

Structural Simulation for Architects: An Introduction to Structural Thinking for Design Students

David R Beach (Speaker)
Hammons School of Architecture at Drury University

Class Code: ED2398

Class Description:

Teaching structural design to architecture students is a bit like teaching a bowling ball to float. Both design students and bowling balls require a change in their core states to be successful in their relative tasks. Visual thinkers, like most architects, struggle with the analysis and calculation process of structural design. As a result, they rarely gain comfort with the iterative requirements of designing compelling structures that are additive to design expressions. By introducing architecture students to structural simulation in Autodesk® Revit® software, the learning process is modified to work with visual thinkers—developing a stronger connection to the design process and improved direct feedback (visual in nature) to the ramifications and potentials of design decisions. This class will outline the opportunities and pedagogy of structural simulation as a predesign effort and design development strategy in the architectural education studio course.

Learning Objectives:

1. Understanding the process of modeling with the structural tool set in Revit.
2. Application of structural simulation tools inside of Revit.
3. Modifications and enhancements that a simulation process can create in learning structural design.
4. Understanding, reading, and applying simulation data as part of a design process.

About the Speaker:

David R Beach is an architect and Assistant Professor of Architecture at the Hammons School of Architect at Drury University. Specializing in digital design technology, David is an advocate of full digital immersion as part of a traditional design process augmenting workflow to leverage technology to inform the design process, collaborate with clients and communities, and rationalize decision making through an analysis only allowed through the Building Information Modeling process. At the Hammons School of Architecture David teaches in the design studio curriculum 2nd Year experience, the Center for Community Studies working at the urban design scale, and both the introductory and advanced digital design technology courses.

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Teaching structural design to architecture students is a bit like teaching a bowling ball to float. Both design students and bowling balls require a change in their core states to be successful in their relative tasks. Visual thinkers like most architects, struggle with the analysis and calculation process of structural design. As a result they rarely gain comfort with the iterative requirements of designing compelling structures that are additive to design expressions. By introducing architecture students to structural simulation in Revit, the learning process is modified to work with visual thinkers developing a stronger connection to the design process, and improved direct feedback (visual in nature) to the ramifications and potentials of design decisions. This class will outline the opportunities and pedagogy of structural simulation as a pre-design, and design development strategy in the architectural education studio course.

In the academy, I want students to learn to manage the conflict between two modes of design thinking: Analytical and Visceral. It is not enough to simply respond to form and functionality in the current state of design, the relevant designer also has to manage significant amounts of analytical data to drive architectural design. It could be argued that the profession does a poor job of using analytical data to drive design thinking. For instance, an environmental analysis is often performed at the conclusion of the design development on a project resulting in data that is not capable of informing key design decisions. The data is *informative*, but not *formative* to the design process. A result of not engaging analytical processes as part of a design process is a component of the devaluation of architecture service of the last three decades. Designers and architects must become far more engaged with the processes of managing data to manifest design. This process of leveraging analytical data must begin at the academic level in the studio setting, creating skills that can begin to modify the design process, and push forward new modes of design thinking.

Building simulation is one of the key paradigm shifts brought about by the Building Information Modeling process. In particular, Revit® acts as a central hub (Figure 1) in a design process that can include: cost and constructability, rendering, object creation, project management, construction documentation, interactive files, and simulation. The process of simulation can occur on the same file generating visceral design information such as formality, materiality, and spatial sequence. In the same mode of thinking that allows a designer to modify and manipulate materials, one can also make modifications through simulation to evaluate environmental performance, cost analysis (as a form of simulation), or structural performance.

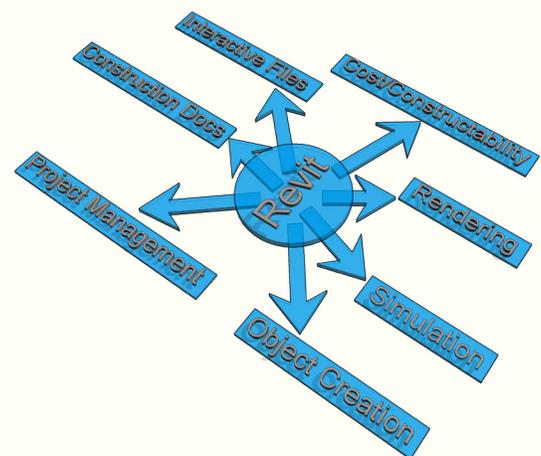


Figure 1. The BIM Hub.

The Model of a Digital Design Pedagogy:

Within a digital design curriculum very specific goals need to be developed and tracked ensuring that there is both depth to the subject matter (learning what the buttons do is not enough), and breadth to the application of the tools. Equally critical is the developing the means to assess student performance, and progress of the curriculum goals. There are four modes of design thinking

(specifically digital design thinking) that are relevant to every new piece of curriculum we roll out to our students, structural simulation being the latest addition. They are: spaces within spaces, blank screens equals blank thoughts, design criticality, and think•experiment•design•play.

Spaces in spaces describes the placement of digital design practice that I desire for each student to implement throughout their process and carry into practice. Tim Brown, in his book *Change by Design*, discusses three overlapping spaces of a project being “inspiration space, in which insights are gathered from every possible source; an ideation space, in which those insights are translated into ideas; and an implementation space, in which the best ideas are developed...” (Brown, 2009). The new beauty being discovered in a rich BIM environment is that these spaces of process are less sequential, and more parallel. That is, a new inspiration late in a project doesn’t require waiting until the next project for implementation. Manipulations of a design can be made, modified, and implemented while still being well coordinated throughout the project. In a digital design curriculum, the student should maintain a constant mode of research to gain new inspiration. The student should continually make objects, both analog (real) and virtual manifesting their concepts into ideas. The ideas should constantly be tested (implemented) through critical analysis both during the programming phase of the design process, as well as throughout final implementation. Understanding how the data from each of the three spaces (inspiration, ideation, and implementation) impacts process is a core objective to the digital design curriculum.

Blank screens = blank thoughts accounts for the difficulty of both learning design, and learning digital design. Design is a mode of thinking that is difficult to learn, and it is compounded when faced with a computer screen, and a legion of (at last count) 400 plus unique buttons in the base Revit interface (not counting non-modal windows). When Revit in particular opens, the student is faced with four arrows (Figure 2) taunting them with the notion of “design here.” Digital design is part of a design process, when fully revealed the medium of digital can certainly be inspirational in the creative phase, but for most designers it is rarely visceral. Staring at a blank screen, especially when learning design, and learning software, has to be replaced with the activity of building, drawing, sculpting, and actions that help manifest thoughts to analog things. The student in a digital design curriculum should learn a computer process early in their education, but it should be taught as something that augments the work flow. Starting digital is often counter productive, as the software has the potential of controlling the student’s design through their limitations of program understanding (often designing to their comfort level of the software, rather than designing with freedom). Starting with physical elements that allow for visceral gestures promotes a freedom of expression, connects design driven by conceptual thinking, and reduces the sensation of nausea acquired from looking at a blank screen. Once objects are created, the computer can begin developing and informing the process.

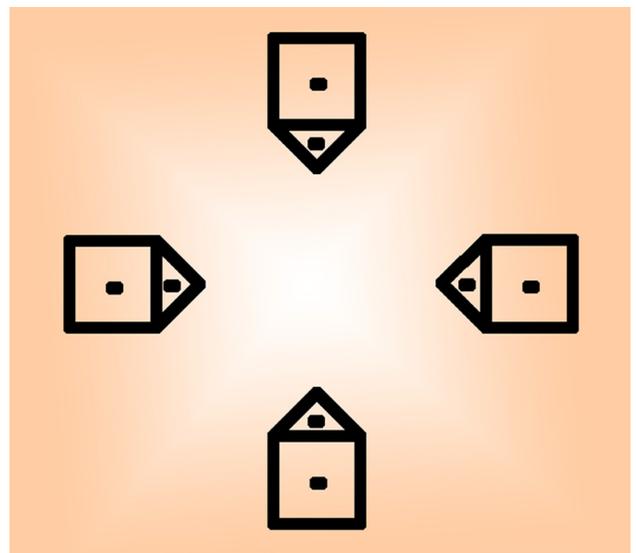


Figure 2. The Opening Screen.

Design criticality is a mode of thinking within a projects process that emphasizes constant evaluation. Trying to visualize what the process of design looks like (Figure 3) we end up with a path referred to as the design spline. This is the causality of responding to the multiple factors that inform process, and shape the project from concept to manifestation of form. While on some level we desire for

the spline to flatten out, and become a quantifiable linear expression, the reality is that will never happen. As a designer we are better served by the ability to manage and effectively utilize the amount of data that we are presented with by thoughtful critical analysis. The goal then is to not just see the plate of spaghetti, but what each twist and turn represents. This process introduces a layer of critical thinking missing in many educational studies, and as a result many architectural design firms: the collaboration of analytical and visceral design thinking to push, pull, and to inform the process of design. Embracing and learning to navigate the information gracefully through criticality requires the right toolset to generate, visualize, and respond to the data generated. Students have to learn to generate data, (both in terms of design content, and design information) and critique their own work through a process of critical thinking.

Think.Experiment.Design.Play describes the state of mind I want our digital design students to be immersed in. If you have seen Tim Brown's TED Talks video, than you also know that he treats play as a serious business, evoking the fun and joy of discovery, passion, and creativity. Digital design and BIM should be the virtual playground that allows for the discovery of ideas (think), the development of a concept (experiment), the manifestation of ideas into form (design), and tying this to the notion that the creative process is an act of joy and not a laborious task intent on consuming the weak of spirit (play). Taking a second and reflect back on the design spline, we can reiterate that the design process is not neat. In teaching design, struggling students are often seeking for a linear process, and approach the process of *revision* and *edit* with the negative connotation that both words carry. The approach is usually at fault, as the student designer is looking for immediacy in results and responses. If the process is valued, then the act of creativity is introduced with the rigor of thoughtful exploration, and embraces the notion that great work is executed through the joy and passion of play.

The Relevance of Design Thinking with Analytical Data:

Now, Coming, Change:

At the Association of Collegiate Schools of Architecture conference in spring of 2012 (ACSA 100), Phil Bernstein,



Figure 3. *The Design Spline.*

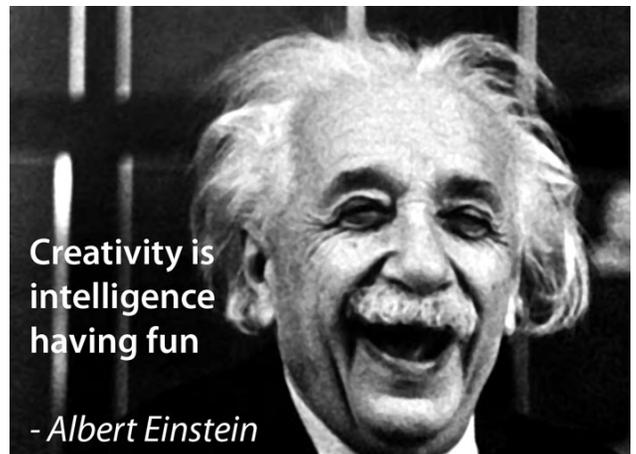


Figure 4. <http://gramilano.com/2012/08/photo-quotes-albert-einstein-on-creativity/einstein-creativity/>.

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The New York Times
Tuesday, February 21, 2012

Business Day

WORLD U.S. N.Y. / REGION BUSINESS TECHNOLOGY SCIENCE HEALTH SPORTS OPIN

Economix
Explaining the Science of Everyday Life

January 5, 2012, 11:00 AM

Want a Job? Go to College, and Don't Major in Architecture
By CATHERINE RAMPELL

Say it with me, readers: [College is worth it.](#)

For all the bellyaching about wasted degrees and the many [indebted grads stuck on their parents' couches](#), recent college graduates are still doing a lot better than their less-educated counterparts. Unemployment for new graduates is around 8.9 percent; the rate for workers with only a high school diploma is nearly three times as high, at 22.9 percent.

That's according to a new [report \[PDF\]](#) from Georgetown's Center on Education and the Workforce. The report also had some fascinating statistics on earnings and jobless rates by college major, something [we've written about](#) before.

The chart below shows unemployment rates sorted by major, based on 2009-10 census data. You can also see jobless rates for graduates of a given undergraduate major who went on to receive further education (not necessarily related to their college major). In the chart, "recent college

Figure 5. *New York Times.*

FAIA, provided a unique overview of the architecture industry in three categorical definitions: *Now*, *Coming*, and *Change*.

In understanding the current state of architecture (now), the industry is experiencing very high unemployment when compared to other sectors carrying professional degrees, specifically 13.9% unemployment for recent college graduates (Figure 6). This trend of increased unemployment prompted The New York Times article (Figure 5) titled “*Want a Job? Go to College and Don’t Major in Architecture.*” While the architecture industry can certainly blame a weak economy, and a slow down in the construction sector, another reality that designers have to observe is the limited scope in the performance of design work relating to buildings. Engineering (still tied to construction and manufacturing) has unemployment listed at 7.9% for recent college graduates. This implies at least two things: Engineers have greater diversity in their job potential due to their education and skillset. Engineers are creating a product (design) that carries a marketable value to their clients. To increase stability and the value of the architecture industry, designers must improve the ability to leverage technology expand the scope of services, and improve upon the ability to evaluate and apply analytical data to design thinking.

The immediate future (coming) of the architectural industry is the development and management of increasingly complex elements that make up the building process. The capability to manage and analyze the complexity of future construction opens up an increasingly expanding set of opportunities. By looking at Bernstein’s Technology versus Processes matrix (Figure 7) there are immediate opportunities presented to the industry that must be embraced, and developed to move the industry forward with a broader sense of relevance. *Analysis during design* is a key process currently available that imposes the necessity of critical thinking regarding simulation data as applied during the most creative stages (ideation) of development. This requirement builds a broader understanding of design decisions, builds value to the client, and is a key step to building the scope of work provided by a design team. This increase in the work scope can then begin to include elements such as *printed building components* and *construction reality capture* as potential services not often offered that have profound capabilities of transforming the business of design.

Paoli Tombesi “holds the Chair in Construction at the University of Melbourne, and in particular has studied the relationship between the intellectual dimension of architecture and the socio-technical aspects of its physical construction” (ACSA Video 2011). In *The Five Dimensions of Building Design*

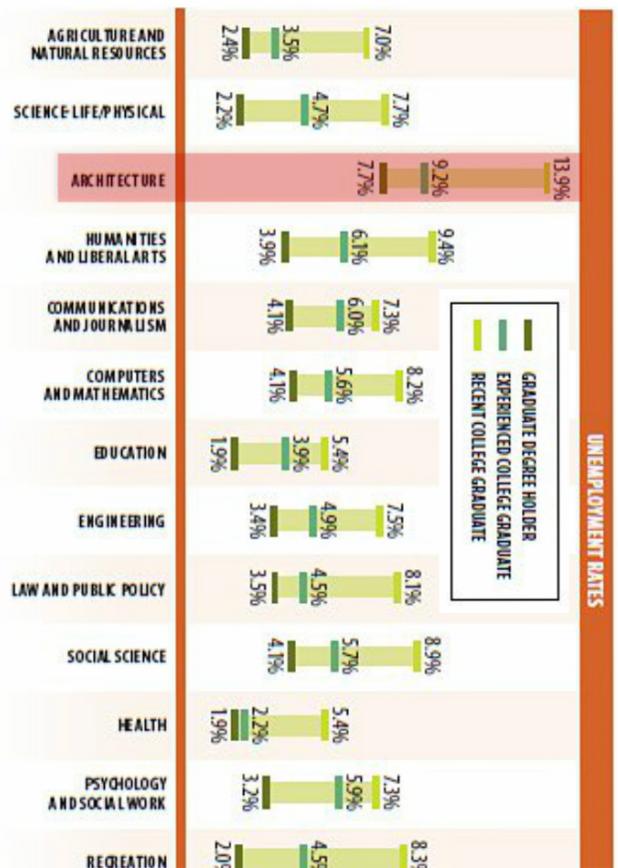


Figure 6. Unemployment data set from talk by Phil Bernstein, ACSA 100 (2012).

		Processes			
		Representation	Analysis and Simulation	Collaboration	Realization
Technologies	Digital Reality	High Resolution BIM	Analysis during design	Immersive environments	Construction reality capture
	Infinite Computing	Complex perpetual modeling	Perpetual analysis, multi-discipline optimization		High-speed translation of geometry to print
	Digital Realization	Reverse constructibility		Supply chain insight	Printed building components
	Crowd and social networking	Institutionalized, distributed knowledge		Shorter deeper transactions	

Figure 7. Technologies vs. Processes from talk by Phil Bernstein, ACSA 100 (2012).

(Figure 8) Tombesi lays out the connectivity of tasks within the process of design and construction on an architectural project. Building design being in the center, surrounded by a project's definition and control, scope formulation, production, erection and use and maintenance. The connectivity of the different phases must all communicate to, and inform the design process. (WATCH TOMBESI VIDEO TOMORROW!!) This notion is a driver of necessary change in the profession of architecture and will be a design imperative not just to complete projects of a complex nature, but to be able to provide an improved service that leverages the ability to navigate the relationships gracefully and successfully. Effective navigation will require improved application of technology and an understanding of the BIM Hub (Figure 1) workflow.

The Pedagogy of Analysis:

There are currently three key pieces of analysis rolling into our design curriculum at Hammons School of Architecture. At the forefront, this requires Building Information Modeling in Revit to be a compulsory piece of our curriculum. The concept of applying analysis is not to study how a design will perform, but to use performance to help guide design thinking. Understanding the difference between performing an analysis pass on a design, and analyzing to inform the design is a critical piece of our student performance criteria in our digital design curriculum. We have an immediate goal of establishing analysis on energy and environmental response, structural design, and human behavior.

Environmental response simulation should happen in the pre-design or building programming phase. "A green agenda did not used to be about 'fashion,' it used to be about survival" (Foster, 2007). Norman Foster is articulating a point that many designers are sensing in the current trend of environmental design, that a green design process is more about marketability than a response to an emerging environmental crisis. Despite our efforts in moving toward sustainable thinking, we are still acting on a trend, not a necessity. If environmental factors are going to inform our work, they should be researched at the outset of design by implementing current technology, our tool of choice at the Hammons School of Architecture is Project Vasari®. The early phases of the design process, especially building programming, still rely heavily on intuition, and a singular vision rather than pragmatic information which can shape both the quantitative and qualitative aspects of design. Our practice is that designers must begin integrating a process of intense information modeling and simulation for economic, social, and environmental sustainability to create work that moves past trend, and begins to approach environmental design thinking as necessity.

Structural simulation allows the designer to begin an earlier understanding of schematic performance as it relates to forces imposed on the design. By implementing structural simulation

Paolo Tombesi, the five dimensions of building design
The idea of the building procurement process as a network of design and coordination activities.

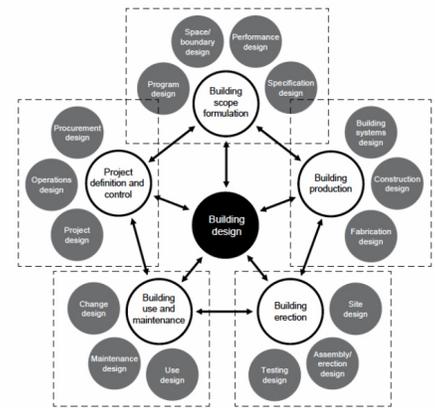


Figure 8. Paolo Tombesi - the five dimensions of building designer, from talk by Phil Berstein, ACSA 100 (2012).

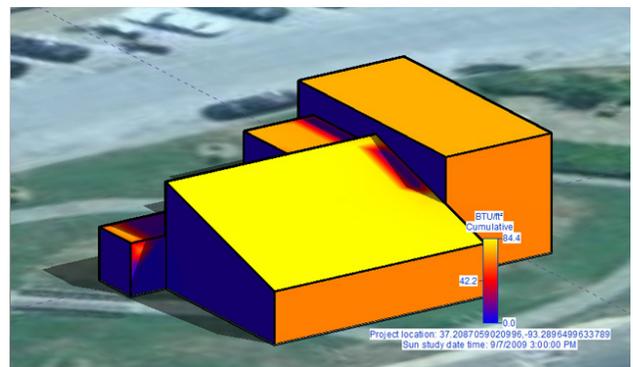


Figure 9. Solar Heat Gain in Project Vasari

the designer can be more technically prepared to engage the building team (engineers, contractors, clients) in building performance, but can also leverage structural thinking as a design process. This process is often overlooked by designers who are typically visual thinkers that are categorically comfortable responding and reacting to the concepts of form, scale, materiality, and tectonics. Visual thinkers however, often struggle with the mathematical implications imposed upon a process of resolving a structural system which **drives** the design's potential form, scale, materiality and tectonics. Introducing structural simulation in Revit and Robot® allows for design process studies based on building information models that generate visual feedback of analytical data regarding forces and deflection. This creates an opportunity for the design student to test concepts, understand the relationship between structural components, and generate structures that are integrated into the design concept.

Behavioral simulation utilizes virtual crowd control technology to target responses and interactions between design occupants and their built environment. While this mode of research is easily performed by observation of existing spaces, predicting interactions of occupants is typically only performed based on building code requirements (such as location and amounts of egress), or instinctual based on assumptions of motion. The process is not iterative or experimental, but only applies assumptions based on previously generated data. Applying behavioral simulation can resolve potential traffic and circulation problems, improve egress rather than applying the lowest common denominator (building code), and create design based on an analytical understanding of flow and motion of spatial sequence.

Structural Design Thinking:

This is a simplification, but an important one, and like all things by Francis DK Ching brilliantly articulated. "The Architecture of Space, Structure, and Enclosure" regards three elemental formal tools. *Spaces* as the organizational patterns, relationships and hierarchy. *Enclosure* as the system that defines light, view, focus and acoustics. And, the one we don't deal with often on a high level: *structure*, which is capable of informing surface, shape, edges, and openings. What I often observe in studios at all levels (academic, and professional) that designers are well prepared to deal with Ching's artistic notions regarding the composition of space and enclosure, but disregard the potential for structural expression. Perhaps designers don't respond to structural thinking with a truly critical process, or perhaps the thought of charts, graphs, and numbers make visual thinkers queasy. Regardless of the reasons, the inability of any designer to not thoughtfully resolve a structural solution devalues our ability to perform design tasks, reduces the scope of work, and relegates design decisions to a team that is not trained to evaluate the

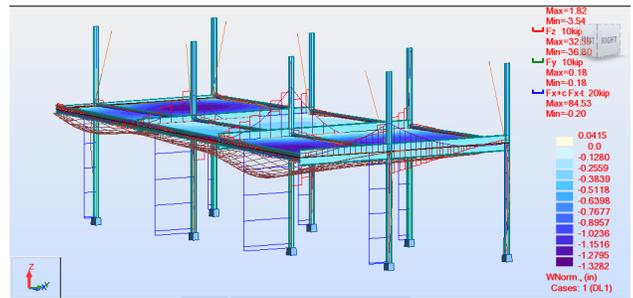


Figure 10. Structural Simulation in Robot.



Figure 11. Behavioral simulation in Project Geppetto®.

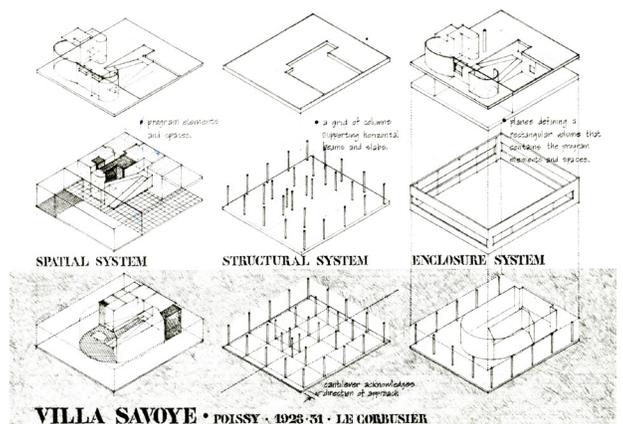


Figure 12. Spatial, Structural, and Enclosure systems of Villa Savoye in Form Space and Order by Francis DK Ching.

broader context of a project.

Moving back to gain perspective, I looked at both the Architectural Registration Exams (ARE) and my own structural education for context. What do we expect designers to know about structures (ARE) and what prerequisite knowledge is the academy providing to build successful professionals? How do we teach structural thinking? How do we create a process that allows the student to respond to structure as a major (one of three) element that is driving formal design qualities: Space, Enclosure, Structure?

The ARE looks specifically at General Forces, Seismic Forces, Wind Forces, and Lateral Forces, as well as a design vignette covering a simple structural solution for a basic building. The requirements of the test cover breadth of knowledge, but as multiple choice tests do, require little to no depth in the application of structural thinking. My personal structural education, which I do value, prepared me for both the ARE and to have basic communication skills with a structural engineer. However, my structural education was centered around texts like *Load Resistance and Factor Design* (excerpt shown in Figure 13). While informative, manuals are not capable of helping students think of structure as a formative element in the design process. They are non-visual by design (charts like designing). They limit the potential of finding structural solutions to the mathematical “lid” on the student’s capabilities usually set by either by college level trigonometry, or precalculus. The potential of structural simulation in the studio is the removal of the mathematical “lid” which is replaced by the students limitation of creating a building information model, and their imagination. Students can begin to tackle more complex problems, work on whole building solutions, and develop structural designs that are additive to, or integral to the design quality. Problem resolutions can become iterative in process allowing for experimentation, and depth in the exploration of possible solutions to the structural problems.

The resultant of not learning the language of structural design is a passive aggressive approach to employing structure as a design element in the educational studio. Students are often either not comfortable at all with the application of structure to their design and seek the lowest common denominator of resolution: the default Revit bar joists everywhere. Or, the design student comes up with an elaborate solution, often with no idea of how well it might actually work. Simulation can begin bringing resolution to

$$X_2 = \frac{4C_w}{I_y} \left(\frac{S_x}{GJ} \right)^2 \quad (F1-9)$$

$$M_r = (F_y - F_r) S_x \quad (F1-7)$$

$$M_p = Z_y F_y$$

$$F_r = 10 \text{ ksi for rolled shapes}$$

The unbraced length in the charts may be either the total span or any part of the total span between braced points. The plots shown in these charts were computed for beams for which $C_b = 1.0$. When a moment gradient exists between points of bracing, C_b may be larger than unity. (See Table 4-1.) Using this larger value of C_b may provide a more liberal flexural strength for the section chosen if the unbraced length is greater than L_p . In these cases, the design moment can be determined using the provisions of Section F1.2a of the LRFD Specification.

$$\phi_b M_n = \phi_b C_b \left[M_p - (M_p - M_r) \left(\frac{L_b - L_p}{L_r - L_p} \right) \right] \leq \phi_b M_p$$

The unbraced length L_b , ft, with the limit indicated by an open symbol \circ , is the maximum unbraced length of the compression flange beyond which the design moment is governed by Specification Section F1.2b. For unbraced lengths greater than L_r :

$$\phi_b M_n = \phi_b M_{cr} = \phi_b C_b \frac{\pi}{L_b} \sqrt{EI_y GJ + \left(\frac{\pi E}{L_b} \right)^2 I_y C_w} \leq \phi_b C_b M_r \text{ and } \phi_b M_p$$

In computing the points for the curves, C_b in the above formulas was taken as unity, $E = 29,000$ ksi and $G = 11,200$ ksi. The properties of the beams are taken from the Tables of Dimensions and Properties in Part 1 of this LRFD Manual. The beam strengths have been reduced by multiplying the nominal flexural strength M_n by 0.9, the resistance factor ϕ_b for flexure.

Over a limited range of length, a given beam is the lightest available for various combinations of unbraced length and design moment. The charts are designed to assist in selection of the lightest available beam for the given combination.

The solid portion of each curve indicates the most economical section by weight. The dashed portion of each curve indicates ranges in which a lighter weight beam will satisfy the loading conditions.

The curves are plotted without regard to shear strength and deflection criteria, therefore due care must be exercised in their use. The curves do not extend beyond an arbitrary span/depth limit of 30.

The following examples illustrate the use of the charts.

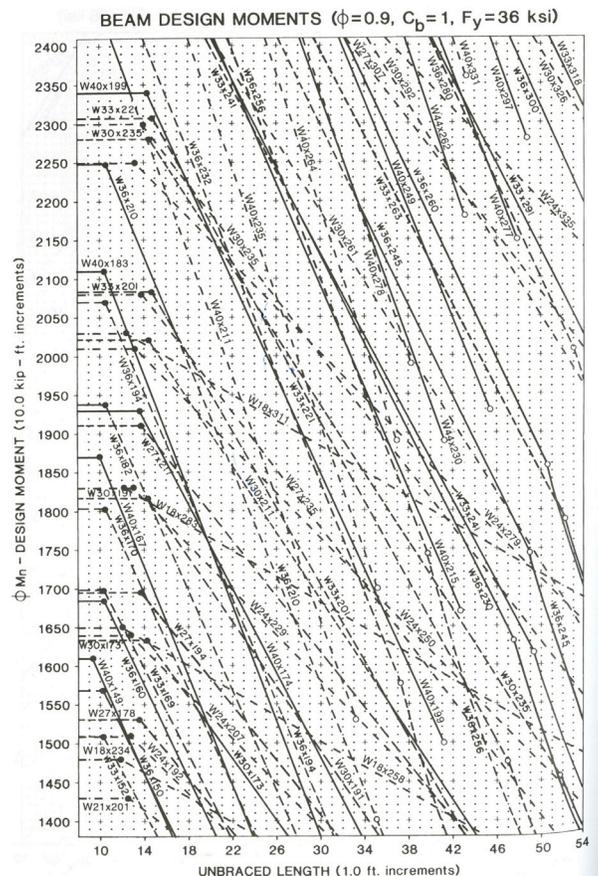


Figure 13. Load and Resistance Factor Design Volume 1, Second Edition by AISC.

structural design, giving the students the chance to apply loads, modify the structural size and spacing, observe deflection and resultant forces, and iterate the process to generate multiple solutions providing depth and breadth to the structural solution.

Applying a broader scope to structural learning, Professor Keith Hedges (2012) has developed a strategy of three realms of structural thinking: Rigid body statics and deformable body engineering mechanics, material design and analysis, and building stabilization.

First, **rigid body statics and deformable body engineering mechanics** covers *reactions, shear and moment transfer, and section modulus*. This mode of study allows a student to understand forces and reactions within an overall structural system, application of forces on structural members, and an understanding of structural scale. There are several opportunities for students to explore these issues on their design solutions, but one of the most intuitive and productive pieces of software for rigid body statics is Autodesk ForceEffect®. The process of working through ForceEffect should occur in the preliminary, pre-design phase (massing) of an architectural project and should be incorporated into the building programming documentation.

1. Export a sectional view in .jpg format of the massing model and push the file to a device with ForceEffect (my personal mode of transferring images is via email).

2. Start a new scene in ForceEffect and use Photo Albums to import the section image as a background.

3. Using the Create Element tool (A.), draw the first line (B.), then select the numerical length value (C.) to a known dimension (in the example, 24'-0") (D.). This will establish the scale of the objects relative to the background image. As long as you are essentially tracing the background image, there will be no need to modify the lengths of elements (Figure 14).

4. Finish tracing the key pieces of the structure using the section cut as an underlay for their location.

5. Add fixed pin supports (E.) under the columns (F. and G.) that will be transferring the load to the ground (Figure 15).

6. Note that the icon in the top right (The Degree of Freedom Indicator (H.)) is red, this essentially means that the system is not statically determinate, and a cross brace may be required to provide reaction calculations. Add in a cross member if/as required (I.) (Figure 15).

7. Select the forces toolset, and distributed load (J.). Start placing a distributed load by touching first on the

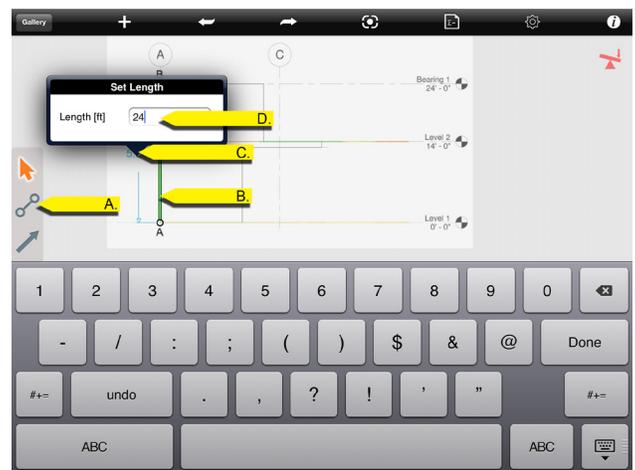


Figure 14. Step 3 ForceEffect.

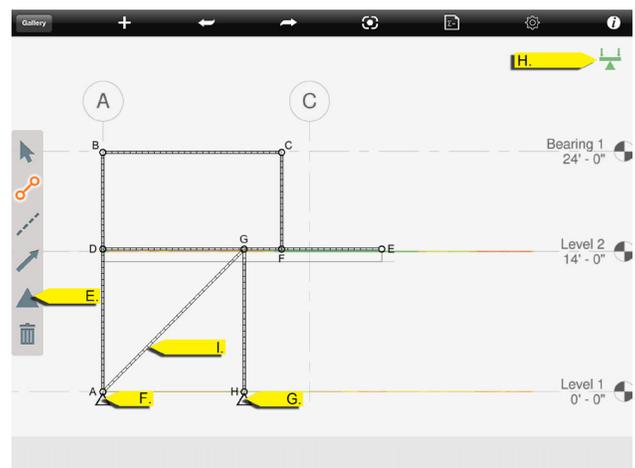


Figure 15. Step 5 and 6 ForceEffect.

element (K.) (structural member) that you want to load applied to. Drag up to set the initial load, drag over to begin distributing the load.

8. **NOTE:** You will probably want to scale the force vectors to fit on screen. Click and hold on any blank space in the project, and click the scale vectors tool (top icon of the menu that pops up during the hold) to modify the sizes of all vectors to fit proportionally within the view.

9. To edit the load location and values: Click on the select icon (L.), select the distributed load. Touch the numerical lb/ft number (M.) to modify the load amount. Touch and drag the grips in the lower corners of the distributed load (N.) to modify the load location.

10. **NOTE:** Understand that you are applying a distributed loads representing the loading value placed on beams from either a floor or roof system. A good starting point might be assuming a structure that is either 10' or 20' on center. Using building codes, resolve the type of loading condition per square foot and multiply this by the span. A 10lb/sqft load with a structure that is 20' on center creates a 200lb/ft distributed load across an element in ForceEffect.

11. Complete the distributed loads (Figure 18).

12. Output the file by selecting the Report button on the top right (O.). You can then either print or email the report by using the Send icon in the top left. The report from the example project is in the following pages.

13. Analysis: There are a couple of key elements that are especially important for a student to understand. First, offset columns are a problem unless (columns HG and CF) there is a truly significant design reason forcing this decision. Along with the offset problem, the issue is being compounded by the cantilever with the upper column landing on the cantilever side. Finally, column HG is carrying more than three times the load as column AD. Design solutions exist to normalize the situation, distribute the loads more evenly between the columns, and improve the situation with the cantilever. By building this diagram and report in the pre-design phase, thoughtful resolution can be incorporated into the design.

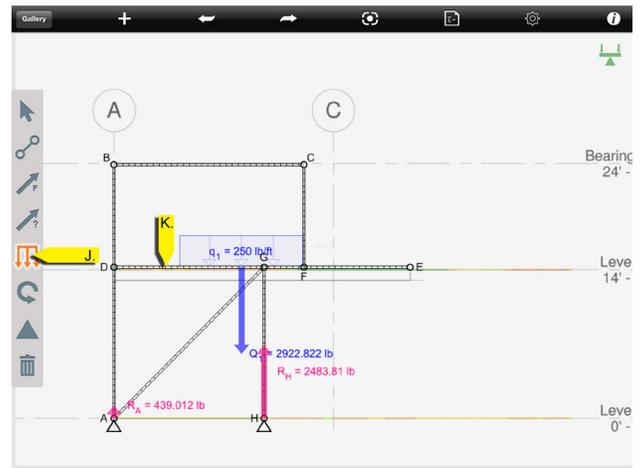


Figure 16. Step 7 ForceEffect.

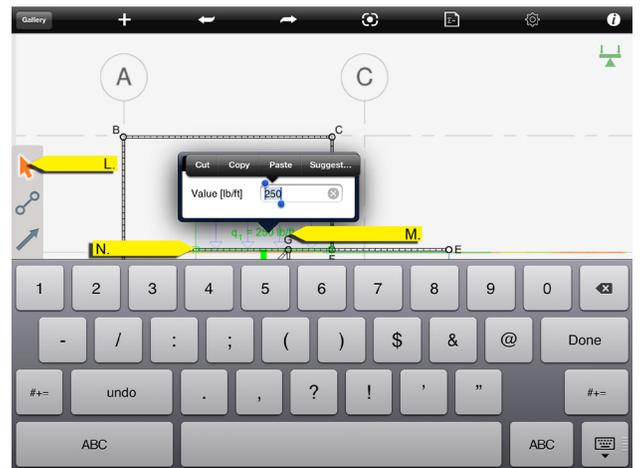


Figure 17. Step 9 ForceEffect.

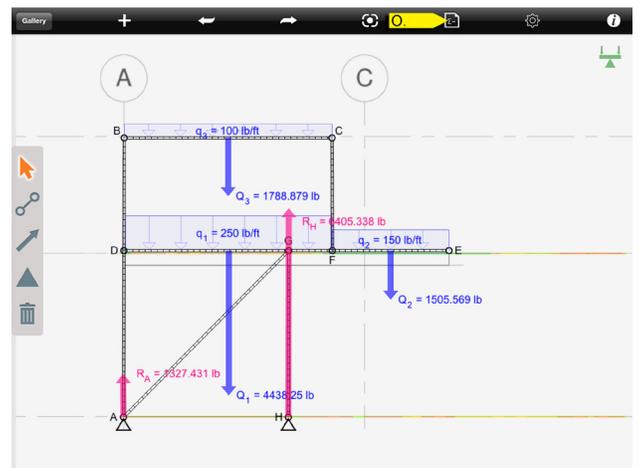
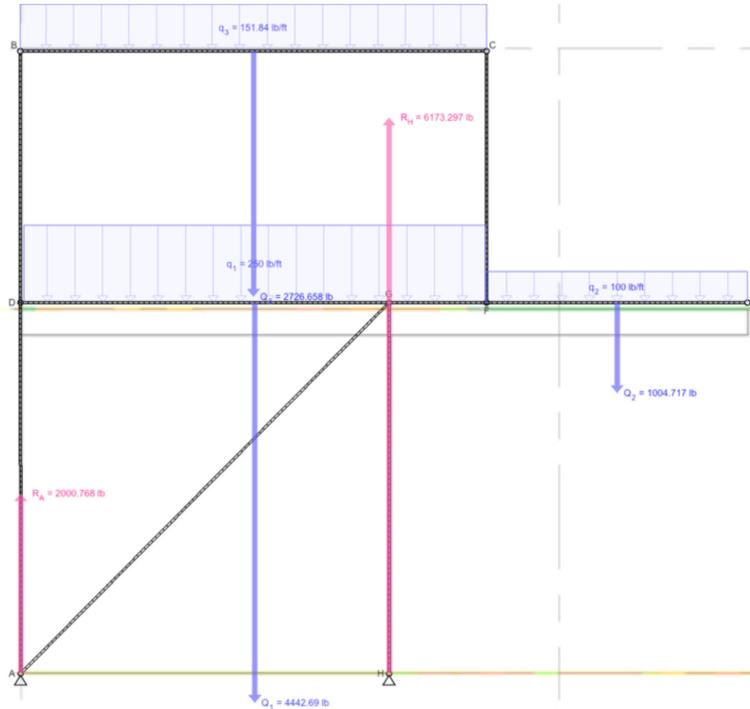


Figure 18. Step 11 and 12 ForceEffect.



Inputs:

Elements

Element	Length	Weight
A-B	24.000 ft	
B-C	17.957 ft	
D-E	28.000 ft	
C-F	9.694 ft	
G-H	14.306 ft	
A-G	20.149 ft	

Distributed Loads

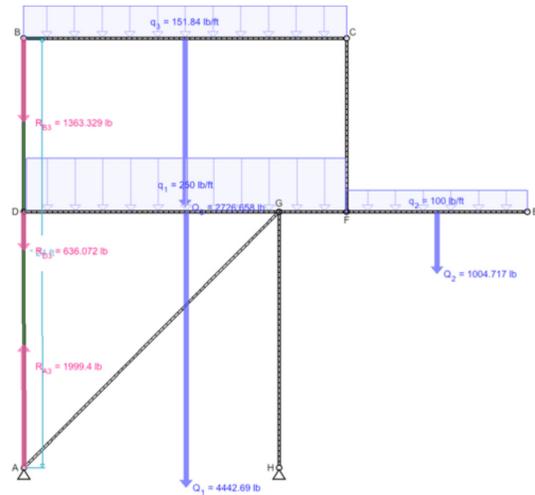
Distributed Load	Direction	Size
Q_1	↓	4442.690 lb (250.000 lb/ft)
Q_2	↓	1004.717 lb (100.000 lb/ft)
Q_3	↓	2726.658 lb (151.840 lb/ft)

Results:

Reaction Forces

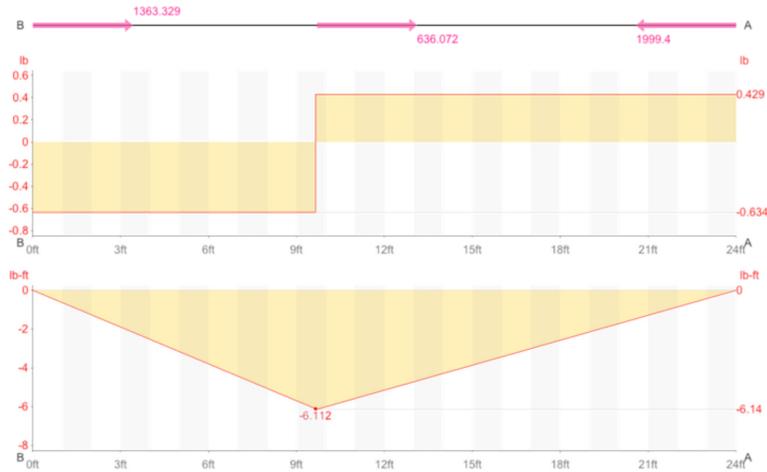
Force	Direction	Size	Angle
R_A	↑	2000.768 lb	90.0°
R_H	↑	6173.297 lb	90.0°

Element A-B

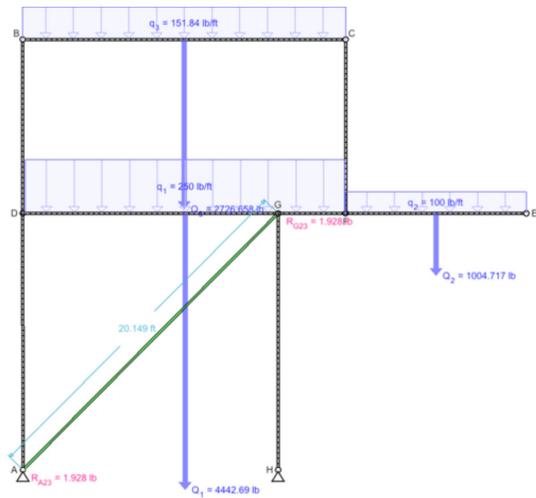


Equations	Results
$\Sigma M = 0 \Rightarrow -0.011 \times R_{B3[Y]} - 24.000 \times R_{B3[X]} - 0.007 \times R_{D3[Y]} - 14.306 \times R_{D3[X]} = 0$	$R_{A23[X]} = 1.358 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow R_{A3[X]} + R_{B3[X]} + R_{D3[X]} = 0$	$R_{A23[Y]} = 1.369 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow R_{A3[Y]} + R_{B3[Y]} + R_{D3[Y]} = 0$	$R_{A3[X]} = -1.359 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow R_{A[X]} - R_{A3[X]} - R_{A23[X]} = 0$	$R_{A3[Y]} = 1999.399 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow R_{A[Y]} - R_{A3[Y]} - R_{A23[Y]} = 0$	$R_{B3[X]} = 0.000 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow -R_{B3[X]} - R_{B6[X]} = 0$	$R_{B3[Y]} = -1363.329 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow -R_{B3[Y]} - R_{B6[Y]} = 0$	$R_{B6[X]} = -0.000 \text{ lb}$
	$R_{B6[Y]} = 1363.329 \text{ lb}$

Shear Force and Moment Diagram

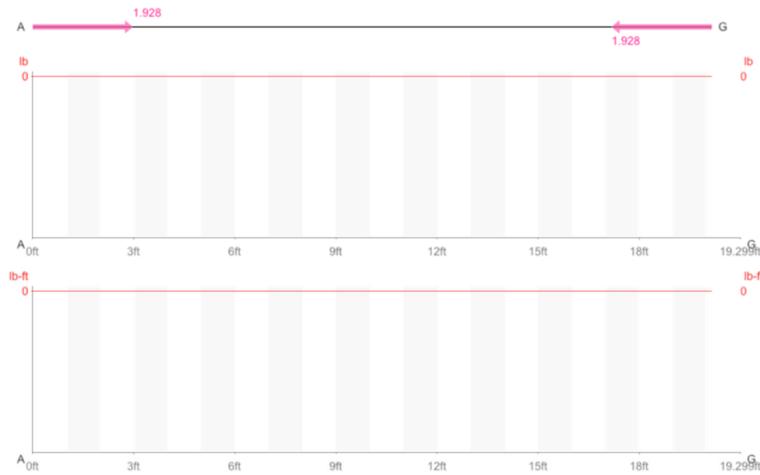


Element A-G

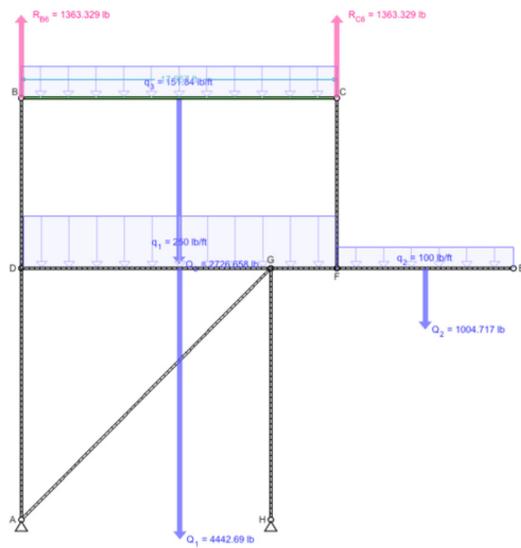


Equations	Results
$\Sigma M = 0 \Rightarrow 14.189 \times R_{G23[Y]} - 14.306 \times R_{G23[X]} = 0$	$R_{A23[X]} = 1.358 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow R_{A23[X]} + R_{G23[X]} = 0$	$R_{A23[Y]} = 1.369 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow R_{A23[Y]} + R_{G23[Y]} = 0$	$R_{A3[X]} = -1.359 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow R_{A[X]} - R_{A3[X]} - R_{A23[X]} = 0$	$R_{A3[Y]} = 1999.399 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow R_{A[Y]} - R_{A3[Y]} - R_{A23[Y]} = 0$	$R_{G14[X]} = 1.359 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow -R_{G14[X]} - R_{G19[X]} - R_{G23[X]} = 0$	$R_{G14[Y]} = 6174.666 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow -R_{G14[Y]} - R_{G19[Y]} - R_{G23[Y]} = 0$	$R_{G19[X]} = -0.001 \text{ lb}$
	$R_{G19[Y]} = -6173.297 \text{ lb}$
	$R_{G23[X]} = -1.358 \text{ lb}$
	$R_{G23[Y]} = -1.369 \text{ lb}$

Shear Force and Moment Diagram



Element B-C

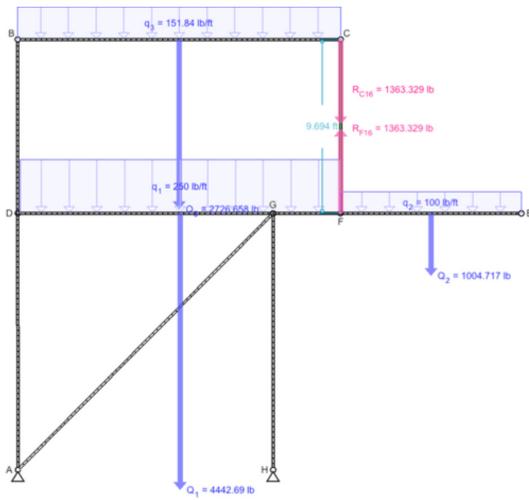


Equations	Results
$\Sigma M = 0 \Rightarrow 17.957 \times R_{C6[Y]} - 0.000 \times R_{C6[X]} = -Q_3[X] \times -0.000 - Q_3[Y] \times 8.979$	$R_{B3[X]} = 0.000$ lb
$\Sigma F_{[X]} = 0 \Rightarrow R_{B6[X]} + R_{C6[X]} = -Q_3[X]$	$R_{B3[Y]} = -1363.329$ lb
$\Sigma F_{[Y]} = 0 \Rightarrow R_{B6[Y]} + R_{C6[Y]} = -Q_3[Y]$	$R_{B6[X]} = -0.000$ lb
$\Sigma F_{[X]} = 0 \Rightarrow -R_{B3[X]} - R_{B6[X]} = 0$	$R_{B6[Y]} = 1363.329$ lb
$\Sigma F_{[Y]} = 0 \Rightarrow -R_{B3[Y]} - R_{B6[Y]} = 0$	$R_{C16[X]} = -0.000$ lb
$\Sigma F_{[X]} = 0 \Rightarrow -R_{C6[X]} - R_{C16[X]} = 0$	$R_{C16[Y]} = -1363.329$ lb
$\Sigma F_{[Y]} = 0 \Rightarrow -R_{C6[Y]} - R_{C16[Y]} = 0$	$R_{C6[X]} = 0.000$ lb
	$R_{C6[Y]} = 1363.329$ lb

Shear Force and Moment Diagram

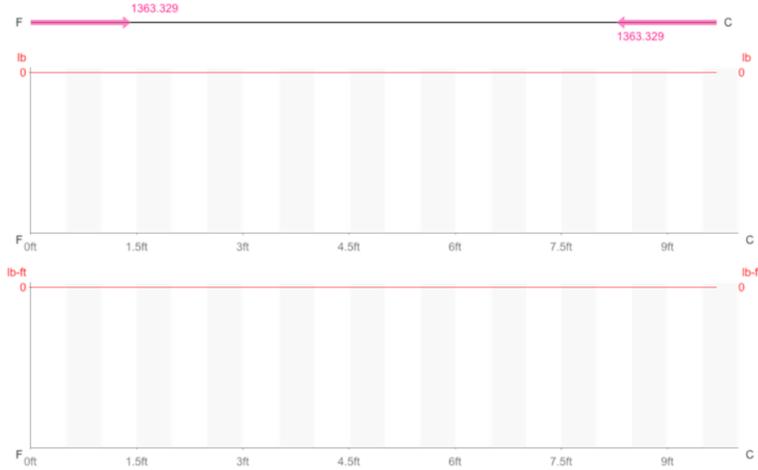


Element C-F

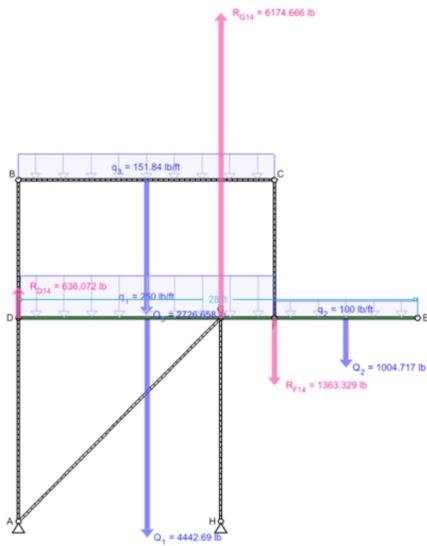


Equations	Results
$\Sigma M = 0 \Rightarrow -0.000 \times R_{F16[Y]} + 9.694 \times R_{F16[X]} = 0$	$R_{C16[X]} = -0.000 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow R_{C16[X]} + R_{F16[X]} = 0$	$R_{C16[Y]} = -1363.329 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow R_{C16[Y]} + R_{F16[Y]} = 0$	$R_{C6[X]} = 0.000 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow -R_{C6[X]} - R_{C16[X]} = 0$	$R_{C6[Y]} = 1363.329 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow -R_{C6[Y]} - R_{C16[Y]} = 0$	$R_{F14[X]} = -0.000 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow -R_{F14[X]} - R_{F16[X]} = 0$	$R_{F14[Y]} = -1363.329 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow -R_{F14[Y]} - R_{F16[Y]} = 0$	$R_{F16[X]} = 0.000 \text{ lb}$
	$R_{F16[Y]} = 1363.329 \text{ lb}$

Shear Force and Moment Diagram

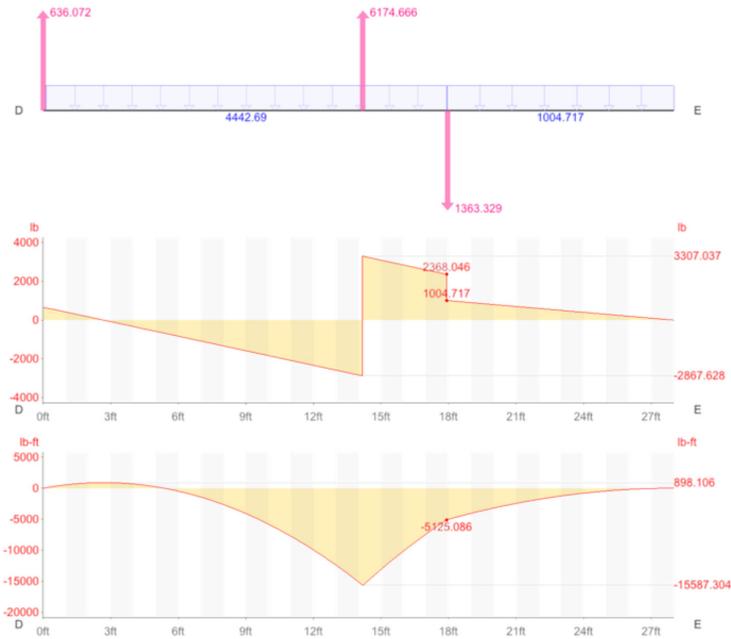


Element D-E

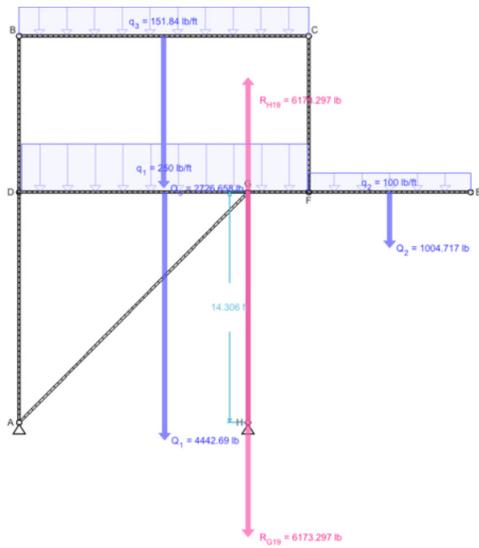


Equations	Results
$\Sigma M = 0 \Rightarrow 28.000 \times R_{E14[Y]} - 0.000 \times R_{E14[X]} + 17.953 \times R_{F14[Y]} - 0.000 \times R_{F14[X]} + 14.196 \times R_{G14[Y]} - 0.000 \times R_{G14[X]} = -Q_1[X] \times -0.000 - Q_1[Y]$ $\times 9.025 - Q_2[X] \times -0.000 - Q_2[Y] \times 22.976$	$R_{D14[X]} = -1.359 \text{ lb}$ $R_{D14[Y]} = 636.070 \text{ lb}$ $R_{D3[X]} = 1.359 \text{ lb}$ $R_{D3[Y]} = -636.070 \text{ lb}$ $R_{E14[X]} = -0.000 \text{ lb}$ $R_{E14[Y]} = -0.000 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow R_{D14[X]} + R_{E14[X]} + R_{F14[X]} + R_{G14[X]} = -Q_1[X] - Q_2[X]$	
$\Sigma F_{[Y]} = 0 \Rightarrow R_{D14[Y]} + R_{E14[Y]} + R_{F14[Y]} + R_{G14[Y]} = -Q_1[Y] - Q_2[Y]$	
$\Sigma F_{[X]} = 0 \Rightarrow -R_{D3[X]} - R_{D14[X]} = 0$	
$\Sigma F_{[Y]} = 0 \Rightarrow -R_{D3[Y]} - R_{D14[Y]} = 0$	
$\Sigma F_{[X]} = 0 \Rightarrow -R_{E14[X]} = 0$	
$\Sigma F_{[Y]} = 0 \Rightarrow -R_{E14[Y]} = 0$	

Shear Force and Moment Diagram

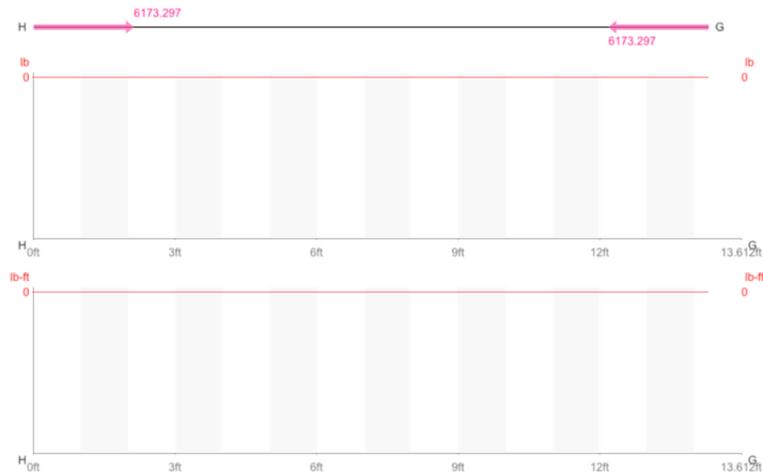


Element G-H



Equations	Results
$\Sigma M = 0 \Rightarrow -0.000 \times R_{H19[Y]} + 14.306 \times R_{H19[X]} = 0$	$R_{G14[X]} = 1.359 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow R_{G19[X]} + R_{H19[X]} = 0$	$R_{G14[Y]} = 6174.666 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow R_{G19[Y]} + R_{H19[Y]} = 0$	$R_{G19[X]} = -0.001 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow -R_{G14[X]} - R_{G19[X]} - R_{G23[X]} = 0$	$R_{G19[Y]} = -6173.297 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow -R_{G14[Y]} - R_{G19[Y]} - R_{G23[Y]} = 0$	$R_{G23[X]} = -1.358 \text{ lb}$
$\Sigma F_{[X]} = 0 \Rightarrow R_{H[X]} - R_{H19[X]} = 0$	$R_{G23[Y]} = -1.369 \text{ lb}$
$\Sigma F_{[Y]} = 0 \Rightarrow R_{H[Y]} - R_{H19[Y]} = 0$	$R_{H19[X]} = 0.001 \text{ lb}$
	$R_{H19[Y]} = 6173.297 \text{ lb}$

Shear Force and Moment Diagram



Second, **material design and analysis** covers *preliminary member size, beam lateral buckling, and column slenderness*. This mode of study allows a student to understand specific structural member sizing, and the relationship between scale and materiality. Utilizing Revit (in particular the Revit Extensions) and Autodesk Robot® students can resolve preliminary sizing, eliminate unnecessary complexity, work through multiple material solutions in an iterative process, and introduce an understanding of the structural systems attributes during design formation.

1. Starting with the base massing model, navigate to the first area of study, a floor plan view, and establish a structural grid (A.). Remember, the structural grid system in Revit is not as much about stating emphatically “a column will go here” as it is a means to control columns, footings, beams, and cross bracing. Moving one grid line is easier than moving all of previously mentioned elements, so establishing grids is a mode of manipulation at this point, not a mode of location (Figure 20).

2. Isolate the structural grid (B.) making it easier to select the intersection of structural grids. And select the column tool (C.) (Figure 21). Using the “at grids” tool, highlight all of the grid lines that you want to include columns and press the green OK check to place the default column at each grid intersection.

3. Moving to a 3d view (this particular view was built by duplicating the default 3d view, and hiding all of the massing elements in the view, and renaming the view “structure”) modify the structural columns by establishing connections at the Base and Top Levels (D. and E.). Yes, you should do this prior to making the columns, but I never do, you probably don’t either! You can also make any material or construction modifications you would like to the columns at this time as well. For this tutorial, we are going to be using steel (Figure 22).

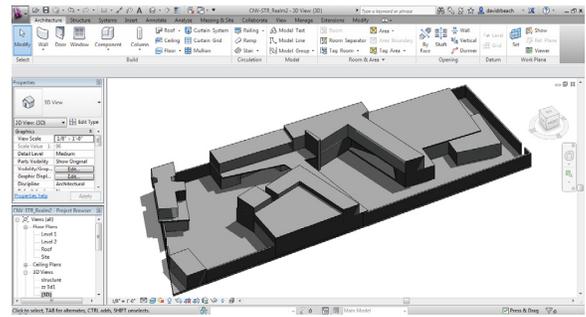


Figure 19. Massing Model.

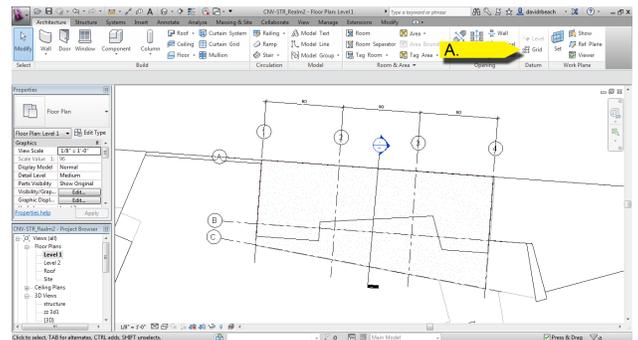


Figure 20. Establish Structural Grid.

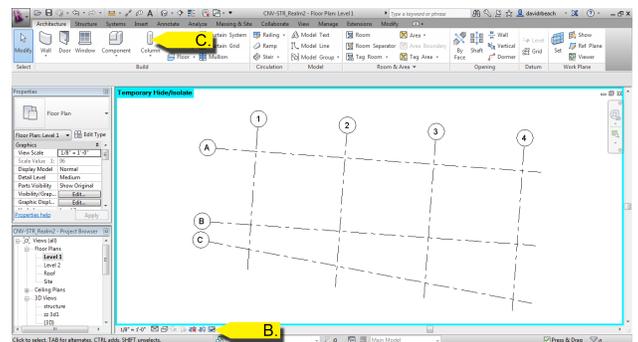


Figure 21. Isolate and Add Columns.

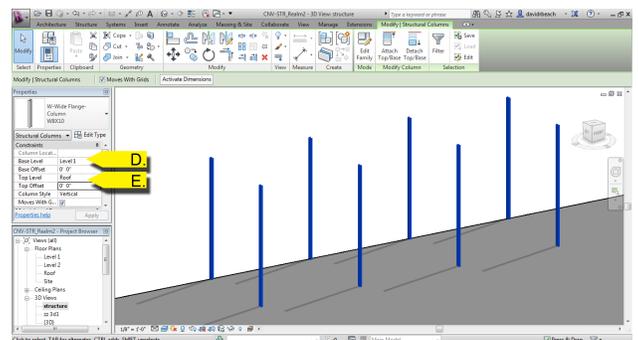


Figure 22. Modify Columns.

4. Moving to level two, select the beam tool (F.) under the Structure tab. Using the “On Grids” tool, select each grid line that has a beam associated with it using “Ctrl Click” to select multiple grid lines. Click the green finish check to create the beams. Repeat this process for any necessary levels (Figure 23). Note: You can also trace column line to column line on each level...it is just more work and less fun.

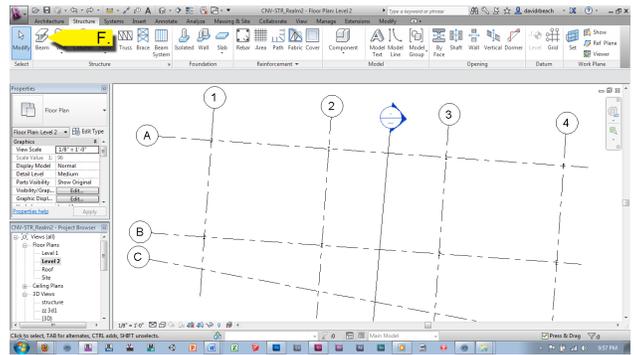


Figure 23. Add Beams.

5. Add Isolated Footings (under the Structure tab) for each column using the “At Column” method in the 3d view (G.) verifying that the footings will be added at level 1 (H.). Select each column using “Ctrl Click” to select multiple columns, and click the green finish check mark to create the footings (Figure 24).

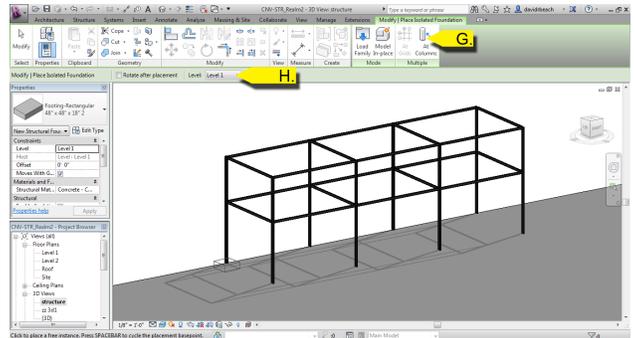


Figure 24. Add Isolated Footings.

6. Add a structural floor slab to the second level. Note: This is not an architectural floor! It is located under both the Architecture and Structure tabs, but you need to verify that you are using the Floor: Structure tool. Use the “Pick Supports” tool (J.) to select each beam (J.) that forms the perimeter of the floor. Make sure the purple lines forming the floor boundary are a closed loop (no gaps, overlaps, or duplicates in line work) and then click the green finish check mark to create the floor (Figure 25).

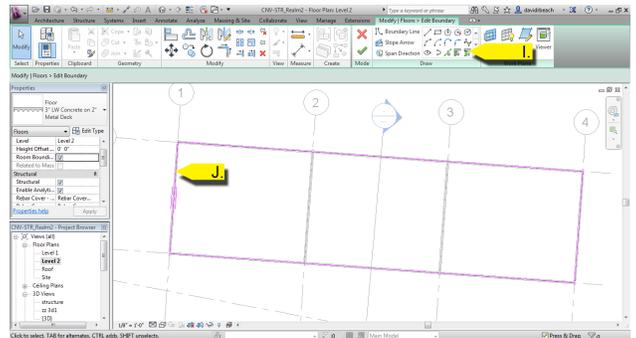


Figure 25. Create structural floor.

7. NOTE: Revit materials are not just defining the appearance of virtual objects, but performance as well. Material properties contain physical values that allow complete thermal and structural simulation (Figure 26). You can review and modify the properties (I would highly recommend not modify the properties without expert advise on material performance) by selecting materials in the object properties (K.), double clicking on the desired material for review in the material browser (L.), to open up physical properties (M.).

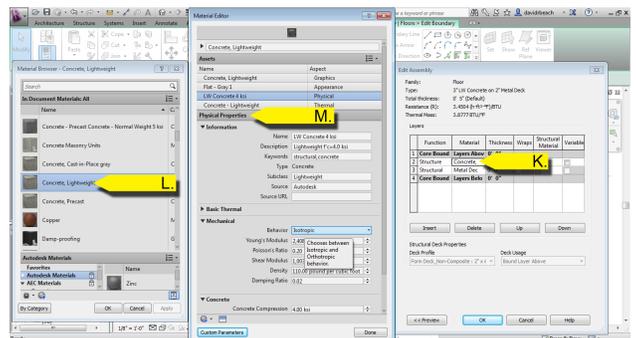


Figure 26. Concrete material properties.

8. Modeling problem one: The beams and floor were both created on level two. That means the top of the beams and the top of the floor are both in the same plane, which is doable but not probable in construction. The working solution that I used prior to running simulation was to duplicate the Level Two elevation tag in the section view (Figure 27) renaming it to TO Beams (Top of Beams). However, the simulation we will be running on composite beams looks for a slab and beam associated to the same reference tag. So, for simulation reasons use an offset to the depth of the slab.

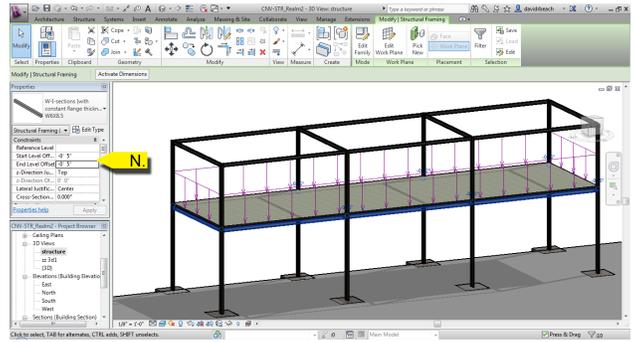


Figure 27. TO beam.

9. Next, we are going to add a load onto the floor system that will create forces distributed through the structural members, down to the footings. Select the Loads toolset is under the Analyze tab, and click on Area Load (O.) (Figure 28). Add the area load to the outside edge of the concrete slab, and take time to lock the load boundary lines to the slab edge (Figure 29, P.).

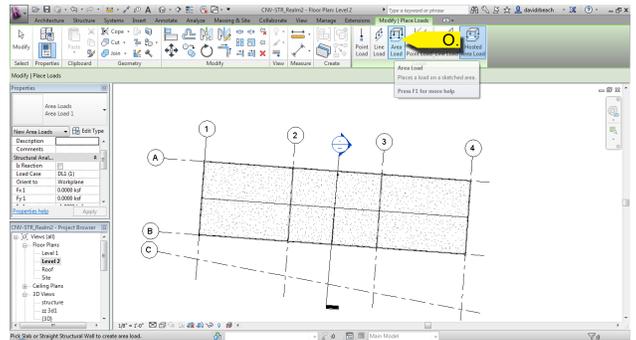


Figure 28. Area load.

10. Set the parameters of the of the area load in the properties panel. For the sake of simplicity (remember, the goal is to resolve and discovery basic information in the formative design phases!) we will assume all vertical loading under the DL1 or dead load category, and all lateral loads under the WIND1 or wind load category. The goal is simplicity, additional modifications, parameters, detailing and data sets can be added later in the process. For the example project we are only using DL1 (Q.) and -0.1 ksi (one hundred pounds per square foot down) (R.) as the loading condition (Figure 29).

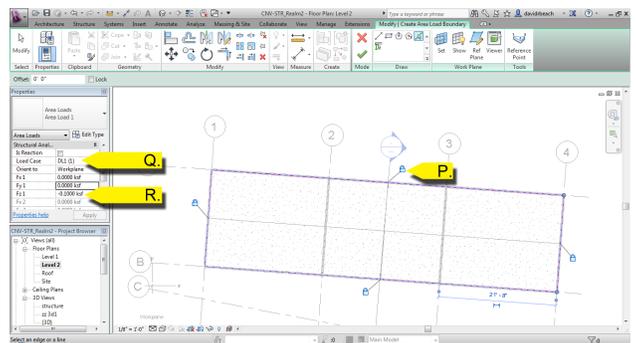


Figure 29. Area load parameters.

11. Switching back to a 3d view, launch the composite beam design tool by selecting a beam (S.), then the Extensions tab (T.), the Analysis drop down list (U.) and Composite Design (V.). This will launch a portion of Robot within the Revit workspace (Figure 30).

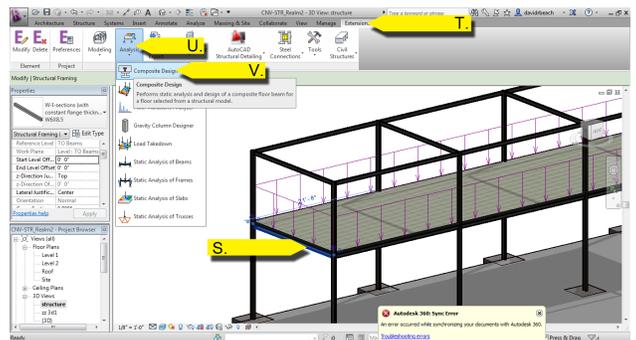


Figure 30. Launch composite beam design.

12. Select the Design tool (W.) and change the view workspace mode to Beam (X.). Note the big red “X” on the bottom right of the screen (Y.), this denotes that the beam has failed the simulation. Choose the option of “Design Non-Composite” (Z.) for the design parameters (as a an architect, we are not in the best position to use composite parameters to weigh cost versus labor, and we are only looking for a schematic understanding of size and scale). Click Design Selected Beam (A.), verify that the results and click OK (B.) to apply the new beam design to the Revit model. Note: Similar to ForceEffect, but with additional detail, a full report can be output to either word or excel from the Composite Design tool (Figure 31).

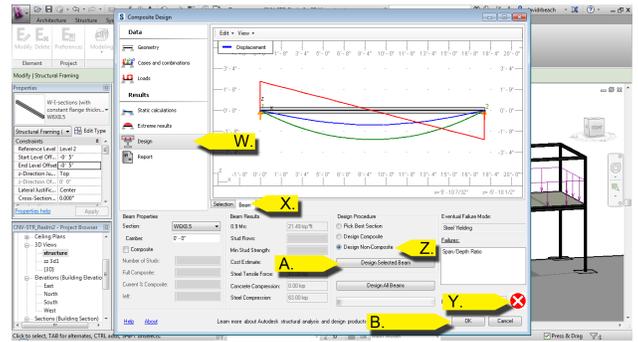


Figure 31. Composite beam design.

13. In the 3d view, isolate the beam category (C.) and apply the new beam parameters to all the beams with a similar loading condition using the Match Properties tool (D.) by selecting the designed beam (E.) to the beam to be modified (F.). Or, repeat step 12 as necessary for conditions with any beam with a variance in their conditions.

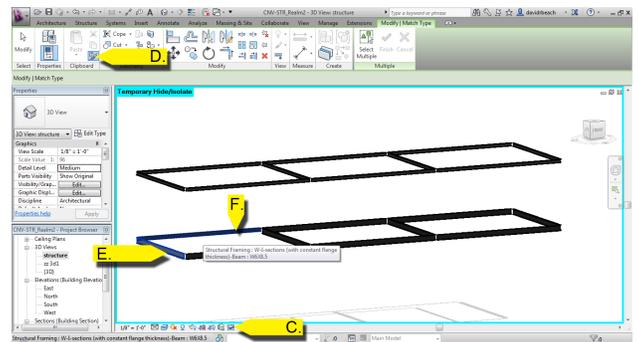


Figure 32. Match Properties.

Third, **building stabilization** covers rigid and braced buildings, and centers of lateral forces and stiffness. This mode of study allows a student to understand overall structural performance and the implicit interaction between elements of the construction. Utilizing Autodesk Robot on a model imported from Revit overall forces and deflection can be studied. The model can then be updated with model modifications inside of Revit to iterate the structural simulation in Robot.

1. In preparing the file to be pushed to Robot, we want to keep as much as possible in Revit (the tool we are familiar with), so make any changes to the model to resolve or expand on the structure, and add any additional forces. For this case, we are adding a lateral load by setting the work plane along the columns to the outside of the structure. Under the analyze tab select Loads and Area Load. Establish the load by using the Pick Lines tool (A.) to select the outside edges of the columns (B.). Set the force type Wind Load (C.), and set the wind value in Kips/square foot (D.) (Figure 33).

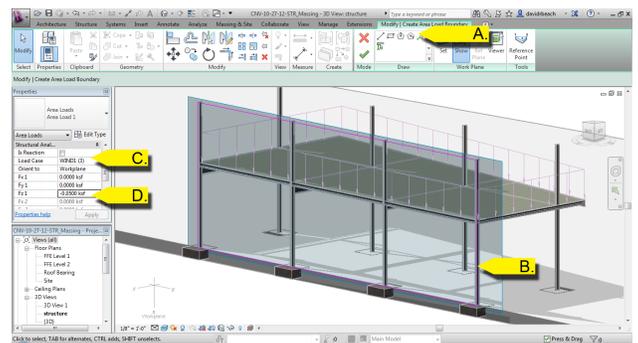


Figure 33. Wind Loads.

2. Because we are adding in a wind load, we should begin adding in some cross bracing (a reality most architects are in denial over) by starting in plan view, and under the structure tab select Brace (E.), and then add a brace A10 to A11 (F-G.). NOTE: For the purposes of demonstrating values in Robot, I am going to leave the cross bracing only on one side. This should create a clearly visible disparity in the lateral loading of the columns (Figure 34).

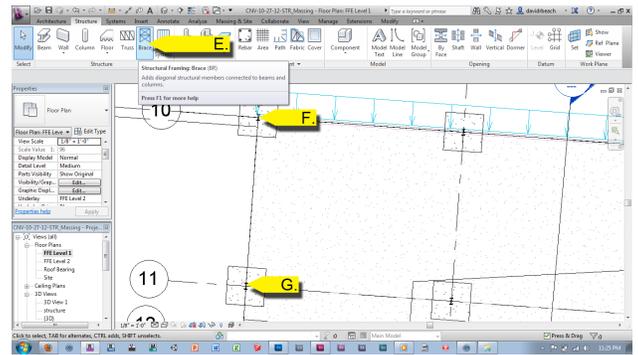


Figure 34. Brace.

3. Still working on cross bracing, move the Start Attachment setting in the Properties menu (H.) to FFE Level 2. This places the brace (I.) at a diagonal along the column line grid (Figure 35).

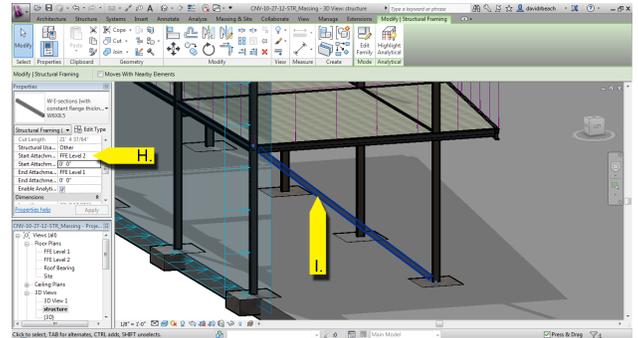


Figure 35. Brace diagonal.

4. Under the analyze tab (J.), select Structural Analysis (K.), and then the Robot Structural Analysis Link tool (L.). Verify that Send Model is selected, and then click OK. You use the same method to update the file in Robot, and you can use the update button to update your Revit file from any changes made in Robot. (Figure 36).

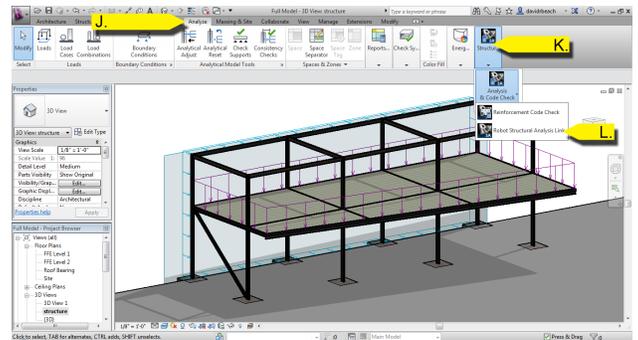


Figure 36. Robot link.

5. In Robot, select Section Shapes (M.), Load Symbols (N.), and then set the load case to DL1 in the top center drop down list (O.). This begins to set up a visual work space that allows us to see the elements, and forces. You can switch the load case to any loading scenario that has been built in Revit (Figure 37).

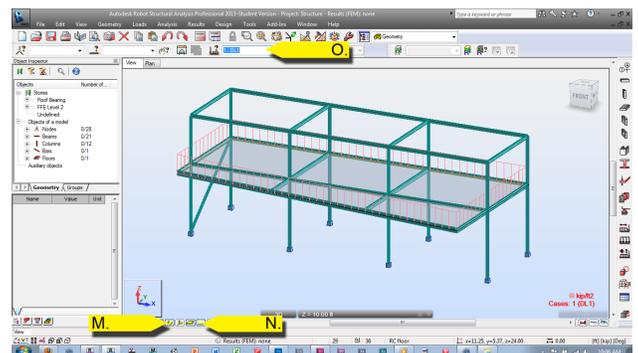


Figure 37. Robot - Display Settings.

6. Press the calculate button (P.), then switch the display mode layout to Results - Diagrams (Q.). Under the Deformations tab, check Deformation, Exact Deformation on Bars, and Deformation in Structural Scale (R.), and set the scale to 1 (S.), then click the Apply button (T.). If you don't notice much, that is probably a good thing, as this value setting is designed to display the exact deformation of the structure. On the bottom right (U.), take note of the maximum deformation, in the case of this sample project it is 4", which is totally unacceptable (Figure 38).

7. To develop a better understanding of the deformation results, we can modify the representation scale of the deformation and animate it by modifying the scale factor (V.), set the number of frames to animate, and frames per second (W.) (I used 30 frames at 10 frames per second to build a 3 second animation). By pressing start Robot will build an animation showing how the structure deforms under the provided loads. Press the stop button (Y.) to return back to the Robot workspace (Figure 39).

8. Verify that you are still on the results - diagrams (Z.) in the drop down list. Move to the NTM tab in the diagrams menu (A.) and turn on the Forces (B.) and Moments (C.) and select apply to show the diagrams (D.). If the visual created is too busy, make sure you turn off the loading diagrams (E.), minimize the selections, or increase the diagram representation size (F.). The diagram visuals allow you to see the beams under their load conditions, variables across the structure, and provides the maximum forces and moments overall across the readout on the right (Figure 40).

9. Change the display drop down to Maps (G.), and select the xy Moment map (H.) and select Apply (I.). This displays a map on the concrete slab conveying the direction and amount of shear force in the concrete slab (Figure 41).

10. The mapping system has a ton of depth, but one of the other major ones for architects to pay attention to provides another visualization of displacement. Go to the Principal tab (J.), Total Displacements (K.), and then select Apply (L.). The map will provide information regarding displacement amount and location across a slab (Figure 42).

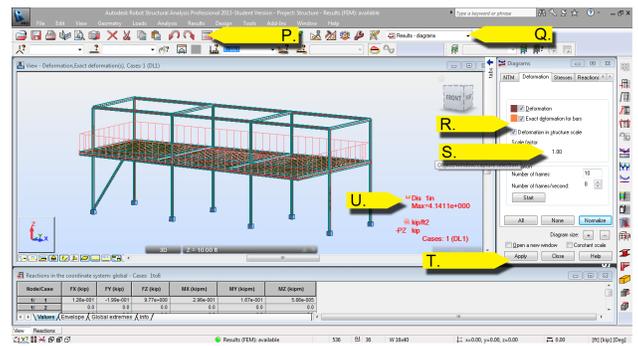


Figure 38. Robot - Deformation (1:1 Scale).

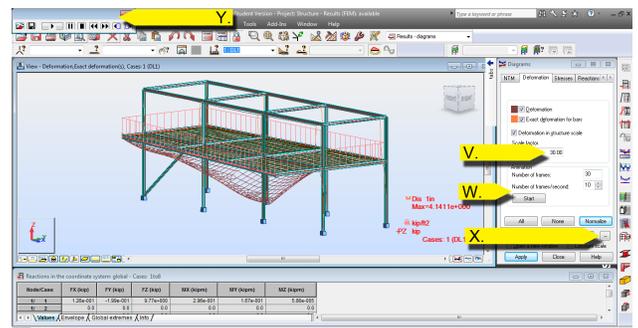


Figure 39. Robot - Animate Deformation (30:1 Scale).

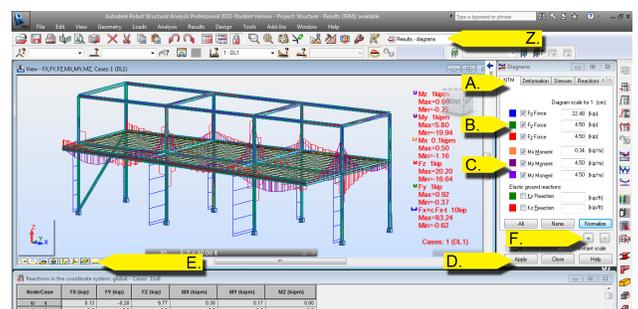


Figure 40. Forces and Moments Diagram.

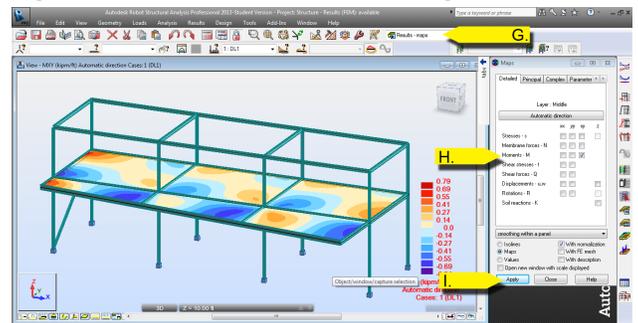


Figure 41. Moment Map.

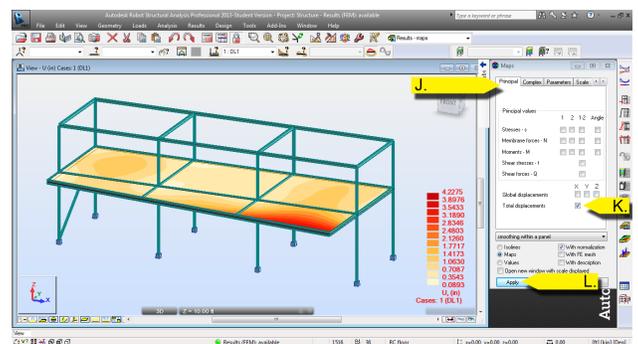


Figure 42. Displacement Map.

The goal from these steps is to build up the understanding of how the structure is going to perform in its basic configuration by the designer. For instance, providing cross bracing at only one side creates a massive discrepancy in the lateral loading of the columns. The cantilever that extends on the front right of the imagery has the most deflection, helping resolve that if it is to remain in the design configuration, it should be a priority discussion with the structural engineer, or an alternate design (columns, or additional connections) should be designed into the structure. As the design evolves, the complexity of the structure evolves, and the structural system is updated through articulation, simulation, and an iterative design process.

Floating the Bowling Ball:

The potential of architectural designer mastery of a structural simulation tool set is largely unknown, as it has not been applied in mass. Bjarke Ingels describes in his May 2011 TED Talk: *Hedonistic Sustainability* that “If people don’t know they can’t act.” While the quote was covering the topic of sustainability, it applies directly to any area where knowledge is available, but either not uncovered or applied. Expanding the design process with structural thinking through simulation creates the opportunity for moving further with structural expression as an element of design, expanding the ability to learn and engage structural education, and improves the ability for the architectural design team to communicate with the structural design team.

Santiago Calatrava described at a 2002 lecture at MIT: “If we consider engineering an art – as I believe it is – and if we go back to a time when there was no difference between the art of architecture and the art of engineering...then we can consider that it is in ourselves, and especially in the new generation, that a rebirth of art happens.” That rebirth of design has the potential to evolve largely due to advancements in technology that allow earlier testing of concepts, and more advanced testing by a larger pool of users (anyone using Revit).

Ove Arup discusses the collaborative nature of designer in a letter to Walter Gropius expressing that “the conceptual process (is) a total entity, form, structure and economy being inseparable within it...Education of architects, engineers, and artists alike must then, first of all, be directed towards understanding and accepting the collaborative process...Within this process the final control will fall to that individual who has the broadest scope and is willing to accept from his teammates everything which can enrich the total conception.” Collaboration is one of the key elements in the process of design. Improved communication comes through broadening the education of design students to be more engaged in the structural design process, matching design thinking to structural thinking. As students move to practice they should be equipped with the ability to resolve, at least at the schematic level, the structural system of their design.

Rafael L. Bras, the former Director for the Department of Civil and Environmental Engineering at MIT explains that “The divorce of architecture and engineering is long standing and now, at least in the United States, almost ubiquitous. This divorce injures both parties. The ambition of architects to build well is diminished. Engineering becomes formulaic and uncomprehending of its social, environmental, and aesthetic dimensions.” Improved communication between the structural design team and architectural design team is imperative in the complexity of the future of design. Discussion over a shared BIM model residing in the cloud which runs structural simulation in realtime is part of the near future. Without the basic understanding of how this will shape our design thinking, further distance will be created in the gap between engineer and architect. With a rich understanding of structural simulation as a design tool, there is an incredible opportunity to evolve both the collaboration process and creative thinking.

The engagement of the science of design is as fundamental as the aesthetic qualities of building form.

As new technology emerges, it will not resolve the technical issues, and it will certainly not resolve formal issues. Utilizing technology though to augment a personal process of design thinking that manages insight from multiple stake holders through collaboration, creates opportunity to explore environmental responsiveness through energy simulation, and allows for greater depth of exploring multiple options and possibilities of building solutions through structural simulation. A lack of development on how to properly engage the design process with technology at the academic level will certainly add to the continual devaluation of the profession of architecture. It will continue a wave of missed opportunities for a field that can have an expansive and extroverted process, to become isolated by having fewer clients in need of service, and introverted in terms of its value system and priorities.

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