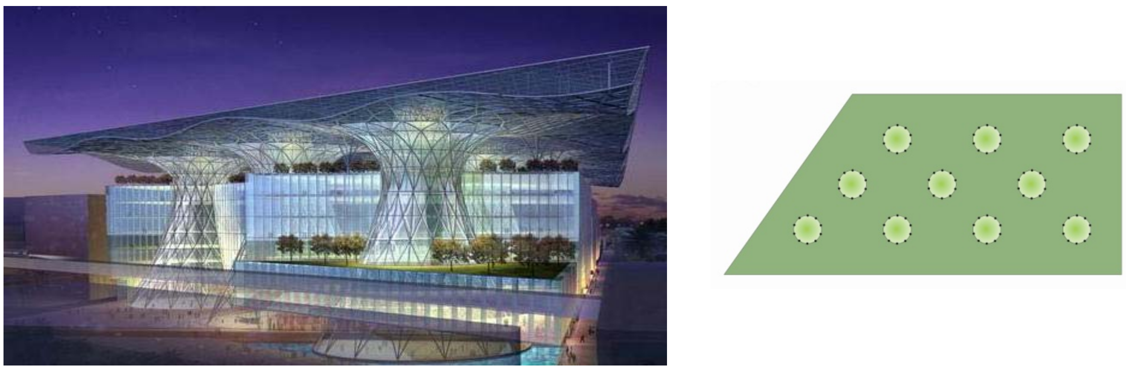


Figure 12. Masdar Headquarters, Abu Dhabi, UAE (source: E-architect) and its floor plan

Masdar Headquarters is designed as the world's first large-scale, mixed-use "positive energy" building which produces more energy than it consumes (E-architect 2008). The structure of the building is composed of conical towers enclosed in diagrid (Figure 9). Apart from supporting floor loads and providing lateral bracing, the towers serve as building atriums. The diagrid-laced atriums create stack ventilation, and are reminiscent of such elements of Islamic architecture as wind towers and Arabic courtyards. The large roof is used for solar energy generation using photovoltaic arrays. The building will use sustainable materials, integrated wind turbines, and additional systems to generate energy and reduce waste. Although the Masdar Headquarters is a mid-rise building, the same ideas could be easily applied to the design of tall buildings.

3. SUGGESTED CONCEPTS

Figure 10 represents a model of the desired interaction between architectural form, structural efficiency, and energy efficiency required to design a sustainable structure. The design of such a structure requires collaboration between the architect and engineer, both of whom must have a deep understanding of energy efficient design.

Figure 11 shows the examples of sustainable structures that embrace the energy efficiency ideas addressed above. In the first design solution, the building merges from an undulating organic form at the

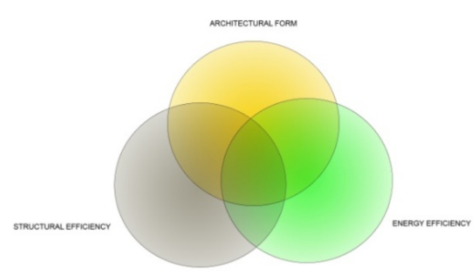
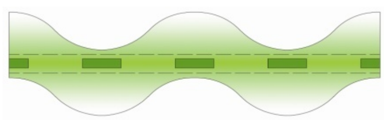


Figure 13. Model of integration

bottom to a rectangular form at the top. In the second design, a similar building is curved along a semicircle. Although the buildings are narrow and tall, these undulating architectural-structural forms resist lateral loads well because of an increased moment of inertia and stiffness. In addition, these narrow forms with curved exterior surfaces enable energy efficiency strategies, such as maximizing daylight penetration, use of natural ventilation, and heat collection. To be truly energy efficient, the proposed sustainable structures should be designed for the corresponding environmental conditions and climate.



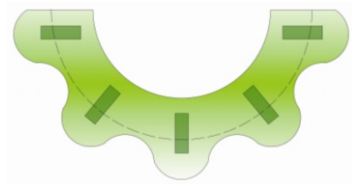


Figure 14. Proposed design solutions for sustainable structures

4. CONCLUSIONS

In this paper, the authors give a brief overview of the relationship between sustainable structure and architectural form for tall buildings. A few building examples showing this relationship are reviewed. The paper suggests some building concepts to enhance architectural and structural form design development with regards to energy efficiency strategies. A successful sustainable structure can only be achieved by collaboration between the architect and structural engineer during the design process. However, both of them must develop great understanding of how to make a building energy efficient. It is time to integrate structure with energy strategies and architectural form generation.

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