Structure at the Velocity of Architecture

This paper outlines a digital design workflow, utilized by the authors, which actively links the geometry platforms being utilized by architects with tools for structural analysis, design, form-finding, and optimization. This workflow leads to an accelerated generation and transfer of information to help guide and inform the design process. The engineering team is thus empowered to augment the architect’s design by ensuring that the design team is conscious of the structural implications of design decisions throughout the design process.

A crucial element of this design process has been the dynamic linkage of parametric geometry models with structural analysis and design tools. This reduces random errors in model generation and allows more time for critical analysis evaluation. However, the ability to run a multitude of options in a compressed time frame has led to ever increasing data sets. A key component of this structural engineering workflow has become the visualization and rigorous interpretation of the data generated by the analysis process. The authors have explored visualization techniques to distill the complex analysis results into graphics that are easily discernable by all members of the design team.
1 Introduction

The pace of building design is accelerating. This acceleration has arisen from basic competitive pressures, increased adoption of digital design tools, and exposure to 3D modeling and BIM within the client base. The proliferation of digital design tools gives the impression that buildings can be designed at the push of a button with full interoperability between geometry, analysis, and documentation platforms. Towards this goal, software vendors continually attempt to improve interoperability and design integration with each new version release.

However, the authors believe that amidst the blitz of publications and marketing, the details of execution and the specific benefits and implications for architectural design have been glossed over. In this paper, we hope to address the specifics.

It is recognized in the design community that the most meaningful cost and performance decisions are made at the concept stage of a project. Our structural group has thus focused our efforts extensively on workflows, data extraction and visualization techniques that are critical in the concept phase of projects. In this phase, it is imperative to ensure quick turnaround and the distillation of data into actionable options.

2 Massing vs. Discrete Geometry

Geometry is the common language in which architects and engineers communicate their ideas to one another. Communication begins to break down when the two groups do not use the same vocabulary. At the conceptual design phase architects are primarily concerned with the overall massing of the building. This can be achieved by a variety of CAD packages and usually involves surface modeling in software such as Rhino or MicroStation (Figure 1). While this surface modeling is acceptable for producing renderings at this early concept stage, the resulting surface geometry is of little value to structural engineers beyond serving as a reference surface. Structural analysis, design, and optimization requires a discretization of these architectural surface models into distinct elements that comprise the structural system. It is this wireframe geometry of straight line segments and straight interior surfaces that describe walls which is required for use in finite element analysis software.

In addition to differences in geometric representation, there is a level of geometric control and complexity necessary for structural analysis models that are not required in architectural massing. For example, architects will likely model all column elements on one group layer/level. While this approach is adequate for architectural modeling purposes, it is often necessary for structural engineers to have a high level of control over the grouping of structural elements (Figure 2). For example, in the analysis models of a tall building, it is beneficial to create a series of tiers over the height of the building. These tiers correspond to transitions in column sizes as load requirements vary over the height of the tower. In addition to vertical grouping of elements, one might wish to group the columns differently within given tiers. Scripts to allow this dynamic grouping method aid in the process of applying structural properties and material properties during the creation of the structural analysis model. Even when the engineer is provided with a geometrically ‘clean’ wireframe, there can be quite a bit of manipulation needed to be done in order to achieve this necessary level of control.

3 Structural Analysis Workflows

3.1 Traditional Workflow

The traditional analysis and design process followed by structural engineers is usually one of a responsive approach. The geometry is either provided by the architects or generated by the engineer from an architectural massing model. This geometry is imported
into a finite element analysis program (such as ETABS or SAP2000) and the pre-processing is performed by an engineer via the graphical user interface. This method, which is a point-and-click method, requires all structural information (material and section properties, boundary conditions, loads, etc.) to be applied by the engineer manually. For simple geometries and models of rather small scale, this approach is fairly reasonable for analyzing the performance of a structural system. This approach begins to break down when multiple options are being explored and the engineer is required to manually model all the various options proposed by the architect. Often the engineer will finish a preliminary analysis and design of a structural scheme and begin to communicate this scheme to the architect, only to find that the design has been radically changed (Figure 3).

3.2 Proposed Workflow

In response to a rapid design process, our office has developed a more proactive workflow which adapts more efficiently to the continual changes that occur during the conceptual design phase (Figure 4). Rather than manually applying structural information to the wireframe geometry in a point-and-click manner, our workflow leverages parametric modeling, form-finding, optimization routines, and software application programming interfaces (APIs) to effectively move data to and from various software packages. Parametric modeling enables us to respond to architectural massing models and have complete control over the corresponding structural discretization. This ensures that once the parameters and associative relationships have been established, structural analysis models can be generated quickly and respond easily to changes in the underlying form. By utilizing a custom central database with a series of custom scripts, we are freed from the burden of manually generating our structural analysis models and from reliance on vendor-developed interoperability tools which are often limited to specific CAD and analysis packages. This new workflow empowers the design team to move beyond selecting a scheme merely because it was the last one drawn and more critically assess and compare the weaknesses and benefits of all options explored.
4 Adapting to large datasets

The pursuit of exploring numerous design options quickly and efficiently has resulted in the need to manage large datasets (Figure 5). Our workflow relies on a platform-neutral centralized database in order to efficiently manage these datasets. In addition to assisting in the generation of hundreds of the code-specified load combinations required to fully bound the analysis results, the centralized database is utilized for parallel exploration of analysis results by various members of the structural design team. By hosting the database on our network server, analysis results are available to all design team members for use in the design of specific elements, visualization purposes, or generation of special sub-modeling studies.

5 Revision Tracking

When the design concept changes in the traditional workflow, the results of previous analysis models are rarely further explored as there is a large time investment required to generate the updated analysis model. The efficiency our new workflow and centralized database allows the opportunity for revision tracking. This revision tracking ensures that what might be considered outdated data is not overlooked. This data can still be relevant to inform structural solutions for the revised design concept.

6 Sub-modeling

Global analysis models are usually used for capturing the overall behavior of the structural system and general force levels. This is not adequate when analyzing and designing specific parts of the structural system. In order to capture the local behavior of structural components, structural engineers often create sub-models of these specific elements of the global model to more closely analyze these components. The sub-models typically involve a much higher level of detail, which is necessary for design of the element but would only unnecessarily complicate a global behavior model. By utilizing the centralized database, we are able to quickly generate the geometry of the sub model, and ensure continuity of the boundary conditions and applied forces between the sub-model and the global model. This relationship enables accurate and efficient design of the structural system at various levels of scale (Figure 6 and 7).

7 Optimization

Optimization is a process to seek the minimum cost solution while meeting a clearly defined set of objectives. For example, in the building industry, a macro level optimization problem might involve varying a building’s massing to meet a given program while taking into account floor plate depths and occupant views.

In the structural engineering realm, optimization problems involve the selection of a structural system or geometry that most efficiently resists the imposed loads. In projects of significant height or span, this usually means sizing structural elements (wall thickness, beam sizes, and column areas) to meet a given stiffness criteria. A robust optimization script, thus allows the quick and objective comparison (same structural performance) of different structural systems/geometries that are being explored early on in a project.
For example, a design team might evaluate different truss depths to support the roof of an exhibition space. With custom optimization routines, a tradeoff between truss depth, ceiling heights, and structural cost can be quickly established. In this simple example, the design team is thus presented with a richer dataset to make meaningful design decisions early in the design process.

The authors have implemented this idea in the design of high rise buildings and long-span roofs. This has been executed with VBA and SQL in Microsoft Access with extraction of analysis results from the structural analysis package via an API. The utilization of Microsoft Access as the central data depository has also allowed the extraction of nuanced data that might be project specific and has not been scripted for the general optimization problem. The representation of the large dataset, and optimization results in a “menu” of structural options that have the same structural performance.

7.1 Stiffness optimization

Structural stiffness optimization for a given system is based on the theory of equalizing the work density for all elements (e.g. beams, columns, and walls). The starting work density for all elements is computed with custom scripts. A resizing algorithm accounts for size constraints, such as minimum and maximum dimensions, and grouping. Once run, elements with high work densities are assigned more material (e.g. thicker walls, larger beam) and material is removed from elements with lower work densities. The theoretical optimum occurs when all elements in a structural system have the same work densities under the critical load case (Figure 8).

The power of this approach is that it allows for practical constraints such as constructability (minimum and maximum sizes) and grouping of elements. A practical optimum solution can thus be rapidly computed for multiple geometrical configurations.

7.2 Objective evaluation of options

A result of this robust optimization workflow is that a set of different geometrical configurations and structural systems can be evaluated simultaneously. Presented below are two examples of how different structural systems can be optimized to the same target deflection (same stiffness characteristics) and visually evaluated for both element sizes and porosity (Figure 9 and 10).
7.3 Topology Studies

We have also expanded on the traditional approach of structural optimization to include explorations in topology and beam density (Figure 11). These topology visualizations help the structural team to be more effective in structural proportioning by optimizing the location and density of structure. With these simple intuitive visuals, the appreciation of optimum structure can be shared with the whole design team. While somewhat theoretical, these studies hopefully can provide inspiration for new efficient systems and forms which move beyond traditional design thinking.

8 Parametrics and live linkages to structural analysis and optimization

For smaller optimization problems, we have explored the incorporation of lighter weight optimization scripts directly into the parametric geometry platforms. This serves two purposes. The first is minimizing the number of software platforms utilized for a design problem and the second is the ability to dynamically optimize variations in geometry. Setting up a design exercise can now involve a richer set of variables such as geometry, program requirements, and structural performance.

This ultimately gets closer to the objective of true performance based design. We believe that the hurdles to this aspiration, in the current state of the design industry, is the interoperability of the design tools, the complexity and subjectivity of architectural design problems, and the magnitude of design variables that can result. This rapid expansion of the design space can be overwhelming. However, the authors believe this growing design space can be efficiently managed with a gradual implementation of an expanding set of tools such as live linkages between parametric geometry and structural analysis, efficient data management and processing techniques.

9 Visualizations

Our digital workflow, with its greater interoperability of software and fluid nature of the modern design process, has led to a rapid expansion of datasets for a particular design problem. These datasets might include material quantities, forces in specific elements, optimization results, and stiffness characteristics. Through our utilization of this platform neutral data storage, in contrast to traditional point-and-click workflows, we now have the ability to study a particular option in depth and effectively compare between different options.

In order to fully leverage this vast quantity of data, it is imperative to condense it into meaningful and actionable visualizations. The authors have utilized various means to achieve this: contouring within the structural analysis software, custom graphics generated in Rhino-Grasshopper, and the structural analysis software via its API.

9.1 Native structural analysis visualizations

Structural engineers have traditionally used the native contouring and visualization tools within the structural analysis software to visualize results. This approach is adequate for global views of forces and deflection characteristics (Figure 14). We have also taken advantage of this visualization environment by using scripts and APIs to generate more detailed or specific behavior results.
9.2 Graphing

The authors have also exploited the centralized approach to data and result storage to generate a rich array of charts within Microsoft Excel and in Rhino overlaid with the building form (Figure 15). This is consistent with our overarching goal to provide, what can be, complex analysis results into a manageable and easily comprehensible set of graphics.

9.3 Force trajectory/Beam Density visualizations

Force trajectories involve studying the flow of forces along a given design surface subject to load. While this can be visualized in the native structural analysis platform, the graphic tends to get too dense and hard to discern (Figure 16). In order to produce effective graphics for this situation, the authors have exploited Rhino-Grasshopper to generate graphics that represent a filtered set of data that is more informative. In addition, we leverage the structural analysis API to generate custom groupings to illustrate optimum diagrid density distributions (Figure 17). These visualization techniques will certainly lead to a clearer understanding by the design team as to where placement of structure is more effective on a complex freeform surface.

9.4 Load flow visualizations

In situations of complex load flows such as a perimeter diagrid structure, we have explored producing custom graphics in Rhino-Grasshopper to better visualize natural load paths. This distillation of the structural analysis result dataset to a simple graphic allows the dissemination of structural behavior to both a technical and non-technical audience.

9.5 Earthquake load visualizations

The goal of visualization is to make the hidden visible and to extract meaningful information from a dense dataset. Usually, this involves a more intelligent grouping of data or a more efficient filtering algorithm. However, in the case of earthquake forces acting on a high rise tower, this effort is to make the truly unseen (earthquake forces) visible.
The distribution and intensity of earthquake forces acting on a high rise tower can be highly complex. Variations depend on multiple natural vibration modes and the distribution of mass along the structure’s height. However, the complexity can be reduced to an ultimate shear and moment demand at a particular story and we have implemented scripts to compute these forces and effectively display them in Rhino-Grasshopper. The structural engineering team is thus better able to appreciate the unseen forces that the structure has to resist.

10 Conclusions

This paper illustrates how the authors have utilized a variety of digital design tools to allow for a more efficient and thorough design process at the conceptual and most impactful stage of a project. We have contrasted architectural and structural geometry requirements and illustrated the additional complexity that is necessary within the parametric models to allow for active linkages to structural analysis. We have also discussed the shortcomings of traditional structural analysis workflow and the necessity of developing custom tools to integrate and leverage all available digital design tools.

A consequence of this greater integration of design tools has led to an ever increasing size in the analysis result design set. In this environment, a new set of custom interpretation tools and storage platform had to be developed. This central and custom storage of data and extraction scripts has allowed for greater distillation and dissemination of design information.

With more powerful technology and increasing client demands, the design team is now routinely challenged to propose original designs and to do so at an unparalleled velocity. This compressed design environment will lead to better design only if more effective collaborations and a dramatic paradigm shift towards information-based design, with all stakeholders engaged, is realized. We believe that the mastery of our individual (architecture, MEP, and structure) design process is a crucial first step toward being truly effective in this environment.
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References