Learning From the "Big Box Store" - An Alternative Strategy for Teaching Structural Systems

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Abstract
This paper documents a course which utilized existing “Big Box” stores as learning-labs by “reverse-engineering” the structural systems of their assigned buildings. The goal of the class was to enable the students to apply their developing structural design skills and their knowledge related to building materials to make informed judgements in identifying a wide range of system components including bar joists, girders, and structural decking in a “real world” context. This paper documents the course rationale and strategy, the associated learning objectives, the organization of the assignments, and the outcomes of the course. The effectiveness of the strategy is discussed in the context of the final assessment of the students and their comments.

Introduction
Learning structural design concepts is an essential component of architectural education. Typically, design curricula deliver content related to structural design at the undergraduate level. Many degree programs utilize a sequence that introduces theoretical concepts with a statics and strength of materials course that is then followed by an additional course or courses dedicated to structural design with wood, steel, masonry, and concrete. Historically, this content has been covered in dedicated structures courses that were to some extent independent of other key design components of the curriculum.

Such a strategy does not support the recent shift among the accrediting bodies for professional education in architecture and architectural engineering. Structural design criteria are increasingly emphasizing outcomes focusing on structural systems in support of a more holistic understanding of the functional as well as the aesthetic role of structure in building design with an emphasis on structures as a system. For example, the National Architectural Accrediting Board (NAAB) specifically identifies structural systems as one of four required “technology” criteria to be met, stating that “the graduating student should be able to apply their knowledge of each technical system in the context of an architectural design project” [1]. In the context of structural design for buildings, systems design is defined as “the application of the scientific method to selection and assembly of components or subsystems to form the optimum system to attain specified goals and objectives while subject to given restraints and restrictions” [2]. According to Arciszewski and Lakmazaheri, in order for a structural designer to succeed in the future “he or she must be able to …. understand engineering knowledge on both the systems level and on the level of details necessary for engineering purposes” [3].

Many curricula have attempted to meet this learning outcome by requiring a more robust integration of structures with design studio projects. However, given the diverse demands that a comprehensive studio project places on the knowledge and skill sets of even upper level students, the semester-long time frame for the course is typically insufficient for any in-depth exploration of structural systems. Faculty in the Department of Architecture at Bowling Green State University investigated an alternative strategy for delivering structural systems content that re-considered the format of the stand-alone course model. The conventional lecture format was replaced with a case-study methodology that utilized existing big-box stores, all from the same retail chain, as a “real-world” laboratory. This provided a format for students to document and
analyze an existing structural system in the context of actual gravity and environmental load conditions. The students were then required to “reverse engineer” the structural components to determine the actual member sizes utilized in their case study building. Reverse engineering “is the process of duplication of an existing part, subassembly, or product without drawings, documentation, or a computer model” [4].

**Rationale for the Strategy**

The intent of the “big box” strategy was to take advantage of several key characteristics of the big-box building type:

1. Fixed real-world locations allowed students to collect and ultimately utilize data related to soils, wind loads, and seismic design requirements;
2. Multiple retail location availability which could be easily accessed by students near their place of residence either near their university housing or their home towns.
3. A clear yet uncomplicated relationship between the structural systems and the building envelope;
4. Exposed structural systems that were visible and could easily be documented for analysis;
5. A structural system that, while composed of multiple structural element types, was simple enough to allow for in-depth study and analysis of the members and associated connections and bearing conditions in the time frame of a semester-long course.

**Preliminary Research and Activities**

The class was divided into two teams which were assigned one of two preliminary research assignments focusing on specific structural content not covered in prior coursework: Lateral Forces and Wind Loads and Seismic Design Principles. The team assigned lateral forces content required students to research the implications of wind loads on structures with an emphasis on investigation of wind-loading on horizontal (roofs) as well as all vertical surfaces, both windward and leeward. The team assigned seismic research focused on shear wall, foundation, and moment connection concepts and construction. This team was also required to document foundation and moment connection images and construction details used in seismic design. The teams presented their research and posted their work to serve as a resource for the other students.

Students were also introduced to internet-based resources for documenting and calculating environmental loads. This strategy was supported by various sources. Arciszewski and Lakmazaheri proposed that a contemporary structural designer must learn to utilize Information Technology in every-day practice for designing and learning [3]. Henson, Fridley, Pollock, and Brahler, proposed that in structural design education “the internet provides an interactive environment that requires active student participation in the learning process” and added that “the internet is a valuable tool for the instruction of engineers” and that “Its interactive environment permits students to conduct virtual laboratory tests” [5].

In order to use the course activities to further develop the students skill set, the course activities required students to use Revit Building Information Modeling software to develop, document, and present their work. Digital 3D visualization has been successfully employed in delivering structures content in architecture courses [6][7] and researchers have proposed that “3D digital design tools can be used to assist students to be better and more innovative practicing architects”
Therefore, it was anticipated that the 3D visualization capabilities of Revit would also assist students in understanding the structural systems they were investigating by developing relatively detailed computer models of their case study structure. Additionally, as Revit is widely used by the students in their studio classes, it was intended that gaining experience using the structural modeling tools would assist students in applying their structural knowledge to studio as well as enhancing skills used in the professional environment.

All students in the course had completed prior coursework covering Revit operations. However, most had only cursory experience using the structural tools. In order to support the goals of their current course, mandatory class activities at the beginning of the course were included in order to introduce Revit structural tools and students. It should be noted that Revit does not perform actual structural analysis. Therefore, exporting the computer models to separate structural analysis software was to be one the final course activities.

**Selection of the “Big Box” Case Study**

In developing the assignment, it was decided that each student was to be assigned a unique store location for their project. This would provide some variation in the environmental loads and construction conditions. Prior to the start of the course, the instructor visited several regional “big-Box” stores. These visits were intentionally limited to retail chains based on the assumption that the construction would be very similar in the various locations. It was decided that the Home Depot chain would provide an appropriate example in that it met the previously identified key characteristic criteria and there were an abundance of sites within the region so that each student could be assigned a unique location to utilize.

The Project was to be divided into a sequence of phases, each of which would build on information and/or calculations from prior phases:

**Phase 1:** Preliminary Research and field documentation of the case study conditions. This included dimensions, building assemblies, site-specific conditions, loads and analysis;
**Phase 2:** Demonstration seminars and preliminary 3D parametric modeling of case study structure;
**Phase 3:** Reverse engineering of the structural framing updating 3D parametric model;
**Phase 4:** Development of assumed foundation design based on data from Phase 1 through 3 updating the 3D parametric model with foundation geometry;
**Phase 5:** Exporting structural framing to external structural analysis software;
**Final:** Submission of graphic and written documentation in a bound 11X17 report booklet.

**Phase 1: Field Documentation**

The first step of the assignment required students to visit their assigned site and document the conditions. They were to field measure column spacing in all bays, column dimensions and the dimensions of the slab control joints at the column base, interior slab control joint spacing, and dimensions between columns and exterior walls. The depth of the joists and girders could not be field measured.

The field measurements were supplemented by extensive photo documentation of the interior and exterior of the structure. For the structural system the photo documentation included column
conditions at the floor slab, bearing conditions for beams/girders and joists, and structural conditions at bearing walls. In addition to the structural system photo documentation they were required to document the slab conditions, exterior control joints, and parapet and eave conditions. Examples are shown in figures 5 and 6.

Each student was required to develop a list of the building materials used at their case study locations. In order to establish a knowledge-base to be used in structural calculations, students assembled a “master list” of the building materials that were identified in their field research. As anticipated the materials used at the multiple case study sites were nearly identical since all locations were in the same geographic area. Using multiple sources, the students then developed a list of building material weights that would provide the basis for determining dead-loads to be used in calculations.

Site Analysis
The students were required to utilize on-line tools to document the environmental conditions for their specific site. The required conditions were:

1. Soil composition
2. Wind loads
3. Snow loads
4. Seismic criteria

As part of this assignment, students were also provided supplemental readings on a variety of topics related to analyzing environmental loads on a structure. These included risk factors, exposure factors, and terrain factors. Following are the on-line resources used for these environmental analysis documentation and calculations:

Soil Composition: The resource used for determining site-specific soil composition was the USDA natural Resource Conservation web site: (http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/)

Snow Loads: The resources used for determining site specific snow load conditions was the ASCE Snow Load Map and the Applied Technology Ground Snow Load by Location (ASCE 7 ground snow load data) website (http://snowload.atcouncil.org/)

Seismic Criteria: The resource used for determining site specific seismic criteria was the USGS on-line seismic calculator (http://earthquake.usgs.gov/hazards/designmaps/usdesign.php)

Wind Loads: The resource used for determining site specific wind load conditions were the Applied Technology “Wind speed by Location” website (http://windspeed.atcouncil.org/). This calculator allowed for a wide variety of input parameters related to specific building configurations and dimensions.

Figure 1, 2, 3, and 4 illustrate examples of the output generated by the online resources used in the course.
Phase 1 Discussion
As anticipated, field documentation for the various case study locations indicated nearly identical structural systems with standardized wall and roof assemblies. Typical building widths were approximately 480’ in width (9 bays) at the entry and rear walls and 180’ in depth (4 bays) at the side walls. Bar joists spanning perpendicular to the width dimension were used to support a roof assembly consisting of EPDM roofing over insulation and metal deck. In all cases the structural steel framing was independent of the non-load bearing side walls. Structural girders at each bay spanning the width direction of the building were used for interior bar joist bearing. The number of bar joists between columns was typically eight, although in one case there were nine. Bar joist spacing ranged from 5’- 5” on center to 6’ on center. Minor variations in dimensions of the structural bays were also noted. The variations in bar joist spacing would require students to select an appropriate roof deck profile and gage to accommodate the spans of their case study.

While it was assumed that there may be some variation in the specific components of the case study roof assemblies, it was not possible to document these in the field. Therefore, an assumed assembly was establish allowing for some variation in the metal deck based on research and bar joist spacing. Similarly, floor slabs and foundation dimensions could not be field documented. Floor slabs were assumed to be 6” thick and an acceptable foundation design was to be developed in Phase 4.

Since the case studies were in the same geographic area in the Midwest, environmental loads were similar. Snow loads were typically 20 pounds per square foot with one exception which was 25 pounds per square foot. Wind loads were also similar. The soil conditions did vary as USGS data indicated that each case study site had unique soil composition which would impact the foundation proposals. Using perimeter dimensions, wall heights, and wind load data, each student used the online wind load calculator to generate a wind-load report for their case study final report.

Phase 2: Demonstration seminars and preliminary 3D parametric modeling of case study structure.
Based on the Revit content and skills developed in the initial class activities, the students were required to use their field measurements to develop a preliminary 3D structural model of their case study location’s structural system. The end result was a dimensionally accurate plan configuration which used pre-established estimates for the levels for the vertical dimensions for the framing components and wall heights. The software’s parametric capabilities would then facilitate revisions to the model as the specific dimensions and components were calculated and identified. The model was to include only bearing and non-bearing wall and framing components. Doors, windows, interior partition walls, and ancillary exterior structures were excluded. An assumed floor slab thickness of 6” was to be used. Foundation modeling was not included in Phase 2.

Class lectures and seminars were used to provide instruction on how to proceed with the case study project. The in-class demonstration exercises were based on hypothetical conditions that would differ from each of the specific conditions encountered by the students. For example, in the seminar activity the bar joist spacing was 2 foot on-center, a much closer spacing condition
than would be at any of the case study locations, and the dimensions of the structural bays was only 20 feet, a smaller dimension than any of the case study locations.

**Phase 3: Reverse Engineering the Structural Framing**
Based on the field measurements and documentation, the following structural components were to be identified through the “reverse-engineering” process since they could not be identified directly by measurements on site:

- Metal roof decking (thickness and gage)
- Column section (specific HSS section)
- Bar joists depth and weight
- Girder/beam depth and weight

Both online calculators and manufacturers published data was employed to determine the specific structural components. For consistency in the class, the instructor designated Vulcraft as the source to be used for steel joists, girders and decking. Based on content covered in lectures, students were aware that most conventional steel construction of this type used K-series bar joists which was the most economical solution for the spans involved. Students were required to download and print the following Vulcraft catalogs and publications to create a hard-copy reference guide for the project:

- Vulcraft Steel Roof and Floor Deck catalog (http://www.vulcraft.com/decks/deck-catalog/steel-roof-and-floor-deck)
- Vulcraft Steel Joists and Girders catalog (http://www.vulcraft.com/joists-joist-girders/joist-catalog)

Roof dead loads were established using manufacturer’s data for the components in the roof assembly as well as a pre-established 10 pounds per square foot (PSF) to account for miscellaneous loads including suspended lighting, ductwork, electrical chases, fire protection piping, and bottom chord bracing. The students were instructed to use .75 PSF for the roof membrane and any required substrate. They were also instructed to use 1.5 PSF per 1” extruded polystyrene (XPS) rigid insulation. The standard thermal resistance for extruded polystyrene rigid insulation was established at R=5 per inch of thickness. Students were required to determine the total required thickness needed for the roof assembly to comply with the ASHRAE 189 prescriptive requirements for above deck insulation for the climate zone in which their case study was located. Metal decking weight per square foot was to be based on the specific deck selected for the span between bar joists in their case study. The project requirements stated that students were to identify the lightest weight bar joist that met a deflection value of L/360. They were then to select the lightest weight bar joist that met a roof load deflection of L/240 that was to be used in their Revit model.

**Phase 3 discussion**
The bar joist spacing at the case study locations ranged from 66” to 72” resulting in a selection of 22 gage roof decking (Vulcraft 1.5B steel deck) with a manufacturers specified weight of 1.8
PSF. All case study locations were in Climate Zone 5 which would require a minimum above deck roof insulation R-value of 20 in order to comply with ASHRAE 189 [8]. Therefore, the roof assembly for all case study locations would incorporate 4” rigid insulation. The resulting roof assembly load was determined to be 18.55 PSF including the miscellaneous load of 10 PSF. The dead load value was rounded off to 29 PSF for the joist selection.

Each student selected bar joists and girders using the Vulcraft catalog data. The bar joist loads were determined using a tributary area based on the joist spacing in their case study. Students selected bar joists using both deflection values. The total tributary load was determined to be 294 pounds per lineal foot (PLF) total load and 150 PLF live load for a joist spacing of 6’ and a 44’ span. For an L/360 deflection, a 22K11 was the lightest acceptable member that met both the live load and dead load criteria. For a deflection of L/240, the lightest acceptable member was a 22K9. However, the students noted that the manufacturer’s load tables indicated that if using a 22K9 for the case study span and load the mid span bridging must be installed as bolted diagonal bridging and that hoisting cables were not to be released until after this bolted diagonal bridging was completely installed. Therefore the students selected a 22K10 based on the assumption that any increase in cost for a heavier member would be offset by savings in construction costs.

For the case study located in a location with a 25 PSF snow load the spacing was 5’-5”. Therefore the total tributary load was determined to be 291 pounds per lineal foot (PLF) total load and 135 PLF live load for a 44’ span. For an L/360 deflection, a 22K11 was again the lightest acceptable member that met both the live load and dead load criteria. For a deflection of L/240, the lightest acceptable member was also 22K9 but a 22K10 was selected for the reasons identified for the other case study locations.

Using manufacturers data, the joist girder was determined to be a 48G 9N 13.0K for the case studies with a joist spacing of 6’ on center and a 48G 10N 12.8K for the case study with 5’-5” on center spacing. Columns were established as 10x10x,.5HSS members. Once these members had been selected the Revit models were updated by reassigning the structural members to the appropriate families and types (Figure 7).

Phase 4: Foundation design
Each student researched their case study frost lines based on government data and local codes. The typical frost line was 36” in all cases except one location in which the frost depth was 40”. Students used their Phase 1 analysis of their site soil conditions to determine soil bearing capacity for their location. This was then compared to a standard of 2000 PSI which was to be used if their capacity was actually greater. Wall footings were added to their Revit model to reflect their foundation design (Figure 8).

Phase 5: Structural Analysis
Phase 5 was developed to provide students with experience to export their final Revit structural model to a separate structural analysis software application. However, due to Phase 1 through 4 activities requiring longer time than originally allocated there was insufficient time to introduce content related to the structural analysis software. Therefore Phase 5 activities were not completed.
Review and Assessment of the project
Upon completion of the project students were asked to provide feedback regarding their experience in the course. Students commented on the holistic approach to design of the structure and were generally in agreement that, by collecting all the site related data and associated environmental loads, they felt they had a much greater understanding of the context of a project and related parameters. Several comments indicated that the students appreciated the more “real world” approach to structural design using tables and related design data. The utilization of a structural example that could be seen in person was also cited as a benefit as students were able to clearly visualize the entire system. Revit 3D views were also perceived to be beneficial (Figure 9). The use of online resources was also cited as a benefit that would more closely reflect design processes in actual practices. The primary negative responses were related to the pace of the class and specifically to not having time to cover the structural analysis software as this was perceived to be a valuable skill needed in their future professional practice.

Recommendations
Based on the results, the following recommendations for future iterations of the course are as follows:
1. Expand the wind load analysis to incorporate wall design in response to the actual site conditions. This would include proposing a reverse engineered solution related to vertical reinforcing in the exterior walls
2. Incorporate the structural analysis software as part of the initial class activities
3. Allocate more class time to foundation design.
4. Allocate class time to connection details and lateral bracing (bridging) design to insure students understand more specifics related to structural design
References


Appendix: Figures

Figure 1. USGS Soil data for example location.
Figure 2. Ground Snow Load Calculator

Figure 3. USGS Seismic design map for example location.
Figure 4. Wind load calculator screen shot.
Figure 5 and 6: Examples of student photo documentation
Figure 7. Student axonometric model (roof components hidden)

Figure 8. Student axonometric model with foundation (roof components hidden)
Figure 9: Interior perspective of structural system (roof components hidden)