Structure and Architectural Form of Tall Buildings

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ABSTRACT

Tall buildings, although are architectural entities, structure plays a dominant role in shaping them. Because of their shear height, the need for a well developed structural system has been of paramount importance. During the modern era in Chicago in the 1960s and 70s, tall buildings exhibited a close relationship between structure and aesthetics. Structure and architectural form of that period blend seamlessly in complete harmony. The post modern era that followed started to emphasize form, taking it beyond the initial order and simplicity to an era of free and fluid forms. However, such a shift paid no attention to the discipline that structural system requires which presents a great challenge for the structural engineer.

This paper presents a historical overview of the relationship between structure and architectural form. It also traces current approaches in architectural form design. It concludes by proposing ideas to mitigate the lack of fit between structure and architectural forms in contemporary tall building development.


1. INTRODUCTION

Tall buildings are highly susceptible to wind loads which consequently requires additional structural materials necessary to resist such loads and satisfy serviceability requirements. The cost associated with the added quantity of materials required to provide lateral stiffness is commonly referred to as the premium for height. Due to such premium, the cost of structure is typically estimated to constitute up to 30% of the total construction cost, Figure 1. Such high premium combined with the speculative nature of tall building development demands that structural design considerations be addressed in the very early stages of design.

During the modern era, the development of tall buildings has been a product of close collaboration between the structural engineer and the architect. A number of notable tall buildings constructed during that period stand as a testament to such productive collaboration.

The post modern movement in early 1980s, however, witnessed a shift in the direction of development of tall buildings as architectural trends began to deliberately seek non-orthogonal treatments of architectural form. This was primarily driven by the continuing quest for “iconic” tall buildings in new urban developments.

Newly emerging approaches in tall building design have been towards promoting architectural style through
continues search for novel morphological schemes. This has manifested in a notable proliferation of architectural form typologies in which contemporary tall buildings are “emerging with an increasing degree of geometrical variation” and complexity [Vollers, 2008]. The role of the new generation of generative tools, which employ parametric and associative geometry modeling techniques, has been pivotal in driving such new design trends. Despite their powerful implications of on the “spatial form,” however, such approaches make no extension to include, among others, the structural performative aspects along with other factors that directly influence the architectural form.

In the context of current tall building design processes, issues pertaining to structure are typically left to be dealt with after the articulation of the architectural form. This consequently requires that the form undergo an extensive process of “rationalization” in order to overcome its limitations regarding structure, material, and constructability. While such an approach may enable a building stand up, it will not yield solutions that “perform fully in conceptual, formal, technical, financial and material sense,” particularly with reference to structure [Kloft, 2005].

Pursuing the formal and structural agendas concurrently in a very early stage of design can open up a great window of opportunity to explore novel yet structurally viable architectural forms. In recent years, a number of research initiatives, [Shea, Aish, and Gourtovaia, 2005], [Maher and Burry, 2003] and [Hozer Hough and Burry, 2007], have been carried out with the aim to establish a synergy between generative tools and structural analysis and optimization in order to allow cross-referencing of the formal and structural design considerations. The aim is to unveil the potential of combining such tools for advancing performance-based approaches of design. The methods proposed, however, are rather project-specific and none of which deal with tall buildings in particular along with their respective design considerations.

In this paper, the authors propose ideas to mitigate this lack of fit between the architectural form and structure within a methodological approach. It intends to address the qualitative and quantitative aspects of structure of tall buildings (in concert with other formal and planning design considerations) as part of the guiding design principles that influence early architectural form development. The objective is to provide the architect with a tool by which tall building forms can be evolved in response to not only formal preferences, but also basic structural principles.

2. OVERVIEW AND ANALYSIS OF STRUCTURE AND ARCHITECTURAL FORM

2.1 The Modern Movement, 1965-1975

The relationship between structure and architectural form reached its peak during the Modern Era. Form and structure became inseparable and complementary. Since structure constituted a significant portion of the total construction cost, its close coordination with architecture was not only desirable but necessary.

The John Hancock Building built in 1969, presents a clear example where the architecture (form and function) and the structural system (exterior braced tube) are in complete harmony. The building is well-known for its exposed bracing elements which provide a powerful and distinct visual expression, Figure 2. The architectural form serves both architectural and structural requirements. From a planning point of view, the tapered architectural form for the building allows for accommodating a mix of different functions with varying lease span requirements. Structurally, on the other hand, the wide base provides greater structural stability while the narrow uppermost part significantly reduces the lateral forces caused by wind. The building is one of the earliest to employ a braced tube system which consists of diagonals, carrying both gravity and lateral loads, in conjunction with widely spaced columns. When well proportioned, such assembly creates a highly efficient structure.
Another example of modern skyscrapers is the 110-story Sears Tower, Willis Tower, which was built in 1974. “The building consists of nine equally sized square tubes bundled together (See figure 3). The bundled tubes, cut off at different heights, result in a series of stepped volumes” [Architecture of Tall Buildings, CTBUH, 1995]. The termination of the tubes at varying heights, thus reducing the floor area, was necessitated by the functional requirements since less space is needed as the building increases in height. Structurally, on the other hand, it helps reduce the amount of surface area exposed to lateral loads due to velocity wind especially at the upper portion of the building. With the building soaring height and atypically wide base, the bundled tube system was introduced as an efficient solution to provide greater stiffness by mitigating the shear lag exhibited when using a single framed tube.

2.2 The Post Modern Era, 1980-present

The Post Modern Era marked the beginning of a separation between the architectural form and structure in architectural practice. During the first half of the 1980s, buildings started to adopt rather articulate and varied forms with aesthetic and formal aspects taking precedence over the structural requirements. While paying no attention to the discipline that structural system requires, the concept in many cases was not sensitive to structure and construction. This presented the structural engineer with a paramount challenge as his role became peripheral and comes after the concept of the design was well established. On the one hand, he has to pursue structural efficient solutions, while on the other hand, he has to conform to architectural form that may not be tolerable; limiting his role to solving the problem rather than integrating the solution with the architectural form.
The 550m Tower 2, was the tallest of the proposed Lagoon Towers project to be built in Dubai, 2007. The tower demonstrates a quite challenging exercise to incorporate a rationalized structural system into a highly irregular architectural form. Figure 4. The tower exhibits three independent geometric transformations that define its unique form. First, the tower leans away from vertical according to a sinuous curve that establishes the centroid of each floor, forming a spine shape not unlike that of the human backbone. The tower also tapers by applying a reduction in floor diameter as the height increases based on a mathematical curve. Finally, the tower twists as a result of rotating each floor in relation to the one below it by a constant factor [Elnimeiri, 2008].

Figure 4. Lagoon Towers, Dubai, UAE. (architect, tvs)

Tower 29 incorporates an exterior structural steel tube in addition to a core shear wall. The exterior tube consists of paired eight mega composite columns located at the corners of the octagonal plan working in conjunction with continuous ribbons of diagonal bracing (sloped columns). The sloped columns run one way upward projecting and twisting in a clock-wise continuous ribbon-like pattern. These sloped columns are spaced vertically at every 4 floors and meet the mega columns at every 12 floors.

The 150 story-high Chicago Spire by Santiago Calatrava (was under construction in 2008) exhibits a highly slender form with twisting and tapering exterior that invokes the image of a vertical shell (See Figure). The building’s plan has seven corner points with concave sides providing a more dramatic expression to the overall form. The floor system of each of the 150 stories rotates around 2° from the one below reaching a 360° twist at the apex.

Figure 2. Chicago Spire, Chicago, USA. (architect, Calatrava)

Structurally, the building is designed to be constructed primarily out of concrete. It employs an outrigger system connecting the cylindrical concrete shear wall to vertical exterior mega columns placed with an inwards offset from the exterior. The vertical mega columns are inwardly staggered...
with respect to the building tapering profile at a number of selective floors where deep girders are employed. The entire structure rests on seven, w-shaped columns circled around the 56ft-tall glass atrium.

The Chicago Spire presents a case where the building exterior is completely independent of the structural system. While the exterior skin is allowed to twist 360°, the mega columns extend rather vertically and independently throughout the entire building height. Incorporating structure in this case could have its significant implications on the architectural form. In this example, the passive relationship between the architectural form and structure stands in utter contrast to those presented during the modern era.

3. Proposed Approach:

The methodological approach proposed herein employs computational methods and digital tools for the development of tall buildings forms based on performance criteria. It utilizes a number of custom developed tools for the automation and acceleration of data flow between Generative component (GC) and ETABS, which are used as the design and analysis tools of choice. This also includes the development of a preprocessor for preliminary member sizing, and loads, properties and releases assignments, as well as a postprocessor for generating instant performance evaluation feedback.

![Figure 5. Conceptual framework of the proposed Process](image-url)

A flowchart of the proposed process, which is intended to be utilized during the conceptual phase of design, is shown in Figure 5. Initiation of the process first requires that the architect conceptually prepare a parametrically defined associative geometry model that represents the initial design intent. A pre-defined set of parametric inputs have been developed utilizing a combination of built-in features within GC to capture the initial geometry at hand. Three types of parametric inputs are identified which include: geometric, functional, and structural. The set of parameters provided for the preparation of the initial geometry has been developed with the aim to capture a vast array of
morphological schemes and potentially encompass most representative tall building forms available today. The initial geometry is generated through the synthesis of the various parametric inputs which can be specified by the architect either numerically by assigning specific values, or intuitively by graphical manipulation of point, lines, B-spline curves etc. See figure 6.

Figure 6. Iterative feedback loop between GC and ETABS

The synthesis process involves preliminary check based on purely geometric criteria. A custom developed script running within GC is utilized to verify various volumetric properties such as the aspect ratio, center of mass, eccentricity etc., and generates useful feedback on the form’s sensitivity to structure with regard to its inherent stability. The aim is to ensure that such properties lie within acceptable, prescribed structural limits. If further enhancement is needed but cannot be achieved through geometric analysis, the process will resort to performance-based check where the form can be subjected to iterative, geometric alteration guided by performance criteria.

The process of selecting a structural system and the generating of the structural layout model are carried out seamlessly throughout the process. A simplified structural analysis is then conducted, with every iteration, to check the impact of altering geometry on the structural performance with regard to stress, serviceability, overturning moment etc.

In the structural evaluation process, results from the structural analysis are checked against a set of predefined structural performance objectives. Instant feedback on the structural performance is then generated and displayed in numerical and graphical formats. The structural performance feedback at hand is utilized for decision support to guide the geometry update process.

Figure 7. Range of possible scenarios produced during the form exploration process
With the initial geometry parametrically defined, it can be easily subject to geometric alteration imposed according to performance criteria. The iterative process is carried out between the generative and analytical tools through manipulating targeted geometric parameter(s) as many times as needed until reaching a parametric value(s) with which the structure performs more reasonably. In order to preserve the architect’s initial intent, the alteration process seeks to modify the geometry but maintain the topology i.e. number of geometric components and their relations.

The range of geometric variations generated through the process is illustrated in Figure 7. The diagram shows potential design scenarios that exist between two ends; one end representing an initial scheme that reflects the architect’s design intent and has a potential for refinement based on structural performance, and the other end representing a hypothetical, structurally efficient design solution. The process is carried out by negotiating between the formal and structural design inputs. The possibilities within the spectrum represent the pool of emergent design solutions from which the choice of final form can be determined.

6. CONCLUSIONS

An overview and analysis of the relationship between structure and architectural form has been discussed. A clean and consistent correlation between architectural form and structure was exhibited during the modern movement. The achievement of that harmony was possible only because of the close collaboration between the structural engineer and the architect. Such collaboration was based on a mutual understanding of the role of each. It was also clearly extended to include the contractor who made the realization of the ideas possible.

The quest for iconic, individualistic forms during the post modern movement, which led to the current state architectural design, presented the structural engineer with a great challenge. It also reasserted the need for collaboration between the architect and engineer as a productive means to making the exploration of novel yet structurally sound and constructible architectural forms possible. While the responsibility of the engineer is to preserve the architectural vision while maintaining the structural integrity, the architect must have a sense of appreciation of the structure rationale and aesthetics.

In this paper, a simple interactive approach within which structure is integrated into the architectural development has been proposed. Such an approach intends to yield architectural forms that respond positively to structure without in any way jeopardizing the visual intent of the architectural design. Working within an associative geometry environment, utilizing generative components, allows for defining the geometry as a flexible model which the architect can easily enhance and modify according to structural performance feedback. The proposed approach will lead to mitigate the lack of fit between the architectural form and structure. Hopefully, it will enrich the architect knowledge base of structure and opens doors for him to explore novel forms that respect structure and construction.

REFERENCES

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