Studying Architectural Structures Using BIM Tools

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***Abstract*- Structure is an essential component of architecture, and has always been. However, studying building structures appears to be deceptively complex. This stems from the roles and meanings that buildings possess in human history and civilizations. Buildings provide shelter, inspire productivity, embody cultural history, and certainly play an important part in many aspects of life. In fact, the role of architectural structures is constantly changing in building design as buildings today are life support systems, communication and data terminals, centers of education, justice, and community, and so much more. Thus, for AEC (Architecture, Engineering, and Construction) students, the subject is quite often marked by difficulty.**

Knowledge, technology and information sharing encompass areas that have significantly affected the learning process for 21st century students. In this environment, computational and simulation tools play a vital supporting and inspiring role. This research proposes a method to develop and enhance the understanding of fundamental principles of architectural and structural analysis using Building Information Modeling (BIM) tools. Without the traditional teaching emphasis on first understanding single elements such as beams, columns, bearing walls, etc., two dimensionally, using the laws of statics and strength of materials, this research will utilize BIM tools to help students create whole three dimensional structural systems and then investigate structural solutions. BIM tools enhance the understanding of structural analysis fundamentals such as the force equilibrium, support reactions, shear force, and bending moment diagrams in an integrated and much inspiring fashion. This approach will allow AEC students to advance a deep learning and long-term retention in studying architectural structures. Understanding the whole structural systems concepts at an earlier stage will enable students to think and later practice in an integrated fashion to meet the demands of today's as well as tomorrow's high-efficient building structures.

Keywords- Studying Structures; BIM Tools; Revit Structure; Structural Melody; Structural Poetry; Conceptual Thinking

I. INTRODUCTION

Studying architectural structures is deceptively complex due to the roles and meanings of buildings to the society. In general, buildings provide shelter, encourage productivity, embody cultural history, and definitely represent an important part of human civilization. Actually, the role of architectural structures is continually changing as buildings today are life support facilities, data and communication terminals, centers of education, justice, health, and civic, and so much more. They are expensive to construct and maintain and must regularly be adjusted to function effectively over their life cycle. The finance and economics of building has become as complex as its design. Hence, for many AEC students, the subject is frequently marked by complexity.

Structural analysis in undergraduate AEC curriculums mainly centers on mathematical computation without emphasizing the significance of conceptual behavior of structural elements and systems. Addis (1991) stated that at all times in architectural engineering history, there have been some kinds of knowledge which have been fairly simple to store and to transfer to other people, for instance by means of drawings or models, numerical rules or in mathematical symbols. Simultaneously, there are also other types of knowledge which, even today, still seem to be problematic to condense and convey to others. They have to be learned anew by each young professional, for instance a feeling for the structural behavior. Presently, in engineering and architecture, educators have inclined to focus predominantly on that knowledge that is easy to accumulate and communicate. Regrettably, other kinds of engineering knowledge received rather less than their fair part of consideration.

To advance other kinds of structural knowledge, this study centers on the conceptual and qualitative aspects of building structures and how to involve the student’s imagination in creative ways similar to musician or artist producing designs. Besides the visualization of a structural form or type of material, which can be performed essentially from memory, there is likewise the opportunity of carrying out structural analysis in the mind - what can be referred to as conceptual analysis. This research aims to stress the importance of qualitative understanding of structural behavior within the framework of AEC education.

With current advancements in information technology, students have more tools to examine and determine how load combinations affect the safety and performance of a structure. Particularly, Building Information Modeling (BIM) has the potential to promote attaining various sorts of structural knowledge learning objectives without conceding their distinctive requirements. BIM is a process that is profoundly changing the role of computation in structural engineering by generating a database of the building elements to be utilized for all levels of building structures from design to construction and beyond.

BIM has transformed the design and construction of buildings primarily due to its ability to postulate the interaction of forces, deformation section properties, and material strength, based on the nature of connections and supports. This study seeks to employ Autodesk Revit Architecture and Structure and their extensions, including Robot Structural Analysis software, to understand the fundamentals of building structures and how to conceptually analyze structural elements, specifically portal frames. This kind of conceptual structural analysis knowledge is similar to the type of knowledge usually allied with craftsmanship talent, or the skill of knowing how to do something (e.g. swim, paint, make docks, play a musical instrument) and normally yields deep learning results.

The investigational research group includes two undergraduate architectural students (2^{nd} year) and two undergraduate students (3^{rd} year) from the College of Engineering, at the University of Florida to examine how BIM would advance learning and understanding of building structures. The research group was introduced to the fundamentals of BIM and Revit Structures (see Fig. 1) in about eight contact hours. The first phase comprised historical overview of Computer Aided Design (CAD) and fundamentals of BIM. The final part of this introduction was an overview of Revit Architecture and Structure, underscoring the key concepts such as model elements, categories, families, types and instances. Students are then assigned simple projects to enhance their command using BIM platforms such as Revit Architecture and Structure in modeling 3D structures. Fig. 1 below demonstrates the process followed in this introduction [13].

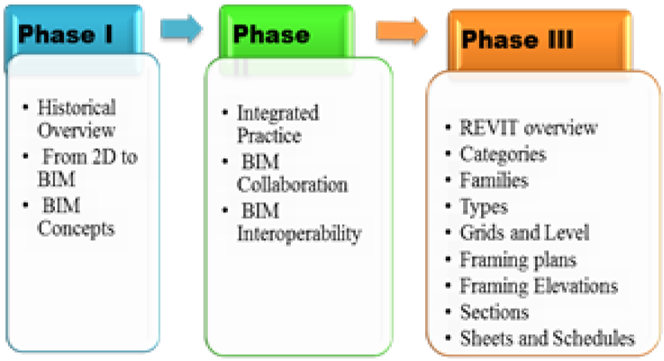


Fig. 1 Phases of BIM Introduction

Subsequent to the introduction, students began to learn about the add-ins analysis tools in Revit Architecture and Structure.

II. METHODOLOGY

A. Phase 1: Structural Melody

After introducing the fundamentals of BIM and BIM platforms, the first phase goal is to help students understand how linear and planar structural elements can be orchestrated to understand spatial order in architecture using BIM tools. It is also the intention to develop this idea as a holistic approach to introduce structural vocabulary, the hierarchy of structural members and the interplay between architectural concepts and structural systems such as stratification, transition, hierarch and heart of spaces.

In the structural melody phase, students learn about the structural vocabulary such as elements names and their order and hierarchy. The study starts incrementally from a simple 3D system and then evolving into whole one and two story buildings. The first assignment is a simple 3D system consisting of 4 wood columns, girders and beam system (joists) as well as single footings as depicted in Fig. 2 below.

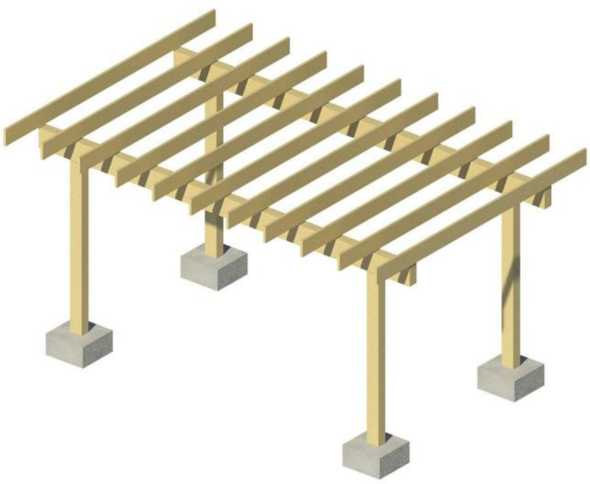
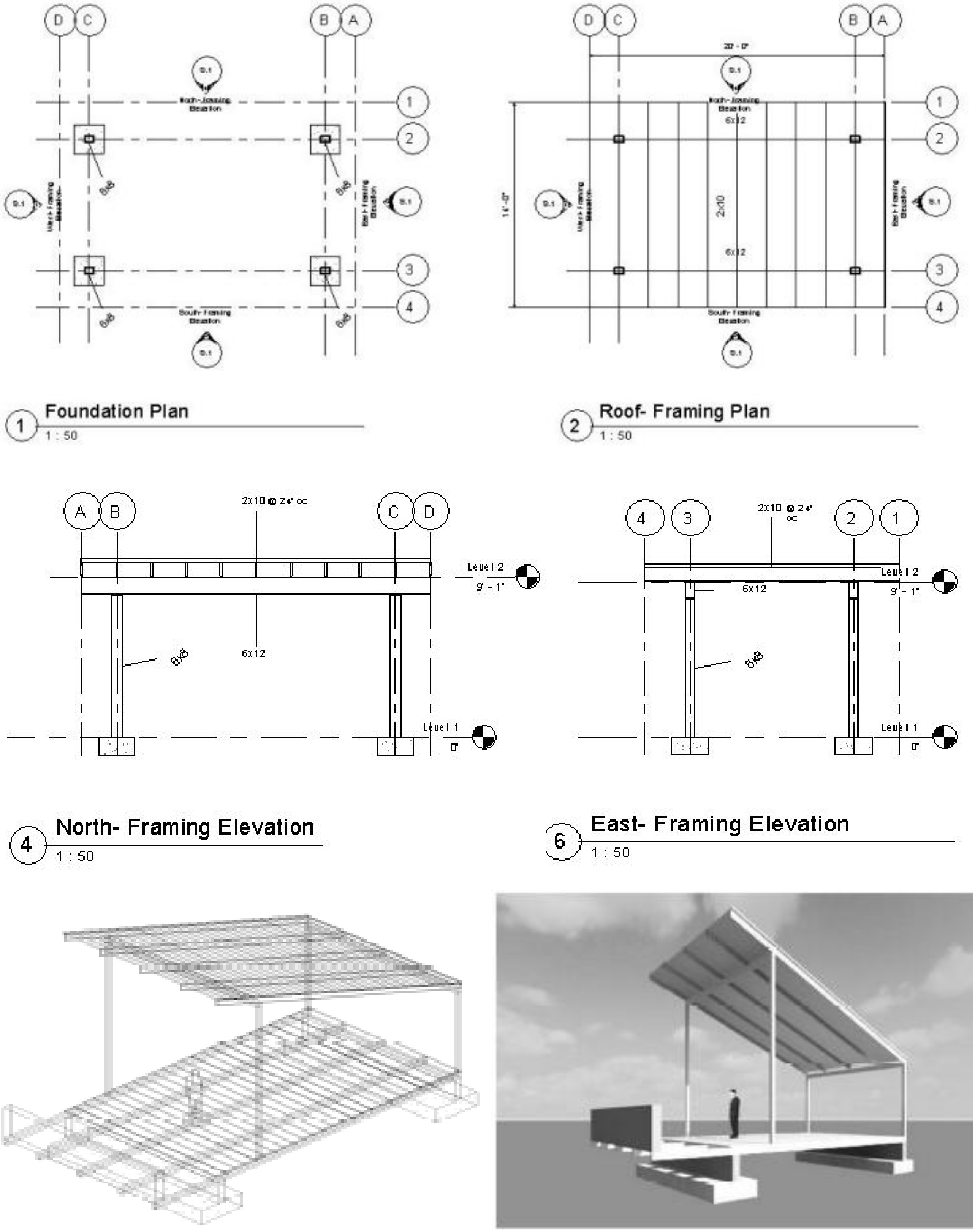


Fig. 2 Simple 3D Structural Model

Using Revit Architecture, students learnt about foundation and framing plans, as well as framing elevations. They are able to create a sheet showing all these elements. Some examples are depicted in Fig. 3. Students started to understand much more about the underlying concepts and the relationships between elements and their tasks in transferring loads as well as their two dimensional representations.



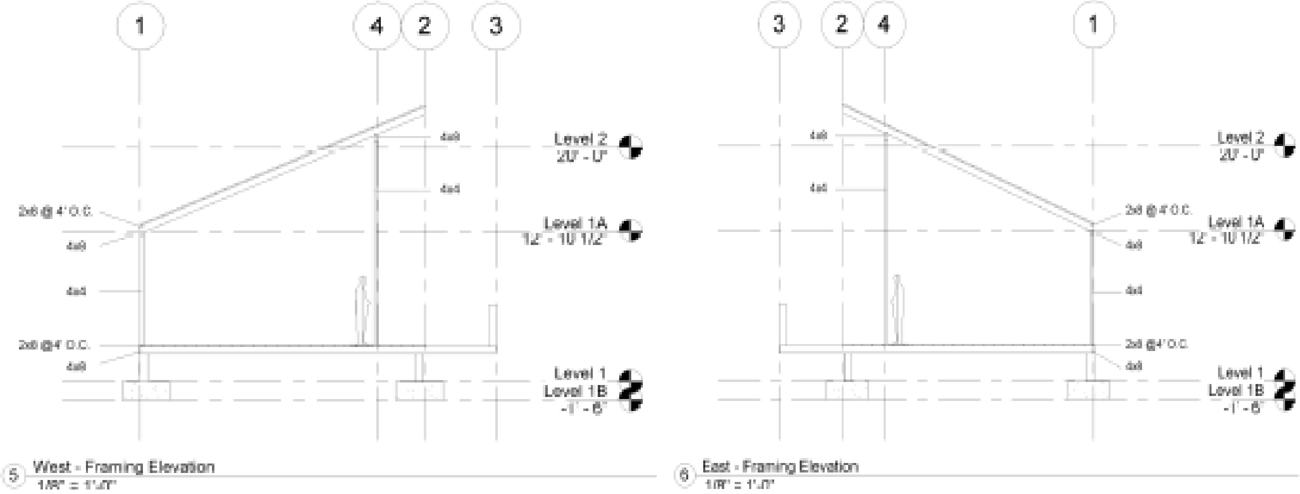


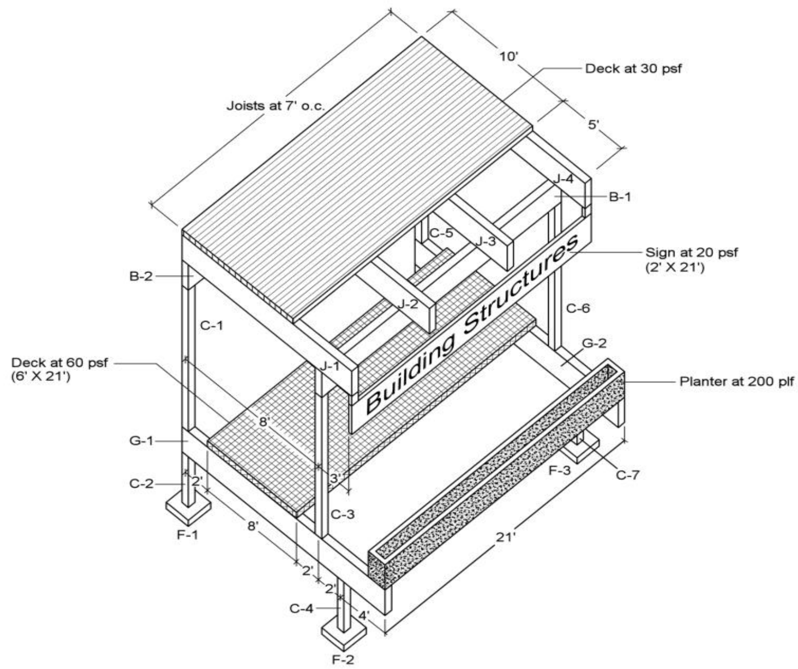
Fig. 3 Introducing “Structural Melody”

B. Phase 2: Structural Poetry

The word poetry has its origin in Greek and means a making: forming, creating or the art in which language is utilized for its appealing and evocative qualities, in addition to, or instead of, its syntactical and semantic content. In other words, poetry is a fundamental creative act using language. Similarly, structural poetry is a creative exercise to provide structural system using structural vocabulary and melodies in order to organize and stabilize architectural spaces. Just like language poetry, structural poetry has evolved over thousands of years and will continue to evolve now and in the future.

In this phase, more examples of advanced 3D structural forms are presented and discussed with the students in the research team. These examples illustrate different elements; structural hierarchy and organization (see Fig. 4). In these examples a parallel is drawn with language poetry to enhance student’s comprehension. For instance, poetry may use shortened or compressed form to convey sensations or ideas to the reader's or listener's ear or mind; structures can be formed using a few members in different form to provide certain aesthetic and framework for spaces; it may also use instruments such as assonance and repetition to achieve musical or incantatory effects, similarly structures can be orchestrated by repeating the same pattern of supports to achieve simplicity and elegance. Poems often rely on their impact on imagery, word connotation, and the musical qualities of the language used. Also, structures can use its form, orientation, type and quality of materials to impact the final design. The interactive layering of all these effects to generate meaning spaces is what marks structural poetry.

(a)



(b)

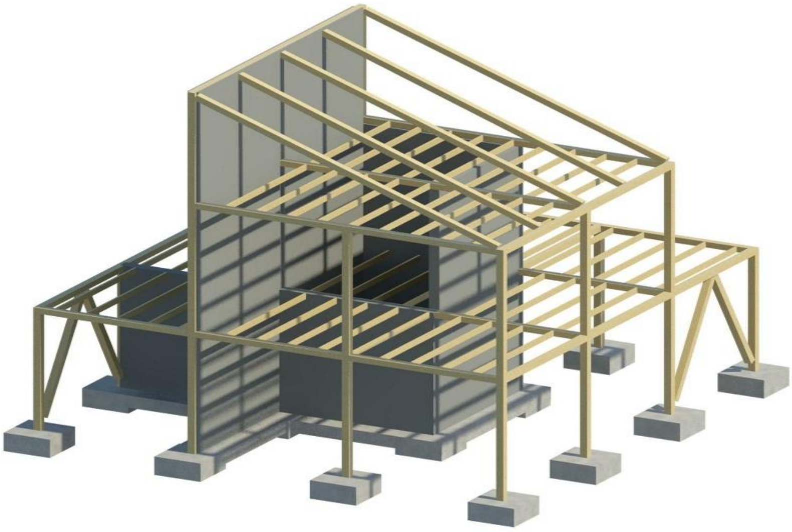


Fig. 4 Examples of Structural Poetry

Professor Billington [3] stated that that structural engineering at its best is a new art form which is parallel to but independent of architecture in the same way that photography is new art of the nineteenth century, is parallel to but independent of painting. However, in this research structural poetry is also an art but it is considered an integral part of architecture which flourishes with engineering knowledge.

The variations of structural systems shown in Fig. (a) and (b) illustrates the idea of elevated floors, cantilevers, simple trusses, frames, shear walls, bracing, two-levels of framing for the elevated floor, three-levels of framing for the roof as well as the two spaces established (interior and exterior spaces).

To explore variations and creativity, students are asked to modify some of the examples presented or create their own models. Analogy is made here to musical composers to write variations on musical themes by others or for poets or philosophers to test others arguments. Such creative interaction with the work of other existing creative models can be a source of ideas and develop an understanding of how architecture structures work more conceptually.

One interesting model created by students is shown in Fig. 5. This model is perhaps an extension of the model depicted in Fig. 4(a). Its outer form consists of distinct and mostly unequivocal basic structural elements. First of these, conceptually, is a pair of not identically sized horizontal rectangular planes: a floor raised above the ground as a platform and a shorter flat roof directly above it. Conceptually (if not in their actual construction) these two planes are identical. These two planes define the living spaces. They establish the special interior space of the human being, separate from and floating above the natural surroundings and a smaller in size exterior space surrounded by railing.

Fig. 5 Example of Progression in Structural Poetry

The model shown in Fig. 5 is based in the discipline of structural simplicity and the dimensions and nature of its materials, habituated by a generous sense of scale.

Students interest and motivation has increased enormously as a comparison is made between their model shown in Fig. 5 and the “Farnsworth House” designed by Mies van der Rohe in 1945 (Fig. 6). Particularly, the statement from Mies van der Rohe, in his inaugural address as a Director of Architecture at the Armour Institute of Technology in 1938 (quoted in [9]):

“Where can we find greater structural clarity than in the wooden buildings of old? Where else can we find such unity of material, construction and form? Here the wisdom of whole generations is stored. What feeling for material and what power of expression there is in these buildings? What warmth and beauty they have! They seem to be echoes of old songs.”

(a)

(b)

Fig. 6 Farnsworth House [9]

Structural poetry seeks to develop student’s creativity as well as conceptual understanding of architectural structures to achieve elegance distilled to its purest essence and like a finely honed poem, cannot be improved, except to obviate its practical problems.

C. Phase 3: Structural Analysis

After finishing phases 1 and 2, the structural models are finalized. Then, students are introduced to the various analysis tools within Revit Structure. The analysis is being conducted using BIM tools such as the beam, frame simulation, the load takedown, and the integration with Robot Structural Analysis. The load takedown played a key role in conveying essential concepts such as load path; flow of forces, constraints, and support reactions in building structures (see Fig. 7). Students had the opportunity to grasp fundamental principles such as tributary areas for beams, girders and columns in visual and interactive manner, which significantly stimulated their interest and motivation to discover other analysis capabilities of the tools (see Fig. 8).

The research is then focused on comprehending the conceptual behavior of frames under gravity and lateral loads using BIM tools. The following sections demonstrate the approach and results achieved. Engineering students took the lead in this part and helped architecture students in the team to follow thoroughly.

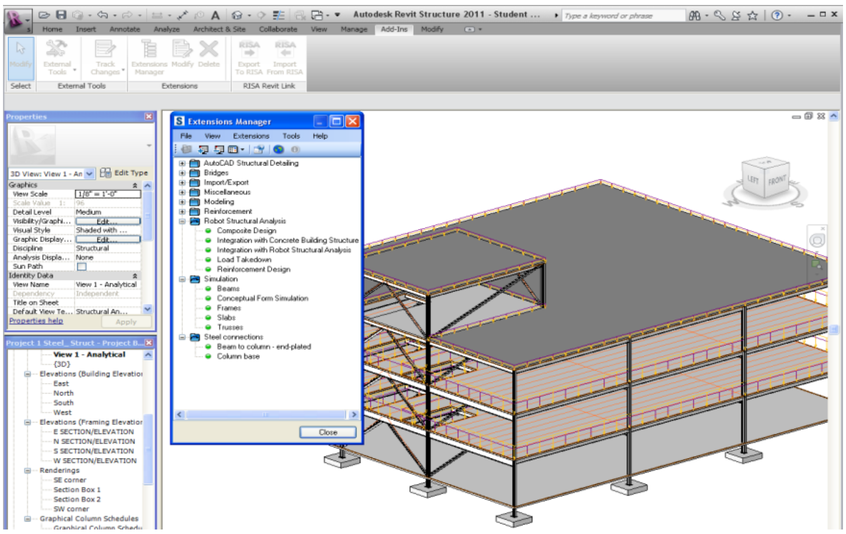
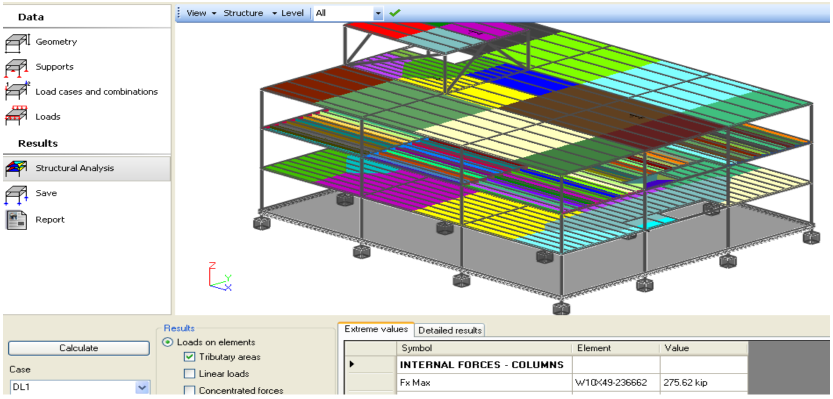
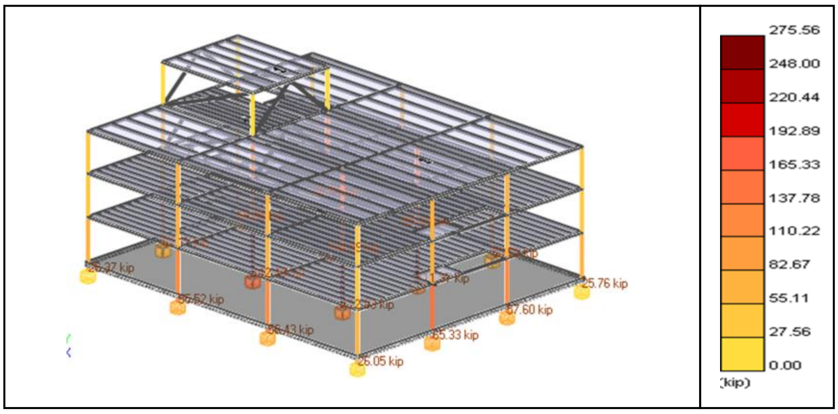


Fig. 7 Structural Analysis Tools in Revit



(a) Tributary Areas for beams and girders



(b) Axial Column Loads Map

Fig. 8 BIM Tools: Results of Load Takedown

Presently, the curriculum in structural engineering schools centers on the mathematical and formalized aspects of structural engineering knowledge. Particularly, those which can readily be communicated through symbols and numbers, or a combination of these, which are of use in design processes and the description and rationalization of proposed designs. However, besides these formal procedures, it is also critical to make use of the concepts behind the symbols and numbers at a more fundamental level, to promote thinking about structures. Most of this thinking is carried out not principally in numerical terms, but also qualitatively. For example, the interesting case given by Addis [1]: a structural beam that is not pin-connected at its ends has a maximum bending moment that could be derived from a simply supported beam, specifically PL/4 (load x span / 4). Alternatively, if it is known to have fixed ends it may be designed using equations derived from a beam with fully restrained ends, using PL/8 (in order to take into account some extra stiffness provided by the floor system). Both of the previous examples might surprise engineers a little in the use of assumptions known to be inexact. Yet his or her astonishment would grow into unease upon investigating the application of the formula PL/6 in the case of a portal frame believed to be "partially restrained". In contrast to the preceding two formulas, the last one has no theoretical validation at all. However, a designer is quite satisfied with such an approach which can yield stable and economical structures. It is this ability to conceptualize in order to characterize the transition from the engineering analysis to having the capacity to reason about, to understand, and to communicate structural performance.

Education in engineering, as well as in architecture should incorporate an improved focus on performance and conceptual analysis as essential activities. It must comprise these as a recognizably distinct skill which needs to be cultivated and advanced distinctly. Recommendations towards this goal have been often suggested by various researchers [1], [2], [3], [4], [5], [6], [7], and [8].

The capacity to use concepts of structural analysis and design effectively in explaining and discoursing engineering behavior gives a direct indication of a student's comprehension of and ability to reason about structures. The application of sound concepts, narratives, and by and large, language in both vocal and written description states a perspective from which an engineer is viewing problems.

This research examines the conceptual knowledge of structural behavior using building information modeling along with design and analysis tools. BIM tools utilized to investigate structures throughout this section of the study primarily employ the integration between Revit Structure and Robot Structural Analysis. Loads such as gravity and lateral are applied to several concrete portal frames to develop and advance the fundamental understanding of the principles of shear and bending moment behavior, as well as how the boundary conditions impact structural performance.

A reinforced concrete portal frame of 20.0 ft. x 20.0 ft. is considered as a reference point in the course of this investigation (see Fig. 9). A pinned and fixed supported frames subjected to a single gravity point load is examined by varying the beam and column member cross-sections. In the first round of analysis, the beam cross-section was set to remain constant as the column's width and depth changed gradually by intervals of 6 in. The second part of the investigation retained the column cross-sections fixed and altered the beam cross-sections by increasing only the height by 6 in. (see Table 1). The investigation is repeated by eliminating the gravity load and substituting it with a point lateral load.

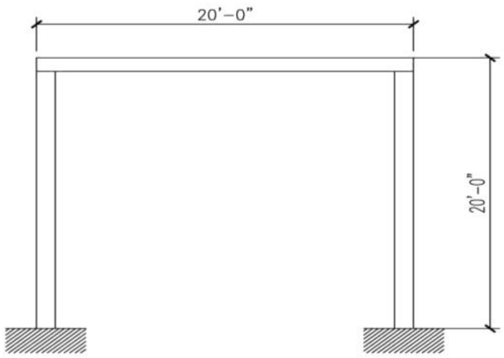


Fig. 9 Reinforced Concrete Portal Frame

1) Case Study:

The following structures (Table 1) are investigated in order to determine the behavior of fixed and pinned supported concrete portal frames subjected to different lateral and gravity loads:

TABLE 1 MEMBERS CROSS-SECTIONS FOR THE STUDY

20 ft. x 20 ft. Frame Subjected to 1.0 kip Gravity & Lateral Point Loads	
Constant beam section of 12 in. x 12 in. variable column section of:	*Constant column section of 12 in. x 12 in. variable beam section of:*
1. 12 in. x 12 in.	*1. 12 in. x 12 in.*
2. 18 in. x 18 in.	*2. 12 in. x 18 in.*
3. 24 in. x 24 in.	*3. 12 in. x 24 in.*
4. 30 in. x 30 in.	*4. 12 in. x 30 in.*
5. 36 in. x 36 in.	*5. 12 in. x 36 in.*

2) Results and Discussion:

In structural analysis, the geometry of the structure, properties of materials, boundary conditions, and applied loads are critical considerations. Each facet plays a substantial role in the equilibrium of any structure. The focal concern of structural analysis is the computation of internal forces and deformation analysis that are involved in the determination of structural performance.

This study centers on statically indeterminate structural frames which normally cannot be analyzed by applying 2D static equilibrium equations. To comprehend the structural behavior and qualitatively analyze these frames, this investigation endeavors to employ the concepts of simple beams, specifically simply supported, fully fixed and cantilever beams (see Fig. 10).

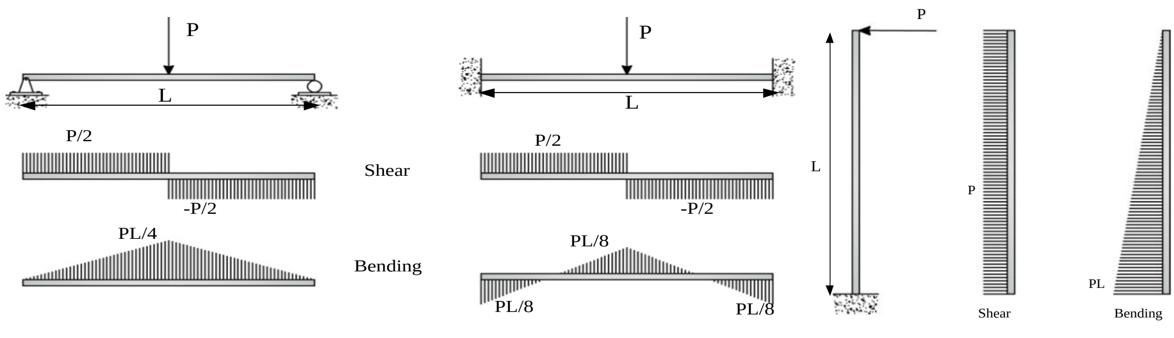
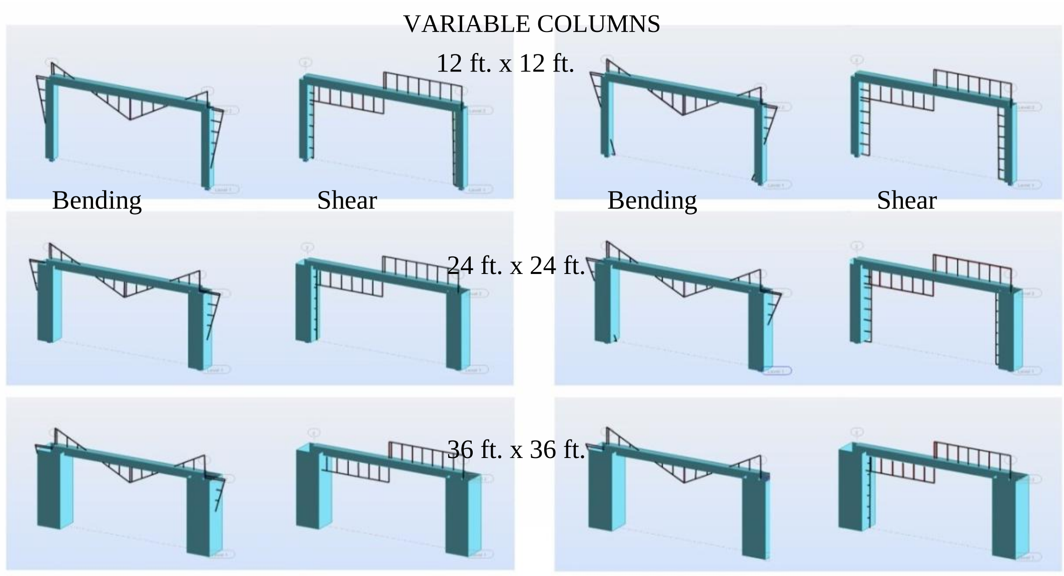


Fig. 10 Basic Beam and Column Concepts utilized

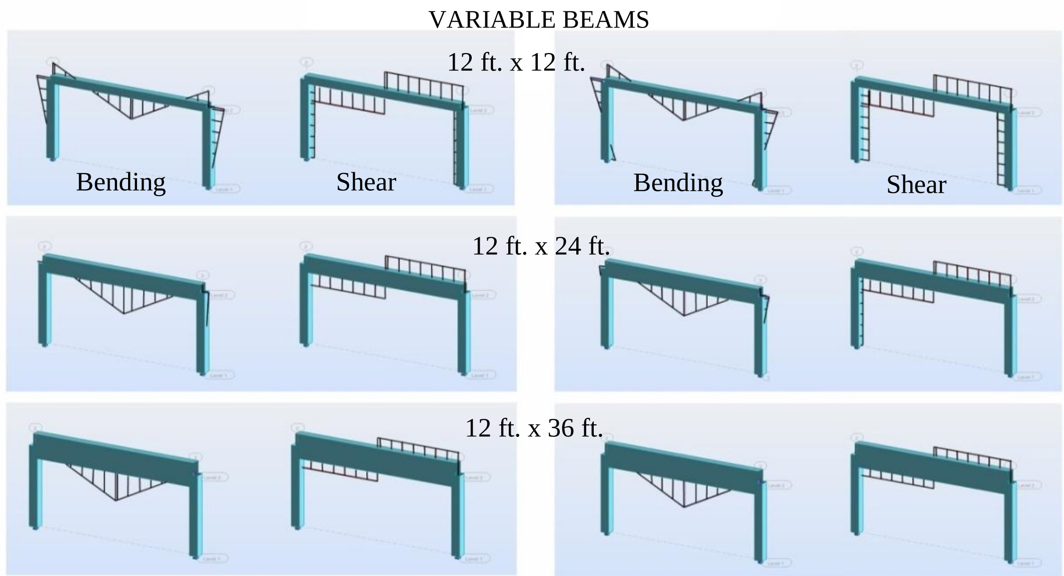
Pinned and fixed supported portal frames acted upon by a 1.0 kip gravity load behave similarly, when analyzing their shear and bending moment diagrams. As the beams section increases in relation to the columns size, the curve of the bending moments steadily shifts towards the center of the frame. The portal frame members behave more like a simply supported beam. On the other hand, as the columns sections increase relative to the beam sizes, the bending moments diagrams gradually shifts away from the center and the frame resembles more a fully fixed structure. In case of using a constant section for both columns and beam, the behavior is the average of simply supported and fully fixed beam (bending moment =1/2 (PL/4 + PL/8) = PL/6). Figs. 11a-d illustrate the diagrams for shear and bending moment under various conditions.

When the portal frame is subjected to a 1.0 kip lateral load, the effects on the shear and bending moment diagrams is insignificant in the case of pinned frame having columns sizes change as the beam cross-section remains fixed. Conversely, in the example of a fixed frame, as the column sizes increase the columns act more similar to a cantilever beam with the maximum bending moment of PL at the support. In the case of pinned-supported portal frames, as the beams progressively grow in size while the column cross-section is restrained, the behavior of the portal frame is identical to the pinned frame when modifying the column cross-sections. Nonetheless, in the case of fixed portal frame, the greater the beam sizes relative to the columns sizes, columns act similar to a half cantilever having a maximum bending moment of PL/2 at both ends.

Figs. 12a-d illustrates the equivalent shear and moment curves for the fixed- and pinned-supported frames. Under lateral load condition for fixed-supported portal frame, when the column sections increase, the magnitudes of the bending moment and shear force on the beam reduces nearly to zero. For the pin-supported frame, the variations in the cross-sections of the beam do not influence the amount of the shear force or bending moment across the beam when exposed to the same lateral load.

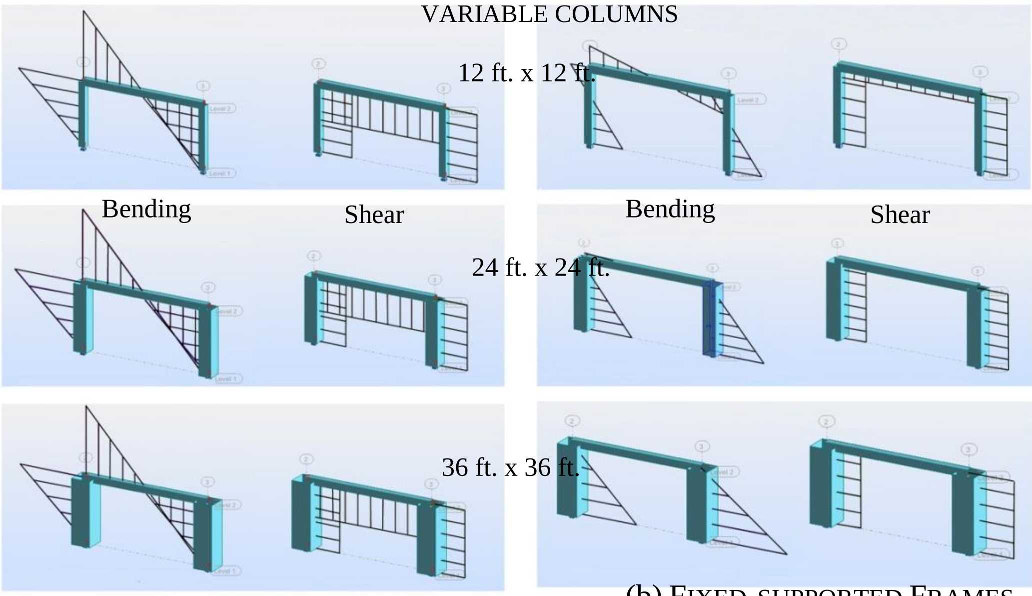


(a) PIN-SUPPORTED FRAMES (b) FIXED-SUPPORTED FRAMES

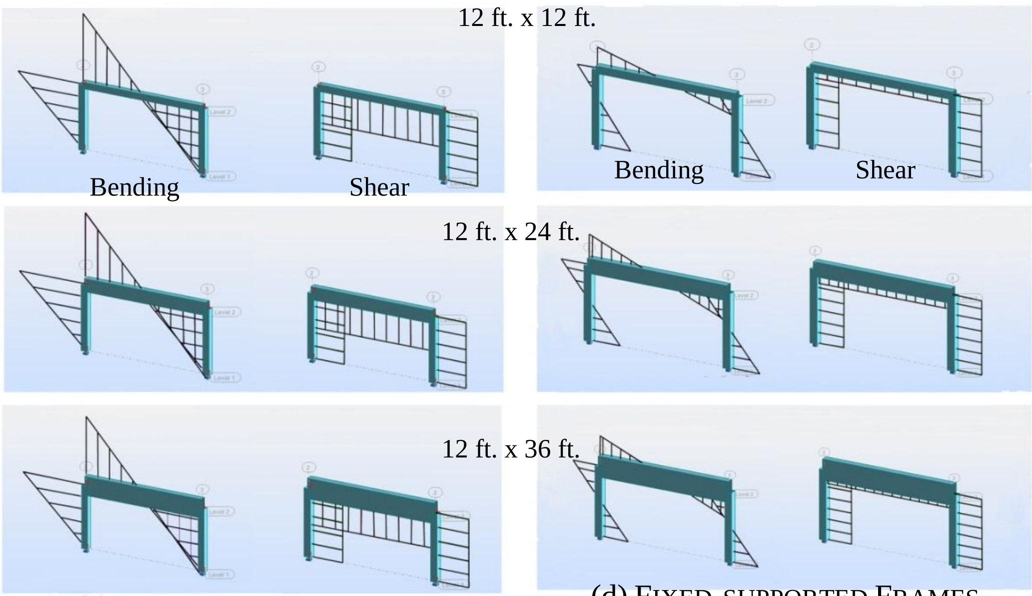


(c) PIN-SUPPORTED FRAMES (d) FIXED-SUPPORTED FRAMES

Fig. 11 Results due to a 1.0 kip Gravity Load



(a) PIN-SUPPORTED FRAMES (b) FIXED-SUPPORTED FRAMES



(c) PIN-SUPPORTED FRAMES (d) FIXED-SUPPORTED FRAMES

Fig. 12 Results due to a 1.0 kip Lateral Load

III. CONCLUSIONS

This research explores the development of more effective methods in which architectural structures can be studied, understood, enhanced, conversed, taught and learned. The investigation stressed the advancement of more effective techniques by which structural and architectural principles, including the understanding of structural behavior, which is vital to the design skills can be cultivated and learned. Academia in the field of structural engineering, as well as in architecture, should integrate an augmented concentration upon structural melody, structural poetry and conceptual analysis as a central activity.

A thorough approach to the understanding of structural behavior is to be accentuated, rather than depending on the supposition that such understanding essentially follows from studying the mathematical computations of structural analysis. Eventually, this kind of knowledge is the only check on the validity of utilizing structural engineering theories in design methodologies and CAD software.

BIM tools promoted focused and collaborative brainstorming activities among architecture and engineering students at all phases of the research project and thus, encouraged an exchange of ideas and information and allowed truly integrated design solutions to take form. The application of BIM tools in such a reflective mode to enrich learning of the fundamentals of architectural structures concepts allowed students to celebrate the full structural behavior and therefore this methodology has promoted deep learning and understanding of architectural structures.

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