Over the last few years, a large majority of construction work has moved overseas. In response to this, our engineering practice has been involved in a large number of Asian and Middle East design competitions, usually executed in a compressed timeframe. Building codes usually include very specific requirements regarding the lateral performance of a building under seismic and wind loads. This is especially true in China. Our structural engineering practice has thus developed a variety of digital tools customized to building code requirements, in order to provide relevant structural feedback in an appropriate design time frame.

The paper will discuss our recent digital design work in the context of building code requirements and information sharing. Our innovations have centered on three progressive spheres of innovation: internal efficiency, communication and collaboration. We propose that only with closer and more transparent collaboration will the building industry be effective and efficient in meeting clients’ needs. However, without first addressing a firm’s internal capabilities of efficiency and communication, the firm will be unable to effectively participate in the collaborative process.

This paper begins by discussing various custom Rhino-Grasshopper components to facilitate our internal design process. We then touch on the communication realm discussing work in lowering the barriers for information sharing. Lastly, we explore the necessary shifts in thinking required to move beyond linear design exploration and the exciting opportunity to deliver truly innovative design solutions.
1 Introduction

Over the last few years, competitive pressures have placed an increased demand on architectural design firms to deliver more thorough designs earlier in the design process. Submission materials for international design competitions often involve detailed floor plans, high quality renderings and dynamic animations. While this front-loaded process might benefit the articulation of the design idea and final quality of the project, much of this competition work is often performed with minimal fee. The need to be efficient thus arises for both marketing and financial reasons.

Our structural design firm has routinely participated as consultants during competition phases. We are thus often challenged to evaluate architectural designs in a timely fashion to provide feedback to the design team. We have responded to this challenge by investing in our digital design process, starting with basic interoperability, and subsequently layering this with other custom and building code-specific structural tools.

In the context of China, where the majority of large design competitions have been recently located, we have developed tools to accelerate our evaluation of tall buildings under seismic and wind loads. The Chinese building code has specific stiffness requirements for lateral performance of a tall building, and an efficient process to study and communicate the feasibility of an architectural design scheme is essential in the competitive environment.

As these digital design tools become more mature and accepted in the industry, we have begun an exploration of how digital design enables further innovation in the following three areas: efficiency, communication and collaboration. This paper will describe how our firm has addressed basic software interoperability, developed various custom tools to further accelerate structural design and finally speculate on what future innovations could further benefit the industry.

2 Spheres of Innovation

During the peak of the building boom, our firm realized that the traditional linear manner of architectural-structural collaboration was not only starting to show its limitations in terms of efficiency but also beginning to handicap the communication process. This was especially true in geometrically intricate projects. The further proliferation of free form 3D modeling tools and the demand for unique architectural expressions also illuminated the need for our structural design firm to innovate and ensure we were able to continue to address structural issues in a relevant time scale.

As our digital tools have matured, we have realized that efficiency is only the beginning of the journey. We have thus reframed our digital design tools around three progressive spheres of innovation.

1. Internal efficiency
   Focus on interoperability, database applications and automated workflows.

2. Communication
   Development of data aggregation methods, custom web based reporting of structural studies and lowering the barrier of information sharing.

3. Collaboration
   Rethinking traditional frameworks of compartmentalized architectural and structural design.

3 Internal Efficiency

The adoption of digital design methods has given the architectural design industry unparalleled freedom for design expression. In order to be constructive in this environment, structural consultants have to respond to design ideas in ever compressed time frames. While it might have been acceptable in the past to respond to architectural design explorations in time scales measured in weeks, this is no longer the case. The use of parametric and script-based design methods allows for change to occur in the time scales
Structural consultants have to provide feedback in a timely fashion in order to stay relevant to the current design theme. To accomplish this, we have developed multiple custom scripts/components to accelerate our workflow.

Structural studies at this stage involve feasibility and typical member (wall thickness, column areas) sizes based on building code requirements. In the realm of tall buildings, it is necessary to evaluate the expected wind and seismic loads that the building will be subject to and the response of the structure in the loading environment. However, prior to application of lateral loads, it is necessary to translate the architectural surface model into discrete structural elements.

3.1 GEOMETRY TRANSLATION

We have invested in custom Rhino-Grasshopper tools to efficiently translate architectural surface models into geometry usable by finite element software. Rhino-Grasshopper components allow for the input of floor elevations to trace structural columns and spandrel beams on a typical surface model (Figure 1). These beam and column elements are then used as input to another Rhino-Grasshopper component to drive these rhino line objects to finite element analysis software. The script-based approach of geometry manipulation has additional benefits in terms of simultaneously assigning structural elements to specific analysis properties and also reducing random errors attributed to the traditional “point and click” approach. This approach has also been used for the translation of core wall layouts into structural analysis objects.

A custom script-based approach has also allowed for efficient computation of geometric properties of floor plates along the height of a tower. Modern skyscrapers are seldom straight extrusions of a basic geometric shape. Tower designs often incorporate tapers, translations and rotations of a geometric form. Floor plates may be different on every floor, implying that the tower’s mass, wind sail and radius of gyration are constantly changing along its elevation. These geometric properties all influence the structural loads (gravity, wind and seismic) that the tower will be subject to, and thus an accurate computation is very valuable. Approximating an intricate tower form into blocks every 5 or 10 stories for analysis simplification is no longer necessary.

3.2 EVALUATION OF BUILDING CODE REQUIREMENTS

The determination of building code requirements for a building's gravity loads is relatively straightforward. This can be determined from tables in code books or the project's design criteria. However, in the realm of wind and seismic loads, a multitude of factors have to be evaluated prior to the determination of a design wind pressure or seismic load profile.

3.3 WIND LOADS

For example, in order to compute the wind pressure of a “dynamically sensitive” tower according to the ASCE 7-05, more than ten variables and constants have to be evaluated. These variables are functions of the building's dimensions and stiffness characteristics.
Modifying a building’s stiffness thus has implications on its loading. Automating this calculation using live geometric information from the Rhino massing model again reduces random error in the communication and collaboration process. This approach also allows for more sophisticated evaluation of a building’s lateral performance. This is especially valuable when the maximum wind loading direction may not be aligned with the maximum stiffness direction (Figure 2).

Wind loads computed from this custom Rhino-Grasshopper component (Figure 3) get applied to the structural analysis model directly without unnecessary “copy and paste” steps which often introduce random error into our design process. See Figure 4 for typical loading of a high rise tower subject to wind loads.

### 3.4 SEISMIC LOADS

The evaluation of seismic loads also requires the determination of multiple constants and factors. Similar to our approach for wind loads in the previous section, we have developed custom Rhino-Grasshopper components that allow us to enter the seismic design spectrum automatically into our finite element analysis software. See Figure 5 for evaluation of a seismic design spectrum in Rhino-Grasshopper and application in finite-element analysis platform.

### 3.5 DATABASE APPLICATIONS

After the geometry of the analysis model has been generated and loads have been applied, the analysis model is run and results (member loads, stiffness characteristics, etc.) are obtained. The size of the result set are often unwieldy. This information needs to be shared with multiple members of the structural design team and performance measures need to be distilled for upper level decision making. We have centered our analysis post-processing around a centralized database (Figure 6) for easy access by different members of a design team. The database also allows a continuous development of various pre-and post-processing tools as project needs evolve. This approach has the primary benefit of reducing manual point-and-click tediousness imposed on the engineering team, allowing them to perform higher value tasks in terms of data interpretation and decision making.

### 4 Communication

While internal efficiency has obvious benefits at the micro level in terms of error reduction and accelerating the design process, its greater value is in its relevance to partners or project managers. The next stage in the evolution of our design process has been centered on rethinking how the massive amounts of analysis data that gets generated by analysis models can be effectively communicated.

Design offices are awash with different mediums of communication. These mediums range from email to pdfs, from CAD drawings to parametric models, from animations to physical models. Compounding the challenges of this flood of data is the fact that they all reside in different platforms. To simply access the various data requires a person to understand
the basics of navigating numerous software platforms. Fear of technology and fatigue of learning the latest version cannot be underestimated in the deployment of software “solutions” within a design office.

4.1 WEB-BASED INFORMATION SHARING

Despite the challenges noted above, one medium with which everybody is familiar is a web page. The simplicity and forced lack of functionality allows information to be presented in simple, consistent formats. Our firm has taken the first steps in the post processing of analysis results for delivery via our intranet. This allows all members of the design team regardless of their sophistication with the latest technology to access information pertaining to the latest structural simulation. This was done leveraging our custom database and VB.net scripting in combination with Javascript charting libraries. See Figure 7 for typical analysis results generated for delivery via our intranet.

Eliminating the tedium of manual “copy and paste” procedures allows us to quickly produce a wealth of information in which different levels within a project team might be interested. For example, partner or manager level team members might only be interested in structural quantities and overall loads on a structure. However, engineers involved in detailed design require peak loads on individual structural elements. Adopting a customized script-based approach of data post processing allows us to efficiently serve the needs of different parties. This also democratizes information sharing and allows sophisticated structural analysis to be easily shared with the architectural design team. See Figure 8 for a sample of structure performance characteristics.

4.2 COMPETITION BOOK PRODUCTION

In the competitive landscape within which the design profession currently operates, competition submissions often see significantly detailed designs. We have frequently supplemented competition submissions by producing structural pages for inclusion, including simplified graphs and visualizations of overall structural performance. We have further leveraged custom scripts to automate the generation of the required image and Adobe InDesign files for delivery to the architectural design team.

5 Collaboration

As discussed in previous sections, internal efficiency and lowering the barriers to communication are the first steps in delivering a more thoughtful and integrated design. However, better design will only be achieved through more open collaboration between design team and consultants. It will be necessary to move beyond binary yes/no interactions...
to more open explorations of geometry and structural solutions. Presented below are some arenas in which we have explored how this might be accomplished.

5.1 GEOMETRY EXPLORATION

Traditional interactions between the architectural design team and structural consultants usually involve linear back and forth exploration of design ideas. Challenges involving different software platforms, varied mediums of exploration (physical and digital) and lag usually arise. However, if design exploration could be moved towards a discussion about what parameters influencing the design we wish to explore, this would open up a greater opportunity for better design execution.

This shift in design exploration could be explained by the following example. In high rise buildings, a desire to express a corner condition is often desirable. This provides greater views for the occupants and reduces the visual weight of the structure. A typical high rise floor plate is shown in Figure 9. Often, a question regarding how far the corner columns might be moved from inboard is posed. This exploration in the traditional process might involve the architectural and structural team trading sketches or CAD files back and forth. This method is often slow and prone to miscommunication.

Instead, we might discuss with the architectural team the range of how far inboard they might look to move these columns. This is conceptually illustrated in Figure 10. It is possible to generate a range of column locations that the design team would like to explore with a simple parametric model. These geometries could be analyzed for structural performance (deflection, stresses) and the results of this analysis could help inform the design direction. See Figure 11 for deflections of the floor slab with different column locations.

5.2 TARGETED COST ENGINEERING

Digital design techniques are also being applied to more downstream tasks such as costing. Despite the proliferation of BIM platforms, cost estimation is still often performed with 2d drawings. Naturally, this has challenges in terms of accuracy and communication. To exacerbate the problem, cost reports are often delivered in static PDF formats which limit the extraction of pertinent data. We have explored ways to display relevant data and incorporate this information into our future parametric models for rough cost estimates.

In Figure 12, we extract structural costs for a particular project that incorporates long concrete walls with significant cantilevers. During the design exploration phase, the architectural design team wished to explore variations in the wall cantilever dimension. Similar to the discussion in the previous section, a parametric model with linkages to structural analysis was leveraged (Figure 14). However, with cost data available in the later stages of the project, this parametric model could also be augmented with cost information (Figure 13). Our team looks forward to building an easily accessible database of cost information that can be used in future projects to incorporate both structural and cost information.

5.3 SIMULATION DATA AGGREGATION

The last avenue we have explored in the collaboration realm involves developing parametric models of prototypical high rise towers in China subject to the different loading conditions in different cities. This allows us to quickly build a knowledge base of likely structural system requirements in different cities within China (Figure 16). This was performed with our custom analysis model manager. See Figure 15 for typical study workflow.

Our custom program allows a user to manipulate multiple analysis models from a consistent external environment which simplifies analysis model set up and reduces error. In the post processing realm, the custom program also allows the user to extract meaningful results. In situations where there is a significant number of analysis runs or longer run times, this allows a user to set up a batch run for processing at the end of a work day.

6 Innovating within the Chinese Building Code

This paper has discussed the various techniques we have used to accelerate our workflow in both the geometry and building code realms. The last innovation we have developed was
demanded by the requirements of the Chinese building code. The Chinese building code has specific requirements regarding lateral performance of a high rise building under both seismic and wind loads. Besides meeting the basic strength demands under multiple load cases, the tower must conform to a specific stiffness requirement along its height. Typically in high rise structures, this requirement is a limitation of $H/500$ in terms of inter-story drift under both wind and seismic loads. Inter-story drift is illustrated in Figure 17. A manual trial and error approach to structural member sizing for multiple load cases and locations proved too inefficient and error prone. Furthermore, a manual approach could never assure that we were delivering a structure utilizing the minimum amount of material.

6.1 MULTI-CONSTRAINT OPTIMIZATION

In order to meet the stipulated code requirements with minimal structural material, custom optimization routines must be employed. In many situations with a dominant load case (wind or seismic direction), single constraint optimization routines are usually sufficient. However, in high rise structures subject to stiffness requirements along its height, a multiple constraint approach must be used. See Figure 4 for a typical high rise tower subject to lateral loads. The objective of the optimization study is to minimize the quantity of structural material required while meeting drift targets at specific elevations along the tower’s height.

A custom program was written to leverage the finite element analysis engine of a third-party software (Strand7). This iterative, gradient-based optimization approach generates a significant amount of data, so automated post processing had to be included in this program for the results to be easily shared and explained. Similar to our approaches for web based sharing of analysis information, results of these optimization routines are displayed via a web page which lowers the barrier to acceptance. See Figure 18 for a screen shot of optimization runs and results.

7 Summary

This paper has discussed the various custom tools and workflow that our office has developed in three innovation spheres (internal efficiency, communication and collaboration). In detail, these served to accelerate our internal process, lower the barriers to communication for large and complicated datasets, and explore possibilities for moving beyond linear modes of collaboration. We have taken basic interoperability of architectural geometry and structural analysis and layered on custom tools for generation of loads according to building code requirements. We have also continuously developed our custom pre-and post-processing routines to manage multiple analysis models simultaneously, allowing the potential for easily exploring the design space. This multi-model approach to analysis has resulted in ever-growing datasets, which we have addressed by developing custom web-based visualization techniques to increase the ease of data sharing and allow for dynamic interaction.
Following this, we explored the potential for such custom tools and workflows to allow for greater collaboration between the architectural and structural design teams. We discuss this potential in the context of geometry explorations (Figure 9), layering of cost information onto lightweight parametric models (Figure 13) and data aggregation for a typical building situated in different cities (Figure 16).

Finally, the three spheres of internal efficiency, communication and collaboration are brought together in the context of a high rise design in China. In order to deliver these projects efficiently, we utilized many custom tools for geometry and load generation, including a robust optimization algorithm to efficiently size structural members while meeting the strict requirements of the building code.

8 Future Work

The true value of digital design will only be realized through greater and more transparent collaboration between design teams. Future innovations have to take place within the collaboration realm. For the author, this means further compressing our workflow and using this acceleration to develop a dataset of typical buildings and geometries that might be accessible at coordination meetings. This further lowers the barrier to information sharing and potentially provides the foundation for breakthrough designs.

References


