A PERFORMANCE-BASED DESIGN APPROACH FOR EARLY TALL BUILDING FORM DEVELOPMENT

Focusing on Formal and Structural Design Considerations

AYMAN M. ALMUSHARAF, MAHJOUB ELMIMEIRI
Illinois Institute of Technology, Chicago, USA
almuaym@iit.edu
elmimeiri@iit.edu

Abstract. This paper presents a methodological interactive design approach within which structure is integrated into tall building form development. The approach establishes a synergy between generative and analytical tools to allow for the parallel interaction of formal and structural design considerations during the conceptual design phase. An integration of the associative modeling system, Grasshopper, and the structural analysis tool, ETABS, was established, and a bi-directional feedback link between the two tools was initiated to guide the iterative form generation process. A design scenario is presented in this paper to demonstrate how the parametric generation and alteration of architectural form can be carried out in response to instant feedback on structural performance. By utilizing such a tool, architects not only can develop improved understanding of structural needs, but also realize their formal ideas structurally and materially.

1. Introduction

One recent direction in the development of tall building forms has been toward promoting diverse architectural styles through a continuous search for novel morphological schemes. Responding to the growing demand for “iconic” tall buildings in new urban developments, newly emerging trends in tall building design favor non-orthogonal treatments of building masses and forms, the aim being to produce new design variations and possibilities. This trend has manifested in a notable proliferation of tall building typologies in which contemporary tall building forms are “emerging with an increasing degree of geometrical variation” (Vollers, 2008). With the continuation of the trend to pursue formal expression has come an
increasing tendency to overemphasize aesthetics and style while paying less attention to structure and the discipline it requires.

The importance of the structure of a tall building is underscored by the fact that structural costs increase significantly with height, primarily due to the drastic increase in the quantity of structural material required to resist lateral loads. Such costs can constitute up to 30% of the building’s total construction cost. For viable design solutions to materialize, therefore, structure must assume its rightful place during the architectural form conceptualization process.

In the context of current tall building design practice, issues pertaining to structure are typically left to be dealt with until after the architectural form is well articulated. Such an approach requires that the form undergo a rigorous after-the-fact rationalization process, which necessarily limits the structural design role to solving the problem rather than integrating the structural solution into the architectural concept. While such an approach may enable a building to stand upright, it will not yield solutions that “perform fully in the conceptual, formal, technical, financial and material sense,” particularly with reference to structure (Kloft, 2005).

Newly emergent generative tools and techniques have been pivotal in driving such design approaches. Parametric and associative modeling systems have emerged as viable and productive design partners that allow for rapid exploration of design alternatives with varying degrees of complexity. However, while these systems’ potent implications for the “spatial form” are clear, a remaining challenge has been to extend their capabilities by allowing performance to directly influence early form development.

Today, emphasis has shifted to the processes of form generation based on performance strategies of design. The convergence of the generative and analytical tools for use in the early stages of design offers a large window of opportunity for moving beyond traditional form-driven approaches. In recent years, a number of research initiatives (Maher and Burry, 2003; Shea, Aish, and Gourtovaia, 2005; Hozler, Hough, and Burry, 2007) have been undertaken with the aim of establishing a synergy between generative tools, structural analysis, and optimization in order to permit the cross-referencing of formal and structural design considerations. The goal has been to investigate the potential of combining such tools in advancing multidisciplinary approaches to design. Little to no research, however, has been published that attempts to address the qualitative and quantitative aspects of tall building structure (in concert with other formal and planning design considerations) within a single work-methodology.

This paper lays the groundwork for a methodological approach within which structure is integrated into the tall building form generation process. The aim is to propose a new work-methodology in which the formal and
A PERFORMANCE-BASED DESIGN APPROACH FOR EARLY TALL BUILDING FORM DEVELOPMENT

structural design considerations pertaining to tall buildings are pursued in parallel at a very early stage of design. The process is intended to help architects evolve tall building forms that not only respond to formal preferences and/or planning considerations, but also adhere to basic structural principles as they pertain to tall buildings.

2. Approach

The methodological interactive design process, seen in Figure 1, employs computational tools and techniques for the development of tall building forms based on structural performance criteria. It builds on the generative capabilities offered by available parametric/associative modeling systems and the added potential of linking them to structural analysis tools to leverage performance-based approaches to design. Through a simple integration of the two mediums, a closed design/analysis feedback loop is established that can foster early and concurrent cross-referencing of the formal and structural design inputs.

![Figure 1](image)

*Figure 1. The processes of form generation and performance-based analysis/evaluation are automated and integrated within a single procedure.*

The proposed process utilizes off-the-shelf software namely Grasshopper and CSI ETABS, which are used as the design and analysis tools of choice. In addition, it proposes a number of tools developed by the authors to ensure full integrity and fluidity of the process workflow. These tools include a set of pre and post-processors that facilitate accelerated data transfer between the various components within the integrated design process. It also includes a custom-script built-in within the generative tool to check structurally related aspects of the architectural form based on
geometric criteria. Also, it includes an optimizer tool that automate the member sizing process in sync with any change made to the structural system as a result of the geometric update without resorting to manual input.

2.1. PROCESS INITIATION

The process typically starts with the conceptual preparation of a parametrically defined associative geometry model that represents the initial design intent. A pre-defined set of “parametric inputs” has been developed utilizing a combination of built-in features within Grasshopper to capture the initial geometry at hand.

2.2. PARAMETRIC INPUT

The set of parametric inputs encompasses the various design factors that directly influence the architectural form, particularly during the conceptual phase of design. Such parameters are itemized categorically into three distinct types: geometric, functional, and structural.

The geometric parameters determine the architectural form’s geometric dimensional attributes and relationships. The parameter set has been developed with the aim of capturing a vast array of morphological schemes and the potential to encompass most representative tall building forms available today. They provide a combination of base and top geometries and a variety of vertical transformations to generate the 3D representation of the geometric model. The functional parameters, on the other hand, establish the function-related requirements pertaining to tall building development, such as function type(s), gross area, number of floors, floor-to-floor high(s), lease span requirements, and so on. The functional and geometric parameters in combination determine the overall tall building form. The structural parameters identify the set of inputs required to construct the 3D assembly of the structural layout model and set the non-geometric structural attributes. These include type of structural system, type of structural element, number of bays/bay dimension, structural system’s horizontal/vertical modules, wind zone, and so on. The various parametric inputs can be set in Grasshopper either numerically (by assigning specific values to variables) or graphically (through direct manipulation of points, lines, and B-spline curves).

2.3. SYNTHESIS PROCESS

Once the various parametric inputs have been set, the synthesis process is carried out to generate the initial geometry. A preliminary check based on purely geometric criteria is conducted as a part of the synthesis process to
A PERFORMANCE-BASED DESIGN APPROACH FOR EARLY TALL BUILDING FORM DEVELOPMENT

verify whether the initial form lies within acceptable prescribed structural limits. The checking procedure is a custom code written in VB.net that runs from within Grasshopper. The script checks certain volumetric properties such as the absolute height, aspect ratio, center of mass, and mass eccentricity, and prompts the user whenever a criterion is violated. If the initial geometry is approved but further refinement is needed, it is passed on to the next step, where it is subjected to a geometric modification process guided by performance-based criteria.

Figure 2. Form generation process workflow, Grasshopper.

2.4. STRUCTURAL ANALYSIS

In this step, a simplified structural analysis is conducted to check certain performance-based aspects of the structural system. A VB script was written to automate the generation of the structural input file. Among the many tasks that the script performs are the extraction of points’ coordinates, the definitions of member connectivities, the assignment of joint restraints/releases, the definition and assignment of section properties, the assignment of rigid diaphragms, the definition and assignment of load cases, and so on. Once the input file is populated, it is imported to ETABS for execution. A linear static analysis is conducted in ETABS. Results from the structural analysis are then provided in a series of output files. Finally, key values are automatically extracted from individual analysis results in order to evaluate performance.

2.5. PERFORMANCE-BASED EVALUATION

This paper establishes a set of criteria as the basis for the structural performance evaluation. These criteria include lateral displacement, overturning moment, and structural weight (psf). Based on such criteria,
feedback on structural performance is generated and displayed, which is then used to inform and guide the subsequent geometry update process. Such feedback is typically utilized to perform two types of modifications. The first involves a parametric alteration of the form toward structurally enhanced solutions. At this level, the alteration process seeks to modify the geometry but maintain the topology so as to preserve the architect’s initial design intent. The second type of modification, on the other hand, involves a fine-tuning of the structural system/components without modifying the form. This includes revising the structural member sizes, adjusting the geometric configuration of the structural layout model, and/or employing a different structural system if needed. With the initial geometry is parametrically defined, it can easily be subjected to geometric alterations imposed according to performance criteria.

3. Design scenario

The following design scenario demonstrates an initial implementation of the proposed design process on Tower 29, the tallest of Dubai’s proposed Lagoon development by TVS Design. Tower 29 was chosen due to its unique geometry, in addition to the fact that it presents a quite challenging exercise to incorporate a rationalized structural system into a highly irregular architectural form. See Figure 3.

A parametric model of the tower was initially generated in Grasshopper, (Figure 4). First, three independent geometric parameters were applied to the tower’s octagonal base: an extrusion path based on a sinuous curve, which causes the tower to lean away from the vertical; a taper achieved by
applying a reduction in floor diameter as the height increases based on a Bezier curve; and a twist, which is the result of rotating each floor in relation to the one below it by a constant factor.

The functional parameters were also set. This includes the building’s gross area, base geometric area, floor-to-floor height, and number of floors.

As for the structural parameters, an exterior braced tube was applied that consists of eight megacolumns located at the corners of the octagonal plan and working in conjunction with diagonal bracing. These diagonals are spaced vertically at every 4 floors and meet the megacolumns at every 12 floors. The number of bays is set to 3 per side. The core shear wall is omitted in this study for purposes of simplification. The building was assumed to be in a moderate wind zone, and the minimum wind pressure from the Chicago Building Code (CBC) was used to establish the wind load.

*Figure 4.* Initial geometry of Tower 29 generated in Grasshopper (top); ETABS analytical model. (bottom)
A preliminary check showed that due to the tower’s vertical inclination the center of mass of the initial geometry does not align with the system’s center of rigidity, which is assumed to lie at the center of the base floor. This contributes to excessive mass eccentricity, which in turn generates significant global overturning moment under gravity loads. To mitigate the excessive mass eccentricity, a refinement process was carried out by progressively shifting the center of mass closer to the center of rigidity. The parametric alteration was set by incrementally manipulating the control points of the central sinuous curve. A constant increment was used based on the direction and distance of the center of mass from the center of rigidity and applied to the XY coordinates of the control points (Figure 5).

![Figure 5. Iterative parametric refinement to mitigate the form’s excessive mass eccentricity.](image)

Table 1 shows the resultant global overturning moments with respect to the sequence of altered geometries. The values presented are normalized to the initial geometry, which was set as the base case. A sequence of 6 design scenarios was generated in this example and a close to 30% reduction in overturning moment was achieved through the geometric refinement process. Further refinement was possible but not without undermining the overall visual intent.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overturning Moment</td>
<td>1.00</td>
<td>0.94</td>
<td>0.88</td>
<td>0.83</td>
<td>0.77</td>
<td>0.71</td>
</tr>
</tbody>
</table>
The impact of twist on the structural behavior was also studied. The investigation was conducted by applying a 360° twist to the geometry, based on a 30° increment. A sequence of 13 design cases was generated and tested (Figure 6). The lateral displacement was used here as the key performance indicator. With every iteration, the corresponding exterior braced tube system was generated and analyzed in ETABS, and the resultant tip deflection was retrieved and displayed in a close-to-real-time fashion.

![Figure 6. Parametric variations in the twist angle.](image)

The chart in Figure 7 shows the resulting tip deflections for the varying twist angles. Values are normalized to the 0 angle twist, which is set as the base case. The chart shows that twist has a predominantly favorable effect on the lateral displacement and the overall stiffness of the system. Twisting the form is advantageous in this example because it is applied in a direction opposite to that of the bracing inclination, creating a triangulation similar to that of a diagrid system. A 120° twist was found to be the ideal case.

![Figure 7. Effect of varying twist angle on the lateral displacement.](image)
The tool’s potential for assisting the architect during the conceptual design phase has been illustrated in the previous example. It shows how a parametrically defined model can easily be subjected to geometric modification based on instant feedback on structural performance. As such, the morphological development of form takes place based on informed decisions on structural behavior rather than merely subjective visual judgments.

In both design scenarios, the authors were able to vary the architectural form, through accelerated iterations, by manipulating targeted geometric parameter(s) as many times as needed until reaching a parametric value(s) with which the structure performs more reasonably. The range of geometric variations generated throughout the process represents the pool of emergent design solutions from which the final form can be chosen.

4. Conclusion

This paper presented an interactive approach that employs computational methods and digital tools for the development of tall buildings’ forms. Working within a parametric/associative modeling environment utilizing Grasshopper permits the definition of the geometry as a flexible model that the architect can easily modify and enhance according to structural performance feedback. Automating and managing the information flow between generative and analytical tools is crucial to supporting the iterative design/evaluation process and maintaining the fluidity of the process workflow.

The proposed approach aims to yield architectural forms that respond positively to structure without in any way jeopardizing the visual intent of the architectural design. It seeks to mitigate the lack of fit between architectural form and structure by negotiating between the formal and structural design inputs concurrently and at an early stage of design. It is hoped that utilizing such a process will enrich architects’ structural knowledge base and open doors by which they can explore novel forms that also respect structure and construction.

References

